Technical Report

Performance Analysis of Wireless-enabled PROFIBUS Networks

Paulo Baltarejo Sousa

HURRAY-TR-070607

Version: 1.0

Date: 10-06-2007

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Paulo Baltarejo Sousa

IPP-HURRAY!

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8340509

E-mail: pbs@dei.isep.ipp.pt

http://www.hurray.isep.ipp.pt

Abstract

Most of the industrial community is very reluctant to integrate new technologies in their consolidated automation systems, either by preconception or by the lack of matureness of these technologies. When addressing communication systems for control applications, these fears become even more acute. Usually, these communication systems are based on fieldbus networks, which provide adequate levels of performance, dependability, timeliness and maintainability. The PROFIBUS (PROcess FIeldBUS) is the most widely used fieldbus, with over 15 million nodes worldwide, in applications ranging from discrete-part automation to process control.

During the cellular phone and WLAN boom of the last decade, soon it became evident that wireless (radio-based) communications could leverage a whole new set of potentialities in field level and control applications. Moving parts in machinery, hand-held equipment, wearable computers, transportation equipment and autonomous vehicles are just a few examples requiring wireless/mobilecommunications.

However, the requirements of real-time systems, usually served by fieldbuses, impose the use of predictable and reliable communication services, which provide certain guarantees on eventual delivery of packets and delivery times. Therefore, running real-time applications using wireless technology can be especially challenging, because the real-time and reliability requirements are more likely to be jeopardized than they would be over a wired channel.

The RFieldbus architecture, driven by the European Project IST-1999-11316 consortium has provided a complete solution where multiple segments and multiple wireless cells are interconnected via Physical Layer (PhL) Intermediate Systems (operating as repeaters). This solution is compatible with standard PROFIBUS, but the fact that all messages are broadcast throughout the network leads tosome problems, namely no error containment between different segments and low responsiveness to failures. Additionally, it is also necessary to set the network parameters in a particular way which guarantees the operation of the network and leads to a lower performance.

These facts triggered the analysis and proposal of an alternative approach where the Intermediate Systems (ISs) operate at the Data Link Layer (DLL) level as bridges. This approach required two new protocols, one for supporting the communication between stations in different network segments – the Inter Domain Protocol (IDP), and another to support the mobility of wireless stations between different wireless segments – the Inter-Domain Mobility Procedure (IDMP).

The main objective of this dissertation is to compare the timing behaviour of the bridge and repeater-based approaches over error free and error prone environments. Additionally, we also intended to show that the bridge-based approach implementation is feasible and propose additional error detection and correction mechanisms which would improve its performance over error proneenvironments. To achieve these objectives two simulation tools have been developed, one for the repeater-based approach and another to the bridge-based approach, and a set of result analysis tools. Additionally, we have also developed another tool to simulate the mobility of wireless stations.

UNIVERSIDADE TÉCNICA DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

Performance Analysis of Wireless-enabled PROFIBUS Networks

Paulo Manuel Baltarejo de Sousa

(Licenciado)

Dissertação para obtenção do Grau de Mestre em

Engenharia Electrotécnica e de Computadores

Orientador: Doutor Luís Miguel Moreira Lino Ferreira

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Júri

Presidente:	Doutor Mário Serafim dos Santos Nunes
Vogais:	Doutor Manuel Alberto Pereira Ricardo
	Doutor Luís Miguel Moreira Lino Ferreira
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Keywords: Hybrid wired/wireless networks; Network simulation; Real-time systems; Real-time communications; Fieldbus networks.

Análise de Performance para Redes PROFIBUS Sem Fios

Resumo

A maioria da comunidade industrial apenas integra novas tecnologias nos seus sistemas de automação, após estas terem sido extensivamente testadas e amadurecidas. No caso dos sistemas de comunicação usados por aplicações de controlo esta tendência é ainda mais exacerbada devido à sua criticalidade para o funcionamento de qualquer planta fabril. Geralmente, estes sistemas de comunicação são baseados em redes de campo (*fieldbus*), dado que estas disponibilizam níveis adequados de desempenho, confiança de funcionamento, comportamento temporal e capacidade de manutenção. As redes baseadas na tecnologia PROFIBUS (acrónimo de PROcess FIeld BUS) são o tipo *fieldbus* mais utilizado em todo o mundo em aplicações de automação e controlo.

Durante a última década assistiu-se ao aumento exponencial da utilização de sistemas de comunicação sem fios (*wireless communications*), quer através do telefone celular (vulgo telemóvel) quer através das redes locais sem fios (*wireless local area network*), cedo ficou evidente que a tecnologia de comunicação sem fios poderia impulsionar um novo conjunto de potencialidades nas aplicações de automação e controlo. Veículos auto guiados, sensores em partes móveis de maquinaria e terminais portáteis, são alguns dos exemplos que requerem comunicação sem fios.

Todavia, os requisitos dos sistemas de tempo real, geralmente servidos por *fieldbuses*, impõem a utilização de serviços de comunicação previsíveis e confiáveis, que proporcionem certas garantias relativas à entrega de mensagens e do respectivo tempo em que são entregues. Consequentemente, o uso de comunicações sem fios em aplicações de tempo real pode ser um desafio, dado que a probabilidade dos requisitos de tempo real não serem cumpridos é maior do que usando sistemas de comunicação cablados.

O projecto Europeu RFieldbus, executado entre os anos de 2000 e 2002, foi uma importante iniciativa no sentido da concepção de um sistema de comunicação industrial do tipo *fieldbus* híbrido suportado pela tecnologia PROFIBUS. Num sistema RFieldbus, a ligação entre componentes cablados e componentes sem fios é feita através de dispositivos de interligação que operam ao nível da Camada Física (como repetidores). Esta solução é compatível com o standard PROFIBUS, mas o facto de todas as mensagens serem enviadas para todos os nós da rede, a não contenção de erros entre os diferentes segmentos e a necessidade de se efectuar uma configuração especial dos parâmetros da rede, levam a uma diminuição do seu desempenho.

Estes factos levaram à análise e proposta de uma nova abordagem, na qual os dispositivos de interligação operam como pontes (*bridges*, em inglês), e por isso ao nível da Camada de Ligação de Dados. Esta abordagem define dois novos protocolos, um para processar transacções entre estações pertencentes a meios de comunicação diferentes – o *Inter Domain Protocol* –, e outro para processar a mobilidade das estações móveis entre os segmentos sem fios – o *Inter Domain Mobility Procedure*.

O principal objectivo desta dissertação é comparar o comportamento temporal destas duas abordagens em ambientes sem e com erros. Adicionalmente, também se quer mostrar que a abordagem baseada em *bridges* é possível de ser implementado num sistema real. Para tal, foram desenvolvidas duas ferramentas de simulação, uma para a arquitectura baseada em *bridges* e outras para arquitectura baseada em repetidores, assim como um conjunto de ferramentas auxiliares de análise de resultados. Foi também desenvolvida uma outra ferramenta que permite simular a mobilidade das estações móveis.

Palavras-chave: Redes de comunicação híbridas cabladas e sem fios; Simulação de redes de comunicação; Sistemas de Tempo-Real; Comunicações de Tempo-Real; Redes Industriais.

Chapter 1

Overview

Fieldbus communications are now the most common way of interconnecting sensors, actuators and control devices in manufacturing and process control applications. The widespread use of wireless communication systems in the information technology industry and the availability of mature technology has triggered the appearance of fieldbus solutions which operate based on wireless technologies. This dissertation compares two of those approaches, based in results extracted from simulation. One approach extends PROFIBUS fieldbus technology by the use of repeaters, which interconnect, wired and wireless network segments and the other approach uses bridges for the same purpose.

1.1. Introduction

Most of the industrial community is very reluctant to integrate new technologies in their consolidated automation systems, either by preconception or by the lack of matureness of these technologies. When addressing communication systems for control applications, these fears become even more acute. That is why only a few fieldbus communication systems consolidated their market position, due to their technical features and also to big enterprise lobbies. From these, PROFIBUS (PROcess FIeldBUS) (IEC, 2000) is the most widely used, with over 15 million nodes worldwide (Weber, 2006), in applications ranging from discrete-part automation to process control.

During the cellular phone and WLAN boom of the last decade, soon it became evident that wireless (radio-based) communications could leverage a whole new set of potentialities in the field level and control applications. Moving parts in machinery, hand-held equipment, wearable computers, transportation equipment and autonomous vehicles are just a few examples requiring wireless/mobile communications.

However, the requirements of real-time systems, usually served by fieldbuses, impose the use of predictable and reliable communication services, which provide certain guarantees on eventual delivery of packets and delivery times. According to (Stankovic, 1989) a real-time computing system is a system in which its correctness depends not only on the logical results of computation, but also on the time at which results are produced. Therefore, running real-time applications using wireless technology can be especially challenging, because the real-time and reliability requirements are more likely to be jeopardized than they would be over a wired channel.

Traditionally, real-time systems are classified as being either *hard* or *soft* (Burns and Wellings, 2001). For hard real-time systems, it is imperative that no deadline is missed, whilst in soft real-time systems it is acceptable to miss some of them occasionally. In practical engineering contexts, the occasional loss of some deadline can be tolerated. This is either because the consequences of the loss can be negligible (i.e. one defectuous part per thousand) or because the robustness of the involved control algorithms imply the ability to react properly at the next invocation step without serious consequences.

Within this context, some commercial (Siemens, 2005) and research solutions (Lee and Lee, 2001; Willig, 2002; Miorandi and Vitturi, 2004) for providing the traditional PROFIBUS with wireless extensions have been proposed. Nevertheless, these solutions are quite limited either in terms of number of segments or wireless cells and in the support of mobility.

The RFieldbus architecture (RFieldbus, 2000; RFieldbus, 2000a), driven by the European Project IST-1999-11316 consortium has provided a complete solution where multiple segments and multiple wireless cells (hereafter, segments and wireless cells will be referred as domains) are interconnected via Physical Layer (PhL) Intermediate Systems (operating as repeaters). This solution (henceforth referred as repeater-based) is compatible with standard PROFIBUS, but the fact that all messages are broadcast throughout the network leads to some problems, namely no error containment between different domains and low responsiveness to failures.

These facts triggered the analysis and proposal of an alternative approach where the Intermediate Systems (ISs) operate at the Data Link Layer (DLL) level as bridges (Ferreira, Alves et al., 2002; Ferreira, Alves et al., 2003; Ferreira, Tovar et al., 2003). This approach (henceforth referred as bridge-based) required two new protocols, one for supporting the communication between stations in different domains – the Inter Domain Protocol (IDP), and another to support the mobility of wireless stations between different wireless domains – the Inter-Domain Mobility Procedure (IDMP).

1.2. Research Context

PROFIBUS was standardised in 1996 as an European standard (CENELEC, 1996). It is based on the International Standards Organisation (ISO) Open System Interconnection (OSI) reference model, however collapsed to just three layers: Physical Layer (PhL), Data Link Layer (DLL) and Application Layer (AL).

It is designed to provide different qualities of service in terms of timeliness, providing intrinsic mechanisms that distinguish the way high and low priority messages are transmitted. Its DLL employs a token passing mechanism to grant the medium access. Moreover, the PROFIBUS Medium Access Control (MAC) protocol, being based on the measurement of the real token rotation time, induces a well-defined timing behaviour to the worst-case message response time, since the upper bound for the actual token rotation time can be know *a priori* (Tovar and Vasques, 1999). Therefore, the PROFIBUS protocol is able to support guaranteed real-time traffic.

There are two kinds of stations: master and slaves. Only masters have access to the medium and slaves only have access to the medium when they reply to a master request.

The benefits of using wireless technologies are manifold. The ease of equipment installation, the systems configuration flexibility, the ability to evolve and the cuts in cabling and maintenance costs just to mention some. However, wireless channels are prone to more transmission errors caused by either channel outages (which occur when the received signal strength drops below a critical threshold) and/or interference. Therefore, the use of wireless technologies in a real-time system can jeopardize the timing requirements and reliability of this kind of system.

To integrate wired and wireless technologies in the same network system, there is the need of a special purpose device that is able to interconnect the different mediums systems, called Intermediate System (IS). The behaviour of the ISs is very important in this context. Within the context of this dissertation only IS operating as repeaters and as bridges are considered.

Traditionally, a repeater act as signal regenerator, but it can also interconnect communication systems with different Physical Layer (PhL) protocols. For that purpose, a repeater may require the implementation of more than bit-by-bit repeating functionality. This is the case when it interconnects communication systems with different frame formats or different bit rates, for instance. A repeater does not perform any address filtering, thus a "broadcast" network is created. Consequently, the use of repeaters implies a single MAC address space.

To give a better intuition of the interconnection of wired and wireless communication systems, a repeater-based hybrid wired/wireless network example is presented in Figure 1.1. The network comprises four domains. Two are wired domains (D^2 and D^4) and the other two are wireless domains (D^1 and D^3). Three intermediate systems operating as repeaters (R1, R2 and R3) interconnect the wired and wireless domains. The network comprises two wired masters (M1 and M2), five wired slaves (S1, S2, S3, S4 and S5) and three wireless mobile stations, two masters (M3 and M4) and one slave (S6).

Wireless communications are relayed through Base Stations (BSs). A BS operates using two wireless channels: one to receive frames from wireless stations (uplink channel) and other to transmit frames to wireless stations (downlink channel). The network comprises two BSs, BS1 and BS2, which relay the wireless communications of wireless domains D^1 and D^3, respectively.

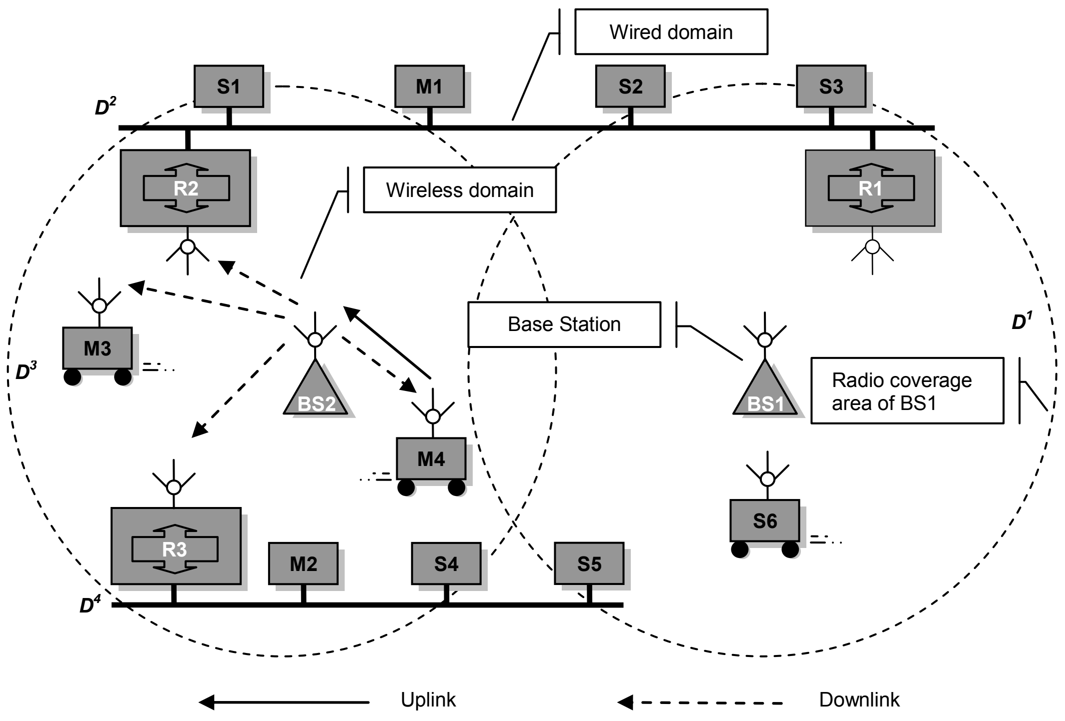

Figure 1.1 – Repeater-based network example

In this approach, all messages transmitted either by the masters (e.g., the token or request messages) or by the slaves (e.g., responses to masters' requests) are broadcasted throughout the overall network. Moreover, all masters in the network belong to the same logical ring. For this particular example, the token rotation can have the following sequence: … → M1 → M2 → M3 → M4→M1… .

In the repeater-based approach, inter-domain mobility is supported, and is implemented in a very simple and efficient way. Periodically, one specific master in the system (denoted as Mobility Master) emits a special non-acknowledged request: the `Beacon Trigger`. This message is received by all BSs in the system, which in turn start to transmit `Beacon` frames in their respective radio channels. When the wireless stations receive the `Beacon` frames, they start assessing the quality of the different radio channels operating in the network. At the end of this assessment phase, wireless stations switch to the channel with the best quality. Due to the broadcast nature of the network, other timing parameters must also be properly set for the system to work correctly.

Bridges operate at DLL level. Assuming, a two-port bridge interconnecting two different network segments, frames arriving to one bridge port are only relayed to the other port if the destination address embedded in the frame corresponds to the MAC address of a station physically reachable through that other port.

With a MAC protocol as the one used in PROFIBUS (timed token passing), a bridge needs to have two network interfaces, both supporting the same DLL and specifically the same MAC protocols. This means that such a dual-port PROFIBUS bridge would contain two master stations.

Figure 1.2 presents a bridge-based hybrid network example similar to the repeater-based hybrid network example presented in Figure 1.1. The network is composed by two structured wireless domains D^1 and D^3, and two wired domains D^2 and D^4. In the system there are two wired masters (M1 and M2), two wireless mobile masters (M3 and M4), five wired slaves (S1, S2, S3, S4 and S5) and one wireless mobile slave (S6). Three bridge devices are considered (B1 (M8:M5), B2 (M6:M9), B3 (M10:M7)).

Network operation is based on the Multiple Logical Ring (MLR) approach (Ferreira and Tovar, 2004). Therefore, each wired/wireless domain has its own logical ring. In this example, four different logical rings exist, one for each domain: (D^1 (M3 → M8), D^2 (M1 → M5 → M6), D^3 (M4 → M9 → M10) and D^4 (M2 → M7)).

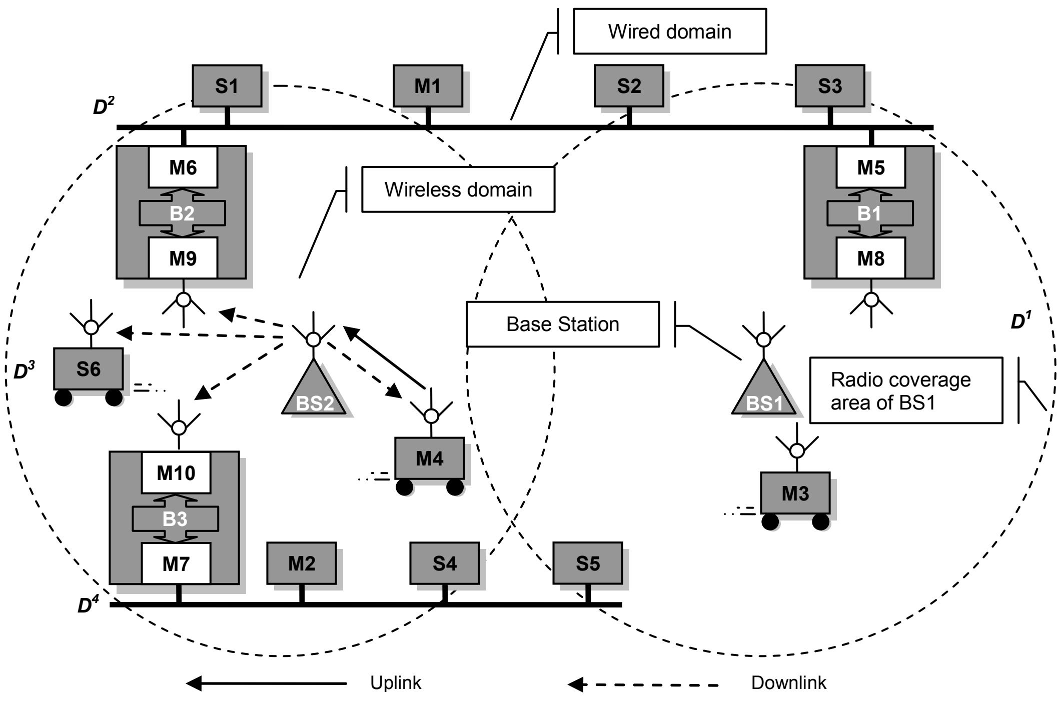

Figure 1.2 – Bridge-based network example

As a consequence of the MLR, this approach requires two new protocols, one for supporting the communication between stations in different domains – the Inter Domain Protocol (IDP), and another to support the mobility of wireless stations between different wireless domains – the Inter-Domain Mobility Procedure (IDMP).

1.3. Research Objectives

The main objective of this dissertation is to compare the timing behaviour of the repeater and bridge-based approaches over error free and error prone environments. Additionally, we also intended to show that the bridge-based approach implementation is feasible and propose additional error detection and correction mechanisms which would improve its performance over error prone environments. To achieve these objectives two simulation tools have been developed, one to the repeater-based approach and another to the bridge-based approach, and a set of result analysis tools. Additionally, we have also developed another tool to simulate the mobility of wireless stations.

1.4. Contributions of this Dissertation

The main research contributions of this dissertation are the following:

- An analysis of the timing behaviour of the repeater and bridge-based approaches based on simulation results;
- The proposal of error correction and detection protocol for the bridge-based approach;
- A comparative performance analysis between repeater and bridge-based approach considering communications over error free medium (Sousa, Ferreira et al., 2006);

- A comparative performance analysis between repeater and bridge-based approach considering communications over error prone medium (Sousa and Ferreira, 2007).

The above research contributions were based on a set of tools which have been developed within the objectives of this dissertation:

- The Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator.
- The Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator.
- The Mobility Simulator.
- Tools for simulation output analysis, which have been used to validate the simulation models and to extract information from the output data files generated by the simulators:
    - Timeline Visualization Tool;
    - Output data Analysis Tool
        - Message Stream Response Time Analysis
        - Central Limit Theorem
        - State Machine Statistical Analysis
        - Frame Accounting

1.5. Structure of the Dissertation

The structure of this dissertation is as follows.

Chapter 2, presents an overview of the PROFIBUS protocol and the most relevant aspects of the repeater and bridge-based architectures. In Chapter 3, some problems of the bridge-based architecture related to the management of errors are identified and a new set of mechanisms to overcome these problems is proposed.

Chapter 4 surveys some of the existing simulation tools for the development of network simulation models and describes in more detail the adopted simulation environment.

The repeater and the bridge-based architectures are both compatible with standard PROFIBUS, therefore their simulation model implementation share the same standard PROFIBUS modules. Chapter 5 describes the entities which enable the simulation of a standard PROFIBUS network which are common to both architectures.

The simulation model implementation by the Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator is detailed in Chapter 6 and Chapter 7 describes the simulation model implemented by the Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator.

In the approaches analysed in this dissertation, wireless stations are able to move between different domains. Therefore, in order to achieve more realistic simulation results, it is necessary to know, at which points in time a wireless mobile station moves between different wireless domains. To obtain this information, a tool was developed which simulates the mobility of wireless stations over a factory floor and the radio signal quality of different wireless domains at station location – the Mobility Simulator. This tool is described in Chapter 8.

A comparative performance analysis between the repeater and bridge-based architectures is performed in Chapter 9 which evaluates the influence of varying some network parameters in the timing behaviour of each approach.

In order to evaluate the performance of both architectures considering transmission over an error prone medium, Chapter 10 presents simulation results in which the transmission errors are modelled according to the Gilbert-Elliot Channel Model. Additionally, the changes proposed, in Chapter 3 for the bridge-based architecture of this dissertation are evaluated.

Finally, Chapter 11 summarises the contributions of this dissertation, provides conclusions, and describes some lines of work that can potentially be explored as a natural sequence of the work described in this dissertation.

Chapter 2

Technological Context: Communication Infrastructure

This chapter presents an overview of the PROFIBUS protocol as also the most relevant aspects of the repeater and bridge-based architectures.

2.1. Introduction

The repeater and bridge-based architectures extend the PROFIBUS protocol to support wireless communications and mobility of the stations between wireless domains. Both approaches are compatible with PROFIBUS protocol.

In this chapter, we describe the most relevant characteristics of PROFIBUS protocol (Section 2.2). The chapter continues by presenting the most relevant issues of the repeater (Section 2.3) and bridge-based architectures (Section 2.4). The objective is to provide the reader with the necessary background and intuition for tackling the remaining chapters of this dissertation.

2.2. Relevant Details on PROFIBUS

2.2.1. General Features

PROFIBUS was standardised in 1996 as an European standard (CENELEC, 1996). It is based on the International Standards Organisation (ISO) Open System Interconnection (OSI) reference model, however collapsed to just three layers: Physical Layer (PhL), Data Link Layer (DLL) and Application Layer (AL). There is also a transversal management functionality called Fieldbus Management (FMA1/2), which is responsible for the management of the layers 1 and 2, the PhL and the DLL, respectively.

The PROFIBUS PhL can use the RS-485 standard over twisted pair or coaxial cable for the transfer of data, with bit rates up to 12 Mbit/s. For special applications, it is also possible to use other types of physical media, like optical fibre, power cable or RS-485-IS (for intrinsically safe applications).

The PROFIBUS DLL uses a token passing procedure to grant bus access to masters, and a master-slave procedure used by masters to communicate with slaves (or other masters). Slaves do not have communication initiative. They are only capable of transmitting a response (or an acknowledgement) upon master request. The token is passed between masters in ascending Medium Access Control (MAC) address order, thus the masters organise network access in a logical ring fashion.

The PROFIBUS standard considers two different types of Application Layer profiles: PROFIBUS-FMS (Fieldbus Message Specification), which is being abandoned due to design complexity and cost, and PROFIBUS-DP (Decentralised Peripherals), which is being increasingly adopted for industrial automation and process control applications. PROFIBUS-DP is particularly suited for the cyclic exchange of data between master (Programmable Controllers, PC, etc.) and slave devices (valves, I/O devices, drives, etc.). In this dissertation DP is assumed to be used in master and slave devices.

2.2.2. Data Link Layer (DLL)

Message Cycle

In PROFIBUS, only master stations may initiate transactions, whereas slave stations do not transmit on their own initiative, but only upon (master) requests. The station that sends an *Action Frame* (the first frame transmitted in each transaction) is the *initiator* of the transaction, while the addressed one is the *responder*. A transaction (or message cycle) consists on the request or a send/request frame from the initiator (always a master station) and the associated acknowledgement or response frame from the responder (either a master station or a slave station, but typically a slave station).

All stations monitor all the requests but will only acknowledge or respond if, and only if, they are the addressees in the initiator's request. Moreover, the acknowledgement or response frame must arrive before the expiration of the `Slot Time` (T_{SL}), which is a master DLL parameter otherwise the initiator repeats the request a number of times defined by the `max_retry_limit`, another master's DLL parameter.

Token Passing

The token is passed between masters in ascending address order. The only exception is that in order to close the logical ring, the master with the highest address must pass the token to the master with the lowest one. Each master knows the address of the previous station (PS – `Previous Station` address), the address of the following station (NS – `Next Station` address) and, obviously, its own address (TS – `This Station` address).

If a master station receives a token addressed to itself from a station (`Source address` (SA) of the token frame, a frame format description is presented latter) registered in the `List of Active Stations` (LAS) as its predecessor (PS = SA) then this master becomes the token owner, and may start processing message cycles. On the other hand, if a master receives a token frame from a station which is not its PS, it assumes that an error has occurred, and it will not accept the token frame. However, if it receives a subsequent token from the same station, it accepts the token and assumes that the logical ring has changed. In this case, it updates the original PS value by the new one in its LAS table.

If after transmitting the token frame and within the `Slot Time`, the master detects bus activity, it assumes that its successor owns the token. Therefore, it ceases monitoring the activity on the bus. In case the master does not recognise any bus activity within the T_{SL}, it repeats the token frame and waits another T_{SL}. If it recognises bus activity within the second T_{SL}, it stops working as an active master, assuming a correct token transmission. Otherwise, it repeats the token transmission to its NS for the last time. If after the second retry there is no bus activity, the token transmitter tries to pass the token to the next successor. It continues repeating this procedure until it finds a successor from its `List of Active Stations` (LAS).

Token Cycle

After receiving the token, a master station is allowed to execute message cycles during `Token Holding Time` (T_{TH}) that is computed as follows:

$$T_{TH} = T_{TR} - T_{RR} \tag{2.1}$$

T_{TH} is equal to the difference, if positive, between the `Target Rotation Time` (T_{TR}) and the `Real Rotation Time` (T_{RR}) of the token. T_{TR} is a parameter common to all masters in the network, which must be set to the expected time for the token cycle. T_{RR} is the time measured between two consecutive token receptions – the token cycle.

PROFIBUS defines two main categories of messages: high-priority and low-priority, each using a different transmission queue that is handled differently by the DLL. At the arrival of the token, the T_{TH} timer is loaded with the value corresponding to the difference between T_{TR} and T_{RR}. If the token is delayed, then T_{TH} is set to zero and the master is only allowed to perform, at most, one high-priority message transaction. Otherwise, the master is allowed to perform high-priority message transactions until the value of the T_{TH} timer becomes negative. Low-priority messages are only transmitted when the high-priority queue is empty and T_{TH} is still positive. Note that once a message cycle is started it is always completed, including any retries, even if in meanwhile T_{TH} expires.

(Re)Initializing the Logical Ring

The logical ring of PROFIBUS is supported by two tables: the `Gap List` (GAPL) and the LAS. It may also optionally maintain a `Live List` (LL) table.

The GAPL consists on the address range from address TS until NS. This includes all possible addresses, except the address range between `Highest Station Address` (HSA), which cannot be a master's address, and 127, which does not belong to the Gap.

Initialization is primarily a special case of updating the LAS and the GAPL. If after power on of a master station in the LISTEN_TOKEN state a time-out is encountered, i.e., no bus activity within `Time-Out Time` (T_{TO}), it shall claim the token in the CLAIM_TOKEN state and it starts initializing the logical ring.

The master station with the lowest station address starts initialization by transmitting two token frames addressed to itself (`Destination Address` (DA) = SA = TS) it informs any other master stations (entering a NS into the LAS) that it is now the only station in the logical token ring. Then it transmits an `FDL_Request_Status` frame to each station in an incrementing address sequence, in order to register other stations. The first master station to answer with `Ready_to_Enter_Logical_Ring` is registered as NS in the LAS and thus closes the Gap range of the token holder. Then the token holder passes the token to its NS.

When a master station is in the LISTEN_TOKEN state, it shall monitor the bus activity in order to identify those master stations which are already in the logical token ring. For that purpose token frames are analyzed and the station addresses contained in them are used to generate the LAS.

After listening to two complete identical token rotations, the master must remain in the LISTEN_TOKEN state until it is addressed by an `FDL_Request_Status` transmitted by its predecessor (PS). If it succeed, it must respond with `Ready_to_Enter_Logical_Ring` and waits for the token frame addressed to it in the ACTIVE_IDLE state.

When a master station is in the LISTEN_TOKEN state all frames are neither acknowledged nor answered.

Ring Maintenance

The ring maintenance mechanism is distributed by all master stations. As mentioned, each PROFIBUS master maintains two tables: the GAPL and the LAS.

Each master station when holds the token frame checks its Gap addresses every time its `Gap Update Timer` (T_{GUD}) expires. If a station acknowledges positively to the GAP request (an `FDL_Request_Status` frame), with the state `Not_Ready_to_Enter_Logical_Ring` or `Slave_Station`, it is accordingly marked in the GAPL and the next address is checked. If a station answers with the state `Ready_to_Enter_Logical_Ring`, the token holder changes its GAPL and passes the token to the new NS. This (master) station, which has newly been admitted to the logical ring, has already built up its LAS when it was in the LISTEN_TOKEN state, so it is able to determine its GAPL and its NS. This mechanism allows masters to track changes in the logical ring due to the addition (joining) and removal (leaving) of stations. This is accomplished by examining (at most) one Gap address per token visit, using an `FDL_Request_Status` frame after the execution of all high-priority transactions, and if the value of T_{TH}, is still positive.

Error Handling

Additionally, in order to enhance the communication system's reliability, PROFIBUS handles some operational or error states, concerning logical ring management. In (Carvalho, Carvalho et al., 2005) and (Willig and Wolisz, 2001) is presented which fault-tolerant mechanisms are activated and their effects on the network behaviour. The most important error situations within the context of this document are the token lost, “heardback removal” and error skipping:

– Token lost. This abnormal situation is clearly recovered by means of a continuous monitoring activity performed by each master in the logical ring. If a period of inactivity longer than the T_{TO} is detected, then the token is claimed by the master with the lowest address in the logical ring, and the logical ring is re-initialised.
– Heardback removal. Whenever a master is sending a token frame it must hear from the medium all transmitted bits in order to detect a defective transceiver. If the token frame sender detects differences between the transmitted and the received token frame in two consecutive transmissions then it must remove itself from the logical ring.
– Error skipping. A master station must remove itself from the logical ring when a token frame is transmitted, in which its address is “skipped” (i.e., the address of TS lies within the address range spanned by the sender and the receiver of the token frame).

DLL Frame Formats

PROFIBUS DLL defines three types of request/response frames, which are the `Fixed Length with no Data Field`, the `Fixed Length with Data Field` and the `Variable Data Field Length`, as illustrated in Figure 2.1 a), c) and d), respectively.

Each of these three types includes the following fields: `Destination Address` (DA), `Source Address` (SA) and `Frame Control` (FC). The FC field is an octet where the frame type is specified and the function code (for more details the reader is referred to Section 4.7.3 of (CENELEC, 1996)). These frames also include the `Start Delimiter` (SDx), `Frame Check Sequence` (FCS) and the `End Delimiter` (ED).

Variable data field length frames additionally contain two `Data Length` fields (LE and LEr) and they can optionally include the `Destination Address Extension` (DAE) and `Source Address Extension` (SAE), in the `Data` field. These extension fields can be used to identify the AL service which originated the frame, as well as the destination service.

PROFIBUS also defines the `Short aCknowledgement` frame (SC) and the `Token` frame, illustrated in Figure 2.1 b) and e), respectively. The first consists of a single byte frame, and it is used as positive acknowledgement to a request.

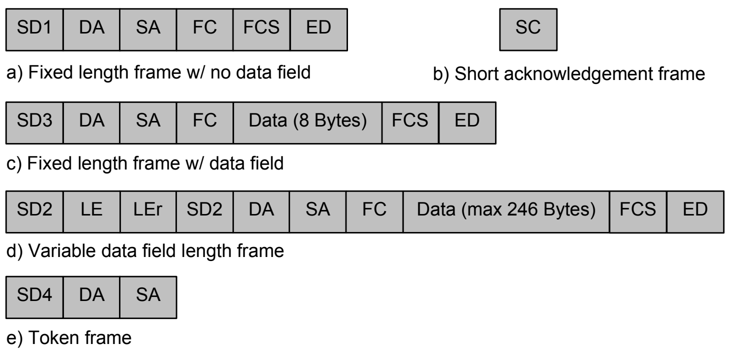
SD1
DA
SA
FC
FCS
ED
SC
a) Fixed length frame w/ no data field
b) Short acknowledgement frame
SD3
DA
SA
FC
Data (8 Bytes)
FCS
ED
c) Fixed length frame w/ data field
SD2
LE
LEr
SD2
DA
SA
FC
Data (max 246 Bytes)
FCS
ED
d) Variable data field length frame
SD4
DA
SA
e) Token frame

Figure 2.1 – PROFIBUS DLL frame formats

Data Link Layer Services

PROFIBUS defines 4 types of data transfer services: `Send Data with Acknowledge` (SDA); `Send Data with No acknowledge` (SDN); `Send and Request Data` (SRD) and `Cyclic Send and Request Data` (CSRD).

The SDA service allows a user to transmit data to another station and receive a `Short Acknowledge` confirming its reception by the responder station. The SDN service permits to transfer data to a single station, to a group of stations (multicast) or to all stations (broadcast). The SRD service allows the transmission of a message to another station and the retrieval of a response. This service can be used, for example, to send the output settings for an I/O device and retrieve the state of the device's input ports. The CSRD builds upon the SRD service adding the capability of transferring data periodically, according to the user requirements. The CSRD service is usually not implemented in current commercial hardware platforms.

Timing Parameters

The PROFIBUS standard defines several timing parameters, some of which are relevant in the context of this document, such as the `Idle Time` (T_{ID}), the `Slot Time` (T_{SL}) and `Time-Out Time` (T_{TO}) parameters, which are briefly explained next.

There are two `Idle Time` (T_{ID}) parameters - T_{ID1} and T_{ID2}. T_{ID1} is a period of inactivity, inserted by a master station, after an acknowledgment, response or token frame. This parameter must be set as follows:

$$T_{ID1} = \max\{T_{SYN} + T_{SM}, \min T_{SDR}, T_{SDI}\} \tag{2.2}$$

where, T_{SYN} (`Synchronisation Time`) is the minimum time interval for an idle bus state before a station may accept the beginning of an action or token frame. T_{SM} (`Safety Margin Time`) is the time that elapses after the end of the T_{SYN} which is required by the receiver circuitry to be ready to start receiving a frame. $minT_{SDR}$ is the `minimum Station Delay of a Responder Time`. T_{SDI} is the `Station Delay of the Initiator Time`, after which the initiator is ready to start receiving a frame from the responder. Figure 2.2 depicts an example where the `Transmission Delay Time` (T_{TD}) due to the network propagation delay is also illustrated.

T_{ID2} is the idle time inserted by a master station after transmitting an unacknowledged request frame. T_{ID2} must be set as follows:

$$T_{ID2} = \max\{T_{SYN} + T_{SM}, \max T_{SDR}\} \tag{2.3}$$

where, $maxT_{SDR}$ is the `maximum Station Delay of a Responder Time`.

The `Slot Time` (T_{SL}) is used by a master station to detect if a transaction with a slave (or with its successor, in the token passing) has failed. A timer is loaded with T_{SL} at the end of the transmission of a request frame. Upon its expiration, the master station may execute another retry for the same request, if the number of retries executed is smaller than the `max_retry_limit` parameter, or it may inform the upper layers of a transmission failure. A timer is also loaded with T_{SL} after transmitting the token frame. If it expires before a master has detected any activity in the bus then it signals the MAC layer in order to take the appropriate actions according to the token passing procedure.

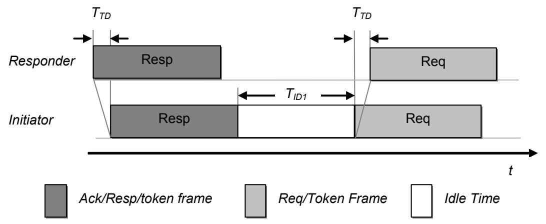

Figure 2.2 – `Idle Time` parameter – T_{ID1}

The `Slot Time` parameter (T_{SL}) must be set to the maximum between two values – T_{SL1} and T_{SL2}. T_{SL1} can be calculated as follows:

$$T_{SL1} = 2 \times T_{TD} + \max T_{SDR} + 11 bit + T_{SM} \tag{2.4}$$

where *bit* is the time duration of a bit. T_{SL2} can be calculated as follows:

$$T_{SL2} = 2 \times T_{TD} + \max T_{ID1} + 11 bit + T_{SM} \tag{2.5}$$

Note that all masters in the network must hold the same T_{SL} value, due to the token passing mechanism.

The `Time-Out Time` (T_{TO}) controls the token passage, in PROFIBUS, a token lost is detected when a master does not detect any network activity for a time period defined by its T_{TO}, which is set to as follows:

$$T_{TO} = 6 * T_{SL} + 2 * n * T_{SL} \tag{2.6}$$

where n is the master address. In Eq. 2.6, the first term makes sure that there is sufficient difference to the maximum possible T_{ID} between two frames (recall Eq. 2.4 and Eq. 2.5). The second term ensures that the master stations start their token claiming procedure in different moments after an error has occurred.

2.2.3. Application Layer (AL): PROFIBUS-DP

The PROFIBUS-DP (DP for short) protocol (IEC, 2000) is specially suited for the exchange of data between controllers (typically masters) and field devices like I/O, drives or valves (typically slaves). DP provides the functionalities to configure field devices and to perform cyclic exchange of data between the controller and the field devices.

The main functionalities of PROFIBUS-DP are related to the reading and writing of variables from/to slave devices. The retrieval of data is made cyclically by the DP protocol, according to the timing parameters configured by the user. This is an important feature of this protocol, since it enables the communication between stations in different domains in the Bridge-based solution.

2.3. Relevant Details on the Repeater-Based Hybrid Wired/Wireless PROFIBUS Architecture

A hybrid wired/wireless fieldbus network is composed of wired and wireless stations. A wired domain is a set of stations physically connected through a wired bus. A wireless domain is composed by a set of wireless stations that intercommunicate either directly or indirectly via wireless (e.g., radio) channels. Wireless communications may be achieved by two ways: in a direct way or via Base Station (BS). If wireless stations are able to intercommunicate directly, the wireless domain is called an *ad-hoc* domain. Otherwise, if messages are relayed by a BS the wireless domain is usually called a *structured* domain. In this dissertation we always assume that we are using the structured approach since this is the only one that permits the mobility of wireless stations.

A BS operates as a wireless repeater using two radio channels, one to receive frames from the wireless stations (the uplink channel), and another to transmit frames to wireless stations (the downlink channel). The interconnection between wireless and wired domains is done through a special device designed as Intermediate Systems (IS). This device has to be provided with two communication interfaces: one to connect to the wired domain (wired communication interface) and another to connect to the wireless domain (wireless communication interface).

In the Repeater-Based Hybrid Wired/Wireless PROFIBUS approach (Alves, 2003), the ISs operate essentially as repeaters, that is, they receive frames from one communication interface and retransmit those frames using the other communication interface.

Figure 2.3 depicts a wired/wireless fieldbus network scenario. The ISs (operating as repeaters) may include the BS functionalities in their wireless communication interfaces. This network scenario comprises four domains, two wired domains (D^2 and D^4) and two structured wireless domains (D^1 and D^3). Three repeaters (R1, R2 and R3) interconnect the domains. The wireless communications are relayed by two BSs (BS1 and BS2), included in the repeaters. The network also comprises three wired masters (M1, M2 and MM), two wireless mobile masters (M3 and M4), five wired slaves (S1, S2, S3, S4 and S5) and one wireless mobile slave (S6).

In order to guarantee the operation and interoperability of the hybrid wired/wireless fieldbus network there can be no more than one possible path between any two domains (tree-like topology), i.e., no closed loops can exist. The mobility procedure only makes sense when there are more than one wireless domain and when these domains are structured. The mobility procedure will be detailed later.

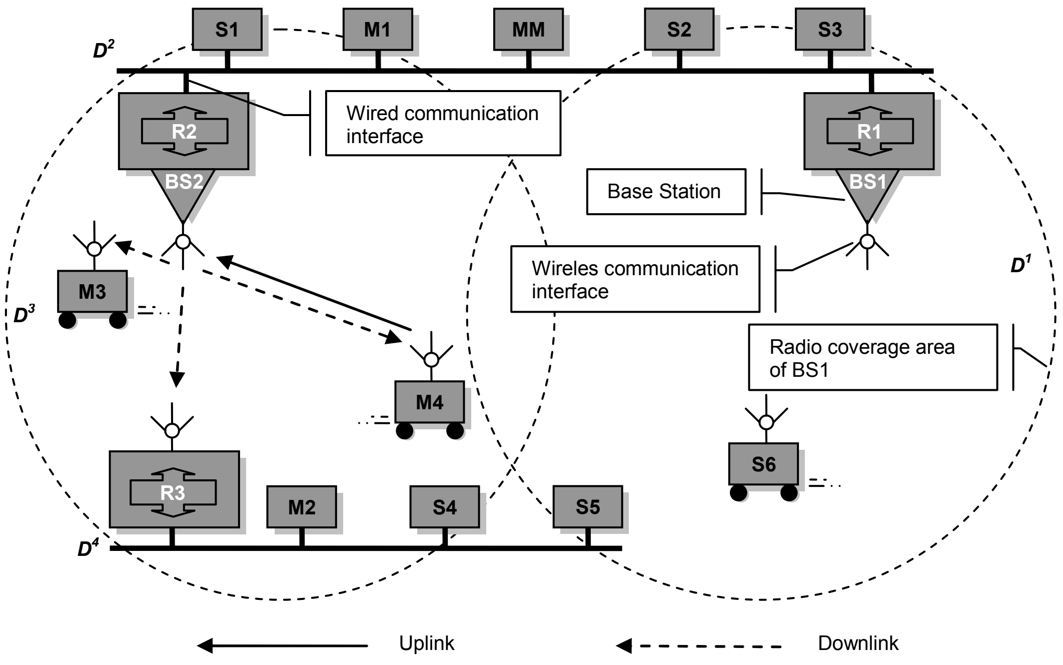
S1
M1
MM
S2
S3
D2
R2
BS2
Wired communication interface
R1
BS1
Base Station
Wireles communication interface
D1
M3
D3
M4
Radio coverage area of BS1
S6
R3
M2
S4
S5
D4
Uplink
Downlink

Figure 2.3 – Repeater-based hybrid wired/wireless PROFIBUS network example

2.3.1. Repeater Operation

As mentioned, in this approach the interconnection between domains is done by ISs operating as repeaters. Traditionally operating just as a signal regenerator, a repeater can also interconnect two networks with different PhL protocols (e.g., different bit rates).

A repeater is classified according to its relaying behaviour: *store-and-forward*, when a PhL frame must be completely received from one port before being transmitted to the other port; *cut-through*, when a repeater starts relaying a PhL frame which has not been completely received yet.

A repeater does not perform any address filtering. This result in a broadcast network, i.e., every station listens to every frame transmitted by any other station in the network. The use of repeaters implies a single MAC address space and that only one logical ring exists in the network. For that the network operation is based on the Single Logical Ring (SLR).

2.3.2. Wired/Wireless Domains Interconnection

A repeater may need to implement more than a bit-by-bit repeating functionality. This is the case when it interconnects communication media with different PhL frame formats. In order to encompass the functionalities referred, each repeater has an associated internal `relaying delay time` (t_{rd}). It is assumed that the repeaters always introduce a minimum inactivity period – `minimum idle time` (T_{IDm}) – between any consecutive PhL frames.

When a repeater receives a PhL frame from one port it must start the transmission in an instant, the `start relaying` instant ($t^{i \to j}_{sr}$), that guarantees that the retransmission is done without time gaps. $t^{i \to j}_{sr}$ is defined as the earliest time instant for start relaying a specific PhL frame from domain D^i to domain D^j, counted since the beginning of the reception of the PhL frame in domain D^i. The $t^{i \to j}_{sr}$ instant for a specific repeater depends on its operation mode – either store-and-forward or cut-through. For a cut-through repeater, the following is assumed:

- When relaying a frame from D^i to D^j, it cannot start being relayed while the first char of the DLL frame of D^i is not completely received by the repeater;
- The PhL frame cannot start being relayed while the length of the DLL frame is not known (by the repeater);
- When relaying a frame from D^i to D^j, the instant for start relaying the PhL frame must take into account that the repeater cannot run out of bits to relay from D^i to D^j, i.e., the transmission of a PhL frame in D^j must be continuous, without time gaps.

Taking these assumptions into account, which are illustrated in Figure 2.4, the `start relaying` instant for a cut-through operation mode repeater is defined as:

$$t^{i\to j}{}_{sr} = \max\left\{t^{i}{}_{dr}, t^{i}{}_{lk}, t^{i\to j}{}_{ng}\right\} \tag{2.7}$$

where:

- $t^i{}_{dr}$, the `data ready` instant, is the instant at which a predefined amount of DLL data has been received from D^i (ready to be relayed), counted since the beginning of the PhL frame in D^i. For the cut-through behaviour, it is considered that it is the instant at which the first DLL character is completely received;
- $t^i{}_{lk}$, the `length known` instant, is the instant at which the length of the DLL frame in D^i is known, counted since the beginning of the PhL frame in D^i;
- $t^{i\to j}{}_{ng}$, the `no gaps` instant, is the earliest instant to start relaying the PhL frame from D^i to D^j in a way that guarantees that the transmission in D^j is continuous.

Consider the example depicted in Figure 2.4. The first time instant is the data ready ($t^i{}_{dr}$), followed by the time instant when the length of the frame is known ($t^i{}_{lk}$). The last instant (thus the maximum of the three) is the time instant that guarantees a continuous retransmission of the PhL frame ($t^{i\to j}{}_{ng}$). This situation usually happens when the duration of the PhL frame in D^j is smaller than in D^i.

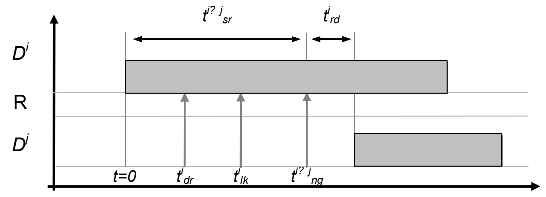

Figure 2.4 – Timing behaviour of a repeater

2.3.3. Traffic Adaptation

Network interconnection often brings up the problem of network congestion. Generally, if for any time interval, the total sum of demands on a resource is more than its available capacity, the resource is said to be congested for that interval. In the case of computer networks, resources include buffer space and processing capacity in the ISs and for example, if during a short interval, the buffer space of an IS is smaller than the one required for the arriving traffic, frame loss may occur (dropped frames) and the IS is said to be congested.

It is also true that the congestion problems depend dramatically on the type of IS used in the interconnection. Particularly if the ISs act as repeater, traffic congestion may occur as a result of the heterogeneous characteristics of the interconnected physical media. The heterogeneity in bit rates and in PhL frame formats in a broadcast network imposes the consideration of some kind of traffic adaptation scheme.

The timing diagram depicted in Figure 2.5 illustrates a sequence of transactions where one repeater interconnects the two domains and it is assumed that the PhL frame duration in D^j is twice the PhL frame duration in D^i and that $t^{i\to j}{}_{sr}$ is constant (for the sake of simplicity). Note that since the idle time is defined as the duration of a predefined number of (idle) bits separating consecutive frames in the network, its duration is assumed to be different for the two domains.

Figure 2.5 illustrates an increasing queuing delay ($q_1 < q_2 < q_3$), caused by the different physical media, that will impact on the `system turnaround time` (t_{st}) for certain transactions. The t_{st} for a message transaction is the time elapsed since an initiator ends transmitting a request frame until it starts receiving the correspondent response frame. For example, in the case of the request that corresponds to transaction 3, which is addressed to a responder in domain D^j, the system turnaround time for this transaction (t_{st3}) will be affected by the cumulative queuing delay (q_3) in the repeater.

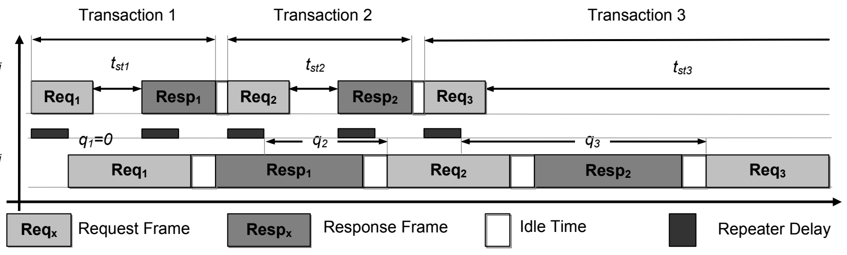

Figure 2.5 – Increasing queuing delay by a repeater

Traffic congestion in a repeater can be avoided through the insertion of additional inactivity (idle) intervals before issuing a message transactions (Alves, Tovar et al., 2002). Obviously, the insertion of this additional idle time reduces the number of transactions per time unit when the responder is not in the same domain as the initiator. The PROFIBUS MAC mechanism allows only one station (master or slave) to transmit at a given moment in time.

Every master in PROFIBUS has two different `Idle Time` parameters – T_{ID1} and T_{ID2}. As mentioned in Section 2.2.2, a master always waits T_{ID1} after receiving a response/acknowledgement or a token frame, before transmitting another frame. It must also wait T_{ID2} after transmitting an unacknowledged request frame, and before transmitting another frame (request or token). For a traditional wired network all masters may set their T_{ID1} and T_{ID2} parameters to the minimum default value, which is usually adequate to cope with bit synchronisation requirements.

In this approach, the traffic adaptation is based on the computation of the additional idle time that must be inserted by each master, in order to properly encompass the interconnection of heterogeneous physical media. The timing diagram depicted in Figure 2.6 illustrates a sequence of transactions where queuing delay is zero for all transactions, on the first repeater. This is due to the additional extra idle time.

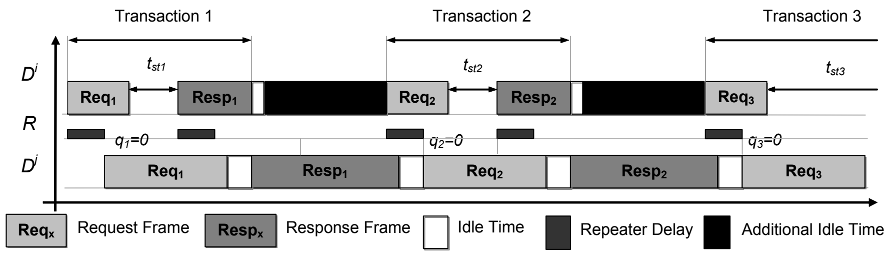

Figure 2.6 – Using additional idle time for media adaptation

Another consequence of using ISs that act as repeaters is related to the master PROFIBUS DLL parameter, the `Slot Time` (T_{SL}). Within the context of this approach, T_{SL} assumes a particular importance. On one hand, T_{SL} must be set large enough to cope with the extra latencies introduced by the repeaters. On the other hand, T_{SL} must be set as small as possible such as the system responsiveness to failures does not decrease dramatically, that is, a master must detect a message/token loss or a station failure within a reasonably small time. The timing diagram depicted in Figure 2.7 illustrates a transaction sequence that is relayed by two repeaters. One interconnects domains D^i and D^j and another interconnects domains D^j and D^k. It is assumed that the PhL frame duration in D^i and D^k is half the PhL frame duration in D^j and that $t^{x \rightarrow y}_{sr}$ is constant (for the sake of simplicity).

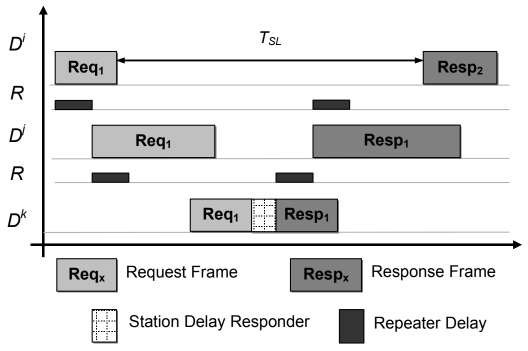

Figure 2.7 – `Slot Time` **(T_{SL})**

The setting of these parameters must be performed according to the procedures described in (Alves, 2003).

2.3.4. The Mobility Procedure

The mobility procedure (Alves, Bangemann et al., 1999) provides a seamless handoff for all kinds of wireless mobile stations (master/slave).

Due to the broadcast nature of the network, the mobility procedure just encompasses a mechanism for radio channel assessment and switching. The basics of this procedure are outlined next.

The `Mobility Master` (MM) (i.e., the master that has the responsibility of triggering the mobility procedure) sends periodically a special (unacknowledged) frame – the `Beacon Trigger` (BT). This BT frame is broadcast to the entire network and causes each BS to start transmitting a pre-defined number of `Beacon` frames in its downlink radio channel. Wireless mobile stations receive these `Beacon` frames, assess the signal quality of all (downlink) radio channels and switch to the radio channel set with best quality. Figure 2.8 shows the simplified operation of the mobility mechanism considering the network scenario depicted in Figure 2.3, in which master MM is operating as `Mobility Master`.

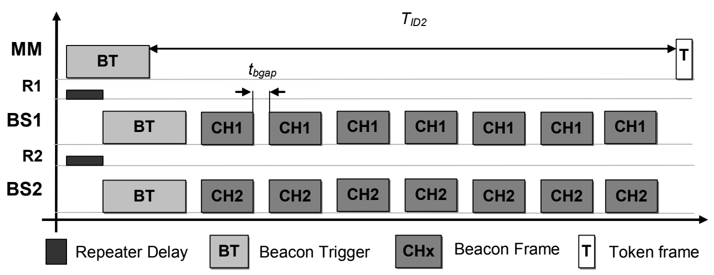

Figure 2.8 – Mobility procedure

In (Alves, 2003) the author shows how to calculate the number of beacons to be transmitted in each domain which guarantees that every wireless station is capable of evaluating the signal quality of each radio channel set. The setting of this parameter is different between each repeater and it must be set prior to runtime as well as the mobility period (i.e., the time interval between the queuing of each BT by the MM).

2.4. Relevant Details on the Bridge-Based Hybrid Wired/Wireless PROFIBUS Architecture

A Bridge-Based Hybrid Wired/Wireless PROFIBUS Network is composed by wired and wireless stations. The wireless stations have a wireless interface as defined in RFieldbus (Alves, Tovar et al., 2002; Rauchhaupt, 2002). The communication between stations is based on the PROFIBUS protocol with specific extensions to support wireless communications and mobility. In this approach, the IS operate as bridges. A bridge is a network device capable of relaying PROFIBUS DLL frames between the domains to which the bridge is connected. Although, a bridge can interconnect more than two different domains, for the sake of simplicity it is assumed that a bridge only interconnects two different domains.

The bridge relaying decision is based on a `Routing Table` (RT) which determines whether an incoming frame is to be relayed to the other port or not. A bridge is constituted by two `Bridge Masters` (BMs). A BM is a modified PROFIBUS master capable of receiving all frames arriving to its physical interface, and forwarding them to the other BM of the bridge according to the routing information contained on RT. These BMs operate almost as standard PROFIBUS masters and are assigned a PROFIBUS DLL address. Consequently, they take part of the domain's logical ring to which they are connected. For the sake of simplicity, it is assumed that BMs do not support any AL functionalities. Figure 2.9 presents a bridge (B3) with two BMs (M7 and M10). Wireless domains in the bridge-based architecture are structured. Therefore, in each wireless domain there is the need of a BS, which can be included in the bridge wireless front-end. Bridge B2 depicted in Figure 2.9 is such kind of bridge.

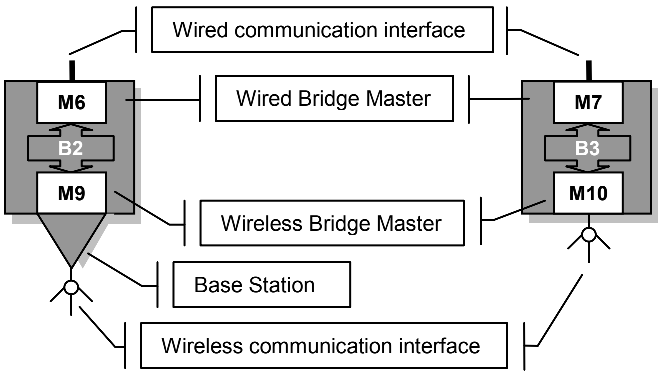

Figure 2.9 – Basic components of a bridge

Figure 2.10 illustrates an example network that comprises two structured wireless domains D^1 and D^3, and two wired domains D^2 and D^4. In the system there are two wired masters (M1 and M2), two wireless mobile masters (M3 and M4), five wired slaves (S1, S2, S3, S4 and S5) and one wireless mobile slave (S6). Three bridge devices are considered (B1 (M8:M5), B2 (M6:M9), B3 (M10:M7)).

Network operation is based on the Multiple Logical Ring (MLR) approach described in (Ferreira, Alves et al., 2002). Therefore, each wired/wireless domain has its own logical ring. In this example, four different logical rings exist: (D^1 (M3 $\rightarrow$ M8), D^2 (M1 $\rightarrow$ M5 $\rightarrow$ M6), D^3 (M4 $\rightarrow$ M9 $\rightarrow$ M10) and D^4 (M2 $\rightarrow$ M7)).

This approach requires two new protocols, one for supporting the communication between stations in different domains – the Inter Domain Protocol (IDP), and another to support the mobility of wireless stations between different wireless domains – the Inter-Domain Mobility Procedure (IDMP).

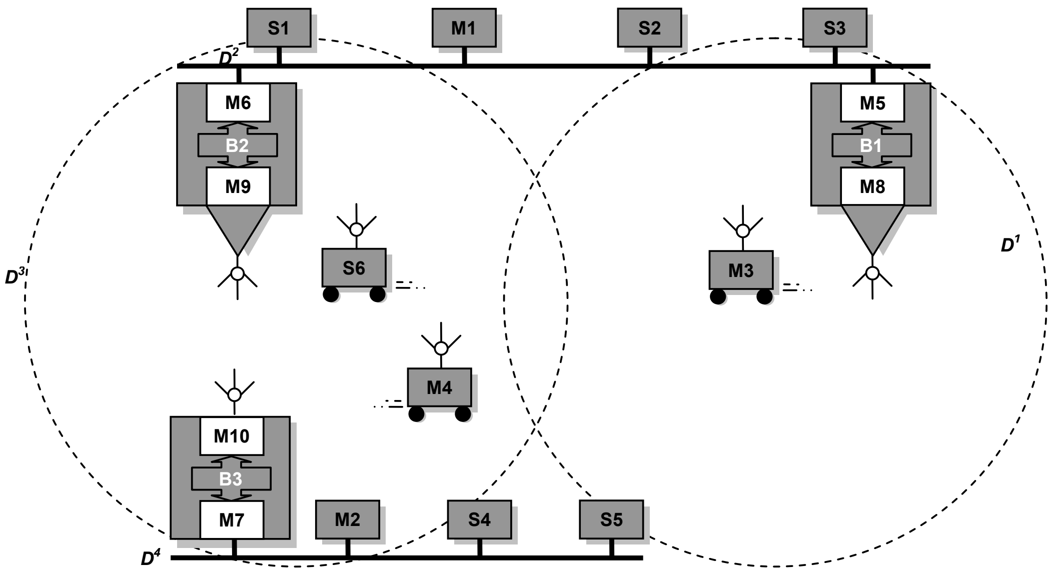

Figure 2.10 – Bridge-based hybrid wired/wireless PROFIBUS network example (IDP)

2.4.1. Supporting Inter-Domain Transactions

Definitions and Concepts

In PROFIBUS, a message transaction involves a request by the initiator and an "immediate" response by the responder station. In a bridge-based network, when a transaction involves stations in two different domains (which is a consequence of the MLR), that sequence of events is not possible, since the request frame must be relayed by the bridge(s) until reaching the responder. Similarly, the response must be relayed by the bridge(s) until reaching the initiator. Thus, three types of transactions must be considered: Intra-Domain, Inter-Domain and Intra/Inter-Domain transactions.

An IntrA-Domain Transaction (IADT) is a transaction that involves stations in the same domain. In this case, the initiator and responder stations operate according to the rules defined by the standard PROFIBUS protocol.

An Inter-Domain Transaction (IDT) is a transaction which involves stations in different domains. In such type of transaction, the request and response frames are relayed by the bridge(s) and their respective BMs using a specific protocol: the Inter-Domain Protocol (IDP). The frames involved in IDTs (both the standard PROFIBUS frames and the frames exchanged between the BMs) are referred to as Inter-Domain Frames (IDFs). IDFs conveying the request are called Inter-Domain Request (IDreq) frames and, equivalently, the frames which convey the response are called Inter-Domain Response (IDres) frames.

An Intra/Inter-Domain Transaction (IIDT) is a transaction that can be either an IADT or an IDT, depending if the involved stations are either in the same domain or in different domains. The stations involved in this kind of transactions are the wireless mobile stations.

Bridges perform routing based on the MAC addresses contained in the frames and on the RT entries of the incoming side.

The Inter-Domain Protocol

The IDP explores some PROFIBUS protocol features at the DLL and AL level, which enable a master to repeat the same request until receiving a response from the responder station. It defines the behaviour of the bridges and the codification of the frames exchanged between them, related to a specific IDT.

When a master starts a transaction with a station belonging to another domain (an IDT), it starts by transmitting a request frame addressed to the responder station (an IDreq frame). This frame is then relayed by only one of the BMs (denoted as BM_{ini} – *ini* stands for initiator) belonging to the initiator domain. BM_{ini} receives the IDreq frame, codes it according to the IDP (the frame format of IDP is presented in Table 2.1), and stores internally information about the transaction, in a structure called `List of Open Transactions` (LOT). Meanwhile, the PROFIBUS DLL of the initiator retries transmitting the same request since the BM_{ini} does not respond before the expiration of the T_{SL}. The DLL retries are executed by the initiator a number of times specified by the `max_retry_limit`, a DLL parameter.

