Hybrid Wired/Wireless PROFIBUS Networks Supported by Bridges/Routers

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Abstract

Fieldbus networks are becoming increasingly popular in industrial computer-controlled systems. More recently, there is the eagerness for extending the capabilities of fieldbuses to cover functionalities not previously considered in such type of networks, with particular emphasis to industrial wireless communications. Thinking about wireless means considering hybrid wired/wireless solutions able to interoperate with legacy (wired) systems. One possible solution is to use intermediate systems (IS) acting as repeaters to interconnect the wired and wireless parts. Contrarily, in this paper, we analyze a solution where intermediate systems are implemented as bridges/routers. We detail the main advantages in terms of dependability and timeliness, and propose mechanisms to manage message transactions and inter-cell mobility.

1. Introduction

Fieldbus networks are becoming increasingly popular in industrial computer-controlled systems, allowing field devices like sensors, actuators and controllers to be interconnected at low cost, using less wiring and requiring less maintenance than point-to-point connections. PROFIBUS [1] is one of the most popular fieldbuses, and has been granted the status of an international standard by CENELEC [2].

The research works [3-5] on the timing behaviour of PROFIBUS networks have proved the capabilities of this fieldbus standard to support distributed computer-controlled systems with stringent real-time requirements. More recently, there is the eagerness of extending the capabilities of PROFIBUS to cover functionalities not previously considered in such type of networks: industrial wireless communications and ability to support industrial multimedia traffic. One example is reflected in the IST (Information Society Technology) project RFieldbus (High Performance Wireless Fieldbus in Industrial Multimedia-Related Environment) [6], supported by the European Commission.

PROFIBUS networks are widely used, with several hundreds of thousands of installations currently in operation worldwide. A traditional fieldbus network consists of several end-systems (ES) physically connected through a wired bus. Therefore, and due to the market penetration, thinking about wireless means considering hybrid wired/wireless solutions able to interoperate with legacy (wired) systems.

A hybrid wired/wireless system can potentially rely on the use of intermediate systems (IS) acting as repeaters for interconnecting the wired and wireless parts of the network. This particular solution was proposed within the framework of the European project RFieldbus [6]. The reason for this solution mainly relies on the fact that the PROFIBUS standard does not encompass ISs for the data link and network layers. Additional reasoning can be found in [7-8].

In this paper, we discuss the alternative solution of using hybrid wired/wireless PROFIBUS networks supported by bridges/routers. Although it requires some more complex mechanisms, its potential is rewarding in terms of dependability and timeliness, as discussed in Section 3. Therefore, the rest of this paper is organised as follows. In Section 2 we introduce some concepts on the hybrid wired/wireless system which are relevant in the context of this paper. In Section 4 we briefly describe the solution based on repeaters and point out some of its limitations. In Section 5 we introduce the basic concepts behind our proposal, and illustrate in Section 6 how the intrinsic PROFIBUS mechanisms (described in Section 3) can potentially be exploited to support the mobility functionalities. In Section 7, a numerical example is introduced and pre-run-time schedulability analysis is devised to show the advantages of the proposed solution in terms of responsiveness. Finally, in Section 8, we draw some conclusions.

2. Basic Definitions

A traditional fieldbus network consists of several nodes physically connected through a reliable medium – the wired bus. A wireless fieldbus consists of wireless stations that are interconnected by a radio channel via the air.

This work was partially funded by the European Commission under the IST Project RFieldbus (IST-1999-11316) and by FCT under CIDER Project (POSI/1999/CHS/33139)

A wireless fieldbus network is supposed to include at least one *radio cell*. Basically, a radio cell can be described as a space where all associated wireless nodes are able to communicate with each other. This common radio coverage area is here defined as *radio cell*. A *Domain is* as a set of stations (of any kind) communicating via a unique medium. Therefore, a *Wired Domain* corresponds to the set of (wired) stations that intercommunicates via a wired segment. Correspondingly, a *Wireless Domain* is a set of (wireless) stations intercommunicating via the air.

Usually the antennas used by wireless nodes have omni-directional characteristic, so the real dimension of the radio cell coverage area is defined by the interception of the radio coverage area of every wireless node. Taking into account that radio cells may be overlapping (sometimes it is intended), the distinction may be achieved through the use of different radio channels.

The wireless communications in a radio cell may be achieved in two ways (specific details are ignored): in a direct way, also called *Direct Link Network* or via a B*ase Station* (BS), in an *Indirect Link Network*.

A *Link Station* (LS) connects wireless stations belonging to a Wireless Domain to wired stations belonging to a Wired Domain. In the case of a Direct Link Network, wireless stations within range are able to communicate directly between them. In order to have improved and structured radio coverage, Base Stations may be used, leading to an Indirect Link Network. In this case, the Base Station must relay every communication between wireless stations, using up-link and down-link channels. It is also possible to combine the functionality of a Base Station and a Link Station in one physical device – a *Link Base Station* (LBS). For more details on this, the reader is referred to [7].

The support for node mobility is one of the most advanced features presented by wireless networks*. Intra-cell* mobility is defined as the capability of a node to move inside a radio cell. Thus, the term *mobility* is usually applied when a node moves between different cells - *inter-cell mobility*, where an efficient *handoff mechanism* must be supported. The efficiency of a handoff mechanism is mainly judged by its ability to provide operational as well as performance transparency, i.e., it must be done, preferably, without loss of frames and within a bounded time, to guarantee the system's real-time and dependable behaviour.

