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Timing Analysis of an Inter-Cell Mobility Procedure for a Wired/Wireless PROFIBUS Network

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Abstract. Recently, there have been a few research efforts towards extending the capabilities of fieldbus networks to encompass wireless support. In previous works we have proposed a hybrid wired/wireless PROFIBUS network solution where the interconnection between the heterogeneous communication media was accomplished through bridge-like interconnecting devices. The resulting networking architecture embraced a Multiple Logical Ring (MLR) approach, thus with multiple independent tokens, where the communication between different domains was supported by the Inter-Domain Protocol (IDP). The proposed architecture also supports mobility of stations between different wireless cells. To that hybrid wired/wireless networking architecture we have proposed a worst-case response timing analysis of the IDP, without considering inter-cell mobility (or handoff) of stations. In this paper, we advance that previous work by proposing a worst-case timing analysis of the mobility procedure.

1 Introduction

There has been an enormous eagerness towards extending the capabilities of fieldbus networks to encompass wireless support [12-13, 15]. The RFieldbus European project [1-2] was just one example of that effort, where PROFIBUS (acronym for Process Field Bus) [11] was extended to support hybrid wired/wireless communication systems. In RFieldbus, repeaters were used to provide interoperability between wired and wireless network components. In any case, in the RFieldbus approach there is only one Single Logical Ring (SLR), therefore with only one token rotating between all the masters (wired or wireless) in the network. The main advantage of such SLR approach is that the effort is not significant for protocol extensions to PROFIBUS, since the adaptation is essentially at the physical layer level.

However, there are a number of advantages in using a Multiple Logical Ring (MLR) approach to support such type of hybrid systems. This concept was introduced and discussed in [3], and further detailed in [4-5], where a bridge-based approach (thus, layer 2 interoperability) was outlined. Each logical ring is comprised of stations that communicate via a unique medium – a domain. Therefore, a wired domain corresponds to the set of (wired) stations that intercommunicate via a wired segment. Correspondingly, a wireless domain is a set of (wireless) stations intercommunicating via the air. Those works describe the functionalities provided by the Inter-Domain Protocol (IDP), which enables the communication between stations in different domains. They also describe the mechanisms and functionalities that allow the mobility of wireless stations between different wireless cells. These protocol extensions can be supported with mostly no impact to the original PROFIBUS protocol, and thus, those extensions provide compatibility with legacy PROFIBUS technologies.

In a more recent work [14], we proposed a worst-case timing analysis for the IDP transactions. This work addressed an hybrid wired/wireless architecture on which wireless station were not able to move between wireless cells, thus not considering the inter-cell mobility protocols on the Worst-Case Response Time (WCRT) of the various types of message transactions. In this paper, we advance that work by proposing a worst-case timing analysis for the inter-cell mobility procedure.

Other works had also suggested the extension of the PROFIBUS standard to support wireless communications. In [12, 15], the authors propose an approach which uses a gateway between the wired PROFIBUS network and the wireless IEEE 802.11 network, This gateway acts as a proxy, periodically polling the wireless nodes and retrieving responses to wired nodes, whenever requested by them. A similar approach was proposed in [13], but the wireless communication is supported by PROFIBUS over IEEE 802.11. Nonetheless, none of these works supports any kind of inter-cell mobility procedure.

The reminder of this paper is organized as follows. In Sect. 2, the main concepts related to bridge-based hybrid wired/wireless PROFIBUS architectures, including the ones related to the MLR timing analysis, are briefly presented. Then, in Sect. 3, we propose a worst-case timing analysis of the inter-cell mobility procedure, followed, in Sect. 4, by a numerical example. In Sect. 5, we draw some conclusions.

2 System architecture and previous relevant work

In this Section we describe, to the extent required for reasoning the rest of the paper, the main characteristics of PROFIBUS, the main characteristics of the MLR hybrid wired/wireless architecture which builds upon PROFIBUS, and the previous work on timing analysis of MLR networks.

2.1 Basics of the PROFIBUS protocol

The PROFIBUS Medium Access Control (MAC) protocol uses a token passing procedure [16] to grant bus access to masters, and a master-slave procedure used by masters to communicate with slaves. A PROFIBUS master is capable of processing transactions during its token holding time (T_{TH}), which, for each token visit, is the value corresponding to the difference, if positive, between the target token rotation time (T_{TR}) parameter and the real token rotation time (T_{RR}). For further details, the reader is referred to [7].

A transaction (or message cycle) consists on the request or send/request frame from a master (which in this case is also denoted as the initiator) and of the associated acknowledgement or response frame from a master/slave station (the responder). The response (called in this case "immediate" response) must arrive to the master before the expiration of the *Slot Time* (T_{SL}), a master parameter, otherwise the master repeats the request a number of times defined by the *max_retry_limit*, another master parameter.

In order to maintain the logical ring, PROFIBUS provides a decentralized ring maintenance mechanism. Each PROFIBUS master maintains two tables – the *Gap List* (GAPL) and the *List of Active Stations* (LAS), and may optionally maintain a *Live List* (LL).

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 formed by the token rotation). Every time the *Gap Update Timer* (T_{GUD}) expires in a master in the logical ring, it starts checking the addresses in its GAPL. This mechanism allows masters to track changes in the logical ring, such as addition (joining) or removal (leaving) of stations. This is accomplished by examining (at most) one *Gap address* per token visit, using the *FDL_Request_Status* (FDL stands for Fieldbus Data Link Layer) frame. If a new master replies, then the requesting master passes it the token and updates its 'Next Station' address. Otherwise, the requesting master continues its operation. This mechanism is used for enabling the mobility of wireless master stations, as detailed later in this section.

The LAS is a list of all the masters in the logical ring, and the LL contains all active stations (both masters and slaves).

2.2 Basics on the MLR approach

Our hybrid wired/wireless fieldbus network is composed of wired and wireless network stations. The wireless stations have a wireless interface as defined in RFieldbus [1-2]. The communications between stations is based on the PROFIBUS protocol with specific extensions to support wireless communications and mobility. The communication between stations in different domains is supported by the bridges and a specific protocol – the Inter-Domain Protocol (IDP).

