ARCHITECTURES FOR AN INTEGRATED HYBRID (WIRED/WIRELESS) FIELDBUS

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ABSTRACT:
This paper examines two alternative architectures of a hybrid industrial networking structure, consisting of a wired part (conventional fieldbus) which is based on the Master/Slave communication model (as in the case of the EN50170 Std.) and a wireless extension based on the philosophy of a dominant wireless technology (like the IEEE802.11, HiperLAN etc.). The purpose of this work is to analyze the basic operational features of these architectures, their advantages/disadvantages, and to estimate the main factors of the message cycle (delay) time. Furthermore, new devices, which are required for the efficient interconnection of the wired and wireless segments of the integrated industrial network, are proposed.

1. INTRODUCTION

Communications play a dominant role in solving problems in an industrial environment. The use of a network (fieldbus) simplifies the traditional point-to-point connections of the field devices by introducing a bus topology. Several industrial networks have been developed to solve problems at the field as well as the shop floor level. The most influential among the fieldbuses, that already exist, are the WorldFIP, the PROFIBUS and the P-Net, which are parts of the European Fieldbus Standard CENELEC EN50170 [1].

A wireless industrial communication system is required to offer an overall performance comparable with that of existing wired fieldbus. Such a wireless system can extend the functionality of an existing fieldbus in order to cover additional important operational features, like the support of mobile control devices, the wireless connection of devices located in "difficult" places where the cabling effort is too high etc. Therefore, a wireless fieldbus structure will ease the resolution of problems found in manufacturing plants, some of which are the need for re-cabling or installation of new cables, as well as the connection of new, probably moving control devices like sensors and actuators.

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Generally, it is required an integrated design of a high performance wireless industrial system to be able to cope with the real-time control traffic, to guarantee interworking with existing communication infrastructure and to support mobility and probably industrial-type multimedia services (like audio, still images and low resolution video sequences).

In the past, low speed radio systems applied, mainly, at situations, in the process industries, where copper wires or fibbers are either uneconomic or technically unfeasible. Some other wireless versions of fieldbus systems, such as LonWorks, only address special application areas (Building Automation Management systems), providing a low-speed, not hard real-time communication infrastructure [2].

Recently, significant R&D effort has been spent in the framework of some European Programs regarding problem of the high-speed industrial wireless networking problem. Specifically, the ESPRIT Project OLCHFA addressed the issue of the development of a low–cost, 1 Mbit/s fieldbus based on the philosophy of the WorldFIP protocol (MPS version), providing some application services and tools to facilitate easy configuration and management of the network [3]. Also, the ESPRIT Project MOFDI is dealing with the development of a wireless industrial network, focused mainly on the wireless physical medium [4]. Finally, the recent IST Project R-Fieldbus deals with the problem of the wireless extension of existing fieldbus systems (EN50170 compatible), providing an integrated approach for high speed networking in a typical industrial related multi-media environment [5].

In this paper the basic concepts of two architectures of an integrated hybrid (wired/wireless) fieldbus are presented and analysed. The basic idea is to build a hybrid fieldbus, which will extend the features and capabilities of existing wired fieldbus architectures, focused especially on the fieldbus systems contained in the European Fieldbus Standard CENELEC EN50170. The main characteristic of these fieldbus systems is that they are based on the token and polling (master-slave) accessing mechanisms.

2. THE PROPOSED NETWORK ARCHITECTURES

This work is focused on the master / slave communication mechanism, which is used in a number of standard fieldbus systems. In this case, a master station (or node) commands one or more slaves, which respond by transmitting their reply (data packet) to the network. There are single- or multi-master systems, like the WorldFIP and PROFIBUS, respectively. In the case of the multiple masters, it is required a mechanism in order to ‘pass’ the control of the network from master to master. A typical example of such a network is the PROFIBUS, which uses the token passing protocol for passing the network control between the multiple masters. Therefore, every time one master has the right to communicate with its slaves for a certain amount of time.