In the following sections we will discuss how it is possible to devise a hybrid wired/wireless PROFIBUS based network system by the proper use of bridges/routers acting as intermediate systems. Figure 1 summarises the envisaged functionalities, considering the existence of the following stations: wired master and slave stations; wireless static master and slave stations; wireless mobile master and slave stations; mobile wired domains (composed of ISs and wired ESs) and intermediate systems (which in the case of this paper will be working at the data link or network layer levels).

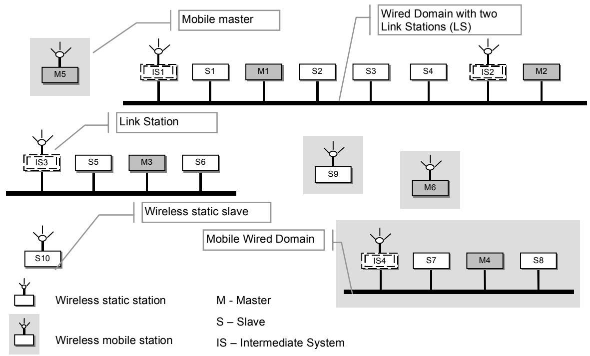

Figure 1. Wireless Fieldbus components.

3. Fundamentals of PROFIBUS

This section addresses some aspects of PROFIBUS which are relevant within the context of this paper.

3.1 Message Cycle

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

Generally, all the stations except the initiator monitor all the requests and acknowledge/responses only if they are addressed. Moreover, the acknowledgement or the response must arrive before the expiration of the *Slot Time* (T_{SL}), otherwise the initiator repeats the request the number of time defined by the *max_retry_limit*, a FDL variable.

PROFIBUS defines two categories of messages: high priority and low priority. After receiving the token, the measurement of the token rotation time begins. This measurement expires at the next token arrival and results in the real token rotation time (T_{RR}). A target token rotation time (T_{TR}) must be defined in a PROFIBUS network and is common to all masters. When a station receives the token, the token holding time (T_{TH}) timer is given the value corresponding to the difference, if positive, between T_{TR} and T_{RR}. If at the arrival, the real token rotation time (T_{RR}) was greater than the target rotation time (T_{TR}), the master station may execute, at most, one high priority message cycle. Otherwise, the master station may execute high priority message cycles while $T_{TH} > 0$. The low priority message cycles are executed if there are no high priority messages pending, and while $T_{TH} > 0$.

3.2 Ring Maintenance

In order to maintain the logical ring, PROFIBUS provides a decentralised (in every master station) ring maintenance mechanism. Each PROFIBUS master maintains two tables – the Gap List (LGAP) and the List of Active Stations (LAS) and may optionally maintain a Live List.

The Gap List consists of the address range from TS ('This Station' address) until NS ('Next Station' address, i.e., the next master in the logical ring). Each master station in the logical ring starts to check its Gap addresses every time its Gap Update Timer (T_{GUD}) expires. 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 the '*FDL_Request_Status*' frame.

The LAS comprises all the masters in the logical ring and is generated in each master station when it is in the 'Listen Token' state, after power on. This list is also dynamically updated during operation, upon receipt of token frames.

Concerning the Live List, there is the need for an explicit demand from the Fieldbus Data Link Layer (FDL) user, via a management (FMA1/2) request. A '*FDL_Request_Status*' frame is sent (in a cyclic way) for each destination address (0 to 126), except to master stations, because they are already registered in the LAS. The correctly responding stations and the master stations in the LAS are entered in the Live List as existing master or slave stations.

Additionally, in order to enhance the communication system's reliability, PROFIBUS handles the following operational or error states, concerning logical ring management: multiple tokens (in one segment), lost token, error in token passing, multiple assignment of station addresses and stations with faulty transceivers.

3.3 Token Passing

The token is passed between masters in ascending address order. The only exception is that 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 registered in the *List of Active Stations* (LAS) as its predecessor (PS = TS) then this master is said to be the token owner and may start processing message cycles. On the other hand, if a master receives the token from a station, which is not its previous station, it shall assume an error and not accept the token. However, if it receives a subsequent token from the same station, it shall accept the token and assume that the logical ring has changed. In this case, it updates the originally PS value by the new one.

If after transmitting the token frame and after expiration of the *Syn Time* (idle bus for a 33 bits period) within the Slot Time, the master detects valid bus activity , it assumes that its successor owns the token and is executing message cycles. Therefore, ceases monitoring the activity on the bus.

In the case that the master does not recognise any bus activity within the Slot Time, it repeats the token frame and waits another Slot Time. If it recognises bus activity within the second Slot Time, it assumes a correct token transmission. Otherwise, it repeats the token transmission to its next station 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 on its list of active station. It continues repeating this procedure until it has found a successor.

Master and slave stations may be connected or disconnected from the network at any moment. Each master station in the logical ring is responsible for the addition of "new" stations and the removal of existing stations, but only whose addresses belong to its GAP (from TS to NS, included), by means of the GAP update mechanism.