The wireless part of the fieldbus network is supposed to include at least one wireless (radio) cell. Fig. 1 illustrates an example network. In that example, the following set of wired PROFIBUS master (M) and slave (S) stations are considered: M10, M7, S22, S24, S25, S26 and S27. Additionally, the following set of wireless stations is considered: M6, M1, S21 and S23. From this last set, only M6 and S23 are mobile stations, and thus can be associated with wireless domain 1 or wireless domain 2. Wireless stations are standard PROFIBUS stations equipped with a radio front-end containing specific wireless extensions. Three bridge devices are considered: B1, B2 and B3. Each bridge includes two modified PROFIBUS masters implementing the required protocol extensions. We denote each of these masters as Bridge Masters (BM). In our system, the network has a tree-like topology, and bridges perform routing based on MAC addresses.

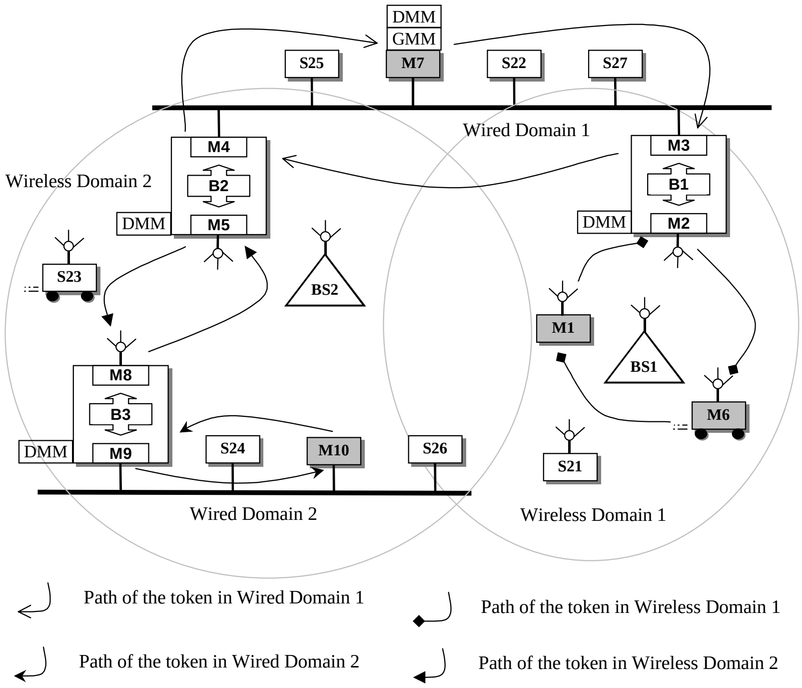

Fig. 1. Hybrid wired/wireless MLR PROFIBUS network example

All wireless communications are relayed through base stations (BS), operating in cut-through mode. The communication between the stations and the base station is made using two radio channels, one to communicate between the wireless station and the base station (the uplink channel) and another to communicate between the base station and the wireless stations (the downlink channel). Since the radio cells are overlapping, the stations in both domains must use different set of radio channels.

In the example, BS1 and BS2 are considered, thus structuring wireless domains 1 and 2, respectively. In the remainder of this paper, we will consider that M5 and M2 include the base station functionalities in their wireless front-end [1].

Network operation is based on the Domain-Driven MLR approach described in [3]. Therefore, each wired/wireless domain has its own logical ring. In this example, four different logical rings exist: {(M1 $\rightarrow$ M2 $\rightarrow$ M6), (M3 $\rightarrow$ M4 $\rightarrow$ M7), (M5 $\rightarrow$ M8), (M9 $\rightarrow$ M10)}.

2.3 The Inter-Domain Protocol (IDP)

A consequence of the MLR approach is that when a master makes a request addressed to a station in another domain (an Inter-Domain Request), it will not receive an immediate response from the responder, within the slot time. In [5], we proposed a protocol extension supported by the bridges (the IDP), suitable for handling such kind of transactions.

The IDP protocol specifies that when an initiator makes an Inter-Domain Request (a “normal” request but addressed to a responder in another domain), only one of the BMs belonging to the initiator’s domain – denoted as bridge BM_i, codes the frame using the IDP, and relays it. The decision, either to receive or discard the frame, is based on a routing table contained in the BMs. Then, this frame – the Inter-Domain Frame (IDF) is relayed by the bridges until reaching bridge master BM_r (the last bridge master in the path). This bridge decodes the original request frame and transmits it to the responder, which can be a standard PROFIBUS station (for example a PROFIBUS-DP slave). The response is again coded using the IDP and routed back until reaching bridge master BM_i, where it will be decoded and stored. As the actual response to the original request takes more time than if the responder would belong to the same domain as the initiator, the initiator must periodically repeat the same request until receiving the related response. During this period, from the reception of the initial request until the retrieval of the response from the BM_i, we refer to the state of the IDT in BM_i as a pending or open IDT. In Fig. 2, we illustrate this behavior for a transaction between master M3 and slave S23 related to the network example illustrated in Fig. 1.

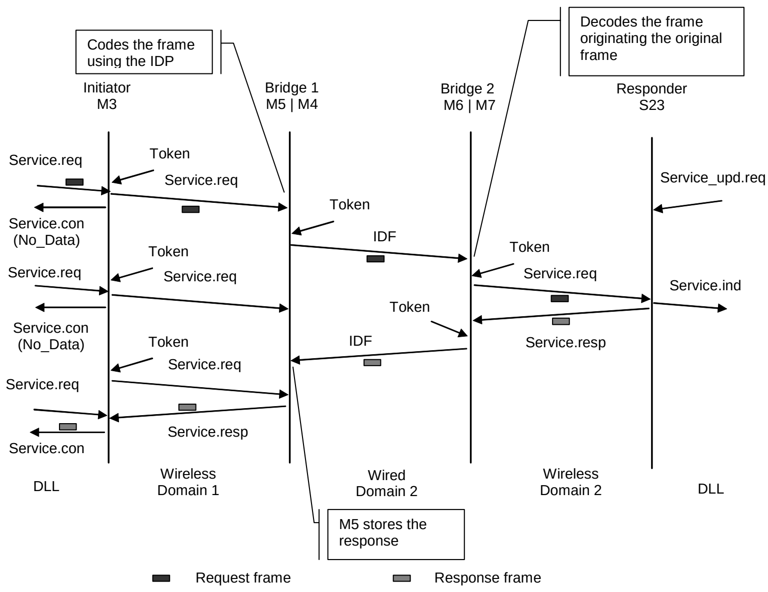

Fig. 2. Example for an Inter-Domain Transaction (IDT)

In this example, the initiator makes a request and after the expiration of the slot time, the PROFIBUS DLL returns a confirmation with the “no data” information. We assume that slaves read their inputs periodically, updating data structures in their Data Link Layers (DLL), using the PROFIBUS *Service_upd.req* primitive. On the initiator side, it is also necessary that the user of the DLL periodically repeats the same request. The DLL returns a confirmation with the data when a response, transmitted by M5, is received.