The IDreq frame is relayed by the bridges until reaching the last BM, which belongs to the responder domain (denoted as BM_{res} – *res* stands for responder). BM_{res} decodes the original request frame and transmits it to the responder, which can be a standard PROFIBUS station (for example a wired PROFIBUS slave). When decoding the frame, the BM_{res} reconstructs the original frame as transmitted by the initiator (it even puts the initiator address (SA) on the request frame). Thus, from the responder's perspective the initiator seems to belong to the same domain. When the BM_{res} receives the response to that request, it codes that frame using the IDP and forwards it through the reverse path until reaching the BM_{ini}, where it will be decoded and properly stored.

Since for an IDT the response to the original request takes longer than for an IADT, the initiator AL must periodically repeat the same request until receiving the related response. After BM_{ini} having received (and stored) the correspondent response frame, it is ready to respond to a new (repeated) request from the initiator. The response frame is exactly equal to the frame transmitted by the IDT responder.

Considering the network scenario illustrated in Figure 2.10, Figure 2.11 represents a simplified timeline regarding a transaction between master M3 and slave S6. Figure 2.11 assumes the typical behaviour of PROFIBUS-DP, where the slaves read their inputs periodically, placing their image on the DLL by using the generic `Service_upd.req` primitive. The image of the input values is placed in a buffer, which is used by the protocol to build a response to a specific request. An indication can be transmitted to the higher layers every time a slave receives a request. This type of procedure is usually referred to as buffered operation.

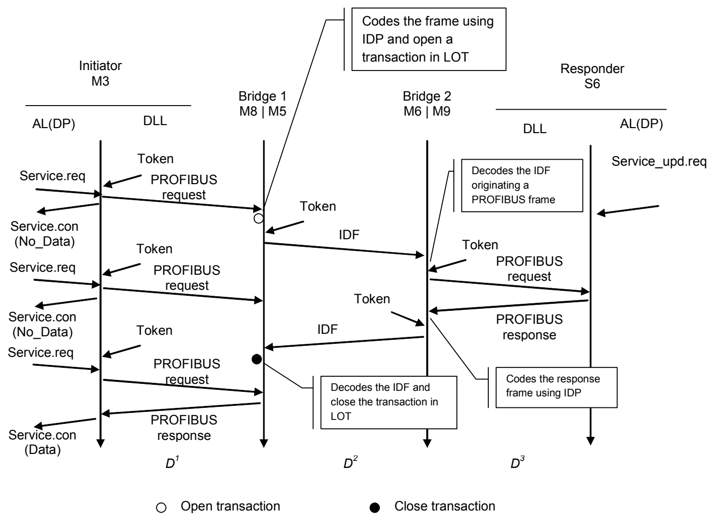

Figure 2.11 – Example timeline for an Inter-Domain Transaction (IDT) between master M3 and slave S6

The initiator also uses a buffered communication mode, where the user and the initiator's protocol stack interface with the PROFIBUS-DP through a memory area, which allows reading and writing variables that, represent the state of local or remote variables. It is the responsibility of PROFIBUS-DP to periodically update the variables using primitives of the type `Service.req`.

Inter-Domain Frame Formats

IDFs are used by the IDP for proper transmission of frames between bridges. These frames must contain information that enables decoding the embedded original request/response and matching the information stored in the BM_{ini} LOT and the respective response.

The PROFIBUS protocol allows a request using a variable data field length frame with DAE, to be answered by a fixed length response frame without data field (thus not supporting DAE). Therefore, BM_{ini} would not be capable of matching two different requests from the same initiator, addressed to the same responder, but with different DAE. The PROFIBUS DLL protocol also defines that requests using variable data field length frames can be replied with a SC frame. Obviously, if no special IDF format was used, the bridges would be unable to route the SC frame back to the initiator station, since that type of frame does not have a DA field. Therefore, the first problem can be solved by using a `Transaction Identifier` (TI), which enables matching the request and the respective response, while to solve the second problem it is required that every IDF must have a destination address field. The TI is a sequence number, assigned by the BM_{ini}, which must also be included in the response frame (similar to a TCP/IP sequence number). This field is used by the BM_{ini} to distinguish between response frames related to different pending transactions. The IDF is a new frame that embeds the original frame. Therefore, to reconstruct the original frame, one of the fields that must be stored in the IDF frame is the original frame function code (which is stored as `Embedded Function Code` (EFC)) and an identifier which enables BM_{ini} and BM_{res} to identify the type of the embedded frame – the `Embedded Frame Type` (EFT).

Considering the three types of data frames defined in PROFIBUS, the IDP converts `Frames of Fixed Length with no Data Field` to `Frames of Fixed Length with Data Field`, and both `Frames of Fixed Length with Data Field` and `Frames with Variable Length Data Field` to `Frames with Variable Length Data Field`.

Table 2.1 illustrates the proposed mapping between standard PROFIBUS frames and the IDFs. In the table, a rectangle with a dash means that the field is not used in the IDF because it is not present in the original frame. A rectangle with diagonal stripes means that the field is not available to the IDF (in this specific case, fixed length frames with no data are mapped into frames of fixed length with data field). The equal symbol means that the field must the equal to the original embedded frame field.

Table 2.1 – Mapping between standard PROFIBUS frames and IDFs

Original Type of Frame		**Frame Header (PROFIBUS defined)**					**Frame Data (IDP defined)**					
		LE	**SD**	**DA**	**SA**	**FC**	**DAE**	**SAE**	***TI***	***EFT***	***EFC***	**Data Unit**
Fixed length no data	Req	▨	SD3	=	=	10	-	-	TI	1	EFC	-
	Ack	▨	SD3	=	=	10	-	-	TI	2	EFC	-
	Short ack	▨	SD3	Req. SA	Req. DA	10	-	-	TI	3	EFC	-
Fixed length w/ data	Req	Data len	SD2	=	=	10	=	=	TI	4	EFC	=
	Res	Data len	SD2	=	=	10	=	=	TI	5	EFC	=
Var. length	Req	Data len	SD2	=	=	10	=	=	TI	6	EFC	=
	Res	Data len	SD2	=	=	10	=	=	TI	7	EFC	=

In the conversion, the IDFs preserve the same DA and SA, except in the case of the SC frame, which does not have DA or SA. In this case, the IDF includes the DA and SA obtained from the request frame. To distinguish IDFs from other frame types, the `Function code` of the FC field must be equal to 10 (note that this feature also imposes a non standard behaviour by the BMs DLL). And its remaining sub-fields should be filled with the appropriate values (for a PROFIBUS frame). Note that all frames defined in Table 2.1 are transmitted as individual requests. Finally, SDN frames do not need any conversion, so they can be relayed by the bridges as received (without being coded). Note that response frames are transformed into request frames by the IDP.

2.4.2. Supporting Inter-Domain Mobility

The Inter-Domain Mobility Procedure (IDMP) is a hierarchically managed procedure, where one master in the overall network – the `Global Mobility Manager` (GMM) – is responsible for periodically starting the IDMP and controlling some of its phases. Additionally, in each domain, one master controls the mobility of stations belonging to that domain – the `Domain Mobility Manager` (DMM). Finally, the BMs must implement specific mobility services. The GMM must know the addresses of all BMs and DMMs in the system. Each DMM must know the addresses of the BMs that belong to its domain as well as of the wireless mobile stations.

The wireless mobile stations implement specific services which enable them to evaluate the quality of the radio channels. These services are assumed to be similar to the ones used in the repeater-based approach.

For example, and concerning the network scenario illustrated in Figure 2.12, M6 assumes the role of GMM and DMM for wired domain D^2. BMs M5, M9 and M7 assume the role of DMMs for wireless domain D^1, wireless domain D^3 and wired domain D^4, respectively.

The role of the management agents and the different phases of the proposed handoff mechanism will be described next.

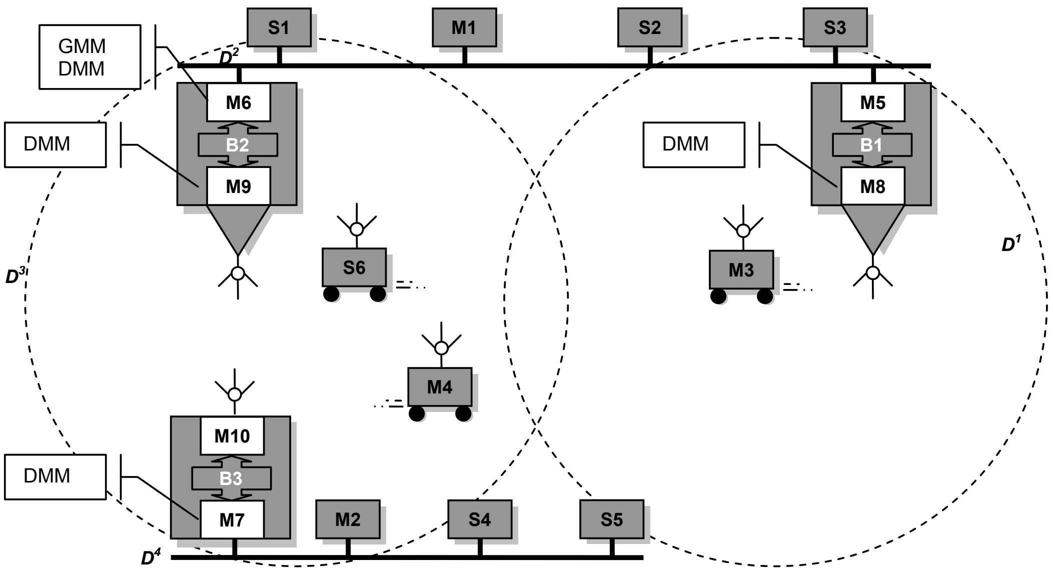

Figure 2.12 – Bridge-based hybrid wired/wireless PROFIBUS network example (IDMP)

Phases of the IDMP

The IDMP evolves through 4 phases, as shown in Figure 2.13. The objective of these phases is to insure that the procedure will not generate errors, that the inaccessibility periods are minimal (especially in the case of IADTs) and that the wireless mobile stations are able to evaluate all wireless radio channels and switch to the best one.

The proposed mechanism is synchronous in some of its phases: Phase 1 and Phase 2 as well as the beginning of Phase 3. But in the case of Phase 3, the ending of it in the domains is not synchronised, and Phase 4 runs asynchronously for each domain.

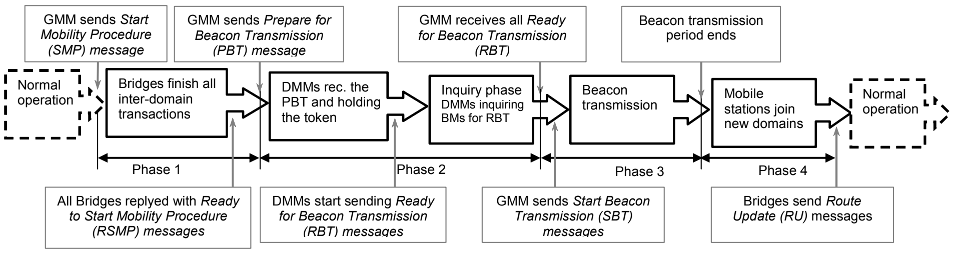
GMM sends Start Mobility Procedure (SMP) message
GMM sends Prepare for Beacon Transmission (PBT) message
GMM receives all Ready for Beacon Transmission (RBT)
Beacon transmission period ends
Normal operation
Bridges finish all inter-domain transactions
DMMs rec. the PBT and holding the token
Inquiry phase DMMs inquiring BMs for RBT
Beacon transmission
Mobile stations join new domains
Normal operation
Phase 1
Phase 2
Phase 3
Phase 4
All Bridges replyed with Ready to Start Mobility Procedure (RSMP) messages
DMMs start sending Ready for Beacon Transmission (RBT) messages
GMM sends Start Beacon Transmission (SBT) messages
Bridges send Route Update (RU) messages

Figure 2.13 – Phases of the Inter-Domain Mobility Procedure

Phase 1

Phase 1 starts with a `Start_Mobility_Procedure` (SMP) message sent by the GMM. This message is sent periodically according to the mobility requirements of the wireless mobile stations involved in the application. When the BMs receive a SMP message, they stop processing new IDTs from the masters belonging to their domains. Nonetheless, they keep handling pending IDTs (still present in their LOTs) and, importantly, they keep relaying IDF originated in other domains. After completing all pending IDTs (those from their LOT), the BMs transmit a `Ready_to_Start_Mobility_Procedure` (RSMP) message to the GMM. When the GMM has received RSMP messages from all BMs in network, the Phase 1 ends.

Figure 2.14 shows a simplified timeline related to IDMP Phase 1 assuming the network scenario presented in Figure 2.12. For the sake of simplicity, it is assumed that when a BM receives a SMP message there is no open transaction in its LOT.

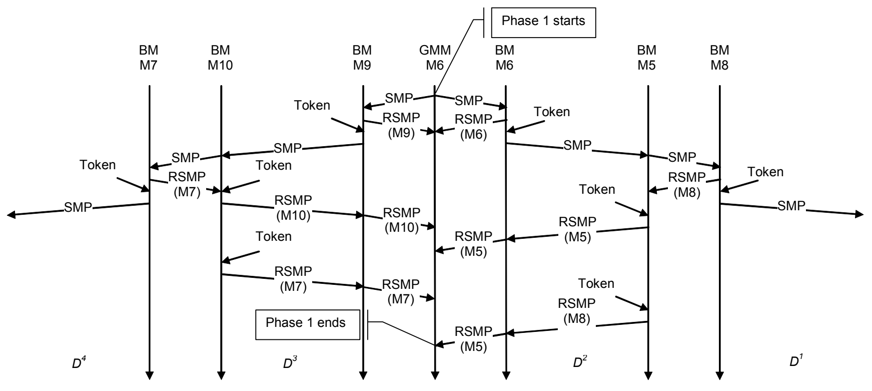

Figure 2.14 – Simplified timeline of IDMP Phase 1

Phase 2

Phase 2 is triggered by the GMM broadcasting the `Prepare_for_Beacon_Transmission` (PBT) message. After receiving the PBT message, a DMM retains the token (after token reception, obviously), starting the inquiry sub-phase. When receiving a PBT message all BMs in the network clear their RT entries related to wireless mobile stations.

On the inquiry sub-phase, the DMMs start by transmitting a `Ready_for_Beacon_Transmission` (RBT) message to the GMM signalling that they are on the inquiry sub-phase, ready for `Beacon` transmission. Then, every DMM sequentially sends `Inquiry` frames addressed to the BMs belonging to its domain. The BMs use the response message to transmit any mobility-related message that they require to transmit.

Wireless terminating domains (i.e., wireless domains connecting to only one bridge) emit `Void` frames in order to maintain network activity. Note that in this kind of domains, a DMM does not have to retrieve any mobility-related message from the other bridges. This procedure allows a faster communication between the GMM and the DMMs, while at the same time the inaccessibility period of the wired stations is kept small. Phase 2 ends when all `Ready_for_Beacon_Transmission` (RBT) messages are received by the GMM. Figure 2.15 shows a simplified timeline related to IDMP Phase 2 assuming the network scenario presented in Figure 2.12.

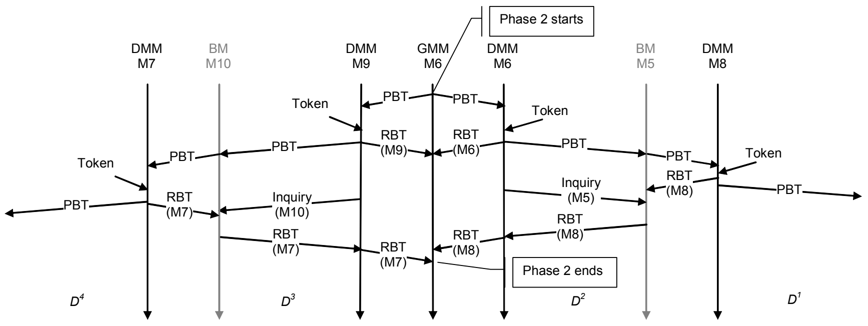

Figure 2.15 – Simplified timeline of IDMP Phase 2

Phase 3

After collecting all `Ready_for_Beacon_Transmission` messages from all the DMMs, the GMM starts the `Beacon` transmission sub-phase by broadcasting the `Start_Beacon_Transmission` (SBT) message. Upon reception of this message, the DMMs start emitting `Beacon` frames. The wireless mobile stations use the `Beacon` frames to evaluate the quality of the different radio channels and to decide if they want to handoff (or not). So, before the end of the `Beacon` transmission, every wireless mobile station that wants to handoff must switch to the new radio channel.

Note that all wired domains that evolved to the inquiry sub-phase may resume IADTs, after the correspondent DMM has received the SBT message, since their intervention is not required on the remaining phases of the IDMP. Note also that, IDTs can be relayed if the neighbouring domains have already their IDTs enabled. IDTs involving wireless mobile stations are only resumed when the BMs receive `Route_Update` (RU) messages specifying the location of the wireless mobile stations.

Figure 2.16 shows a simplified timeline related to IDMP Phase 3 assuming the network scenario presented in Figure 2.12. Phase 3 is started by GMM but is finished by DMM of each wireless domain. The mobility procedure is finished at reception of the SBT message for wired domains.

Phase 4

After the end of the `Beacon` transmission, every wireless DMM (still holding the token) inquires all wireless mobile stations in order to detect if they are present in its domain, using `Discovery` messages. This period can also be referred to as the discovery sub-phase.

From this instant onwards, wireless mobile slaves are already capable of answering requests, but wireless mobile masters must still enter the new logical ring, using the standard PROFIBUS ring management mechanisms. Since the RT entries related to wireless mobile stations have been cleared, only when the BMs receive updated routing information (embedded on RU messages), at the end of the IDMP, they may restart routing IDTs related to wireless mobile stations.

The RU messages are transmitted by the DMMs whenever they detect that a wireless mobile station is ready to start operating, that is, after the entry of a master into the logical ring or after the detection of wireless mobile slave using `Discovery` messages.

When a wireless mobile station continues in the same domain, its presence is detected by a `Discovery` message and a RU message is transmitted by the DMM before releasing the token frame. When a wireless mobile slave changes to another domain, the detection in the new domain is also made by a `Discovery` message.

When a wireless mobile master changes to another domain, its detection is made by the update of the LAS and/or GAPL of the DMM of the new domain. After detecting the presence of wireless mobile stations, the DMM broadcasts a RU message. When a RU message is received by a BM, it updates its RT according to the information contained in the message.

In Figure 2.16 is shown a simplified timeline related to IDMP Phase 4 assuming the network scenario presented in Figure 2.12. Phase 4 is started independently by each DMM and ends also independently after the discovery sub-phase.

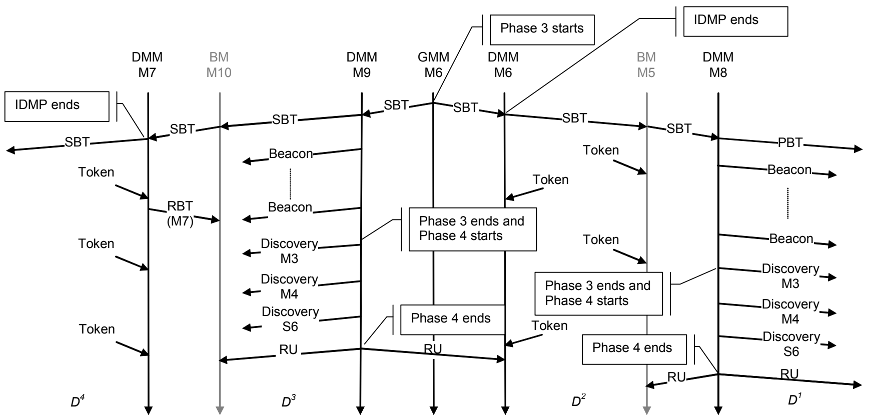

Figure 2.16 – Simplified timeline of IDMP Phase 3 and Phase 4

Inter-Domain Mobility Procedure Messages

To reduce the cost and complexity of implementing the IDMP, this procedure is based on standard features offered by PROFIBUS. Therefore all mobility-related messages use standard Frames of Fixed Length with Data Field, addressed to a specific `Source Address Extension` (SAE), e.g., 55, that handles the IDMP. Table 2.2, synthesizes these messages.

Table 2.2 – Format of the IDMP messages (requests)

Frame	Frame Header						Frame Data	
	SD	DA	SA	FC	DAE	SAE	MC	Data
Start Mobility Procedure	SD3	127	GMM	6	55	55	1	-
Ready to Start Mobility Procedure	SD3	GMM	Bri.	6	55	55	2	-
Prepare for Beacon Transmission	SD3	127	GMM	6	55	55	3	-
Ready for Beacon Transmission	SD3	GMM	DMM	6	55	55	4	-
Start Beacon Transmission	SD3	127	GMM	6	55	55	5	-
Route Update	SD3	127	Bri.	6	55	55	6	Station Addrs
Inquiry	SD3	Bri.	DMM	13	55	55	7	-
Void	SD1	DMM	DMM	6				

Since most of the messages are sent in broadcast mode, thus not requiring any response, the frames are coded using high priority SDN frames. Therefore the FC code value, of most protocol message, is set to 6. The field `Mobility Code` (MC) codes the type of operation that must be performed when the destination station receives the frame.

For the `Beacon` message is used the same type of message used in the RFieldbus system, which is described in (Rauchhaupt, 2002). This message must have a specific format which allows the wireless mobile station to evaluate the radio channel quality.

The `Inquiry` message request may have a response from the addressed BM, thus it is coded as a SRD high service. In that case, the response to that service can only contain a mobility related message from the output queue of the addressed BM. Finally, when a wireless domain has only one BM, and the bridge is also the DMM, it must transmit a `Void` message (to maintain the network activity).

2.5. Summary

This chapter presented an overview of the most relevant features of the PROFIBUS protocol necessary to tackle the remainder of the dissertation, it also highlighted the main architectural features of the repeater and bridge-based approaches. The objective was to provide the reader with the necessary background and intuition for tackling the remainder chapters of this document.

In this chapter, the mobility procedure for the repeater-based architecture was described. It is very simple and errors occurring during its execution can be tackled by native PROFIBUS error handling mechanisms. But, the mobility mechanism used on the bridge-based architecture is more complex and involves the exchange of many messages between the intervening stations. Errors during the execution of the IDMP must be tackled by specific mechanisms implemented in the bridges. The next chapter will analyse those error situations and propose solutions for the error handling problem of the IDMP.

Chapter 3

Error Handling Improvements for the Bridge-based Architecture

The original IDMP protocol did not define any error handling mechanisms, regardless of the mechanism used in PROFIBUS. The IDP also relies on a simple timeout timer to control the success of an IDT. As a consequence, these error handling mechanisms could lead to fault situations and to situations in which the protocol state machines can be blocked. In this chapter, the error situations which can occur during the evolution of the IDP and the IDMP are analysed and solutions to the problems are proposed.

3.1. Introduction

Wired fieldbus networks usually exhibit a low Bit Error Rate (BER), however the integration of wireless communications (radio based) in such kind of network may increase the BER, since a wireless transmission medium can not be shielded from the influence of noise sources. Nevertheless, this increase can be somewhat reduced by the use of more robust modulation technologies like spread spectrum and frequency hopping, and by the use of more sophisticated error detection and correction mechanisms.

The IDP relies on a timeout timer to control the success of an IDT. This timer is started by the BM_{ini} when the IDT is initialised and cleared if it receives a response. The IDMP has been originally developed without error handling mechanisms, but in this protocol if a frame is lost or corrupted due to transmission errors the evolution of the mobility procedure could be blocked. Consequently, one of the main objectives of this chapter is to propose improved error handling mechanism for the IDP and for IDMP.

This chapter is organised as follows. In Section 3.2 we analyse the error handling mechanism used by the IDP protocol and propose some improvements. Then, in Section 3.3 the error situations which can occur during the evolution of the IDMP are analysed and the section continues by discussing two alternative mechanisms which support the error handling. Section 3.4 presents the reasons which supported the error handling mechanism implemented in our simulator.

3.2. Error Handling in the IDP

3.2.1. Possible IDP Error Situations

As outlined in Chapter 2, the bridge-based approach requires a new kind of transaction – Inter-Domain Transaction (IDT) – in which the involved stations do not belong to the same domain. The IDP error handling mechanism is a simple mechanism based on timers which are handled by the IDT's BM_{ini}. Therefore, whenever a new transaction is opened at the BM_{ini} LOT a timer, the `BM_IDT_Abort_Timer` ($T_{BM\text{-}IDTAbort}$), is loaded with the worst-case time required by the BM_{ini} to complete a transaction (for additional details about how to obtain these values see (Ferreira, 2005)). If the timer expires before the completion of the transaction then the entry at the LOT is deleted and the IDT can be reinitialised by the next initiator's request.

In order to illustrate the influence of transmission errors in the IDP, consider the network example presented in Figure 2.10, Figure 3.1 presents a simplified timeline regarding a transaction between master M3 and slave S6. When master M3 is holding the token frame it sends a PROFIBUS request addressed to slave S6. Using the information contained in its RT and `List of Active Stations in Domain` (LASD), BM M8 RT (which operates as BM_{ini} for this transaction) opens a new entry in its LOT related to this transaction. After coding an IDF, BM M8 transmits the frame to BM M5. When BM M5 has the right to access the medium it transmits the IDF, but assuming that a transmission error occurs in domain D^2, the frame is discarded by all stations belonging to domain D^2. Since IDF frames are coded using standard non-acknowledge PROFIBUS frames there is no retransmission by BM M5, and consequently the frame is lost and the IDT can only be recovered when the `BM_IDT_Abort_Timer` expires.

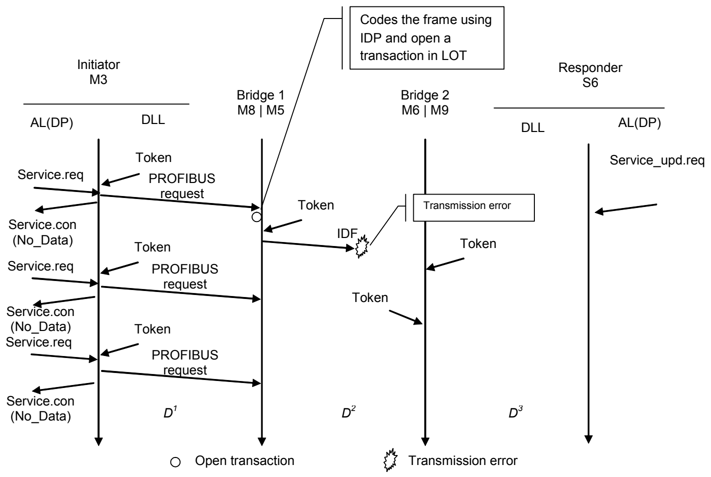

Figure 3.1 – Example timeline for an IDT between M3 and S6 considering transmission errors

3.2.2. Improving Error Handling in the IDP

The main reason for the original protocol was mainly related to provide simple functionalities capable of being implemented, in resource constrained devices, since the receiving BM would only process the received IDF when it had available resources. An obvious improvement to this protocol would be to use the SDA service instead of SDN. Nevertheless, this change requires that the BM must receive the frame, decode its content, consult its RT and send a confirmation to the initiator station. These operations must be done within the time allowed for the transmission of a confirmation frame, which is defined by the T_{SDR} parameter.

Using the SDA service all IDFs, either embedding a request or a response, are acknowledged. Figure 3.2 presents a simplified timeline of an IDT where IDFs are transmitted using the SDA service. In this case a transmission error occurs when the IDF embedding the response is transmitted between BM M6 and BM M5. Since the frame has not been acknowledge by BM M5, the BM M6 retransmits the frame after the expiration of T_{SL}. Although, this mechanism adds some overhead to the network, it improves the error handling in error prone environments as it will be shown in Chapter 10. As illustrated in Figure 3.2, if a transmission error occurs the IDF will be retransmitted. The number of retransmission is defined by `max_retry_limit` DLL parameter.

This mechanism can cause duplication of IDFs, when the acknowledge frame is corrupted. Therefore, the BM has to check for IDFs duplication and it has to assure that only one IDF of each IDT is relayed by the BMs.

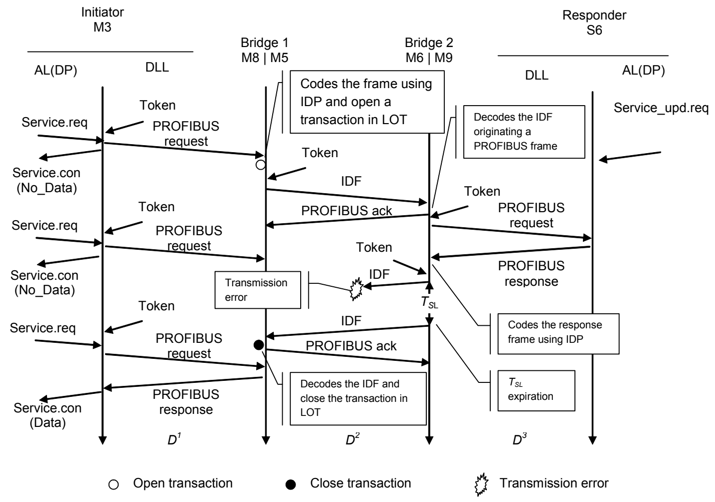

Figure 3.2 – Example timeline for an IDT between M3 and S6 considering transmission errors and using SDA service

3.3. Handling IDMP Errors

The original IDMP version is also prone to errors, similarly to the IDP case. In this section the vulnerabilities of the IDMP are identified and solutions to those problems are outlined.

3.3.1. Possible IDMP Error Situations

Figure 3.3 presents an error scenario for possible IDMP errors. This scenario assumes the network configuration presented in Figure 2.12, where BM M6 assumes both roles, of GMM and DMM of wired domain D^2. BMs M8, M9 and M7 assume the role of DMMs for wireless domain D^1, wireless domain D^3 and wired domain D^4, respectively.

The GMM M6 starts the IDMP by broadcasting a SMP message. After that, it waits for RSMP messages from all BMs in the network. Assuming that a transmission error occurs when BM M9 is sending a SMP message to BM M10, then BM M10 and BM M7 will not receive the SMP message. If they do not receive a SMP message, they will not reply with a RSMP message. Consequently, the IDMP will not evolve because the GMM M6 is expecting RSMP messages from all BMs. Further, the BMs that have replied stop accepting new IDTs, therefore blocking the evolution of the IDMP.

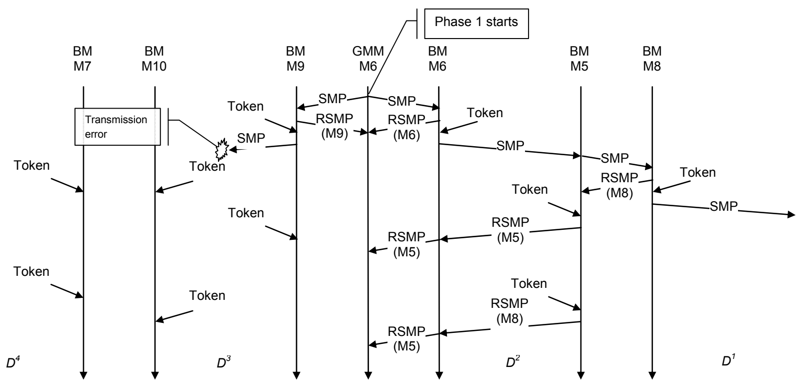

Figure 3.3 – A simplified timeline for the Phase 1

To overcome such problems, we propose two mechanisms, the Tree-like Topology Based and the Timer-Based. These mechanisms respect the main features of the IDMP, they simply add error control and correction detection capabilities to the protocol. The IDMP agents are the same and maintain the same functionalities. The meaning and the purpose of each message is also the same.

3.3.2. Tree-like Topology Based Mechanism

Due to the routing mechanism a bridge-based network can be represented by a tree, since there is no close path between any two stations.

Usually, a *tree* data structure: places one node (called the *root),* then, proceeds down connecting one or more nodes beneath each node on the previous level, until *n* nodes have been placed. The nodes below each node are called its *sons*; the node above each node is called its *father*. The sons are themselves the roots of trees, called the *sub-tree*. A *leaf* node is one which is not a root of any tree or sub-tree.

Figure 3.4 shows the above concepts. Node 0 is the root of the tree and has two sons, nodes 1 and 2, consequently it is the father of these nodes. Since node 1 is not a leaf node then it is a root of a sub-tree.

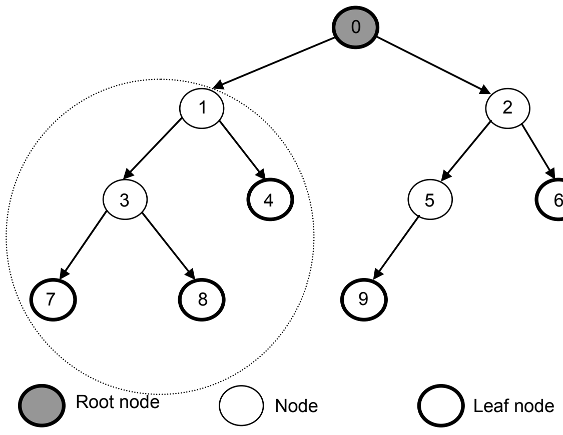

Figure 3.4 –Tree data structure example

This error handling proposal requires some adaptations to the original IDMP. For Phase 1 the tree is composed by the GMM, as root, and the network BMs. Phase 1 is started by the GMM when it sends a SMP message and finishes when all BMs reply with a RSMP message. To handle transmission errors, each root node, of every sub-tree, periodically sends SMP messages until receiving a RSMP message from its son nodes. When all son nodes have replied with a RSMP message, which means that their LOTs are empty, then the root node stops sending SMP message. After, when its LOT is empty, it replies with a RSMP message to its father node. Therefore, Phase 1 ends when the GMM has received a RSMP message from its son nodes. This procedure supports errors on the transmission of the SMP message and on its reply message.

Figure 3.5 illustrates this mechanism considering the network example presented in Figure 2.12. GMM M6 repeatedly sends a SMP message to BMs M6 and M9 until receiving a RSMP message from them. BMs M6 and M9 stop accepting new IDTs and repeatedly send a SMP message until receiving a RSMP message from BMs M5 and M10, respectively. When leaf nodes (BMs M8 and M7) have their LOTs empty, they reply with a RSMP message to their father nodes. Phase 1 ends when the GMM receives a RSMP message from all of its son nodes, BMs M6 and M9.

Note that the occasional transmission errors are overcome by periodic message re-transmissions. In Figure 3.5 a transmission error occurs when BM M10 is sending a RSMP message, consequently BM M9 does not receive a RSMP message from BM M10. In order to receive a RSMP message from BM M10, BM M9 re-transmits the SMP message until receiving a RSMP message.

The mechanism concerning to Phase 2 is very similar to the mechanism used in Phase 1, but now the tree is composed by the GMM, as root, and the DMMs as leafs

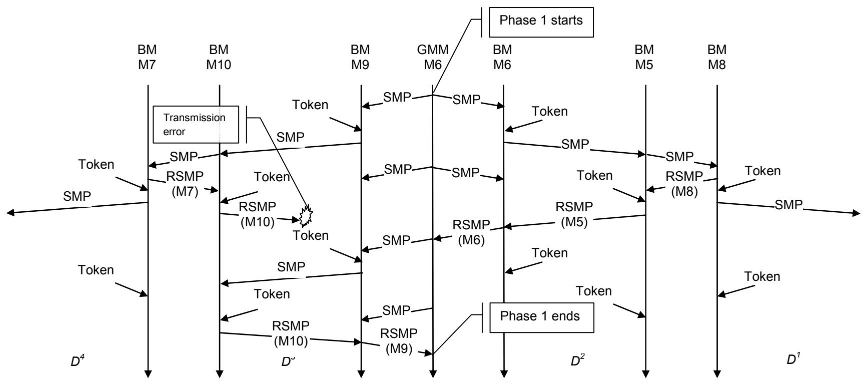

Figure 3.5 – Simplified timeline of the Tree-like topology mechanism for Phase 1

Phase 2 starts when the GMM sends a PBT message to its son nodes. In this schema, the GMM periodically sends a PBT message until receiving a RBT message from all its son nodes. The same mechanism is used by the sub-tree root nodes. They periodically send a PBT message until receiving a RBT message from its son nodes. When all son nodes have replied with a RBT message, then the root node of each sub-tree stops sending PBT messages and, if it is holding the token frame, replies with a RBT message to its father node. When a DMM replies with a RBT it starts the inquiry sub-phase. The BMs at reception of PBT message clear all entries of their RT concerning wireless mobile stations.

Figure 3.6 illustrates this mechanism considering the network example presented in Figure 2.12.

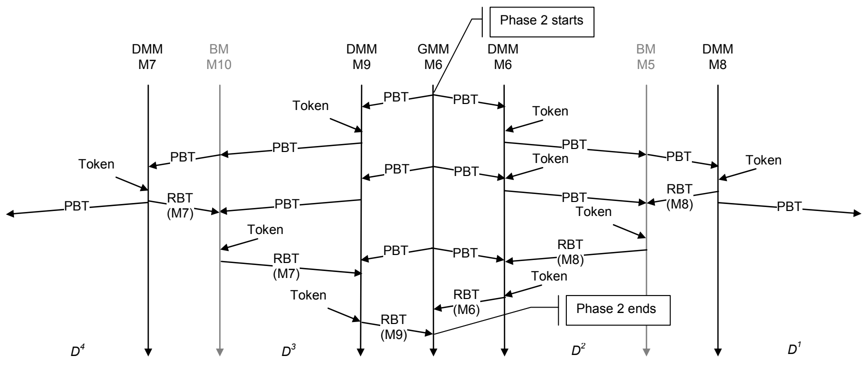

Figure 3.6 – Simplified timeline of the Tree-like topology mechanism for Phase 2

When all DMMs are holding the token frame, the GMM starts Phase 3 by sending a SBT message. This procedure requires the use of a new kind message, the `Emitting_Beacon_Frame` (EBF) message, which signals that a son node is transmitting `Beacon` frames. Contrarily to the IDMP outlined in Section 2.4.2, the GMM will wait for EBF message from its node sons. The mechanism is similar to the previous. When a leaf node receives a SBT message it sends an EBF message to its father. And, in order to assure that its father node receives the transmitted EBF message, it waits during some time for a repeated SBT message. If it does not receive a SBT message it means that its father node received correctly the transmitted EBF message. After, if the domain is wireless it starts emitting `Beacon` frames, otherwise it starts processing message cycles.

This mechanism is illustrated in Figure 3.7, where the GMM repeatedly sends a SBT message until receiving an EBF message from its son nodes, at this point its role in the IDMP ends. However, the IDMP continues in wireless domains controlled by DMMs. Each wireless DMM emits `Beacon` frames during a predefined time.

After the end of the `Beacon` transmission, that is when Phase 3 ends, Phase 4 starts (Figure 3.8). Every wireless DMM (still holding the token) inquires all wireless mobile stations in order to detect if they are present in its domain, using `Discovery` messages. After the discovery sub-phase finish, a RU message is transmitted by the DMMs whenever they detect that a wireless mobile station is in their domain. These messages are used by the BMs to update their RTs.

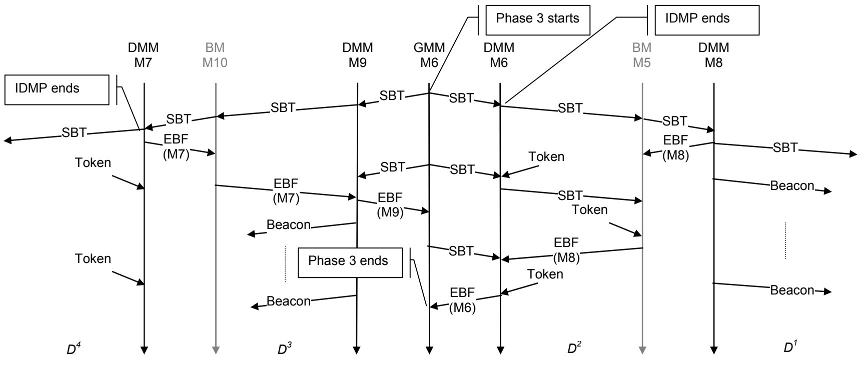

Figure 3.7 – Simplified timeline of the Tree-like topology mechanism for Phase 3

Note that if a wireless mobile station is not discovered during the discovery sub-phase due to transmission errors or if a RU message is corrupted by a transmission error, the transactions with these stations would not possible until the next mobility procedure. In order to handle with problem, the DMMs must periodically send `Discovery` messages addressed to the wireless mobile stations, if such stations are found, the DMMs broadcast RU message.

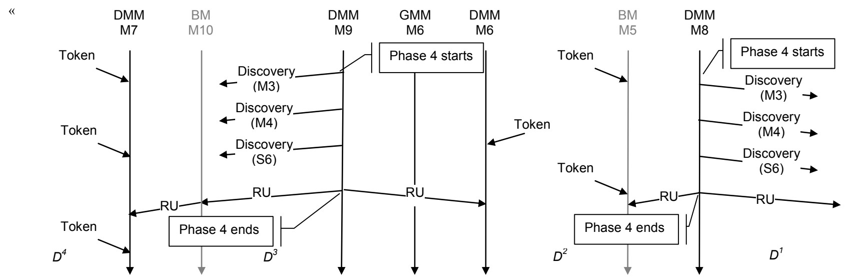

Figure 3.8 – Simplified timeline of the Tree-like topology mechanism for Phase 4

3.3.3. Timer-Based Mechanism

A solution to handle errors in the IDMP can also be based in a set of timers, enabling the error detection and handling during the evolution of the IDMP.

This error handling procedure is based in four timers which are assigned to the GMM, one to each BM and one to each DMM present in the network. Two of the timers associated to the GMM are used to detect and handle the errors during Phase 1, while the other two are related to Phase 2. The timers associated to Phase 1 are designated as `GMM_Phase_1_Alert_Timer` ($T_{GMM-P1Alert}$) and `GMM_Phase_1_Abort_Timer` ($T_{GMM-P1Abort}$). The timers associated to Phase 2 are designated as `GMM_Phase_2_Alert_Timer` ($T_{GMM-P2Alert}$) and `GMM_Phase_2_Abort_Timer` ($T_{GMM-P2Abort}$). The timers associated to BMs and DMMs are designated as `BM_IDMP_Abort_Timer` ($T_{BM-IDMPAbort}$) and `DMM_IDMP_Abort_Timer` ($T_{DMM-IDMPAbort}$), respectively. The purpose of each timer is detailed next.

The $T_{GMM-P1Alert}$ and $T_{GMM-P1Abort}$ are started (the $T_{GMM-P1Alert} < T_{GMM-P1Abort}$) when the GMM sends the SMP message. If the GMM receives a RSMP message from all BMs in the network before the expiration of the $T_{GMM-P1Alert}$ it stops both timers. If $T_{GMM-P1Alert}$ expires, i.e., if it did not receive a RSMP message from all BMs, it sends again a SMP message and waits for the reception of a RSMP message from all BMs in lack. If it receives a RSMP from the BMs in lack before the expiration of the $T_{GMM\text{-}P1Abort}$ it evolves to Phase 2. Otherwise, the IDMP is aborted.

Each BM starts its $T_{BM\text{-}IDMPAbort}$ when it receives the first SMP message. The BM will reply with a RSMP message when its LOT is empty. If a BM has already sent a RSMP message and it receives again a SMP message it also replies again with a RSMP message. If the IDMP takes longer than $T_{BM\text{-}IDMPAbort}$, the BM aborts the IDMP and starts accepting new IDTs. Otherwise, the $T_{BM\text{-}IDMPAbort}$ is stopped at the end of Phase 2.

Considering the system scenario illustrated in Figure 2.12, Figure 3.9 represents a simplified timeline of IDMP Phase 1. For the sake of simplicity, it is assumed that there are no open transactions in the LOTs of the BMs in the network.

When the IDMP is triggered the GMM M6 starts $T_{GMM\text{-}P1Alert}$ and $T_{GMM\text{-}P1Abort}$ and a SMP message is broadcasted by network. As soon as the BMs receive a SMP message they start the $T_{BM\text{-}IDMPAbort}$ and no new IDTs are accepted. In this example, it is assumed that there are no open transactions in their LOTs, therefore the BMs reply with a RSMP message. However, a transmission error occurs when a RSMP message from BM M7 is transmitted by BM M10. As no retries are performed by BM M10, the GMM will not receive all RSMP messages. Consequently, the $T_{GMM\text{-}P1Alert}$ expires. Then the GMM broadcasts again a SMP message. All BMs reply with a RSMP message even the BMs that had already replied. Assuming, that no transmission errors occurred, the GMM receives all RSMP messages from all BMs in the network and then it stops the $T_{GMM\text{-}P1Abort}$.

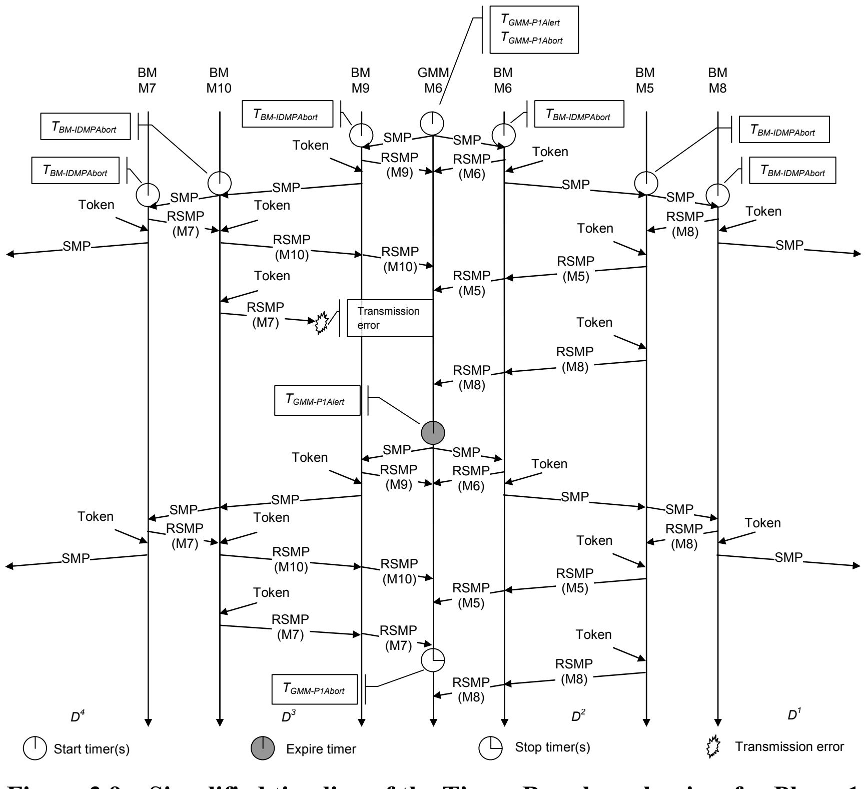

Figure 3.9 – Simplified timeline of the Timer-Based mechanism for Phase 1

A similar mechanism is used to control the Phase 2. When the GMM broadcasts a PBT message, Phase 2 starts and the $T_{GMM\text{-}P2Alert}$ and $T_{GMM\text{-}P2Abort}$ timers are started (the duration of the $T_{GMM\text{-}P2Alert}$ must be smaller than $T_{GMM\text{-}P2Abort}$). At reception of the PBT message, the DMMs start the $T_{DMM\text{-}IDMPAbort}$, and a RBT message is transmitted when it holds the token frame.

The GMM stops the $T_{GMM\text{-}P2Alert}$ and $T_{GMM\text{-}P2Abort}$ if it receives a RBT message from all DMMs in the network and the IDMP evolves to Phase 3. Otherwise, the GMM broadcasts again a PBT message at expiration of the $T_{GMM\text{-}P2Alert}$. If the $T_{GMM\text{-}P2Abort}$ expires before the reception of all RBT messages, then the IDMP is aborted. Otherwise, the $T_{GMM\text{-}P2Abort}$ is stopped and the IDMP evolves to Phase 3.

Considering the system scenario illustrated in Figure 2.12, Figure 3.10 represents a simplified timeline regarding Phase 2.

Assuming that DMM M9 is holding the token frame a RBT message is immediately sent to the GMM and the PBT message is forward to domain D^3 (at the start of Phase 3).

Supposing a transmission error when DMM M9 is sending the PBT message to domain D^3, this means that the DMM M10 will not receive the PBT message. When DMM M6 receives the token frame it replies with an RBT message to the GMM, and forwards the PBT message to domain D^2. As soon as the DMM M8 receives the token frame it replies with an RBT message and the GMM receives the RBT message from DMM M5, i.e., the RBT message is forwarded by BM M5 as a response to an inquiry request from DMM M6 without transmission errors.

At reception of the first PBT message the DMMs start $T_{DMM\text{-}IDMPAbort}$ and the BMs clear all RT entries related to mobile stations.

As DMM M7 did not reply with an RBT message, the $T_{GMM\text{-}P2Alert}$ expires. Therefore the GMM broadcasts again a PBT message and the DMMs reply with an RBT message. Assuming that, at this time no transmission errors occur, then the GMM M6 receives all RBT messages from all DMMs. Thus, Phase 2 ends and the GMM stops the $T_{GMM\text{-}P2Abort}$.

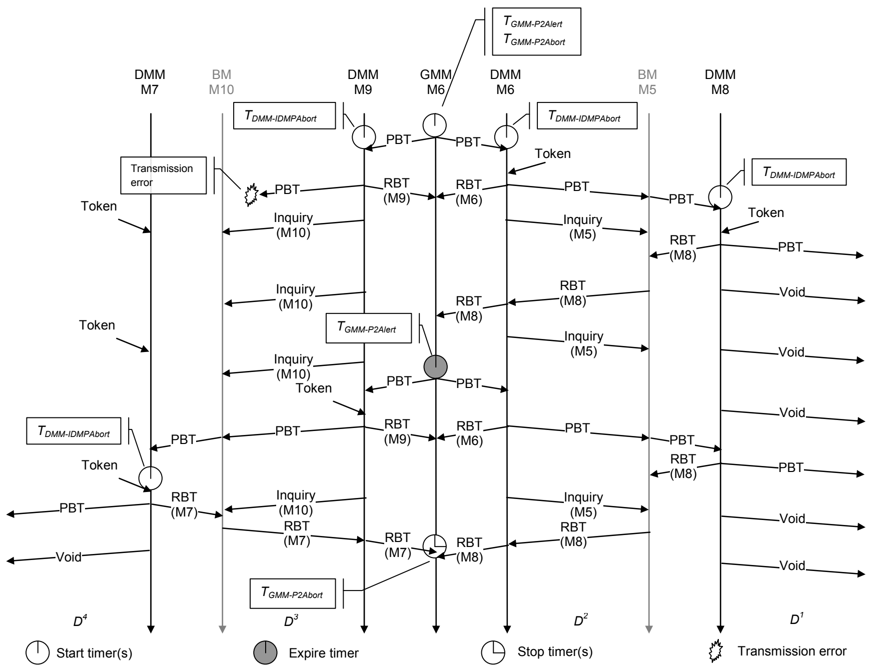

Figure 3.10 – Simplified timeline of the Timer-Based mechanism for Phase 2

After collecting all RBT messages from the DMMs, the GMM broadcasts a SBT message and its role in the IDMP ends.

For the wireless mobile stations to assess the quality of the radio channel in all domains, Phase 3 must occur almost simultaneously in all wireless domains. If a transmission error occurs at the transmission of the SBT message some DMMs will not transmit `Beacon` messages.

If a DMM of a wireless domain does not transmit `Beacon` messages the wireless mobile stations present in its wireless domain are not able to perform radio channel assessment and consequently they stay in the same domain. On the other hand, other wireless mobile stations are not able to evaluate the radio quality of the domain where an error occurred. The IDMP ends when the $T_{DMM\text{-}IDMPAbort}$ expires. But, at the expiration of the $T_{DMM\text{-}IDMPAbort}$ the DMMs send RU messages related to the wireless mobile stations present in its domain. In this way the BMs, which have cleared all entries related to the wireless mobile stations from their RT at the reception of the PBT message, update its RT.

Figure 3.11 presents an example timeline of Phase 3 and Phase 4. In this example, a transmission error occurs when the SBT message is forwarded by DMM M6 and consequently the BM M5, DMM M8 and BM M8 will not receive the SBT. Since domain D^2 is a wired domain, no further IDMP-related action will be taken in this domain. Stations in this domain may start performing message cycles. However, BM M5 will not accept new IDTs, since it did not receive a SBT message. But, when the $T_{BM\text{-}IDMPAbort}$ expires it will accept new IDTs.

Since DMM M8 did not receive a SBT message it did not transmit `Beacon` messages and no wireless mobile stations entered to or left from its domain. Thus, to update the BMs RT, DMM M8 sends a RU message containing the information about wireless mobile station that still belong to its domain when $T_{DMM\text{-}IDMPAbort}$ had expired.

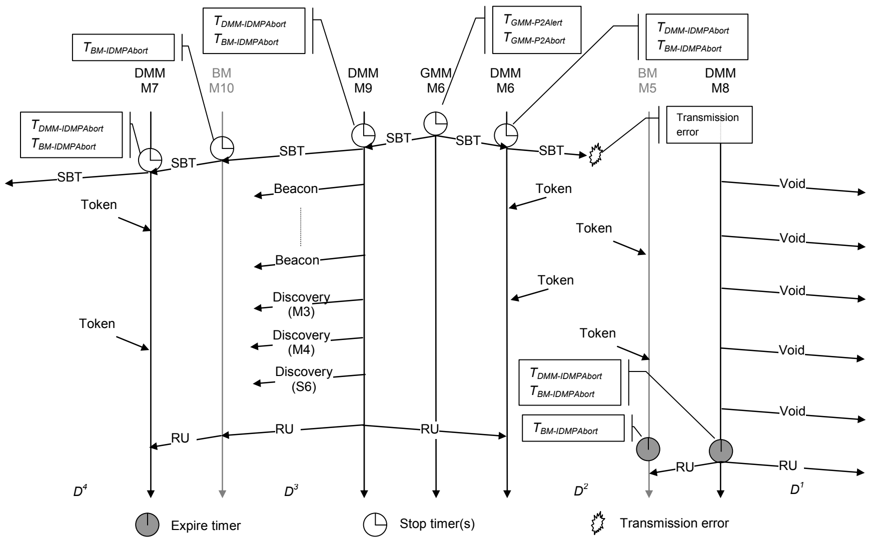

Figure 3.11 –Timeline example for Phase 3 and Phase 4

Due to transmission errors a wireless mobile station may not be discovered during the discovery sub-phase or a RU message may not arrive to all BMs in network. A mechanism similar to the GAP Update mechanism is triggered on the DMMs in order to detect wireless mobile stations. To perform this objective the DMMs periodically send `Discovery` messages to all wireless mobile stations and broadcast RU messages containing information about wireless mobile stations. Obviously, this mechanism introduces a small overhead to the network.

3.3.4. The Adopted Mechanism

The Tree-Like Topology mechanism assures that the four phases of IDMP will always take place. However, this mechanism increases the network traffic in each domain, i.e., some kind of messages are periodically transmitted. Therefore, there is the need to define the periodicity of each repetition. And, in order to minimize the IDMP latencies, this period must take in attention the message's kind. For example, a SMP message takes longer to reach a leaf node than a SBT message, because when a SMP message is transmitted the network is in normal operation, i.e., the token frame is rotating by domain's masters and the IADTs and IDTs are both enabled. When a SBT is transmitted the domains are in inquiry sub-phase, the DMMs are holding the token frame, IADTs and also the IDTs are both disable and therefore these messages are relayed faster.

The Timer-Based mechanism does not assure that the four phases of the IDMP will always take place. It is possible that some wireless mobile stations are not able to assess the quality of the radio channel, because there is no emission of `Beacon` frames in their domains. As a consequence, these wireless mobile stations will continue on same domain.

However, the Timer-Based mechanism was adopted. The reasons for the choice are outlined next. First, the network traffic does not increase as in the Tree-Like Topology mechanism. Second, this mechanism is more similar to the original IDMP than the Tree-Like Topology. Therefore, less implementation effort is required in the Timer-Based solution. Third, the station parameterization is less labour in the Timer-Based than in the Tree-Like Topology mechanism. Fourth and the most important, the Tree-Like Topology implies that the real time analyses proposed in (Ferreira, 2005) for the IDMP to be invalid. On the other hand, the formulations proposed in (Ferreira, 2005) can be used to set the timers according to that worst-case analysis.

3.4. Summary

In this chapter we identified some weaknesses of the error handling capabilities of the original IDP which used the unacknowledged SDN service to transmit IDFs between bridges. To improve the error handling capabilities of the IDP, we had proposed to use, instead of the SDN service, the SDA service which allows the retransmission of faulty frames.

Additionally, the original IDMP had very limited error handling capabilities. In an error prone environment this protocol could lead to blocking situations, therefore we had proposed an error handling mechanism which permits to solve the problems detected. In Chapter 10, we will analyse the behaviour of these enhancements to the original protocols in error prone environments.

Chapter 4

Technological Context: Simulation Software

This chapter gives a description of how a simulation study should be performed and it presents the main characteristics of the simulation environment framework used as a basis for the developed of the simulators used within this dissertation.

4.1. Introduction

A simulation is the imitation of the operation of a real-world process or system over time (Banks, Nelson et al., 2001). For the study of any system, it is necessary to develop a model that represents the *system*. Since a system is a collection of entities, e.g., people or machines, that act and interact together toward the accomplishment of some logical end, the details and behaviour of these entities must be represented in that model.

A simulation model can be classified along three different dimensions. A simulation model can be *static* or *dynamic*, *discrete* or *continuous* and *deterministic* or *stochastic*. A static simulation model is a representation of a system at a particular time while dynamic simulation model represents a system as it evolves over the time. If a simulation model does not contain any random components, it is called deterministic, otherwise, is called stochastic. A discrete model is one for which the state variables change instantaneously at separated points in time. A continuous model is one for which the state variables change continuously according to time. In practice, very few systems are strictly discrete or strictly continuous, but since one type predominates for most systems, it is usually acceptable to classify a system as either being discrete or continuous (Law and Kelton, 2000).

Several aspects have made simulation one of the most widely used and accepted tools in operations research and systems analysis (Banks, Nelson et al., 2001). Particularity, the availability of special-purpose simulation languages, massive computing capabilities at a decreasing cost per operation, and advances in simulation methodologies are some of these aspects.

This chapter starts by presenting the basic steps of a simulation study (Section 4.2). Section 4.3 presents a survey of the simulation tools for the development of network simulation models as well as the reasons that sustained the choice for the OMNeT++ simulation package, to which some further details are provided in Section 4.4.

4.2. The Basic Steps of a Simulation Study

The development of a simulation study involves several steps. Usually, a simulation study is not a simple sequential process but often there is the need to go back to a previous step.

In (Law and Kelton, 2000), the authors divide the simulation study in ten steps. However, in (Banks, Nelson et al., 2001) the development of a simulation study evolves through 12 steps.

Figure 4.1 shows the steps that compose a typical simulation study based on the methodology proposed by (Law and Kelton, 2000). The first step involves defining the goals of the study and determining what needs to be solved. The problem is further defined through objective observations of the process to be studied. Care should be taken to determine if simulation is the appropriate tool for the problem under investigation.

If simulation is the appropriate tool for the problem, then the simulation study evolves to a second step. The goal of this step is to collect data about the system under study and delineates the conceptual simulation model. Information must be collect about system layout, operating procedures, model parameters, input probability functions and performance measures to be analyzed. These tasks must be carefully done because sometimes the information is inaccurate and the operating procedures are not formalized. After collecting information of the system under study the conceptual model can be developed. It is not necessary to do one-to-one correspondence between each element of the conceptual model and the corresponding element of the system. Additionally, the conceptual model must also define the model assumptions. The degree of detail of the conceptual model must be as fine as possible according to the simulation study objectives.

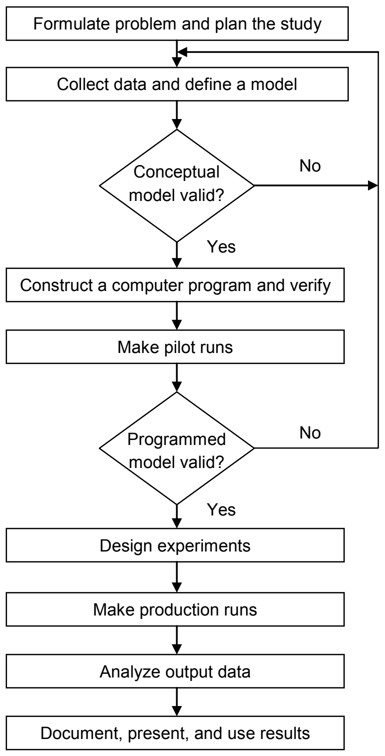
Formulate problem and plan the study
Collect data and define a model
Conceptual model valid?
No
Yes
Construct a computer program and verify
Make pilot runs
Programmed model valid?
No
Yes
Design experiments
Make production runs
Analyze output data
Document, present, and use results

Figure 4.1 – Simulation study steps. Source (Law and Kelton, 2000)

The third step is to validate the conceptual model, which must occur before programming begins. In order to validate the conceptual model a structured walk-through of the conceptual model and simulation objectives must be performed. If the conceptual model is valid, then the simulation study evolves to the next step. Otherwise the simulation study must return to the previous step.

After validating the conceptual model, it must be translated to a computer program (fourth step). The choice of the tools used on the development of the computer program is crucial for the next steps. More details about this will be given later.

After the development of a computer program that implements the conceptual model, there is the need to make pilot simulation runs with the purpose of validating the implemented model.

The sixth step is to verify if the computer program is valid. Validation ensures that no significant difference exists between the programmed conceptual model and the real system. If it is an invalid program the simulation study must return to step 2, otherwise the simulation study evolves to step 7.

After the implemented model has been validated it must be specified for each system configuration the length of each simulation run and the number of independent simulation runs, each run must use different seed numbers for random number generation (step 7).

The following step is to make simulation runs (step 8) and analyze the output data produced by the simulation runs. In the last step documentation must be produced about the simulation runs as well as about the simulation system and simulation implementation.

4.3. Simulator Implementation

One of the most important decisions in a simulation study concerns to the choice of the simulation software. Simulation software can be divided into three categories. The first category includes all general-purpose programming languages such as C, C++ and Java, just to mention some. The second category includes simulation programming languages, such as PARSEC (Meyer and Bagrodia, 1998) , SIMSCRIPT II.5 (Russell, 1999) and SimPy (Vignaux and Muller, 2006). The third category is related to simulation environments, such as OPNET (Chang, 1999), ns-2 (Fall and Varadhan, 2006) and OMNeT++ (Varga, 2004).

Nowadays, the use of the general-purpose languages is considered not appropriate for the development of simulation models with some level of complexity. However, understanding how to develop a simulation model in a general-purpose language helps to understand the basic concepts of the simulation. On the other hand, if the execution speed of the simulation is an important feature, then general-purpose languages can be a good choice.

Simulation languages provide more flexibility for the simulation developer than the general-purpose programming languages. The simulation developer has greater flexibility in designing and implementing the simulation model, since much work has been done at the simulation language level, usually as function libraries.

Network simulation packages can provide a more comprehensive support than simulation languages. They include the basic constructs for the development of network simulations, typically require less programming effort and have a smoother learning curve, when compared to simulation languages. Many network simulation packages include some type of pre-built and reusable models of networking protocols, devices and applications. Additionally, they also provide means for using and creating user interfaces to the simulation models, facilitating the development, debugging and understanding of the code.

Three simulation packages have been evaluated in this dissertation: OPNET, ns-2 and OMNeT++.

OPNET is widely held as the state-of-art in network simulation. It is a suite of products that combines predictive modelling and a comprehensive understanding of networking technologies to enable design, deployment, and management of network infrastructures, network equipments, and networked applications. In particular, OPNET Modeller is a development environment, allowing to design and study communication networks, devices, protocols, and applications. However, OPNET is a commercial product, with some limited academic licensing programmes.

ns-2 (Network Simulator 2) is a discrete event simulator targeted at networking research. ns-2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks. The full source code of ns-2 can be downloaded from the Internet and it can be compiled for multiple platforms, including the most popular Linux flavours and Windows.

OMNeT++ (Objective Modular Network Testbed in C++), is a public-source, object-oriented modular discrete event simulation package that can be used for modelling communication protocols, computer networks, traffic modelling, multiprocessors and distributed systems. OMNeT++ also supports animation and interactive execution.