4. A SLR Solution: Using Repeaters as Intermediate Systems

A solution to interconnect wired and wireless stations would be to use repeaters to broadcast messages throughout the overall network. In this way, the wireless part of the fieldbus network could be seen as a wireless extension of the traditional PROFIBUS, both parts sharing a single logical ring (SLR), resulting in a single token rotating between all masters in the system. Therefore, every message is broadcast to every node (wired or wireless) in the network. In Section 4.1 some brief insights are given about this approach, while Sections 4.2 and 4.3 describe some of its limitations.

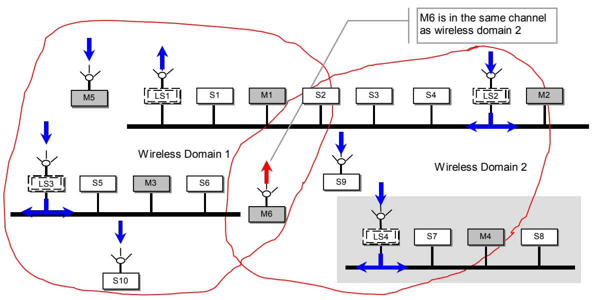

Figure 2. ISs Acting as Repeaters.

4.1 Basics of the SLR Solution

In this solution, the Link Stations act as repeaters, i.e. they receive frames from the wired domain, transmit those frames to the wireless domain and vice versa. Each Wireless Domain (that may be composed of several LSs) has its own transmit/receive channel. For instance, concerning Figure 2, LS1 and LS3 could belong to one wireless domain, and LS2 and LS4 could belong to another wireless domain. Wireless nodes, e.g. like M6, are supposed to be able to measure signal quality and switch channels, when they move from one Wireless Domain to another Wireless Domain, avoiding the need for an explicit registering mechanism. Details on this handoff procedure can be found in [7].

4.2 Token Passing in a Hybrid Wired/ Wireless Network

When the logical ring is supported by wireless/mobile communications (besides wired), there are critical dependability issues that arise. For instance, token loss due to frame corruption (lower reliability of wireless links) or to station mobility (master owning the token goes out of wireless domain radio coverage). Within this context PROFIBUS ring maintenance mechanisms assume a particular importance. Figure 3 illustrates a new logical ring that is created if LS4 becomes "invisible" to the rest of the network. Of course, apart affecting the interoperability between stations, this change in the network also has consequences in the responsiveness of the system (refer to Section 3.2).

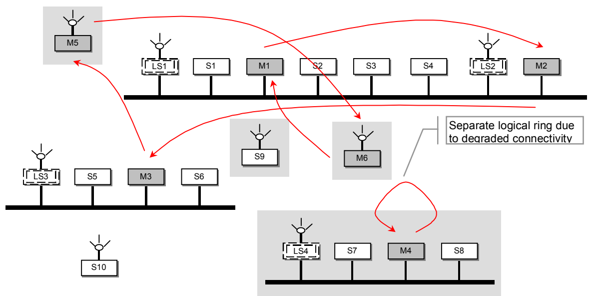

Figure 3. New logical ring due to connectivity degradation or loss.

4.3 Responsiveness to Failures

The existence of wireless links introduces additional delays in the network, since communications must be relayed through Link Stations, Base Stations or Link Base Stations (the relay can be made using cut-through or store and forward mode). These additional delays lead to longer network inactivity periods (idle channel) that must be considered when setting the Slot Time parameter (T_{SL}) (see Section 3.1).

Assume the scenario of Figure 2, where a single logical ring exists. For example, if master M8 wants to access slave S6, the Link Stations LS2, LS1, LS3 and LS4 will be used to relay the request. Each Link Station will introduce a delay of Δ, depending on the type of repeater used. So, the time elapsed between the end of request transmission in M8 and receiving the indication in S6 is equal to $3\times\Delta$, (in a simplified form) for further details the reader is referred to [7].

The setting of the Slot Time must take these delays into consideration, including also the slave's reaction time and the response/acknowledge delays (response will also be relayed back to the master though the same LSs and LBSs). As it was proved in [8], and in order to encompass different bit rates (and/or frame formats) in heterogeneous media, there may be the need to insert extra idle time between consecutive message requests.

Note that T_{SL} must be set according to the previously mentioned delays, considering that:

- If the initiator of a message cycle does not receive anything during a *Slot Time* it will retry (depending of the value of the *max_retry_limit* FDL variable);
- A master claims the token after an inactivity time equal to the *Timeout Timer*: $T_{TO} = 6 \times T_{SL} + 2 \times n \times T_{SL}$, where n is the master's address.

The problem associated to the setting of T_{SL} is a very complex one, since not only latencies in message transfers are concerned, but, also importantly, reduction in network responsiveness to failures is also concerned. This happens because the time to detect a message/token loss or a station failure may significantly increase due to an increase of the slot time parameter.

Moreover, the frequently needed addition/removal of stations (due to non-connectivity periods), which is supported by PROFIBUS ring management, also impacts responsiveness. For instance, in order to have the Gap List always updated, there is the need to set a small G value in $T_{GUD} = G \times T_{TR}$ (G is the *Gap Update Factor*, a PROFIBUS FDL variable). This will lead to an increased flow of low-priority messages that will prejudice low-priority traffic and may affect the response time of high-priority traffic.

5. A MLR Solution Using Bridges/Routers as Intermediate Systems

An alternative to repeaters is the division of the network in several bus segments with independent token management, thus leading to a multiple logical ring (MLR) solution, with more than one token circulating in the overall system.