2.4 Inter-cell mobility procedure

The main objective of the inter-cell mobility procedure is to ensure that a wireless mobile station is able to change from one wireless cell to another, whenever it detects an adjacent radio cell with a higher signal quality. Additionally this procedure must be executed without errors, loss of frames or frame order inversion concerning inter-domain transactions (IDT). In [4], we proposed a hierarchically managed inter-cell mobility procedure, where one master in the system implements the global mobility management functionality, which is responsible for periodically starting the inter-cell mobility procedure and controlling some of its phases. This master performs the role of *Global Mobility Manager* (GMM). Additionally, in each domain, one master controls the mobility of stations belonging to that domain – the *Domain Mobility Manager* (DMM). Finally, the bridge stations implement specific mobility services. Due to the hierarchical structure of the inter-cell mobility procedure, the GMM must know the addresses of all the bridges and DMMs in the system, and each DMM is required to know the addresses of the bridges in its domain.

For the network example depicted in Fig.1, M7 can assume both the role of GMM and DMM for its domain. M2, M5 and M9 can assume the role of DMM for wireless domain 1, wireless domain 2 and wired domain 2, respectively.

The mobility procedure evolves through 4 phases, as illustrated in Fig. 3.

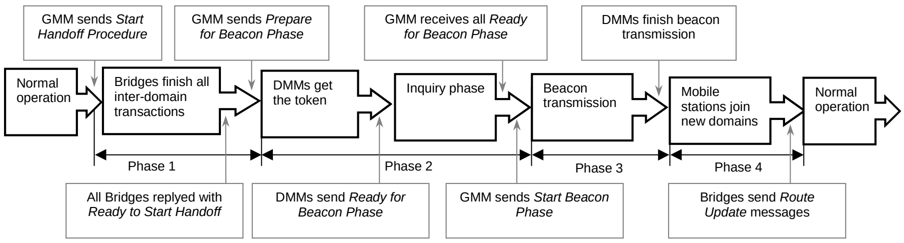

Fig. 3. Phases of the inter-cell mobility procedure

The GMM initiates the procedure by sending the *Start Handoff Procedure* message, which commands the system BMs to finish all pending IDT (for which they are responsible). After receiving the confirmation that all DMMs finished their IDTs (by receiving a *Ready to Start Handoff* message from each DMM) the GMM starts phase 2. During this phase, all DMMs are commanded, using the *Prepare for Beacon Phase* message sent by the GMM, to enter into the inquiry mode (a sort of polling mode commanded by the domain DMM), during which only mobility related messages are exchanged. This type of operation allows a minimal latency for the communication between the GMM with the system DMM, thus allowing a closer synchronization of the beacon emission start. When a DMM enters into the inquiry mode it transmits a *Ready for Beacon Phase* message. The beacon transmission, by the DMMs, is triggered by the *Start Beacon phase* message, sent by the GMM. This phase is used by the wireless mobile stations to evaluate the quality of adjacent wireless channels, so that they can decide to change channels (implicit handoff). During phase 4, the DMMs of wireless domains try to detect which mobile stations are present on their domains (using PROFIBUS ring maintenance mechanisms). If stations are found, the DMMs inform the system bridges about the location of the mobile stations, using the *Route Update* message. In Sect. 3, we present further details which clarify the inter-cell mobility procedure.

2.5 Previous work on timing analysis

The timing analysis of PROFIBUS networks have been addressed by several authors. The approaches presented in [7, 9] can be used as a basis for the timing analysis of our MLR PROFIBUS networks. In [7] the authors suggest an "operational" mode for PROFIBUS networks, the *Unconstrained Low-Priority Traffic Profile*. With this profile it is guaranteed that the real-time requirements for the synchronous (high priority) PROFIBUS traffic are satisfied, even when only one synchronous message is transmitted per token visit, and independently of the asynchronous (low priority) PROFIBUS traffic load. In this way, the worst-case (high priority) response time for a message stream i from a master k, in a SLR network ($Rslr_i^k$) can be computed as follows:

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

where nh^k is the number of synchronous high-priority message streams generated in master k and Ch_i^k is the worst-case duration of a synchronous message cycle i issued by master k. T^k_{cycle} is the worst-case token rotation time, which is equal to: $T_{TR} + n \times C_\sigma$. T_{TR} is the PROFIBUS target token rotation time, n is the number of masters in the network (in this case, in the logical ring) and C_σ is the duration of the longest message cycle in the network. An exact characterization of the token cycle time is given in [7].

In [14], we proposed a worst-case timing analysis of the IDP. Relevant to that analysis is the fact that the initiator of the IDT needs to periodically repeat the request until getting the actual response from the BM_i (Fig. 2). Consequently, the WCRT for a message stream i from master k on a MLR network ($Rmlr_i^k$), can be formulated as follows:

$$Rmlr_i^k = A_i^k \times T_i^k + Rslr_i^k \quad \textbf{(2)}$$

where T_i^k represents the period for message stream i from master k. A_i^k is the maximum number of attempts required to obtain the actual response, which depends on the delay experienced by the IDT, from the reception of the request at BM_i, until the arrival of the respective response to BM_i ($Rbmi_i^k$). Therefore, A_i^k can be obtained by computing $\lceil (Rslr_i^k + Rbmi_i^k - C_i^k) / T_i^k \rceil$.