The OPNET simulation package was discarded because it was a commercial product at the moment when this choice was made. Therefore, only ns-2 and OMNeT++ were assessed has possible solutions for the implementation of the simulation models in this dissertation. While ns-2 is a network simulation classic, it has many drawbacks, when compared with OMNeT++, which is a more modern and structured simulation package. The following summarises a number of advantages of OMNeT++ over ns-2:

– The OMNeT++ simulation kernel is a class library: the components are developed as any other class library, and then linked with the executable library. There is no need to modify OMNeT++ sources anywhere. In contrast, ns-2 tends to be a bit monolithic: to add implementations to it, it is necessary to download the full source and modify it in several places;

- OMNeT++ follows a modular approach: the model is assembled from self-contained building blocks. These components are reusable in other simulations;
- ns-2 has some considerably detailed built-in concepts about nodes, agents, protocols, links, packet representation, network addresses, etc. This often increases the difficulty in developing models that include even slightly different concepts. OMNeT++ is completely flexible and generic: it is possible to simulate anything that can be mapped to active components that communicate by passing messages;
- In OMNeT++, it is possible to fight model complexity by using hierarchical design: any complex component can be implemented as one unit or built out of several smaller components. In ns-2, models are "flat";
- OMNeT++ has a powerful interactive graphical environment, where it is possible to examine nearly everything during execution. ns-2 only includes Network AniMator (NAM), which is a playback tool.

For the reasons presented above OMNeT++ has been chosen.

4.4. OMNeT++ (Objective Modular Network Testbed in C++)

OMNeT++ (Varga, 2004) is an object oriented modular discrete event simulator, which provides a reusable component framework, where the system components can be independently built, characterized and assembled into larger components and models. The basic system components are built using the C++ programming language and then assembled into larger components and models using a high level language, named NED (an OMNeT++ specific scripting language).

An OMNeT++ model consists of hierarchically nested *modules* which communicate between them using messages. OMNeT++ models are often referred to as networks. The top level module is the *system* module. The system module contains *sub-modules*, which can also contain sub-modules themselves. The depth of module nesting is not limited, consequently providing a useful way to reflect the logical structure of the system in the model structure (Figure 4.2).

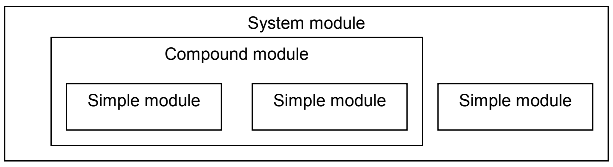

Figure 4.2 – Simple and compound modules

Modules that contain sub-modules are termed *compound* modules, in opposite to *simple* modules which are at the lowest level of the module hierarchy. The simple modules of a model contain the algorithms coded using C++ programming language. The full flexibility and power of the C++ programming language can be used, in conjunction with the OMNeT++ simulation class library. Further, OMNeT++ has a consistent object-oriented design. Thus, Object-Oriented Programming concepts (like inheritance and polymorphism) can be used to extend the basic functionality of the simulator.

4.4.1. Messages, Gates and Links

Modules communicate by exchanging messages which represent frames or packets in a computer network. These messages can contain arbitrarily complex data structures. Simple modules send messages through *gates* or directly based on their unique identifier. Messages can arrive from another module or from the same module (self-messages are used to implement timers).

Gates are the input and output interfaces of modules. Messages are sent out through output gates and arrive through input gates. Each connection (also called a link) is created within a single level of the module hierarchy and is composed by two gates. Within a compound module, one can connect the corresponding gates of two sub-modules, or a gate of one sub-module and a gate of the compound module (Figure 4.3).

Due to the hierarchical structure of the model, messages typically travel through a series of connections, but these messages are sent and received by simple modules. Such series of connections, which go from simple module to simple module, are called routes. Compound modules act as "cardboard boxes" in the model, transparently relaying messages between their inside and their outside world, i.e., they are used to aggregate other modules relaying messages from inside to the outside and vice-versa without any processing.

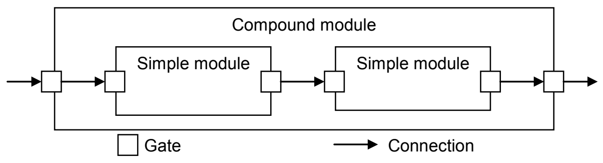

Figure 4.3 – Module's gates and connections

4.4.2. Modelling Delays, Bit Error Rate and Data Rate

Connections can be assigned three parameters which facilitate the modelling of communication networks: *propagation delay* (sec), *bit error rate* (errors/bit) and *data rate* (bits/sec). Each of these parameters is optional. One can specify link parameters individually for each connection, or define link types (also called channel types) once and use them throughout the whole model.

The propagation delay is the amount of time the arrival of a message is delayed when it travels through a communication channel. The bit error rate has influence on the transmission of messages through the channel. The bit error rate is the probability that a bit is incorrectly transmitted. The data rate is specified in bits/second, and it is used for transmission delay calculation. The sending time of a message normally corresponds to the transmission of its first bit, and the arrival time of the message corresponds to the reception of the last bit (Figure 4.4).

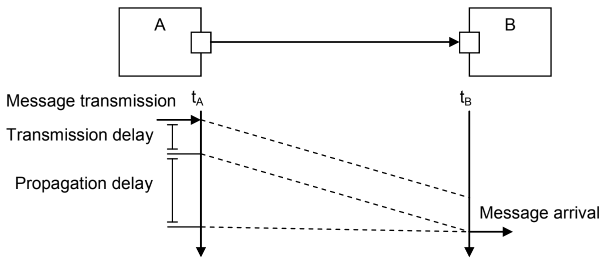

Figure 4.4 – Message transmission

In OMNeT++, the length of a message does not depend of its data structure composition, but on the length attribute. This attribute is used to compute the transmission delay when the message travels through a connection with an assigned data rate.

4.4.3. An OMNeT++ Example Model

An OMNeT++ model consists of the following parts:

- NED language topology description(s) which describes the module structure and respective parameters, gates, etc. These are files with .ned suffix. NED files can be written with any text editor or using the GNED graphical editor.
- Simple modules are C++ sources files, with .h/.cc/.cpp suffix.

The simulation system provides the following components:

- Simulation kernel, which contains the code that manages the simulation and the simulation class library. It is written in C++, compiled and put together to form a library.

- User interfaces. OMNeT++ user interfaces are used with simulation execution, to facilitate debugging, demonstration, or batch execution of simulations. There are several user interfaces, written in C++.
- Simulation programs are built from the above components. First, the NED files are compiled into C++ source code, using the NEDC compiler which is part of OMNeT++. Then all C++ sources are compiled and linked with the simulation kernel and a user interface to form a simulation executable.

The simulation executable is a standalone program, which can be run in any machine. When the program is started, it reads from a configuration file (usually *omnetpp.ini*) settings that control how the simulation is run and values for model parameters. The configuration file can also specify several simulation runs; in the simplest case, they will be executed by the simulation program one after another or executed on a parallel environment.

4.4.4. Event-Based Simulation

As mentioned, an OMNeT++ model consists of hierarchically nested modules which communicate between them using messages. Each message can be exchanged directly between simple modules or via a series of gates and connections. The local simulation time advances when a module receives messages from another module or from itself. Self-messages are used by a module to schedule events at a later time.

In the initialization step, OMNeT++ builds the network: it creates the necessary simple and compound modules and connects them according to the NED definitions. OMNeT++ calls the `initialize()` functions of all simple modules, which is usually used to initialize the data members. The `handleMessage()` function is called during event processing. This means that the behaviour of each module is coded in this function. The `finish()` function is called when the simulation terminates successfully, it is usually used to write statistics at the end of a simulation run.

In order to clarify these concepts, Figure 4.5 presents a typical PROFIBUS network transaction, which consists on the request frame from the initiator (master M1) and the associated response frame by the responder (slave S1). The initiator has to wait an `Idle Time` (T_{ID}) before sending a request frame and the responder has to wait `Station Delay Responder Time` (T_{SDR}) before sending a response frame.

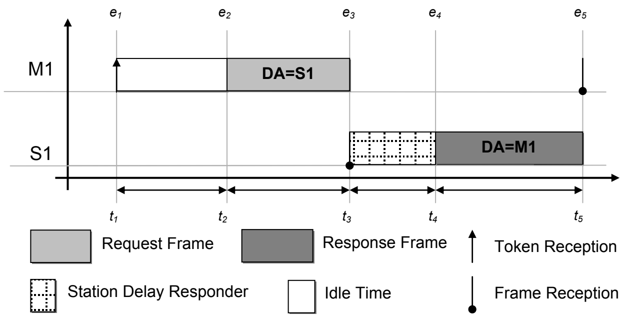

Figure 4.5 – PROFIBUS transactions events

Assuming that master M1 (initiator) has just received the token (event e_0 at the instant t_0), then it will schedule a self message for instant t_1, which marks the beginning of a request frame transmission and the end of the T_{ID} (event e_1).

Event e_2, at instant t_2 represents the reception of the request frame's last bit by slave S1. This instant is calculated as function of the request frame's length and the data rate of the connection. As soon as the slave S1 receives the request frame's last bit it schedules a self message to simulate the end of the T_{SDR} and begin of the response frame transmission (event e_3 at the instant t_3). Event e_4 corresponds to the reception of the response frame's last bit by master M1.

In order to model the system described above two simple modules can be used, one to model the master station (hereafter called `MasterStation` module) and another to model the slave station (hereafter called `SlaveStation` module).

Figure 4.6 shows part of the `handleMessage(cMessage *msg)` function (or method) of the `MasterStation` module. This function is automatically invoked at reception of every message. Therefore, the arriving of the token frame to the `MasterStation` module instance called M1 is handled by this function. This message is a PROFIBUS message where the DA and SA are equal to TS and PS (line 20), respectively. M1 computes the T_{TH} (line 22) and in order to wait T_{ID} before sending a frame it schedules a self message to arrive at instant T_{ID} counted from the current instant (the current simulation time is given by `simTime()` function) (line 24). When M1 receives a self message (line 6) that marks the end of the inactivity time (T_{ID}), it removes a message from its message output queue (line 10) and starts transmitting the request frame addressed to the `SlaveStation` module instance called S1(line 11).

```
1.  void MasterStation::handleMessage(cMessage *msg)
2.  {
3.        cMSG_Profibus *msg_profibus=NULL;
4.        cMSG_Self *msg_self=NULL;
5.        // handle the message according to the simple module algorithm
6.        if (msg->isSelfMessage()) {   //usually used as timer
7.                  msg_self=(cMSG_Self s *) msg;
8.                  switch(msg_self->getAction()){
9.                            case SEND_MESSAGE:
10.                                     dequeueMessage(&msg_profibus);
11.                                     send(msg_profibus, "out");
12.                           }
13.                           ...
14.                 }
15.       }
16.       else{
17.                 msg_profibus=(cMSG_Profibus *) msg;
18.                 switch(msg_profibus->getType()){
19.                           case TOKEN_FRAME: //if it is a token frame
20.                                     if(msg_profibus->getDA()==TS &&msg_profibus->getSA()==PS){
21.                                               ...
22.                                               computeTHT();
23.                                                msg_self->setAction(SEND_MESSAGE);
24.                                               scheduleAt(simTime()+TID, msg_self);
25.                                     }
26.                           break;
27.                           case RESPONSE_FRAME: //if it is a response frame
28.                                     if(msg_profibus->getDA()==TS && ...){
29.                                               scheduleAt(simTime()+TID, msg_self);
30.                                     }
31.                           break;
32.                           ...
33.
34.                 }
35.       }
36. }
```

Figure 4.6 – `handleMessage(cMessage *msg)` function, C++ code (`MasterStation`)

Figure 4.7 presents `handleMessage(cMessage *msg)` function of the `SlaveStation` module. In same way this function is automatically invoked as soon as a `SlaveStation` module instance receives a message. At reception of the message, slave S1 checks if the received frame is addressed to it (line 20). It schedules the sending of the response (line 23) if it is. Otherwise, no action is taken.

```
 void SlaveStation::handleMessage(cMessage *msg)
{
cMSG_Profibus *msg_profibus=NULL;
cMSG_Self *msg_self=NULL;
// handle the message according to the simple module algorithm
if (msg->isSelfMessage()) {          //usually used as timer
      msg_self=(cMSG_Self s *) msg;
      switch(msg_profibus->getAction()){
                case REPLY_MESSAGE:
                          buildResponseMessage(&msg_profibus);
                          send(msg_profibus, "out");
                }
                ...
      }
   }
else{
      msg_profibus=(cMSG_Profibus *) msg;
      switch(msg_self->getType()){
                case REQUEST_FRAME: //if it is a request frame
                          if(msg_profibus->getDA()==TS && ...){

                                              msg_self->setAction(REPLY_MESSAGE);
                                              scheduleAt(simTime()+TSDR, msg_self);
                                    }
                                    ....
                          }
                break;
                ....

      }
   }
}
```

Figure 4.7 – `handleMessage(cMessage *msg)` function, C++ code (`SlaveStation`)

4.5. Summary

This chapter discussed the main characteristics of the OMNet++ simulation environment used in this dissertation. It described its main characteristics and provides an example of how a PROFIBUS message cycle can be modelled in such architecture.

Chapter 5

PROFIBUS Simulation Model

The repeater and the bridge-based approaches are both compatible with standard PROFIBUS, therefore their simulation software share the same standard PROFIBUS modules. This chapter describes the entities which enable the simulation of a standard PROFIBUS network.

5.1. Introduction

The repeater (Alves, 2003) and bridge-based (Ferreira, 2005) approaches are both compatible with standard PROFIBUS and both extend the PROFIBUS protocol in order to support wireless communication.

This chapter describes the architecture of the standard PROFIBUS simulation model (Section 5.2) which is used by the Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (RHW2PNetSim) and the Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (BHW2PNetSim) for the simulation of repeater and bridge-based approaches, respectively. These modules implement most of the relevant features of the PROFIBUS protocol. For each module this chapter also presents its main parameters which can be configured by the use of NED files. This kind of text file allows the definition of the network configuration and the setting of the module parameters. The chapter continues by presenting the implementation of the PROFIBUS DLL simulation model (Section 5.3).

5.2. PROFIBUS Basic Architecture

The PROFIBUS functions are implemented in the `HW2PNet`, `Controller`, `Domain`, `Master` and `Slave` OMNeT++ modules. The left side of Figure 5.1 shows the main OMNeT++ modules used in both simulation models. The `HW2PNet` module represents the entire network, that is, the system module in the context of the OMNeT++ framework. The `Controller` is the module that coordinates the simulation and performs several tasks, such as, parameterization, configuration of the other module instances and it is also responsible for the setup of the simulation run. The `Domain` module models a network domain and interconnects all components in a single network domain. The `Master` and `Slave` modules model a master or slave standard PROFIBUS network device.

On the left side, Figure 5.1 shows how the main modules are interconnected. There are 2 kinds of the connections: `ctrl_con` and `domain_con` connections. The `ctrl_con` connections are used to establish the connections between the `Controller` module instance and all module instances in the overall system. This kind of connection has no delay and is used for simulation control and configuration purposes. The `domain_con` connections are used to establish the connections among all domain components (between `Master` and `Slave` module instances and the `Domain` module instance).

On the right side Figure 5.1 there is a connection example between a `Master` and a `Domain` module instances. The `Master` instance is called M1 and `Domain` instance D1. Each of these connections is composed of four gates, two for each connected module instance. One gate is for input and it is connected to the output gate of the other module instance and vice-versa.

The messages are sent to D1 from M1 through a gate called `domain_gateOut`. Consequently D1 receives messages from M1 through a gate called `station_gateInM1`. D1 sends messages to M1 through a gate called `station_gateOutM1`.

Some station parameters, like T_{SDR} or T_{ID} are modelled either by Probability Distribution Function (PDF) or by a constant value. The PDFs implemented require at most four parameters. One of them defines which PDF is used and the other three are the arguments of the PDF. The name of all these parameters uses the `_pdf` prefix. For example, the parameters associated to T_{SDR} are the following: `_pdf_tsdr_type`, `_pdf_tsdr_par1`, `_pdf_tsdr_par2` and `_pdf_tsdr_par3`. The `_pdf_tsdr_type` indicates which PDF will be used to generate the value of the T_{SDR} and the other parameters are the arguments of the PDF. The PDFs supported by both simulators are described in detail in Annex A. Additionally the same parameters can also be used to make a configuration using constant values.

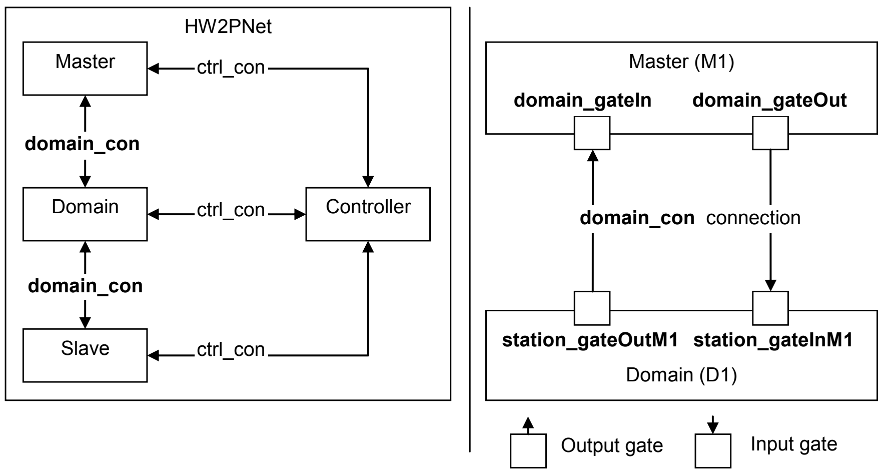

Figure 5.1 – Modules, connections and associated gates

One of the most important steps of a simulation study is to analyze output data generated by the simulator (Law and Kelton, 2000). Our simulators enable gathering information about the response time of transactions, information about state machine transitions of each module, information about the PDFs in use and information about the Bit Error Model (BEM) in use. The name of the parameters related to these functions use the `_output` prefix.

`Master`, `Slave` and `Domain` modules are all identified by a parameter called `_name`. The value of this parameter must be unique in the overall network, since it identifies a module instance.

To simplify the parameterization of the module instances, all common parameters to the network are associated with the `Controller` module and all common parameters to the domain are associated to the `Domain` module. These parameters are used by the `Controller` module instance to do the station parameterization. This characteristic makes the simulation configuration less complex and less error prone.

In the next sections, further details are provided concerning model architecture and implementation.

5.2.1. HW2PNet

In OMNeT++ to actually get a simulation that can be run, it is necessary to write a network definition. A network definition declares a simulation model as an instance of the system module, in this case of the `HW2PNet` module. A network definition is declared with keyword *network*, followed by the network instance's name and ends with the keyword *endnetwork*. Figure 5.2 presents the network definition in which the system module instance is called `theProfibusNet`. No simulation parameters are assigned in the network definition, since they are assigned by the configuration file named *omnetpp.ini*.

```
network
    theProfibusNet:    HW2PNet
Endnetwork
```

Figure 5.2 – Network definition

`HW2PNet` module is a compound module that contains all other module instances. An OMNeT++ network has at least one instance of each module. The number of module instances is specified in the `HW2PNet` module instance.

Figure 5.3 presents part of the OMNet++ NED definition of the `HW2PNet` module. This kind of compound module definition must be contained between the keywords *module* and *endmodule.* It is composed by the module parameters and by its sub-modules. Additionally, in the declaration of the compound modules elements, like gates and connections can be specified.

Parameters are mainly used to define the module behaviours. These parameters can be strings or numeric values as well as random values from different PDFs. Within a compound module, parameters can define the number of sub-modules as well as the number of gates. In this case, the gates and connections are assigned dynamically at run time.

```
module HW2PNet
            parameters:
                        _num_domains:     numeric,
                        _num_masters:     numeric,
                        _num_slaves:      numeric,
                        …
            Submodules:
                        master:            Master[_num_masters];
                        slave:             Slave[_num_slaves];
                        domain:           Domain[_num_domains];
                        ...
                        controller:       Controller;
endmodule
```

Figure 5.3 – `HW2PNet` module NED definition

Figure 5.4 depicts parts of the configuration file with the settings related to the `HW2PNet` module instance, which is the simulation network. This is a typical PROFIBUS network composed by only one domain (`_num_domains` parameter). This network is composed by four masters (`_num_masters` parameter) and six slaves (`_num_slaves` parameter).

```
theProfibusNet._num_domains=1
theProfibusNet._num_masters=4
theProfibusNet._num_slaves=6
```

Figure 5.4 –Configuration file related with `HW2PNet` module instance (excerpt)

Figure 5.5 shows a screenshot of the simulator output window for the network configuration referred to above. In this figure it is clear that the `Controller` instance (labelled *controller*) is able to communicate with all module instances. `Master` and `Slave` module instances are connected to the `Domain` module instance, symbolized by a rectangle.

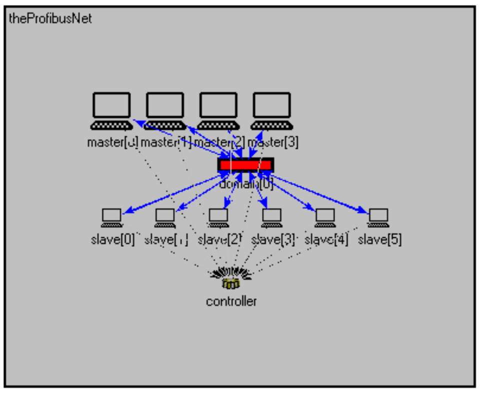

Figure 5.5 – Simulator output window screenshot

5.2.2. Controller

The `Controller` is a simple module that coordinates the simulation and performs several managing tasks, acting as the simulation supervisor. Parameters that are specific of one module instance or common to all module instances in the network are assigned to the `Controller` module instance. On simulation setup, the `Controller` module instance makes the parameter setting of the all other module instances. Additionally, due to memory limitations, the `Controller` module instance is responsible for periodically sending commands to other module instances, commanding them to dump the information gathered to data files. Finally, whenever a `Master` or `Slave` module instance changes between domains, this module updates the network configuration and the corresponding connections. Note that, OMNeT++ does not provide any native mechanism for mobility.

A simple module is declared with keywords *simple*, followed by the modules' name, and *endsimple*. The parameters and the gates can be specified in the declaration of a simple module.

Figure 5.6 presents the NED definition of the `Controller` simple module. Parameter `_domain` is a string which defines the configuration of the domain. It is written using predefined structure based in tags. The `Controller` module instance extracts information from these strings to perform the network configuration.

```
simple Controller
        parameters:
                _output_gant_diagram:     numeric,
                _output_resp_time:        numeric,
                _output_states:           numeric,
                _output_pdf:              numeric,
                _output_bem:              numeric,
                _output_period:           numeric,
                _output_path:             string,
                …
endsimple
```

Figure 5.6 – `Controller` module NED definition

The parameters with the `_output` prefix are related to the output data files. If one of these parameters has a value of one it means that the information referred to, by the parameter, must be gathered by the module instances (Table 5.1). A detailed description of the output data files is presented in Annex D.

Figure 5.7 presents a configuration example of the `_domain` parameter used in BHW2PNetSim (there is a slightly difference in the configuration of the parameter of the two simulators) by the network showed in Figure 5.5.

Table 5.1 – Summary of the output data information

Parameter	Information
`_output_gant_diagram`	Information necessary to build event Gant Diagrams.
`_output_resp_time`	Information about the response time of each transaction.
`_output_states`	Information about module instances' state machine and their transitions.
`_output_pdf`	Information about the probability distribution functions used.
`_output_bem`	Information about the bit error model used.
`_output_period`	Period for dumping the gathered information on to data files.
`_output_path`	The path of the directory output files

The meaning of the tags used in `_domain` parameter are the following: *<d>* and *</d>* specify a domain; the tags *<n>* and *</n>* enclose the name of the `Domain` module instance; *<m>* and *</m>* enclose the name of the masters belonging to the domain, which are separated by a colon; *<s>* and *</s>* tags are similar to the previous case but associated with slaves; *<dmm>* and *</dmm>* define the `Master` module instance that is the DMM of the domain; *<pos>* and *</pos>* indicate the position of the domain for graphical representation purposes. Note that coordinate (0, 0) represent the top-left corner of the window as shown in Figure 5.5. In this particular case, the first domain ("*<d><n>D1</n><m>M1:M2:M3:M4</m><s>S1:S2:S3:S4:S5:S6</s><dmm>M1</dmm><pos> 400:300</pos></d>*") is referred to as D1 and is composed by four `Master` module instances (which are named M1, M2, M3 and M4) and six `Slave` module instances (S1, S2, S3, S4, S5 and S6). Its

DMM is `Master` module instance named M1. The `Domain` module instance is depicted in the screen at position (400, 300).

This information enables the `Controller` to set the LAS of all `Master` module instances as well as PS, NS and GAPL parameters. It also assigns the token frame to the master defined as DMM, thus, avoiding the need to perform the standard PROFIBUS network initialization procedure.

```
…
theProfibusNet.controller._domain="
<d><n>D1</n><m>M1:M2:M3:M4</m><s>S1:S2:S3:S4:S5:S6</s><dmm>M1</dmm><pos>100:200</pos></d>"
…
```

Figure 5.7 – Configuration file related to the `Controller` module instance (excerpt)

5.2.3. Domain

In spite of the OMNeT++ capacities, only one-to-one connections are supported. One-to-many and many-to-one connections can only be achieved using special purpose simple modules. Therefore, it was necessary to develop a simple module – the `Domain` module which is able to connect all stations in a domain and simulate a broadcast network. The connections are created and assigned dynamically enabling the support of mobility. In our model we assume that the propagation delay is ignorable. The transmission delay is simulated by the `Domain` module as a function of the `Baud_rate` parameter and the message length.

The parameters that are common to all modules connected to a domain are assigned to the `Domain` module and the `Controller` module instance performs the domain configuration and other module instance parameterization using this information.

Figure 5.8 presents the `Domain` simple module NED definition. The parameter `_medium` defines if the `Domain` module instance maps into wired (different to zero) or wireless (equal to zero) domain. Due to the use of different media in the network, the format of the wired and wireless frames is different. As an example, each DLL character can be coded using 8 or 11 bit, for wireless and wired frames, respectively. The wireless frames can also include additional preamble and header fields. The parameters `bitsPerChar`, `frameHeadLen` and `frameTailLen` are the number of bits per character, the number on the bits of the frame head and the number of the bit on the frame tail, respectively.

```
simple Domain
        parameters:
                Baud_rate:          numeric,
                bitsPerChar:        numeric,
                frameHeadLen:       numeric,
                frameTailLen:       numeric,
                G:                  numeric,
                HSA:                numeric,
                TTR:                numeric,
                TSL:                numeric,
                max_retry_limit:    numeric,
                _bem_type:          numeric,
                _bem_par1:          numeric,
                _bem_par2:          numeric,
                _bem_par3:          numeric,
                _bem_par4:          numeric,
                _name:              string;
        gates:
                in:                 ctrl_gateIn;
                out:                ctrl_gateOut;
endsimple
```

Figure 5.8 – `Domain` module NED definition

The parameter `G` is the `Gap Update` factor. The `HSA` parameter defines the `Highest Station Address` in the domain. The `TTR` parameter is the `Target Rotation Time` (T_{TR}) of the token and `TSL` is the `Slot Time` (T_{SL}). The number of retries is defined by the `max_retry_limit` parameter. The parameters with `_bem` prefix are used to define the channel Bit Error Model (BEM) in use. In Annex B we describe the BEM supported by these simulators.

Figure 5.9 presents part of the configuration file related to one instance of the `Domain` module. This `Domain` module instance is called D1 and maps a wireless domain operating at 2 MBits/s

(`Baud_rate` parameter). Each frame has a head of 32 bits, no frame tail and each character is coded using 8 bits. The `G` is set to one, therefore the GAP Update mechanism is always active. The `HSA` can be set differently for each domain according to the highest address of the stations that can belong to its domain. The `TTR` and `TSL` parameters are set in bit times and represent the T_{TR} and T_{SL} PROFIBUS parameters, respectively.

Transmission errors are modelled using the Independent Channel Model (Willig and Wolisz, 2001) (`_bem_type` parameter equal to 1) with a bit error probability of 10^{-5} (0.00001) (`_bem_par1` parameter).

```
theProfibusNet.domain[0]._name="D1"
theProfibusNet.domain[0]._medium=0
theProfibusNet.domain[0].Baud_rate=2000000
theProfibusNet.domain[0].frameHeadLen=32
theProfibusNet.domain[0].frameTailLen=0
theProfibusNet.domain[0].bitsPerChar=8
theProfibusNet.domain[0].G=1
theProfibusNet.domain[0].HSA=5
theProfibusNet.domain[0].TTR=300
theProfibusNet.domain[0].TSL=115
theProfibusNet.domain[0].max_retry_limit=1
theProfibusNet.domain[0]._bem_type=1
theProfibusNet.domain[0]._bem_par1=0.00001
```

Figure 5.9 – Configuration file related to `Domain` module instance (excerpt)

5.2.4. Master

A `Master` module is a compound module that maps a master station. It is composed by three modules: `Master_PHY`, `Master_DLL` and `Msg_Stream`. In each `Master` module instance there is one instance of `Master_PHY` and `Master_DLL` modules. The number of the `Msg_Stream` module instances can be from 1 up to 64. A `Master` module is connected to the `Domain` module through gates `domain_gateIn` and `domain_gateOut`. `Master_PHY` and `Master_DLL` model the PhL and DLL of the PROFIBUS protocol, respectively. The `Msg_Stream` module models the operation of the Application Layer (AL), therefore it can be configured to periodically request services from the DLL. These modules are hierarchically organized as illustrated in Figure 5.10.

As mentioned, compound modules are modules composed of one or more sub-modules. Any module type (simple or compound module) can be used as a sub-module. Further, sub-modules may use parameters of the compound module.

The compound module definition specifies how the gates of the compound module and its immediate sub-modules are connected. Connections that span multiple levels of the hierarchy are not allowed. This restriction enforces compound modules to be self-contained. These concepts are presented in the `Master` module NED definition depicted in Figure 5.11. In this definition some parameters are omitted since its definition is very long.

The address of the `Master` module instance is set using the `TS` parameter. The number of message streams is defined by the `_num_streams` parameter. This parameter is used to define the number of `Msg_Stream` module instances and also to specify the number of gates between the `Master_DLL` module and `Msg_Stream` module instances. The parameters with `_pdf_tid1` prefix are related to T_{ID1} PROFIBUS DLL parameter.

Figure 5.12 shows part of the configuration file related to a `Master` module instance. The parameter `_pdf_tid1_type` is set to three meaning that the T_{ID1} duration evolves according to a Triangular PDF. A Triangular PDF requires three parameters. In this case, the value of T_{ID1} will be between 11 bit times (`_pdf_tid1_par1` parameter) and 100 bit times (`_pdf_tid1_par3` parameter) and the mode is 70 bit times (`_pdf_tid1_par2` parameter).

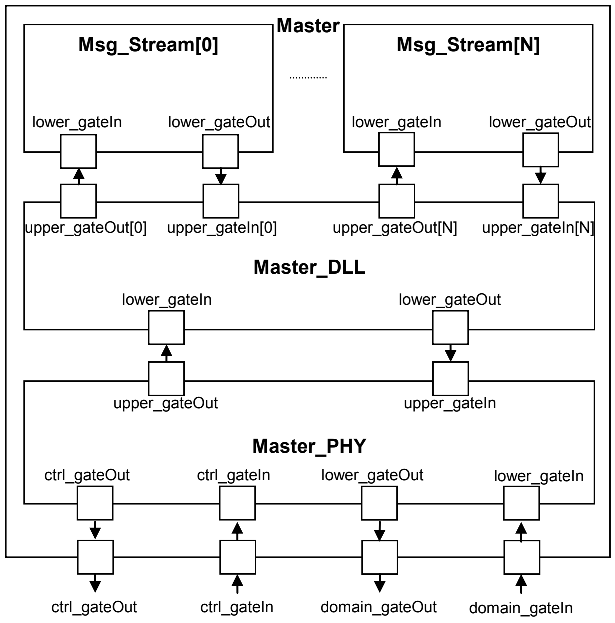

Figure 5.10 – OMNeT++ `Master` module composition

```
module Master
        parameters:
                TS:                     numeric,
                _num_streams:           numeric,
                _name:                  string,
                _pdf_tid1_type:         numeric,
                _pdf_tid1_par1:         numeric,
                _pdf_tid1_par2:         numeric,
                _pdf_tid1_par3:         numeric,
                …
        gates:
                in:                     domain_gateIn,ctrl_gateIn,bridge_gateIn;
                out:                    domain_gateOut,ctrl_gateOut,bridge_gateOut;
        submodules:
                phy_layer:              Master_PHY;
                dll_layer:              Master_DLL;
                            parameters:
                                        TS=TS,
                                        _num_streams=_num_streams,
                                        _pdf_tid1_type=_pdf_tid1_type,
                                        ..
                            gatesize:
                                        upper_gateOut[_num_streams],
                                        upper_gateIn[_num_streams];

                stream:                 Msg_Stream[_num_streams];
        connections nocheck:
                    phy_layer.upper_gateOut --> dll_layer.lower_gateIn;
                    phy_layer.upper_gateIn <-- dll_layer.lower_gateOut;
                    phy_layer.lower_gateIn <-- domain_gateIn;
                    phy_layer.lower_gateOut -->domain_gateOut;
                    phy_layer.ctrl_gateIn <-- ctrl_gateIn ;
                    phy_layer.ctrl_gateOut --> ctrl_gateOut;
                    dll_layer.bridge_gateIn <-- bridge_gateIn;
                    dll_layer.bridge_gateOut -->bridge_gateOut;
                    for i=0.._num_streams-1 do
                                    dll_layer.upper_gateOut[i] --> stream[i].lower_gateIn;
                                    dll_layer.upper_gateIn[i] <-- stream[i].lower_gateOut;
                    endfor;

endmodule
```

Figure 5.11 – `Master` module NED definition

```
theProfibusNet.master[2].TS=3
theProfibusNet.master[2]._name="M3"
theProfibusNet.master[2]._pdf_tid1_type=3
theProfibusNet.master[2]._pdf_tid1_par1=11
theProfibusNet.master[2]._pdf_tid1_par2=70
theProfibusNet.master[2]._pdf_tid1_par3=100
```

Figure 5.12 – Configuration file related to `Master` module instance (excerpt)

The following sections describes the implementation of each module that composes a `Master` module instance and their interactions.

Master_PHY

The `Master_PHY` module models the PhL of the PROFIBUS protocol. It represents the network interface of the `Master` module, it receives messages from a `Domain` or from a `Controller` module instance and passes the messages to the `Master_DLL` module and vice-versa. For that reason, this module is connected to the `Master` compound module through four gates (see Figure 5.10): `domain_gateIn`, `domain_gateOut`, `ctrl_gateIn` and `ctrl_gateOut`, the first two are related to `domain_con` connections and the last two are related `ctrl_con` connections. Figure 5.13 shows the `Master_PHY` NED definition.

```
simple Master_PHY
      gates:
      in: lower_gateIn, ctrl_gateIn, upper_gateIn;
      out: lower_gateOut, ctrl_gateOut, upper_gateOut;
endsimple
```

Figure 5.13 – `Master_PHY` module NED definition

Master_DLL

The `Master_DLL` module is structurally different in RHW2PNetSim and BHW2PNetSim. On the RHW2PNetSim it is a simple module, while on the BHW2PNetSim it is a compound module. However, the behaviour of the PROFIBUS DLL is the same, as well as the implementation.

The `Master_DLL` module is directly connected to the `Master_PHY` and the `Msg_Stream` modules. It is connected to the `Master_PHY` module instance through `lower_gateIn` and `lower_gateOut` gates and it is connected to *N* `Msg_Stream` module instances through 64 gates `upper_gateIn[x]` and `upper_gateOut[x]`, where x is a number between 1 and 64.

Figure 5.14 presents part of the `Master_DLL` NED definition used in the RHW2PNetSim. Its NED definition is very simple since most of its parameters are dynamically configured by the `Controller` module instance.

Msg_Stream

The `Msg_Stream` module models the typical behaviour of the AL. It can be configured to periodically request services from the `Master_DLL` module instance through the `lower_gateOut` gate. Each `Msg_Stream` module instance must be configured with the parameters necessary to build PROFIBUS messages. Figure 5.15 shows the `Msg_Stream` NED definition. The parameters `DA` and `SA` refer to `Destination Address` and `Source Address`, respectively. The local access address to the AL is defined in the `SAE – Source Address Extension` – and the remote access address to the AL is defined in the `DAE – Destination Address Extension`.

The parameter `DATA_UNIT` maps the content of a frame data field. For simplification reasons this parameter is a numeric data field. `Serv_class` parameter defines the priority (high or low) for the data transfer and the `service` parameter defines if a message maps into a `Send Data with No Acknowledge` (SDN) or a `Send and Request Data with Reply` (SRD) PROFIBUS service. If the `service` parameter value is set to 1, it means that it models a SDN service. In the case of being 3, it is a SRD service. The PROFIBUS SDA service can be modelled by using a SRD with a one byte response frame.

```
simple Master_DLL
      parameters:
                TS:                 numeric,
                _pdf_tid1_type:     numeric,
                _pdf_tid1_par1:     numeric,
                …
                _pdf_tid2_type:     numeric,
                _pdf_tid2_par1:     numeric,
                …
                _pdf_tsdr_type:     numeric,
                _pdf_tsdr_par1:     numeric,
                …
      gates:
                in:                 upper_gateIn[],lower_gateIn,bridge_gateIn;
                out:                upper_gateOut[],lower_gateOut,bridge_gateOut;
endsimple
```

Figure 5.14 – OMNeT++ `Master_DLL` module NED definition

The message generation can be active or inactive. If the value of the `_active` parameter is 0, then no messages are generated, otherwise messages are periodically generated.

```
simple Msg_Stream
      parameters:
                DA:                     numeric,
                DAE:                    numeric,
                SA:                     numeric,
                SAE:                    numeric,
                DATA_UNIT:              numeric,
                Serv_class:             numeric,
                service:                numeric,
                _active:                numeric,
                _deadline:              numeric,
                _output_color_red:      numeric,
                _output_color_green:    numeric,
                _output_color_blue:     numeric,
                _pdf_length_type:
                …
                _pdf_period_type:       numeric,
                …
                _pdf_offset_type:       numeric,
                …
      gates:
                in:                     lower_gateIn;
                out:                    lower_gateOut;
endsimple
```

Figure 5.15 – `Msg_Stream` NED definition

Typically, a transaction (or message cycle) consists of the request or a send/request frame from the initiator and the associated response frame from the responder, especially for SRD. The response time of each transaction is computed from the time in which the request frame is queued on the DLL output message queue until it receives the response frame.

However, the response time of a transaction can be theoretically unlimited in error prone environments. In order to deal with transmission medium characteristics, real time systems must be provided with mechanisms to detect and handle these error situations (Burns and Wellings, 2001). In a communication system these mechanisms are implemented at all levels of the communication stack.

At the AL level the `Msg_Stream` module is provided with a parameter (the `_deadline` parameter) which is used to detect if a transaction is not concluded before the expiration of the deadline.

In our simulation model we consider that a transaction misses its deadline in two situations. First, when the response time of a transaction is higher than its deadline even when a valid response is obtained from the IDT BM_{ini}, this is illustrated on the left side of Figure 5.16. The second case is the most common case in which a deadline is considered missed when the response frame is not received within its deadline. This case is illustrated on the right side of Figure 5.16.

As mentioned, these simulators produce information enabling the display of the Gant diagrams concerning message transactions. To distinguish between the different message streams it is possible to assign a colour to each message stream using the parameters with `_output_color_red`, `_output _color_green` and `_output_color_blue`.

The length in bits, the period and offset of the first activation of the message streams can be assigned either using random or constant values.

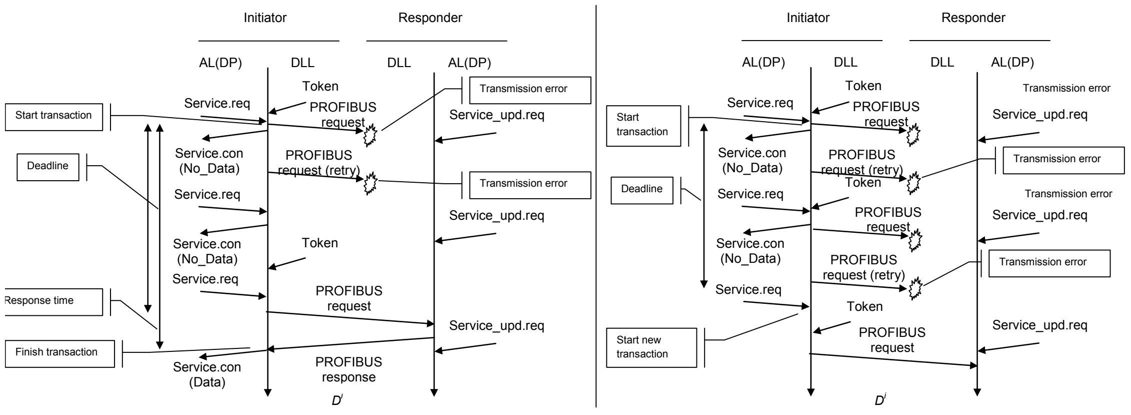

Figure 5.16 – Deadline missing examples

Figure 5.17 depicts an example of an `Msg_Stream` module instance configuration. This message stream involves a `Master` module instance with address 3 (`SA`) and `Slave` module instance with address 46 (`DA`). The SAE and DAE have the same value, which is equal to 7.

```
theProfibusNet.master[2].stream[1].DA=46
theProfibusNet.master[2].stream[1].SA=3
theProfibusNet.master[2].stream[1].DAE=7
theProfibusNet.master[2].stream[1].SAE=7
theProfibusNet.master[2].stream[1].DATA_UNIT=0
theProfibusNet.master[2].stream[1].Serv_class=1
theProfibusNet.master[2].stream[1].service=3
theProfibusNet.master[2].stream[1]._active=1
theProfibusNet.master[2].stream[1]._deadline=100ms
theProfibusNet.master[2].stream[1]._pdf_length_type=0
theProfibusNet.master[2].stream[1]._pdf_length_par1=15
theProfibusNet.master[2].stream[1]._pdf_period_type=0
theProfibusNet.master[2].stream[1]._pdf_period_par1=0.005
theProfibusNet.master[2].stream[1]._pdf_offset_type=0
theProfibusNet.master[2].stream[1]._pdf_offset_par1=0.0
theProfibusNet.master[2].stream[1]._output_color_red=100
theProfibusNet.master[2].stream[1]._output_color_green=255
theProfibusNet.master[2].stream[1]._output_color_blue=0
```

Figure 5.17 – `Msg_Stream` configuration parameters of a `Master`

As the `Serv_class` parameter is equal to 1 this is a high priority message stream using the SRD service (since the `service` parameter is equal to 3).

The period of this message stream is constant (since the `_pdf_period_type` parameter is equal to zero) at 0.005 s (`_pdf_period_par1` parameter). The length of the message is also constant (since the `_pdf_length_type` parameter is equal to zero) at 15 bytes (`_pdf_length_par1` parameter). The first message does not have any initial offset. The colour of this message stream on the Gant diagram is (100, 255, 0) in RGB notation.

5.2.5. Slave

A `Slave` is a compound module which maps into a standard PROFIBUS slave station. It is structured similarly to the `Master` module. The `Slave_PHY` module is equal to the `Master_PHY` module. The `Msg_Stream` module is the same module used by the `Master` module and is used for the same purpose, although in the case of a `Slave` module it generates periodical response messages. The `Slave_DLL` module is a simple module, which maps the PROFIBUS DLL of a slave.

In each `Slave` module instance there is one instance of `Slave_PHY` and `Slave_DLL` modules. The number of the `Msg_Stream` module instances can be from 1 up to 64. As shown in Figure 5.18 the `Slave` module structure is very similar to the `Master` module structure presented in Figure 5.10.

Since the `Master_PHY` and `Msg_Stream` modules were already described in Section 5.2.4, in this sub-section only the `Slave_DLL` module will be described.

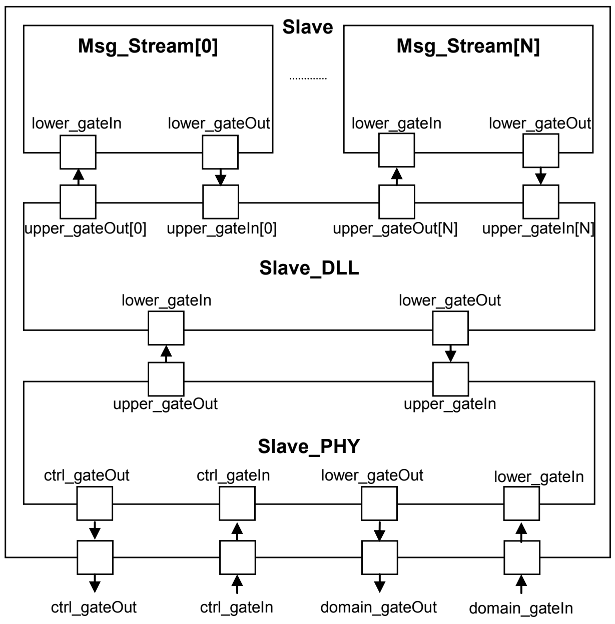

Figure 5.18 – OMNeT++ `Slave` module

Figure 5.19 presents the `Slave_DLL` NED definition. The address of `This Station` is set on its `TS` parameter. The T_{SDR} parameter is assigned according to the mode, defined in Section 5.2 for these types of parameters (which can receive values from PDF functions).

```
simple Slave_DLL
    parameters:
            TS:                 numeric,
            _pdf_tsdr_type:     numeric,
            _pdf_tsdr_par1:     numeric,
            …
    gates:
            in:                 upper_gateIn[],lower_gateIn;
            out:                upper_gateOut[],lower_gateOut;
endsimple
```

Figure 5.19 – `Slave_DLL` module NED definition

5.3. PROFIBUS DLL Basic Implementation

In this Section an overview of the PROFIBUS DLL basic implementation in both simulators is provided. A more detailed description can be found in Annex C.

In a standard PROFIBUS a slave state machine is composed by two states: OFFLINE and PASSIVE_IDLE. In our implementation of both simulators, the slave state machine only uses one state, the PASSIVE_IDLE state.

A slave does not have initiative, it only responds to requests addressed to it. The `Slave_DLL` behaviour depends on the kind of the received frame. In the implementation of both simulators, a slave is only able to receive SDN, SRD and `FDL_Request_Status` request frames. More details about this behaviour can be found in Sections C.1.5 and C.1.6 of Annex C.

The remainder of this Section will focus on the implementation of the `Master_DLL` and the `DLL` simple modules of the RHW2PNetSim and of the BHW2PNetSim, respectively. For that purpose, in this chapter we use the term `Master` when referring to the PROFIBUS DLL module.

The operation mode of a standard master PROFIBUS DLL is supported by a state machine composed by 10 states (IEC, 2000). For simplification reasons, in both implementations only 8 states are considered.

According to the PROFIBUS protocol, after turning on the power of a master station it will go into the LISTEN_TOKEN state in order to generate the `List of Active Stations` (LAS) and `GAP List` (GAPL). However, in RHW2PNetSim and BHW2PNetSim all `Master` module instances start in the ACTIVE_IDLE state with all configurations and parameterization performed by the `Controller` module instance, at the simulation setup. In order to start the network simulation operation, the `Controller` module instance sends a token frame to the `Master` module instance that acts as a `Mobility Master` (MM), in the case of RHW2PNetSim or sends a token frame to the `Domain Mobility Manager` (DMM) of each domain, in the case of the BHW2PNetSim. Then the state machine of the `Master` module instances evolves to the USE_TOKEN state.

Figure 5.20 presents the `Master` state machine diagram related to the implementation of the PROFIBUS DLL in both simulators.

In this state machine diagram an oval shape represents a state and an arrow a transition. For better identification, within of the oval shape the state identification is written and each transition is identified by a number.

In the description of the `Master` state machine diagram it is assumed that the `Time-Out Time` (T_{TO}) and the `Slot Time` (T_{SL}) related timers are automatically started and stopped in the following situations. The PROFIBUS protocol, defines that when a master frame's last bit is transmitted or when a master frame's last bit is received a timer is loaded with the T_{TO} value and is started (hereafter referred to as T_{TO} timer). The T_{TO} timer is stopped after receiving the first bit of the following frame. The value of this timer is set according to the Eq. 2.2. Whenever a request frame's last bit is transmitted by an initiator that requires either a response or an acknowledgement a timer is loaded with T_{SL} parameter value and is started (hereafter referred to as T_{SL} timer).

When a `Master` is in the ACTIVE_IDLE state, 3 transitions (1, 19 and 13) are possible. Transition 1 is triggered either by the reception of a valid token frame from its `Previous Station` (PS) (see Section C.1.2 for more details), or when T_{TO} expires.

Transition 19 occurs when a `Master` receives either a valid frame (without bit errors) not addressed to it or if the frame is valid and addressed to it but is not a token frame, for example an `FDL_Request_Status` frame (more details are given in Section C.1.5). If the received frame is an invalid frame (containing bit errors) the `Master` continues in the same state.

A `Master` in the ACTIVE_IDLE state continually analyses all received frames. If a token frame is received when `This Station` (TS) is "skipped" (i.e., the address of TS lies within the address range spanned from the sender address to the receiver address in the token frame), then it removes itself from the logical ring and evolves to the LISTEN_TOKEN state (transition 13).

When the `Master` is in the USE_TOKEN state, i.e., when it holds the token frame, it behaves according to the message dispatching procedure (a detailed description of this procedure is presented in Section C.1.3). A `Master` in the USE_TOKEN state can perform one of 4 transitions (2, 3, 5 and 7). The `Master` stays on the same state (transition 2) if it transmits a frame that does not need to receive a response frame (e.g., when using the SDN service, see Section C.1.6 for more details). It changes to the AWAIT_DATA_RESPONSE state (transition 3) if it sends a message that requires a response frame (e.g., when using the SRD service, see Section C.1.6) and returns to the USE_TOKEN state when it receives a response frame or the `Slot Time` (T_{SL}) expires (transition 4).

Transition 5 occurs, when the `Master` transmits an `FDL_Request_Status` frame and evolves to the AWAIT_STATUS_RESPONSE state. The `Master` returns to the USE_TOKEN state (transition 6) when it receives either a response frame or the T_{SL} expires (in Section C.1.5 the Gap update procedure is described in detail).

From the USE_TOKEN state it changes to the PASS_TOKEN state (transition 7) when its `Token Holding Time` (T_{HT}) expires. The T_{HT} is computed at token frame reception according to Eq. 2.1.

The transitions 8, 9, 10 and 11 are handled by the pass token procedure (a detailed description of this procedure is presented in Section C.1.4).

From the PASS_TOKEN state it evolves to the CHECK_TOKEN_PASS state (transition 8) after transmitting a token frame to its `Next Station` (NS). In the CHECK_TOKEN_PASS state 2 transitions (9 and 12) can occur. If it detects a valid frame in its domain then it changes to the ACTIVE_IDLE state (transition 12). Otherwise, if after expiring T_{SL} no activity is detected it returns to the PASS_TOKEN state (transition 9) and stays into these two states (PASS_TOKEN and

CHECK_TOKEN_PASS) until passing the token to another station in its LAS or to itself (transition 11).

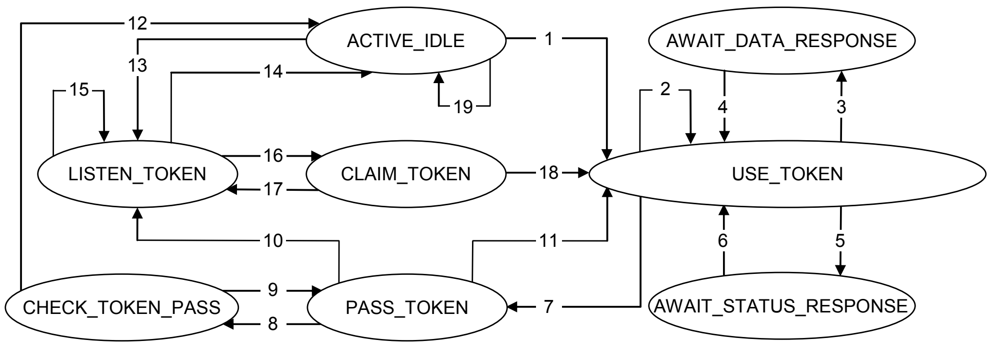

Figure 5.20 – `Master` state machine diagram

In order to detect a defective transceiver when a `Master` is transmitting a token frame, in the TOKEN_PASS state, it also receives the token frame. If it detects a difference between the transmitted and received frame it waits, in the CHECK_TOKEN_PASS state, T_{SL} for activity from its NS. If no activity is detected after expiring T_{SL}, it again transmits the token frame, if it again detects a difference between the transmitted and received frames its state machine evolves to the LISTEN_TOKEN state (transition 10). This process is designated as "heardback removal" in (Willig and Wolisz, 2001).

Whenever a `Master` evolves to the LISTEN_TOKEN state the LAS is cleared and it starts listening on the medium for at least two successive identical token cycles. During this time it is not allowed to send or respond to data frames or to accept the token, but it builds the LAS. After that, its state machine evolves to the ACTIVE_IDLE state (transition 14).

The `Master` state machine evolves to the CLAIM_TOKEN state from the LISTEN_TOKEN state when the T_{TO} timer expires (transition 16). In this case there is the need to recover the token (Section C.1.1 presents more details about this procedure). In this procedure it transmits two token frames addressed to itself and if no difference between transmitted and received frames occur its state machine evolves to the USE_TOKEN state (transition 18). Otherwise, the state machine evolves to the LISTEN_TOKEN state (transition 17) as a consequence of "heardback removal".

5.4. Summary

This chapter provided a high level overview about the implementation of the main PROFIBUS standard functionalities available in both the Repeater and Bridge-based simulators. For details about the implementation of these modules the reader is referred to the Annex C.

The next two chapters describe the implementation of the specific functions required by the repeater and bridge-based approaches.

Chapter 6

Repeater-Based Hybrid Wired/Wireless PROFIBUS Architecture Simulation Model

This chapter describes how the repeater-based approach has been implemented in the Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator by presenting the main architectural modules and its configuration parameters.

6.1. Introduction

The Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (RHW2PNetSim) is based on the network model developed within the aims of the RFieldbus project (RFieldbus, 2000a) and particularly on the architecture detailed in (Alves, 2003). It has been developed using the OMNeT++ discrete event simulation platform, described in the Chapter 4. The RHW2PNetSim is composed by 7 main components (modules): `HW2PNet`, `Controller`, `Master`, `Slave`, `Domain`, `ComFunc` and `Connection_Point`.

The modules `HW2PNet`, `Controller`, `Master`, `Slave` and `Domain` control the main PROFIBUS functionalities, and they were already detailed in Chapter 5. Therefore in this chapter, only the modules which implement the repeater functionalities are described, the `ComFunc` and `Connection_Point` modules. For the sake of simplicity, the functionalities of the Base Stations (BSs) are incorporated into the repeaters and the repeaters are only able to operate in cut-through mode.

This chapter starts by describing the main architectural components of the RHW2PNetSim and its configuration parameters (Section 6.2). Details regarding the implementation of the RHW2PNetSim are discussed in Section 6.3.

6.2. Simulator: Architecture

In order to model a repeater, two simple modules were developed the `Connection_Point` and `ComFunc` modules, Figure 6.1 illustrates these modules.

The `Connection_Point` is a simple module that establishes the connection with the `Domain` module. A repeater must include at least two of these module instances. The `ComFunc` is also a simple module that links `Connection_Point` module instances of the same repeater.

In addition to the `ctrl_con` and `domain_con` connections, already referred to in Chapter 5, there is another kind of connection: the `repeater_con`. This kind of connection is used to connect a repeater to a `Domain` module instance. For that purpose the `Domain` module is provided with a set of input and output gates, whose names use the `repeater_gate` prefix.

Figure 6.2 depicts a graphical representation of the network presented in Figure 2.3. In this figure it is clear that the `Controller` instance (labeled *controller*) is able to communicate with all module instances, for parameterization and control purposes. `Master` and `Slave` module instances are connected to their correspondent `Domain` module instances, symbolized by a rectangle or a cloud for the case of wired or wireless domains, respectively. Each repeater is composed by two `Connection_Point` module instances (labeled *cp[x]*, where *x* is a number between 0 and 5) and one `ComFunc` module instance (labeled *repeater[x]*, where *x* can be 0, 1 or 2). Note that, the `Connection_Point` module instance, which is symbolized by a large ball, also models the BS functions.

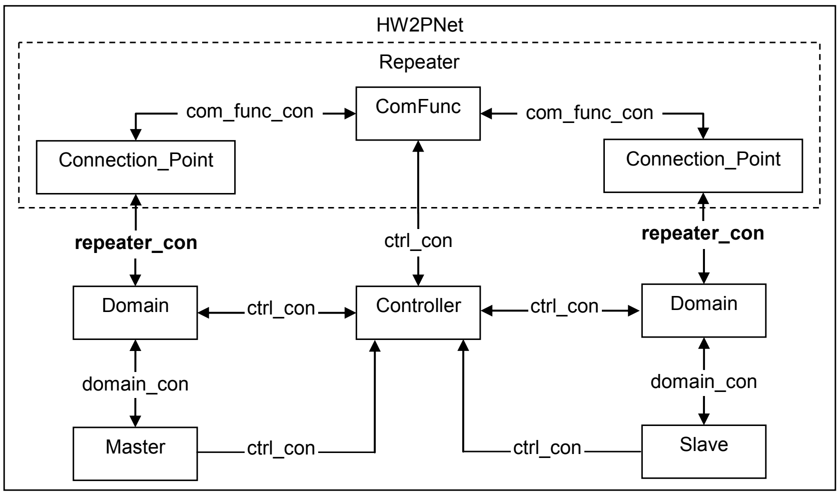

Figure 6.1 – Modules and connections of the RHW2PNetSim

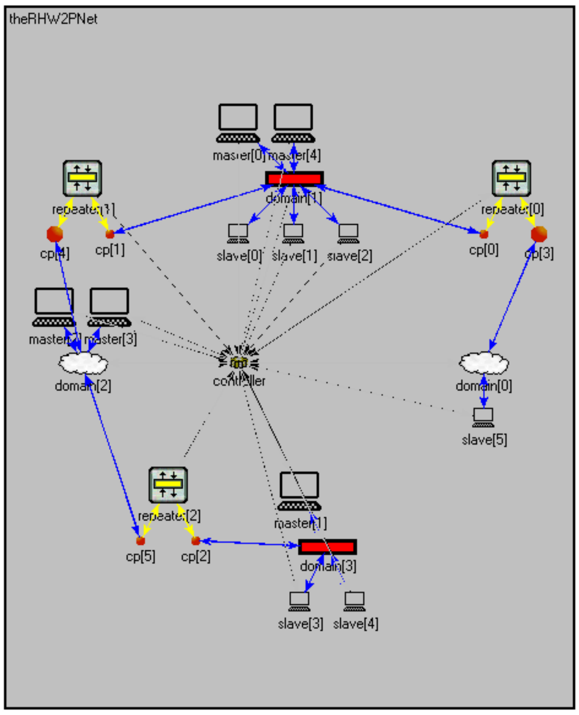

Figure 6.2 – Screenshot of the output window of the RHW2PNetSim

6.2.1. Controller

The configuration mode used by the `Controller` assumes that all `Master`, `Slave`, `Connection_Point` and `ComFunc` module instances have a unique identifier in the overall network. Therefore, each module has a parameter called `_name`.

Figure 6.3 presents part of the NED definition of the `Controller` module related to the configuration of repeater-based networks. To define the `Mobility Master` (MM) of the network it is necessary to assign the name of the `Master` module instance to the `_mm` parameter. The mobility procedure period is defined by the `_tmob` parameter.

The parameters `_domain` and `_inter_domain` are strings, which define the configuration of the network domains and repeaters. Both of them are written using predefined structure based in tags. The `Controller` module instance extracts information from these strings to perform the network configuration.

```
simple Controller
     parameters:
            _mm:                 string,
            _tmob:               numeric,
            …
            _domain:             string,
            _inter_domain:       String;
endsimple
```

Figure 6.3 – `Controller` module NED definition of the RHW2PNetSim

Figure 6.4 presents the parameter values related to the `Controller` module instance, assuming the network depicted in Figure 2.3. This file also includes information about MM (`Master` module instance named M5) and about the periodicity (`_tmob`).

```
theRHW2PNet.controller._mm="M5"
theRHW2PNet.controller._tmob=200ms
…
theRHW2PNet.controller._domain="\
<d><n>D1</n><m></m><s>S6</s><cp>CP8</cp><bs>CP8</bs><pos>400:300</pos></d>\
<d><n>D2</n><m>M1:M5</m><s>S1:S2:S3</s><cp>CP6:CP5</cp><bs></bs><pos>200:150</pos></d>\
<d><n>D3</n><m>M3:M4</m><s></s><cp>CP9:CP10</cp><bs>CP9</bs><pos>50:300</pos></d>\
<d><n>D4</n><m>M2</m><s>S4:S5</s><cp>CP7</cp><bs></bs><pos>250:450</pos></d>"

theRHW2PNet.controller._inter_domain="\
<l><n>R1</n><cp>CP5:CP8</cp><pos>400:150</pos></l>\
<l><n>R2</n><cp>CP9:CP6</cp><pos>50:150</pos></l>\
<l><n>R3</n><cp>CP10:CP7</cp><pos>120:400</pos></l>"
```

Figure 6.4 – Configuration file related to the `Controller` module instance of the RHW2PNetSim (excerpt)

The meaning of most of the tags used on the `_domain` string has been described in Chapter 5. *<cp>* and *</cp>* tags enclose the names of the `Connection_Point` module instances that are connected to the `Domain` module instance, the names must be separated by colon; *<bs>* and *</bs>* tags enclose the name of the `Connection_Point` module instance, which operates as a BS of a wireless domain. In the particular case of Figure 6.4, the second domain D2, is described by: (*"<d><n>D2</n><m>M1:M5</m><s>S1:S2:S3</s><cp>CP6:CP5</cp><bs></bs><pos>200:150</pos></d>"*), it is composed by two `Master` module instance (M1 and M5), and three `Slave` module instances (S1, S2 and S3) and this `Domain` module instance is connected to two `Connection_Point` module instances (CP6 and CP5). The `Domain` module instance is depicted in the screen at position (200,150).

The parameter `_inter_domain` is a string that is similar to the `_domain` string. This string defines the repeater configuration, and the meaning of the tags is the following: *<r>* and *</r>* define a repeater; *<n>* and *</n>* enclose the name of the `ComFunc` module instance; between tags *<cp>* and *</cp>* and separated by a colon appear the names of the `Connection_Point` module instances; *<pos>* and *</pos>* are used to define the location of the repeater. The first repeater presented in Figure 6.4 (*"<r><n>R1</n> <cp>CP5:CP8</cp><pos>400:150 </pos></r>"*) is referred to as R1, it is composed by two `Connection_Point` module instances (CP5 and CP8) and is positioned at (400,150). Note that, this repeater interconnects domains D1 and D2.

The `Controller` module instance stores into internal variables, the structure of the network. By manipulating this information it changes the network configuration when wireless mobile stations (`Master` and `Slave` module instances) move between domains.

6.2.2. Domain

Figure 6.5 presents the `Domain` simple module NED definition. The length of the `Beacon` frame is set by `beacon_len` parameter. `n_beacon` parameter is used to define the number of the `Beacon` frames relayed in the mobility procedure. The time interval between two consecutive `Beacon` transmissions is set on the `beacon_gap` parameter (t_{bgap} parameter referred to in Section 2.3.3). These parameters are used by the `Controller` module instance to parameterize the `Connection_Point` module instance which is operating as a BS.

```
simple Domain
     parameters:
               _beacon_len:     numeric,
               n_beacon:        numeric,
               beacon_gap:      numeric,
               …
               _name:           string;
endsimple
```

Figure 6.5 – `Domain` module NED definition of the RHW2PNetSim

During the mobility procedure a BS will transmit 14 `Beacon` frames with an interval of 25 μs between them and the length of each `Beacon` frame is equal to 10 bytes (Figure 6.6).

```
theRHW2PNet.domain[0].beacon_len=10

theRHW2PNet.domain[0].n_beacon=14
theRHW2PNet.domain[0].beacon_gap=25us
…
theRHW2PNet.domain[0]._name="D1"
```

Figure 6.6 – Configuration file related to the `Domain` module instance of the RHW2PNetSim (excerpt)

6.2.3. Parameters `_location_vector` and `_is_mobile_station`

Besides the parameters referred in Chapter 5, `Master` and `Slave` modules have two more parameters. One called `_location_vector` and the other called `_is_mobile_station`, these parameters are highlighted in Figure 6.7. The `_location_vector` is a string which defines the location of each `Master` and `Slave` module instance during time. In order to limit the size of the configuration files used, the `_location_vector` parameter is written in a compact format. Each location is represented by a tuple (*n_mob*,*Dx*), where *n_mob* represents the number of mobility procedures during which the `Master` or `Slave` module instance will stay on domain *Dx*.