The use of the standard token passing protocol imposes the existence of an explicit control packet, that is the Token Packet, which must be circulated between the multiple master stations of the system. It is known [6] that the loss of the token causes serious problems, affecting strongly the network performance and especially its real-time response. These problems may appear frequently in a harsh environment especially when wireless links are used, given that in this case the BER (Bit Error Rate) if high. Therefore, this work

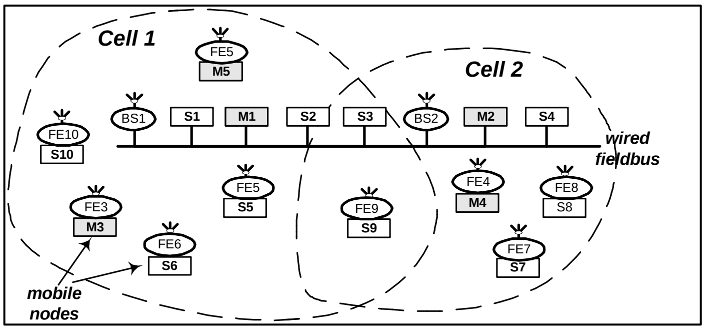

Figure 1. The Serial Architecture

will concentrate in the worst case of a fieldbus system consisting of multiple master and slave stations.

In this paper we present two alternative system architectures. The first (serial) architecture is based on the requirement of the ability to use existing fieldbus devices, which are compatible with the selected wired fieldbus network. On the other hand, the second (parallel) architecture provides better system response and system flexibility. However, this parallel architecture introduces new networking devices necessary for the proper networking operation.

2.1. THE SERIAL ARCHITECTURE

The serial system architecture is depicted in Fig.1. In this figure it is shown that there are only two special devices for the supporting of the wireless communications, that is the Front End (FE) and the Base Station (BS) devices.

The FE device is a multi-channel repeater connected to any existing (compatible to the selected wired fieldbus) master or slave device through its standard fieldbus connection, that is the serial RS485 fieldbus input/output.

The BS device is a multi-channel Base Station connected to the fixed wired fieldbus. It is assumed that each BS defines one radio cell. The multi-channel structure of these devices is required in order to overcome the problems of the overlapping of the operational areas. These problems have already been addressed in existing wireless technologies, like HiperLAN [7], IEEE802.11 [8] etc., and it can be assumed that they are solved in the physical layer.

The FE and BS devices act as store and forward repeaters, which means that messages will be stored before they are transmitted, due mainly to the need of packet encapsulation / decapsulation. Also, BS is used for either the communications between the wireless stations into its wireless domain (up-link, down-link) or the interconnection of its wireless domain with the wired (fixed) part of the system. An important feature of the BS is its ability for power management. Both FE and BS offer additional functionality for the wireless communications, like channel assessment, selection (handover mechanism) and scan, data error detection and correction/encryption.

The solution of the BS, instead of the direct communication between the mobile stations, is selected due mainly to the better radio coverage, as it is generally accepted that it increases the quality of the radio signal. So, the delay introduced by the use of BS is not high compared to the delay introduced in the direct link due to bad channel's quality (high Bit Error Rate), especially in the cases where an explicit token mechanism is used, as it is already mentioned. Also, BS can support handover mechanisms and broadcasting operation, as in many cases it is required for a fieldbus packet to be transmitted to every network section. Using BS simplifies the architecture of the mobile terminal, since frame parsing is implemented only to mobile terminals and frame construction is a dedicated process of the BS. Finally, the re-association function is more complicated than in a direct link mode scheme, given that every mobile terminal has to be aware about every terminal's position (within its coverage range or not).