5.1 Bridges/Routers vs. Repeaters

The pros and cons of using bridges/routers instead of repeaters must be carefully weighed. The decision whether to use repeater or bridge/routers is, among other aspects, dependent on the following issues:

- Are there segments with different characteristics (speed, media, etc.)?
- Is there the interest for having different FDL parameters for each segment (for instance, *Slot Time*)?
- Is there a lot of inter-segment traffic, or can an adequate system planning locate stations in a way that it becomes not significant?
- Is it worthwhile to reduce the token rotation time, allowing simultaneous traffic flowing in different segments?
- What are the latencies imposed by repeater and bridge/router solutions?

- Are there stations/applications more critical than other, and may a less reliable (wireless, mobile) station risk the behaviour of a more critical one?
- Can the system cope with a low responsiveness to failures?

The solution described in Section 4 assumes a single logical ring. As a consequence, the overall system depends on the token being correctly passed to and from wireless masters. Due to both the non-optimal communications of wireless masters with the rest of the network under certain conditions and the fact that wireless masters will have to switch between different radio channels, problems may arise. In fact, a lost token implies an additional delay that may prevent the real-time behaviour of the system. Therefore, non-critical wireless masters may degrade the timing behaviour and dependability of other (critical) network components.

Additionally, the MLR solution provides for traffic segmentation, (thus improved responsiveness for transactions in the same logical ring) and error containment within each domain. However, the delay when a station wants to communicate with another in a different logical ring will be higher than in a single logical ring solution (further analysis on this topic is provided in Section 7). Additionally, the Link Stations will have to support larger buffers than repeaters.

The Link Stations for the MLR solution have to comprise two masters, one belonging to the Wired Domain and another belonging to the Wireless Domain. As it will be seen, this type of ISs demands a kind of explicit registration of mobile nodes. However, as it will be explained, these mechanisms can easily be built upon the PROFIBUS ring maintenance mechanisms described in Section 3.

We consider three versions of the MLR solution: *Domain-Driven*, *Wireless-Master-Driven* and *Domain-Group-Driven*, which will be further described next.

Depending on the adopted technology, an IS may act as a Bridge or as a Router. Therefore, we call it *Brouter Link Station*, from now on.

5.2 Brouters in a Domain-driven Version

In the domain-driven MLR version, each (wired/wireless) domain has its own logical ring. This implies that each Link Station will include two masters: one connected to the wired segment and the other communicating with the wireless stations inside its coverage area. This is illustrated in Figure 4. It shows an example with 5 different logical rings (the real addresses should be in ascending order): {(M8 → M5→ M12), (M3 → M11), (M7 → M1 → M9 → M2), (M10 → M6 → M14), (M13 → M4)}.

If an IS acts as a bridge, the routing is performed on MAC addresses. Traffic is relayed from one port to the other if the destination address is included in a routing table of the incoming side. Obviously two tables must exist in the Brouter Link Station (each one for each port). The bridging solution allows for the use of a single address space. However, it implies that masters belonging to Brouter Link Stations should read all frames even if the destination address does not correspond to their address.

If the Brouter Link Station is acting as a router, then the routing is performed on network layer addresses (e.g., like IP). This implies that masters in Brouter Link Stations read all incoming frames and parse them to obtain network layer addresses. This solution demands the use of a network layer in every station.

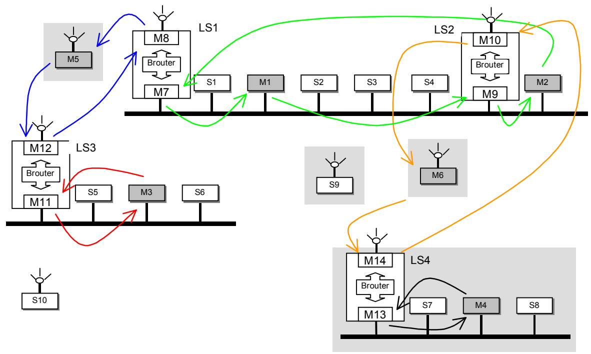

Figure 4. Domain-driven MLR version.

Wireless communications can be based on a multiple-channel system (similarly to the solution presented in Section 4). Wireless stations that belong to the same logical ring use the same radio channel. These include wireless masters (also those belonging to Brouter Link Stations) and wireless slaves.

Wireless/mobile stations are able to change from one wireless domain to another by means of the handoff mechanism described in Section 6.

5.3 Brouters/Repeaters in a Wireless-master-driven Version

The previous domain-driven MLR version overcomes the problem that wireless masters may prejudice the behaviour of wired nodes. Nevertheless, a wireless master can still prejudice the behaviour of other wireless stations in the same logical ring. Thus, a wireless-master driven approach is suggested. This mixes LSs acting as repeaters dedicated to wireless slaves and LSs that act as a Brouter Link Station (dedicated to one wireless master at a time). In this solution there is one "main" logical ring, plus an additional one per wireless master (Figure 5).

Referring to Figure 5, there are two Brouter Link Stations dedicated to wireless masters (LS1 and LS2), and three Link Stations dedicated to wireless slaves (LS3, LS4 and LS5), which are acting as repeaters. In the particular situation presented in the figure, three distinct logical rings exist (the real addresses should be in ascending order): {(M5 → M8), (M7 → M1 → M9 → M2 → M4 → M3), (M6 → M10)}.