The `_is_mobile_station` parameter is used to define if a `Master` or a `Slave` module instance models a mobile station (assigned with one) or not (assigned with zero).

Figure 6.7 depicts part of the configuration file related to a `Master` module instance, which models a wireless mobile station called M3. This station stays in domain D1 for five mobility procedures, and then it changes to domain D3 where it will stay for another 10 mobility procedures. This sequence of events repeats itself until the end of the simulation.

```
theRHW2PNet.master[2]._name="M3"
theRHW2PNet.master[2]._is_mobile_station=1
theRHW2PNet.master[2]._vector_location="5,D1:10,D3:"
```

Figure 6.7 – Configuration file related to the `Master` module instance of the RHW2PNetSim (excerpt)

In order to set the `_location_vector` parameter according to the radio channel quality and the mobility of wireless mobile station the Mobility Simulator (MSim) has been developed. This simulator models the radio wave propagation according to the Log-normal Shadowing model (Rappaport, 1996) and the mobility of wireless mobile stations. A detailed description of this simulator is found in Chapter 8.

6.2.4. Repeater Architecture

There is no module called repeater, the repeater is in fact an abstraction, since its operation is supported by three module instances, one instance of the `ComFunc` module and two of `Connection_Point` module (Figure 6.8).

The `ComFunc` module instance establishes connections between the `Connection_Point` module instances that belong to the repeater through the `com_func_con` connections. The `Connection_Point` module instances establish the connections to the `Domain` module instances by the `repeater_con` connections.

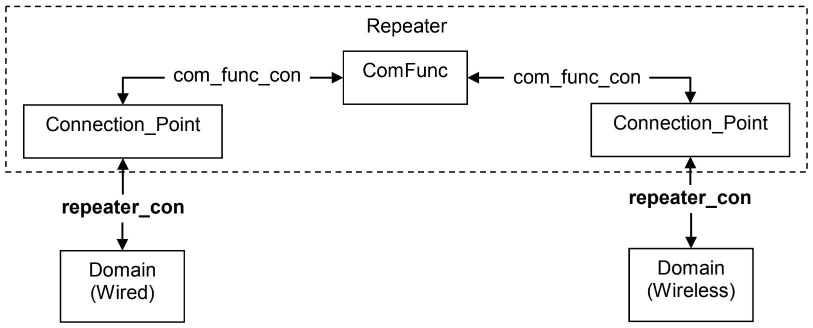

Figure 6.8 – Repeater's module instances and their connections

ComFunc

`ComFunc` is a simple OMNeT++ module. The NED definition of the `ComFunc` module is given in Figure 6.9. The main function of this module is to model the internal `relaying delay` – t_{rd} (see Section 2.3.2).

Frames relayed by the repeater are delayed by this module. The delay value is assigned to the parameters with the prefix `_pdf_delay`.

```
simple ComFunc
    parameters:
            _pdf_delay_type:        numeric,
            _pdf_delay_par1:        numeric,
            _pdf_delay_par2:        numeric,
            _pdf_delay_par3:        numeric,
            _name:                  string;
    gates:
            in:                     ctrl_gateIn;
            out:                    ctrl_gateOut;
endsimple
```

Figure 6.9 – `ComFunc` module NED definition

Figure 6.10 presents part of a configuration file related to a `ComFunc` module instance. This instance is called R1 and the delay introduced is equal to 30 µs. The parameter `_pdf_delay_type` defines if the delay is constant (0) or random according to a PDF, see Annex A for details.

```
theRHW2PNet.repeater[0]._name="R1"
theRHW2PNet.repeater[0]._pdf_delay_type=0
theRHW2PNet.repeater [0]._pdf_delay_par1=0.00003
```

Figure 6.10 – Configuration file related to one `ComFunc` module instance (excerpt)

Connection_Point

`Connection_Point` is a simple OMNeT++ module. This module establishes the connections between the `Domain` module instances and assures that a frame is transmitted without time gaps. Additionally, the BS functions are also modelled in this module like for instance, sending `Beacon` frames during the mobility procedure. Figure 6.11 shows the `Connection_Point` connections.

Figure 6.12 presents the NED configuration of the `Connection_Point` module. The inactivity time between two consecutive frames (T_{IDm} described in Section 2.3.4) can be assigned in a stochastic way. For this reason, the timing delay can be assigned by four parameters. The parameters related to the T_{IDm} have the `_pdf_tidm` prefix.

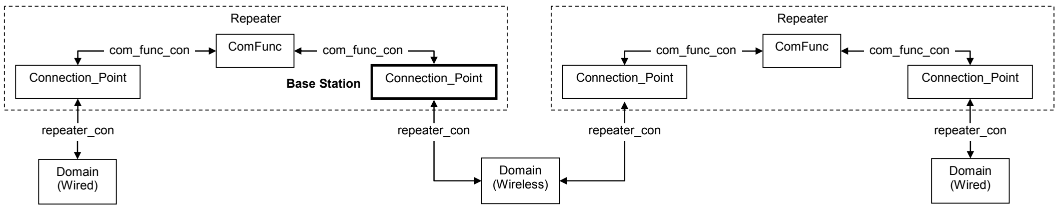

Figure 6.11 – Connection_Point module connections

```
simple Connection_Point
    parameters:
            _pdf_tidm_type:     numeric,
            _pdf_tidm_par1:     numeric,
            _pdf_tidm_par2:     numeric,
            _pdf_tidm_par3:     numeric,
            _name:              string;
    gates:
            in:                 com_func_gateIn,domain_gateIn;
            out:                com_func_gateOut,domain_gateOut;
endsimple
```

Figure 6.12 – `Connection_Point` module NED definition

Figure 6.13 presents part of a configuration file related to a `Connection_Point` module instance. This instance is called CP8. Since the parameter `_pdf_tidm_type` is set to zero, then the inactivity period between the two consecutive frames is constant and equal to 100 bit times.

```
theRHW2PNet.cp[3]._name="CP8"
theRHW2PNet.cp[3]._pdf_tidm_type=0
theRHW2PNet.cp[3]._pdf_tidm_par1=100
```

Figure 6.13 – Configuration file related to the `Connection_Point` module instance (excerpt)

6.3. Simulator Implementation

This simulator encompasses the functions concerning the PROFIBUS (described in Chapter 5), related to the domains interconnection and to the mobility procedure.

As previously mentioned, the repeater model is made up of two simple modules, `ComFunc` and `Connection_Point`. In our simulator implementation IS and BS functions are supported by the modules that model a repeater. It is assumed that the operation mode of the repeater is cut-through.

6.3.1. Interconnection

To interconnect different domains it is necessary to convert the received frame to the format of the destination domain and transmit the frame with a precise timing which guarantees minimal delays. For that purpose, there is the need to know the length of the DLL frame, the `Baud_rate` parameter value of the interconnected domains and how each frame is coded.

Figure 6.14 and Figure 6.15 illustrate a transaction between a `Master` module instance named M2 and a `Slave` module instance named S6, according to the network configuration presented in Figure 6.4, where M2 belongs to domain D4 and S6 belongs to domain D3.

In order to simulate bit by bit reception, `Connection_Point` module instance named CP7 delays the frame just enough time for it to know its length. Note that, the number of bits necessary to know the frame length depends on the PhL frame format and the PROFIBUS DLL frame type. For instance, wireless PhL frames include a head, tail fields and each DLL character is coded using 8 bits. Wired PhL frames do not include any head or tail fields, but each DLL character is coded using 11 bits. Concerning the frame length, PROFIBUS DLL has two kinds of frames: fixed and variable length frame. In order to know the length, in the first case, the first DLL character (SD field) is enough, but in the second case there is the need to receive the second DLL character, the LE field.

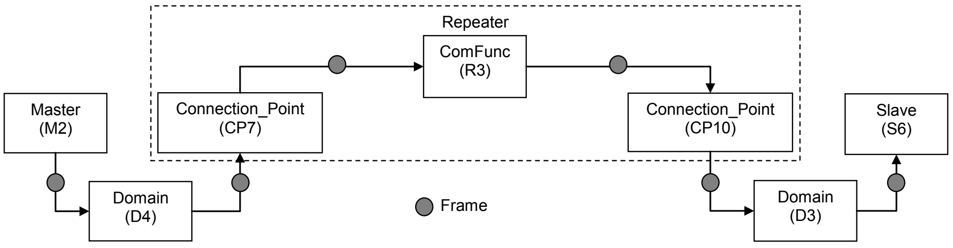

Figure 6.14 – Wired/wireless interconnection example

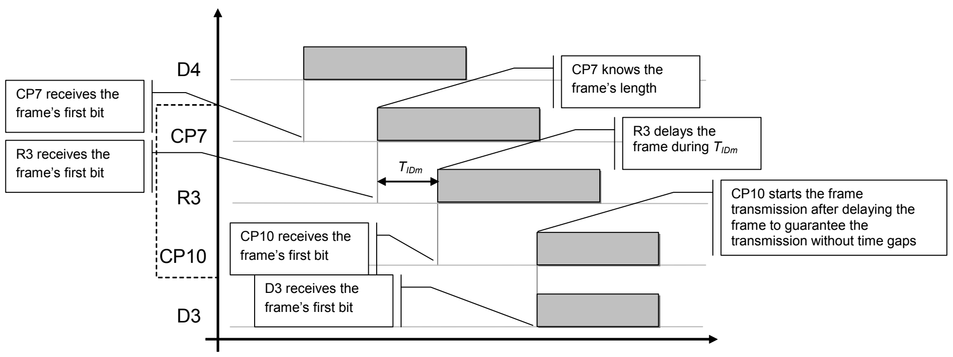
D4
CP7
R3
CP10
D3
CP7 receives the frame's first bit
R3 receives the frame's first bit
CP7 knows the frame's length
R3 delays the frame during T_{IDm}
T_{IDm}
CP10 starts the frame transmission after delaying the frame to guarantee the transmission without time gaps
CP10 receives the frame's first bit
D3 receives the frame's first bit

Figure 6.15 – Simplified timing behaviour of the module instances that model a repeater

After delaying the frame, CP7 passes the frame to the `ComFunc` module instance named R3. The frame is delayed by R3 during the time defined by a PDF configured by its parameters using the `_pdf_delay` prefix, after that, it passes the frame to the `Connection_Point` module instance named CP10. CP10 computes the frame last bit reception instant and the frame last bit transmission instant in order to determine the first bit transmission frame instant in its domain. In this calculation the CP10 has to respect the idle time (defined by parameters that use `_pdf_tidm` prefix) between two consecutive transmissions.

The frame is transmitted to the `Domain` module instance named D3 by CP10 through `repeater_con` connection. D3 delays the frame according to the frame length and then the frame is transmitted through `domain_con` connections arriving at S6.

All these delays had been implemented according to the principles presented in (Alves, 2003) which guarantees that there is no need to queue a frame in the first repeater which relays a frame. Nevertheless, in the following repeaters the queuing of frames might occur. For that reason, each `Connection_Point` module instance is provided with a queue.

6.3.2. Mobility Procedure

The mobility procedure is triggered in a periodical fashion. The periodicity is defined by the `_tmob` parameter. In this implementation we assume that the MM is a dedicated master, i.e., it only controls the mobility procedure. For that reason, a mobility-related timer is loaded, with a value defined by the `_tmob` parameter, which is started when it starts operating.

After the mobility-related timer expires and when it holds the token frame, it broadcasts a `Beacon Trigger` (BT) frame. The BT is an unacknowledged frame, therefore after sending the BT frame it waits T_{ID2} to schedule the next action according to the message dispatching procedure presented in C.1.3. Usually, it passes the token frame to its `Next Station` (NS). After sending the BT the mobility-related timer is reloaded.

`Connection_Point` module instances that are operating as BSs receive a BT frame and after relaying the received BT frame they start sending a pre-defined number (defined by `n_beacon` parameter) of `Beacon` frames (see Section C.2.1 for more details). The BS waits for T_{IDm} before transmitting a `Beacon` frame.

Wireless mobile stations receive these `Beacon` frames and changes to domain according to the `_location_vector` parameter, which defines the domain location for each wireless mobile station (more details in Section C.2.2).

6.4. Summary

This chapter presented the main architectural components used on RHW2PNetSim and some implementation details. Additionally, we had also described the format of the NED files required for the configuration of the modules used in this simulator.

Chapter 7

Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Architecture Model

This chapter describes how the bridge-based approach has been implemented in the Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator. It presents the main architectural modules and the main configuration parameters.

7.1. Introduction

As mentioned in Chapter 2 the Intermediate Systems (IS) of the bridge-based approach operate at Data Link Layer (DLL) level as bridges. A bridge can interconnect two or more domains. Although, it is assumed that a bridge only interconnects two domains.

Each bridge is composed by two modified PROFIBUS masters, called Bridge Master (BM). A BM is capable of receiving all frames arriving at its physical interface, and forwards them to the other BM of the bridge according to the routing information. These BMs operate almost as standard PROFIBUS masters and are assigned a PROFIBUS DLL address. Consequently, they take part on their domain logical ring.

This chapter presents the main architectural components of the Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (BHW2PNetSim) in Section 7.2. In Section 7.3, some relevant details of the implementation of the BHW2PNetSim are described.

7.2. Bridge Architecture

Figure 7.1 illustrates the main building blocks of a two-port bridge. In order to support the required functions, there must be a set of mechanisms related to the Inter-Domain Protocol (IDP) and to the Inter-Domain Mobility Procedure (IDMP). These mechanisms operate at DLL level and consequently the existing PROFIBUS DLL must be adapted. The operation of the IDP and IDMP are managed by three components: `Bridge Master` (BM), `Global Mobility Manager` (GMM) and `Domain Mobility Manager` (DMM).

The BM component, which gives the device its name and is mandatory, contains the routing and the IDF handling functions which are crucial to the IDP and to the IDMP. These two functions are associated with three data structures: the `Routing Table` (RT), the `List of Open Transactions` (LOT) and the `List of Active Stations in Domain` (LASD).

Frames are relayed by a BM according to the information contained in its RT. The LOT is used to store information about on going IDT in which the BM assumes the role of BM_{ini} (see Chapter 2 for details). For the BM which operates as BM_{res} i.e., the last BM in the transaction path, it has to know which masters and slaves belong to its domain. Therefore, the LASD is a list of all masters and slaves that belong to the domain.

The other two components, GMM and DMM, are optional and their functions are related to the IDMP. The DMM functionalities require two data structures: the `List of Bridge Masters in the Domain` (LBMD) and the `List of Wireless Mobile Stations in the Network` (LWMSN). The LBMD is a list that contains the domain's BMs addresses and is used in the IDMP inquiry sub phase. The LWMSN is list of address of all wireless mobile stations present in the network and is used in the IDMP discovery sub-phase.

The GMM must also be provided with two data structures: the `List of Bridge Masters in the Network` (LBMN) and the `List of Domain Mobility Managers in the Network` (LDMMN). The LBMN is a list of address of all BMs present in the network and is used to control the received RSMP messages during the IDMP Phase 1. The LDMMN contains all network DMM addresses and is used to control the received RBT messages during the IDMP Phase 2.

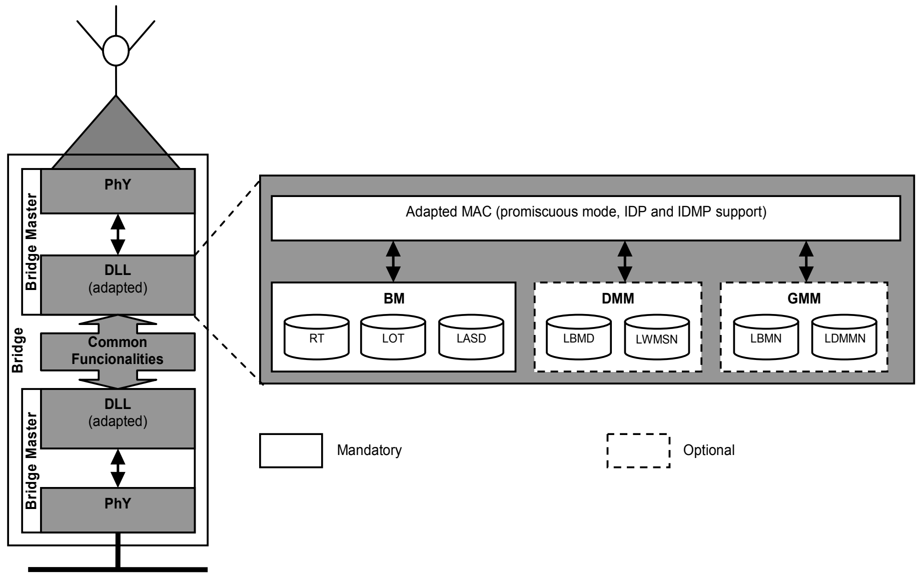

Figure 7.1 – Bridge architecture

Figure 7.1 also shows the `Common Functionalities` box, which is supported by a shared memory area and is responsible for the communication between the two BMs of a bridge.

7.3. Simulator Architecture

The BHW2PNetSim was developed using the OMNeT++ discrete event simulation platform. It is composed by six main components (modules): `HW2PNet`, `Domain`, `ComFunc`, `Slave`, `Master` and `Controller`. Except for the `HW2PNet` and `Controller` modules the others can be clearly mapped on the main devices of the bridge-based architecture.

The main features of the `HW2PNet`, `Controller`, `Master`, `Slave` and `Domain` modules were already detailed in Chapter 5 and the `ComFunc` module was detailed in Chapter 6. Therefore, only the differences and extensions to these modules will be described in this chapter.

Figure 7.2 shows how the main modules are interconnected. Besides the `domain_con` and `ctrl_con` connections (described in Chapter 5), there is another kind of connection called `bridge_con`. This connection is used to model a bridge. In this simulator architecture, there is no module called bridge. A bridge is an abstraction which is composed by two `Master` module instances connected by a `ComFunc` module instance.

Figure 7.3 shows a graphical representation used by the simulator to represent the network scenario shown in Figure 2.12. This network scenario is composed by three bridges. The `ComFunc` module instance of each bridge is labelled *bridge[x]*, where *x* can be 0, 1 or 2.

7.3.1. Controller

Figure 7.4 presents the NED definition of the `Controller` simple module. To define the GMM it is necessary to assign the name of the `Master` module instance to the `_gmm` parameter. The parameter `_tmob` is used to define the period of the IDMP. The duration of the `GMM_Phase_1_Alert_Timer` ($T_{GMM\text{-}P1Alert}$), `GMM_Phase_1_Abort_Timer` ($T_{GMM\text{-}P1Abort}$), `GMM_Phase_2_Alert_Timer` ($T_{GMM\text{-}P2Alert}$), `GMM_Phase_2_Abort_Timer` ($T_{GMM\text{-}P2Abort}$), described in Chapter 3, are set by `_gmm_phase1_alert_timer`, `_gmm_phase1_abort_timer`, `_gmm_phase2_alert_timer` and `_gmm_phase2_abort_timer` parameters, respectively. These parameters are only configured on the `Master` module instance that acts as GMM.

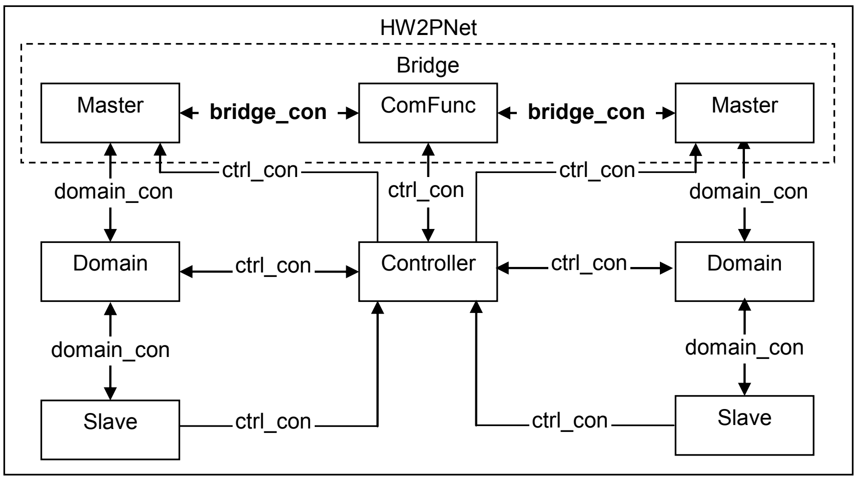

Figure 7.2 – Modules and connections of the BHW2PNetSim

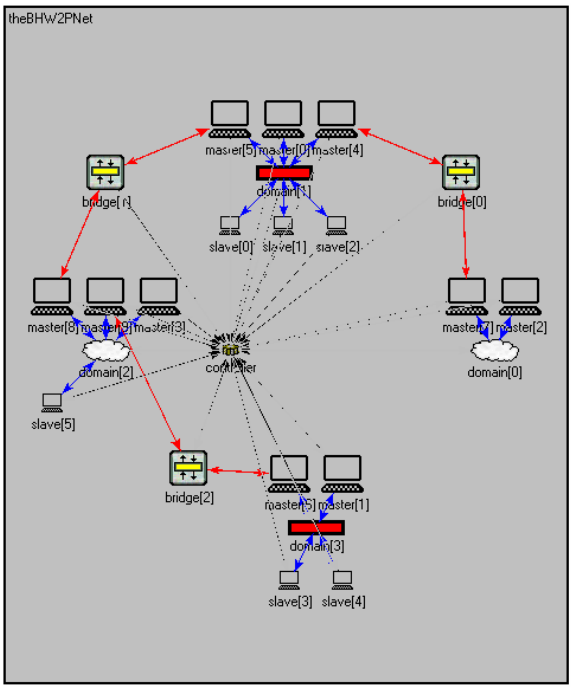

Figure 7.3 – Screenshot of the output window of the BHW2PNetSim

In order to gather the output data files information about aborted IDT and IDMP the `Controller` module is provided with two more parameters (`_output_timeout_idt` and `_output_timeout_idmp`) apart from the parameters described in Chapter 5. A detailed description of the output data files generated by both simulators (the RHW2PNetSim and BHW2PNetSim) is presented in Annex D as well as some tools used to extract information from them.

If `_output_timeout_idt` parameter is set equal to one, it means that the BM module instance will be configured to gather information about which IDT transactions were aborted. In the same way, if `_output_timeout_idmp` parameter is set equal to one the BMs, DMMs and GMM will be configured to gather information about IDMP timers expiration.

```
simple Controller
    parameters:
            _gmm:                          string,
            _tmob:                         numeric,
            _gmm_phase1_alert_timer:       numeric,
            _gmm_phase1_abort_timer:       numeric,
            _gmm_phase2_alert_timer:       numeric,
            _gmm_phase2_abort_timer:       numeric,
            …
            _output_timeout_idt:           numeric,
            _output_timeout_idmp:          numeric,
            …
            _domain:                       string,
            _inter_domain:                 string;
endsimple
```

Figure 7.4 – `Controller` module NED definition of the BHW2PNetSim

The parameters `_domain` and `_inter_domain` (bold lines in Figure 7.5) are strings, which define the configuration of domains and bridges. Both of them are written using a predefined structure based in tags. Figure 7.5 presents an example of the parameter values related to the `Controller` module instance for the network depicted in Figure 2.12.

```
theBHW2PNet.controller._gmm="M6"
theBHW2PNet.controller._tmob=200ms
theBHW2PNet.controller. _gmm_phase1_alert_timer =20ms
theBHW2PNet.controller. _gmm_phase1_abort_timer =30ms
theBHW2PNet.controller. _gmm_phase2_alert_timer =10ms
theBHW2PNet.controller. _gmm_phase2_abort_timer =20ms

theBHW2PNet.controller. _output_timeout_idt =1
theBHW2PNet.controller. _output_timeout_idtmp=1
…
theBHW2PNet.controller._domain="\
<d><n>D1</n><m>M8:M3</m><s></s><dmm>M8</dmm><pos>400:300</pos></d>\
<d><n>D2</n><m>M6:M1:M5</m><s>S1:S2:S3</s><dmm>M6</dmm><pos>200:150</pos></d>\
<d><n>D3</n><m>M9:M10:M4</m><s>S6</s><dmm>M9</dmm><pos>50:300</pos></d>\
<d><n>D4</n><m>M7:M2</m><s>S4:S5</s><dmm>M7</dmm><pos>250:450</pos></d>"

theBHW2PNet.controller._inter_domain="\
<b><n>B1</n><m>M8:M5</m><pos>350:150</pos></b>\
<b><n>B2</n><m>M6:M9</m><pos>50:150</pos></b>\
<b><n>B3</n><m>M10:M7</m><pos>120:400</pos></b>"
```

Figure 7.5 – Configuration file related to the `Controller` module instance of the BHW2PNetSim (excerpt)

The meaning of the tags used in the `_domain` parameter was already defined in Chapter 5. The parameter `_inter_domain` defines the configuration of a bridge. The meaning of the tags is similar to that described in Chapter 6 for the repeaters. Tags *<b>* and *</b>* define a bridge; *<n>* and *</n>* are used to set the name of the `ComFunc` module instance; between tags *<m>* and *</m>* enclose the names of the `Master` module instances composing a bridge separated by colon; *<pos>* and *</pos>* indicate the position of the `ComFunc` module instance for graphical representation purposes.

The first bridge presented in Figure 7.5 (*"<b><n>B1</n><m>M5:M8</m><pos>350:150 </pos></b>"*) is referred to as B1 and it is composed by two `Master` module instances (M5 and M8), which are depicted at position (350,150). This bridge interconnects two domains D1 and D2.

The `Controller` module instance use the `_domain` and `_inter_domain` parameters information to perform the parameterization of the module instances, such as the RT of each BM, LBMD of each DMM and LDMMN of a GMM, just to mention some parameters. It also stores, in internal variables, the structure of the network. Using this information the network configuration can be changed when a `Master` or `Slave` module instance moves between wireless domains.

7.3.2. Domain

Figure 7.6 presents the `Domain` module NED definition. The `_dmm_idmp_abort_timer` parameter is used to set the duration of the DMM `DMM_IDMP_Abort_Timer` ($T_{DMM\text{-}IDMPAbort}$) of this domain. The number of `Beacon` frames that are transmitted by DMM during the IDMP and its length are defined in the `n_beacon` and `beacon_len` parameters, respectively.

```
simple Domain
      Parameters:
                  _dmm_idmp_abort_timer:      numeric,
                  _n_beacon:                  numeric,
                  _beacon_len:                numeric,
                  …
                  _name:                      string;
endsimple
```

Figure 7.6 – `Domain` module NED definition of the BHW2PNetSim

Figure 7.7 shows a configuration example of a domain in which the IDMP must end after 40 ms since the `DMM` receives a PBT message from the GMM and the `DMM` has to transmit 14 `Beacon` frames during Phase 3 of the IDMP. The length of each of `Beacon` frame is 10 bytes.

```
…
theBHW2PNet.domain[0]._dmm_idmp_abort_timer=40ms
theBHW2PNet.domain[0]._n_beacon=14
theBHW2PNet.domain[0]._beacon_len=10
…
theBHW2PNet.domain[0]._name="D1"
```

Figure 7.7 – Configuration file related to the `Domain` module instance of the BHW2PNetSim (excerpt)

7.3.3. Master

On the Bridge-based Hybrid Wired/Wireless PROFIBUS simulator a `Master` module can be used to simulate a PROFIBUS master (wired or wireless) or a BM. It is composed by three modules. Two of them are simple modules (`Master_PHY` and `Msg_Stream`) and the other is a compound module (`Master_DLL`). As described in Section 5.2.4, each `Master` module instance is composed by one instance of `Master_PHY` and `Master_DLL` modules and at most 64 `Msg_Stream` module instances.

This kind of `Master` module (Figure 7.2 and Figure 7.8) is connected to the `Domain` module (through gates `domain_gateIn` and `domain_gateOut`) and it can be connected to the `ComFunc` module (through gates `bridge_gateIn` and `bridge_gateOut`), when it operates as a BM.

`Master_PHY` and `Master_DLL` model the PhL and DLL of the PROFIBUS protocol, respectively. Additionally, the `Master_DLL` also implements the IDP and IDMP functions, namely the ones related to the BM, the DMM and the GMM as well as the necessary extension to the PROFIBUS DLL. These modules are hierarchically organized as illustrated in Figure 7.8.

Figure 7.9 presents part of a `Master` module NED definition (the omitted parameters were defined in Chapter 5). Concerning the parameters presented some were described in Chapter 5 like `TS`, `_name` and `_num_streams` parameters, while `_is_mobile_station` and `_location_vector` parameters were detailed in Section 6.2.3 of the Chapter 6.

When a `Master` module instance is a BM there is the need to assign two timers. One related to the entries in its LOT (`_bm_idt_abort_timer` parameter) and the other one related to the duration of the IDMP (`_bm_idmp_abort_timer` parameter). See Section 3.2.1 and Section 3.3.3 for details.

Figure 7.10 shows part of the configuration file related to one `Master` module instance named M10. If this `Master` module instance acts as a BM all IDTs opened in its LOT must be finalized within 20 ms after being created (`_bm_idt_abort_timer` parameter) and the IDMP must end 40 ms after a `Start_Mobility_Procedure` (SMP) message has been received (defined by the `_bm_idmp_abort_timer` parameter).

In the following section a description of the `Master_DLL` module and its interactions are presented. In Chapter 5, a detailed description of the `Master_PHY` and `Msg_Stream` modules can be found.

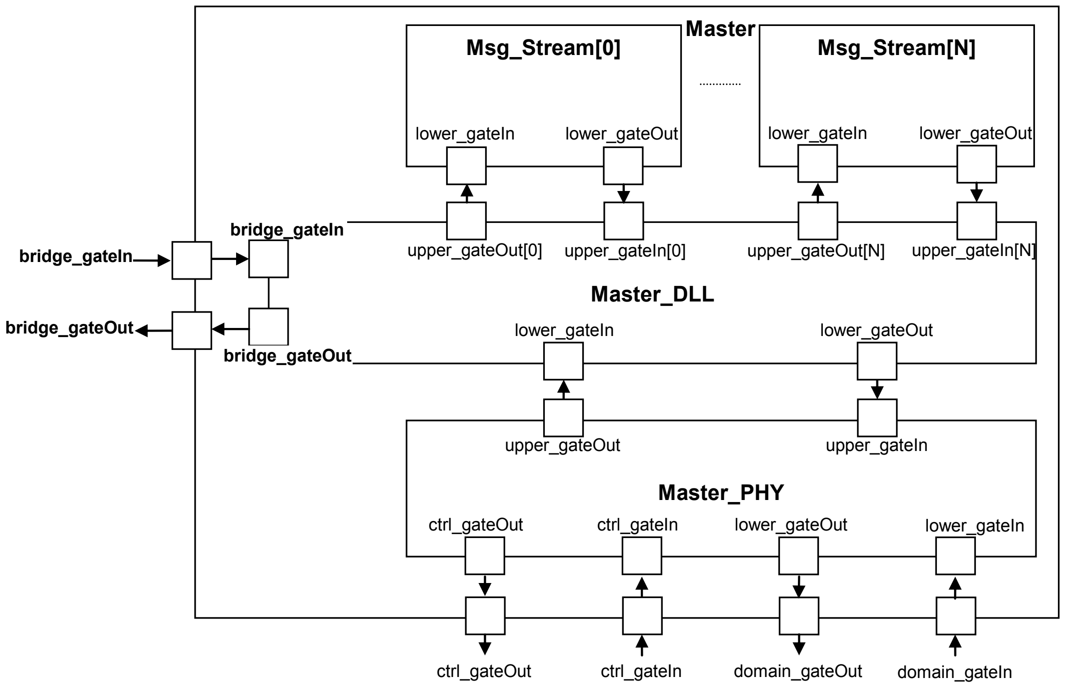

Figure 7.8 – OMNeT++ `Master` module composition of the BHW2PNetSim

```
module Master
    parameters:
            TS:                         numeric,
            _station_mobile:            string,
            _vector_location:           string,
            _bm_idt_abort_timer:        numeric,
            _bm_idmp_abort_timer:       Numeric,
            …
            _name:                      string;
    submodules:
            …
            dll_layer:                  Master_DLL;
                        parameters:
                                        TS=TS,
                                        _vector_location_location_vector,
                                        _bm_idt_abort_timer _bm_idt_abort_timer
                                        _bm_idmp_abort_timer=_bm_idmp_abort_timer
                        gatesize:
                                        upper_gateOut[_num_streams],
                                        upper_gateIn[_num_streams];
            …
    …
endmodule
```

Figure 7.9 – `Master` module NED definition of the BHW2PNetSim

Master_DLL

As mentioned a `Master_DLL` module models the PROFIBUS DLL and the necessary functions to support part of the IDP and IDMP functionalities. Consequently, in the BHW2PNetSim a `Master` module, besides modelling a simple PROFIBUS DLL master, can also operate as a BM and/or as a DMM and/or as a GMM. For that reason, the `Master_DLL` module is a compound module composed by 4 simple modules: `DLL`, `BM`, `DMM` and `GMM`, as shown in Figure 7.11.

The `DLL` module models the PROFIBUS DLL as well as the required adaptations in order to support the IDP and the IDMP. `BM`, `DMM` and `GMM` modules model IDP and IDMP agents.

```
theBHW2PNet.master[9].TS=10
theBHW2PNet.master[9]._name="M10"
theBHW2PNet.master[9]._idt_error_timer=20ms
theBHW2PNet.master[9]._idmp_error_timer=40ms
```

Figure 7.10 – Part of configuration file related to `Master` module instance

The `DLL` module (Figure 7.8 and Figure 7.11) is directly connected to every module that composes a `Master_DLL` module, and also to the `Master_PHY` and the `Msg_Stream` modules through the gates of the `Master_DLL`. It is connected to the `Master_PHY` module instance through `lower_gateIn` and `lower_gateOut` gates and it is connected to *N* `Msg_Stream` module instances through gates `upper_ gateIn[x]` and `upper_gateOut[x]`. Similarly, The `BM` module is connected to `ComFunc` module instance through gates `bridge_gateIn` and `bridge_gateOut`.

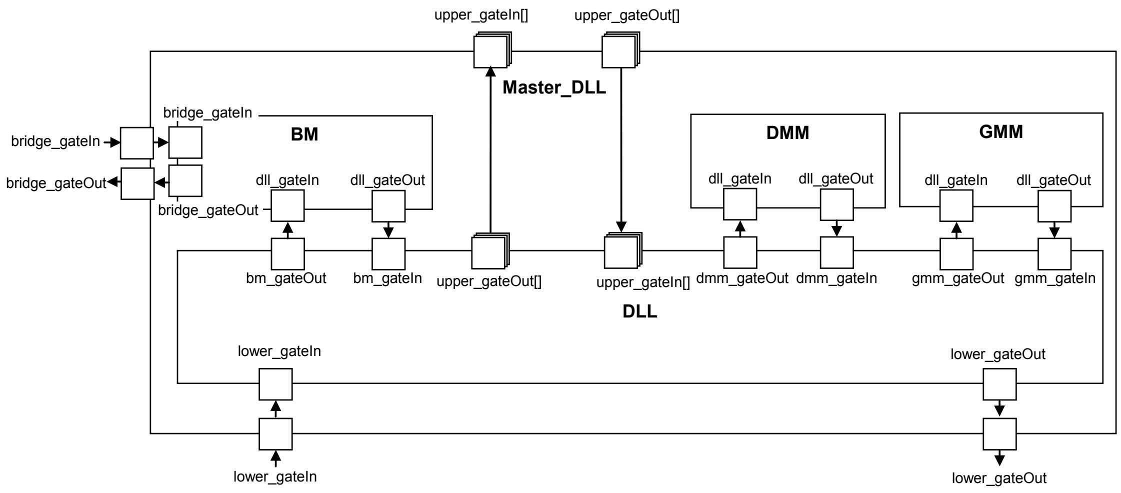

Figure 7.11 – OMNeT++ `Master_DLL` module composition

Figure 7.12 presents the `DLL` NED definition. Its NED definition is very simple and is very similar to the definition of the `Master_DLL` module presented in Chapter 5, except for the definition of the bridge gates.

```
simple DLL
    parameters:
            TS:                 numeric,
            _pdf_tid1_type:     numeric,
            _pdf_tid1_par1:     numeric,
            …
            _pdf_tid2_type:     numeric,
            _pdf_tid2_par1:     numeric,
            …
            _pdf_tsdr_type:     numeric,
            _pdf_tsdr_par1:     numeric,
            …
    gates:
            in:                 upper_gateIn[],lower_gateIn,bridge_gateIn;
            out:                upper_gateOut[],lower_gateOut,bridge_gateOut;
endsimple
```

Figure 7.12 – OMNeT++ `DLL` module NED definition

The `BM` module is a simple module that models the mechanisms necessary for the IDP and the IDMP-related functions. Figure 7.13 presents the `BM` NED definition. The address of the `BM` (the same of the `Master` module) module instance is set by the `TS` parameter.

```
simple BM
    parameters:
            TS:                         numeric,
            _bm_idt_timer:              numeric,
            _bm_idmp_abort_timer:       numeric,
    gates:
            in:                         bridge_gateIn,dll_gateIn;
            out:                        bridge_gateOut,dll_gateOut;
endsimple
```

Figure 7.13 – OMNeT++ `BM` module NED definition

Whenever a new transaction is open in the LOT, an IDT-related timer is started, which is used to clear the transaction from the LOT when it expires. The value of this timer is assigned by the `_bm_idt_timer` parameter. In the same way, at the reception of a SMP message the `BM_IDMP_Abort_Timer` ($T_{BM\text{-}IDMPAbort}$) is loaded and started. This timer is used to detect errors during the evolution of the IDMP. The value of this timer is assigned by `_bm_idmp_abort_timer` parameter.

The `BM` operation depends on its `Routing Table` (RT) and on its `List of Active Stations in Domain` (LASD). These elements are generated by the `Controller` module instance at simulation initialisation and are updated in run time.

The `DMM` module is a simple module that models the DMM functions required by the IDMP. This module is responsible for controlling Phase 3 and Phase 4 of the IDMP

Figure 7.14 depicts the `DMM` module NED definition in which there is only one parameter (`TS` parameter). The LBMD and LWMSD are generated by the `Controller` module instance at simulation initialisation and are updated in run time. There are other parameters that must be assigned to the `DMM` module like `_dmm_idmp_abort_timer`, `_n_beacon` and `_beacon_len` parameters for instance, but to simplify the configuration procedures, they are assigned to the `Domain` module, instead.

```
simple DMM
    parameters:
            TS:         numeric,
    gates:
            in:         dll_gateIn;
            out:        dll_gateOut;
endsimple
```

Figure 7.14 – OMNeT++ `DMM` module NED definition

The `GMM` module is a simple module that models the GMM required functionalities. This module is responsible for the control of Phase 1 and Phase 2 and also the beginning of Phase 3 of the IDMP. For its operation, the `GMM` must be provided with the LBMN and also with the LDMMN. These lists are also generated by the `Controller` module instance at simulation initialisation.

The IDMP is triggered in a periodical fashion. The value for this period is assigned to the `Controller` module through the `_tmob` parameter. Figure 7.15 depicts the `GMM` module NED definition in which there is only one parameter (`TS` parameter).

```
simple GMM
    parameters:
            TS:         numeric,
    gates:
            in:         dll_gateIn;
            out:        dll_gateOut;
endsimple
```

Figure 7.15 – OMNeT++ `GMM` module NED definition

7.4. Simulator Implementation

7.4.1. Bridge IDP Functionalities

When a frame is received by a `BM` it tests if the addressed station (using the `Destination Address` (DA) of the frame and its RT) is reached by forwarding the frame to the other `BM` of the bridge. If the test succeeds then the frame is forwarded to the `ComFunc` module instance. The `ComFunc` module relays the frame to the other `BM` that composes the bridge. The frame received from the `ComFunc` is passed by the `BM` to the `DLL` which queues the message. Figure 7.16 illustrates the interconnection schema between two BMs.

In Section C.3.1 a detailed description of the IDP procedures can be found, namely: the receive frame (from `ComFunc`) procedure; the receive frame (from `Domain`) procedure and the send IDF procedure.

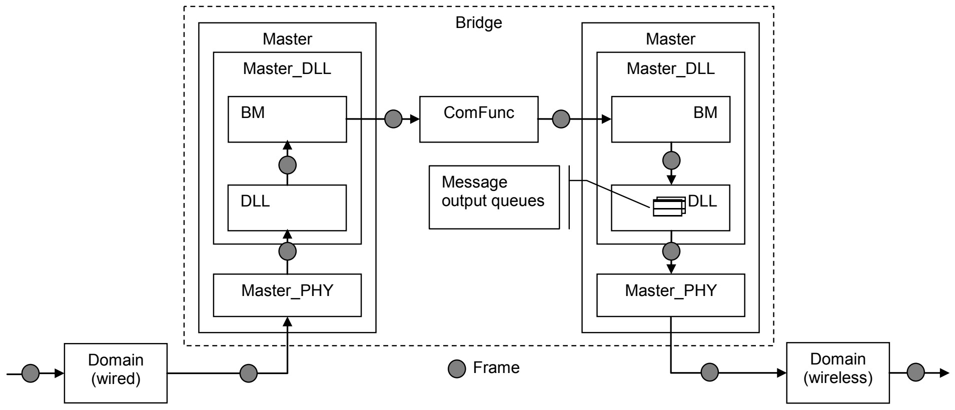

Figure 7.16 – Interconnection schema between two BMs

7.4.2. Operation of the IDMP related Agents

Global Mobility Manager (GMM)

The operation mode of the `GMM` is based on the state machine diagram illustrated in Figure 7.17. The state machine of the `GMM` is composed by three states: INACTIVE, WRSMP (`Wait Ready to Start Mobility Procedure`) and WRBT (`Wait Ready for Beacon Transmission`).

The state machine diagrams shown in this chapter use an oval shape representing a state and an arrow for a transition. For better identification, the name of each state is written within the oval shape and each transition is identified by a number.

The IDMP is triggered in a periodic a fashion. At power on, the `GMM` enters into the INACTIVE state, and the IDMP-related timer is loaded with a time defined by the `_tmob` parameter. When the IDMP-related timer reaches zero the `GMM` sends a `Start_Mobility_Procedure` (SMP) message (starting IDMP Phase 1) and the state machine evolves to the WRSMP state (transition 1). In order to detect and handle IDMP errors two timers are started: $T_{GMM\text{-}P1Alert}$ and $T_{GMM\text{-}P1Abort}$. The duration of each timer is defined by the `_gmm_phase1_alert_timer` and `_gmm_phase1_abort_timer` parameters, respectively.

It stays in the WRSMP state until it receives a `Ready_to_Start_Mobility_Procedure` (RSMP) message from every `BM` (transition 2) in the network. However, if the $T_{GMM\text{-}P1Alert}$ expires before the `GMM` receives a RSMP from every `BM` in the network, then it re-sends a SMP message and waits in the WRSMP state until it receives RSMP messages from `BM`s which had not replied. If it receives the remaining RSMP messages before the expiration of the $T_{GMM\text{-}P1Abort}$ then it sends a `Prepare_for_`

`Beacon_Transmission` (PBT) message and evolves to the WRBT state (transition 3). Otherwise, it aborts the IDMP and returns to the INACTIVE state (transition 6).

When the `GMM` sends a PBT message, Phase 2 starts and it evolves to the WRBT state. In the same way, to detect and handle errors during Phase 2 two timers are loaded and started: $T_{GMM\text{-}P2Alert}$ and $T_{GMM\text{-}P2Abort}$. The timer $T_{GMM\text{-}P2Alert}$ is loaded with a time defined by the `_gmm_phase2_alert_timer` parameter while the $T_{GMM\text{-}P2Abort}$ is loaded with a time defined by the `_gmm_phase2_abort_timer` parameter. It stays in this state until it receives a `Ready_for_Beacon_Transmission` (RBT) message from every `DMM` in the network. If $T_{GMM\text{-}P2Alert}$ expires before the `GMM` receives a RBT from every `DMM` in network, then it re-sends a PBT message and waits in WRBT state for the reception of RBT messages from the `DMM`s in lack. If $T_{GMM\text{-}P2Abort}$ expires before the `GMM` receives a RBT from the remainder `DMM`s, then it aborts the IDMP and evolves to INACTIVE state (transition 5). Otherwise, it sends the `Start_Beacon_Transmission` (SBT) message and evolves to INACTIVE state (transition 5).

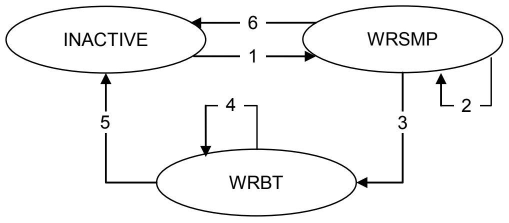

Figure 7.17 – `GMM` state machine

A detailed description of the procedures related to the `GMM` operation can be found in Section C.3.2.

Bridge Master (BM)

The role of a BM in the IDMP is based on the state machine, presented in Figure 7.18. The state machine of the `BM` is composed of the 3 states: INACTIVE, WIDT_END (`Wait Inter-Domain Transactions End`) and WINQUIRY (`Wait Inquiry`).

The `BM` role during the evolution of the IDMP is essential in ensuring the finalization of pending IDTs and in the relaying of IDMP-related messages. When the IDMP is not active the `BM` is in the INACTIVE state. In this state, a `BM` can update its RT according to the information contained into `Route_Update` (RU) messages (transition 1).

When a `BM` receives a SMP message the timer `BM_IDMP_Abort_Timer` ($T_{BM\text{-}IDMPAbort}$) is loaded with the value of the `_bm_idmp_abort_timer` parameter and is started. It evolves to either WIDT_END state (transition 2) or WINQUIRY state (transition 3), depending if its LOT is empty or not, respectively.

In the WIDT_END state a `BM` waits until all open IDTs contained in its LOT are finalized (transition 4). In this state, if it receives a duplicated SMP message, then it replies with a RSMP message. After this, the `BM` will not accept new IDTs. When all IDTs have been completed, it sends a RSMP message to the `GMM` and enters into the WINQUIRY state (transition 5).

In the WINQUIRY state `BM` only communicates with its domain `DMM` using the `Inquiry` service. In this state, when a `BM` receives an `Inquiry` request (IQ_REQ) message (transition 6) and if there is a IDMP-related message on the `DLL` high priority output message queue, then it commands the `DLL` to transmit that message as a response, otherwise no response is transmitted. In this state, if it receives another SMP message, then it will reply with another RSMP message (transition 6).

When a `BM` receives a PBT message it clears all wireless mobile station related entries in its RT and stays in the same state. When it receives a SBT message it changes into INACTIVE state (transition 7) and the $T_{BM\text{-}IDMPAbort}$ is stopped.

If the $T_{BM\text{-}IDMPAbort}$ expires the `BM` evolves to the INACTIVE state from either the WIDT_END state (transition 8) or WINQUIRY state (transition 7).

A more detailed description of the procedures that support this transition is presented in Section C.3.2.

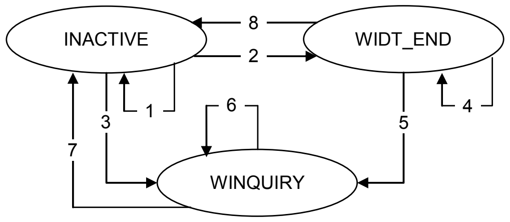

Figure 7.18 – BM state machine

Domain Mobility Manager (DMM)

The operation mode of the DMM is based on the state machine diagram presented in Figure 7.19. The state machine of the DMM is composed of five states: INACTIVE, WTOKEN (Wait Token), INQUIRY, BEACON_TX (Beacon Transmission) and IDENT (Identification).

The DMM goes into the INACTIVE state after power-on. When the DMM receives a PBT message, the DMM_IDMP_Abort_Timer ($T_{DMM\text{-}IDMPAbort}$) is loaded with _dmm_idmp_abort_timer parameter value and is started. Then, it evolves to either WTOKEN state (transition 2) or INQUIRY state (transition 3), if the DLL is holding the token or not, respectively. If the DLL is holding the token at reception of a PBT message, it sends a RBT to the GMM and its state machine evolves to the INQUIRY state (transition 2), otherwise it evolves to the WTOKEN state (transition 1) and waits for the token frame reception. As soon as its DLL receives the token frame, it sends a RBT message to the GMM and evolves to the INQUIRY state (transition 3).

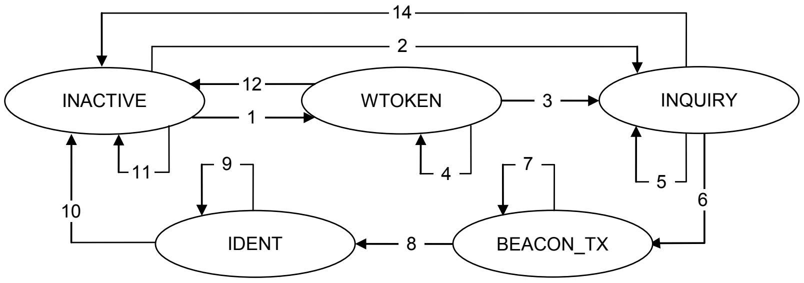

Figure 7.19 – DMM state machine

Thereafter, the DMM uses the Inquiry service in order to exchange IDMP-related messages with the BMs present in its domain (transition 5). If a DMM does not have any other BM belonging to its domain, then it transmits Void frames in order to maintain the network activity. When it is in the WTOKEN state or in the INQUIRY state, a DMM may again receive a PBT message, transition 4 and 5, respectively. If a DMM is in the WTOKEN state then it again checks if the DLL is holding the token. If it is, it sends again a RBT message and evolves to INQUIRY state (transition 3). It also sends another RBT message if it is already in the INQUIRY state (transition 5).

When a DMM receives a SBT message from the GMM two transitions may occur (transition 6 or 13). The DMM evolves either to INACTIVE state, if it is a wired domain (transition 13), or to the BEACON_TX state (transition 6), if is a wireless domain. The $T_{DMM\text{-}IDMPAbort}$ is stopped in both cases.

In the BEACON_TX state it transmits (transition 7) a predefined number of Beacon frames (defined by the _n_beacon parameter). It is in this Beacon frame transmission period that wireless mobile stations may change to a new domain. When this period ends (transition 8) the DMM evolves to the IDENT state and the DMM tries to detect if wireless mobile stations are present in its domain by inquiring them using `Discovery` request (D_REQ) messages (transition 9). If wireless mobile stations are detected then it broadcasts a RU message and its state machine evolves to the INACTIVE state (transition 10).

If the $T_{DMM\text{-}IDMPAbort}$ timer expires its state machine evolves to the INACTIVE state from either WTOKEN or INQUIRY states. This event is supported by transitions 12 and 14, respectively. When the $T_{DMM\text{-}IDMPAbort}$ expires it means that no wireless mobile stations have entered or left of domain, and in order to update the RT of the `BM`s, a RU message is broadcasted by the `DMM` with information about which wireless mobile stations continue in its domain.

Section C.3.2 presents a detailed description of the `DMM` procedures that support it state machine transitions.

PROFIBUS master DLL

The IDMP has been designed in order to keep the number of protocol modifications low, therefore most of the functions can be implemented as an independent module above the DLL or at PhL level (like channel assessment functionalities required by the mobile wireless stations). However, some functionality related to the DMM must be implemented at the DLL level. Figure 7.20 depicts the changes required in the state machine of the `DLL` of a `Master` to support the functions required by a DMM.

The operation of the `DLL` is based on the state machine diagram present in Figure 7.20. There is the need for five more states: INQUIRY_MODE, WAIT_INQUIRY_RESPONSE, BEACON_TX (`Beacon Transmission`), DISCOVERY and AWAIT_DISCOVERY_RESPONSE.

After beginning the IDMP the `DLL` state machine of a `BM` which also operates as a DMM, evolves according to the IDMP message received and the current state of the `DMM` state machine. In this case, i.e., when a `Master` is also acting as a DMM then it repeatedly sends messages. During the mobility procedure IDMP-related messages have more priority than other messages, even the PROFIBUS high priority messages.

After the `DMM` state machine has left the INACTIVE state, the `DLL` enters into the INQUIRY_MODE state at the reception of the token (transition 20) or after completing any task when it is holding the token (transition 21).

In the INQUIRY_MODE state four transitions may occur (transition 22, 23, 25 and 26). If it sends an `Inquiry` request (IQ_REQ) message then the `DLL` evolves to the WAIT_INQUIRY_ RESPONSE state (transition 19) and when it detects a valid frame or the T_{SL} expires its state machine evolves to the INQUIRY_MODE state (transition 24). At this moment the `DLL` notifies the `DMM` about what happened.

In the INQUIRY state, the `DMM` commands its domain `BMs` (if it is the case) to send messages. For that purpose, it sends IQ_REQ messages to its domain `BMs` in sequence, allowing them to transmit any mobility–related messages on their output message queue (transition 22).

From the INQUIRY_MODE state the `DLL` state machine can evolve to the USE_TOKEN state (transition 25) or to the BEACON_TX state (transition 26). If the domain's type is wired the `DLL` state machine evolves to the USE_TOKEN state and the `DMM` state machine evolves to the INACTIVE state. Therefore, the IDMP ends and the `DLL` performs another action according to the message dispatching procedure presented in Section C.1.3. If the domain is wireless, then the `DLL` evolves to the BEACON_TX state and the `DMM` state machine also evolves to the BEACON_TX state.

When the `DMM` is in the BEACON_TX state it passes to the `DLL` a number of `Beacon` messages defined by `_n_beacon` parameter (transition 27).

At the end of the `Beacon` messages transmission the `DMM` state machine evolves to the IDENT state and the `DLL` state machine evolves to the DISCOVERY state (transition 28). When the `DMM` is in the IDENT state it sends `Discovery` messages (D_REQ) addressed to the wireless mobile stations to the `DLL`, in order to detect which stations belong to its domain. When the `DLL` sends D_REQ message its state machine evolves to the AWAIT_DISCOVERY_RESPONSE state (transition 29) and, as soon as, it receives a response or when T_{SL} expires, it returns to the DISCOVERY state (transition 30). Whenever this happens, the `DMM` is notified and in case it has received a message, it passes it to the `DMM`. When this operation ends, the `DMM` builds and broadcasts RU messages

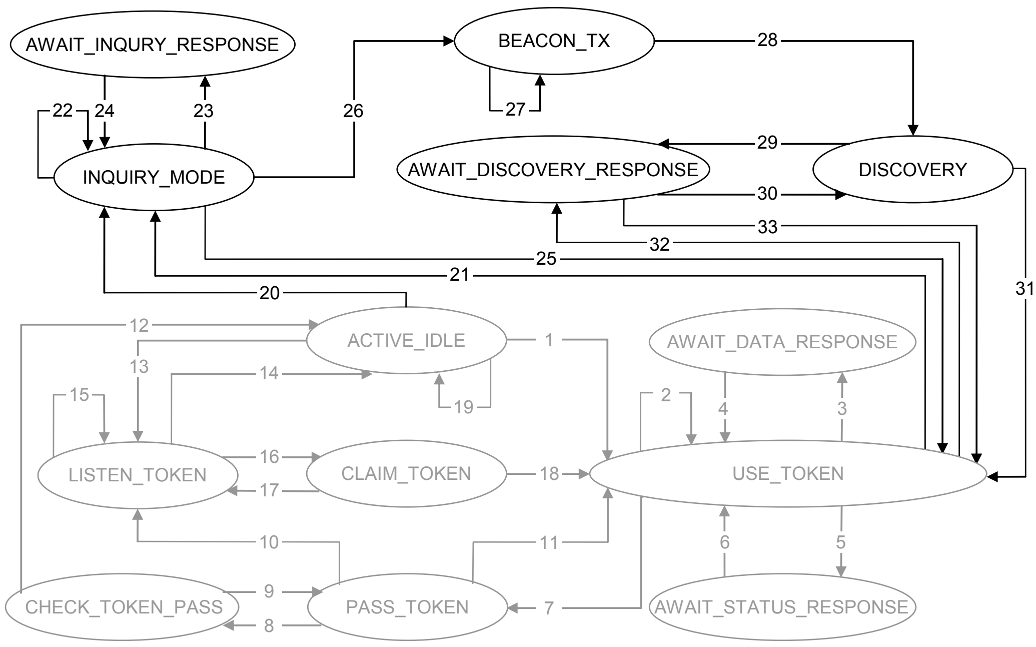

Figure 7.20 – DLL state machine (IDMP)

After that, the DMM state machine evolves to the INACTIVE state and the DLL state machine enters into the USE_TOKEN state (transition 31). Therefore, the IDMP ends and DLL perform another action according to the dispatching message procedure presented in Section C.1.3.

In order to handle transmission errors of the RU message, when the IDMP is not active, the DMM sends in a periodical fashion D_REQ messages to wireless mobile stations and if the wireless mobile stations acknowledge positively the DMM sends a RU message containing information about the new stations in a domain. When the DLL sends the D_REQ message its state machine evolves to the AWAIT_DISCOVERY_RESPONSE state (transition 32) and returns to USE_TOKEN state (transition 33) when it receives a response or T_{SL} expires.

Section C.3.2 presents a detailed description of the DLL procedures that these transitions.

7.5. Summary

This chapter presented the main architectural components of a bridge and the implementation of the Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator. Additionally, we have also described the format of the NED files required for the configuration of the modules used in this simulator.

The following chapters will present the mobility simulator, used to simulate the physical displacement of the wireless mobile station and results obtained by the simulators.

Chapter 8

Mobility Simulator

In order to achieve more realistic simulation results it is necessary to know, at which points in time a wireless mobile station moves between different wireless domains. To obtain this information a tool was developed which simulates the mobility of wireless stations over a factory floor and the signal quality of the different wireless domains at station location – the Mobility Simulator. This chapter describes this tool.

8.1. Introduction

Every radio technology has a limited physical coverage area within which radio communications can be performed in acceptable conditions. The area characteristics depend on several aspects such as the dimensions and layout of obstacles, the existence of electromagnetic interference and the radio technology (including its antenna type) in use. Therefore, to cover wider areas it is necessary to divide the application area into several radio cells, each one operating at its own radio channel.

While moving wireless mobile stations will always try to use the best radio cell signal to communicate, therefore these stations will belong to different radio cells, also called domains within the context of this dissertation. The domain, to which a wireless mobile station belongs, depends on its location over time and on the signal strength in that location. In a simplified model the signal strength depends on the distance to the wireless cell base station.

There are several models to estimate the radio signal strength (Rappaport, 1996). Simple models estimate radio signal strength between a transmitter and a receiver based solely on the distance between them. More sophisticated models use environment information, such as buildings, mountains, wall materials and location of obstacles. These models require a very detailed representation of the objects in the environment and are computationally very demanding.

This chapter describes the Mobility Simulator (MSim) which simulates the mobility of wireless mobile stations and the radio signal strength on the current wireless mobile station location. With this information it is possible to generate a vector containing the wireless domains to which the wireless mobile station belongs. That information is used by the Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (RHW2PNetSim) and in the Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (BHW2PNetSim), in order to determine the points in time at which the stations must move to another domain. The results from this simulator are feed into the other simulators on the content of the `_location_vector` parameter.

The MSim has been developed using an open source high performance 3D graphics toolkit called OpenSceneGraph (Barros, 2005) and the C++ programming language.

This chapter is structured as follows. A brief description of the simulation environment used to develop the MSim is presented in Section 8.2. A detailed description of the adopted radio signal model is given in Section 8.3. Section 8.4 presents a description of the simulation model of the MSim. The architecture of the MSim and the simulator configuration are presented in Section 8.5 and Section 8.6, respectively. The output data files generated by this simulator are presented and described in Section 8.7.

8.2. OpenSceneGraph

The OpenSceneGraph is an open source cross platform graphical toolkit for the development of high performance graphical applications such as visual simulation, flight simulation games, virtual reality, scientific visualization and modelling. Based around the concept of scene graph (detailed below), it provides an object oriented framework on top of OpenGL freeing the developer from implementing and optimizing low level graphics calls, and provides many additional utilities for rapid development of graphics applications.

Written entirely in standard C++ and OpenGL, it makes full use of the Standard Template Library and it runs on all Windows platforms, OSX, GNU/Linux, IRIX, Solaris and FreeBSD operating systems.

8.2.1. Scene Graph Concept

The scene graph concept is tree-like. It starts with a top-most root node which encompasses the whole virtual world, be it 2D or 3D. The world is then broken down into a hierarchy of nodes representing spatial groupings of objects, object positions, object animations, or definitions of logical relationships between objects. The leaves of the graph represent the physical objects themselves, the drawable geometry and their material properties.

A scene graph is not a complete game or simulation engine, although it may be one of the main components of such an engine. Its primary focus is the representation of 3D worlds, and efficient rendering. Physics models, collision detection and audio are left to other development libraries that a user may integrate with it, like Open Dynamics Engine (Smith, 2004).

8.2.2. OpenGL

OpenGL (Shreiner, Woo et al., 2005) is a software interface to the graphical hardware. This API consists of about 150 distinct commands that developers use to specify the objects and operations needed to produce interactive 2D and 3D applications.

OpenGL is designed as a streamlined, hardware-independent interface to be implemented on many different hardware platforms. In order to achieve these qualities, no commands for performing windowing tasks or obtaining user input are included in OpenGL.

OpenGL does not provide high-level commands for describing models of 2D and 3D objects. With OpenGL, models must be built from a small set of geometric primitives (points, lines, and polygons).

8.3. Wireless Communications: Radio Signal Propagation

In wireless communication the information is delivered to the transmitter and modulated into radio waves. The radio wave is radiated through the air, using a radio channel, to the receiving antenna. At the receiving antenna, the radio wave is demodulated and the transmitted information is extracted (Figure 8.1).

In a wireless communication based on Base Station (BS), the coverage area is divided into small coverage areas (called cells) in which wireless communications are all relayed by a BS. In such systems, all stations transmit on one channel (uplink) and listen on a second channel (downlink). The BS functions are to receive a frame from one station through its uplink channel and retransmit the frame on its downlink channel.

Several aspects have influence in the quality of wireless communications. The transmission path between transmitter and receiver can vary from a simple line-of-sight to one severely obstructed by objects, like buildings, mountains and other surrounding objects. These objects can cause *reflection*, *diffraction* and *scattering* of the radio waves.

Reflection of the radio waves occurs when the radio wave impinges upon an object which has very large dimensions compared to the wavelength. Diffraction occurs when a radio wave encounters obstructions and propagates around the edges, corners and behind the obstruction causing secondary radio waves to form behind the obstruction. Scattering, results from rough surfaces whose dimensions are of the order of the wavelength, which causes the reflected energy to scatter in all directions.

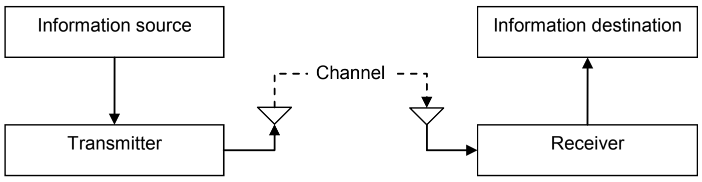

Figure 8.1 – Wireless communication model

Additionally, the objects could be perfect *dielectric*, perfect *conductor* or in-between. A dielectric object absorbs some of the radio wave energy, while the remainder is reflected back to the medium. A perfect dielectric object absorbs all radio wave energy without reflection. A perfect conductor reflects all radio wave energy. As a consequence, a radio wave breaks into several parts so that the received signal is a multiple delayed copy of the transmitted signal. This phenomenon is known as multipath propagation.

Radio wave quality depends on the type of antennas, the frequency and the bandwidth. On the other hand, the strength of a radio wave decreases as the distance between transmitter and receiver increases (fading) and a radio wave may be altered due to electromagnetic interference and noise.

Another aspect is, the Doppler spread. Doppler spread results when radio waves transmitted to or from a moving device undergo a shift in frequency if transmit-receive distance changes with time. The difference in frequency of the received signal and the transmitted signal is called the Doppler shift. In a multipath propagation the angles of arrival of the multipath components are different and each has a different Doppler shift.

Consequently, the wave propagation is very difficult to characterize, because it requires a very detailed representation of the objects in the environment, and is computationally very complex to treat.

In (Tranter, Shanmugan et al., 2003) several simulation models for radio wave propagation are presented. In (Rappaport, 1996) the author presents the main wireless communication principles and more specifically it also presents some models for radio wave propagation. According to this author the Log-normal Shadowing is a more general and widely-used model. In this models the power at the receiver ($P_r(d)$) can be calculated as follows:

$$P_r(d) = P_t + G_t - \overline{PL}(d) + G_r \tag{8.1}$$

where P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, d is the distance between transmitter and receiver in meters. $PL(d)$ is the average path loss at distance d between transmitter and receiver and is given by:

$$\overline{PL}(d) = PL_0(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{8.2}$$

where n is the path loss exponent which indicates the rate at which the path loss increases with distance. X_σ is the shadowing term (the zero-mean Gaussian random variable in dB with standard deviation of σ). $PL_0(d_0)$ is the free-space path loss distance d_0 (d_0 is the close-in reference distance which is determined from measurements close to the transmitter) and is given by:

$$PL_0(d_0) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \tag{8.3}$$

where λ is the wavelength in meters and is related to the carrier frequency by:

$$\lambda = \frac{c}{f} \tag{8.4}$$

where f is the carrier frequency in Hertz and c is the speed of the light ($3*10^8$m/s).

