# Industrial Ethernet: Building Blocks for a Holistic Approach

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## Abstract

*For industrial environments it is true that Ethernet technologies are there to stay. In fact, a number of characteristics are boosting the eagerness of extending Ethernet to also cover factory-floor applications. Full-duplex links, non-blocking and priority-based switching, bandwidth availability, just to mention a few, are characteristics upon which that eagerness is building up.*

*But, will Ethernet technologies really manage to replace traditional field bus networks?*

*Fieldbus fundamentalists often argue that the two things are not comparable. In fact, Ethernet technology, by itself, does not include features above the lower layers of the OSI communication model. Where are the higher layers and the application enablers that permit building real industrial applications? And, taking for free that they are available, what is the impact of those protocols, mechanisms and application models on the overall performance of Ethernet-based distributed factory-floor applications?*

## 1. Introduction

Arguments against Ethernet in industrial environments have almost disappeared. “Familiarity”, “high availability” (subsequently, low cost) and improved timeliness and dependability are driving this phenomenon. But still, there are obstacles to overcome.

The control community argues that Ethernet itself does not include any features above data link layer. TCP/UDP/IP protocols can of course be used to fill up some of the layers above Ethernet. However, what about layers above the transport layer? Moreover, which performance characteristics will be attained with the ensemble?

Recent research efforts on Ethernet technologies have been focusing on timeliness, trying to find solutions to issues such as bounded response time, optimal scheduling policies, switching topologies or clock synchronisation. Essentially, they consider the timing characteristics at the Data Link Layer. How do these approaches extend to provide timeliness guarantees up to the application level? This is the topic of an ongoing research which has recently started within the IPP-HURRAY research group [1]. The goal is to address holistic approaches to Ethernet based industrial systems.

The rest of this paper is organised as follows. In Section 2 a survey of research works that are driving the eagerness towards using Ethernet for time-critical factory floor applications is provided. In Section 3 we introduce the missing item for the holistic approach: consideration of suitable upper level protocols and application models on top of Ethernet technologies. Section 4 describes some commercially available proposals to fill up that gap. Finally, in Section 5, on-going work is briefly outlined.

## 2. What Gives Ethernet a Factory-floor Flavour?

### 2.1. Physical Layer

Ethernet must be rugged enough for harsh environments. Robustness against vibration demands the use of industrialised Ethernet connectors, instead of the usual RJ45 connectors. Additionally, Ethernet cable must offer adequate immunity against electromagnetic interference, harsh chemicals, and high humidity and extended temperature ranges. Regulation for installing and verifying the physical media is being standardised, and some hints on main options can be found in [2].

Another issue that is going under standardisation process (IEEE 802.3af) is how to power field devices over Ethernet cables.

### 2.2. Switching and Network Topologies

With switched-Ethernet technology, systems can be built that realise a completely deterministic behaviour. Typically each end system (station or device) of the network must have its own intermediate system (switch) port. If the connection between the end system (ES) and the intermediate system (IS) is realised through full duplex connections, no collisions on the medium occur, thus removing one of the obstacles to achieve determinism in Ethernet-based systems.

Different topologies can be used to interconnect ESs through switches. Examples are the line (switches

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connected in bus), ring (switches connected in a physical ring) or tree topologies (hierarchy of switches - e.g., binary tree).
There has been a number of research works addressing the issue of finding out the influence of the topologies in the overall performance of the network. Comparisons of line, ring and tree topologies have been carried in [3]. In this particular work, tree topologies are shown to perform better in terms of cycle-time (receiving sensor input from all field devices and transmitting actuator output to all devices), although the number of switch levels influences the cycle time. Typically, the lower is the number of switch levels, the higher is the required number of ports per switch connecting to the ESs. However, a large number of ports may not be appropriate for typical factory-floor applications. On one hand, more ESs (located apart) need to connect to the same switch. This may mean extra cabling costs and lower system flexibility. On the other hand, a large number of switch levels may result in higher latencies and, definitely, the cost in switches will also increase.

Several research works have been focusing on finding optimal trade-offs. In [4], the authors propose an approach based on the use of spectral algorithms borrowed from the graph theory, to adjust the size of communication groups in regard the switches port number and the minimum interaction between groups. In that work, the performance evaluation calculates mean delay values but not end-to-end maximum delays or end-to-end jitters, which are important parameters for real-time distributed applications.

### 2.3. Switching and Quality of Service

The IEEE 802.1p standard has been introduced to improve the queuing characteristics inside the switches. The standard specifies a layer 2 mechanism for giving mission-critical data preferential dispatching over non-critical data. The concept has been driven by the multimedia industry, and is based on priority tagging of packets and implementation of multiple queues within the network elements in order to discriminate packets. For tagging purposes, the IEEE 802.1Q defines an extra field for the Ethernet MAC header.