To obtain $Rbmi_i^k$, in the formulation, we will refer to the BMs in the path, from the initiator to the responder as r_1, r_2 until r_{2b}, where r_1, r_2 refer to the BMs of the first bridge in the path, r_{2b-1} and r_{2b} refer the BMs of the last bridge in the path. b is the number of bridges between the initiator and the responder. Note that BM r_{2b} is attached to the same domain where the responder is located, thus it will execute a complete transaction (including a request and a response). The network domains are numbered in the same order, being the first domain in the path domain number 1 and the last domain in the path numbered as $b+1$. Then, $Rbmi_i^k$ can be obtained as the sum of all the delays experienced by the IDT in the bridges[1] (ϕ), plus the queuing delays in the path BMs and the transmission time in each domain traversed by the IDT, both for the inter-domain request and response frames:

$$
\begin{aligned}
Rbmi_i^k &= \sum_{f=1}^{b-1} (nh^{r_{2f}} \times T_{cycle}^{r_{2f}} + (Creq_i^k)^{f+1}) + b \times \phi \\
&+ nh^{r_{2b}} \times T_{cycle}^{r_{2b}} + (Ch_i^k)^{b+1} + \\
&+ b \times \phi + \sum_{f=2}^{b} (nh^{r_{2f-1}} \times T_{cycle}^{r_{2f-1}} + (Cresp_i^k)^f)
\end{aligned}
\qquad \textbf{(3)}
$$

In this equation, $(Creq_i^k)^s$, $(Cresp_i^k)^s$, $(Ch_i^k)^s$ are, respectively, the latency associated with the request, the response and for completing a message cycle on network domain *s*. The number of high priority message streams in the BMs (nh^{bm}) is equal to the number of IDTs that are relayed by it and which can be simultaneously queued on the BM output queue. Equation (3) can be rewritten in a more compact format as follows:

$$
Rbmi_i^k = \sum_{f=2}^{2b} Rslr_i^{r_f} + 2 \times b \times \phi \qquad \textbf{(4)}
$$

where $Rslr^{bm}_i$ is the response time on a single logical ring domain for a bridge master *bm*, which can be calculated by equation (1).

Most of the mobility related messages are transmitted using the PROFIBUS Send Data without Acknowledge (SDN) service provided by the DLL. In such kind of service, a transaction only involves the transmission of a request message, which can be sent in unicast, broadcast or multicast mode.

In this case, it also possible to determine the worst-case time required by a request, from a message stream *i*, to go from a station *k* (which can be a master or a bridge master) to another station *w* ($Ru_i^{k\to w}$, with *u* meaning unicast), can be obtained by adapting equation (4) as follows:

$$
Ru_i^{k\to w} = \begin{cases} Rslr_i^k + \sum_{f=1}^{b} Rslr^{r_{2f}} + (b + df) \times \phi, k \in \Pi_{\text{master}} \cup \Pi_{BM\_d} \\ \sum_{f=1}^{b} Rslr^{r_{2f-1}} + (b + 1 + df) \times \phi, k \in \Pi_{BM\_i} \end{cases} \qquad \textbf{(5)}
$$

where Π_{master} represents the set of master stations in the overall system, Π_{BM_d} represents the set of BMs in the message path between station *k* and station *w*, and which are responsible for the actual transmission of the request. Π_{BM_i} represents the set of BMs in the message path between station *k* and station *w* which are responsible for the reception of the request and respective forwarding for the other BM. The BMs in the path are numbered as r_1, r_2, etc., being station *k* the transaction initiator. *df* is

[1] This delay includes the time required to decode the frame by the receiving BM, plus the time required to queue the frame on the other BM of the bridge.

equal to zero if the destination station is a master, a slave or a BM directly connected to the last domain in the path. *df* is equal to one if the destination station is a BM not directly connected to the last domain where the message is transmitted. In [14], we also present a more detailed formulation which allows reducing the pessimism inherent to considering the simultaneous queuing in a BM of all message streams handled by it.

3 Inter-cell mobility procedure timings

Throughout the progress of the inter-cell mobility procedure (Fig. 3), there are periods of time during which some network domains are inaccessible. That is the case of the period corresponding to the beacon transmission and inquiry phase, where normal transactions, between any two nodes in the same domain, are not possible. Additionally, IDTs are disabled from the middle of phase 1 until the end of the beacon transmission. Thus, the mobility procedure affects the worst-case time for transactions depending on the location and type of the stations involved.

As an example, assume a message stream that involves two stations in the same wireless domain – an Intra-Domain Transaction (IADT). This type of transactions is disabled during the inquiry sub-phase, the beacon emission sub-phase and the identification sub-phase. Thus, in order to include the effect of the inter-cell mobility procedure, the worst-case response time must be updated to $Rslr\_h_i^k = Rslr_i^k + t_{IADT\_dis}$. The *h* in *Rslr_h* denotes the inclusion of the handoff related delays. t_{IADT_dis} represents the time during which IADT are disabled in a domain. On the other hand, the impact of the mobility procedure on the WCRT for IDTs, is reflected on the way in which parameter A_i^k is obtained. In this paper we do not elaborate any further on the characterisation of the impact of the inter-cell mobility procedure on the WCRT for IDTs. In this paper we will concentrate on a thorough characterisation of the inter-cell mobility procedure timings. Each of the phases will be thoroughly analyzed in the following sub-sections.

3.1 Phase 1

The inter-cell mobility procedure starts with the transmission, by the GMM, of the *Start Handoff Procedure* (SHP) message, which must be received by all BMs in the system. The worst-case time for the *Start Handoff Procedure* message to reach a BM *bm* is denoted as t_{SHP}^{bm}, and can be calculated considering an unicast IDT (equation (5)): $t_{SHP}^{bm} = Ru_{SHP}^{GMM\rightarrow bm}$. Note that since the *Start Handoff Procedure* message must be relayed by the bridges, for computing this time span it is necessary to include the SHP message as a message stream contending with the other messages in the bridges.

After receiving the *Start Handoff Procedure* message, the BMs stop accepting new IDTs from masters belonging to their domains. Nonetheless, they keep handling pending IDTs and, importantly, they keep handling IDTs originated in the other domains. After completing all pending IDTs, the bridges signal their new state by transmitting a *Ready to Start Handoff Procedure* message, addressed to the GMM. Fig. 4, illustrates phases 1 and 2 timings assuming the network scenario depicted in Fig. 1.