It is obvious that, in this case, mobile/wireless masters can only access the network if they are in the range of the Wireless Domains defined by LS1 or LS2.

Slave nodes will be able to move between Link Stations using the same methods described in [7].

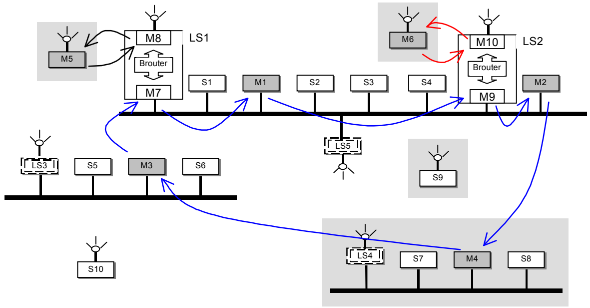

Figure 5. Wireless-master-driven MLR version.

5.4 Brouters/Repeaters in a Domain-group-driven Version

This version of the MLR system assumes that domains will be grouped in Domain Groups. A Domain Group is a set of wired and/or wireless domains sharing the same logical ring and interconnected through the use of repeaters (small latency). The communication between different Domain Groups is achieved via Brouter Link Stations (higher latency).
This version is different from the wireless-master-driven one since here the Brouter Link Stations serve as Link Stations not only for wireless masters but also for wireless slaves. This solution permits to reduce communication latency between domains belonging to the same logical ring (domain group), while providing for "traffic isolation" to other domains.

An exemplifying scenario of the domain-group-driven MLR version is depicted in Figure 6. In this scenario, a direct link network is considered, but Base Stations may also be used, as in the other versions. In order to avoid traffic interference between Domain Group 1 and Domain Group 2, a Brouter Link Station is used instead of a repeater, in LS1.

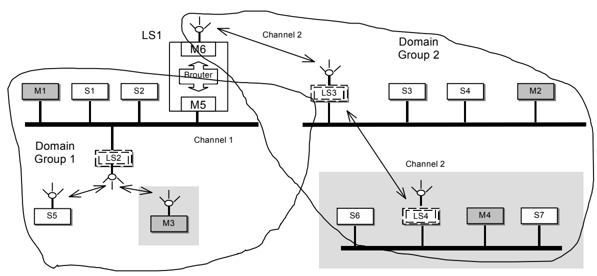

Figure 6. Domain-group-driven MLR version.

The Brouter Link Stations (LS1) separates the network into two logical rings, one comprising M1, M3 and M5 and the other composed by M2, M4 and M6. All the stations belonging to the same Domain Group share the same logical ring, even if they belong to different Domains (M1 and S5, for example). Therefore, the communication between stations sharing the same Domain Group (e.g. M1 and S5) has smaller latency than the communication between two stations belonging to different Domain Groups (e.g. M1 and S3).

It is obvious that LS1 will have to maintain a registering table with all the addresses from both sides of the network. This way, mobility is supported, allowing wireless stations to move (e.g. M3 moving and joining Domain Group 2). The registering mechanism may be the same as in the previously described MLR versions.

6. Some Details on the Inter-cell Mobility Support in MLR Networks

The mobility of a node between different radio cells is supported by the handoff mechanism. During this procedure a node will have to de-register from the original wireless domain, switch to the new channel of the destination wireless domain and register in the new wireless domain before it can start communicating. In this section we will describe how the native PROFIBUS functionalities can be used to support the handoff procedure.

6.1 Routing Tables - Providing "Registering" of Wireless Nodes

Brouter Link Stations will have to perform a filtering function, i.e., they should only parse messages whose destination station belongs to another domain (another logical ring). Each Brouter Link Station will have to support two routing/bridging tables that will have information specifying the nodes that are beyond its wireless side (denoted as *wl* in Table 1) and the nodes beyond its wired side (denoted as *wr* in Table 1). This will give information that will allow a Brouter Link Station to route the received frames to the correct side of the network. Table 1 presents a routing table example for some of the nodes on the scenario depicted in Figure 4.

	LS1		LS2		LS3		LS4	
	wl	wd	wl	wd	wl	wd	wl	wd
M1	✓		✓			✓		✓
M3		✓	✓		✓			✓
M4	✓			✓		✓	✓	
M5		✓	✓			✓		✓
M6	✓			✓		✓		✓
S1	✓		✓			✓		✓
S5		✓	✓		✓			✓
S7	✓			✓		✓	✓	
S9	✓			✓		✓		✓
S10		✓	✓		✓			✓

Table 1. Routing tables of the Brouter Link Stations.

It is obvious that to support the relaying mechanism, the masters included in the Brouter Link Station must be implemented in a different way, i.e, they must parse all frames, independently of the destination address. This allows for a master to check if the destination address belongs or not to its routing table.

Referring to Figure 4, if M5 sends a frame to S2, both M8 (in LS1) and M12 (in LS3) will receive the frame. M12 receives the frame, detects that the destination address is not in its registering table, so it does not relay the frame. On the other hand, M8 notices that the destination address (S2) is in its registration table, so it relays the frame to the wired segment.