Packet scheduling inside the switch has not been devoted a significant research effort, and this is one of the ongoing works.
Besides standard compliant devices, there has been also some proprietary switches proposed in the literature. For example, EtheReal is a scalable real-time Ethernet switch that can deliver connection oriented bandwidth guarantees without requiring any changes to the end host operating system and network hardware/software [5], which were some identified drawbacks of other attempts. EtheReal is implemented in software over standard Ethernet switches. It supports QoS, automatic fault detection and recovery mechanisms as well as server-side push applications with a guaranteed bandwidth link-layer multicast scheme. An alternative was developed to the standard propagation order spanning tree, in which is based the fault detection and recovery mechanism, because the 30s spanning tree algorithm execution (referred in IEEE 802.1D) was considered inadequate to operate within the constraints of real-time Ethernet [6].
A different device, the Synchronous Hybrid Router (SHR) is described in [7]. The basic idea behind SHR is to get the best from a router (forwarding for an infinite number of hops) and from a repeater (static short delay time), while retaining interoperability with conventional IP routers. There are two SHR working modes: shared mode, causing unpredictable transmission delay (conventional router behaviour); exclusive mode, just in case of time-critical packet transmission, acting as a repeater and reaching destination within a minimum delay. A synchronous changer selects the operating mode and the changing time is synchronised with all of SHRs by a network resource management system like in RSVP (Resource reSerVation Protocol). To guarantee end-to-end bounded delay values a resource reservation system (Synchronous Time Division Internet - STDI) between source and destination is used.

### 2.4. Shared Ethernet

In industrial environments, any device requiring hard real-time constraints or bandwidth intensive network access should be connected with full duplex to a single switch port. In less restrict conditions, shared-Ethernet may still be considered, and when, at field level, micro-segmentation is not affordable, hubs may eventually be used instead of switches.
Even so, the research works describing efforts that try to minimise or avoid collisions (the main cause for non-determinism) by modifying the Ethernet MAC access protocol will probably be discontinued. Proposals to control the network load, where the non real-time traffic in each station/device is limited (traffic smoothing) thus enabling bounded time delay for real-time traffic, are worth to be considered in the framework of our research goals. Traffic smoothing [8] and priority schemas [9] ensure the soft real-time characteristics, but also some modification in the Ethernet standard (or at the OS kernel) is required.

## 3. What is Missing: Holistic Approaches

The previous section described important but unstructured pieces of research on the use of Ethernet for

industrial environments. Moreover, the referred pieces of work are bounded, in terms of OSI layers, to at most layer 4.

This is one of the reasons why the fieldbus community usually fights back saying that the incomparable is being compared. Indeed, in industrial environments the applications must provide rather different functionalities of those provided by FTP, SMTP, HTTP, etc., the traditional IP-based application protocols that typically run on top of Ethernet.

The efforts made in order to provide the usual features of common control application protocols running over Ethernet consist, most of the times, on the integration of upper layer fieldbus protocol stacks on the top of the TCP/IP/Ethernet stack. There is indeed a lack of a general, overwhelming analysis, where the overall assemble is evaluated in terms of performance/behaviour.

Let us take the example of a remote I/O reading. In typical fieldbus networks (PROFIBUS, P-NET, etc.) this functionality is supported by a "read" application layer service which, in terms of lower layer communication services, is mapped into a message transaction. A message transaction may consist of a requester's action frame (request or send/request frame) and the associated responder's acknowledgement or response frame. User data may be transmitted in the action frame or in the response frame. Theoretically speaking, messages are generated by communicating tasks (application processes) running on the ESs.

In order to guarantee that the timing requirements are met, the communication delay between a sending task issuing a request, and the related receiving task being able to access that request, must be upper bounded. This total delay can be termed “end-to-end communication delay”, and, briefly speaking, is composed of the following four major components:

1. generation delay: time taken by the sender’s task to generate and issue the related message to the communication stack;
2. access delay: time taken by the message to gain local access to the communication medium;
3. transmission delay: time taken by the message to be transmitted in the communication medium;
4. delivery delay: time taken to process the message at the destination network node before finally delivering it to the destination task.

Assume again the reading of the remote I/O. For this simple case, the response time for the task results, briefly speaking, from the concatenation of 9 components (Fig. 1). The end-to-end communication delay starts when the sending task is released and starts competing with other running tasks on the sender-hosting computer. The task may suspend as soon as the message request is passed to the communications stack (①). Then, the message request waits in a queue (assuming a simplified stack protocol) until it gains access to the communication medium. This queuing delay depends on how the queue is implemented (first-come-first-served queue, priority queue, etc.) and how the medium access control (MAC) behaves (②). The message request is then transmitted. This time interval depends on the data rate and length of the transmission media and also depends on the propagation delay (③). Note that if ISs (e.g., switches) are used, this "propagation" turns out to be a more complex component.