Table 8.1 and Table 8.2 list some typical path loss values exponents and the standard deviation on specific environments, respectively.

Table 8.1 – Path Loss Exponents for Different Environments. Source (Vignaux and Muller, 2006)

Environment		**Path Loss Exponent, n(dB)**
Outdoor	Free space	2
	Shadowed Urban area	2.7 to 5
In building	line-of-sight	1.6 to 1.8
	Obstructed	4 to 6

Table 8.2 – Standard Deviation for Different Environments. Source (Vignaux and Muller, 2006)

Environment	**Standard deviation , σ (dB)**
Outdoor	4 to 12
Office, hard partition	7
Office, soft partition	9.6
Factory, line-of-sight	3 to 6
Factory, obstructed	6.8

It is important to select a free space reference distance that is appropriate for the propagation environment. Usually, in large coverage cellular systems, a 1 km reference distance is commonly used, in microcellular systems, much smaller distances (such as 100 m or 1 m) are used. The reference distance should always be in the far field of the antenna so that near-field effects do not alter the reference path loss.

8.4. Simulation Model

This simulator models the radio signal strength using the Log-normal Shadowing model. Since, this model takes into account, not only, the distance between the transmitter and receiver, but also, the empirical characteristics of the environment.

The station mobility is calculated according to the wireless mobile station velocity and its path on the plant floor. In order to illustrate the simulation model, Figure 8.2 presents an example, with the same topology as the scenarios presented in Figure 2.3 and Figure 2.12.

The network comprises four domains, two wired domains (D^2 and D^4) and two wireless domains (D^1 and D^3). Three intermediate systems (IS1, IS2 and IS3) interconnect the wired and wireless domains. The network also comprises seven wired stations (S1, S2, S3, S4, S5, M1 and M2), three mobile wireless stations (M3, M4 and S6).

The wireless communications are relayed by two base stations (BSs), which are included in the ISs. Wireless mobile stations (M3, M4 and S6) move in a specific path, consequently the radio signal quality varies according to the propagation model. Further, in the mobility model of the wireless mobile station it is possible define stop points.

The handoff procedure is triggered in a periodic fashion and the BSs transmit a special purpose frame (the `Beacon` frame) during a pre-configured amount of time, which the wireless mobile stations use to assess the radio signal quality and change to the radio frequency of the BS with the strongest radio signal.

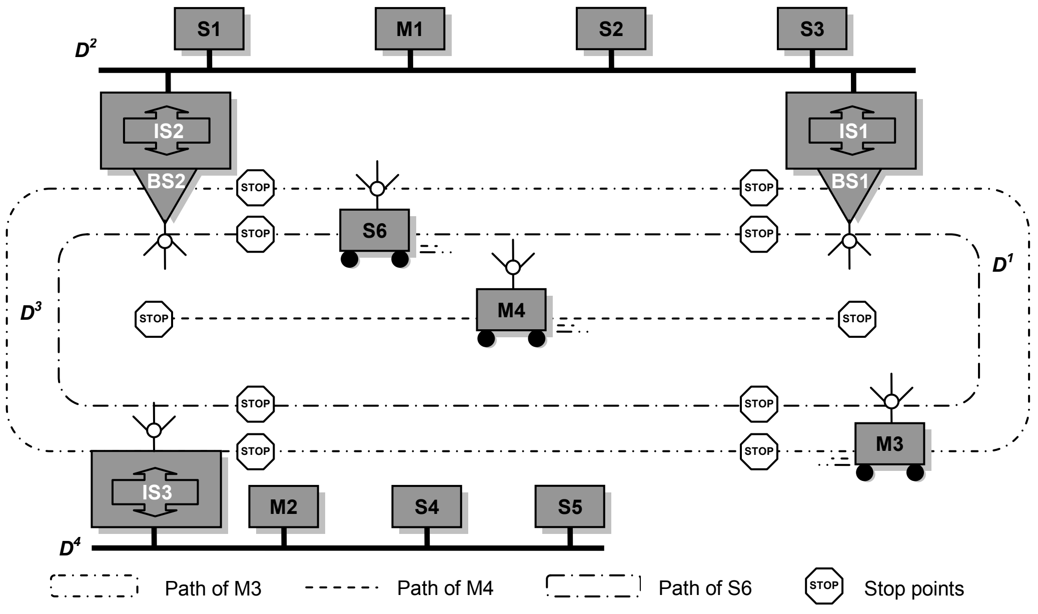

Figure 8.2 – Network scenario

8.5. Simulator Architecture

The following modules compose the MSim: `bs`, `agv`, `box`, `pc`, `antenna`, `camera`, `nhp` and `ground`. All these modules are implemented as C++ classes. There are two kinds of modules, the modules used for simulation and the modules used to compose the scenario. The first group includes the modules: `antenna` (which models a radio antenna), `bs` (which models a BS), `agv` (which models a wireless mobile station) and `nhp` (which models the handoff procedure). The second group includes: `box`, `pc` and `camera`. The `box` can be used to model a wall or a machine, the `pc` is used to model a personal computer or similar device. The `camera` is used on the `agv` module with esthetical purpose.

The main parameters (or attributes in the context of object-oriented programming) of the `antenna` module are: `frequency`; `Pt`; `Gt` and `Gr`. The `frequency` parameter contains the main radio frequency in use. `Pt`, `Gt` and `Gr` parameters are the transmitted power, the transmitter gain and the receiver gain of the antenna, respectively.

The `bs` module includes an instance of the `antenna` module. Each `bs` module instances is characterized by the parameters `name`, `domain_name`, `position` and `color`. The parameter `name` identifies a BS instance in the overall network, its value should be equal to the domain name (defined by `domain_name` parameter) in which it is operating. The `position` parameter specifies the `bs` module instance position and is used to calculate the distance between `bs` and `agv` module instances and the correspondent signal quality at the wireless mobile station location. The `color` parameter permits the assignment of a colour for easy visual identification of the wireless domain.

The `agv` module also includes an instance of the `antenna` module. The main parameters of the `agv` module are: `name`, `path`, `velocity` and `color`. The parameters `name` and `color` have the same purpose as in the `bs` module. The parameter `path` is used to assign a path to the `agv` module instance, using a list of points in Cartesian notation. Additionally, it is possible to define stop points by defining the stop duration together with path point coordinates.

To network handoff procedure is modelled by the `nhp` module. This module has the following parameters: `period`, `duration`, `exponent`, `std_dev` and `d0`. The `period` parameter is used to define the periodicity of the mobility procedure and the parameter `duration` the respective duration. The `exponent`, `std_dev` and `d0` are related to the Log-normal Shadowing model used in this simulator.

The values of path loss exponent, standard deviation and close-in reference distance are assigned to the parameters `exponent`, `std_dev` and `d0`, respectively.

Each simulation run has a predefined duration which is set in global simulation parameter called `sim_duration`.

The MSim is composed by two components, one is the front end and the other one is the simulator engine. The front end component can show two graphical 3D views of the simulation. It is useful to validate the simulation configuration. Figure 8.3 and Figure 8.4 present a screenshot of the simulator views.

In the view presented in Figure 8.3 the user is able to zoom and rotate of the simulation environment. The other view (Figure 8.4) shows a top level view of the simulator execution. This component allows checking the position and the radio frequency of `bs` instances, the path and the stop points of the `agv` instances. When these screenshot were taken, the `agv` instances M4 and S6 were operating at the same frequency as bs instance BS2 (at 2.3GHz) and `agv` instance M3 was operating at the same frequency of BS1 (at 2.4GHz). This means that M4 and S6 belong to domain D^3 and M3 belongs to domain D^3.

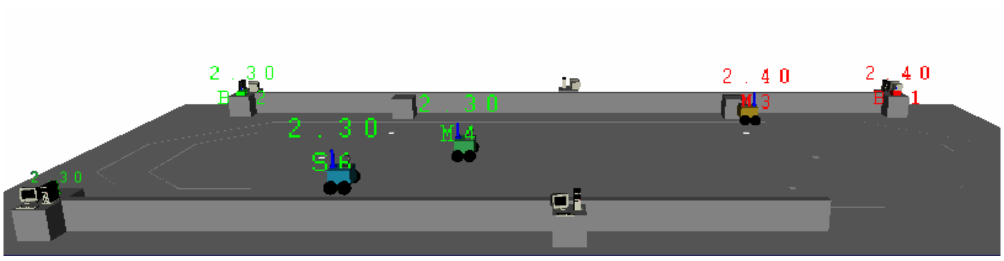

Figure 8.3 – View of the MSim front end component

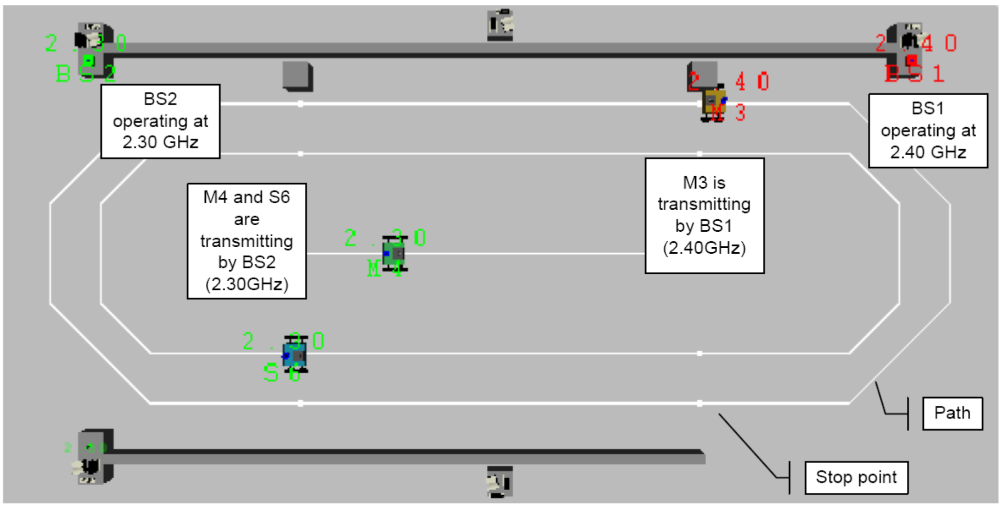
2.30
BS2
BS2 operating at 2.30 GHz
2.40
BS1
BS1 operating at 2.40 GHz
2.40
M3
M4 and S6 are transmitting by BS2 (2.30GHz)
M3 is transmitting by BS1 (2.40GHz)
2.30
M4
2.30
S6
Path
Stop point

Figure 8.4 – Top view of the MSim front end component

It is also possible to interact with this simulator using the keyboard. The ‘Esc’ key finishes the simulation run, The ‘f’ key allows increasing the simulation clock and in opposite the ‘s’ key decreases the clock. The goal of this component is not to run a simulation, but to validate the simulation environment. The ‘r’ key allows running simulation runs in a background process (which was referred as the simulation engine module). Since this component does not have any graphics output, then the simulation runs can be performed in much less time.

8.6. Simulator Configuration

The simulation configuration is done through two text files. One of them specifies the parameter values of all components and the other specifies the seed number for the generation of random values used in the Log-normal Shadowing model. For each seed number a simulation run is done. Therefore, the number of simulation runs depends on the number of text lines.

Figure 8.5 presents part of configuration file. The duration of each simulation run (defined by the `sim.duration` parameter) is equal to two minutes. The network mobility procedure is triggered every 0.2 s (defined by the `nhp.period` parameter). The duration of each network handoff procedure is equal to 0.005 s (defined by the `nhp.duration` parameter).

The path loss exponent (defined by `nhp.exponent` parameter) is set to five and the standard deviation (defined by `nhp.std_dev` parameter) is set to 6.8. The close-in reference distance (defined by `nhp.d0` parameter) is set equal to one meter.

The simulated factory floor dimensions are 100 m per 200 m (defined by `ground.width` and `ground.length` parameters). The output directory for the simulation output files is called "output_files" (defined by the `output.dir` parameter).

```
sim.duration=2
nhp.period=0.2;
nhp.duration=0.005;
nhp.exponent=5
bnp.std_dev=6.8
bmp.d0=1
ground.width=100
ground.length=200
output.dir=../output_files;
```

Figure 8.5 – Configuration file related to global simulation parameters (excerpt)

Figure 8.6 presents part of a configuration file related to the `bs` module instance parameters. The system is composed by two `bs` instances (defined by the `sim.bs_num` parameter). One is called BS1 and the other is called BS2 (defined by the `bs[x].name` parameter). Wireless communications in domains D1 and D3 are done through BS1 and BS2, respectively (`bs[x].domain` parameter).

```
sim.bs_num=2;

bs[0].name=BS1;
bs[0].domain=D1;
bs[0].position=80.0,37,5.0,5.0;
bs[0].color=1.0,0.0,0.0,1.0;
bs[0].ant.freq=2.4;
bs[0].ant.pt=1;
bs[0].ant.gt=1;
bs[0].ant.gr=1;


 bs[1]. name =BS2;
 bs[1]. domain =D3;
 bs[1].position=-80.0,37,5.0,5.0;
 bs[1]. color =0.0,1.0,0.0,1.0;
 bs[1]. ant.freq =2.3;
 bs[1]. ant.pt =1;
 bs[1]. ant.gt =1;
 bs[1]. ant.gr =1;
```

Figure 8.6 – Configuration file related to the `bs` parameters (excerpt)

The definition of the `bs` module instance position (defined by `bs[x].position` parameter) is done by Cartesian coordinate (x,y,z) with origin at the centre of the ground. In this case, BS1 is located at position (50.0, 0.0, 5.0) and BS2 is located on the opposite side, at (-50, 0.0, 5.0). The colour of the `bs` module instances is defined by `bs[x].color` parameter and is set by four values (all in the range between 0.0 to 1.0). The first three are the RGB values and the fourth is the transparency.

Each `bs` module instance operates at different radio channel, BS1 operates on the 2.4GHz bandwidth and BS2 on the 2.3GHz bandwidth (defined by `bs[x].ant.freq` parameter). The transmitted power of each `antenna` module instance is defined by `bs[x].ant.pt` parameters, the transmitter gain is defined by the `bs[x].ant.gt` parameters and the receiver gain is defined by `bs[x].ant.gr` parameters, which have been set equal to one in all `bs` module instances.

Figure 8.7 shows part of the configuration file related to an `agv` module. In this example there are two `agv` module instances (defined by `sim.agv_num` parameter). One is called M3 and the other S6 (defined by the `agv[x].name` parameter). Their velocity is set to 8 m/s and 6 m/s for M3 and S6, respectively.

The path and the stop points are defined by the `agv[x].path` parameter. This parameter is a string that is written using a pre-defined structure as follows. Each point of the path is defined using the coordinates x, y and z. The path is a set of points separated by colons. When a point is also a stop point, the stop time is defined after character '$'. For example, M3 starts at point (90, 10, 0), it follows in the direction of point (80, 20, 0), then goes to point (70, 30, 0). As soon as it arrives to the last point it follows to the next point in the path (40, 30, 0) where it stops for 0.125 seconds. After that, it follows to the next point (-40, 30, 0) and it again stops for 0.125 seconds. The path definition is cyclical, therefore when it reaches the last point it continues to the first.

The parameter `freq` of the `agv antenna` module instance changes during the simulation run, its value depends on the domain to which the `agv` module belongs to.

```
sim.agv_num=3;

agv[0].anme=M3;
agv[0].vel=8;
agv[0].path=90,10,0:80,20,0:70,30,0:40,30,0$0.125:-40,30,0$0.125:-70,30,0:-80,20,0:-90,10,0:-90,-10,0:-80,-20,0:-70,-30,0:-40,-
    30,0$0.125:40,-30,0$0.125:70,-30,0:80,-20,0:90,-10,0;
agv[0].color= 0.6,0.5,0.1,1.0;
agv[0].ant.freq=2.4;
agv[0].ant.pt=1;
agv[0].ant.gt=1;
agv[0].ant.gr=1;

agv[1].name=M4;
agv[1].vel=6;
agv[1].path= -50,0,0$0.250:0,0,0$0.250:50,0,0$0.25;
agv[1].color= 0.2,0.6,0.3,1.0;
agv[1].ant.freq=2.3;
agv[1].ant.pt=1;
agv[1].ant.gt=1;
agv[1].ant.gr=1;

agv[2].name=S6;
agv[2].vel=6;
agv[2].path=-80,-10,0:-70,-20,0:-40,-20,0$0.125:40,-20,0$0.125:70,-20,0:80,-10,0:80,10,0:70,20,0:40,20,0$0.125:-40,20,0$0.125:-
    70,20,0:-80,10,0;
agv[2].color= 0.1,0.5,0.6,1.0;
agv[2].ant.freq=2.3;
agv[2].ant.pt=1;
agv[2].ant.gt=1;
agv[2].ant.gr=1;
```

Figure 8.7 – Configuration file related to the `agv` parameters (excerpt)

8.7. Output Data Files

This simulator produces two kinds of output files. One contains information about the timings when the network handoff procedure was active, the domains to which the stations belong to and additional information (these files use the extension ".li"). The other type of file contains a text file with the information required to set the `_location_vector` parameter used in the RHW2PNetSim and BHW2PNetSim (these files use the extension ".sd").

Figure 8.8 presents part of the output file related to the `agv` module instance named M3 using the network configuration presented in Figure 8.2.

The first column (Time) refers the timestamp when the radio signal quality was evaluated. The second column (SHandProc) indicates the instant in time when the handoff procedure started and the third column (EHandProc) refers to the end of the handoff procedure. The radio frequency value, the BS name and domain name are in fourth (Freq), fifth (BS) and sixth (D) columns, respectively. The seventh column (Position(x,y,z)) contains data related to the `agv` position. The distance between the `agv` instance and the `bs` instance with the best radio quality is presented in the eighth column (Dist). The signal power at the receiver location appears in the last column (Pr).

```
Time        SHandProc   EHandProc   Freq   BS    D    Position(x,y,z)      Dist    Pr
...
0.200000    0.200000    0.205000    2.30   BS2   D3   -49.17,0.00,0.00     48.80   -104.40
0.400500    0.400000    0.405000    2.30   BS2   D3   -48.33,0.00,0.00     49.34   -120.04
0.600500    0.600000    0.605000    2.30   BS2   D3   -47.50,0.00,0.00     49.87   -117.47
0.800500    0.800000    0.805000    2.30   BS2   D3   -46.67,0.00,0.00     50.42   -127.38
1.000.000   1.000.000   1.005.000   2.30   BS2   D3   -45.84,0.00,0.00     50.97   -120.68
1.200.500   1.200.000   1.205.000   2.30   BS2   D3   -45.00,0.00,0.00     51.54   -120.72
1.400.500   1.400.000   1.405.000   2.30   BS2   D3   -44.17,0.00,0.00     52.11   -117.13
1.600.500   1.600.000   1.605.000   2.30   BS2   D3   -43.33,0.00,0.00     52.68   -128.74
1.800.500   1.800.000   1.805.000   2.30   BS2   D3   -42.50,0.00,0.00     53.27   -128.30
2.000.500   2.000.000   2.005.000   2.30   BS2   D3   -41.67,0.00,0.00     53.86   -115.78
2.200.500   2.200.000   2.205.000   2.30   BS2   D3   -40.84,0.00,0.00     54.45   -124.12
2.400.500   2.400.000   2.405.000   2.30   BS2   D3   -40.00,0.00,0.00     55.06   -123.01
2.600.500   2.600.000   2.605.000   2.30   BS2   D3   -39.17,0.00,0.00     55.66   -126.10
2.800.500   2.800.000   2.805.000   2.30   BS2   D3   -38.34,0.00,0.00     56.28   -118.07
0.200000    0.200000    0.205000    2.30   BS2   D3   -49.17,0.00,0.00     48.80   -104.40
0.400500    0.400000    0.405000    2.30   BS2   D3   -48.33,0.00,0.00     49.34   -120.04
0.600500    0.600000    0.605000    2.30   BS2   D3   -47.50,0.00,0.00     49.87   -117.47
0.800500    0.800000    0.805000    2.30   BS2   D3   -46.67,0.00,0.00     50.42   -127.38
...
```

Figure 8.8 – Output file of wireless mobile station M3 (excerpt)

Figure 8.9 presents part of the output file related to the `agv` module instance M3, which contains the domain sequence to which a wireless mobile station belongs to during the simulation runs. In this file the information is organized as tuples separated by a colon. The first element indicates during how many handoff procedures the `agv` module instance stays in the domain referred in the second element. In this example, the `agv` module instance M3 stays in domain D1 for 43 network handoff procedures, and then it changes to the domain D3 where it stays for another 10 handoff procedures.

The information contained in this file can be assigned to the `_location_vector` parameter (see Section 6.2.3 for details) which determines to which domain a `Master` or a `Slave` module instance belongs to.

```
43,D1:10,D3:29,D1:1,D3:12,D1:2,D3:3,D1:3,D3:3,D1:
```

Figure 8.9 – Output location file of wireless mobile station M3 (excerpt)

8.8. Summary

This chapter describes the Mobility Simulator, which permits to determine to which domain a wireless mobile station belongs to at a specific point in time. That information is then feed into the RHW2PNetSim and BHW2PNetSim through the setting of the `_location_vector` parameter. The information produced by this simulator is very important for the quality of the simulation results since it provides a way to determine the domain to which a station belongs through time.

Chapter 9

Comparative Performance Analysis in an Error Free Environment

This chapter provides a comparative performance analysis between the repeater and bridge-based architectures. In this comparison study we studied the influence of varying certain network parameters on the response time and throughput of message streams existing in a network scenario. Additionally, we also present several response time histograms which characterize the network behaviour of both architectures.

9.1. Introduction

This chapter provides a comparative performance analysis between the repeater and bridge-based architectures. For that purpose, we performed a set of simulation runs varying several important network parameters on the network performance, like bit rate, internal delay of the Intermediate Systems (ISs) and the frame size.

This comparative performance analysis is based on the message stream response time and on the number of transactions of each message stream. These comparative metrics were chosen because the response time of the message streams reflect the timing behaviour of the entire network. The number of transactions gives us an idea of the throughput which can be achieved by the network.

This chapter starts by presenting, in Section 9.2, the network scenario and respective parameters to be used on the comparison study. Section 9.3 presents simulation results upon variation of the some network parameters. Finally, in Section 9.4 we summarize our comparative study.

9.2. Network Scenario Configuration

The network scenarios presented in the Figure 9.1 and Figure 9.2 were used to compare the performance of the two approaches. In the remainder of this chapter these scenarios are referred to as network base configuration.

The network comprises four domains: two wired domains (D^2 and D^4) and two wireless domains (D^1 and D^3). These domains are interconnected by three Intermediate Systems (ISs), which act either as a repeater or as a bridge according to the correspondent network scenario.

It is assumed that the wireless domains, D1 and D3, use the 802.11b Direct Sequence Spread Spectrum (DSSS) PhL at 2.0 Mbit/s, coding every character using 8 bits. The frames have a head of 32 bits and no tail. The reason for the use of a frame head is related to the specific requirements of the DSSS modulation schema used by 802.11b. These bits are used by the receiver to acquire the incoming signal and to synchronise the demodulator.

The wired domains, D^2 and D^4, use a standard PROFIBUS Physical Layer (PhL) operating at 1.5 Mbit/s and 0.5 Mbit/s, for domains D^2 and D^4, respectively. Since these domains use the RS-485 standard for the transmission of the PhL frames, each character is coded using 11 bits. The three additional bits are related to one start, one stop, and one parity check bit. In wired domains, the PhL frames do not have a head or a tail sequence of bits. Table 9.1 shows for each domain the bit rate, the length (in bits) of the frame head and of the frame tail as well as the number of bits used to code a character.

We have assumed that the time required by a slave to answer a request frame (T_{SDR}) can be modelled stochastically using a triangular distribution function with apex at 70 bit times and extremes at 11 and 100 bit times (*triang*(*11, 70, 100*)). This distribution has been chosen since the triangular distribution function is a rough model when there is no data available about the real distribution function (Law and Kelton, 2000). Henceforth the following notation, for the triangular distribution function, *triang(minimum, apex, maximum)* will be used.

Table 9.1 – Physical media parameters

Domain	Parameters
D^1 and D^3	(2000000, 32, 0, 8)
D^2	(1500000, 0, 0, 11)
D^4	(500000, 0 , 0, 11)

The internal delay of the ISs is equal to 30 μs and the maximum number of master DLL retries (`max_retry_limit`) parameter has been set to one.

The mobility procedure is triggered every 200 ms and it is assumed that the wireless mobile stations move in the simulated environment according to pre-defined path. In this path there are several stop points at specific locations (see Figure 9.1 and Figure 9.2).

The domain location of each wireless mobile station was set according to the results provided by the Mobility Simulator (MSim) described in Chapter 8.

Another important detail concerns the `Gap Update` factor (G), which is set to 1 in all domains, in order to have the GAP Update mechanism always active. This feature effectively increases the network load, but since the `FDL_Request_Status` frames used by the GAP Update mechanism have low-priority, the response time of the high-priority message streams is only minimally affected.

9.2.1. Repeater-Based Scenario

The repeater-based network scenario (Figure 9.1) is comprised of three wired masters (M1, M2 and MM), two mobile wireless master (M3 and M4), five wired slaves (S1, S2, S3, S4 and S5), and one mobile wireless slave (S6). Master MM is the `Mobility Master` (MM).

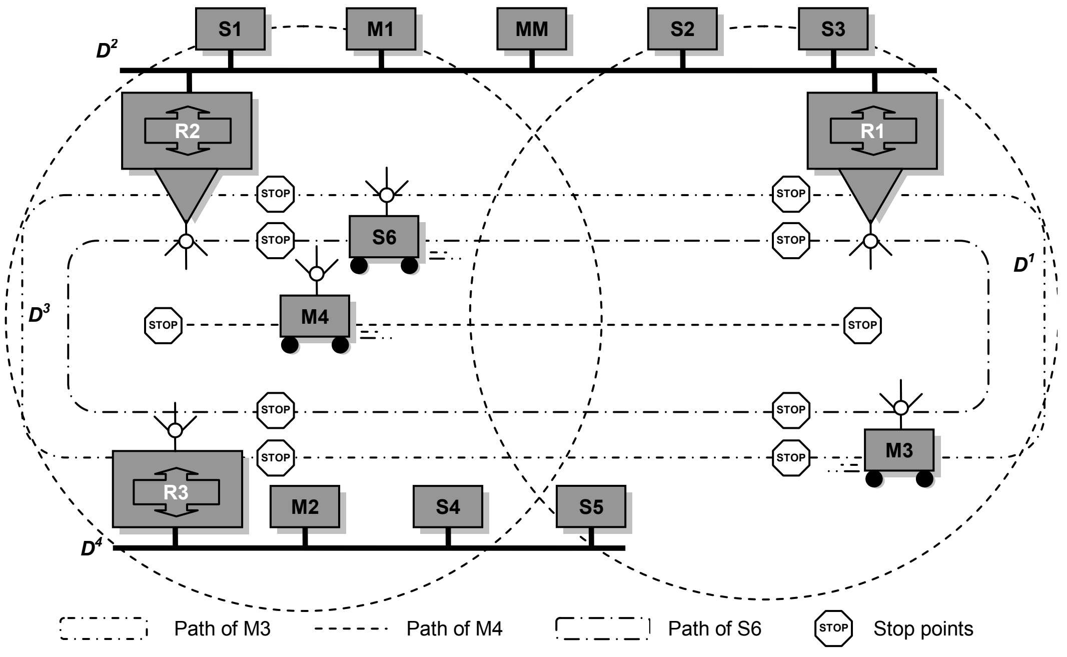

Figure 9.1 – Repeater-based hybrid wired/wireless PROFIBUS network

Table 9.2 presents the station's address used in this network scenario. The `Highest Station Address` (HSA) master parameter was set equal to five in all masters. The repeater-based approach requires the specific setting of the T_{ID} and T_{SL} parameters, which depend on the maximum size of the frames relayed by the repeaters, the number of repeaters in cascade, the bit rate in each medium and the delays in each repeater. These parameters and the parameters related to the `Beacon` message were calculated with the help of the RFieldbus System Planning application, which is described in (Behaeghel, Nieuwenhuyse et al., 2003).

Table 9.2 – Station's address

Master	Address	Slave	Address
M1	1	S1	41
M2	2	S2	42
M3	3	S3	43
M4	4	S4	44
MM	5	S5	45
		S6	46

In this approach the setting of the T_{ID2} parameter on the MM (2677 bit times) must be made differently in relation to the remaining stations in the network. This is because after transmitting the `Beacon Trigger` message this master enters into an inactivity period for the duration of the channel assessment period, which allows the wireless mobile stations to assess the quality of the other radio channels.

Additionally, a repeater always introduces a minimum inactivity period between two consecutive frames being forwarded. This value, the minimum idle time (T_{IDm}), has been set to 100 bit times.

In order to guarantee that, at the token arrival, there will always be enough time to execute all pending high-priority traffic the master T_{TR} parameter has been set according to the formulations proposed in (Tovar and Vasques, 1999), assuming no errors. However, the T_{TR} parameter has to be equal to all masters in each domain, therefore the T_{TR} parameter was set considering the high value computed of each domain. Table 9.3 presents the settings of the T_{ID1}, T_{ID2}, T_{SL} and T_{TR} master DLL parameters for each domain.

Table 9.3 – Repeater-based domain parameters

Domain	T_{ID1}	T_{ID2}	T_{SL}	T_{TR}
D^1 and D^3	2132	1088	2856	39712
D^2	1447	740	2142	27520
D^4	100	100	714	4858

9.2.2. Bridge-Based Scenario

The bridge-based network scenario (Figure 9.2) comprises two wired master (M1 and M2), two mobile wireless master (M3 and M4), five wired slaves (S1, S2, S3, S4 and S5), and one mobile wireless slave (S6). Domains are interconnected by three bridges (B1, B2 and B3) and each of them is composed by two `Bridge Masters` (BMs) - B1 (M8, M5), B2 (M6, M9) and B3 (M10, M7).

Each wired/wireless domain has its own logical ring. In this example, four different logical rings exist: (D^1 (M8 →M3→ M5), D^2 (M1 → M5 → M6), D^3 (M9 →M4→ M10) and D^4 (M2 → M7)). Note that, the wireless mobile stations M3 and M4 can belong to wireless domains $D^1$and D^3.

Concerning the IDMP, M6 assumes both the role of GMM and the DMM of wired domain D^2. BMs M5, M9 and M7 assume the role of DMMs for wireless domain D^1, wireless domain D^3 and wired domain D^4, respectively.

Table 9.4 presents the addresses of the master stations. The slave addresses are equal to those addresses used in the repeater-based scenario, presented in Table 9.2.

The timing parameters have been set according to the recommendation of the PROFIBUS standard (IEC, 2000), therefore the T_{ID} and the T_{SL} parameter have been set to 100 and 115 bit times, respectively. The T_{TR} parameter has been set according to the formulations proposed in (Tovar and Vasques, 1999) in order to guarantee that, at token arrival, there will be enough time to execute all pending high-priority messages. The HSA was set differently for each domain according to the highest address for all stations belonging to that domain. This setting reduces the impact of the GAP Update mechanism, since in this way the master with the highest address has a minimum number of station addresses to inquiry (from 0 to the station with the lowest address in the logical ring). Table 9.5 presents the settings of the T_{ID1}, T_{ID2}, T_{SL}, T_{TR} and HSA master DLL parameters for each domain.

Table 9.4 – Master's address

Master	Address	Master	Address
M1	1	M6	6
M2	2	M7	7
M3	3	M8	8
M4	4	M9	9
M5	5	M10	10

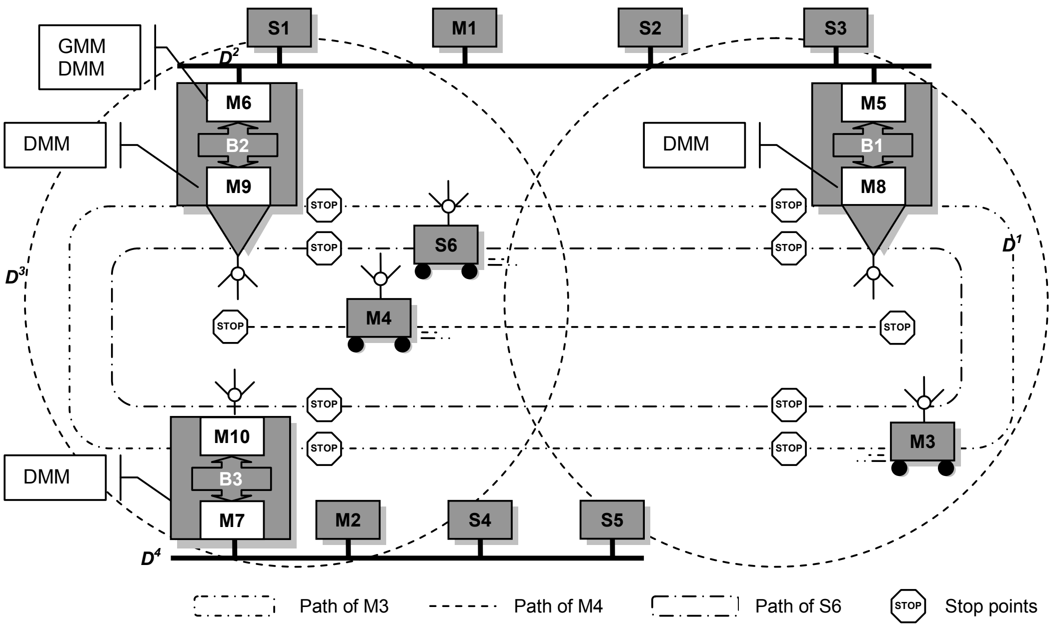

Figure 9.2 – Bridge-based hybrid wired/wireless PROFIBUS network

Table 9.5 – Bridge-based domain parameters

Domain	T_{ID1}	T_{ID2}	T_{SL}	T_{TR}	has
D^1 and D^3	100	100	115	2076	8/10
D^2	100	100	115	2046	7
D^4	100	100	115	1306	6

9.2.3. Message Streams

A message stream is a periodic sequence of message cycles, related for instance, to the reading of a sensor. Each message stream associates an initiator (a master) with a responder (usually a slave). The notation S_i^x is used to identify a message stream *i* from an initiator station *x* (e.g. S_1^{M1} is the first message stream of master M1).

The set of message streams presented in Table 9.6 tries to illustrate some probable transaction scenarios in the network. The message streams are specified as tuples (destination address, request frame length (in bytes), response frame length (in bytes) and priority).

As an example, S_1^{M1} and S_2^{M1} are IADTs between master M1 and slaves S1 and S2, respectively. S_3^{M1} is an IDT between master M1 and slave S5. S_2^{M3} is a transaction between two wireless mobile stations: master (M3) and slave S6. When both are in same domain this transaction is an IADT, but if they are in different domains the system handles it as an IDT. To simplify, we will refer to this transaction as an Intra/Inter Domain Transaction (IIDT).

Table 9.6 – Message streams

Stream	Parameters	Stream	Parameters	Stream	Parameters
S_1^{M1}	(S1, 15, 20, high)	S_1^{M2}	(S3, 15, 20, high)	S_2^{M3}	(S6, 15, 20, high)
S_2^{M1}	(S2, 15, 20, high)	S_2^{M2}	(S6, 15, 20, high)	S_3^{M3}	(S3, 15, 20, high)
S_3^{M1}	(S5, 15, 20, high)	S_1^{M3}	(S4, 15, 20, high)	S_1^{M4}	(S6, 15, 20, high)

A PROFIBUS standard master is usually a dedicated device composed by a communication module (mostly in hardware) and a CPU module running the control software. Therefore, master stations used in our simulation have been modelled according to the following operational characteristic assumptions:

- The variability of the master timing parameters is usually reduced, as confirmed by some experimental measurements (Behaeghel, Nieuwenhuyse et al., 2003);
- It is expected that the clocks of the master stations in the system may have some drift between them;
- The masters are not synchronised between them.

These assumptions were applied to the simulation models of both approaches by setting the offset of the message streams and its period using probabilistic variables. However, the response time depends on the message stream period (particularly in the Bridge-based approach), for that reason the simulation runs have been made independently for each master's message stream set:

- For the master to which we want to perform the measurements, the message stream periods were set to a constant value;
- For the other masters, the message streams parameters were set using a triangular distribution function.

In the repeater-based approach, the period of the message streams being measured has been set to 40 ms with no initial offset. The period and the initial offset of the other message streams has been set using *triang*(38, 40, 42) and *triang*(0, 38, 40), respectively. Similar rules are used in the bridge-based approach, the period of the message streams being measured has been set to 8 ms with no initial offset and the period and the initial offset of the other message streams has been set using *triang*(7.8, 8, 8.2) and *triang*(0, 7.8, 8), respectively

In the following section a performance analysis based in simulation results is presented. The results for each master message stream set have been obtained as the aggregate result of 100 runs, each with 120 s of duration, using a different seed value, in order to improve the randomness of the data. It is interesting to note that the results presented in this chapter are equivalent to the aggregate of the 170 hours of real operation.

According to the Central Limit Theorem (Law and Kelton, 2000), the simulation results presented in the next section presents a confidence level higher then 99.95%. The largest confidence interval for a message stream response time has a range of +/- 8% of the mean response time value.

9.3. Performance Analysis

In this section, we present and analyse some simulation results upon variation of some network parameters: bit rate, ISs internal delay and maximum frame size.

The message streams used on the comparison between these two approaches were S_1^{M1}, S_1^{M2} and S_3^{M3}, one IADT and two IDTs, respectively, where S_3^{M3} involves mobile stations.

In the repeater-based scenario there was the need to adjust the period of the message streams, because with some parameter setting, the network enters into saturation since the network is used beyond its maximum throughput.

9.3.1. Base Configuration Results

This subsection discusses the results obtained using the base configuration described in Section 9.2. Figure 9.3 shows a histogram of the measured response time values for S_1^{M1} in both scenarios. Note that, in the subtitle of this figure and on the remaining figures in this chapter, a R or a B before the message stream symbol (RS_i^k and BS_i^k) specify that the values are related to the repeater-based or to the bridge-based architecture, respectively.

In the repeater-based scenario, the minimum response time (MinRT) value is equal to 1.23 ms and the maximum response time (MaxRT) value to 16.09 ms.

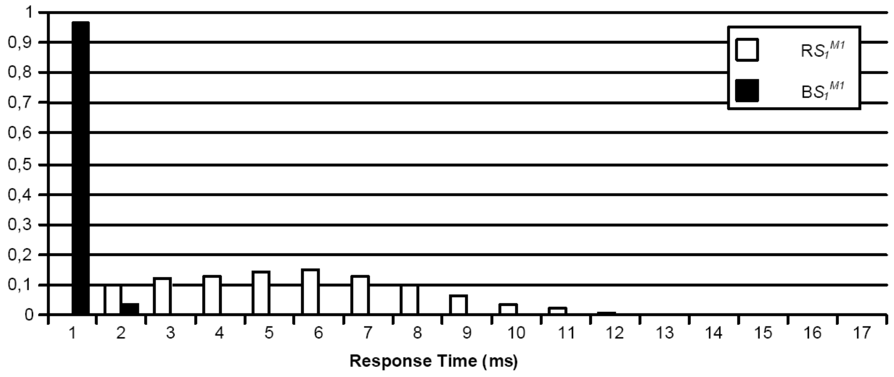

Figure 9.3 – Response time histogram for the message stream S_1^{M1}

In the bridge-based scenario, the MinRT value and the MaxRT value of message stream S_1^{M1} are 0.27 and 4.27 ms, respectively. Nevertheless, it is important to note that 96.20% of the transactions present a response time smaller or equal to 1 ms (see Table 9.7) and 98.25% of the transactions have a response time value smaller than 1.23 ms, which is the MinRT of the repeater-based scenario. In this scenario, S_1^{M1} benefits from the smaller setting of the T_{ID} parameters as well as from the traffic segmentation resulting from the use of the bridges. The first reduces the message cycle duration, while the second reduces the traffic within domain D^1.

Table 9.7 – Response time of the message stream S_1^{M1}

Interval (ms)	R S_1^{M1} (%)	B S_1^{M1} (%)	Interval (ms)	R S_1^{M1} (%)	B S_1^{M} (%)^1	Interval (ms)	R S_1^{M1} (%)	B S_1^{M} (%)^1
]0-1]	0	96,20190	]6-7]	12,43433	0	]12-13]	0,34800	0
]1-2]	10,06433	3,65463	]7-8]	9,87200	0	]13-14]	0, 12200	0
]2-3]	11,88800	0,13480	]8-9]	6,67867	0	]14-15]	0, 04700	0
]3-4]	12,65600	0,00840	]9-10]	3,76400	0	]15-16]	0,01000	0
]4-5]	14,38667	0, 00027	]10-11]	1,92033	0	]16-17]	0,00033	0
]5-6]	14,93633	0	]11-12]	0,87200	0			

Figure 9.4 depicts a response time histogram for message stream S_1^{M2} in both scenarios. The repeater-based scenario presents the MinRT (1.22 ms) and MaxRT (18.49 ms) values smaller than in the bridge-based scenario. The MinRT and MaxRT values, in the bridge-based scenario, are 8.80 ms and 26.80 ms, respectively.

In the repeater-based scenario, the histogram for S_1^{M2} is similar to the histogram of S_1^{M1} as it would be expected, since the use of repeaters creates a broadcast network.

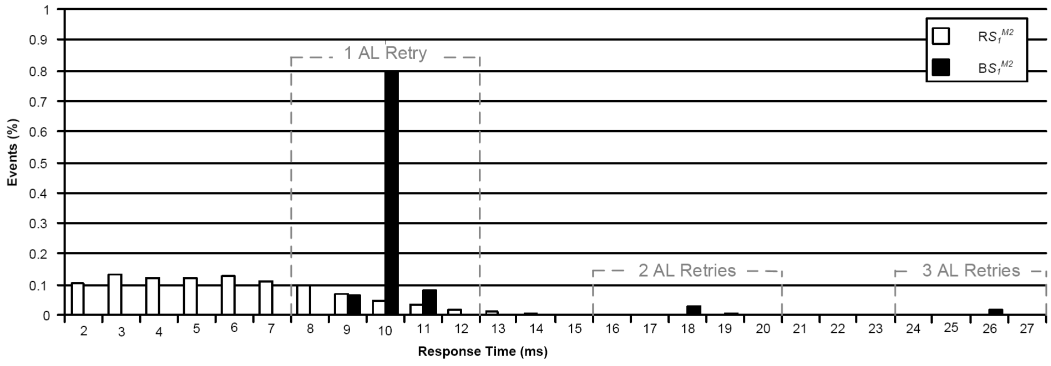

Figure 9.4 – Response time of the message stream S_1^{M2}

In the bridge-based scenario, the timing behaviour of message stream S_1^{M2} is different than for S_1^{M1}, since S_1^{M2} is an IDT. Therefore, such kind of transaction requires that the initiator performs at least one Application Layer (AL) retry before obtaining a response (meanwhile stored at the BM_{ini} (BM M7)). The period of this message stream is equal to 8 ms, and consequently the MinRT value in the bridge-based scenario is greater than 8 ms. It is noticeable that 94.23% (which is sum of the percentage or results in the intervals]8-9]…]11-12]) of the transactions require only one AL retry and 4.13% (which is sum of the percentage in the intervals]16-17]…]19-20]) of the transactions required two AL retries and the remaining (1.64%) three AL retries. The mean response time (MeanRT) value is equal to 10.02 ms on bridge-based scenario.

Table 9.8 – Response time histogram for the message stream S_1^{M2}

Interval (ms)	R S_1^{M2} (%)	B S_1^{M2} (%)	Interval (ms)	R S_1^{M2} (%)	B S_1^{M2} (%)	Interval (ms)	R S_1^{M2} (%)	B S_1^{M2} (%)
]1-2]	10,55100	0	]10-11]	3,18733	8,15101	]19-20]	0	0, 01120
]2-3]	13,25933	0	]11-12]	1,76800	0, 28249	]20-21]	0	0
]3-4]	12,34733	0	]12-13]	0, 92533	0	]21-22]	0	0
]4-5]	11,97600	0	]13-14]	0, 48300	0	]22-23]	0	0
]5-6]	12,60500	0	]14-15]	0, 09400	0	]23-24]	0	0
]6-7]	10,97600	0	]15-16]	0, 03367	0	]24-25]	0	0, 14035
]7-8]	9,55333	0	]16-17]	0,00767	0, 18625	]25-26]	0	1,47371
]8-9]	7,21067	6,13680	]17-18]	0,00233	3,09011	]26-27]	0	0,02337
]9-10]	4,84000	79,66181	]18-19]	0	0, 84291			

The response time histogram of message stream S_3^{M3} is shown in Figure 9.5 and Table 9.9. The results are very similar to message stream S_1^{M2}. However, in the repeater-based scenario the MinRT (4.61 ms) and MaxRT (19.85 ms) values are higher than the MinRT and MaxRT of the message streams S_1^{M1} and S_1^{M2}.

The main reason for these results is due to the simulation model in which message stream S_3^{M3} is always queued in third place on M3 output queue. Therefore, frames related to message stream S_3^{M3} have to wait for the transmission of frames related to the other two message streams in which the initiator is M3. This operation mode is similar to the typical behaviour of a Programmable Logical Controller (PLC) running PROFIBUS.

In the bridge-based scenario, the MinRT and MaxRT values for message stream S_3^{M3} are 8.66 ms and 26.08 ms, respectively. These results are similar to the results presented by message stream S_1^{M2} as would be expected since both are IDT.

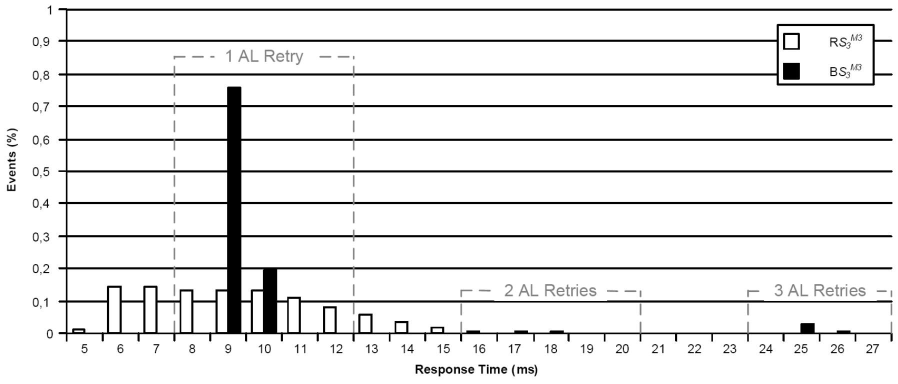

Figure 9.5 – Response time histogram for the message stream S_3^{M3}

Table 9.9 – Response time of the message stream S_3^{M3}

Interval (ms)	R S_3^{M3} (%)	B S_3^{M3} (%)	Interval (ms)	R S_3^{M} (%)	B S_3^{M3} (%)	Interval (ms)	R S_3^{M3} (%)	B S_3^{M} (%)^3
]4-5]	1,28067	0	]12-13]	5,47100	0	]20-21]	0	0
]5-6]	14,19700	0	]13-14]	3,19200	0	]21-22]	0	0
]6-7]	14,40467	0	]14-15]	1,65500	0	]22-23]	0	0
]7-8]	13,35167	0	]15-16]	0, 68300	0	]23-24]	0	0
]8-9]	13,15400	75,89062	]16-17]	0, 26800	0,75880	]24-25]	0	2,60896
]9-10]	12,97300	19,69454	]17-18]	0,07233	0, 31097	]25-26]	0	0, 64214
]10-11]	11,11733	0, 08483	]18-19]	0,02233	0,00858	]26-27]	0	0,00028
]11-12]	8,15633	0,00014	]19-20]	0,00167	0,00014			

It is important to note that, if message stream S_3^{M3} had been queued in first place instead of third, the results obtained, in the repeater-based scenario, would be equal to 1.41 ms and 16.30 ms, for MinRT and MaxRT, respectively. In the bridge-based scenario the results would be equal to 8.18 ms and 25.05 ms, for MinRT and MaxRT, respectively. From this results we conclude that the message streams queuing order has higher influence in the repeater-based scenario than in the bridge-based scenario, due to the fact of a single transaction in the repeater-based scenario takes much more time.

It is also important to note that the bridge-based scenario presents a much higher throughput than the repeater-based scenario. Figure 9.6 shows a histogram of the number of transaction for each message stream.

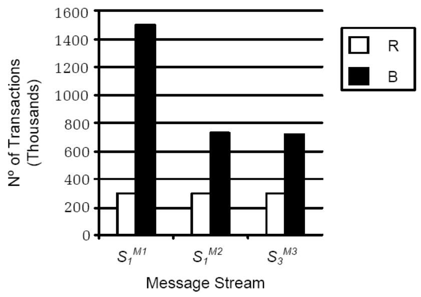

Figure 9.6 – Number of message stream transactions

In the bridge-based scenario the number transactions for message stream S_1^{M1} is approximately 500% more, for message streams S_1^{M2} and S_3^{M3} the ratio drops to 240% more since these are IDTs. The main reason to this disparity in results is due to the traffic segmentation provided by the MLR approach, the lower overhead caused by the IDTs, smaller settings of T_{ID} parameter and additionally the message stream period is much lower (8 ms and 40 ms for the bridge and repeater-based scenarios, respectively).

In the following subsections, we will analyse the network timing behaviour when certain network parameters are varied.

9.3.2. Variability of the Message Stream Response Time as a Function of the Bit Rate

This subsection analyses how the setting of different bit rates in some network domains affects the timing behaviour of the two approaches. For this purpose, the results presented were obtained by varying the bit rate in domain D^4.

Figure 9.7 compares the MinRT, MeanRT and MaxRT values of the two scenarios for messages streams S_1^{M1} and S_3^{M3}, assuming the base configuration described in Section 9.2 and by varying the bit rate in domain D^4 from 0.5 Mbit/s to 5 Mbit/s.

In these conditions, parameters T_{SL}, T_{ID1} and T_{ID2} must be recalculated for every bit rate in the repeater-based approach and these changes are applied to all domains. In the bridge-based scenario the parameter changes only affect domain D^4.

In Figure 9.7 and in the following figures of this section the MinRT, MeanRT and MaxRT values are identified by a dash. The MinRT and MaxRT values are placed on the lower and upper extremes of the line and the MeanRT is placed between MinRT and MaxRT using a wider dash.

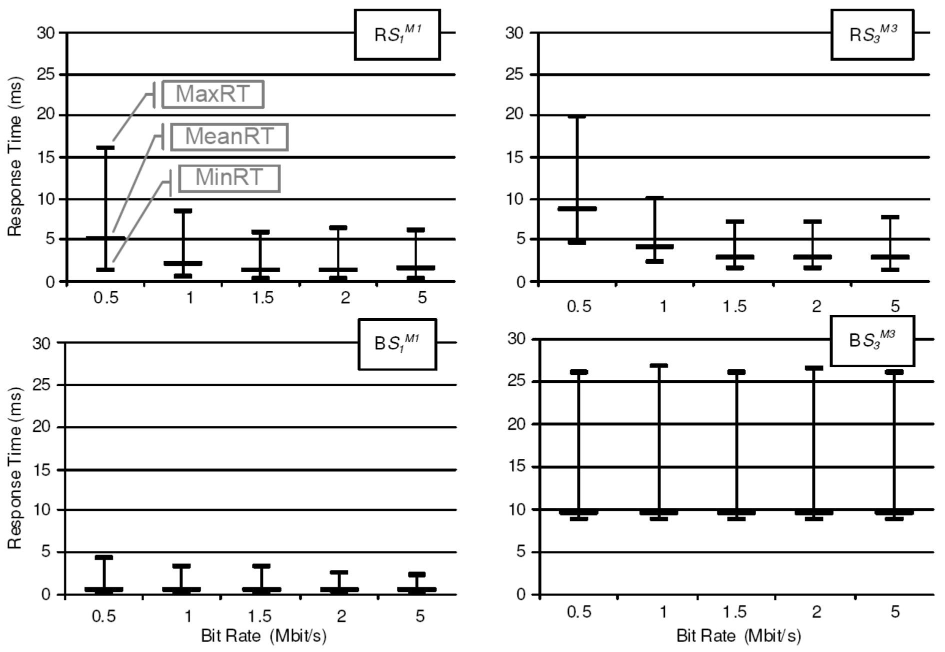

Figure 9.7 – Influence of D^4 bit rate on the message stream response time values

From the observation of Figure 9.7, we can conclude that in the repeater-based scenario the variability of the bit rate in domain D^4 has a strong influence on response time of these message streams. In this scenario, the lower MaxRT occurs when D^4 is operating at 1.5 MBit/s but it keeps increasing afterwards. The main reason for this behaviour is due to the need of inserting an additional idle time to compensate the dissimilarities of the bit rates.

In the bridge-based scenario the bit rate variation in domain D^4 has a small influence on the response time values of message streams $S_1^{M1}$and S_3^{M3}, since these message streams are not relayed by domain D^4. The decrease verified in the MaxRTs value when the bit rate increases is mainly due to a reduction of the IDMP–related latencies.

Again in this case, in the bridge-based scenario the number of concluded transaction is almost more 500% for IADTs, and 240% for IDTs than in the repeater-based scenario. For instance, the number of transactions for message streams $S_1^{M1}$and S_3^{M3} in the bridge-based scenario, considering a bit rate in domain D^4 of 5 MBit/s is 1500000 and 722900, respectively. In the repeater-based scenario, the number of transactions is 300000 for both message streams.

9.3.3. Variability of the Message Stream Response Time as a Function of the ISs Delays

The ISs delay is the time required by an IS to relay a frame between the domains which it connects, either a bridge or a repeater. In the repeater-based approach it is the time required by the repeater to convert between frame formats. In the bridge-based approach it is the time required for the routing decisions, for the conversion of frame formats and for its queuing on the output queue of the other BM of a Bridge.

In order to analyze the ISs internal delay influence on the network timing behaviour we performed six simulations in which the internal delay varied between 30 and 1000 µs.

In the repeater-based scenario, there was the need to increase the message streams period to 80 ms since with higher values of the internal delay (500 and 1000 µs) the network entered into saturation. The period for the other messages streams has been set using *triang*(78, 80, 82) and the offset has been set using *triang*(0, 78, 80).

Figure 9.8 presents the MinRT, MeanRT and MaxRT values for message streams S_1^{M1} and S_3^{M3}as a function of the ISs delays.

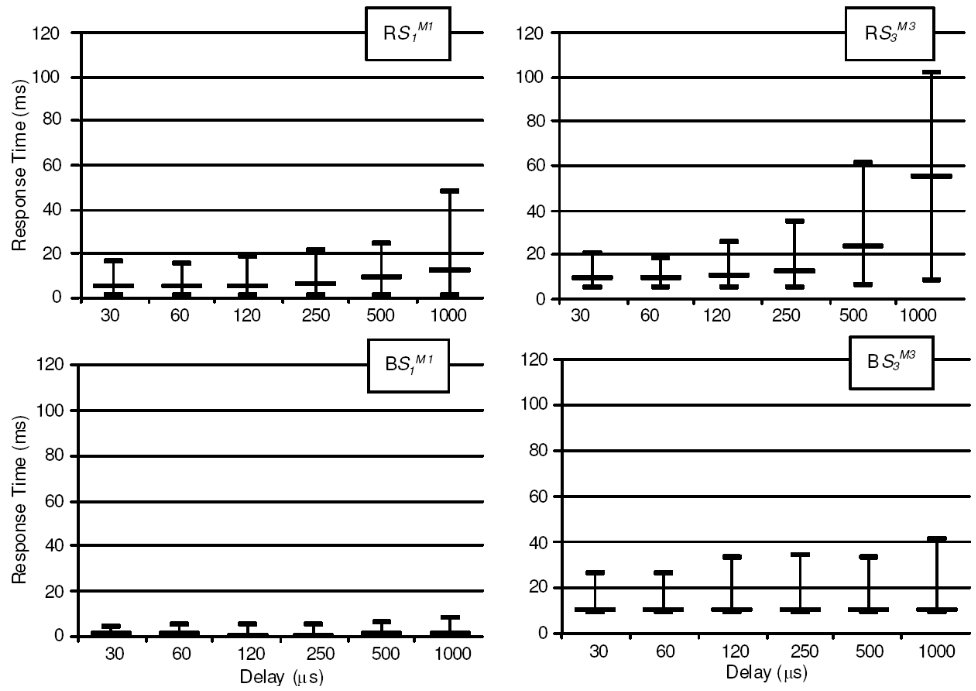

Figure 9.8 – Influence of the IS delay on MaxRT

In the repeater-based scenario, the internal delay of the repeater has a stronger influence on the MeanRT and MaxRT values, due to the increase on the message cycle latencies. Additionally, the internal delay of the repeater requires a new setting of the T_{ID2} parameter of the MM, and consequently, the mobility procedure takes longer.

In the case of the bridge-based scenario, the internal delay of the bridge has a small influence on the response time values of message stream S_1^{M1} (an IADT), since the frames exchanged in these kind of transactions are not relayed by bridges. The small MaxRT value increase is mainly due to the increase of the IDMP-related latencies. The effect on message stream S_3^{M3} (an IDT) is attenuated due to several repetitions performed by the initiator until retrieving a response from the IDT BM_{ini}.

It is also important to note that the internal delay of the ISs has a strong influence in the repeater-based scenario throughput. As mentioned, there was the need to increase the message stream period to 80 ms, which is twice the message stream period of the base configuration. Consequently, the number of transaction decreased for half. For this reason, in the bridge-based scenario the number of concluded transaction is 1000% more for IADTs, and 480% more for IDTs.

9.3.4. Variability of the Message Stream Response Time as a Function of the Maximum Frame Size

The variation of the frame size impacts the duration of message transactions not only due to the increase on the message cycle time, but also, in the case of the repeater-based approach, due to the need to increase some network timing parameters.

To perform this comparison we have chosen to vary the frame size of message stream S_1^{M3}. This message stream is the first message stream of master M3, a wireless mobile station and the responder is slave S4, which belongs to domain D^4. The size of the request and response frames varies between 15 and 250 bytes. Figure 9.9 depicts those results.

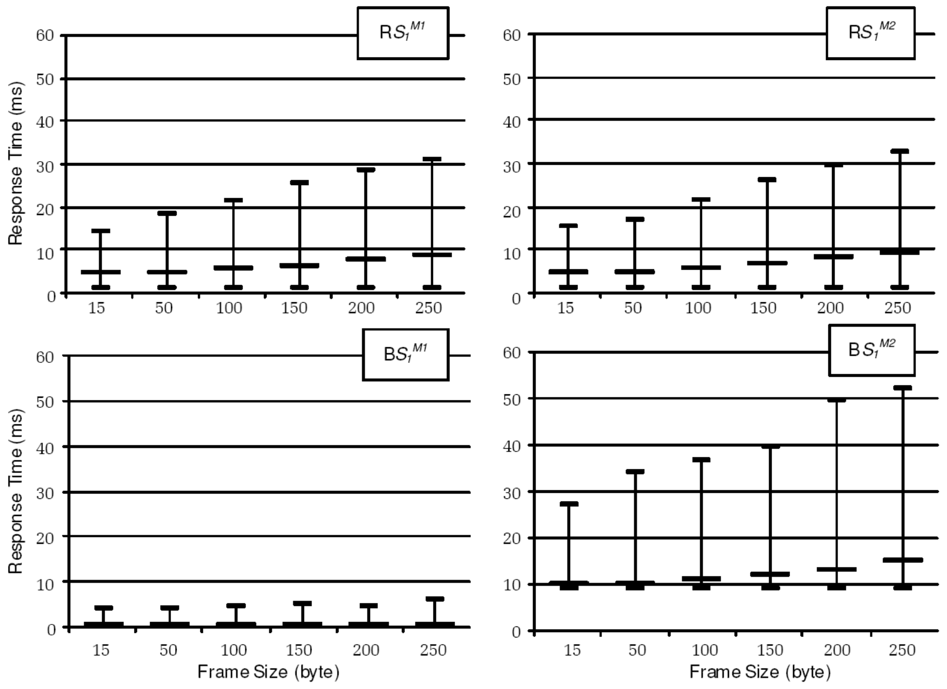

Figure 9.9 – Influence of the maximum frame size on response time

Once again, in the repeater-based scenario there was the need to increase the period to 160 ms and to adjust the T_{SL}, T_{ID1} and T_{ID2} parameters for every frame size. The period for the others messages streams was set using *triang*(140, 160, 180) and the offset was set using *triang*(0, 140, 160).

All message streams are affected by the increase of the maximum frame size. In the bridge-based scenario, this influence is stronger for message streams which are routed through the same domains as S_1^{M3}, which is the case of message stream S_1^{M2}. But for S_1^{M1} that influence is ignorable, contrarily, in the repeater-based scenario all message streams are severely affected.

It was necessary to increase the message stream period in the repeater-based scenario to 160 ms, consequently, the number of transaction performed in the bridge-based scenario is 2000% more for IADTs, and 943% more for IDTs. As an example, the number of transactions for message streams $S_1^{M1}$and S_1^{M2} in the bridge-based scenario considering a frame size of 250 Bytes is 1500000 and

707809, respectively, in the repeater-based scenario the number of transactions is 75000 for both message streams.

9.4. Summary

In this chapter, we have performed a performance comparison between the repeater and the bridge-based architectures based on simulations results in an error free environment. We have carried out experiments which showed the influence of varying certain network parameters in message response times.

From these experiments, we noted that in the bridge-based approach the variability of the response time histograms is smaller than in the repeater-based approach. Although, in some cases, the maximum response time for IDTs can be superior.

The bridge-based approach benefits from the multiple logical ring segmentation, which isolates the traffic between domains permitting lower response times for IADTs. Additionally, the network segmentation permits the independent setting of the network parameters (e.g. T_{ID} and T_{SL}) in every domain. Contrarily, in the repeater-based approach, the parameter setting depends on the network parameters and configuration, resulting on higher duration for a message cycle. The segmentation also permits a better responsiveness to errors (transmission and token loss) in the bridge-based approach since T_{SL} can be set to smaller values.

Additionally, the segmentation operated by the bridges permits a higher throughput of the overall network, which can be confirmed in our experiments, since in the bridge-based case the number of message transaction performed is in all cases much higher.

It is also noticeable that the messages queuing order has practically no influence in the maximum response time of a message stream in the bridge-based approach, contrarily to the repeater-based approach.

From the experiments in which the network parameters have been varied, it can be concluded that the repeater-based approach is more influenced by these changes especially when the maximum frame size in the network is increased. Nevertheless, the use of repeaters leads to a simpler solution since the repeater devices only operate at the PhL level, contrarily to the bridge-based approach which requires a more complex set of protocols – the IDP and the IDMP – implemented at the DLL level. Additionally, the mobility procedure used in the bridge-based approach leads to higher inaccessibility times for the wireless mobile stations, since these stations must deregister from the original domain and register in the destination domain.

The results in this chapter were obtained considering the inexistence of errors in message transactions in the following chapter we will present some results which characterise the behaviour of both networks in the error prone environments.

Chapter 10

Comparative Performance Analysis in an Error Prone Environment

This chapter provides a comparative performance analysis between the repeater and bridge-based architectures considering its operation over error prone mediums. In this comparison study, we analysed the influence of transmission errors on the network performance of both architectures. Additionally, a set of rules are proposed, which try to reduce the impact of the PROFIBUS token recovery mechanism in the bridge-based approach.

10.1. Introduction

When considering communications over an error prone and lossy medium, performance degradations mainly stem from two sources: one, is the loss of data, making retransmissions necessary, the other is the station outage (i.e., when a master station is out of the logical ring), as a consequence of the fault-recovery mechanisms used by the PROFIBUS protocol to handle and detect errors.

The simulation models used in this study, considers that a frame is corrupted if it contains a bit error, independently of which bit or bits are wrong. Three stations outage situations can occur: "heardback" removal, token lost and error skipping.

A master leaves the logical ring, i.e., its state machine evolves to the LISTEN_TOKEN state, if it transmits two consecutive corrupted token frames ("heardback" removal). A consequence of the "heardback" removal is the token loss. When the token is lost there is the need to reinitialize the logical ring.

Error skipping occurs when a master in the logical ring receives a token frame in which its address is skipped, after detecting such event it removes itself from the logical ring. Note that, in PROFIBUS networks every station in the logical ring receives all transmitted messages.