One can easily figure out that if mobility (inter-cell mobility) features were not considered, it would be sufficient to have static tables configured prior to run-time. Without mobility, Table 1 would not have to be changed. In order to support inter-cell mobility, the routing tables must be updated dynamically (through adequate protocols and services), as it is outlined in the following example.

Let us consider that S9 moves to the logical ring defined by M8, M5 and M12. The routing tables must change, as illustrated in Table 2, in order to reflect this new operational scenario.

	LS1		LS2		LS3		LS4	
	wl	wd	wl	wd	wl	wd	wl	wd
S9	✕	✓	✓	✕		✓		✓

Table 2. Changes in the routing tables.

While the registering tables in LS3 and LS4 do not change, the registering tables in LS1 and LS2 must reflect the dislocation of S9.

6.2 Handoff Using the Native PROFIBUS Mechanisms

The PROFIBUS network already provides several functionalities to support the ring maintenance and the passage of the token between masters, as described in Section 3. This MLR solution can efficiently exploit these functionalities to support handoff between wireless cells. The handoff procedure is different for mobile masters, slaves and wired domains, so, each one will be described separately.

6.2.1 Master's handoff procedure

<u>Assessment phase</u>

During the assessment phase a node evaluates the quality of other radio channels. This should be done with minimal interference with the system operation, especially without generating any errors.

The assessment phase consist in switching the radio receiver to another frequency, receive all or part of a frame, store its quality value, switch to another frequency and repeat the same procedure until all the possible frequencies were scanned. At the end of this procedure the node must decide if it wants to handoff. Of course, during this period, the node will not be able perform any transactions.

One possibility is that periodically one of the wireless domain Brouter Link Station, the *mobility master*, creates an artificial period without communications, which can be used by the stations to make the assessment of the other channels. This will prevent the occurrence of errors due to the inaccessibility of nodes.

This period is created, during part of the wireless master Brouter Link Station token holding time by the transmission of special beacon frames. The duration of the beacon frames periods must be enough for the master nodes to make the assessment of adjacent channels, Figure 7.

The assessment phase periodicity depends on the mobile node speed and the characteristics of the overlapping area of the two cells.

With the information about the quality of the adjacent channels, now the master can decide if it wants to handoff or not and to which channel.

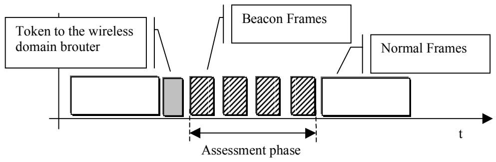

Figure 7. Assessment phase.

<u>Channel switching</u>

At this point the node stops its operation in the original channel and switches to the new one.

<u>De-registering</u>

This phase occurs in parallel with the entrance in the new logical ring.

The de-registering is not made explicitly, since the leaving master station must be detected by other master stations by means of the ring maintenance mechanisms, as described in Section 3.

The consequence of this process is that errors may occur if there is the arrival of messages addressed to the moving node after the switching. Also, the detection of the successor node by the predecessor of the moving station will evolve the execution of several message cycles.

Additionally, this process may take a considerable amount of time, thus contributing to the token delay on the original domain, and reducing its performance.

<u>Entrance in the new logical ring</u>

The entrance on the new ring is made by the use of the GAP update mechanism. Using this mechanism, master stations periodically send *FDL_Request_Status* frames in order to detect if there are any master station with address higher than its address and smaller than its successor, ready to enter the logical ring.

The periodicity of this mechanism is determined by the Gap Update parameter, which is given by the expression: $T_{GUD} = G \times T_{TR}$, thus the G factor must be set to a sufficiently low value so that the handoff latency is reduced. Nevertheless, this will increase the overhead of the logical ring maintenance, thus decreasing the performance of the network.

When a Brouter Link Station in the new logical ring detects the presence of a new node, then it broadcasts this information to all the other Brouter Link Stations in the network, which will update their routing tables accordingly. This detection can be made either by the reception of a message from the mobile master or by means of the live list mechanism. Obviously, *FDL_Request_Status* frames must not be forwarded by the Brouter Link Stations to other domains.

6.2.2 Slave's handoff procedure

The Assessment phase and Channel switching are similar to the master case. The other phases are described next.

De-registering

Like in the case of master nodes the de-registering phase is not made explicitly. In PROFIBUS each master contains a list of active stations (LAS), which is cyclically updated using a *FDL_Request_Status* frame. In this case, if the slave node does not answer, it is withdrawn from the LAS list.

Entrance in the new logical ring

The entrance on the new ring is made using an equivalent procedure to de-registering. Each master periodically updates its LAS table using a *FDL_Request_Status* frame. When one of the domain Brouter Link Stations detects the presence of the slave node, that information is broadcast to all other Brouter Link Stations on the network.

6.2.3 Mobile wired domain handoff procedure

In this case we will have to consider two cases. In the first one the mobile wired domain contains a LS that acts as a repeater. In the second case, the LS is a Brouter.

For both cases the assessment phase and the channel switching are similar to the master case and should be done by the wired domain LS.

De-registering

On the first case when the wired domain LS switches to the new wired domain, the original domain will detect (using the mechanism described for the master and slave case) that the mobile wired domain nodes had changed its domain.

On the second case only the absence of the LS wireless master will be detected on the original domain using the master de-registering mechanisms.

Entrance on the new ring

The nodes on the first case will use the same mechanism has described for the master and slave case.