The main advantage of this architecture is that conventional master and slave devices can be used with no modifications of their Data Link Layer (DLL). In this case, the additional functionality that is required by the wireless link will be implemented in a transparent way and will consist of an intermediate layer, called Wireless Intermediate Layer (WIL), between the DLL of the selected fieldbus and the wireless Physical Layer (PL). This WIL layer must guarantee the seamless interconnection with existing protocol modules (for instance existing ASICs) that implement the DLL of the selected fieldbus. Also, this WIL must implement all the necessary additional mechanisms, like the mobility, association / re-association and security mechanisms. It must be mentioned that the selection of the wireless PL (technology) must take into account the structure of the DLL of the adopted wired fieldbus, given that this wireless PL simply replaces the wired PL.

2.1.1. TIMING ANALYSIS

In order to estimate the delay performance of the proposed serial architecture, it is assumed that the wired fieldbus is the standard PROFIBUS network, which is based on a multiple master architecture and the explicit token mechanism. In this case, the possible communication scenarios are presented in the Table 1.

For each scenario, the maximum path distance can be calculated, measured in store & forward hops, along with the token or message cycle time (T_{TC} and T_{MC} respectively), according to the equations of the PROFIBUS Standard [1] for a single wired PROFIBUS segment, that is,

$$T_{TC} = T_{TF} + T_{TD} + T_{ID} \tag{1}$$

$$T_{MC} = T_{S/R} + T_{TD} + T_{SDR} + T_{A/R} + T_{TD} + T_{ID} \tag{2}$$

where:
T_{TF}: Token Frame Time
T_{TD}: Transmission Delay Time
T_{ID}: Idle Time
$T_{S/R}$: Send/Req. Time
T_{SDR}: Station Delay of Responders
$T_{A/R}$: Ack./Response Time

As an example, we can calculate the T_{TC} and T_{MC} for two indicative typical communication scenarios (scenarios 5 and 6 in Table 1), concerning token and message tra-

Table 1. Communication Scenarios

Receiver \ Transmitter		**Wired Segment Master**	**Mobile Master**
Wired Segment Master		Scenario 1	Scenario 3
Mobile Master	**Same Cell**	Scenario 2	Scenario 4
	Different Cell		Scenario 5
Fixed Segment Slave		Scenario 6	Scenario 8
Mobile Slave	**Same Cell**	Scenario 7	Scenario 9
	Different Cell		Scenario 10

nsmissions, respectively. It is assumed that there is the same bit-rate in the wire and the wireless parts, the communication links are error-free (no retransmissions, no lost tokens), there is zero delay inside the FEs and BSs, zero transmission delays (T_{TD} = 0) and zero RF switching time between Receive/Transmit modes. Furthermore, the values T_{TF}, $T_{S/R}$ and $T_{A/R}$ are multiplied in each scenario by the total number of transmissions of a frame passing the repeaters (number of hops + 1) until reaching the addressed node, while the values T_{ID} and T_{SDR} are equal with the time needed for the complete propagation of frame. Due to the fact that only one T_{ID} / T_{SDR} parameter is defined for a node for all frames (from the PROFIBUS standard), the propagation time value should be calculated for the maximum frame length in a network configuration.

Taking into account all these assumptions, the scenarios 5 and 7 are analysed as follows:

Scenario 5: A mobile master passes the token to a mobile master in a different cell.

Description: The FE Device of the mobile master M5 (FE5) stores & forwards the token to the cell's up-link. The BS of the segment's cell (BS1) stores the received token and forwards it both to the down-link of the same cell (where other FEs listen) and to the wired segment (M1, M2 receive). The rest of the BSs (BS2) receive from the wired segment and forward to the downlink of their cells. M4 will receive the data after the FE4, stores and forwards the token.

Max path distance: 4 store & forward operation, that is
Mx->FEx->BS1->BS2->FEy->My, so,

$$T_{TC} = 5T_{TF} + T_{ID} \quad (3)$$

Scenario 6*:* A master located on the wired segment transmits a request to a slave in the wired segment.