In this chapter, we present simulation results considering transmission over error prone mediums These simulation results were obtained using the Gilbert-Elliot Channel Model (Gilbert, 1960; Elliot, 1963) to model the transmission errors, a brief description of this model is presented in Section 10.2. Error detection and correction algorithms were not previously considered in the bridge-based approach proposed in (Ferreira, 2005). Therefore, this approach has been enhanced with the mechanisms proposed in Chapter 3, enabling operation over error prone mediums. The proposed mechanisms are based on timers. Section 10.3 shows how to set these timers.

We have also proposed an enhancement to the IDP, in which the IDFs are transmitted using the SDA PROFIBUS service instead of using the SDN PROFIBUS service. In Section 10.4 we present a comparative performance analysis of both alternatives.

Section 10.5 presents a comparative performance analysis between the repeater and bridge-based architectures considering transmission over error prone mediums. Additionally, in Section 10.6 we also propose a set of rules for MAC address distribution which tries to reduce the impact of the PROFIBUS token recovery mechanism in the bridge-based approach. Finally, in Section 10.7 we summarize our comparative study

The metrics used in these comparisons were the following: response time, number of transactions and percentage of concluded transactions. The response time of a message streams reflect the timing behaviour of the entire network. The number of transactions gives us an idea of the throughput of the network and the percentage of concluded transactions shows how the network recovers from errors. In both the simulation models a transaction can miss the deadline in two situations: when the response time of a transaction is higher than its deadline and when, due to queuing delays, the action frame (the first request frame of a transaction) is sent after its deadline (see Section 5.2.4 for details).

The simulation results presented in this chapter were obtained as the aggregate result of 100 runs, each using a different seed value for random value generation. It is interesting to note that the results presented in this chapter are equivalent to the aggregate of the 130 hours of real operation.

According to the Central Limit Theorem (Law and Kelton, 2000), the simulation results presented in the next sections present a confidence level higher then 99.95%. The largest confidence interval for a message stream response time has a range of +/- 5% of the mean response time value.

10.2. Gilbert-Elliot Channel Model

It is well known that transmission errors occur in bursts (Willig and Wolisz, 2001), i.e., there is a correlation between consecutive errors. The Gilbert-Elliot model takes into account this correlation. This model is a two-state discrete-time Markov chain as illustrated in Figure 10.1.

One state represents *good* channel conditions and the other *bad* channel conditions. To each state is assigned a steady state Bit Error Rate (BER) probability. In this model we define $p_{g|g}$ as the probability of continuing in the good state, $p_{b|b}$ the probability of continuing in the bad state. Each of these states has a BER probability, p_g and p_b, for good and bad state, respectively. Consequently 1- $p_{g|g}$ is the probability of evolving from good to bad state, and 1- $p_{b|b}$ is the probability of evolving from bad to good state.

The algorithm works by generating, for each bit in a frame a random number and compares it to the respective BER. A second random number is generated to determine whether the model stays in the actual state or changes into the other state for the next bit. It is assumed that bit errors occur independently from each other. A detailed description of this model is found in Annex B.

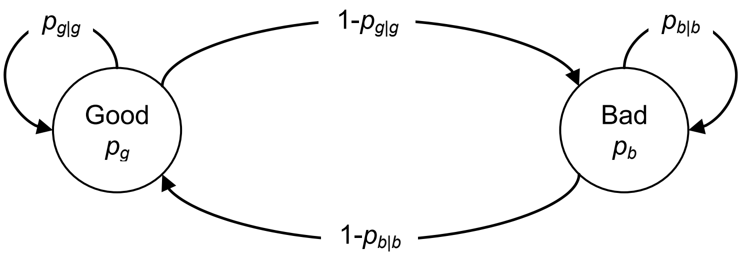

Figure 10.1 – State machine for the Gilbert-Elliot error model

Table 10.1 summarizes the Gilbert-Elliot Channel Model parameters according to each mean BER (*MeanBER*) probability used in the comparative analysis presented in this chapter (see Section B.3 for more details).

Table 10.1 – Parameters for Gilbert-Elliot Channel Model

MeanBER	$P_{g\|g}$	$P_{b\|b}$	p_g	p_b
10^{-5}	0.925074102	0.074925898	0.00000082	0.00012334105
10^{-4}	0.925074102	0.074925898	0.0000082	0.0012334105
10^{-3}	0.925074102	0.074925898	0.000082	0.012334105

The bad and good steady state probabilities are set to 7.5% and 92.5%, respectively. The BER probability for each state varies according to the *MeanBER* probability. For instance, the bad state BER probability (p_b) is $1.23*10^{-4}$ and the BER probability in good state (p_g) is $8.2*10^{-7}$, for a *MeanBER* probability equal to 10^{-5} and for the *MeanBER* probability equal to 10^{-4}, p_b increases to $1.23*10^{-3}$ and p_g increases to $8.2*10^{-6}$. These parameters are set according to the work of (Willig and Wolisz, 2001).

10.3. Network Scenario Configuration

Error detection and correction algorithms were not previously considered for the IDMP in the bridge-based approach proposed in (Ferreira, 2005). Therefore, in Chapter 3 an enhanced version of the IDMP, with error correction and detection mechanisms was proposed. The enhanced version of the IDMP uses a set of timers to detect and handle errors in its messages. Four timers are assigned to the GMM, two timers are used to detect and handle errors during the Phase 1 (`GMM_Phase_1_Alert_Timer` ($T_{GMM\text{-}P1Alert}$) and `GMM_Phase_1_Abort_Timer` ($T_{GMM\text{-}P1Abort}$)) and the other two are related to the Phase 2 (`Phase_2_Alert_Timer` ($T_{GMM\text{-}P2Alert}$) and `GMM_Phase_2_Abort_Timer` ($T_{GMM\text{-}P2Abort}$)). Additionally, each BM and each DMM also controls a timer, the `BM_IDMP_Abort_Timer` ($T_{BM\text{-}IDMPAbort}$) and the `DMM_IDMP_Abort_Timer` ($T_{DMM\text{-}IDMPAbort}$), respectively. For a detailed description of this mechanism the reader is referred to Section 3.3.3. The setting of these timers can be based on the Worst Case Response Time (WCRT) analysis proposed in (Ferreira and Tovar, 2004), but that would probably lead to a very low network performance. Therefore, we based our setting on simulation results

According to our simulation results, the maximum duration of IDMP Phase 1 and IDMP Phase 2 are 11.156 ms and 4.090 ms, respectively. Since these results were obtained considering an error free medium, these values can be used to set the alert and the abort timers. Therefore, the $T_{GMM\text{-}P1Alert}$ was set to 11.156 ms and the $T_{GMM\text{-}P1Abort}$ was set to 22.311 ($2*T_{GMM\text{-}P1Alert}$). The abort timer was set to the double of the alert timer, since this setting permits the completion of Phase 1, even when the SMP message is not received by any BM. The same rules were used to set the $T_{GMM\text{-}P2Alert}$ and the $T_{GMM\text{-}P2Abort}$, equal to 4.090 ms and 8.181 ms respectively.

The $T_{BM\text{-}IDMPAbort}$ was set equal to 30.490 ms, which is the sum of $T_{GMM\text{-}P1Abort}$ and $T_{GMM\text{-}P2Abort}$. The $T_{DMM\text{-}IDMPAbort}$ was set equal to $T_{GMM\text{-}P2Abort}$ (8.181 ms) because this timer is started at the begining of Phase 2 and finishes at the end of Phase 2. The relation between the IDMP timers is illustrated in Figure 10.2.

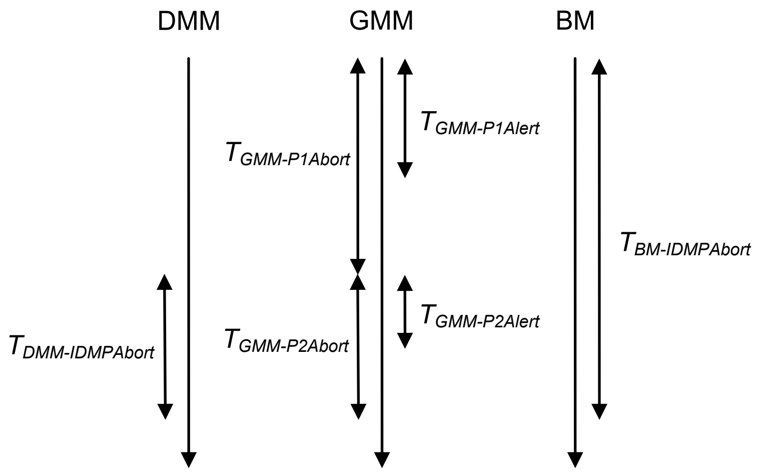

Figure 10.2 – IDMP timer's settings

To detect and handle errors during the execution of an IDT, a BM_{ini} assigns to every entry in its `List of Open Transaction` (LOT) a timer, called `BM_IDT_Abort_Timer` ($T_{BM\text{-}IDTAbort}$). If an entry is still in the LOT when the associated timer expires, then the entry is deleted from the LOT.

$T_{BM\text{-}IDTAbort}$ timer must be set with a value which allows the execution of a transaction. Two approaches were possible to set this timer, one based in the WCRT presented in (Ferreira, 2005) and the other based on simulation results. Obviously, the first mechanism is much more pessimist. Therefore we have set the $T_{BM\text{-}IDTAbort}$ equal to 33.022 ms, which is the MaxRT of all message streams provided by the simulation results presented in Section 9.2.

In an error prone environment a message stream response time can potentially be unlimited, since errors can occurs in all frames related to a transaction. Therefore, the Application Layer (AL) handles these events by assigning a timer to each message stream. This timer is loaded using the `_deadline` parameter of the `Msg_Stream` module, and it is reloaded every time a variable related to a transaction is updated. The simulations in this chapter were performed using a `_deadline` parameter of 100 ms, which is higher than the WCRT of all message streams, calculated according to the formulations presented in (Ferreira, 2005).

In this chapter we assume the same parameter setting and the same message streams as used in Chapter 9.

10.4. IDP Performance using SDA Frames

In Section 3.2.2 we proposed changes to the IDP protocol which can improve its performance in error prone environments. In the original IDP, IDF frames were transmitted using the SDN unconfirmed service. One possible improvement is to use the SDA service which permits, for a BM receiving an IDF to transmit a confirmation, and in case of error the initiator can repeat the request

The left side of Figure 10.3 shows a SDN message cycle example. The initiator (I) sends a request frame to the responder (R), which receives and processes the frame, after waiting T_{ID}, a new message cycle can be initiated. The right side of Figure 10.3 shows a SDA message cycle example. The initiator sends a request frame and waits for the acknowledge frame from the responder confirming the correct reception of the request. After receiving the acknowledge frame, the initiator prepares the next message cycle. Otherwise, it performs a number of retries according to the setting of the `max_retry_limit` parameter.

These changes are expected to improve the error correction characteristics of the IDP, since the protocol can now recover from frame errors faster than using the timer associated with each LOT entry. In the remainder of this section we show a comparative analysis between both services.

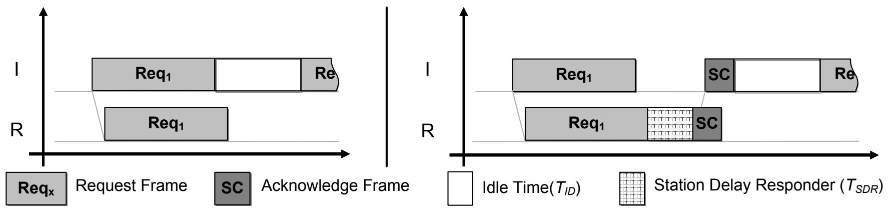

Figure 10.3 – Message cycle using the SDN or the SDA service

For both cases, the MeanRT, the number of transactions and the percentage of transactions that do not miss the deadline are presented in Figure 10.4, Figure 10.5 and Figure 10.6, respectively. In these figures the simulation results which were obtained using the SDN service are identified by the SDN tag and the SDA tag for simulation results obtained using the SDA service.

Using the SDA service the MeanRT is globally smaller for all message streams than using the SDN service, except for message stream S_1^{M1}, an IADT. The reason for these results is that there are less failed transactions, therefore IDTs errors are recovered using PROFIBUS retries, instead of using the timer on the BM_{ini} LOT. The exception is the message stream S_1^{M1}, which is affected by the increase on the network traffic.

Globally, the number of transactions is higher using the SDA service than using the SDN service. The exception is message stream S_3^{M3} when the *MeanBER* probability is equal to 10^{-3}.

Concerning the percentage of transaction that do not miss the deadline, using the SDA service the percentage is higher than using the SDN service, once again the exception is message stream S_3^{M3} which has a value somewhat worst when considering the *MeanBER* probability equal to 10^{-5} and 10^{-3}.

Although the results for message stream S_3^{M3} were not very interesting, globally, the results using the SDA service are better than using the SDN service. Nevertheless, we show in Section 10.6.1 that these results can be improved by the proper setting of master stations MAC addresses.

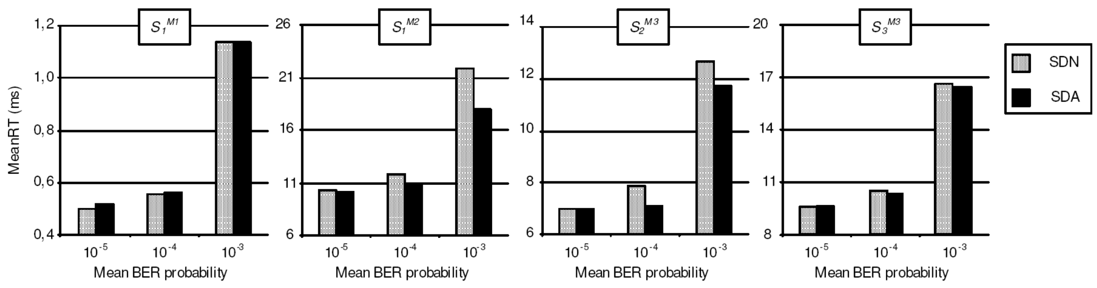

Figure 10.4 – MeanRT using the SDN and the SDA services

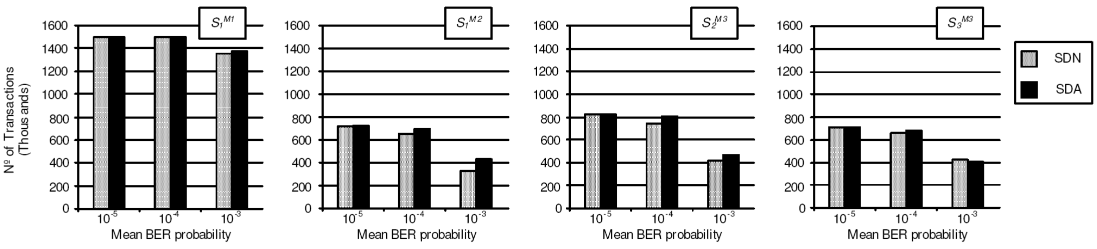

Figure 10.5 – Number of transactions using the SDN and the SDA services

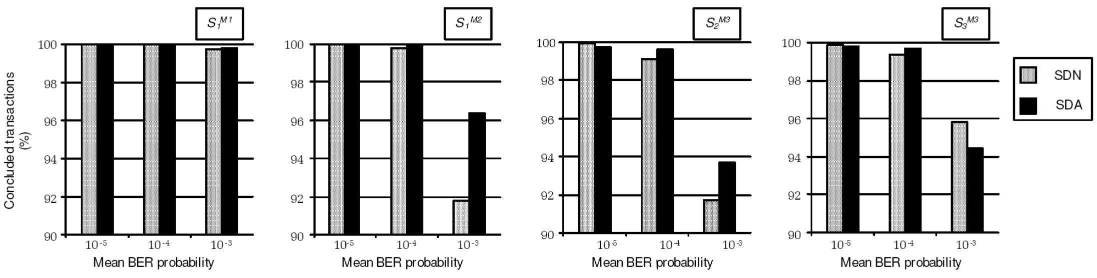

Figure 10.6 – Percentage of transactions that do not miss its deadline using the SDN and the SDA services

10.5. Performance Comparison between Repeater and Bridge-based Architectures

In this section we use the network scenarios described in Section 9.2 to compare both approaches. For that purpose, we performed two sets of simulation runs. On the first set, the *MeanBER* probability varies from 10^{-5} to 10^{-3} in all domains, independently of its type. On the second set, the *MeanBER* probability of the wired domains was set to 10^{-5} while the *MeanBER* probability of wireless domains varies from 10^{-4} to 10^{-3}. This second set emulates a scenario in which the BER in a wireless domain is different from the BER in a wired domain.

10.5.1. Comparison Using the same BER in All Domains

In this section we present the simulation results considering the *MeanBER* probability equal for all domains. Figure 10.7, Figure 10.8 and Figure 10.9 show the response time, the number of transactions and the percentage of transaction that do not miss the deadline for the message streams set used in this study. In the legend of these figures an R or a B specifies that the values are related to the repeater or to the bridge-based architecture, respectively.

Figure 10.7 shows the response time graphics where the MinRT, MeanRT and MaxRT values are signalled. However, we focus on the MeanRT to do the comparative analysis. Since, it reflects more adequately the timing behaviour of the network. In this set of figures, it is also shown the message stream response times obtained in an error free environment (the simulation results presented in Section 9.3.1), these results are identified by the tag "EF".

Using the *MeanBER* probability equal to 10^{-5} or to 10^{-4} the influence of transmission errors on the MeanRT is smaller, since these results are very similar to the results provided from the simulation runs considering an error free medium. But the effects of errors are clearly visible on the MaxRT for all message streams.

As expected, the simulation results in the repeater-based scenario are very similar for all message streams. The simulation results in the bridge-based scenario show that the MeanRT values appear very close to the MinRT values and the influence of the transmission errors on the MeanRT is smaller than in the repeater-based scenario. Further, it is noticeable that MeanRT increases much more in the repeater-based scenario than in the bridge-based scenario when the *MeanBER* probability is equal to 10^{-3}.

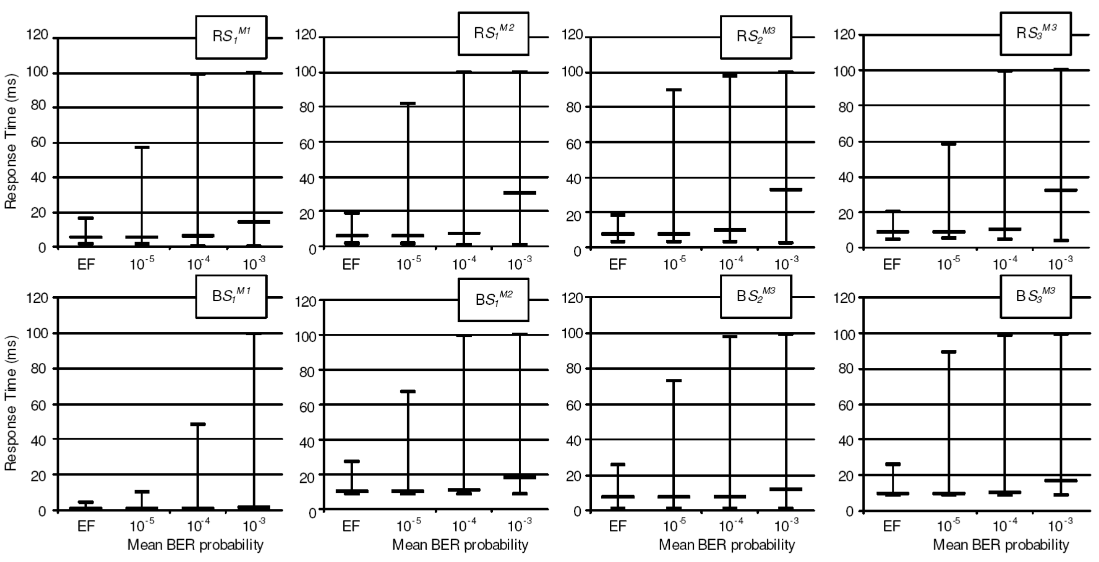

Figure 10.7 – Message stream response time considering the *MeanBER* probability equal for all domains

As it would be expected the number of transactions (Figure 10.8) is much higher for the bridge-based scenario than for the repeater-based scenario.

The AL deadline for each message stream was set according to the WCRT analysis considering an error free transmission. In both scenarios the percentage of concluded transactions for message stream S_1^{M1} is 100% considering the *MeanBER* probability equal to 10^{-5} and equal 10^{-4}. With *MeanBER* probability equal to 10^{-3} the percentage of concluded transactions is slightly lower in the repeater-based scenario than in the bridge-based scenario. Additionally, in the bridge-based scenario the number of transactions is approximately 500% more than in the repeater-based scenario.

In both scenarios, message stream S_1^{M2} presents basically the same percentage of concluded transactions considering a *MeanBER* probability of 10^{-5} and 10^{-4}. However, with a *MeanBER* probability equal to 10^{-3} the percentage of concluded transaction is significantly lower in the repeater-based scenario than in the bridge-based scenario. Further, the number of transactions is approximately 250% more in the bridge-based scenario than in the repeater-based scenario.

The percentage of concluded transactions for message streams S_2^{M3} and S_3^{M3} considering the *MeanBER* probability equal to 10^{-5} and equal 10^{-4} are slightly smaller in the bridge-based scenario than in the repeater-based scenario. The main reason is that the initiator of these message streams is a wireless mobile master, which must use the IDMP service (also affected by errors) to move between wireless domains. However, with *MeanBER* probability equal to 10^{-3} the roles are inverted and the bridge-based approach has a higher number of successful transactions.

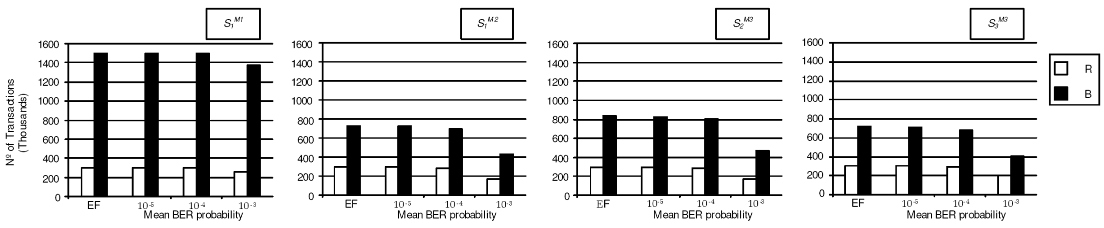

Figure 10.8 – Number of transactions considering the *MeanBER* probability equal for all domains

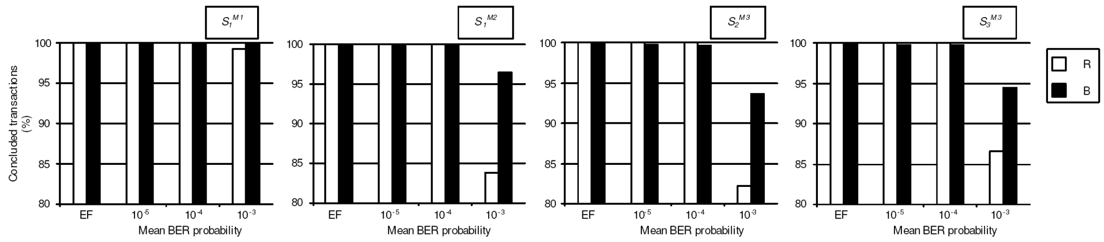

Figure 10.9 – Percentage of transactions that do no miss its deadline considering the *MeanBER* probability equal for all domains

10.5.2. Comparison using different BERs in Each Domain

Usually a wired medium has a lower BER than a wireless medium. Therefore we have also performed a comparative analysis where we fixed the *MeanBER* probability of wired domains equal to 10^{-5} and varied the *MeanBER* probability of wireless domains between 10^{-4} and 10^{-3}.

Figure 10.10, Figure 10.11 and Figure 10.12 present the response time values, the number of transactions and the percentage of transactions that do not miss its deadline. On the left side of these figures the *MeanBER* probability used was set to 10^{-4} for wireless domains and on the right side the wireless domains BER was modelled using a *MeanBER* probability equal to 10^{-3}.

The results presented in Figure 10.10 show that in the repeater-based scenario the MeanRT is more affected by the increase of the BER than in the bridge-based scenario.

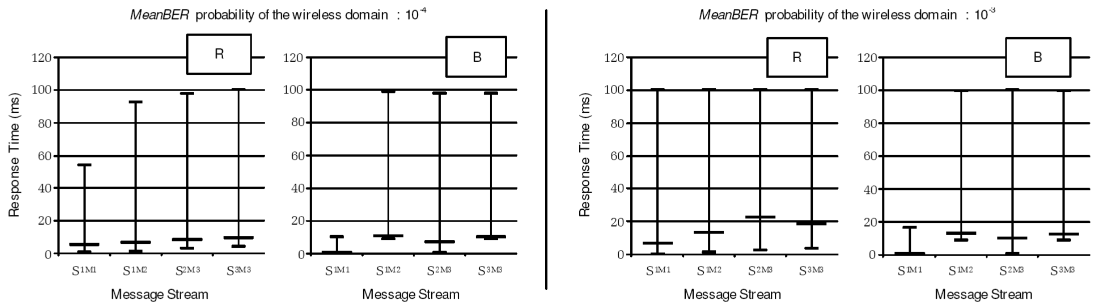

Figure 10.10 – Response time using different *MeanBER* probability in wired and wireless domains

The number of transactions for each message stream is depicted in Figure 10.11. In the bridge-based scenario the number of transaction is much higher for all message streams. As would be expected, the number of transactions is smaller when the *MeanBER* probability is equal to 10^{-3} on both scenarios, especially for IDTs. In the bridge-based scenario the decrease on the number of transactions is especially higher for message streams S_2^{M3} and S_3^{M3}. The larger decrease for both message streams is related to the fact that the initiator is a wireless mobile station, which is more influenced by the transmission errors, not only on message transmission, but also on the IDMP.

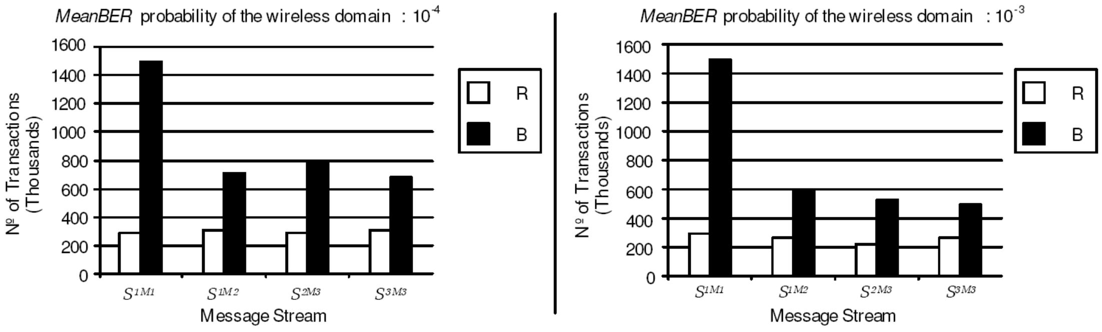

Figure 10.11 – Number of transactions using different *MeanBER* probability in wired and wireless domains

Figure 10.12 presents the percentage of transactions that do not miss its deadline for each message stream. In the repeater-based scenario the percentage of transactions that do not miss the deadline is higher than in the bridge-based scenario, especially for message streams S_2^{M3} and S_3^{M3}.

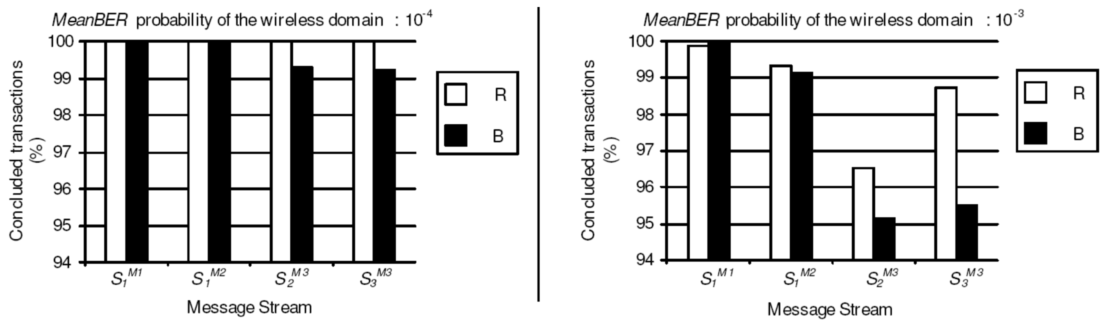

Figure 10.12 – Percentage of transactions that do not miss its deadline using different *MeanBER* probability in wired and wireless domains

Although the results seem to be more favourable to the repeater-based architecture (particularly in terms of transaction that do not miss its deadline) we will show, in the next section, that using a careful setting of master station addresses the performance of the bridge-based architecture can be improved.

10.6. Address Assignment Rules

In order to handle token loss due to an error on the current token owner: every master listens permanently on the medium. Every time the medium goes idle, each master starts the T_{TO} timer which is reset when the medium goes busy. If the T_{TO} timer expires (no activity on the medium for some time) a master claims the token (always the master with the lowest address), i.e., it starts behaving as if it is the current token owner and performs some frame transmissions: it sends data frames or passes the token to its current `Next Station` (NS). If a master was not in the LISTEN_TOKEN state then when T_{TO} expires, no changes occur on its parameters, specifically to its `List of Active Station` (LAS), NS, and `Previous Station` (PS) parameters. If it is in the LISTEN_TOKEN state when the T_{TO} expires then it evolves to the CLAIM_TOKEN state and assumes that it is the only station in the logical ring (note that when a master evolves to the LISTEN_TOKEN state it clears all entries from its LAS and the NS and the PS parameters are set equal to `This Station` (TS)).

In order to recover the token and reinitialize the logical ring the master, which is in the CLAIM_TOKEN state, transmits two token frames addressed to itself. After that, every master will be joining to the logical ring using the GAP update mechanism. However, when a master transmits a token addressed to itself, all masters that are not in the LISTEN_TOKEN state evolve to that state, since they are "skipped" of the logical ring.

When a master station is in the LISTEN_TOKEN state, it shall monitor the bus activity in order to identify which master stations already belong to the logical token ring. For that purpose, token frames are analyzed and the station addresses contained in them are used to generate the LAS.

After listening to two complete identical token rotations, the master must remain in the LISTEN_TOKEN state until it is addressed by an `FDL_Request_Status` transmitted by its predecessor to which it must respond indicating its readiness to enter into logical ring. When a master station is in the LISTEN_TOKEN state all frames are neither acknowledged nor answered, except `FDL_Request_Status` frames.

In order to clarify the problem of this mechanism, suppose a network situation in which the token owner is the station with the lowest address in the logical ring and it loses the token frame, due to two consecutive errors in token frame transmissions. Therefore, it evolves to the LISTEN_TOKEN state and clears its LAS as well as it NS and PS parameters. As it has the lowest address, its T_{TO} timer expires first. Consequently, it evolves to the CLAIM_TOKEN state and starts the token recovery mechanism sending a token frame addressed to itself. At this instant, the others masters which were in the ACTIVE_IDLE state evolve to the LISTEN_TOKEN state and will stay in this state until two identical token rotations were performed.

The availability of the bridge-based network can be degraded due to this mechanism, since when a BM is out of the logical ring, then it is not able to process IDTs. To decrease the impact of the PROFIBUS token recovery mechanism we defined a set of rules for the attribution of master station addresses. This schema is called Master Station Address Setting Rules (MSASR):

- The lowest address in each logical ring must be given to a BM;
- The following addresses should be separated by two or more addresses between them. For instance, if the lowest address in a logical ring is 2, the second one must be 4 or more.

The goal of the first rule is for the token recovery mechanism to be always performed by a BM. The second rule is used to reduce the time that a station is out of the logical ring. As mentioned a station which address is skipped evolves to the LISTEN_TOKEN state and waits in this state for two identical token frame rotations. After that, it waits for an `FDL_Request_Status` message to enter into the logical ring. On the other hand, when a master claims the token, it sends two token frames addressed to itself. Therefore, the first transmission leads that the other station evolves to the LISTEN_TOKEN state. The second token frame transmission counts as the first token rotation. After the second token transmission the token claimer processes message cycles and tries to discovery the station with the address following its during its T_{HT}. At the expiration of T_{HT} usually it did not found any station, therefore it passes the token to itself – second token rotation. At this point the other stations (particularly the stations whose address differ by two) are ready to enter in logical ring.

Table 10.2 shows the master's address considering the network scenario (identified by B) used in Section 9.2.2 and the master address assignment according to the MSASR rules (B_{MSASR}).

Table 10.2 – Master's address

	Address			Address	
Master	**B_{MSASR}**	**B**	**Master**	**B_{MSASR}**	**B**
M1	5	1	M6	2	6
M2	3	2	M7	1	7
M3	9	3	M8	7	8
M4	10	4	M9	6	9
M5	4	5	M10	8	10

To evaluate the impact of these rules we performed two sets of simulations. First we used a *MeanBER* probability equal in all domains and varied the *MeanBER* probability between 10^{-5} and 10^{-3}.

These results were compared with the simulation results presented in Section 10.5.1. In the second set, we fixed the *MeanBER* probability of the wired domains to 10^{-5} and varied the *MeanBER* probability of wireless domains equal between 10^{-4} and 10^{-3}. These results were also compared with the simulation results presented in Section 10.5.2.

10.6.1. Comparative Performance Analysis using the same BER in All Domains

Figure 10.13, Figure 10.14 and Figure 10.15 present the MeanRT, the number of transactions and the percentage of transactions that do not miss its deadline, respectively.

These simulation results show that the MeanRT increases using the MSASR. The number of transactions is very similar using both network configurations. But with the MSASR the percentage of transaction that do not miss its deadline increases, especially for simulation results in which the *MeanBER* probability is equal to 10^{-3}.

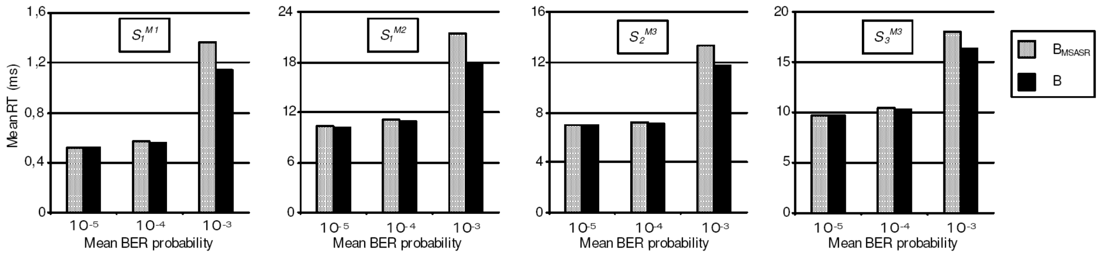

Figure 10.13 – MeanRT using equal *MeanBER* probability in all domains and the MSASR rules

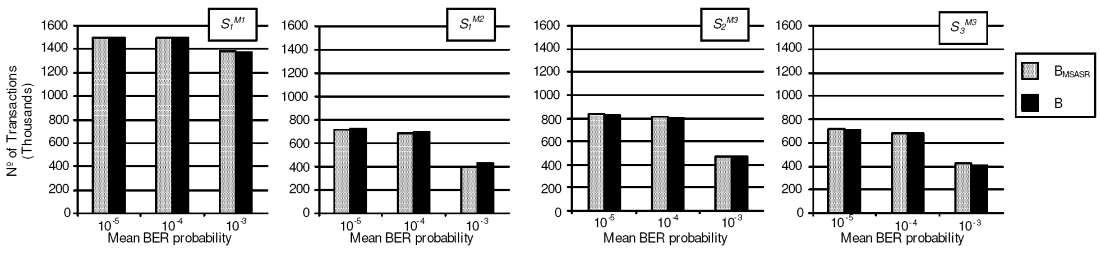

Figure 10.14 – Number of transactions using equal *MeanBER* probability in all domains and the MSASR rules

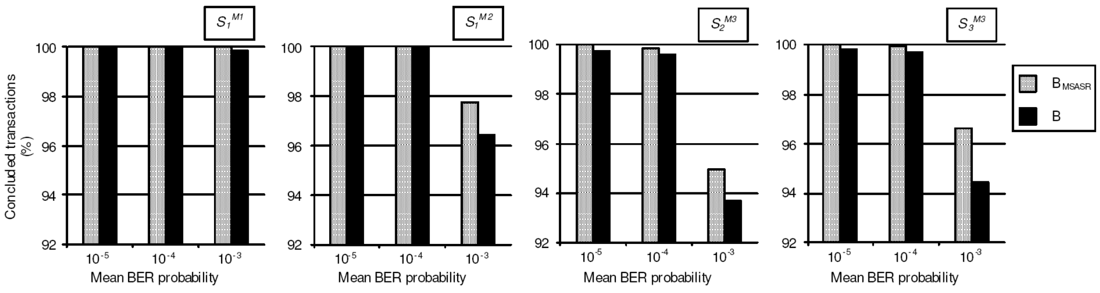

Figure 10.15 – Percentage of transactions that do not miss its deadline using equal *MeanBER* probability in all domains and the MSASR rules

The increase on the percentage of transactions that do not miss its deadline is a consequence of having a more available network, since the BMs are less time out of the logical ring. However, the increase in the MeanRT is related to the fact that transaction initiators (the system masters) are more time out of the logical ring than using the MSASR, since the lowest addresses are assigned to the BMs.

10.6.2. Comparative Performance Analysis using different BERs in Each Domain

The MeanRT, the number of transactions and the percentage of transactions that do not miss its deadline are presented in Figure 10.16, Figure 10.17 and Figure 10.18, respectively. On the left side of these figures the results for both network scenarios in which the *MeanBER* probability of wired domains is equal to 10^{-5} and of the wireless domains is equal to 10^{-4} are presented. On the right side of these figures, the *MeanBER* probability of wired domains is equal to 10^{-5} and on the wireless is equal to 10^{-3} are presented.

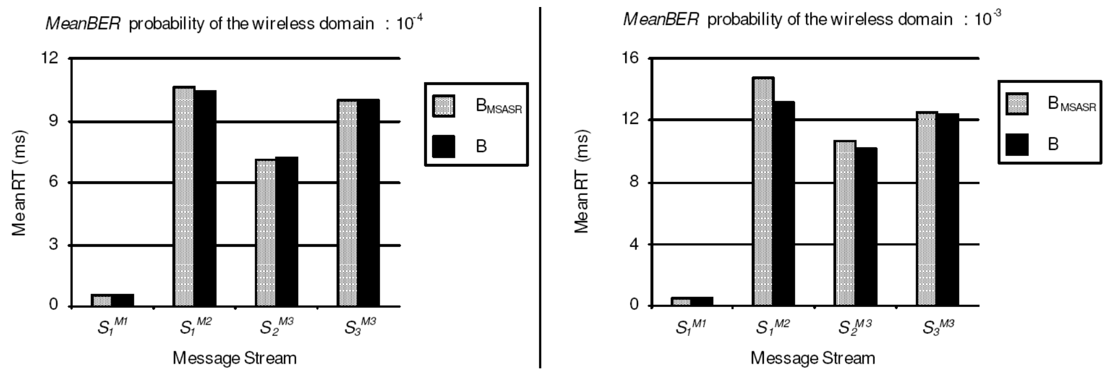

Figure 10.16 – MeanRT using different *MeanBER* probability in wired and wireless domains and the MSASR rules

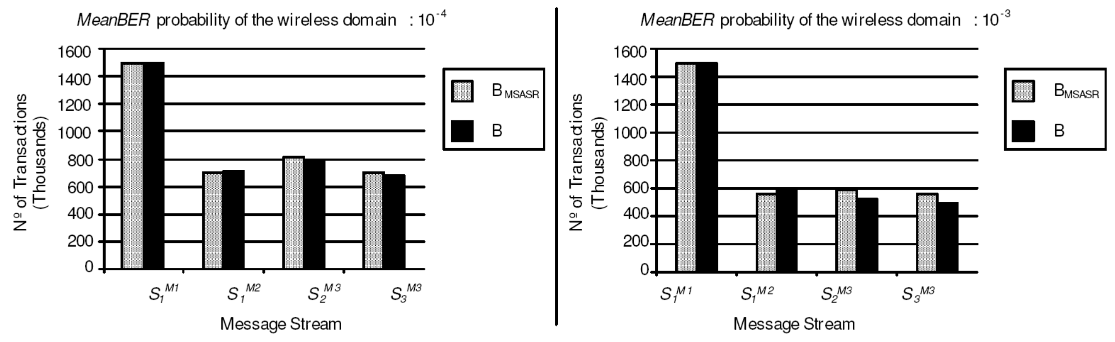

Figure 10.17 – Number of transactions using different *MeanBER* probability in wired and wireless domains and the MSASR rules

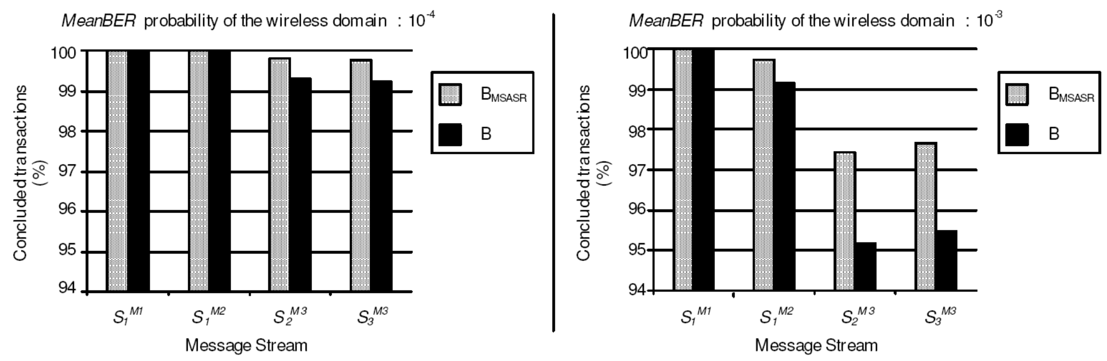

Figure 10.18 – Percentage of transactions that do not miss its deadlines using different *MeanBER* probability in wired and wireless domains and the MSASR rules

These simulation results show that using the MSASR the MeanRT of message streams is slightly higher. However, the number of transaction and the percentage of transactions that do not miss its deadlines are higher. The number of transactions increases slightly, especially for message streams S_2^{M3} and S_3^{M3}, using the MSASR. In spite of a small decrease for message stream S_1^{M1}, the other messages streams increase the percentage of transactions that do not miss its deadline.

In Section 10.5.2, we presented a performance comparison between the repeater and bridge-based approaches using a *MeanBER* probability of 10^{-5} in wired domains and a *MeanBER* probability of 10^{-4} and 10^{-3} in wireless domains. The percentage of transactions that do not miss its deadline was higher for all message streams in the repeater-based scenario than in the bridge-based scenario. Figure 10.19 shows the percentage of transactions that do not miss its deadline for repeater-based scenario from the simulation presented in Section 10.5.2 (which are identified by a R) and the percentage of transaction that do not miss its deadline for the bridge-based scenario using the MSASR schema proposed in this section.

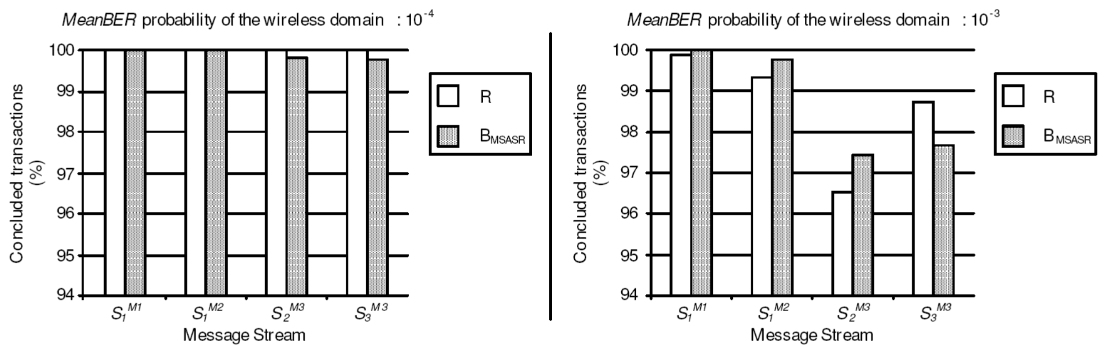

Figure 10.19 – Percentage of transactions that do not miss its deadline using different *MeanBER* probability in wired and wireless domains

From these results we can conclude that using the MSASR the percentage of transactions that do not miss its deadlines increases significantly, when compared with the results of the repeater-based scenario it is shown that for some message streams the bridge-based scenario presents a higher percentage of transactions that do not miss its deadline.

10.7. Summary

In this chapter we presented set of simulation results where transmission errors were modelled according to the Gilbert-Elliot Channel Model.

These results were used to make three comparative performance analyses. First, we made a comparative analysis of the bridge-based approach considering two version of the IDP. Originally, the IDP defined that IDFs were transmitted using the unacknowledged SDN service. Therefore, any IDF transmission error leads to an error on an IDT, which can only be solved using the LOT timer associated with that IDT. In this dissertation we proposed that an IDF should be transmitted using the acknowledge SDA service. Our simulation results show that it is possible to achieve a higher performance using the SDA service. Globally there is a reduction on the MeanRT and an increase on the number of transactions which do not loose its deadline

In the second comparative analysis, we compared the performance of the repeater-based approach and the bridge-based approach considering communications over error prone mediums. Two transmission error configurations were used. In the first, we performed simulations in which the *MeanBER* probability was set equal in all domains, either wired or wireless. In the second configuration we used a fixed *MeanBER* probability for the wired domains and varied the *MeanBER* probabilities for wireless domains.

From the simulation results provided by the first set of simulation runs we conclude that the repeater-based approach is much more influenced by transmission errors than the bridge-based approach, since the MeanRT increases considerably with an increase in the *MeanBER* probability. Contrarily, the MeanRT of the bridge-based approach increases less significantly. The decrease on the number of transactions is similar in both approaches when the *MeanBER* probability increases. The percentage of transactions that do not miss its deadline is similar for *MeanBER* equal to 10^{-5} and 10^{-4}, but for *MeanBER* equal to 10^{-3}, the percentage of transactions that do not miss its deadline is always higher for the bridge-based approach than for the repeater-based approach. The results of these last experiments were a little surprising. The MeanRT of the bridge-based approach is more constant, the number of transactions is also higher, but the percentage of transactions that do not miss its deadline is higher for the repeater-based approach than for the bridge-based approach. These results triggered a carefully analysis of the results. We realise that the setting of master station addressees should be done in a way which permits achieving a higher number of transactions that do not miss its deadline. Since, the network availability depends strongly on the BMs we defined a set of rules to assign an address to master stations.

To evaluate the impact of these rules in the bridge-based approach we performed another set of simulation runs using two transmission error configurations, one in which the *MeanBER* probability was set equal to all domain and another in which the *MeanBER* probability is higher for wireless domains. From these simulation sets we concluded that the MeanRT increases slightly and that the number of transactions is equivalent. But the percentage of transactions that do not miss its deadline increase significantly. Also, when comparing with the repeater-based approach the percentage of transactions that do not miss its deadline is now higher for the bridge-based approach.

Chapter 11

Conclusions and Future Work

This chapter reviews the research context and objectives of this dissertation, summarizes the most relevant contributions and highlights the possible directions of future work.

11.1. Research Context and Objectives

Nowadays, industrial automation applications collect large benefits from the use of fieldbuses for the interconnection of distributed devices. Usually, these systems are supported by a wired infrastructure. But, there is now an increased pressure to extend the capabilities of fieldbuses with wireless communication functionalities, in order to support mobile devices. Wireless communication systems are of particular interest in supporting mobile machine parts, mobile vehicles and temporary or frequently reconfigured production lines, for example.

The integration of wireless communications in a fieldbus system creates new challenges. It is expected that the level of performance of the wireless extensions to be at least similar to those existing in wired fieldbus. On the other hand, there is the need to interconnect different media. To sum up, the level of throughput, reliability and real-time performance of such hybrid wired/wireless network must fulfil the requirements of industrial automation applications.

In this dissertation, we analysed the performance of two approaches that extend the PROFIBUS standard to support wireless communications. One based on repeaters and another based on bridges.

In the repeater-based approach the interconnection between wired and wireless segments (called as domains) is supported by Intermediate Systems (ISs) operating as repeaters, i.e., at Physical Layer (PhL) level. The support of repeaters requires a specific settings of some PROFIBUS timing parameters (`Slot Time` and `Idle Time`), which results in a lower responsiveness to errors and on an increased latency of the message cycles. Additionally, the use of repeaters creates a broadcast network.

The bridge-based approach triggered an alternative approach where the ISs behave as bridges, i.e., at Data Link Layer (DLL) level. This approach – the bridge-based approach – solves some of the problems of the repeater-based approach. The bridge-based approach creates a Multiple Logical Ring (MLR) network and, as consequence, there is the need of two more protocols. One, for supporting the communication between stations that belong to different domains – the Inter-Domain Protocol (IDP). Another to support the mobility of wireless mobile stations between different wireless domains – the Inter Domain Mobility Procedure (IDMP).

The main objective of this dissertation is to compare the timing behaviour of the repeater and bridge-based approaches in an error free and error prone environments. Additionally, we also intended to show that the bridge-based approach implementation is feasible and propose additional error detection and correction mechanisms which would improve its performance over error prone environments. To achieve these objectives two simulation tools have been developed, for the repeater-based approach and another to the bridge-based approach, and a set of analysis tools. Additionally, we have also developed another tool to simulate the mobility of wireless stations. As outlined next, the objectives of this dissertation were achieved.

11.2. Main Contributions

11.2.1. Enhancements to the Bridge-Based Approach

Error detection and correction algorithms were not previously considered in the bridge-based approach proposed in (Ferreira, 2005). Therefore, this approach has been enhanced with the necessary mechanisms to be used over error prone mediums as summarised next.

Originally, the IDP defined that IDFs were transmitted using the SDN PROFIBUS service. This service is an unacknowledged service. Therefore, any IDF transmission error results in a failed IDT. In this dissertation we proposed that IDFs must be transmitted using the SDA PROFIBUS service. The SDA service is an acknowledge service, i.e., the frame sender receives a special frame (`Short Acknowledge` frame) confirming the reception by the responder. The simulation results presented in Section 10. 4 showed that using the SDA service, would lead to a better performance than using the SDN service.

The original IDMP only had very limited error handling capabilities. In an error prone environment this protocol could lead to blocking situations, therefore we have proposed an error handling mechanism which permits to solve the detected problems. This mechanism is based on timers, which control the IDMP phases.

These enhancements provide the bridge-based approach with the necessary mechanisms to be used in an error prone environment.

11.2.2. Comparison between the Repeater and Bridge-Based Approaches

In Chapter 9 a performance comparison between the repeater and the bridge-based approaches was performed considering an error free medium and by varying some important network parameters. From that comparison, it has been shown that the performance of the bridge-based approach is less influenced by changes on the network parameters. Additionally, the bridge-based approach is not dependent on the network parameters or configuration, i.e., the impact of changes on the network parameters or configuration is minimum in relation to the repeater-based approach, in which any change on the network parameters or configuration implies changes to the parameters settings in all stations. This performance comparison was based on response time and throughput results. From these results it was possible conclude that the bridge-based approach presents a better performance. The response time of IADTs is much smaller in any case and for the IDTs, if it is not smaller is very close of the response time obtained by the repeater-based approach and less influenced by parameter settings. The throughput is always higher for all message streams (in same cases 2000% more).

Another important aspect is that we have also proposed a set of rules for address attribution to all master station in the network (BM included), and showed that this set of rules results in performance gains, particularly on the number of transactions that do not miss their deadlines.

Chapter 10 presents a performance comparison between these two approaches considering communication over error prone mediums. From the simulation results we can conclude that the bridge-based approach presents a better performance. Since, globally, the response time of its message streams is smaller, the throughput is always higher and the percentage of transactions that do not miss their deadline is higher for most message streams.

11.2.3. Software Tools

The software tools developed within this thesis are also a very important contribution for further studies on hybrid wired/wireless PROFIBUS networks. These tools are available for free, and they can be downloaded from the web site http://www.hurray.isep.ipp.pt/activities/hw2pnetsim/.

The following list describes a set of tools which were developed:

- Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (RHW2PNetSim).
- Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (BHW2PNetSim).

– Mobility Simulator: is a tool which is used to simulate the mobility of wireless mobile stations, the radio signal strength at a certain point in space and the wireless domain to which the station belong through time.
– Timeline Visualization: provides a way to show the network events, like frame transmissions, using Gant Diagrams. This tool can also be used with any other kind of network simulator.
– Output Data Analysis: this tool provides a set of options to extract information from the output data files generated by the RHW2PNetSim and BHW2PNetSim.

11.3. Future work

The work performed during this thesis permitted to adequately characterise and compare the timing behaviour of the repeater and bridge-based hybrid wired/wireless PROFIBUS networks. However, we envision some improvements, mainly in relation to the bridge-based architecture which might considerably improve their performance.

The operation of the bridge-based architecture relies completely on bridge devices, which are new components in a PROFIBUS network infrastructure. The BMs defined in this architecture do not implement AL functionalities. An obvious add-on would be to include AL functionalities in the bridges, as in a standard PROFIBUS-DP master. This would permit to improve the performance of the network, and at the same time, reduce the number of devices required.

In our opinion the token recovery mechanism of the PROFIBUS is not very efficient, therefore we think that if the BMs were provided with better mechanisms, then the network performance can be improve, particularly over error prone environments.

The Mobility Simulator used in this thesis assumed that wireless mobile stations always change to a new radio channel whenever the quality of the radio channel in another domain is better than the actual, this can possibly result in performing more handoffs than necessary. Consequently, a possible enhancement to the handoff mechanism is to implement a histeresis mechanism. Additionally, our mobility simulator should also provide results, considering the influence of obstacles in the environment and noise sources, like welding machines.

It is also clear from our results that the IDMP has a high impact on message streams response time, therefore a potential improvement would be to develop an enhanced IDMP with a better timing performance.

Most of the work and methodologies developed within context of this thesis can also be applied to evaluate other wireless technologies, like IEEE 802.11 or ZigBee network in industrial scenario.

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Annex A

Probability Distribution Functions

The simulators developed within the aim of this dissertation permit the setting of some its parameters using probabilistic distribution functions (PDFs). This annex describes the characteristics of the PDFs which can be used.

A.1. Introduction

Most simulation studies have variables which exhibit a stochastic behaviour. This is also the case of the simulators developed within this dissertation, where it is possible to use PDFs in some of its parameters, like the message stream period and T_{ID} parameters, just to mention two. This annex describes the PDFs which have been implemented to model the behaviours of certain parameters of the Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (RHW2PNetSim) and Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (BHW2PNetSim).

A.2. Parameterization of Continuous Distributions

For a given family of continuous distributions, e.g., normal or gamma, there are usually several alternative ways to define, or parameterize, the probability density function. However, if the parameters are defined correctly, they can be classified, on the basis of their physical or geometric interpretation, as being on of three basic types: *location*, *scale*, or *shape* parameters.

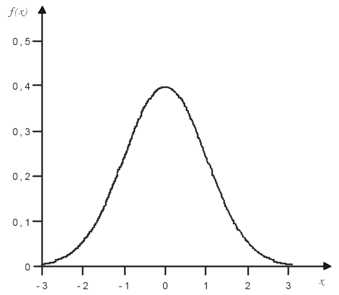
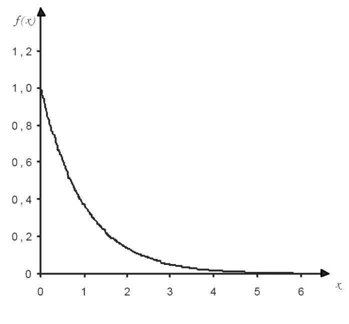
A location parameter γ specifies an abscissa (x axis) location point of a distribution's range of values; usually γ is the midpoint or the lower endpoint of the distribution's range. (in the latter case location parameters are sometimes called shift parameters). As γ changes, the associated distribution merely shifts left or right without otherwise changing. Also, if the distribution of a random variable X has a location parameter of 0, then the distribution of the random variable $Y = X + \gamma$ has location parameter of γ.

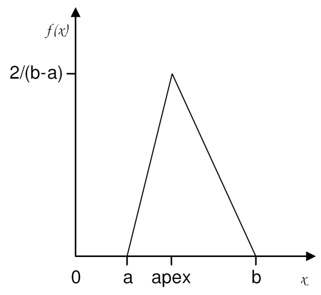
A scale parameter β determines the scale (or unit) of measurement of the values in the ranges of the distribution. (The standard deviation σ is a scale parameter for the normal distribution). A change in β compresses or expands the associated distribution without altering its basic form. Also, if the distribution of a random variable X has a scale parameter of 1, then the distribution of the random variable $Y = \beta X$ has a scale parameter of β.

A shape parameter α determines, distinct from location and scale, the basic form or shape of a distribution within the general family of distributions of interest. A change in α generally alters a distribution's properties (e.g. skewness) more fundamentally than a change in location or scale. Some distributions (e.g., exponential and normal) do not have shape parameter, while others (e,g., beta) may have two.

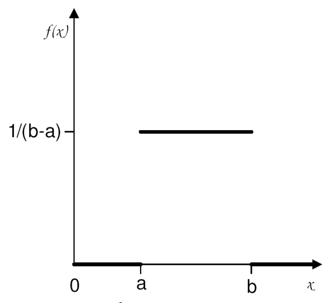
The Table A.1 gives the information relevant to the PDFs implemented in both simulators. The range indicates the interval where the associated random variable can take on values. Also listed are the mean (expected value), variance, and mode, i.e., the value at which the density function is maximized.

Table A.1 – Probability Distribution Functions features

1- Normal	$N(\mu,\sigma^2)$
Possible applications	Errors of various types, e.g., in the impact point of a bomb; quantities that are the sum of a large number of the other quantities (by virtue of central limit theorems)
	$f(x)=\dfrac{1}{\sqrt{2\pi\sigma^2}}e^{\frac{-(x-\mu)^2}{2\sigma^2}}$ for all real numbers x
Density	
Distribution	No closed form
Parameters	Location parameter $\mu\in(-\infty,\infty)$ Scale parameter $\sigma>0$
Range	
Mean	$(-\infty,\infty)$
Variance	μ
Mode	σ^2
2- Exponential	$\exp o(\beta)$
Possible Applications	Interarrival times of “customers” to a system that occur at constant rate, time to failure of a piece of equipment
	$f(x)=\begin{cases}\frac{1}{\beta^2} & \textit{if } x\geq 0\\ 0 & \textit{otherwise}\end{cases}$
Density	

Distribution	$F(x)=\begin{cases} 1-e^{\frac{-x}{\beta}} & if \;\; x\geq 0 \\ 0 & otherwise \end{cases}$
Parameters	Scale parameter $\beta > 0$
Range	$[0,\infty)$
Mean	β
Variance	β^2
Mode	0
3-Triangular	$triang(a, apex, b)$
Possible applications	Used as rough model in absence of data $f(x)=\begin{cases} \frac{2(x-a)}{(b-a)(apex-a)} & if \;\; a\leq x\leq apex \\ \frac{2(b-x)}{(b-a)(b-apex)} & if \;\; apex < x\leq b \\ 0 & otherwise \end{cases}$
Density	
Distribution	$F(x)=\begin{cases} 0 & if \;\; x<a \\ \frac{(x-a)^2}{(b-a)(apex-a)} & if \;\; a\leq x\leq apex \\ 1-\frac{(b-x)^2}{(b-a)(b-apex)} & if \; apex < x\leq b \\ 1 & if \;\; b<x \end{cases}$
Parameters	a , b and $apex$ real numbers with $a < apex < b$. a is a location parameter. $b-a$ is a scale parameter. $apex$ is a shape parameter
Range	$[a,b]$
Mean	$\frac{a+b+apex}{3}$

Variance	$\dfrac{a^2 + b^2 + apex^2 - ab - aapex - bapex}{18}$
Mode	$apex$

4-Uniform	$uniform(a,b)$
Possible applications	Used as a "first" model for quantity that is felt to be randomly varying between *a* and *b* but about which little else is known.
Density	$f(x) = \begin{cases} \dfrac{1}{b-a} & if\ a \le x \le b \\ 0 & otherwise \end{cases}$ 
Distribution	$F(x) = \begin{cases} 0 & if\ x < a \\ \dfrac{x-a}{b-a} & if\ a \le x \le b \\ 1 & if\ b < x \end{cases}$
Parameters	a and b real numbers with $a < b$. a is a location parameter. $b - a$ is a scale parameter.
Range	$[a,b]$
Mean	$\dfrac{a+b}{2}$
Variance	$\dfrac{(b-a)^2}{12}$
Mode	Does not uniquely exists

A.3. Parameterization of Stochastic Parameters in the Simulators

The RHW2PNetSim and BHW2PNetSim allow setting some parameters using PDFs. The name of all these parameters uses the `_pdf` prefix. For example, the parameters associated to T_{SDR} are the following: `_pdf_tsdr_type`, `_pdf_tsdr_par1`, `_pdf_tsdr_par2` and `_pdf_tsdr_par3`. Where the `_pdf_tsdr_type` indicates which PDF will be used to generate the value of the T_{SDR} and the other parameters are the arguments of the PDF. Table A.2 presents how the simulator parameters must be set according to the PDF.

Table A.2 – Probability Distributions Functions simulators parameters

		Probability Distribution Functions			
Parameters	**Constant**	**Normal**	**Exponential**	**Triangular**	**Triangular**
`_pdf_..._type`	0	1	2	3	4
`_pdf_..._par1`	Value	μ	β	a	a
`_pdf_..._par2`		σ^2	–	$apex$	b
`_pdf_..._par3`		–	–	b	–

Annex B

Bit Error Models

The use of bit error models in communication simulation has been widely studied. In this dissertation we had used three models: The Independent Channel Model; the Gilbert-Elliot Model and the Burst-Error Periodic Model, which are described in detail in this annex.

B.1. Introduction

The purpose of this annex is to describe the Bit Error Model (BEM) supported by the Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (RHW2PNetSim) and Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (BHW2PNetSim). Independent Channel Model (Willig and Wolisz, 2001); the Gilbert-Elliot Channel Model (Gilbert, 1960; Elliot, 1963) and the Burst-Error Periodic Model (Hazim, 2006). This Annex describes the implemented BEMs.

B.2. Independent Channel Model

This model is very simple and determines if a frame is correct or wrong, that is, there is a bit error in a frame. As there is no correlation between two consecutive errors, this model is called *Independent* Channel Model.

The result of this model is obtained using Bernoulli function (Law and Kelton, 2000) with parameter P_{fr_err}. This parameter is computed as follows:

$$P_{fr\_err} = 1 - (1 - p_{ber})^L \tag{B.1}$$

where L is the length (in bits) frame and p_{ber} is the Bit Error Rate (BER) probability associated to the channel.

B.3. Gilbert-Elliot Channel Model

It is well known that transmission errors occur in bursts, that is, there is correlation between consecutive errors. The Gilbert-Elliot model (Gilbert, 1960; Elliot, 1963) takes into account this correlation. This model is a two-state discrete-time Markov chain as shown Figure B.1.

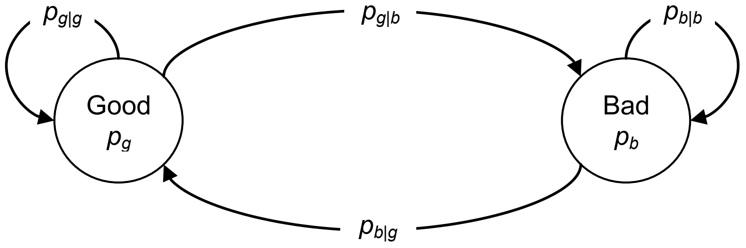


Figure B.1 – Gilbert-Elliot model

One state represents a *good* channel conditions and the other one *bad* channel conditions. Each state is assigned a constant Bit Error Rate (BER) probability, p_g in good state and p_b in bad state. It is assumed that the bit errors occur independently from each other.

Let t_g and t_b the mean duration in good state and in bad state, respectively. The steady state probability for being in good state can be obtained as follows:

$$p_{g|g} = \frac{t_g}{t_g + t_b} \tag{B.2}$$

In same way, the steady state probability for being in bad state can be obtained as follows:

$$p_{b|b} = \frac{t_b}{t_g + t_b} \tag{B.3}$$

The mean BER is given by:

$$MeanBER = p_{g|g} * p_g + p_{b|b} * p_b \tag{B.4}$$

The probability of a transition occurs from good to bad state is computed as:

$$p_{b|g} = 1 - p_{g|g} \tag{B.5}$$

The probability of a transition occurs from bad to good state is computed as:

$$p_{g|b} = 1 - p_{b|b} \tag{B.6}$$

The Gilbert-Elliot model is computationally expensive, since for each frame's bit two uniform experiments have to be executed. The algorithm works by generating, for each bit in a frame a random number and compares it to the respective BER. A second random number is generated to determine whether the model stays in the actual state or changes into the other state for the next bit.