The message indication is then queued in the remote communication stack (④). The receiving task processes the message indication, and performs the actual reading of the required data. The response frame is produced and queued (⑤). The message response will suffer similar types of delays. A queuing delay (again assuming a simplified stack protocol) in the remote transmitting queue (⑥), a transmission delay (⑦), a queuing delay in the local receiving queue (⑧), and finally the time for the local task to process the response (⑨).

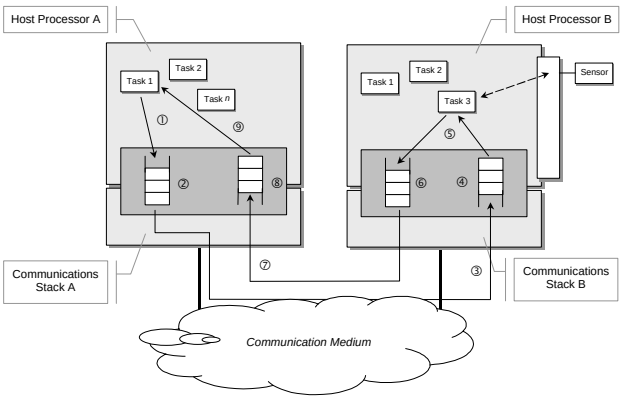


**Figure 1**

In terms of the response time analysis of communicating tasks, distribution brings the need to include the end-to-end communication delays, as one of the components of the overall task’s response time. This is a quite complex approach to real-time analysis, and it involves the provision of methodologies for the evaluation of the worst-case messages’ response times in the communication network, which are then "embedded" with the communicating task, operating system and communication stack models. We call this a holistic approach.

## 4. Higher Layer Solutions for Ethernet-based Systems

There have been some efforts to offer overall communication solutions for Ethernet-based systems. Some of the approaches are based on “encapsulation technologies” like Ethernet/IP [10]. The term

encapsulation is used to describe the embedding of a frame into a TCP or UDP container as "user data". The packet is then sent over Ethernet (ensuring downward compatibility to the respective field buses protocols). The disadvantage of encapsulation is that poor protocol efficiency may be attained.

Another interesting approach is the Interface for Distributed Automation (IDA) [11]. IDA was natively developed for Ethernet and Web technologies.

## 5. On Going Work

As referred in Section 2 the ongoing work is trying to put together some worst case response time analysis related with lower layers, considering essentially topologies, scheduling policies inside the switches and traffic distribution.

Additionally, and considering the holistic approach described in Section 3, our goal is how to map the overall Ethernet/IP (sketched in Fig. 2) stack or IDA stack into a model which briefly is outlined by Fig. 1.

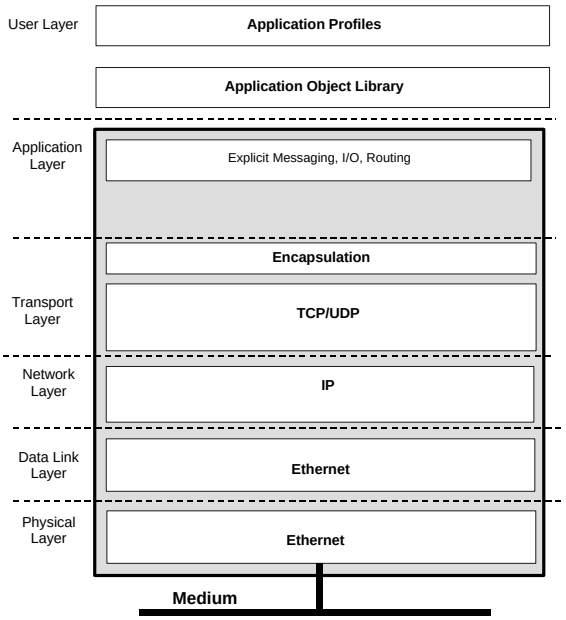


**Figure 2**

This will permit us to have a holistic worst-case response time of Ethernet/IP (or IDA) communicating tasks.

In parallel, we have recently started to evaluate the possibility of developing simulation modules (e.g., using a discrete event simulation tool such as OPNET [14]) in order to have complementary performance analysis (not based on the worst-case).

Finally, it is worth to mention that the current design practices in real-time systems are quite inadequate to address issues such as dynamic arrival of ESs. This may be a requirement as a result of system re-structuring or a result of the wireless/mobile nature of the ESs. Therefore, an important line of ongoing research consists of applying the models on-line to enable such type of functionalities while still guaranteeing timeliness. In one way this is related to the Real-Time Publish/Subscribe (RTPS) protocol of IDA. One of the functionalities of RTPS is to keep track, in the background, of "who is talking to whom" and automatically discover new applications in the network. This makes possible to build dynamic networks, where new applications join and leave the network. The challenge here will be to refine the real-time nature of this approach and consider it in both Ethernet/IP and IDA approaches.

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