Description: S1, S2, S3 & S4 receive immediately. BS1 & BS2 store the received request and forward it through their downlink to both cells. The mobile nodes will listen after the store & forward operation of their FEs. S1 should respond after the completion of the previous path. BS1 & BS2 will initiate the repetition of the same procedure, that is, they

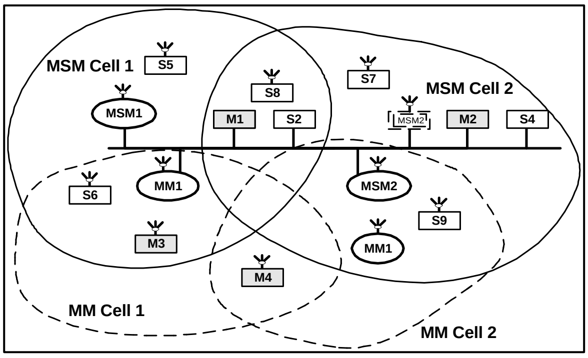

Figure 2. The Parallel Architecture

will store the received response and forward it through the down-link to both cells, where all mobile nodes will listen after the store & forward operation of their FEs.

Max path distance: 4 store & forward operations, that is M1->BSx->FEx->Sy, S1->BSx->FEx->My/Sy, so,

$$T_{MC} = T_{S/R} + \max\{2 \max T_{SR/AR}, T_{SDR}\} + T_{A/R} + \max(2 \max T_{TF/AR}, T_{ID}) \quad (4)$$

Following this methodology we can calculate the maximum delays (path distances) for all the possible operational scenarios, according to the serial system architecture. The main conclusion is that, due to the fact that the communication steps along the hybrid communication path are implemented in a serial way, the packet delays (message cycles) are, in general, high.

2.2. THE PARALLEL ARCHITECTURE

As it was mentioned in the previous section, the main disadvantage of the proposed serial architecture of the hybrid fieldbus system is the high message cycle time, due to the "serial" operation of the communication steps. Therefore, in order to overcome this disadvantage, it is proposed an advanced architecture where the wireless and wired parts work in parallel, as it is explained later in this section (Fig.2).

This approach offers the capability to select the most appropriate wireless technology for the proposed hybrid network. This selection can be based in many factors, like real-time performance, power consumption or efficient operation under harsh environment conditions.

This architecture offers higher performance in comparison with the previous one, but its implementation is more complicated since new devices have to be implemented.

In order the parallel operation of the wired and wireless parts of the system to be achieved, a new device, called Multi Slave Module (MSM), is introduced (Fig.3).

The MSM implements the protocol and all the necessary radio services (mobility, handover etc.) of the selected wireless system, acting as a BS. Moreover it acts as a concentrator gathering all the information for the operation of the wireless slaves, which are

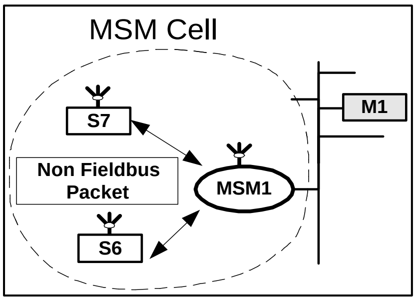

Figure 3. The Multi Slave Module (MSM)

located in its domain. On the other hand MSM implements the wired fieldbus protocol services on the wired side representing each one wireless slave.

The slave devices are new devices supported by the wireless interface (appropriate DLL and PL), which is defined by the selected wireless technology. These slave devices send the required fieldbus compatible data via the wireless network to the MSM. Such data could be input/output values, parameterisation data, alarms etc. MSM uses this information to create a database for each one of the wireless slaves in its domain. Therefore, MSM creates proxy representations (images) of the slaves in the wired part of the network.

According to this architecture, all the master-slave (wireless) communications actually take place between the master and the MSMs, which have the images of the wireless slaves. So, although the master 'talks' directly to a slave (the packet is addressed to the slave's address), it is the corresponding MSM that actually answers.