This will slow down the simulation performance. In order to overcome this drawback a simplified Gilbert-Elliot model can be used. This simplification is accomplished by assuming that in good state all frame's bit are correctly transmitted. Therefore, in good state there is the need to compute if state transition occurs. In context of this dissertation this model is called Simplified Gilbert-Elliot Channel Model.

B.4. Burst-Error Periodic Model

The Burst-Error Periodic Model assumes that the transmission errors occur in a periodic way. In this model it is assumed that there are a lower (T_{em}) and a higher (T_{eM}) period threshold. The burst length is also bounded by a minimum (N_{em}) and maximum (N_{eM}) number of bits. The T_{em} and T_{eM} parameters are set in milliseconds and the N_{em} and N_{eM} are set in bits.

Figure B.2 shows a simplified timeline using this model. The transmission error period is computed using the Eq. B.7 and burst length is computed using the Eq. B.8.

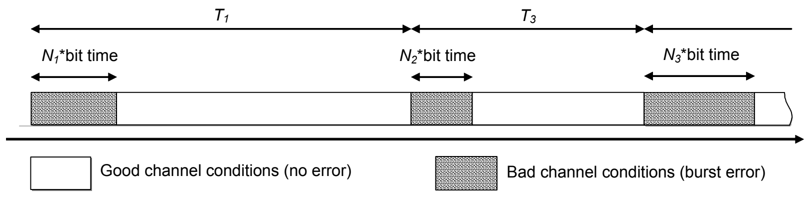

T_1
T_3
N_1*bit time
N_2*bit time
N_3*bit time
Good channel conditions (no error)
Bad channel conditions (burst error)

Figure B.2 – Simplified timeline of Burst-Error Periodic Model

$$T_x = uniform(T_{em}, T_{eM}) \tag{B.7}$$

$$N_y = uniform(N_{em}, N_{eM}) \tag{B.8}$$

To compute the transmission error period and the burst length a uniform probability distribution function (Law and Kelton, 2000) is used (Eq. B.8). This function was chosen because this model imposes thresholds, i.e., the transmission error period has to be enclosed within of the range [T_{em} , T_{eM}] and burst length has to be enclosed within of the range [N_{em}, N_{eM}]. On the other hand, is assumed that either period or burst lengths are uniformly distributed in their defined ranges.

B.5. Parameterization of the Bit Error Model Parameters Used in both Simulators

The RHW2PNetSim and BHW2PNetSim define a set of parameters to specify which BEM to use. The name of all these parameters uses the `_bem` prefix. The `_bem_type` is used to define the BEM and the other parameters (`_bem_par1`, `_bem_par2`, `_bem_par1`, `_bem_par3` and`_bem_par4`) are used to set the BEM parameter. Table B.1 presents how the simulator parameters must be set according to the BEM to be used.

Table B.1 – Bit Error Model simulators parameters

		Bit Error Model			
Parameters	**No errors**	**Independent Channel Model**	**Gilbert-Elliot Channel Model**	**Simplified Gilbert-Elliot Channel Model**	**Periodic Burst Model**
`_bem_type`	0	1	2	3	4
`_bem_par1`	–	p_{ber}	$p_{g\|b}$	$p_{g\|b}$	T_{em}
`_bem_par2`	–	–	$p_{b\|g}$	$p_{b\|g}$	T_{eM}
`_bem_par3`	–	–	p_g	p_b	N_{em}
`_bem_par4`	–	–	p_b	–	N_{eM}

Annex C

Implementation of the Simulation Models

In Chapter 5, Chapter 6 and Chapter 7 the main architecture of the Repeater-Based Hybrid Wired/Wireless Network Simulator and the Bridge-Based Hybrid Wired/Wireless Network Simulator were described. In this annex we describe the implementation details of the Repeater-Based Hybrid Wired/Wireless Network Simulator and the Bridge-Based Hybrid Wired/Wireless Network Simulator

C.1. PROFIBUS DLL

The goal of this annex is to provide a more detailed description of the implementation of the Repeater-Based Hybrid Wired/Wireless Network Simulator (RHW2PNetSim) and the Bridge-Based Hybrid Wired/Wireless Network Simulator (BHW2PNetSim). In Chapter 5, Chapter 6 and Chapter 7 the behaviour of each module was described using the description of its state machine. The particular specification of each transition is detailed in this annex. Therefore, this annex is a complement to those chapters.

C.1.1. Token Recovery Procedure

In the PROFIBUS protocol, a token lost is detected when a master does not detect any network activity for a time defined by its `Time-Out Time` (T_{TO}) parameter (which is set by Eq. 2.2).

A timer is loaded with T_{TO} parameter value and is started in two situations. First, when the frame transmitter transmits the frame's last bit. Second, when a master receives frame's last bit. The timer is stopped when the first bit of the following frame is received.

When T_{TO} timer expires and the `Master` module instance is in the ACTIVE_IDLE state it starts performing message cycles according to the message dispatching procedure (described in Section C.1.3). But if it is in the LISTEN_TOKEN state, then it evolves to the CLAIM_TOKEN state and the token recovery procedure starts. This procedure has two objectives. First, recovering the token frame and, second to reinitialize the logical ring.

Note that, when a `Master` evolves to LISTEN_TOKEN state all `List of Active Stations` (LAS) entries are deleted (Figure C.1).

```
handleSelfMessage(msg)
{
switch (getAction(msg)) {
      case TTO_TIMEOUT:
                switch (state) {
                          case ACTIVE_IDLE:
                                    messageDispacthing();
                          end;
                          case LISTEN_TOKEN:
                                    state=CLAIM_TOKEN;
                                    tokenRecovery();

                          end;
                }
      end;
      ...
   }
}
```

Figure C.1 – `handleSelfMessage(msg)` function, pseudo-code algorithm

In order to recover the token and reinitialize the logical ring the `Master`, which is in the CLAIM_TOKEN state, transmits two token frames addressed to itself (Figure C.2). The pass token procedure will be described in Section C.1.4. In this way the token frame is recovered. After that, every `Master` will be joining to the logical ring using the GAP update procedure (described in Section C.1.3).

Note that, when a `Master` transmits a token addressed to itself, all `Masters` that are not in the LISTEN_TOKEN state evolves to that state, since they are "skipped" of the logical ring.

```
tokenRecovery()
{
passToken(TS);
passToken(TS);
state=USE_TOKEN;
messageDispacthing();
}
```

Figure C.2 – `tokenRecovery()` function, pseudo-code algorithm

C.1.2. Token Reception Procedure

The token frame is passed between masters in ascending Medium Access Control (MAC) address order. The only exception is that to close the logical ring the master with the `Highest Station Address` (HSA) must pass the token frame to the master with the lowest one. Each master knows the address of its `Previous Station` (PS), the address of the `Next Station` (NS) and its own address (`This Station` (TS)).

When a master receives a token frame addressed to itself from a master registered in the LAS as its PS then this master is said to be the token owner. On the other hand, if a master receives a token frame from a master, which is not its PS, it shall assume an error and will not accept the token frame. However, if it receives a second subsequent token frame from the same master, it shall accept the token frame and assumes that the logical ring has changed. In this case, it updates the original PS value by the new one and updates the LAS and the `Live List` (LL).

Figure C.3 illustrates the token reception procedure. A token frame is discarded when it is an erroneous frame or if it is not addressed to the `Master`. If the token frame is addressed to the `Master` and it does not contain bit errors, then the `Master` behaviour depends on the token frame transmitter (i.e., if the token frame `Source Address` (SA) is registered as its PS).

If the token frame transmitter is registered as its PS, it evolves to the USE_TOKEN state, calculates the `Token Holding Time` (T_{HT}) according to the Eq. 2.1, sets to false `GAP_Turn` variable and then the token reception procedure ends. Otherwise, the received token frame is discarded when a `Master` token frame sender is not its PS. However, if it receives a second token frame from the same `Master`, then it updates the original PS value with the new one and updates its LAS.

In the same way it evolves to the USE_TOKEN state, calculates the new T_{TH} sets to false the `GAP_Turn` variable and then the token reception procedure ends. According to the PROFIBUS DLL only one GAP Update procedure can be performed per token visit, the `GAP_Turn` variable is used to avoid that more than one GAP Update procedure is performed when a `Master` is holding the token frame.

The execution of the token reception procedure forces the execution of the message dispatching procedure described in the Section C.1.3.

C.1.3. Message Dispatching Procedure

Figure C.4 presents the message dispatching procedure when a `Master` holds the token frame. This procedure is repeatedly performed until the `Master` expires T_{TH} and the pass token procedure is executed.

At token frame reception, the period during which the `Master` is allowed to perform messages cycles (T_{TH}) is computed according to the Eq. 2.1.

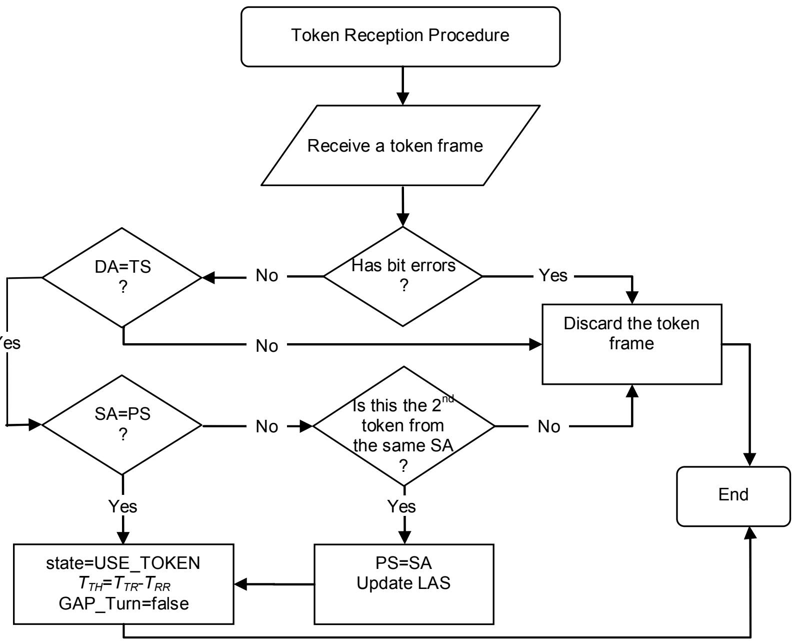


Figure C.3 – Token Reception procedure

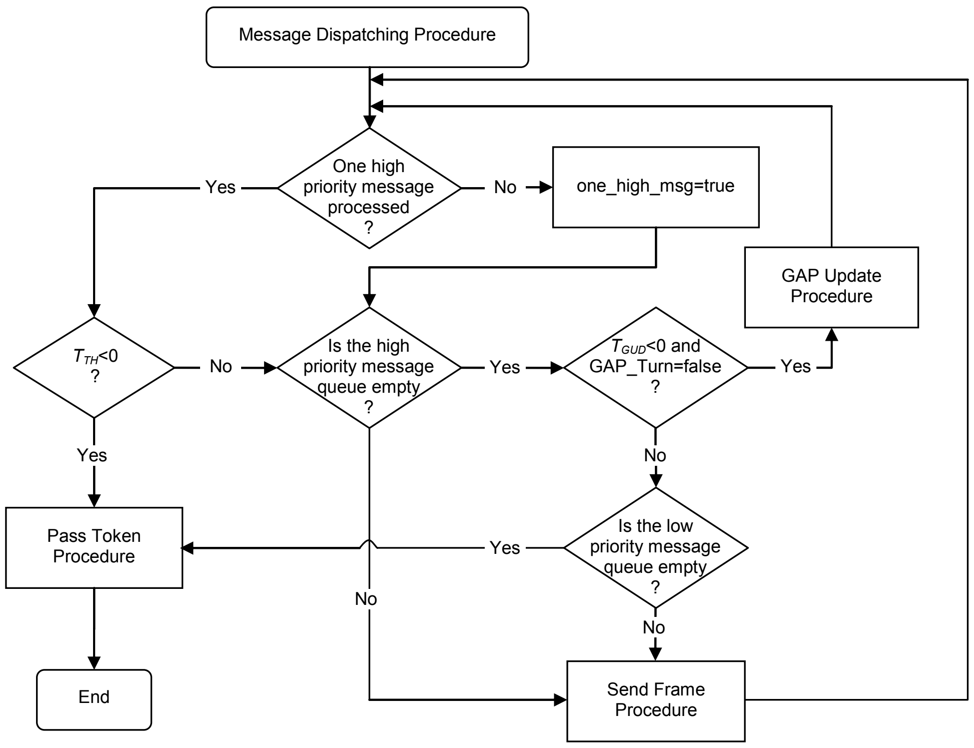

Message Dispatching Procedure
One high priority message processed ?
Yes
No
one_high_msg=true
GAP Update Procedure
$T_{TH}<0$?
No
Is the high priority message queue empty ?
Yes
$T_{GUD}<0$ and GAP_Turn=false ?
Yes
Yes
No
Pass Token Procedure
Yes
Is the low priority message queue empty ?
No
No
End
Send Frame Procedure

Figure C.4 – Message dispatching procedure

Independently of the T_{TH} value a `Master` is allowed to transmit at least one high priority message. After, high priority message will be processed while $T_{TH} > 0$. When there are no more high priority messages to dispatch then low priority messages and GAP update related messages can be transmitted.

The GAP update procedure is triggered when the `Gap Update Timer` (T_{GUD}) expires and the $T_{TH} > 0$. If $T_{TH} < 0$, the GAP update procedure is postponed for the next token holding period. However, only one GAP update procedure is performed per token visit.

It should be pointed out that once a high or low priority message cycle or GAP update procedure is started, it is always completed (it is not pre-empted), including any retry (or retries), even if $T_{TH} < 0$. When $T_{TH} < 0$ or when the output message queues are empties, the `Master` passes the token frame to another station.

In this section, a high level message dispatching mechanism was described. The pass token, send frame and GAP Update procedures are detailed in the following sections.

C.1.4. Pass Token Procedure

The PROFIBUS protocol defines that token frames are passed between masters in ascending MAC address order. The only exception is that to close the logical ring the master with the HSA must pass the token to the master with the lowest one. Each master knows the address of the PS, the address of the NS and its address (TS) as well.

When T_{TH} expires or when no more messages are available on the queues (low and high priority), a master passes the token frame. If, after transmitting the token frame and after the expiration of `Slot Time` (T_{SL}) timer the token transmitter detects bus activity, it assumes that its NS owns the token and is performing message cycles. Otherwise, if the token transmitter does not recognize any bus activity within the T_{SL}, it re-sends the token frame and waits another T_{SL}. It assumes that its NS owns the token frame thereafter, if it recognizes bus activity within the second T_{SL}.

If, after the second retry, there is no bus activity, the token transmitter tries to pass the token to the next master on its LAS. It continues repeating this procedure until it has found a successor from its LAS. If it does not succeed, the token transmitter assumes that it is the only one left in the logical ring and transmits the token frame to itself.

In order to detect a defective transceiver when a master is transmitting a token frame it reads back from medium all transmitted bits. If it detects a difference between the transmitted and received bits it waits T_{SL} for any activity from NS. If no activity is detected after expiring T_{SL}, it transmits again the token frame, if an error occurs, then it removes itself from the logical ring.

Figure C.5 depicts the token pass procedure. The first step is to evolve the `Master` from the USE_TOKEN state to the PASS_TOKEN state and sets the `retry_counter` variable to zero. After that, it builds the token frame addressed to its successor (NS) and transmits the token frame. If the token frame received is equal to the token frame transmitted then it evolves to the CHECK_TOKEN_PASS state. If after transmitting the token frame and before the expiration of the T_{SL}, the `Master` receives a frame, it assumes that its NS owns the token and that it is executing message cycles, and evolves to the ACTIVE_IDLE state. If the `Master` does not receive a frame within the T_{SL}, it returns to the PASS_TOKEN state and it repeats the transmission of the token frame (its state machine evolves again to the CHECK_TOKEN_PASS state) for the last time (`retry_counter` = `2`) and waits another T_{SL}. If it receives a frame within the second T_{SL}, it assumes a correct token frame transmission. Otherwise, it continues repeating this procedure until it has found a successor from its LAS (`getNS()`). If it does not succeed, it transmits the token frame to itself.

At the first time that the received token frame is different from the transmitted frame it transmits again the token frame. At the second time it evolves to the LISTEN_TOKEN state.

C.1.5. GAP Update Procedure

Each master in the logical ring is responsible for the addition and removal of masters that have addresses between TS and NS. This range of addresses in the logical ring is referred as GAP, whereas the list containing the status of all stations in the GAP is called `GAP List` (GAPL).

Each master in the logical ring examines its GAP periodically in the interval given by the T_{GUD} timer. Its expiration indicates the moment for GAP maintenance. GAP addresses are examined in ascending order, except the GAP addresses which surpasses the HSA, i.e., the HSA and address 0 are not used by a master station. In this case the procedure is continued at address 1 after checking the HSA. If a station acknowledges positively with the state `Not_Ready_to_Enter_Logical_Ring` or

Slave_Station, it is accordingly marked in the GAPL and the next address is checked. If a station answers with the state Ready_to_Enter_Logical_Ring, the token frame holder changes its GAPL and LAS accordingly, as well as its NS and passes the token frame to the new NS.

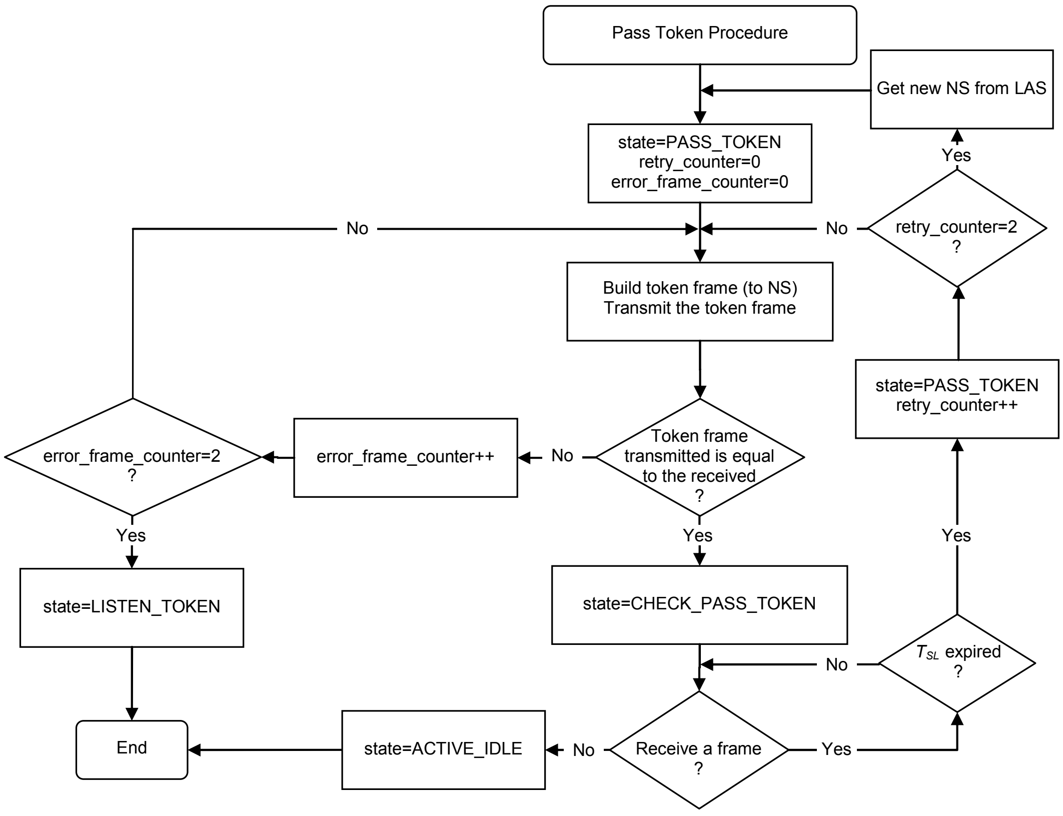


Figure C.5 – Pass Token Procedure

This is accomplished by examining at most one address per token cycle by means of sending an FDL_Request_Status once T_{GUD} has expired. After a complete GAP check, which may last several token rotations, the timer T_{GUD} is loaded with the value resulting from the multiplication of the T_{TR} by the GAP Update Factor (G). G represents the number of tokens rounds between GAP maintenance. Upon receiving the token, a GAP maintenance cycle starts immediately after all queued high priority message cycles have been processed and if there is still T_{TH} available. Otherwise, the GAP maintenance is postponed to the next token reception. Note that FDL_Request_Status messages have higher priority than low-priority messages used in PROFIBUS, but lower than high priority messages.

Send FDL_Request_Status Procedure

Figure C.6 presents the send FDL_Request_Status procedure. The first step is to evolve the Master state machine from the USE_TOKEN to the AWAIT_STATUS_RESPONSE state. After that, it builds the FDL_Request_Status frame addressed to the selected station and transmits it. Thereafter, it waits for a valid (without bit errors) response frame from the addressed station within the T_{SL}. If either T_{SL} expires or the received response frame is an invalid, the Master evolves to the USE_TOKEN state and then the procedure ends.

If a valid response frame was received from the addressed station the message is parsed. If the responder is a master and its state is Ready_to_Enter_Logical_Ring the Master changes the NS and updates the LAS and GAPL. Otherwise, it updates only the GAPL. In any cases, the Master evolves to the USE_TOKEN state.

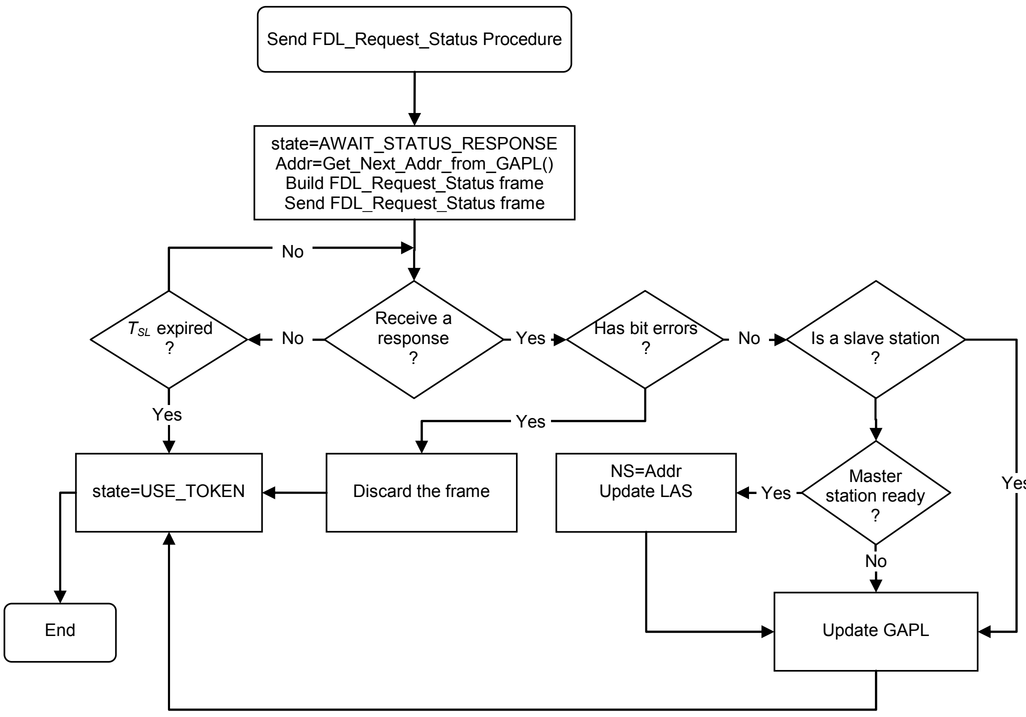


Figure C.6 – Send FDL_Request_Status procedure

Receive FDL_Request_Status Procedure

Figure C.7 presents the procedure when a station receives an `FDL_Request_Status` frame. The frame is discarded if it contains bit errors or if is not addressed to it. Otherwise, a response frame containing the state of the responder is transmitted. In spite of, PROFIBUS DLL defines three states in our simulator only two were implemented: `Slave_Station`, if it is a slave station, and `Ready_to_Enter_ Logical_Ring`, for the master stations.

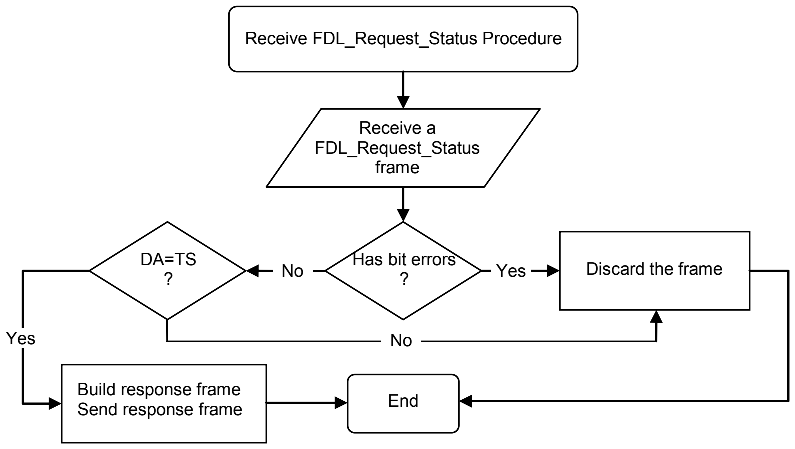


Figure C.7 – Receive FDL_Request_Status procedure

C.1.6. Send Frame Procedure

The PROFIBUS DLL protocol defines four data transfer services. The `Send Data with Acknowledge` (SDA) service, which allows an initiator to send a message and immediately receive the confirmation. The `Send Data with No Acknowledge` (SDN) is an unacknowledged service. The `Send and Request Data with Reply` (SRD) is based on a reciprocal connection between an initiator and a responder and requires either an acknowledgement or a response. The `Send and Request Data with Reply` (CSRD) is a cyclic service (based on the acyclic SRD). In this simulator only the SDN and SRD services were implemented. The SDA service was implemented based on SDR service, just by adequate the setting of the request and response frame sizes.

The `Msg_Stream` module emulates the behaviour of an AL protocol. Periodically it produces messages which are passed to the `Master_DLL` module in case of the RHW2PNetSim or `DLL` module in case of the BHW2PNetSim which stores the message in its output message queues as a function of the message priority.

When a `Master` has the right to access the medium, i.e., when it holds the token frame, it pops messages from its output message queues and it checks which service will be used. If it is a SDN, then after transmitting the message, it can schedule a new action according to the message dispatching procedure. Otherwise, it has to wait for the response or the T_{SL} expiration (Figure C.8).

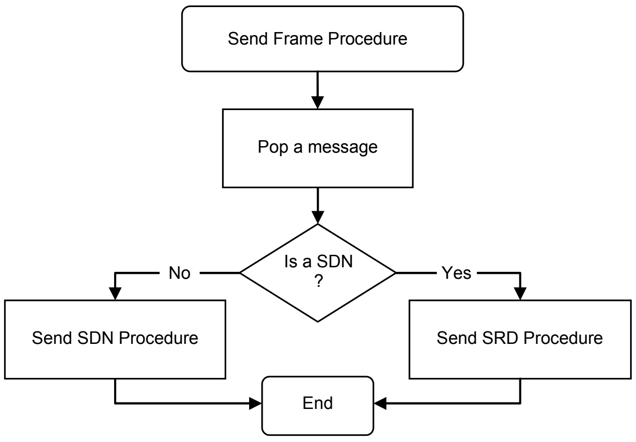


Figure C.8 – Send Frame Procedure

Send SDN Procedure

A SDN is an unacknowledged service, therefore when an initiator sends a SDN frame, it will not receive a response or acknowledge from the responder.

Figure C.9 illustrates a SDN transaction between a `Master` and a `Slave`. In a `Master`, the `Msg_Stream` emulates the behaviour of an AL protocol, periodically producing messages which are passed to the `Master_DLL`. The `Master_DLL` stores the message in its output message queues (high or low) according to the message priority. In a `Slave`, a `Msg_Stream` has a similar behaviour, but in this case, the `Slave_DLL` only refreshes the content of the variables modelled by the `Msg_Stream` module.

When a `Master` holds the token frame it processes messages cycles according to message dispatching procedure described in Section C.1.3. If a `Master` has messages in its output queues it pops a message, builds a frame, passes to the `Master_PHY` and then sends to the `Domain` module to which it is connected. The `Domain` broadcasts the frame to every `Master` and `Slave` connected to it.

The `Slave_PHY` receives the frame from `Domain` and passes to the `Slave_DLL`. The `Slave_DLL` matches the frame information (`Destination Address` (DA), SA `Destination Address Extension` (DAE) and `Source Address Extension` (SAE)) with its configured message streams. If it succeeds then it registers the information about this transaction for output analyses and discards the frame. Otherwise, the `Slave_DLL` discards the frame.

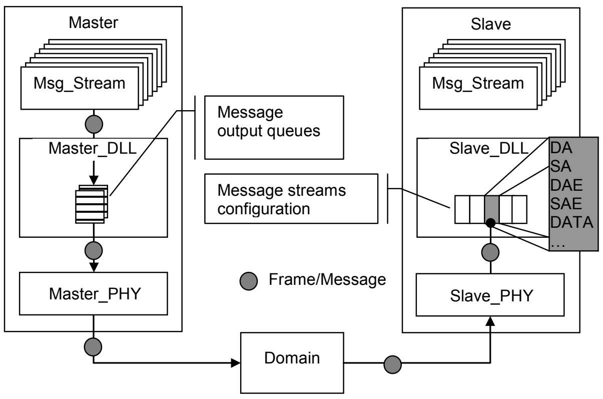


Figure C.9 – SDN transaction schema between master and slave

Figure C.10 presents the send SDN procedure. The `Master` pops a message from message output queues, builds a frame and then transmits it. Thereafter, `Master` waits T_{ID2} before performing another action according to the message dispatching procedure. Note that, it stays on the same state (USE_TOKEN).

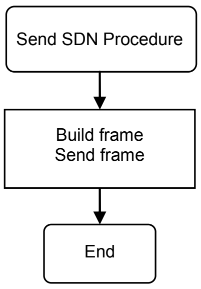


Figure C.10 – Send SDN Procedure

Receive SDN Procedure

Figure C.11 presents the receive SDN procedure. At frame reception the `Slave_DLL` starts by checking if it is a valid frame or not. The frame is discarded if it is an invalid frame. Otherwise, it checks if it is addressed to it or not (DA=TS). If not, the frame is discarded. If it is, the information about this transaction is stored for output analysis and the frame is discarded.

Send SRD Procedure

The SRD is based on a reciprocal connection between an initiator and a responder and requires either an acknowledgement or a response from the responder. Using this service, the initiator is able to send data in the request frame and receive data, from the addressed station, in the response frame.

Figure C.12 illustrates the transaction schema between a `Master` and a `Slave`. When a `Master` holds the token frame its `Master_DLL` pops a message from one of its message output queues, builds a frame and passes it to the `Master_PHY` which sends to the `Domain` to which it is connected. The `Domain` broadcasts the frame to every `Master` and `Slave` connected to it.

The `Slave_DLL` receives the frame from `Slave_PHY` and tries to determine if there is a match between the frame and a message stream configuration. If it finds a match, then it builds a response frame and passes it to the `Slave_PHY` that sends it to the initiator through the `Domain`, otherwise the frame is discarded. The `Domain` broadcasts the frame to all `Master` and `Slave` module instances connected to it. The `Master_PHY` passes the response frame to the `Master_DLL`. If it is the addressed to the `Master`, it stores the information about this transaction and then discards the frame. If is not addressed to it, then the frame is discarded.

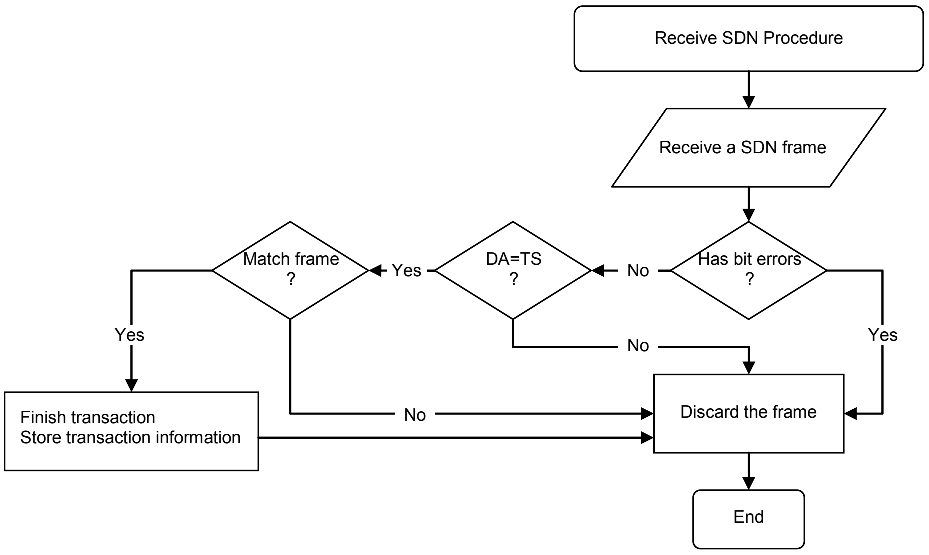


Figure C.11 – Receive SDN Procedure

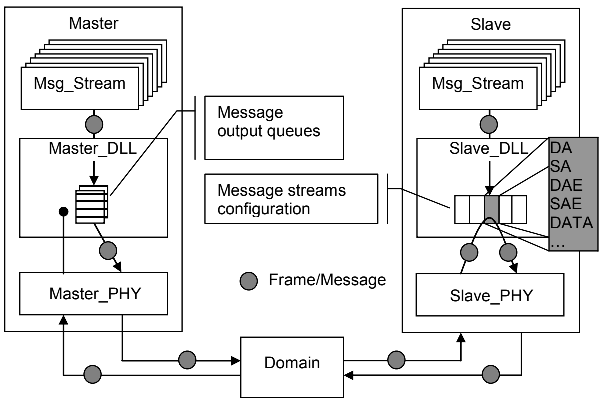


Figure C.12 – SRD transaction schema between Master and Slave

Figure C.13 presents the send SDR procedure. The first step is to evolve the `Master` state machine from the USE_TOKEN to the AWAIT_DATA_RESPONSE state and set the `retry_ counter` variable to zero.

After that, the `Master` pops a message from its message output queue, builds a frame and transmits it. After, it waits for the reception of a response frame. If an invalid response frame is received (with bit errors) then it is discarded and the `retry_counter` variable is increased. The `retry_counter` variable is also increased if no frame is received within the T_{SL}. When the `retry_counter` variable reaches the `max_retry_limit` (a `Master` parameter) limit then the `Master` state machine returns to the USE_TOKEN state.

Receive SRD Procedure

Figure C.14 presents the receive SRD procedure. The frame is discarded either if it is an invalid frame (with bit errors) or if it is not addressed to it (a master or a slave). Otherwise, if it is a valid frame addressed to the station, then it tries to find a match with one pre-configured message stream. If a match is found, then it builds a response frame using the value of the internal variable. After waiting T_{SDR}, it transmits the response frame.

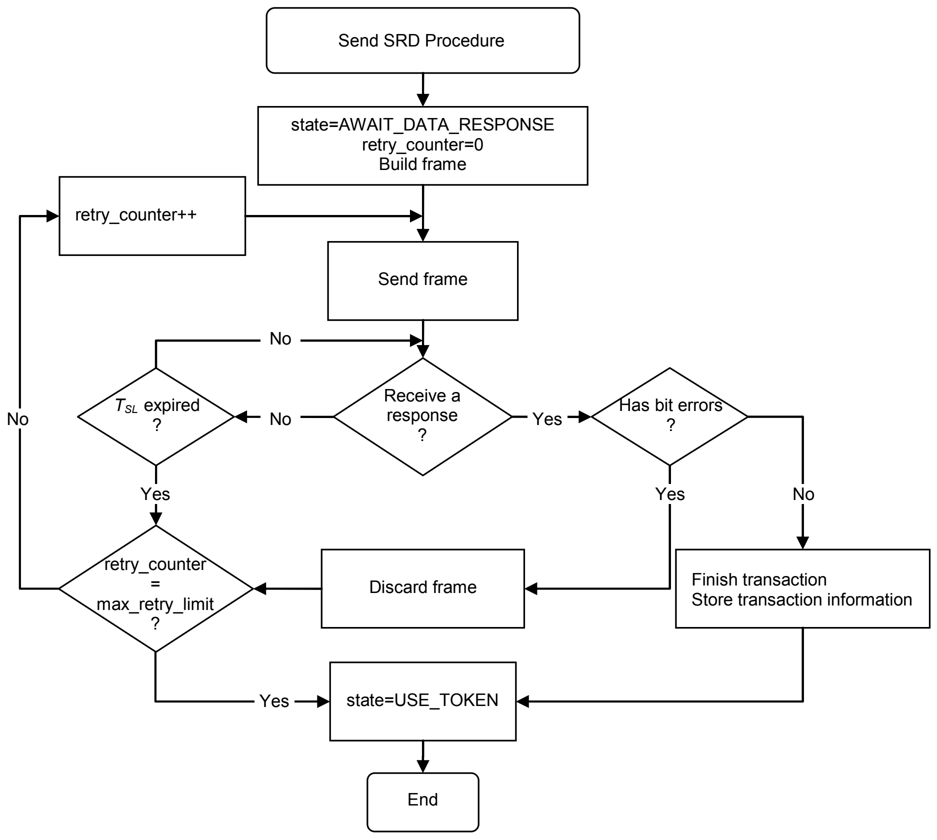


Figure C.13 – Send SRD Procedure

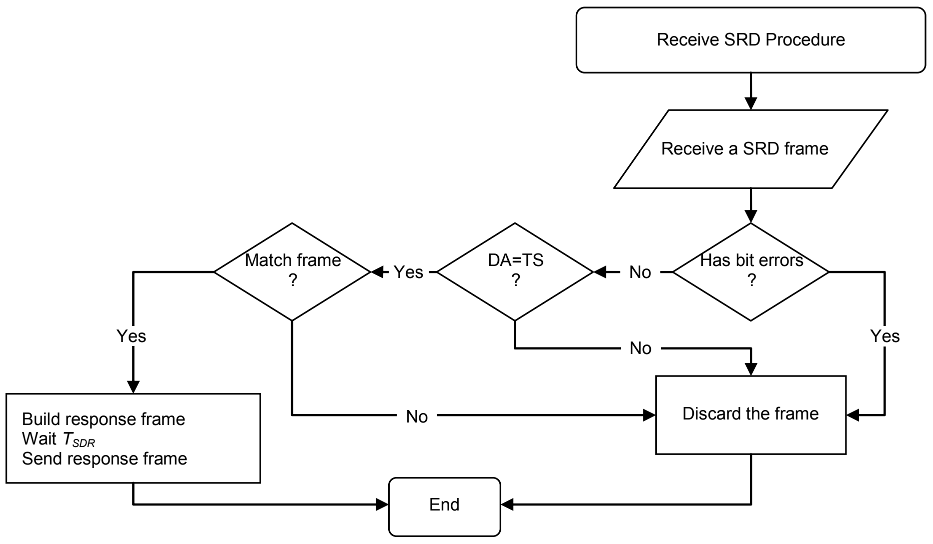


Figure C.14 –Receive SDR Procedure

C.2. Repeater-Based Hybrid Wired/Wireless PROFIBUS Architecture Simulator

Following are described the procedures that are specific of the Repeater-Based Hybrid Wired/Wireless Network Simulator. This section is a complement of the Section 6.3.

C.2.1. Send Beacon Procedure

Figure C.15 presents the send Beacon procedure. The first step is to set the `n_beacon_counter` variable equal to `n_beacon`, a BS parameter. After that, while `n_beacon_counter` variable is higher than zero, the BS waits T_{IDm}, builds a `Beacon` frame and then transmits the `Beacon` frame.

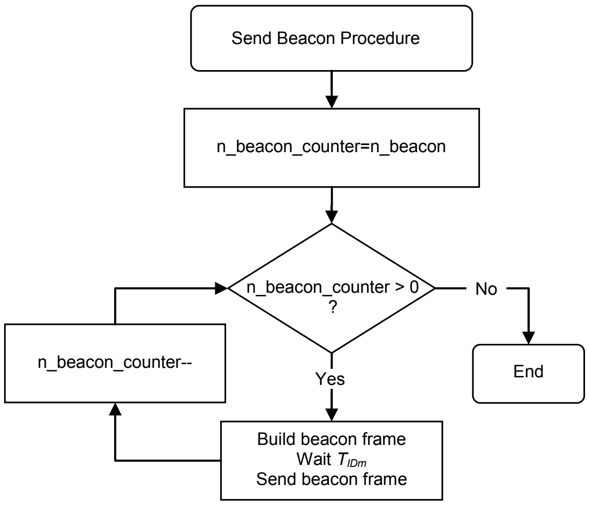


Figure C.15 – Send Beacon Procedure

C.2.2. Stations Mobility

In order to model the mobility of a station between domains, in the Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator (RHW2PNetSim), the `Connection_Point`, which is operating as a BS, at reception of the `Beacon Trigger` frame from the `Mobility Master` (MM), sends to the `Controller` (through `ctrl_con` connection) a message indicating that `Beacon` frames will be transmitted. After ending the transmission of the `Beacon` frames, according to the procedure described in C.2.1, they sends to the `Controller` a new message indicating that they finish the `Beacon` frames transmission.

The `Master` and `Slave` module instances which model wireless mobile stations, at reception of the `Beacon` frames, send to `Controller` (through `ctrl_con` connection) a message indicating which domain they want to change, according to their `_location_vector` parameter. The `Controller` manages this information in order to disconnect the `Master` or the `Slave` from `Domain` to which they are connected, and connect to the destination `Domain`. However, a `Master` or a `Slave` can only change to a domain where the `Beacon` frames were transmitted.

C.3. Bridge-Based Hybrid Wired/Wireless PROFIBUS Architecture Simulator

In this section are detailed the procedures specific of the BHW2PNetSim. These procedures are presented separately and are related to the state machine diagram transitions described in Section 7.4.

C.3.1. Inter-Domain Protocol

Receive Frame (from `Domain`) Procedure

Figure C.16 presents the procedure performed by a `BM` when it receives a frame from its `DLL` module instance. The `BM` starts by checking if the frame is addressed to a station in another domain using the `isRoute()` function, which consults its `Routing Table` (RT). If no match is found the frame is discarded. Otherwise the frame is processed.

Next, the `BM` verifies if the initiator of the transaction (through the SA of the frame) belongs to its domain. If it does not belong, it checks if it is a duplicate frame and if it is the frame is discarded. Otherwise, a SC frame is sent and the frame is forwarded to the other `BM` using the `ComFunc`.

If the frame sender belongs to the `BM` domain, there is the need to check the type of frame. If the kind of frame is a response frame (it means that this `BM` was the last BM in the transaction path – BM_{res}), an Inter-Domain Frame (IDF) is coded using the received frame and is forwarded to `ComFunc`. If the frame is a request frame (it means that this is the first BM in the transaction path – BM_{ini}) then it is necessary to check the service's type.

If it is not a SRD service (then it must be a SDN service) the frame is forwarded to `ComFunc`. Otherwise, if it is a SRD service, it matches the received frame with all entries in the `List of Open Transactions` (LOT). Each entry in LOT can be in one of two states: WAITING and FINALISED.

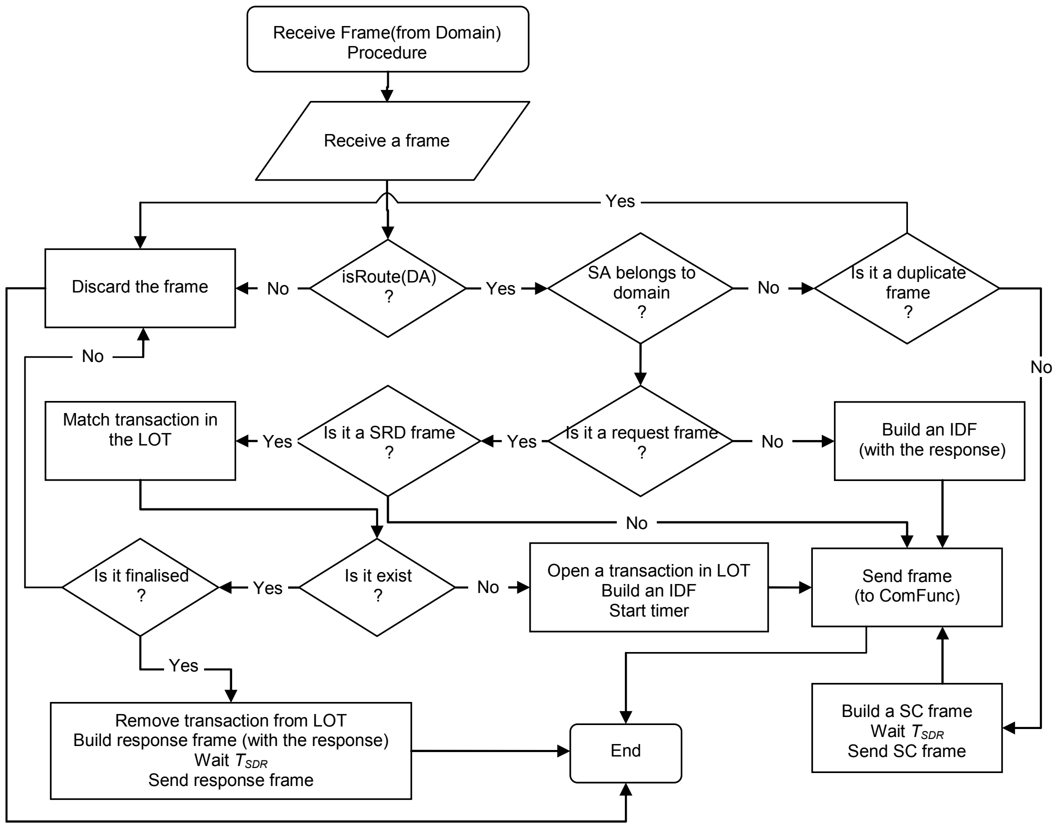

Receive Frame(from Domain) Procedure
Receive a frame
Yes
Discard the frame
No
isRoute(DA) ?
Yes
SA belongs to domain ?
No
Is it a duplicate frame ?
No
No
Match transaction in the LOT
Yes
Is it a SRD frame ?
Yes
Is it a request frame ?
No
Build an IDF (with the response)
No
Is it finalised ?
Yes
Is it exist ?
No
Open a transaction in LOT Build an IDF Start timer
Send frame (to ComFunc)
Yes
Remove transaction from LOT Build response frame (with the response) Wait T_{SDR} Send response frame
End
Build a SC frame Wait T_{SDR} Send SC frame

Figure C.16 – Receive Frame (from `Domain`) Procedure

A LOT entry is in the WAITING state since its creation until receiving a response. At reception of the related response frame the LOT entry changes to the FINALISED. It is deleted from LOT when the response frame is sent to initiator.

If there is no entry in the LOT associated with this request then a new entry is opened in the LOT and a timer loaded with the `_bm_idt_timer` parameter value is started. After that, an IDF is coded and sent to the `ComFunc`. If there is a match with another LOT entry the frame is discarded.

If there is a LOT entry with same parameters and its state is FINALISED, then a response frame is built and transmitted as a response to the initiator. After that, the associated entry is deleted from LOT.

Receive Frame (from ComFunc) Procedure

Figure C.17 shows the procedure when a `BM` receives a frame (an IDF) from the `ComFunc` (i.e., from the other BM of a bridge). The BM starts by consulting its RT, using the `isRoute()` function, to determine if the frame should be relayed or not.

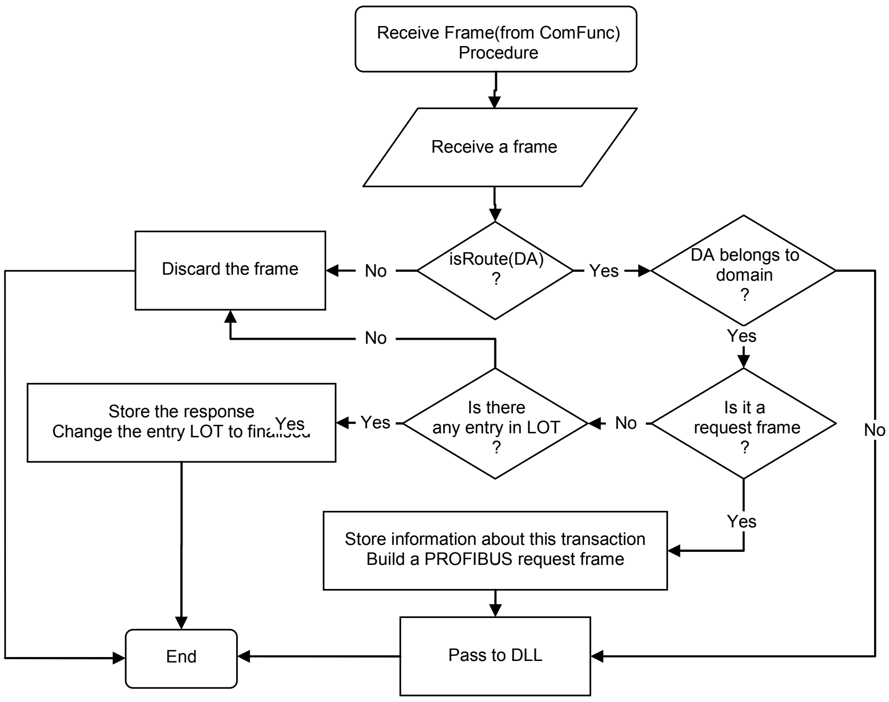

Receive Frame(from ComFunc) Procedure
Receive a frame
isRoute(DA) ?
Yes
No
Discard the frame
DA belongs to domain ?
Yes
No
Is there any entry in LOT ?
Yes
No
Is it a request frame ?
No
Yes
Store the response Change the entry LOT to finalised
Store information about this transaction Build a PROFIBUS request frame
Pass to DLL
End

Figure C.17 – Receive frame (from `ComFunc`) procedure

If the frame must be relayed, the `BM` verifies, using the DA frame field, if the addressed station belongs to its domain. If it does not belong then the `BM` queues the frame for transmission without changes. If it succeeds then this `BM` will act as either a BM_{ini} or a BM_{res}.

If it acts as BM_{ini} it checks in LOT for an entry related to this transaction, and if it succeeds then it changes the entry's state to finalised, stores the response frame and stops timer associated with this LOT entry. Otherwise, it discards the response frame.

If it acts as BM_{res}, the `BM` stores information about this transaction, which will enable it to code an IDF containing the response. The received IDF is decoded and queued in exactly in its original frame format (as transmitted by the transaction initiator).

Send IDF Procedure

Once the SDA service is only implemented to be used by IDP, then the SDA service is presented in this section as send IDF procedure (Figure C.18). This procedure is performed by `DLL` module instance of each `Master` module instance which is operating as BM. As mentioned the SDA service can be modelled using the SDR service.

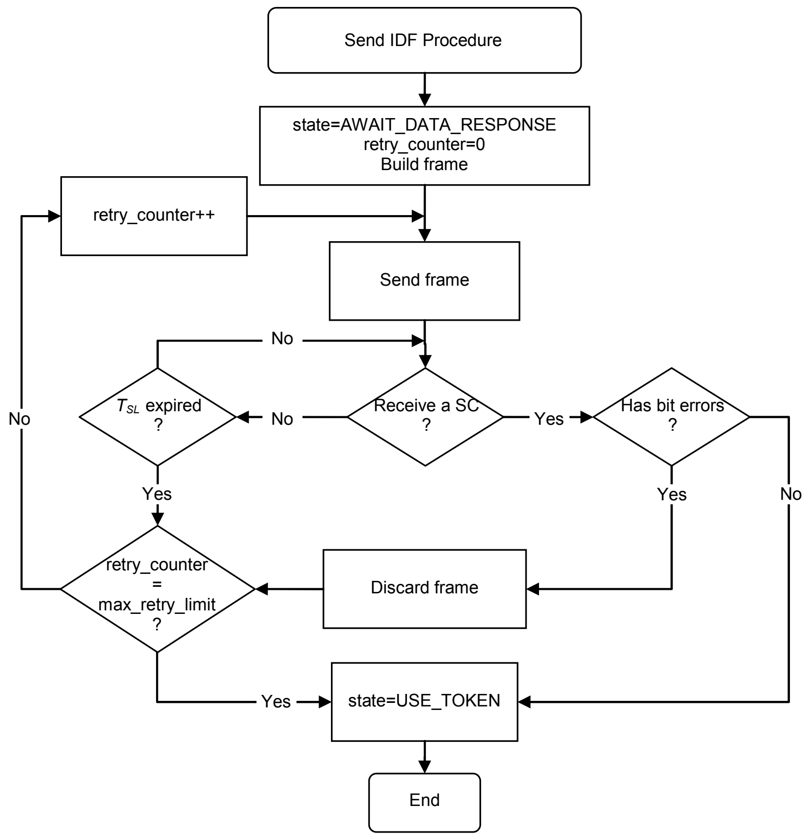


Figure C.18 – Send IDF Procedure

The first step is to evolve the Master state machine from the USE_TOKEN to the AWAIT_DATA_ RESPONSE state and set the retry_counter variable to zero. After that, the Master pops a message from its message output queue, builds a frame and transmits it. After, it waits for the reception of a SC frame. If an invalid SC frame is received (with bit errors) then it is discarded and the retry_counter variable is increased. The retry_counter variable is also increased if no frame is received within the T_{SL}. When the retry_counter variable reaches the max_retry_limit (a Master parameter) limit then the Master state machine evolves to the USE_TOKEN state.

C.3.2. Inter-Domain Mobility Procedure: Implementation

GMM Operation

In this Section we explain the operation of the GMM with the error handling mechanism described in Chapter 3. Figure C.19 presents the procedure that corresponds to Phase 1 of the IDMP. We assume that the GMM is configured prior to runtime with the List of Bridge Masters in the Network (LBMN) and the List of Domain Mobility Managers in the Network (LDMMN), which are the list of all BMs and a list of all DMMs present in the network, respectively. See Section 7.4.2 for more details.

In order to control from which BMs the GMM received a Ready_to_Start_Mobility_Procedure (RSMP) message a copy of the LBMN is used, the BMlist. After that it builds a Start_Mobility_ Procedure (SMP) message, starts the GMM_Phase_1_Alert_Timer ($T_{GMM\text{-}P1Alert}$) and the GMM_Phase _1_Abort_Timer ($T_{GMM\text{-}P1Abort}$) timers, sets the retry variable to false (which is used to control the retry of the SMP message), evolves to the WRSMP state and then passes the SMP message to the DLL.

After that, it waits for a RSMP message from the BMs in the network. Whenever it receives a RSMP message from a BM it removes the corresponding address (SA) from the list. It stays on this state until receiving a RSMP form all BMs in network, i.e., until the list of BM address is empty.

Meanwhile if the $T_{GMM\text{-}P1Alert}$ expires, it sends again a SMP message and continues waiting for the RSMP from the BMs. However, if $T_{GMM\text{-}P1Abort}$ expires, the GMM aborts the IDMP and then evolves to the INACTIVE state.

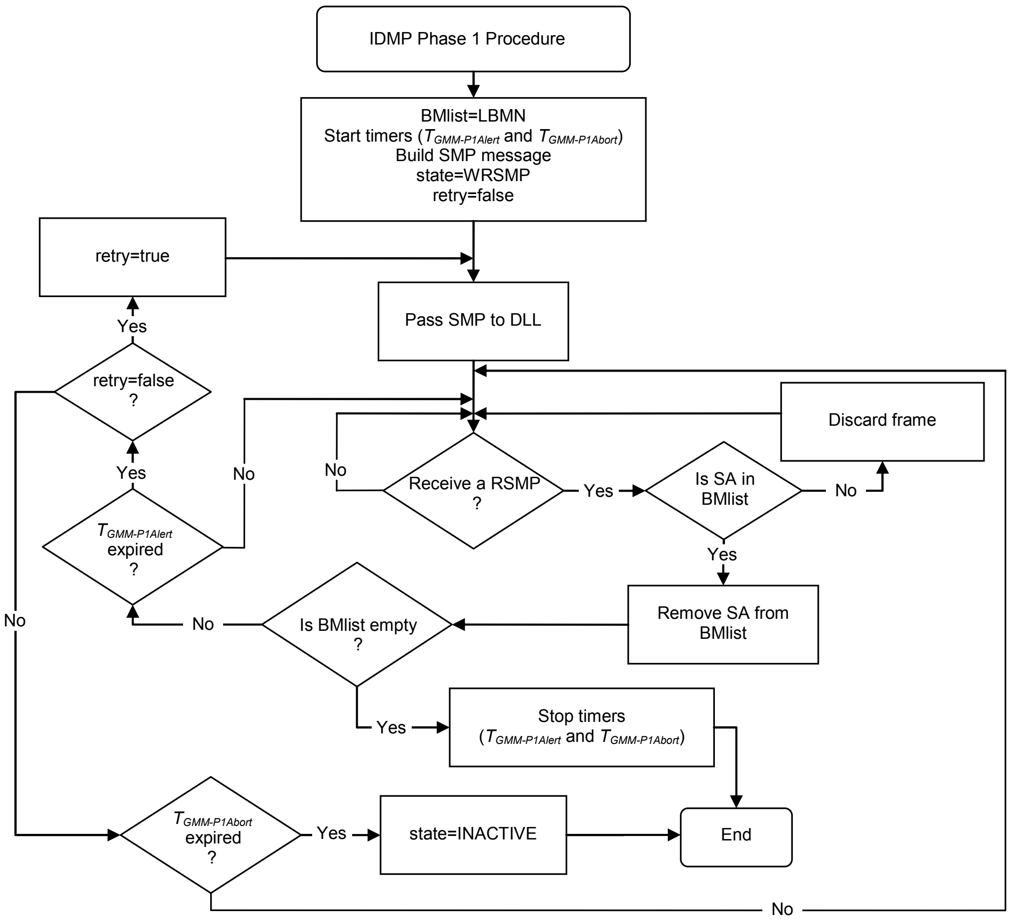


Figure C.19 – IDMP Phase 1 procedure

Figure C.20 presents the IDMP Phase 2 procedure. This procedure is similar to the previous, but now the GMM sends a `Prepare_for_Beacon_Transmission` (PBT) message to all DMMs in the network, and they should reply to the GMM using a `Ready_for_Beacon_Transmission` (RBT) message when they are holding the token frame. The reception of the RBT message from a DMM means that it is operating in inquiry mode.

In order to start the IDMP Phase 2, the GMM builds a PBT message, starts the `GMM_Phase_2_Alert_Timer` ($T_{GMM\text{-}P2Alert}$) and the `GMM_Phase_2_Abort_Timer` ($T_{GMM\text{-}P2Abort}$) timers, sets the `retry` variable to false (which is used to control the retry of the PBT message), evolves to the WRBT state and it sends the PBT message to the DLL.

After that, it waits for a RBT message from each DMM in the network. Whenever it receives a RBT message from a DMM it removes the corresponding `Source Address` (SA) of the DMM from the list. It stays on this state until receiving a RBT from all DMMs in the network, i.e., until the list of DMM address is empty. Meanwhile if the $T_{GMM\text{-}P2Alert}$ expires, the GMM retransmits a PBT message and continues waiting for RBT messages from remaining DMMs. However, if $T_{GMM\text{-}P2Abort}$ expires the GMM aborts the IDMP and evolves to the INACTIVE state.

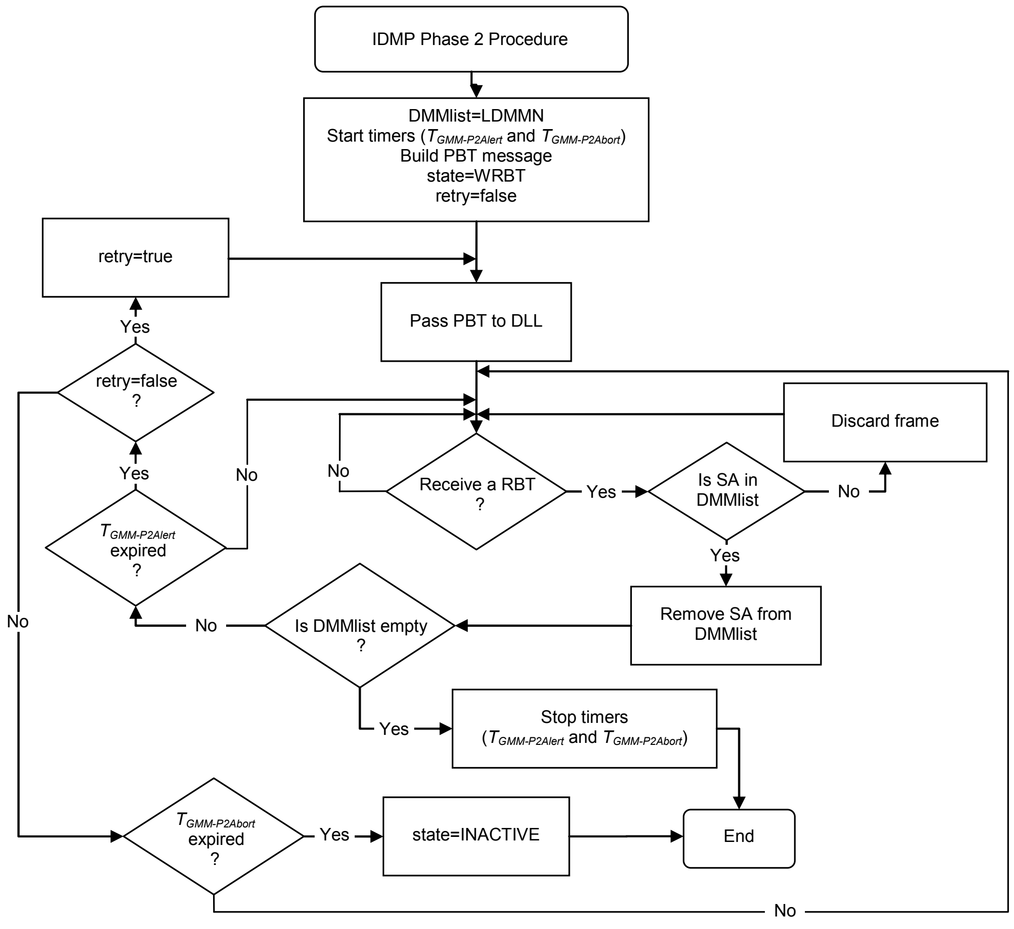


Figure C.20 – IDMP Phase 2 procedure

When the `GMM` receives a RBT from all `DMM`s in the network it builds a SBT message and passes the `Start_Beacon_Transmission` (SBT) message to the `DLL`. This message commands the `DMM`s to start emitting `Beacon` frames. After, the `GMM` evolves to the INACTIVE state. The remaining actions of the IDMP are controlled independently by the `DMM`s in each domain.

BM Operation

A received message is catalogued by a `BM` according to the frame format (described in Chapter 2). If it is an IDMP-related message, then it is handled by the `handleIDMPMessage(msg)` function presented in Figure C.21.

A received message is passed to the `DLL` (using the `passToDLL(msg)` function) if it is received from `ComFunc` (through `bridge_gateIn` gate). Otherwise, if a message is received from the `DLL` it is only forwarded to `ComFunc` (by `sendToComFunc(msg)` function) if the addressed station (line 6) can be reached by forwarding the message through the other `BM`. In any case the message will be processed by `processIDMPmessage(msg)` function (Figure C.22).

```
handleIDMPMessage(msg)
{
if msgArrivalGate(msg)=bridge_gateIn then
      passToDLL(msg);
else
      if isRoute(msg.getDA()) then
            sendToComFunc(msg);
processIDMPmessage(msg);
}
```

Figure C.21 – `handleIDMPMessage(msg)` function, pseudo-code algorithm

```
1.  processIDMPmessage(msg)
2.  {
3.  switch(state){
4.        case INACTIVE:
5.              switch(msgKind(msg)){
6.                    case SMP:
7.                          startIDMPerrortimer();
8.                          if isLOTempty() then {
9.                                processRSMPmessage();
10.                               state=WINQUIRY;
11.                         }
12.                         else
13.                               state=WIDT_END;
14.                         end;
15.                   case RU:
16.                               updateRT(msg);
17.                   end;
18.             }
19.       end;
20.       case WIDT_END:
21.             if msgKind(msg)=SMP and isLOTempty() then {
22.                   processRSMPmessage();
23.                   state=WINQUIRY;
24.             }
25.       end;
26.       case WINQUIRY:
27.             switch(msgKind(msg)){
28.                   case SMP:
29.                         processRSMPmessage();
30.                   end;
31.                   case PBT:
32.                         clearWirelessMobileAddrFromRT();
33.                   end;
34.                   case SBT:
35.                         stopIDMPtimer();
36.                         state=INACTIVE;
37.                   end;
38.                   case IQ_REQ:
39.                         sendCommandToDLL();
40.                   end;
41.                   case RU:
42.                         updateRT(msg);
43.                   end;
44.             }
45.       end;
46.   }
47. }
```

Figure C.22 – `processIDMPmessage(msg)` function, pseudo-code algorithm

The behaviour of the `BM` operation executed by the `processIDMPmessage(msg)` function depends on the `BM` state and the type of the IDMP message received.