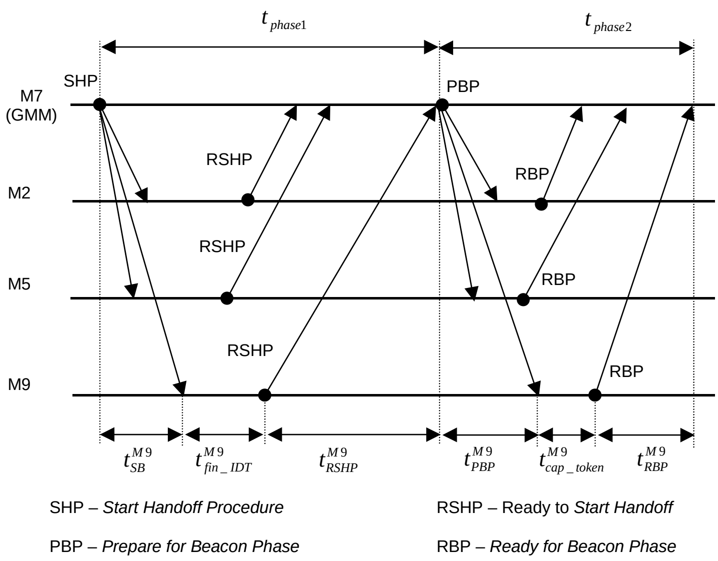

Fig. 4. Phase 1 and Phase 2 main events

The worst-case time until all pending IDTs are completed is different on the considered BMs, and depends on the characteristics of the message streams served[2] by the BMs. To obtain that value, we assume the following conditions:

- all initial requests, related to the IDTs served by BM *bm*, arrive just before to the reception of the *Start Handoff Procedure* message, thus BM *bm*, has its maximum number of IDTs (nh^{bm}) queued on its output queue;
- the corresponding IDT response arrives, to BM_i, just after the transmission of the same request frame by the initiator.

In these conditions, equation (6), gives the worst-case time until all inter-domain transactions are completed for a particular BM *bm*.

$$t^{bm}_{fin\_IDT} = \max\{Rbmi_i^k + T_i^k\}, S_i^k \in \Omega_{IDT} \qquad \textbf{(6)}$$

where Ω_{IDT} refers to the set of message streams which are also IDTs served by BM *bm*, master *k* belongs to the domain where the BM *bm* is connected, and uses BM *bm* as the first BM in the path – BM_i. T_i^k is the period of message stream *i* from master *k*. $Rbmi_i^k$ is the response time, counting from the reception of the initial IDT request until the reception of the corresponding IDT response by BM_i, which can be calculated using equation (3).

[2] In this context we are considering that a BM serves a message stream when the message stream originates from a station on its domain and the BM is the first in the path (from the initiator to the responder).

After finalizing all IDTs, the bridges transmit the *Ready to Start Handoff Procedure* (RSHP) message (see Fig. 4). The worst-case time needed by this message to go from a BM *bm* to the system GMM (t_{RSHP}^{bm}) can also be calculated using equation (5): $Ru_{RSHP}^{bm \to GMM}$.

Phase 1 only stops when all *Ready to Start Handoff Procedure* messages (coming from all DMMs) have been received by the GMM. Since the duration of this sub-phase is different for the diverse BMs, then the worst-case duration of phase 1 is equal to the maximum of the time required by the *Start Handoff Procedure* message to reach a BM *bm*, plus the time required by BM *bm* to finalize its pending IDTs, plus the time required by the *Ready to Start Handoff Message* to reach the system GMM:

$$t_{phase1} = \max(t_{SHP}^{bm} + t_{fin\_IDT}^{\mathrm{bm}} + t_{RSHP}^{bm}), \forall bm \qquad \textbf{(7)}$$

Only at this point in time the GMM can proceed to phase 2.

3.2 Phase 2

Phase 2 starts immediately after the end of phase 1, when the GMM sends the *Prepare for Beacon Phase* (PBP) message. After receiving this message, and as soon as a DMM receives the token, it will retain the token in its possession and will not pass it to other masters in its domain. Following that, the DMMs send a *Ready for Beacon Phase* (RBP) message to the GMM and enter into inquiry mode. In this mode, the domain DMMs inquire, in sequence, their domain BMs, whether they have any *Ready for Beacon Phase* message available. The inquiry is made using an *Inquiry* message which is defined by the inter-cell mobility protocol, see [4] for details on the exchanged messages. The inquiry mode helps in reducing the communication latency between the GMM and the DMMs, and keeps small the inaccessibility period of the network. When a BM, with or without domain management capabilities, receives the *Prepare for Beacon Phase* message, it will only be able to communicate using the *Inquiry* service, and it clears all its routing table entries related to mobile stations. See Fig. 4 for further intuition on the message and event sequence.

The worst-case time required for the *Prepare for Beacon Phase* message (time span denoted as t_{PBP}^{dmm}) to reach DMM *dmm* is given by $Ru_{PBP}^{GMM \to dmm}$. Note that, during this phase there are no other IDTs going on. So, the only inter-domain traffic in the network is related to the *Prepare for Beacon Phase* message and, as a consequence, the BMs only queue messages related to the “branches” below it (remember that network topology is tree-like). Using again Fig. 1 as an example, and to illustrate this case, M3 would have to forward one message related to DMM M2, and M4 would have forward two messages, one related to DMM M5 and another related to DMM M9.

After receiving the *Prepare for Beacon Phase* message, the DMMs will have to capture the token on their respective logical rings. The worst-case time required until capturing the token (denoted as $t_{\mathrm{cap\_token}}^{\mathrm{dmm}}$) is equal to the worst-case token rotation time of the domain where the DMM *dmm* is located, T_{cycle}^{dmm}, which can be computed as explained in Sect. 2.5.

With the network operating in inquiry mode, the worst-case delay for the *Ready for Beacon Phase* message to go from the DMM *dmm* until the GMM can be computed as follows:

$$t_{RBP}^{dmm} = \sum_{x=0}^{b-1} \left(Rinq_{RBP}^{2x \to (2x+1)} + \phi \right) \quad \textbf{(8)}$$

where $Rinq_{RBP}^{2x \to (2x+1)}$ is the delay encountered by the *Ready for Beacon Phase* message when being transmitted from a BM *x* to another BM *x+1*, in the path to the GMM. For this formulation we assume that the BMs in the path, between DMM *dmm* and the system GMM are numbered as follows: {0, 1, 2, …, 2×*b*-1), where 0 refers to DMM *dmm* and 2×*b*-1 to the GMM. *b* is the number of bridges in the path. Since the GMM is also a DMM for its domain, then it is not necessary to transmit the *Ready for Beacon Phase* message in this domain.