On the second case, only the Brouter's wireless master will enter the new domain ring. So, the LS (a Brouter) must be responsible for the updating of all the network Brouter routing tables.

7. Worst-Case Response Time Analysis (WCRT)

The PROFIBUS medium access control (MAC) protocol is based on a token passing procedure (simplified version of the timed token protocol [9]) used by masters to grant the bus access to each one of them, and a master-slave procedure used by masters to communicate with slaves.

The timing properties of the PROFIBUS protocol have been a focus of research. In [3] the authors suggest two different approaches to guarantee the real-time behaviour of the synchronous traffic in the PROFIBUS networks. In one of the approaches – the *Unconstrained Low Priority Traffic Profile*, the real-time requirements for the synchronous traffic are satisfied, even when only one synchronous message is transmitted per token visit, independently of the asynchronous traffic load. In this way, it is possible to have a guaranteed real-time approach for the message streams provided that the relative deadline for the synchronous message streams is larger than the worst-case message response time, which is given by:

$$R_i^k = Q^k + Ch_i^k = nh^k \times T_{cycle}^k + Ch_i^k \quad (1)$$

where nh^k is the number of synchronous message streams generated in master k, T^k_{cycle} is the worst-case token rotation time and Ch_i^k is the worst-case duration of synchronous message cycle i issued by master k. The exact characterisation of the cycle time properties of the PROFIBUS token is described in [4], which permits the evaluation the T^k_{cycle} parameter in equation (1). An upper bound on the token cycle time can be given by:

$$T_{cycle}^k = T_{TR} + n \times C_\sigma \quad (2)$$

where T_{TR} is the PROFIBUS target token rotation time, n is the number of masters and C_σ is the longest message cycle in the network.

7.1 WCRT for Inter-domain Transactions

In PROFIBUS, a message cycle is composed by a request and related response. As explained in Section 3, when a master makes a request, the response should arrive within the slot time. The use of Brouters as intermediate systems demand breaking down this message cycle concept. In fact, when the master sends a request destined to a node outside its own domain, the Brouter Link Station must send a response frame to the initiator specifying that the response will arrive later. Some PROFIBUS FDL services do not require an answer (unacknowledged requests). In these cases the Brouter Link Stations must simply forward the request without answering the initiator. The system Brouter Link Station can use the information about the type of frame, which is contained, on the FC field of a PROFIBUS frame [1].

For the scenario described in Figure 4, and concerning transactions between master M1 and slave S5, Figure 8 depicts the sequence of transactions.

The problem of evaluating the worst-case response time (WCRT) for high priority PROFIBUS transactions in a SLR scenario has been addressed in [3-5], and strictly applies to the case of intra-domain transactions.

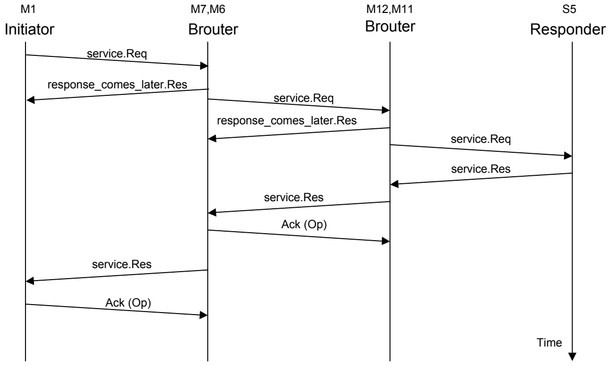

Figure 8. Inter-domain transactions.

To evaluate the WCRT for inter-domain transactions, analysis can be adapted from the P-NET networks case [10].

Considering the example of Figure 4, if a transaction concerning message stream S_i^1 is made between master M1 and slave S9, the response time is given by:

$$R_i^1 = nh^1 \times T_{cycle}^1 + Creq^1 + \phi + nh^9 \times T_{cycle}^2 + + Ch_i^2 + \phi + nh^{10} \times T_{cycle}^1 + Cresp_i^1 \quad (3)$$

nh^1 is the number of high priority message streams generated in master M1 and T^1_{cycle} is the token cycle time in network domain 1. C_{req}^1 is the duration of the request frame in network domain 1. The symbol ϕ represents the time needed by the Brouter Link Stations to forward the request.

$nh^9 \times T^2_{cycle}$ and $nh^{10} \times T^1_{cycle}$ are the queuing delays on the masters M9 and M10 (of the Link Station), respectively. Ch_i^2 is the transaction duration time between M9 and S9 and $Cresp_i^1$ is the duration of the response frame and other associated latencies.

Generalising equation (3), we consider that each request is forwarded from the initiator to the responder through b Brouters and that the first Brouter master on the path, from the initiator to the responder, is numbered as r_1 and the last master is numbered as r_{2b}. The network domains are numbered on the same order, being the first domain of the path, domain number 1 and the last domain numbered as $b+1$.