Images are created and destroyed dynamically when a slave enters or leaves the MSM cell. Although slave and master devices compatible with the selected wired fieldbus could be used in the wire line side, only the new slave devices can exist in the wireless side.

The configuration of the MSM devices can be achieved easily if they are considered as wired slave devices.

Concerning the operation of a wireless master, it must be mentioned that generally it is required that a master must "listen" continuously all the information transmitted (as in the case of the PROFIBUS protocol).

Therefore, it is required a new device that will transmit continuously the traffic of the wire line side to the corresponding wireless master (and vice versa). Such a device, which can be considered as a repeater, is called Master Mapper (MM) (Fig 4). Using a pair of frequencies for transmission and reception the device can support more than one masters in the same cell.

2.2.1. SYSTEM RESPONSE TIME

In the proposed parallel architecture the reaction time of the integrated network is not affected directly by the performance of the wireless part of system, since the two parts operate in parallel.

Specifically, the worst case, concerning the message cycle time, occurs when a wireless master communicates with a wireless slave located in any wireless domain, as it is depicted

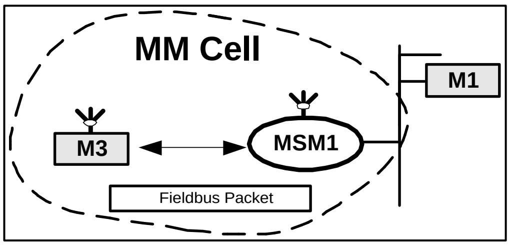

Figure 4. The Master Mapper (MM)

in Fig.3. A wireless master initiates this communication (request) through the corresponding MM device. This communication transaction is concluded in the corresponding MSM device, which provides the image of the specific radio slave. The reply of the slave will follow the opposite direction. Therefore, this procedure will only extend the normal message cycle time, T_{MC}, of the wireline system with the delay added by the wireless link between the wireless master and the corresponding MM device, that is,

$$T_{MC} = T_{MC\_WIRED} + 2T_{M/MM} \qquad (5)$$

where,
T_{MC_WIRED}: Message cycle time of the wired fieldbus
$T_{M/MM}$: Transmission delay time between wireless Master and MM.

According to the mentioned communication scenario the images of the slave data, which are collected by the MSMs, may be "old" when they are requested by a master. This is true because the MSM uses a specific mechanism, which is defined by the selected wireless system, to collect information from all the slave nodes located in its domain. In many cases this mechanism implements a polling procedure. Therefore, the worst case appears when data from a specific wireless slave are requested by a master, just before this slave is to be polled. In this case, the image of the slave that will be sent (as a reply) to the requesting master, is "old" by a full radio polling cycle.

Concerning the token cycle time, T_{TC}, the worst case is when a wireless master transmits it to another wireless master. The following equation holds,

$$T_{TC} = T_{TC\_WIRED} + 2T_{M/MM} \qquad (6)$$

where,
T_{TC_WIRED}: Token cycle time of the wired fieldbus
$T_{M/MM}$: Transmission delay time between wireless Master and MM
given that the path of the token is defined as,

W. Master->MM->Wired.Fieldbus->MM->W. Master

From Eqs.5, 6 it is shown that the system overhead is the $2T_{M/MM}$ time. This delay overhead can be reduced if the transmission speed of the wireless part is higher than the speed of the wired segment. It is evident that the parallel architecture offers lower reaction time in comparison with the serial architecture.

3. CONCLUSIONS

In this work two network architectures are proposed for the design of a hybrid (wired/wireless) fieldbus, based on the master/slave communication scenario. The purpose of this work is to analyse the operational features of these architectures, their advantages and disadvantages, as well as to estimate the main factors of the message cycle time. The main characteristic of the first (serial) architecture is the ability to use existing master and slave devices supported by the necessary wireless interface. The structure of the second (parallel) architecture provides higher flexibility and lower reaction times due to the fact the wired and the wireless parts of the system operate in parallel.

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