To support the timing analysis of the Inquiry operation mode, Fig. 5, depicts a detailed example showing the operation of the network during the *Inquiry* and *Beacon* sub-phases. This example is based in Fig. 1, for simplification purposes we are not considering any more traffic in the network besides the mobility-related messages. In Fig. 5, Wr and Wl denote wired and wireless domains, respectively.

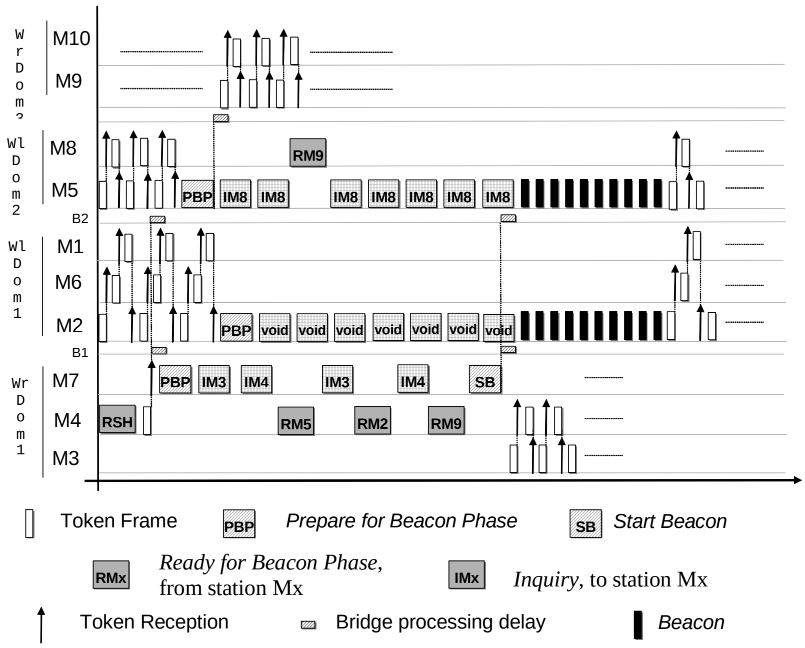

Fig. 5. Inquiry mode example

The inquiry mode starts, in wired domain 1, after the transmission of the *Prepare for Beacon Phase* message by M7 (the system GMM). In this mode M7 sends, in sequence, the inquiry message (denoted as IM3) to BM M3 followed by IM4 to BM

M4. If any of these stations have a *Ready for Beacon Phase* message on its output queue then that message is transmitted. BM M3 must transmit a *Ready for Beacon Phase* message related to the DMM of wireless domain 1 (RM2), and BM M4 must transmit two *Ready for Beacon Phase* messages, one related to the DMM of wireless domain 2 (RM5) and another related to the DMM of wired domain 2 (RM9).

To calculate the worst-case latency of a transaction when the system is in the inquiry mode, we assume the following conditions about the network operation:

- the BMs only transmit mobility related messages, IDTs are disabled;
- the message to be transmitted arrives at a BM *a*, just after the domain DMM has inquired BM *a*;
- at any given instant the maximum number of queued messages in a BM *bm* is equal to the number of bridges belonging to the branches under that BM.

In these conditions, the worst-case time needed to forward a message stored on a BM *a*, to another BM *b*, in the same domain, is given by the following equation:

$$Rinq_{msg}^{a \to b} = ((C_{Inq})^{dmm} + (C_{msg})^{dmm}) \times (n_{bridges})^{dmm} \times n_{msg}^{BM} \quad \textbf{(9)}$$

where, $(C_{Inq})^{dmm}$ and $(C_{msg})^{dmm}$ is the latency of the inquiry message and the response message on a domain (represented by its DMM), $(n_{bridges})^{dmm}$ is the number of bridges that connect to the domain of *dmm*, and n_{msg}^{BM} is the maximum number of messages that may be stored in BM *a*. Just as an example, in the case a *Prepare for Beacon Phase* message is being transmitted from M4 to M7 then $Rinq_{PBP}^{M4 \to M7} = ((C_{Inq})^{M7} + (C_{PBP})^{M7}) \times 2 \times 2$.

Therefore, to obtain the worst-case time span for phase 2, the following analytical formulation may then be applied:

$$t_{phase2} = \max(t_{PBP}^{dmm} + t_{cap\_token}^{dmm} + t_{RBP}^{dmm}), \forall \text{ dmm} \quad \textbf{(10)}$$

3.3 Phase 3

After collecting all *Ready for Beacon Phase* messages from all the DMMs, the GMM starts the channel assessment sub-phase by broadcasting the *Start Beacon Phase* (SBP) message. Upon receiving this message, the DMMs start emitting beacons. Obviously, in wired domains no beacons are transmitted, and therefore stations in these domains may resume Intra-Domain Transactions (IADT). Stations in a wired domain can execute IDTs with other wired stations, if the domains to which they are connected are able to complete those transactions, i.e. they are wired domains.

Mobile stations use the beacon frames to evaluate the quality of the diverse radio channels (associated to the diverse base stations) and to decide whether switch to another radio channel or not..

Therefore, the duration of phase 3 will be equal to the time needed by a DMM, to receive the *Start Beacon* (SB) message, added to the duration of the beacon sub-phase. Fig. 6 depicts a time-line for the sequence of events during phases 3 and 4.

The worst-case time required by the *Start Beacon* message to reach a DMM *dmm* in the system is given by the following equation:

$$t_{SB}^{dmm} = \sum_{x=0}^{b-1} Rinq_{SB}^{2x \to 2x+1} \quad \textbf{(11)}$$

where *x* represents the list of BMs in the path, from the GMM to a DMM *dmm*, which transmit the *Start Beacon* message, as in equation (8). The only difference is that, in this case, station 0 represents the GMM and station 2×*b*-1 represents the DMM *dmm*. *b* is the number of domains between the GMM and DMM *dmm*.