Taking this into consideration the WCRT for inter-domain transactions can be calculated as follows:

$$\begin{aligned} R_i^k &= nh^k \times T_{cycle}^k + (Creq_i^k)^1 + b \times \phi + \\ &+ \sum_{f=1}^{b-1} (nh^{r_{2f}} \times T_{cycle}^{r_{2f}} + (Creq_i^k)^{f+1}) + \\ &+ nh^{r_{2b}} \times T_{cycle}^{r_{2b}} + (Ch_i^k)^{b+1} + \\ &+ b \times \phi + \sum_{f=2}^{b} (nh^{r_{2f-1}} \times T_{cycle}^{r_{2f-1}} + (Cresp_i^k)^f) + \\ &+ nh^{r1} \times T_{cycle}^{r1} + (Cresp_i^k)^1 \end{aligned} \quad (4)$$

where $(Cresp_i^k)^s, (Creq_i^k)^s, (Ch_i^k)^s$ are respectively the time needed to transmit: the response, the request and for completing the message cycle on network domain s. In the Brouters case, nh^x is equal to the number o inter-domain message streams being relayed by Brouter Link Station master x.

The calculation of Ch_i^k can be made using the following equation:

$$Ch_i^k = T_{ID1} + C'req + T_{SL} + C'resp \quad (5)$$

where, T_{ID1} is the duration of the idle time after the receipt of an acknowledge/response/token by master i. $C'req$ and $C'resp$ are respectively the duration of the request and response frame. T_{SL} is the slot time parameter.

Based on equation (5), we can now determine the values of $(Cresp_i^k)^s$ and $(Creq_i^k)^s$, as follows:

$$\begin{aligned} (Creq_i^k)^s &= T_{ID1} + C'req \\ (Cresp_i^k)^s &= T_{SL} + C'resp \end{aligned} \quad (6)$$

7.2 Numerical Example

In this sub-section we illustrate how the MLR approach improves the response time for intra-domain transactions. To simplify the example (but without loss of generality) we consider a network with wired nodes only. We assume that the T_{TR} parameter is equal to 1ms and will be the same in both SLR and MLR networks. We also assume that: T_{SL} is equal to 250µs, T_{ID1} is equal to 100µs. Thus, if $C'req$ is equal to 100µs and $C'resp$ is equal to 80µs then $(Cresp_i^k)^s$ will be equal to 330µs, $(Creq_i^k)^s$ will be equal to 200µs and Ch_i^k will be equal to 530µs. In the example we presuppose that all domains of the MLR network have the same characteristics.

The exemplifying scenario is represented in Figure 9 (for the SLR), and its MLR counterpart on Figure 10.

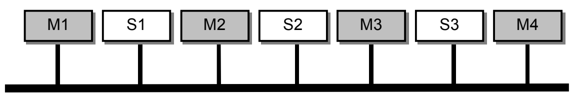

Figure 9. SLR network.

All message transactions generated in a master will have similar WCRT (implicit from equation (1)). Table 3 gives the number of streams and related response time for all four masters in the SLR scenario.

Master	nh^k	R^k_i (ms)
M1	15	47.33
M2	5	16.13
M3	6	19.25
M4	7	22.37

Table 3. SLR network response time.

The overall responsiveness of the network can be improved if MLR is used (Figure 10). The reasoning for the nodes breakdown between domains relies on the eventuality that most of the transactions generated in M1 are with S1, M2 are with S2 and M3/M4 with S3.

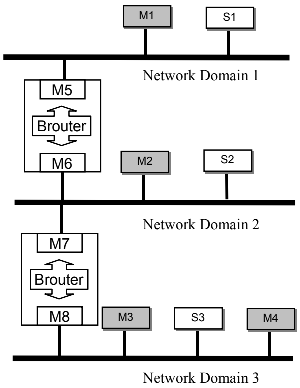

Figure 10. MLR network scenario.

For the example, we still consider that it will exist inter-domain transactions between M1/S2, M1/S3, M2/S3 and M4/S1.

The inter-domain network traffic will originate message streams in the Brouter Link Station masters, respectively 2 in M5 and 3 on the remaining masters.

In Table 6, we present the WCRT for intra-domain transactions (applying equation (1)).

Master	nh^k	n	T_{cycle} **(ms)**	R^k_i **(ms)**
M1	15	2	2.06	31.43
M2	5	3	2.59	13.48
M3	6	3	2.59	16.07
M4	7	3	2.59	18.66

Table 4. Intra-domain message response time.

For inter-domain transactions, the results (applying equation (4) with ϕ equal to 0.3ms) are as illustrated in Table 5.

Stream	**Nodes**	R^k_i ***(ms)***
Sh_2^1	***M1-S2***	44.45
Sh_3^1	***M1-S3***	61.12
Sh_2^2	***M2-S3***	30.15
Sh_4^4	***M4-S1***	48.35

Table 5. Inter-domain message response time.

As it can be seen from the comparison between the WCRT obtained in Tables 6 and 3, there is a significant reduction on the intra-domain WCRT. While the values for inter-domain transactions present a not much higher value, except for the case of transactions between M1 and S2 that sees its response time reduced in relation to the SLR situation (Table 7 as compared to Table 3). This last event becomes even more noticed if the number o message stream related to master M1 tends to be higher.

8. Conclusions

In this paper we analysed several solutions that enable PROFIBUS networks to support hybrid wired/wireless communication. Special focus was given to multiple logical ring (MLR) approaches supported by bridges/routers. The main drawback of solutions based on repeaters is the negative impact on the system responsiveness to failures and on the network reliability. Additionally, message responsiveness is also penalised in applications where transactions occur, in majority, between groups of nodes. Multiple logical ring solutions are able to overcome these disadvantages.

9. References

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