If the `BM` is in the INACTIVE state, then only SMP or RU messages are processed. The `BM` RT is updated when it receives a `Route_Update` (RU) message independently of the `BM` state. If it is a SMP message, `BM_IDMP_Abort_ Timer` ($T_{BM\text{-}IDMPAbort}$) is loaded with the `_bm_idmp_abort_timer` parameter value and is started using `startIDMPerrortimer()` function (line 7). According to its LOT, the `BM` can evolve to either the WIDT_END state, if the LOT is not empty, or to the WINQUIRY state, if the LOT is empty. It stays in the WIDT_END state until all pending transaction are finalised. When the LOT is empty the `BM` evolves to the WINQUIRY state.

The `processRSMPmessage()` function (Figure C.23) is called whenever a SMP message is received and the LOT is empty. This function builds a RSMP message, which can be forward to the other `BM` of the bridge or queued in its own `DLL`.

When a `BM` is in the WINQUIRY state the `DMM` controls the message cycles of its domain and a `BM` only responds to `Inquiry` request (IQ_REQ) message from its `DMM`. When a `BM` receives the IQ_REQ message from its `DMM`, it commands its `DLL` to send IDMP-related messages. If there is any IDMP-related message in the output queue then these messages, otherwise it does not respond. In this way all IDMP-related message are relayed during inquiry sub-phase.

```
processRSMPmessage()
{
msg=buildIDMPmessage(RSMP,addr_gmm,TS);
if isRoute(msg) then
      sendToComFunc(msg);
else
      sendToDLL(msg);
}
```

Figure C.23 – `processRSMPmessage()` function, pseudo-code algorithm

When a `BM` receives the PBT message it clears all entries related to wireless mobile stations (using the `clearWirelessMobileAddrFromRT()` function) from the RT. At the reception of the PBT message a `BM` stops the $T_{BM\text{-}IDMPAbort}$ and enters into the INACTIVE state. From this point, forward the `BM` is capable of relaying IDTs, except for the ones related to wireless mobile stations.

As mentioned in Chapter 3, all LOT entries have an associated timers (`BM_IDT_Abort_Timer` ($T_{BM\text{-}IDTAbort}$)), that is used to avoid endless IDTs. When either of the timer $T_{BM\text{-}IDTAbort}$ or the $T_{BM\text{-}IDMPAbort}$ expires the `handleTimers(msg)` function (see Figure C.23) is automatically invoked. If it is a timer related to the LOT entry (`IDT_TIMEOUT` action (line 6)) its correspondent entry is deleted. If the LOT is empty and the `BM` is in the WIDT_END state then the `processRSMPmessage()` function is called and the `BM` evolves to the WINQUIRY state.

In order to recover from IDMP errors the `BMs` are provided with the $T_{BM\text{-}IDMPAbort}$. When this timer expires (`IDMP_TIMEOUT` action (line 9)) a `BM` evolves to the INACTIVE state and the IDMP ends.

```
1.  handleTimers(msg)
2.  {
3.  switch (getAction(msg)) {
4.        case IDT_TIMEOUT:
5.                  removeEntryFromLOT(msg);
6.                  if state=WIDT_END and isLOTempty()then
7.                            processRSMPmessage();
8.        end;
9.        case IDMP_TIMEOUT:
10.                 state=INACTIVE;
11.       end;
12. }
13. }
```

Figure C.24 – `handleTimers(msg)` function, pseudo-code algorithm

DMM Operation

Figure C.25 presents the pseudo-code algorithm of the `dllReceiveToken()` function which is called by the `DLL` whenever its `Master` acts as a `DMM` at the token reception. The `dllholdtoken` variable is set to true and if the `DMM` is in the WTOKEN state (that means it has already received a SMP message), then the `DMM` evolves to the INQUIRY state and the `processRBTmessage()` is called (Figure C.26).

```
dllReceiveToken()
{
dllholdtoken=true;
if state=WTOKEN then{
      state=INQUIRY;
      processRBTmessage();
}
}
```

Figure C.25 – `dllReceiveToken()` function, pseudo-code algorithm

The `processRBTmessage()` function builds a RBT message and sends it to the `DLL`. If this `Master` is also acting as a `BM` then the `DLL` forwards the message to it. The `BM` forwards the RBT message to `ComFunc` module instance connected to it or passes the RBT message to the `DLL` (according to the routing information).

```
processRBTmessage()
{
msg=buildIDMPmessage(RBT,addr_gmm,TS);
passToDLL(msg);
}
```

Figure C.26 – `processRBTmessage()` function, pseudo-code algorithm

When a `DMM` receives an IDMP-related message, the `processIDMPmessage(msg)` function is automatically invoked. The pseudo-code algorithm depicted in Figure C.27 is only related to the reception of the PBT message. Depending on the `DMM` state the actions triggered by the PBT reception are different.

```
processIDMPmessage(msg)
{
switch(state){
      case INACTIVE:
            switch(msgKind(msg)){
                  case PBT:
                        startIDMPaborttimer();
                        if dllholdtoken=true then {
                              state=INQUIRY;
                              processRBTmessage();
                        }
                        else
                              state=WTOKEN;
                  end;
                  …
            }
      end;
      case WTOKEN:
      end;
      case INQUIRY:
            switch(msgKind(msg)){
                  case PBT:
                        processRBTmessage();
                  end;
                  …
            }
      end;
      …
 }
}
```

Figure C.27 – `processIDMPmessage(msg)` function, pseudo-code algorithm

If it is in the INACTIVE state the `DMM_IDMP_Abort_Timer` ($T_{DMM\text{-}IDMPAbort}$) is loaded with `_dmm_ idmp_abort_timer` parameter value and is started (by the invocation of the `startIDMPaborttimer()` function). Then, if its `DLL` is holding the token it evolves to the INQUIRY state and the `processRBTmessage()` function is called. Otherwise, the `DMM` evolves to the WTOKEN state. When another PBT message is received and if the `DMM` is in the INQUIRY state the `processRBTmessage()` function is called again (i.e., a new RBT is sent). If the `DMM` is in the WTOKEN state then no action is taken.

When $T_{DMM\text{-}IDMPAbort}$ expires the `handleTimer(msg)` function (see Figure C.28) is automatically invoked and it evolves to the INACTIVE state from any other state.

```
handleTimer(msg)
{
switch (getAction(msg)) {
      case IDMP_TIMEOUT:
                  dllholdtoken=false;
                  state=INACTIVE;
                  …
      end;
 }
}
```

Figure C.28 – `handleTimer(msg)` function, pseudo-code algorithm

When a `DMM` is in the INQUIRY state, the relaying of the IDMP-related messages is ensured by transmitting IQ_REQ messages to the `BMs` belonging to its domain (Figure C.29). The goal of this message is to allow the `BMs` to perform the relaying of IDMP-related messages to the `GMM` or broadcast by `GMM`. For that purpose, the `DMM` selects a `BM` which belongs to its domain, builds an IQ_REQ message and passes it to DLL. After that, it waits for the DLL notification before processing a new message. Meanwhile, the DLL sends an IQ_REQ message and informs the DMM if it received a response or if the T_{SL} expired. During this process the DMM can receive a SBT message and it sets variable `sbt_rcv` to true. After ending the current IQ_REQ message processing, the IDMP Phase 2 ends and $T_{DMM\text{-}IDMPAbort}$ is stopped. If DMM's domain is a wired domain then the IDMP ends and its state machine evolves to the INACTIVE state. After, the message dispatching procedure presented in Section C.1.3 is performed. Otherwise, it evolves to the BEACON_TX state and the IDMP Phase 3 begins.

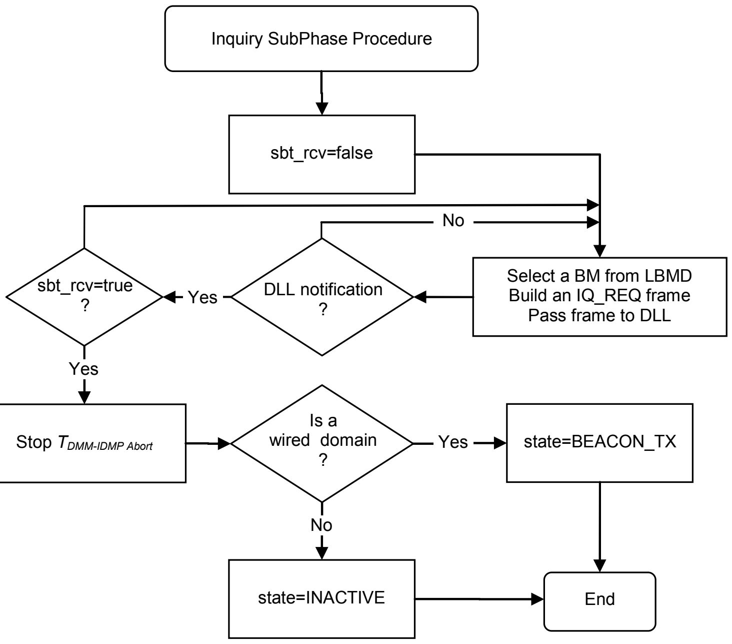


Figure C.29 – Inquiry SubPhase Procedure (Phase 2)

The GMM starts the Phase 3 by issuing a SBT message, but the remainder of this phase is commanded by the DMMs in the wireless domains. For the wired domains the IDMP ends and the message dispatching procedure presented in Section C.1.3 is performed. The `Beacon` messages are used by the wireless mobile stations to evaluate the quality of adjacent radio channels. The DMM sends a pre-defined number of `Beacon` messages. Figure C.30 presents the send Beacon procedure.

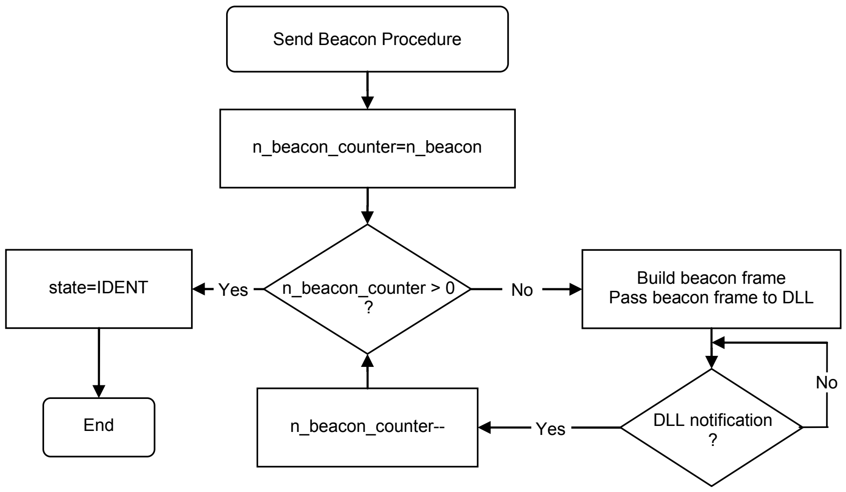
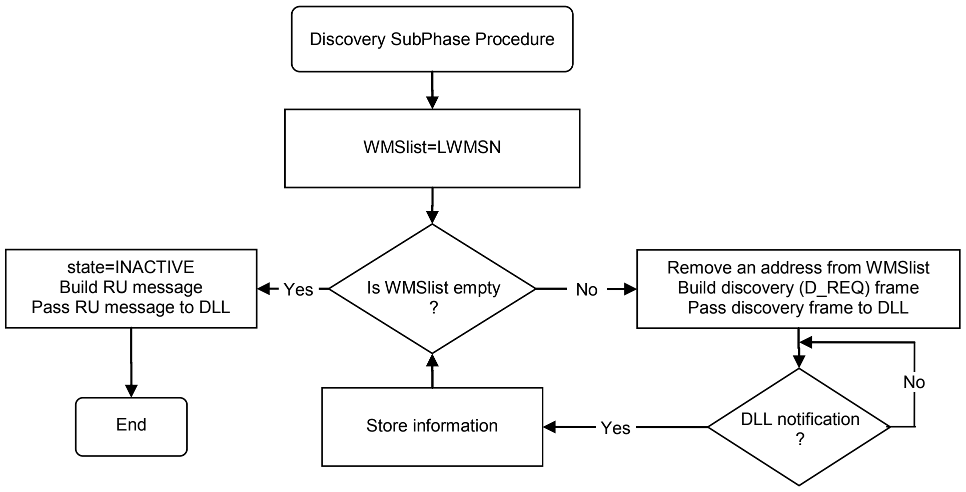


Figure C.30 – Send Beacon Procedure (Phase 3)

During Phase 4, the DMMs of the wireless domains try to detect which wireless mobile stations are present in their domains. Every DMM knows the addresses of all the wireless mobile stations belonging to the network (LWMSN). And for each of them transmits a `Discovery` message (D_REQ) using the DLL services. After sending, the D_REQ message the DLL informs the DMM with the result, which can be the reception of a response or the T_{SL} expiration. The DMM collects this information and after all D_REQ messages have been processed it broadcasts a RU message containing the addresses of the wireless mobile stations in its domain. The IDMP ends and the DMM evolves to the INACTIVE state. Figure C.31 presents the Send Discovery Procedure.



Discovery SubPhase Procedure
WMSlist=LWMSN
Is WMSlist empty ?
Yes
No
state=INACTIVE Build RU message Pass RU message to DLL
Remove an address from WMSlist Build discovery (D_REQ) frame Pass discovery frame to DLL
DLL notification ?
No
Yes
Store information
End

Figure C.31 –Discovery SubPhase Procedure (phase 4)

Station Mobility

In order to model the mobility of station between domains, in the BHW2PNetSim, the DMM of the wireless domains also operates as a BS. At reception of the SBT message from GMM sends to the `Controller` (through the `ctrl_con` connection) a message indicating that it is starting to transmit `Beacon` frames and sends another message to indicate the end `Beacon` message transmission.

Wireless mobile stations at reception of `Beacon` frames send to the `Controller` (through the `ctrl_con` connection) a message indicating to which domain they want to change, according to their `_location_vector` parameter (see Section 6.2.3). The `Controller` manages this information in order to disconnect the `Master` and `Slave` from the `Domain` to which they are connected, and connect them to the destination `Domain`. However, a `Master` or a `Slave` can only change to a `Domain` where Phase 3 has taken place.

DLL Operation

As mentioned the DLL must support additional functionalities. In order to perform the mobility procedure, when the DLL state machine is in the ACTIVE_IDLE or the USE_TOKEN state after the execution of any tasks it must check if this station acts as a DMM. If it does succeed, in which the state DMM is, more precisely if it is not in INACTIVE state (Figure C.32).

Figure C.33 presents the DLL mobility procedure. All IDMP-related messages are transmitted as high priority messages. Therefore, whenever there are IDMP-related messages into the output queues, the DLL sends them. Its state machine evolves according to the message's type or to the DMM state machine. Therefore, it has to check the message type and in the case of being an IQ_REQ message the DLL evolves to the WAIT_INQUIRY_RESPONSE state. After that, it waits for a valid frame or for the expiration of the T_{SL} and changes to the INQUIRY_MODE state. Similarly, if the message is a D_REQ the DLL evolves to the AWAIT_DISCOVERY_RESPONSE state and waits for a response or for the expiration of the T_{SL} timer and changes to the DISCOVERY state.

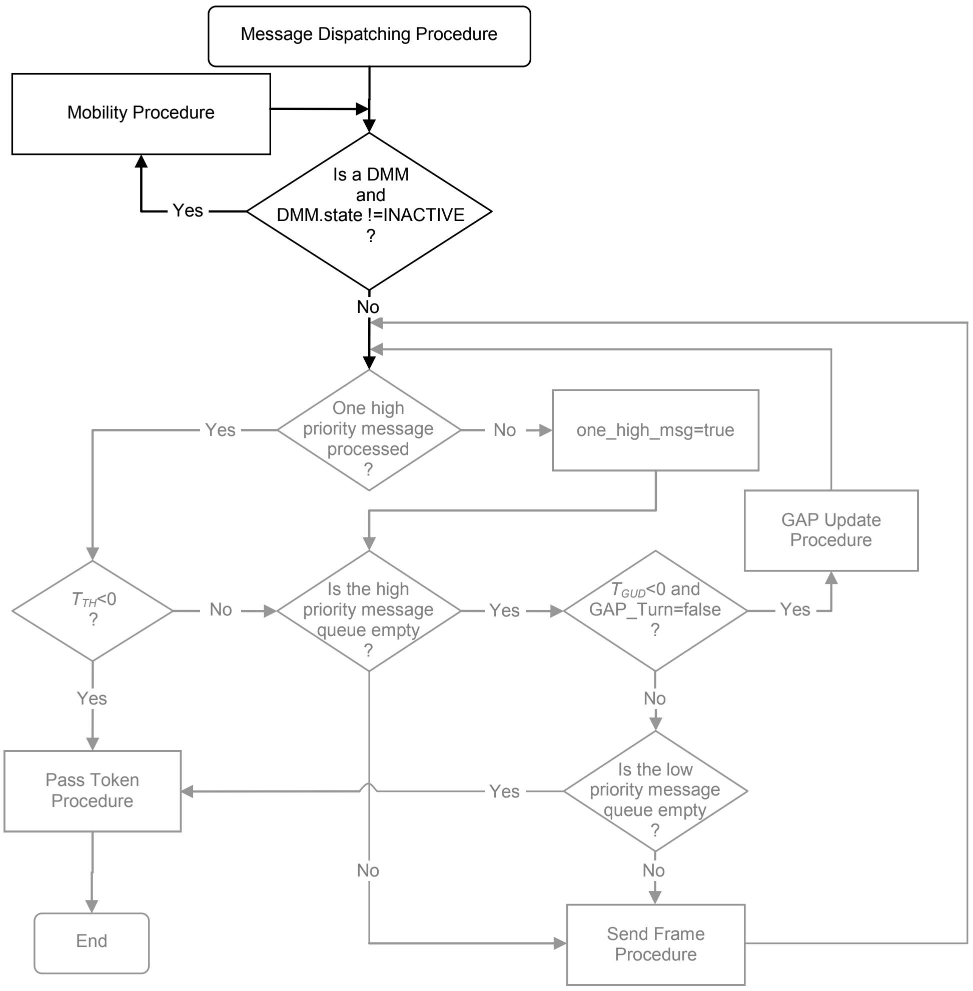

Message Dispatching Procedure
Mobility Procedure
Is a DMM and DMM.state !=INACTIVE ?
Yes
No
One high priority message processed ?
Yes
No
one_high_msg=true
GAP Update Procedure
T_{TH}<0 ?
No
Is the high priority message queue empty ?
Yes
T_{GUD}<0 and GAP_Turn=false ?
Yes
Yes
No
Pass Token Procedure
Yes
Is the low priority message queue empty ?
No
No
End
Send Frame Procedure

Figure C.32 – Message dispatching procedure (IDMP)

Whenever a message is received or T_{SL} timer expires, the DMM is notified about this. If a message is received it is passed to the DMM. If it is neither an IQ_REQ nor a D_REQ messages the DLL simply sends the frame. The evolution of the DLL state machine related with the INQUIRY_MODE, DISCOVERY and BEACONT_TX states is controlled by the DMM.

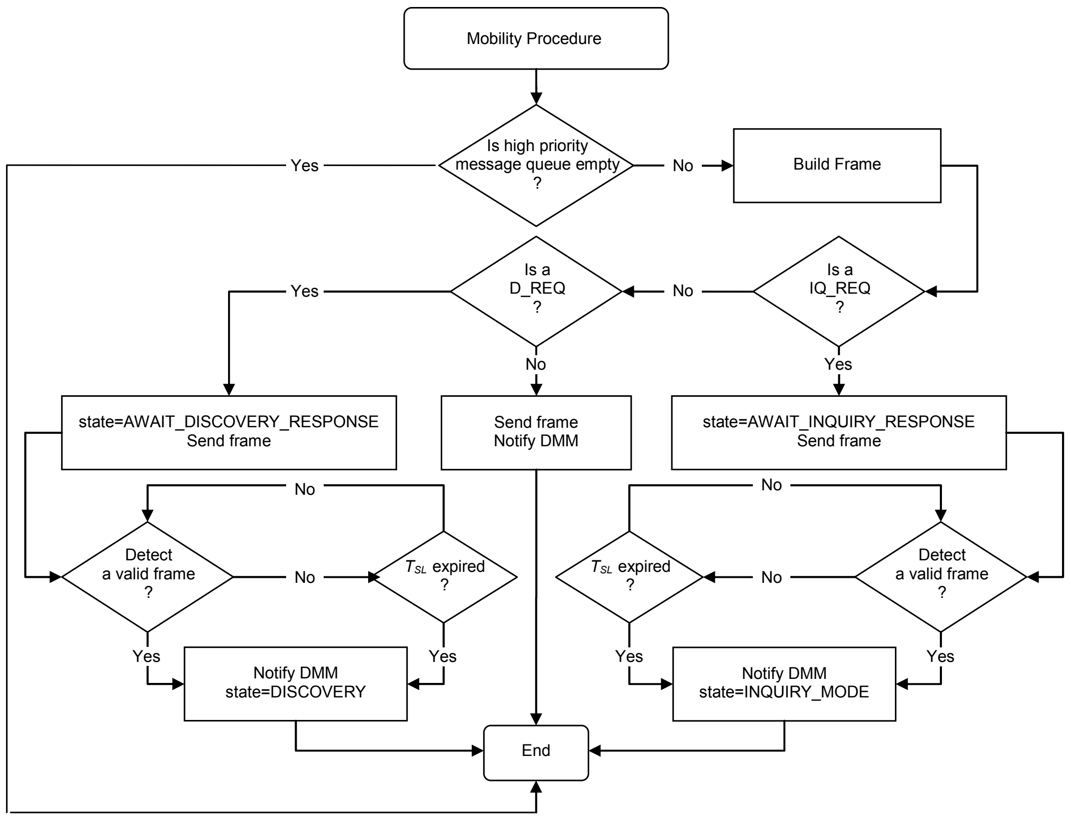


Figure C.33 – Mobility procedure

Annex D

Tools for Simulation Output Analysis

This annex presents a description of the output data files and the tools which support the analysis of the output data files generated by the Repeater-Based Hybrid Wired/Wireless Network Simulator and the Bridge-Based Hybrid Wired/Wireless Network Simulator.

D.1. Introduction

Output data analysis is the examination of the data generated by a simulator and this examination has two purposes. Firstly, it is used to verify and validate the simulator and its simulation model. Secondly, it is used for testing, evaluating the performance of different scenarios and different systems configurations. Additionally, when the input variables are random values, the output data exhibits random variability. Therefore, the output data is used to estimate the confidence level, or to determine the number of observation required to achieve a desired precision.

The objective of this annex is to present and describe the information produced by the RHW2PNetSim and by the BHW2PNetSim. It describes the output data files generated by both simulators from which it is possible to extract results. To help on the analysis of the results some specific tools have been developed: The Timeline Visualization Tool and a Microsoft Excel-based tool to output data analyse.

D.2. Timeline Visualisation Tool

Figure D.1 shows a screenshot of the Timeline Visualisation Tool which provides a way to show the network events using Gant Diagrams. This tool was developed using Microsoft Foundation Classes (MFC) (Prosise, 1999) and C++ programming language. This figure depicts a diagram drew using the data files generated by BHW2PNetSim concerning the network scenario presented in Figure 9.2. In this figure it is possible to see the events accomplished by each module instance. When a `Master` module instance operates also as BM the events related to `BM` module instance are separately shown. On the other hand, the events accomplished by a bridge are also separated by each `BM` module instance that composes it. For example, Figure D.1.shows that the bridge B3 is composed by BMs M7 and M10, thus the events of each `BM` module instance (BM_M7 and BM_M10) that composes a bridge are individually shown.

To illustrate the importance of this tool, in Figure D.1 three transactions are highlighted using arrows: one IADT (between master M1 and slave S1) and two IDTs (between master M2 and slave S6 and master M1 and slave S5).

The transaction between master M2 and slave S6 can be surprising, since this transaction is an IDT and it finishes during the first AL request of this transaction. This happen because when master M2 sends the request, an open a transaction is created by BM M7 and when master M2 finishes the retry BM M7 already has received the response frame from the responder. One of the factors that cause this situation is related to the difference between the bit rates of domain D^4 (0.5 Mbits/s), to which master M2 belongs, and domain D^3 (2 Mbits/s), to which slave S6 belongs.

This tool was also of paramount importance for debugging and validating of the both simulation models, since it provides a temporal overview of the network events. Further, it is possible to check the characteristics of all events by a double click on the event object. Figure D.2 shows a screenshot of this feature using output data files generated by RHW2PNetSim concerning the network scenario presented in Figure D.1. In this figure a message box shows the information related to the indicated event.

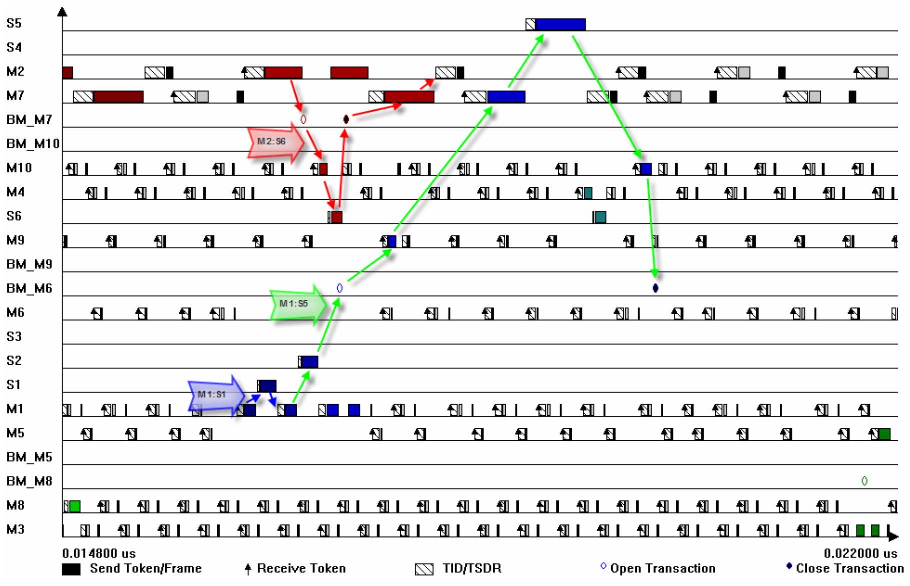
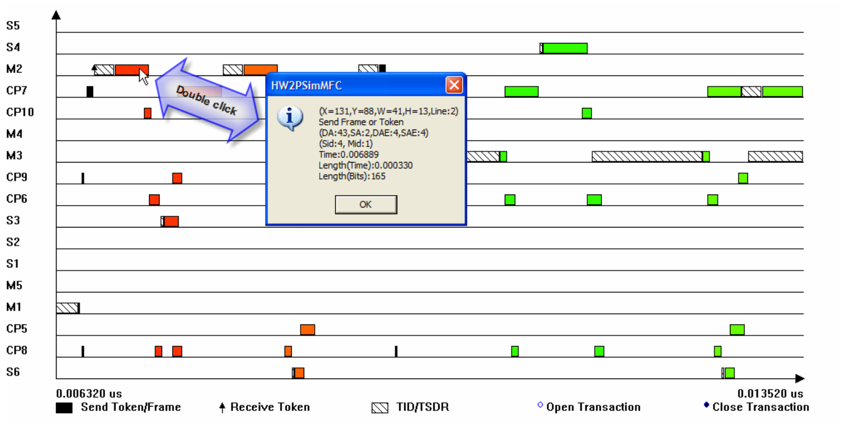


Figure D.1 – Screenshot of Timeline Visualisation Tool (BHW2PNetSim)



```
(X=131,Y=88,W=41,H=13,Line:2)
Send Frame or Token
(DA:43,SA:2,DAE:4,SAE:4)
(Sid:4, Mid:1)
Time:0.006889
Length(Time):0.000330
Length(Bits):165
```

Figure D.2 – Screenshot of Timeline Visualisation Tool (RHW2PNetSim)

In order to the RHW2PNetSim and BHW2PNetSim gather this information the `Controller` module `_output_gant_diagram` parameter must be set equal to 1. This diagram is built using two kinds of files. One kind contains the network configuration (with extension ".cfg") and is generated by the `Controller` module instance. The other kind contains the module instance events (with extension ".evt") which are generated by the other modules instances.

D.3. Output Data Analysis Tool

In order to extract information from the output data files and especially due to amount of information generated by he RHW2PNetSim and BHW2PNetSim a tool was developed which provides a fast way to decode text files containing the simulation results and present simulation statistical results in a convenient format. Output Data Analysis Tool was developed using Microsoft Excel and Visual Basic for Applications (VBA) (Simon, 2002).

Figure D.3 depicts a screenshot of this tool. This tool permits the analysis of the message stream response time, stations state machine evolution over time, probability distribution functions and data related to bit error models.

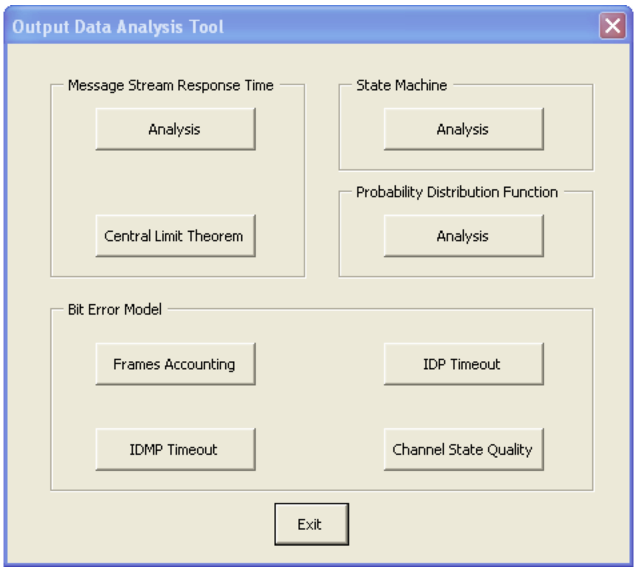
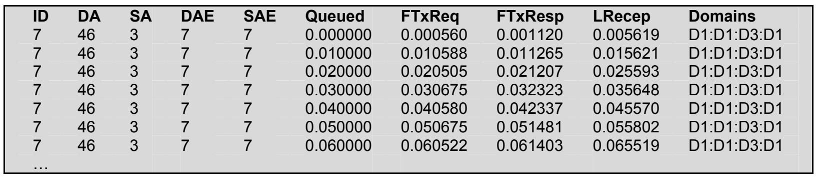


Figure D.3 – Screenshot of the Output Data Analysis Tool

D.3.1. Message Stream Response Time

In order to compute the message stream response time `Master` and `Slave` module instance are able to gather information about transactions. This information is stored in text files which use the ".srt" extension and contain information depicted in Figure D.4. In the first column (with the header "ID") is the identifier of the stream. The follows column contains the `Destination Address` (DA), the `Source Address` (SA), the `Destination Address Extension` (DAE) and the `Source Address Extension` (SAE).

The sixth column contains the time when the stream is queued on the `DLL` module instance output queue. The first transmission of the request frame appears in the seventh column (named FTxReq), the first transmission of the response frame appear in the eighth column (named FTxResp) and the last reception, i.e., when the transaction is finished appears in the ninth column (named LRecep). The last column displays path related information, the first item is the initiator's domain, when message is queued; the second item is the domain name to which the initiator belongs when the first request is transmitted; on the third item appears the domain name to which the responder belongs when it replies; on the fourth item contains the domain name to which the station belongs when the transaction finishes.



ID	DA	SA	DAE	SAE	Queued	FTxReq	FTxResp	LRecep	Domains
7	46	3	7	7	0.000000	0.000560	0.001120	0.005619	D1:D1:D3:D1
7	46	3	7	7	0.010000	0.010588	0.011265	0.015621	D1:D1:D3:D1
7	46	3	7	7	0.020000	0.020505	0.021207	0.025593	D1:D1:D3:D1
7	46	3	7	7	0.030000	0.030675	0.032323	0.035648	D1:D1:D3:D1
7	46	3	7	7	0.040000	0.040580	0.042337	0.045570	D1:D1:D3:D1
7	46	3	7	7	0.050000	0.050675	0.051481	0.055802	D1:D1:D3:D1
7	46	3	7	7	0.060000	0.060522	0.061403	0.065519	D1:D1:D3:D1
...									

Figure D.4 – Output response time file (excerpt)

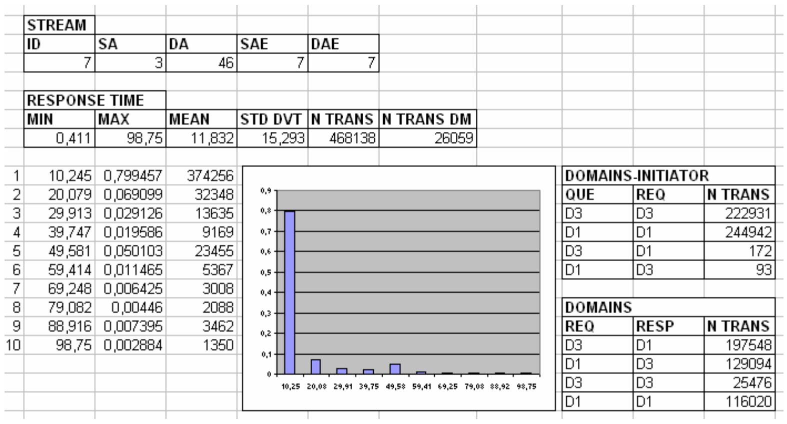
Note that, if the transaction is a SDR the transaction, then it only finishes when the initiator receives the response frame. But if it is a SDN then the transaction finishes when the "responder" receives the request frame. In the last case no contain any information.

The number of transaction that missed its deadline is also stored in a file. This information is recorded in text files (using the ".sdm" extension) by each `Master` module instance.

Message Stream Response Time Statistical Analysis

The tool is capable of decode the text files described in the last Section and retrieve statistical results. The response time is computed as a difference between the timestamp of the last reception (ninth column of the text file) and of the timestamp when the message was queued (sixth column of the text file).

Figure D.5 shows a screenshot of a spreadsheet created by this option. It provides information about message streams characteristics, like: minimum (MIN); maximum (MAX); mean (MEAN); standard deviation (STD DVT); number of transaction (N TRANS) and number of transaction that missed the deadline (N TRANS DM). Further, this option builds a histogram of the message stream response time values.



STREAM				
ID	SA	DA	SAE	DAE
7	3	46	7	7

RESPONSE TIME					
MIN	MAX	MEAN	STD DVT	N TRANS	N TRANS DM
0,411	98,75	11,832	15,293	468138	26059

1	10,245	0,799457	374256
2	20,079	0,069099	32348
3	29,913	0,029126	13635
4	39,747	0,019586	9169
5	49,581	0,050103	23455
6	59,414	0,011465	5367
7	69,248	0,006425	3008
8	79,082	0,00446	2088
9	88,916	0,007395	3462
10	98,75	0,002884	1350

DOMAINS-INITIATOR		
QUE	REQ	N TRANS
D3	D3	222931
D1	D1	244942
D3	D1	172
D1	D3	93

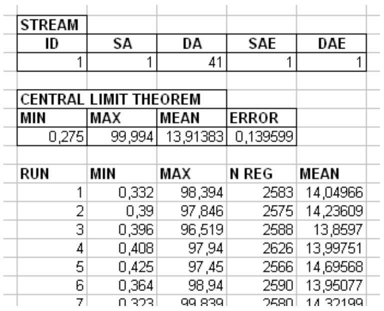
DOMAINS		
REQ	RESP	N TRANS
D3	D1	197548
D1	D3	129094
D3	D3	25476
D1	D1	116020

Figure D.5 – Screenshot of spread sheet created by Message Stream Response Time Analysis option

Additionally, it also provides information about the domain location of the initiator and responder during a transaction. This information is particularly important for IDTs involving wireless mobile stations. Since this option shows to which domain the initiator was belonging when a message was queued (QUE) and to which domain it belongs when the message was sent (REQ). Another kind of information provide by this option is related to the domain location when the initiator sends the request (REQ) the domain location of the responder when it replies (RESP).

Central Limit Theorem

The Central Limit Theorem is an option (Figure D.6) that provides a way to compute the confidence interval of the message stream response time values according to the central limit theorem (Law and Kelton, 2000). The lower bound and the upper bound of this interval is computed as mean value (MEAN) less error (ERROR) value and mean value more error value, respectively.



STREAM				
ID	SA	DA	SAE	DAE
1	1	41	1	1

CENTRAL LIMIT THEOREM			
MIN	MAX	MEAN	ERROR
0,275	99,994	13,91383	0,139599

RUN	MIN	MAX	N REG	MEAN
1	0,332	98,394	2583	14,04966
2	0,39	97,846	2575	14,23609
3	0,396	96,519	2588	13,8597
4	0,408	97,94	2626	13,99751
5	0,425	97,45	2566	14,69568
6	0,364	98,94	2590	13,95077
7	0,323	99,839	2580	14,32199

Figure D.6 – Screenshot of spreadsheet created by Message Stream Response Time Central Limit Theorem option

D.3.2. State Machine

A `Master` module models a PROFIBUS master and additionally can model the BM, DMM and GMM functionalities separately or simultaneously. Each of these elements has its own state machine. The information about the state machine transitions of these elements are recorded in text files (with ".stt" extension). Each line of this kind of file represents a transition. The transition instant (Time), the state name and a brief explanation about reason that causes the transition appear in first, second and third column, respectively. Figure D.7 illustrates an example of this kind of files related to a `Master` module instance.

```
Time        State name                 Description
…
0.019468    USE_TOKEN                  Received token from [6]
0.019534    AWAIT_STATUS_RESPONSE      Waiting for a FDL response from [3]
0.019648    USE_TOKEN                  Slot time expired
0.019648    PASS_TOKEN                 Trying to pass the token to [5]
0.019671    CHECK_TOKEN_PASS           Waiting for activity from [5]
0.019759    ACTIVE_IDLE                Activity detected from [5]
0.019848    USE_TOKEN                  Received token from [6]
0.019914    AWAIT_STATUS_RESPONSE      Waiting for a FDL response from [4]
0.020028    USE_TOKEN                  Slot time expired
0.020028    PASS_TOKEN                 Trying to pass the token to [5]
0.020051    CHECK_TOKEN_PASS           Waiting for activity from [5]
0.020139    ACTIVE_IDLE                Activity detected from [5]
0.020228    USE_TOKEN                  Received token from [6]
0.020294    PASS_TOKEN                 Trying to pass the token to [5]
0.020317    CHECK_TOKEN_PASS           Waiting for activity from [5]
…           .                          .
```

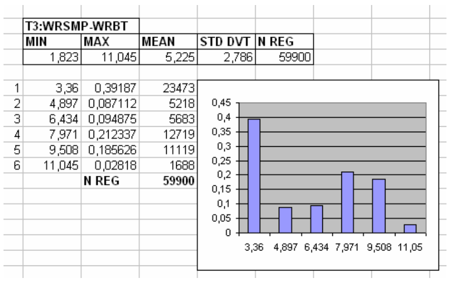
Figure D.7 – Output state machine file (excerpt)

State Machine Statistical Analysis

The State Machine Analysis option (Figure D.8) provides a fast way to summarise the information. This option builds histogram related to each transition computing the number of times (N REG) that a `Master` module instance was in each state. Additionally, it computes the minimum (MIN) and maximum (MAX) time spending in each state as well as the mean (MEAN) and the standard deviation (STD DVT).

D.3.3. Probability Distribution Function

The information about the random values generated by the probability distribution function (PDF) are recorded into several text files (different extension are used, for example, the files related with the T_{ID} and with the T_{SDR} has ".tid" and ".tsdr" extensions, respectively). Figure D.9 presents an example of this kind of files. The first line is used to identify the PDF and its parameters. In this case, the PDF is a triangular distribution function with apex at 50 bit times and extremes at 11 and 70 bit times.



T3:WRSMP-WRBT				
MIN	MAX	MEAN	STD DVT	N REG
1,823	11,045	5,225	2,786	59900

1	3,36	0,39187	23473
2	4,897	0,087112	5218
3	6,434	0,094875	5683
4	7,971	0,212337	12719
5	9,508	0,185626	11119
6	11,045	0,02818	1688
		N REG	59900

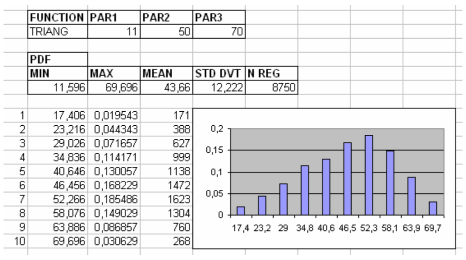
Figure D.8 – Screenshot of spreadsheet created by State machine Analysis option

```
TRIANG#11.000000#50.000000#70.000000
18.103736
54.119785
62.908148
51.248531
26.079176
43.094876
66.415956
```

Figure D.9 – Output PDF file (excerpt)

Probability Distribution Function Statistical Analysis

This output of the Probability Distribution Function Analysis option is similar to the previous. It computes some statistical elements like mimimum (MIN), maximum (MAX), mean (MEAN), standard deviation (STD DVT) values as well as a histogram. Figure D.10 shows a screenshot of a spreadsheet created by this option.



FUNCTION	PAR1	PAR2	PAR3
TRIANG	11	50	70

PDF				
MIN	MAX	MEAN	STD DVT	N REG
11,596	69,696	43,66	12,222	8750

1	17,406	0,019543	171
2	23,216	0,044343	388
3	29,026	0,071657	627
4	34,836	0,114171	999
5	40,646	0,130057	1138
6	46,456	0,168229	1472
7	52,266	0,185486	1623
8	58,076	0,149029	1304
9	63,886	0,086857	760
10	69,696	0,030629	268

Figure D.10 – Screenshot of spreadsheet created by the Probability Distribution Functions Analysis option

D.3.4. Bit Error Model

The information about the Bit Error Model (BEM) used in simulation runs are recorded in several output data files. First, includes information about the number of correct and corrupted transmitted frames. Second includes detailed information about corrupted frames transmitted. Third, includes information about IDT deleted and fourth includes information about IDMP aborted. The last one includes information about channel state quality and the frame transmitted by each `Domain` module instance. The third and fourth are only generated by the BHW2PNetSim and fifth is generated only if the BEM used is either Gilbert-Elliot Model (simplified or not) or Burst-Error Periodic Model.

Frame Accounting

The number of valid and invalid frames is also recorded to files (with ".cfr" and ".efr" extensions), as well as the information about the invalid frames relayed by each `Domain` module instance. The information is grouped into four groups: PROFIBUS, BEACON, IDP and IDMP-related frames, where the first is related to standard PROFIBUS frames, the second are the beacon frames, the third are the IDF used by the IDP protocol and the last group represents the frames related to the IDMP. For each group is presented the number of valid and invalid frames relayed by a `Domain` module instance. Figure D.11 presents the information generated by a `Domain` module instance of the BHW2PNetSim.

```
PROFIBUS:8954:57
BEACON::
IDP: 246: 6
IDMP: 131:2
```

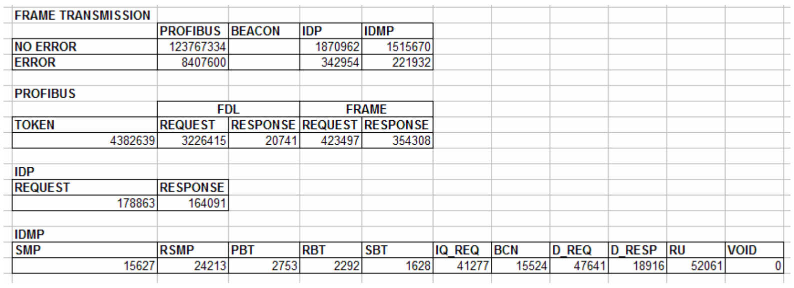
Figure D.11 – Output frame accounting file (excerpt)

Detailed information about corrupted frames is also recorded to file. In such kind of file each line is composed by several fields separated by colons (see Figure D.12). The first field is the timestamp at which an invalid frame was detected, the second and the third fields are the DA and SA contained in the frame, respectively. The frame's type appears in the fourth field. The remaining fields contain the remaining frame parameters: `Start Delimiter` (SD), `Frame Control` (FC) and the `Mobility Code` (MC).

```
0.209914:4:6:IDMP::IQ_REQ:REQUEST_OR_SEND_REQUEST_FRAME:SEND_DATA_WITH_NO_ACKNOWLEDGE_HIGH
0.214466:44:3:IDF:::REQUEST_OR_SEND_REQUEST_FRAME:SEND_AND_REQUEST_DATA_HIGH
0.220326:5:4:PROFIBUS:FDL_REQUEST_STATUS::REQUEST_OR_SEND_REQUEST_FRAME:REQUEST_FDL_STATUS_WITH_REPLY
0.222138:42:1:PROFIBUS:::REQUEST_OR_SEND_REQUEST_FRAME:SEND_AND_REQUEST_DATA_HIGH
0.226439:5:4:PROFIBUS:FDL_REQUEST_STATUS::REQUEST_OR_SEND_REQUEST_FRAME:REQUEST_FDL_STATUS_WITH_REPLY
0.226918:45:1:PROFIBUS:::REQUEST_OR_SEND_REQUEST_FRAME:SEND_AND_REQUEST_DATA_HIGH
0.227865:4:1:PROFIBUS:TOKEN:::
…
```

Figure D.12 – Information about invalid frames relayed by a `Domain` module instance

Figure D.13 depicts a screenshot of the spreadsheet generated by Bit Error Model Frame Accounting option, where the information contained on the referred kind of files is summarized.



FRAME TRANSMISSION

	PROFIBUS	BEACON	IDP	IDMP
NO ERROR	123767334		1870962	1515670
ERROR	8407600		342954	221932

PROFIBUS

	FDL		FRAME	
TOKEN	REQUEST	RESPONSE	REQUEST	RESPONSE
4382639	3226415	20741	423497	354308

IDP

REQUEST	RESPONSE
178863	164091

IDMP

SMP	RSMP	PBT	RBT	SBT	IQ_REQ	BCN	D_REQ	D_RESP	RU	VOID
15627	24213	2753	2292	1628	41277	15524	47641	18916	52061	0

Figure D.13 – Screenshot of spreadsheet created by the Bit Error Model Frame Accounting option

IDP Timeout

The IDP has a error recovery mechanism which deletes an entry from a BM_{ini} LOT if the timeout timer associated with that transaction expires. This behaviour allows the BM_{ini} to initialise a new LOT entry related to the same message stream.

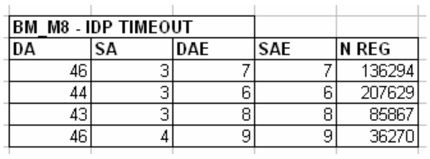
The information about deleted IDTs in a $\mathrm{BM}_{\mathrm{ini}}$ LOT is recorded in a file with the ".tidt" extension. Figure D.14 shows an example of this kind of file. The information gathered in this file is the DA, SA, message ID and the timestamp when the deletion occurred.

Based on the information contained in this file a spreadsheet tool allows the analysis of the results.

Figure D.15 depicts a screenshot of the spreadsheet where the information concerning IDTs deleted by BM M8 is shown. The information is organized by message stream.

```
DA    SA    DAE    SAE    Timestamp
…
43    2     4      4      0.080469
46    2     5      5      0.156737
46    2     5      5      0.237376
43    2     4      4      0.250335
46    2     5      5      0.260427
46    2     5      5      0.293211
46    2     5      5      0.332400
46    2     5      5      0.445243
46    2     5      5      0.518283
46    2     5      5      0.565210
46    2     5      5      0.668706
46    2     5      5      0.748602
46    2     5      5      0.773215
43    2     4      4      0.080469
46    2     5      5      0.156737
…
```

Figure D.14 – Output deleted IDTs file (excerpt)



BM_M8 - IDP TIMEOUT				
DA	SA	DAE	SAE	N REG
46	3	7	7	136294
44	3	6	6	207629
43	3	8	8	85867
46	4	9	9	36270

Figure D.15 – Screenshot of spreadsheet created by the Bit Error Model IDP Timeout option

IDMP Timeout Timers

Concerning IDMP, four timers are assigned to the GMM and one to each BM (($T_{BM\text{-}IDMPAbort}$)) and another to each DMM (`DMM_IDMP_Abort_Timer` ($T_{DMM\text{-}IDMPAbort}$)) presents in the network. Two of the timers associated to the GMM are used to detect and handle the errors during the Phase 1 (`GMM_Phase_ 1_Alert_Timer` ($T_{GMM\text{-}P1Alert}$) and ($T_{GMM\text{-}P1Abort}$)), while the others two are related to the Phase 2 (`GMM_ Phase_2_Alert_Timer` ($T_{GMM\text{-}P2Alert}$) and `GMM_Phase_2_Abort_Timer` ($T_{GMM\text{-}P2Abort}$)).

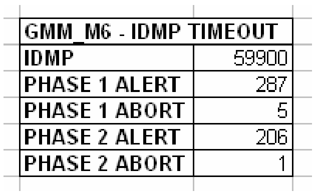
In Chapter 3 a mechanism was proposed to provide the IDMP with capabilities to operate in error-prone environments. This proposed mechanism is based on the timers: `BM_IDMP_Abort_Timer`, `DMM_ IDMP_Abort_Timer`, `GMM_Phase_1_Alert_Timer`, `GMM_Phase_1_Abort_Timer`, `GMM_Phase_2 _Alert_Timer` and `GMM_Phase_2_Abort_Timer`. Whenever a timer expires the simulator records information about it.

Figure D.16 depicts part of this file (".tidmp" extension) which contains information about the expiration of the IDMP timers concerning the GMM. The first column contains the time when the timer expired and in second contains the identification of the expired timer.

```
timestamp          Timer
…
108.211156         Phase 1 alert
109.211156         Phase 1 alert
109.222311         Phase 1 abort
109.412431         Phase 2 alert
109.611156         Phase 1 alert
109.622311         Phase 1 abort
111.211156         Phase 1 alert
111.216033         Phase 2 alert
111.413714         Phase 2 alert
113.011156         Phase 1 alert
114.211156         Phase 1 alert
114.222311         Phase 1 abort
108.211156         Phase 1 alert
109.211156         Phase 1 alert
109.222311         Phase 1 abort
…
```

Figure D.16 – Output IDMP alerts and aborts file (excerpt)

To analyse this results a spreadsheet-based tool has also been developed. Figure D.17 depicts a screenshot of these results which contains the number of timer that the IDMP was triggered and the IDMP timers that expired.



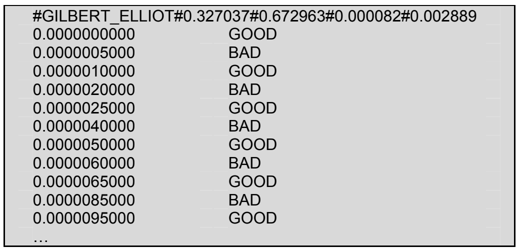
GMM_M6 - IDMP TIMEOUT	
IDMP	59900
PHASE 1 ALERT	287
PHASE 1 ABORT	5
PHASE 2 ALERT	206
PHASE 2 ABORT	1

Figure D.17 – Screenshot of spreadsheet created by the Bit Error Model IDMP Timeout option

Channel State Quality

In order to model burst sensitive models like the Gilbert-Elliot bit error model, there is the need to compute the state of the channel during time. This information can also be recorded to output data files by each `Domain` module instance. Figure D.18 shows an example of this kind of file (which uses the ".cst" extension). The identification of the BEM used and its parameters are written in the first line. The following lines show, in the first column, the timestamp when state change occurred and the second column show when the new state.

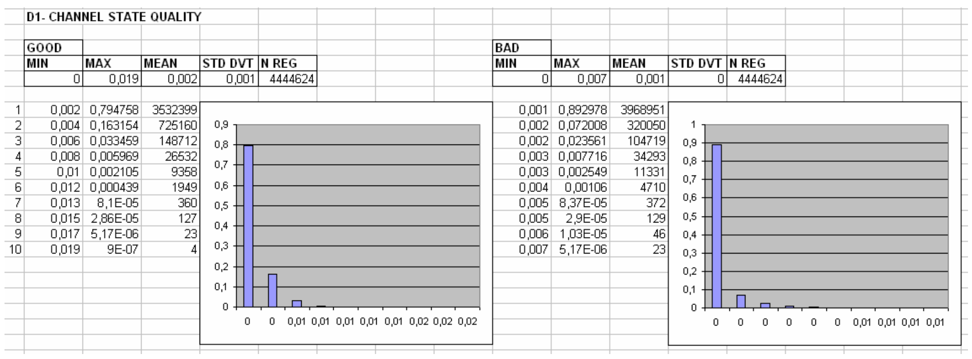
The main objective of this feature is to validate the error model in use, by displaying statistical data regarding its operation.



```
#GILBERT_ELLIOT#0.327037#0.672963#0.000082#0.002889
0.0000000000            GOOD
0.0000005000            BAD
0.0000010000            GOOD
0.0000020000            BAD
0.0000025000            GOOD
0.0000040000            BAD
0.0000050000            GOOD
0.0000060000            BAD
0.0000065000            GOOD
0.0000085000            BAD
0.0000095000            GOOD
...
```

Figure D.18 – Output channel state quality file (excerpt)

Figure D.19 shows a screenshot of the spreadsheet related to channel state quality of one domain. This tool summarizes information regarding the periods in time during which the channel in one domain has been in the good or in the bad state of the Gilbert-Elliot bit error model. The tool provides some statistical parameters, like minimum (MIM), maximum (MAX), mean (MEAN), standard deviation (STD DVT) and the number of times that this domain was in this state (N REG). Additionally it also constructs a histogram of these timings.



D1- CHANNEL STATE QUALITY

GOOD				
MIN	MAX	MEAN	STD DVT	N REG
0	0,019	0,002	0,001	4444624

1	0,002	0,794758	3532399
2	0,004	0,163154	725160
3	0,006	0,033459	148712
4	0,008	0,005969	26532
5	0,01	0,002105	9358
6	0,012	0,000439	1949
7	0,013	8,1E-05	360
8	0,015	2,86E-05	127
9	0,017	5,17E-06	23
10	0,019	9E-07	4

BAD				
MIN	MAX	MEAN	STD DVT	N REG
0	0,007	0,001	0	4444624

0,001	0,892978	3968951
0,002	0,072008	320050
0,002	0,023561	104719
0,003	0,007716	34293
0,003	0,002549	11331
0,004	0,00106	4710
0,005	8,37E-05	372
0,005	2,9E-05	129
0,006	1,03E-05	46
0,007	5,17E-06	23

Figure D.19 – Screenshot of spreadsheet created by the Bit Error Model Channel State Quality option

Annex E

Acronyms and Symbols

This annex presents two lists one containing the acronyms and another containing the symbols used in this dissertation.

E.1. Acronyms

Acronyms	Description
AGV	Automatic Guided Vehicle
AL	Application Layer
BEM	Bit Error Mode
BER	Bit Error Rate
BHW2PNetSim	Bridge-Based Hybrid Wired/Wireless PROFIBUS Network Simulator
BM	Bridge Master
BM_{ini}	First bridge master in the path from the initiator to the responder of a transaction
BM_{res}	Last bridge master in the path from the initiator to the responder of a transaction
BS	Base Station
BT	Beacon Trigger
CSRD	Cyclic Send and Receive with Data (PROFIBUS standard)
DA	Destination Address (PROFIBUS standard)
DAE	Destination Address Extension (PROFIBUS standard)
DCCS	Distributed Computer-Controlled System
DLL	Data Link Layer
DMM	Domain Mobility Manager
DSSS	Direct Sequence Spread Spectrum
EBF	Emitting_Beacon_Frame
ED	End Delimiter
EFC	Embedded frame Function Code
EFT	Embedded Frame Type
FC	Frame Control (PROFIBUS standard)
FCS	Frame Check Sequence (PROFIBUS standard)
FMA1/2	Management for PROFIBUS networks layers 1 and 2
GAPL	Gap List
GMM	Global Mobility Manager
HSA	Highest Station Address
I/O	Input/Output
IADT	Intra-Domain Transaction
ICM	Independent Channel Model
IDF	Inter-Domain Frame
IDMP	Inter-Domain Mobility Procedure
IDP	Inter-Domain Protocol

IDreq	Inter-Domain Request frame
IDres	Inter-Domain Response frame
IDT	Inter-Domain Transaction
IEC	International Electrotechnical Commission
IIDT	Intra/Inter Domain Transaction
IS	Intermediate System
ISO	International Organization for Standardisation
LAN	Local Area Network
LAS	List of Active Stations (PROFIBUS Standard)
LASD	List of Active Stations in Domain
LBMD	List of Bridge Masters in the Domain
LBMN	List of Bridge Masters in the Network
LDMMN	List of Domain Mobility Managers in the Network
LE	Frame Length (PROFIBUS Standard)
LEr	Frame Length repeated (PROFIBUS Standard)
LL	Live List (PROFIBUS Standard)
LOT	List of Open Transactions
LWMSN	List of Wireless Mobile Stations in the Network
MAC	Medium Access Control
MaxRT	maximum response time
MC	Mobility Code
MeanBER	Mean Bit Error Rate
MeanRT	Mean response time
MinRT	Minimum response time
MLR	Multiple Logical Ring
MM	Mobility Master
MSim	Mobility Simulator
NS	Next Station (PROFIBUS Standard)
OMNeT++	Objective Modular Network Testbed in C++
OSI	Open System Interconnection
PBT	Prepare_for_Beacon_Transmission
PC	Personal Computer
PCF	Point Coordinator Function (IEEE 802.11)
PDA	Personal Digital Assistant
PDF	Probability Distribution Function
PDU	Protocol Data Unit
PhL	Physical Layer
PLC	Programmable Logical Controller
PROFIBUS	PROcess FIeld BUS
PROFIBUS-DP	PROFIBUS – Decentralised Peripherals
PROFIBUS-FMS	PROFIBUS – Fieldbus Message Specification
PS	Previous Station (PROFIBUS Standard)
RBT	Ready_for_Beacon_Transmission
RFieldbus	High Performance Wireless Fieldbus in Industrial Multimedia-Related Environment
RHW2PNetSim	Repeater-Based Hybrid Wired/Wireless PROFIBUS Network Simulator
RSMP	Ready_to_Start_Mobility_Procedure
RT	Routing Table
RU	Route_Update

SA	Source Address (PROFIBUS standard)
SAE	Source Address Extension (PROFIBUS standard)
SBT	Start_Beacon_Transmission
SC	Short Acknowledge (PROFIBUS standard)
SD	Start Delimiter (PROFIBUS standard)
SDA	Send Data with Acknowledge (PROFIBUS Standard)
SDN	Send Data with no Acknowledge (PROFIBUS Standard)
SLR	Single Logical Ring
SMP	Start_Mobility_Procedure
SRD	Send and Request Data (PROFIBUS Standard)
$T_{BM\text{-}IDMPAbort}$	BM_IDMP_Abort_Timer
$T_{BM\text{-}IDTAbort}$	BM_IDT_Abort_Timer
TCP/IP	Transport Control Protocol/Internet Protocol
$T_{DMM\text{-}IDMPAbort}$	DMM_IDMP_Abort_Timer
$T_{GMM\text{-}P1Abort}$	GMM_Phase_1_Abort_Timer
$T_{GMM\text{-}P1Alert}$	GMM_Phase_1_Alert_Time
$T_{GMM\text{-}P2Abort}$	GMM_Phase_2_Abort_Timer
$T_{GMM\text{-}P2Alert}$	GMM_Phase_2_Alert_Time
T_{GUD}	Gap Update Time
TI	Transaction Identifier
T_{ID}	Idle Time
T_{IDm}	Minimum idle time
T_{RR}	Real Rotation Time
TS	This Station (PROFIBUS Standard)
T_{SDI}	Station Delay of the Initiator Time
T_{SDR}	Station Delay of a Responder Time
T_{SL}	Slot Time
T_{SM}	Safety Margin Time
T_{SYN}	Synchronisation Time
T_{TD}	Transmission Delay Time
T_{TH}	Token Holding Time
T_{TO}	Time-Out Time
T_{TR}	Target Rotation Time
WCRT	Worst-Case Response Time

E.2. Symbols

Symbol	**Description**
a	Lower limit of an interval
apex	Mode
b	Upper limit of an interval
c	The speed of the light
d	The distance between transmitter and receiver in meters
d_0	The close-in reference distance which is determined from measurements close to the transmitter
D^i	Communication Domain i
f	Carrier frequency in Hertz

$F_{(x)}$	Probability function
$f_{(x)}$	Density function
G	Gap Update Factor
G_r	The receiver antenna gain
G_t	the transmitter antenna gain
L	Number of characters in a frame
$maxT_{SDR}$	Maximum delay before a responder starts transmitting a response to a request.
$minT_{SDR}$	Minimum delay before a responder starts transmitting a response to a request.
$MeanBER$	Mean Bit Error Rate
n	The path loss exponent which indicates the rate at which the path loss increases with distance
N_{eM}	The maximum burst length
N_{em}	The minimum burst length
N_y	The transmission error burst length
p_b	The BER probability in bad state
$p_{b\|b}$	The steady state probability for being in bad state
$p_{b\|g}$	The probability of a transition occurs from bad to good state
p_{ber}	Bit Error Rate (BER) probability
P_{fr_err}	The frame error probability
p_g	The BER probability in good state
$p_{g\|b}$	The probability of a transition occurs from good to bad state
$p_{g\|g}$	The steady state probability for being in good state
$PL(d)$	The average path loss at distance *d* between transmitter and receiver
$PL_0(d_0)$	The free-space path loss distance *d0*
$P_r(d)$	The power at received radio signal
P_t	The transmitted power
S_i^x	Message stream *i* from an initiator station *x*
t_b	The mean duration of bad state
T_{em}	Lower period threshold
T_{eM}	Higher period threshold
t_g	The mean duration of good state
T_{GUD}	Gap Update time, defines the periodicity of the GAP update mechanism
$t^{i\to j}_{ng}$	The no gaps instant
$t^{i\to j}_{sr}$	The start relaying instant
T_{ID1}	Idle time inserted by a master station after an acknowledgement, response or token PDU
T_{ID2}	Idle time inserted by a master ES after an acknowledged request PDU (PROFIBUS).
t^{i}_{dr}	The data ready instant
t^{i}_{lk}	The length known instant
T_{QUI}	Transmitter fall time
t_{rd}	The relaying delay time
T_{RDY}	Time within which a master station shall be ready to receive an acknowledgement or response after transmitting a request.
T_{RR}	Real Rotation Time

T_{SDI}	Station delay of the initiator, which is measured with respect to the receipt of the last frame last bit until an initiator is ready to transmit again.
T_{SDI}	Station Delay of the Initiator
T_{SDR}	Station Delay of a Responder
T_{SET}	Set-up time which expires from the occurrence of an event (e.g. interrupt: last octet sent or Synchronous Time expired) until the necessary reaction is performed (e.g. to start Synchronous Time or to enable the receiver).
T_{SL}	The Slot Time is a parameter set in every master that defines the timeout for listening for activity in the bus, after having transmitted an acknowledged request or token.
T_{SL1}	Maximum time the initiator waits for the complete reception of the first frame character of the acknowledgement/response frame, after transmitting the last bit of the request frame
T_{SL2}	Maximum time the initiator waits after having transmitted the last bit of the token PDU until it detects the first bit of a PDU (either a request or the token) transmitted by the station that received the token
T_{SM}	Safety margin (PROFIBUS)
t_{st}	System turnaround time
T_{SYN}	Synchronization period of (at least) 33 idle bit periods
T_{TD}	Transmission Delay is the propagation delay in the bus.
T_{TH}	Token Holding Time
T_{To}	Time-out time
T_{TR}	Target Token Rotation time
T_x	The transmission error period
X_σ	The shadowing term (the zero-mean Gaussian random variable in dB with standard deviation of σ)
β	Constant rate
λ	The wavelength in meters
$\sigma2$	Standard deviation
μ	Mean value