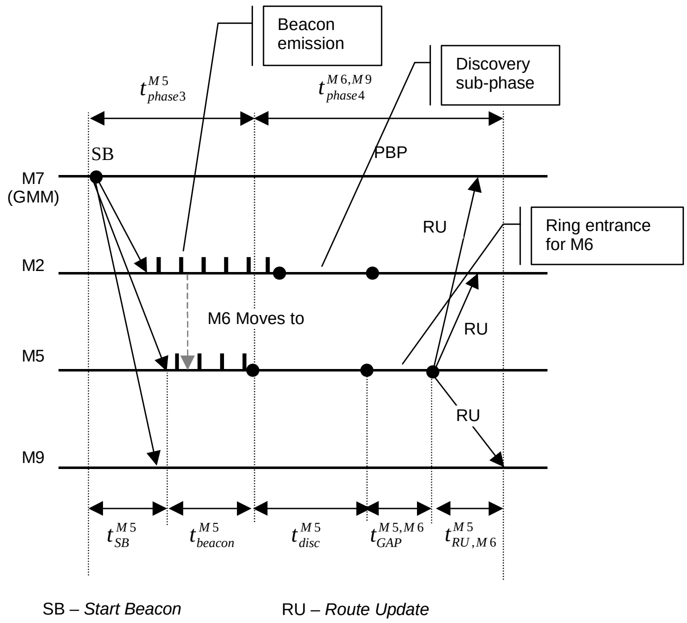

Fig. 6. Time-line for phases 3 and 4

The duration of the beacon sub-phase (t_{beacon}^{dmm}) is a parameter that is setup individually on every domain. It must be set in a way that guarantees that every mobile station has enough time to evaluate all the available radio channels, the reader is referred to [1] for further details on this. Thus, the duration of phase 3, calculated for every wireless domain (represented in the equation by its DMM), is given by:

$$t_{phase3}^{dmm} = t_{SB}^{dmm} + C_{beacon} \times n_{beacon}^{dmm} \quad \textbf{(12)}$$

3.4 Phase 4

After the end of the beacon sub-phase, every wireless DMM (still holding the token) inquires all mobile stations, using the *Discovery* message, in order to detect if they still belong to its domain or to detect new “entries” on its domain. After this, mobile slaves are capable of answering requests, but new mobile masters must still enter the logical ring using the standard PROFIBUS *Gap List* mechanisms (briefly described in Sect. 2.1). At this point in time, the DMMs can send *Route Update* messages containing the addresses of the mobile slaves and mobile masters that are still in their domains. This information is used by the other bridges in order to update their routing tables, and, after that, they may restart routing IDTs related to the updated mobile stations (that is, wireless stations that have moved between wireless domains) **.**

To obtain the duration of the station discovery sub-phase, the following conditions must be assumed:

- a wireless domain DMM (still holding the token) will inquiry all mobile stations, starting from the station with lower address;
- all mobile station are on the same domain (the worst-case situation).

It follows that the worst-case duration of the station discovery sub-phase can be computed as follows:

$$t_{disc}^{dmm} = n_{mob\_stations} \times C_{dic}^{dmm} \qquad \textbf{(13)}$$

where $n_{mob\_stations}$ is the number of mobile stations (including masters and slaves), and C_{disc}^{dmm} is the latency associated with the *Discovery* message on the domain represented by *dmm*, including the response from the addressed station.

To determine the worst-case time span for a master *i* to enter into the logical ring, after a station *k* ($t_{master\_entry}^{k,i}$), it is necessary to make some adaptation on the timing analysis available for PROFIBUS, since this analysis do not account for the GAP update mechanism. As previously described, the *Unconstrained* PROFIBUS *Low-Priority Traffic Profile* [6] assumes that only one high-priority message is transmitted per token visit. Thus, it can only be applied to the *Gap List* mechanism if the following conditions are assumed:

- the *FDL_Request_Status* frames are transmitted after all high-priority message streams, queued on master *k*, are transmitted:
- all *FDL_Request_Status* frames start their transmission just prior to the expiration of the T_{TH} timer (like any other high-priority message);
- after the transmission of all high-priority messages the *FDL_Request_Status* frames are transmitted on consecutive token cycles;
- the period of the high-priority message streams is much higher than the duration of the gap update period (T_{GUD}).

Based on these assumptions, the worst-case time for a master station *i* entering the ring, after master *k*, can be computed as follows:

$$t_{master\_entry}^{k,i} = T_{GUD} + nh^{k} \times T_{cycle}^{k} + D_{k\to i} \times T_{cycle}^{k} + C_{FDL} + 2 \times C_{token\_pass} \qquad \textbf{(14)}$$

where T_{GUD} is the Gap Update time, which is defined by PROFIBUS standard as a multiple (factor *G*) of T_{TR} [18]. $D_{k\to i}$ is the distance parameter, which is defined as the number of addresses that master *k* must visit before inquiring station *i*, $D_{k\to i} = addr(i) - addr(k)$, where *addr*(*x*) gives the numeric address of master *x*. C_{FDL} is the latency of the *FDL_Request_Status* message and respective response. C_{token_pass} is the latency required to pass the token. Note that the PROFIBUS standard defines that if a master detects that its predecessor station has changed, it will only accept the token on its second try. That is the reason for the term $2\times C_{token}$ in equation (14).

If several mobile masters are added to the ring in the same GAP interval, then the time required until mobile master *i* enters the logical ring is given by the following equation:

$$t^{k,i}_{m\_master\_entry} = t^{k,m_1}_{master\_entry} + t^{m_1,m_2}_{master\_entry} + \ldots + t^{m_n,i}_{master\_entry} \quad \textbf{(15)}$$

where m_x is the set of mobile stations that enter into the logical ring in the same gap interval as mobile station *i*.

It is worthwhile to point out that in order to reduce the time required for a master to enter the logical ring, the following should be accounted:

- the address of the mobile masters must be as near as possible from the address of the fixed stations preceding them;
- preferably, the length of the GAP parameter should be 1, for every master in the domain, i.e. after every non-mobile master at most one mobile master can enter into the ring;
- the *G* factor must be as small as possible.

Once the discovery of stations is complete, or a new master has entered into a different domain, the domain DMM sends a *Route Update* message, which will be used by the bridges to update their routing tables. The worst-case time span that the *Route Update* message, relative to station *s*, needs to go from DMM *dmm* to a BM *bm* (this time span is denoted as $t_{RU,s}^{bm}$) can be calculated by $Ru_{RU,s}^{dmm \rightarrow bm}$ (using equation (5))

To summarize, the time required before a BM *bm* knows that a station *s* is again operational in a wireless domain is given by the following formulation:

$$t^{s,bm}_{phase4} = \begin{cases} t^{dmm}_{disc} + t^{bm}_{RU,s},\ s \in \Pi_{slave} \\ t^{dmm}_{dis} + t^{k,j}_{m\_master\_entry} + t^{bm}_{RU,s},\ s \in \Pi_{master} \end{cases} \quad \textbf{(16)}$$

where, *dmm* represents DMM of the domain in which station *s* is or to where it has entered. Π_{slave} and Π_{master} are the set of mobile slaves and mobile masters in the system, respectively.

3.5 Worst-case inter-cell mobility procedure duration

The worst-case duration of the inter-cell mobility procedure is measured from the sending of the *Start Handoff Procedure* message, by the GMM, until all mobile stations are able to receive and make requests in normal operation. This time span can therefore be calculated by using the following equation:

$$t_{mob} = t_{phase1} + t_{phase2} + \max(t^{dmm}_{phase3} + t^{s,dom}_{phase4}),\ \forall\ dmm \quad \textbf{(17)}$$

This quantity is only indicative about the performance of the system, since the effect of the inter-cell mobility procedure varies of as a function of the type of transactions, as already mentioned.

4 Numerical example

In this Section we illustrate how the analysis and formulations provided in Sect. 3 can be applied in practice. For this numerical example, consider the network example as illsutrated in Fig. 1, and described in Sect. 2.2. In any case, and for the sake of smplicity, master M10 is not considered in the scenario. We assume the set of network parameters as depicted in Table 1. The reader is referred to [10-11] for further reasoning on T_{SDR}, T_{ID}, frame head length, and frame tail length parameters.

Table 1. Network parameters

Parameter	Value	Notes
bit rate (Wired)	1.5 Mbit/s	-
bit rate (Wireless)	2.0 Mbit/s	-
bits per char (wired)	11	due to the start, stop and parity bits
bits per char (wireless)	8	-
T_{SDR}	60 bits	40μs (Wr) 30μs (Wl)
T_{ID}	65 bits	43.3μs (Wr) 33.5μs (Wl)
T_{TR}	0.6ms	-
Frame head length	32 bits	(only for wireless domains)
Frame tail length	16 bits	(only for wireless domains)
ϕ	0.030ms	Bridge delay

The system masters have the set of high priority message streams as depicted in Table 2. In PROFIBUS a message stream is always made between master station, the initiator and a slave, the responder, both are represented by their addresses.

To calculate the duration of the request and response frames, the approach formulated in [10] was used. We are also assuming that all streams have the same period, which was set to 20ms.

Table 2. IDT message streams

Stream	Initiator	Responder	L_{req} (Bytes)	L_{resp} (Bytes)
S^1_1	M1	S22	15	20
S^1_2	M1	S24	20	20
S^6_1	M6	S22	30	30
S^6_2	M6	S23	15	20
S^7_1	M7	S23	20	20
S^7_2	M7	S21	30	30
S^7_3	M7	S24	15	20
S^7_4	M7	S22	15	20
S^7_5	M7	S22	15	20

In Table 3, we are representing in shading the worst-case duration results of each phase, calculated using equations (8), (10) and (12), for phase 1, 2 and 3, respectively.

It is worthwhile to note that the major contribution for the value obtained for phase 1 comes from the time needed to finish pending IDTs on a BM ($t_{fin\_IDT}^{bm}$). For example, for BM M2 this time is equal to 27.0ms.

Phase 2 only involves communications between the GMM and the DMMs. During this phase IDTs are not active and therefore, phase 2 duration results mainly from the number of hops required for messages to reach the system DMMs and to go from the DMMs to the GMM.

For the computations of the timings related to phase 3, we assumed that each mobile master makes the quality assessment of 2 radio channels, one for each wireless domain, requiring a time of 0.63ms. The total duration of this phase is quite small when compared to the duration of the others. This results from the fact that the network is in inquiry mode, and thus the communication between the GMM and the DMMs is much faster. As explained before, this feature makes the synchronisation between domains, for the start of the beacon transmission phase, much more precise than if the network was operating in a normal mode.

Table 3. Phases 1 to 3 timings

BM	Phase 1 (ms)	Phase 2 (ms)	Phase 3 (ms)
M7 (GMM)	0	0	0
M2 (DMM)	**44.7**	15.2	**1.0**
M3	23.0	-	-
M4	32.2	-	-
M5 (DMM)	42.9	15.0	**1.0**
M8	30.3	-	-
M9 (DMM)	30.3	**17.0**	0.588

Phase 4 timings depend on the mobile stations and on the domains where they are entering. Table 4 resumes the timings, when M6 and S23 enter into wireless domain 1 or wireless domain 2. It is clear, that slave nodes are able to enter into the wireless domains faster than master nodes, as expected.

Table 4. Phase 4 timings

Station	Entering wl domain 1 (ms)	Entering wl domain 2 (ms)
M6	18.8	16.1
S23	18.0	11.3

Finally, and for closing the example, by using equation (17), it is possible to obtain the worst-case duration of the inter-cell mobility procedure, which will be equal to 81.2ms.

The impact of the inter-cell mobility procedure on the IDT is the theme of ongoing work. Just as an example, for message stream S_4^7 the WCRT, without considering the inter-cell mobility procedure is equal to 51.1ms, but considering the influence of the handoff procedure this time grows up to 68.1ms.

5 Conclusions

Recently, there have been a few research efforts towards extending the capabilities of fieldbus networks to encompass wireless support. In previous works [3-5] we have proposed a hybrid wired/wireless PROFIBUS network solution where the interconnection between the heterogeneous communication media was accomplished through bridge-like interconnecting devices. The resulting networking architecture embraced a Multiple Logical Ring (MLR) approach, thus with multiple independent tokens, to which a specific bridging protocol extensions, the Inter-Domain Protocol (IDP) and inter-cell mobility procedure, were proposed.

A worst-case timing analysis of the IDP has been proposed in [14]. In this paper, we proposed a timing analysis for the inter-cell mobility procedure. Ongoing work is being carried in order to incorporate the inter-cell mobility latencies into the worst-case timing analysis for the IDP transactions.

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