Technical Report

The Influence of Inter-domain Mobility on Message Stream Response Time in Wired/Wireless PROFIBUS-based Networks

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Abstract

In previous works we have proposed a hybrid wired/wireless PROFIBUS solution where the interconnection between the heterogeneous media was accomplished through bridge-like devices with wireless stations being able to move between different wireless cells. Additionally, we had also proposed a worst-case timing analysis assuming that stations were stationary. In this paper we advance these previous works by proposing a worst-case timing analysis for the system's message streams considering the effect of inter-cell mobility.

THE INFLUENCE OF INTER-DOMAIN MOBILITY ON MESSAGE STREAM RESPONSE TIME IN WIRED/WIRELESS PROFIBUS-BASED NETWORKS

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Abstract: In previous works we have proposed a hybrid wired/wireless PROFIBUS solution where the interconnection between the heterogeneous media was accomplished through bridge-like devices with wireless stations being able to move between different wireless cells. Additionally, we had also proposed a worst-case timing analysis assuming that stations were stationary. In this paper we advance these previous works by proposing a worst-case timing analysis for the system's message streams considering the effect of inter-cell mobility.

Keywords: Fieldbus, Wireless, Real-time, Industrial Automation

1 INTRODUCTION

In the past years several solutions have been proposed for extending the capabilities of fieldbus networks to encompass wireless support [6-7, 9]. PROFIBUS (acronym for PROcess FIeld BUS) is a natural candidate to support such an ensemble, especially due to its market penetration and range of covered applications.

The Multiple Logical Ring (MLR) concept was introduced and discussed in [2], and further detailed in [3-4], where a bridge-based approach (thus, layer 2 interoperability) was outlined. In such an approach, each logical ring is comprised of stations that communicate via a unique medium – a domain, which can be wired or wireless. The Inter-Domain Protocol (IDP) supports the communication between stations in different domains, and the mobility of wireless stations between different wireless domains is based on the Inter-Domain Mobility Procedure (IDMP). These protocol extensions provide essential compatibility with legacy PROFIBUS technologies.

In [8], we proposed a worst-case timing analysis for transactions supported by the IDP, considering that wireless stations were stationary. In [10], that work has been applied to calculate the latencies associated with the IDMP evolution.

In this paper, we advance that previous work by analysing the impact of the IDMP on the worst-case response time (WCRT) of message streams, considering that wireless stations can move between different wireless domains.

The rest of this paper is organized as follows. In Section 2, the main concepts related to bridge-based hybrid wired/wireless PROFIBUS architectures, including the ones related to the MLR approach, are briefly presented. Then, in Section 3, we briefly present the timing analysis of the latencies associated to the mobility procedure (IDMP), which is then used in Section 4 to derive analytical formulations for the WCRT of message streams in a system allowing inter-cell (domain) mobility. Finally, in Section 5, we draw some conclusions.

2 SYSTEM ARCHITECTURE AND PREVIOUS RELEVANT WORK

2.1 *Basics of the PROFIBUS protocol*

The PROFIBUS Medium Access Control (MAC) protocol uses a token passing procedure to grant bus access to masters. After receiving the token, 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 [5].

A transaction (or message cycle) consists on the request or send/request frame from a master (the initiator) and of the associated acknowledgement or response frame from a master/slave station (the responder). The response must arrive to the master before the expiration of the `Slot Time` (T_{SL}), a 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 GAPL consists of the address range from 'This Station' address until 'Next Station' address, i.e., the next master in the logical token ring. Every time the

Gap Update Timer (T_{GUD}) expires in a master, it starts checking the addresses in its GAPL. This is accomplished by inquiring (at most) one master on the GAPL per token visit. If a new master replies, then the requesting master passes the token to this new master and updates its 'Next Station' address. Otherwise, the requesting master continues its operation. In the MLR approach, this mechanism is used for enabling the mobility of wireless master stations, as detailed later.

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 of the MLR approach

Our hybrid wired/wireless fieldbus network is composed of wired and wireless stations. Communication is based on the PROFIBUS protocol, and the communication between different domains is supported by special-purpose bridges supporting the Inter-Domain Protocol (IDP) [4]. Fig. 1 illustrates an example network.

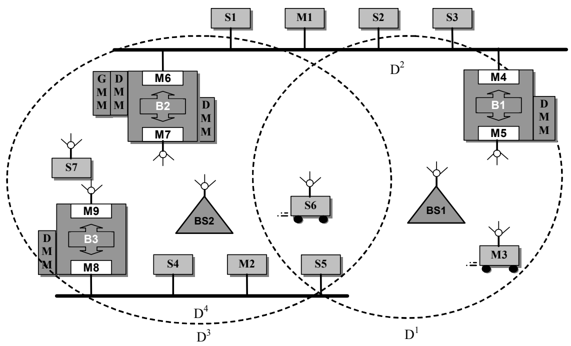

Fig. 1 – Hybrid wired/wireless PROFIBUS network

In this example, the following set of wired PROFIBUS masters (M) and slaves (S) are considered: M1, S1, S2, S3, S4 and S5. Additionally, the following set of wireless stations is considered: M3, S6 and S7. From this last set, only M3 and S6 are referred as Mobile Wireless Master/Slave station, therefore being capable of moving inside a wireless domain and between them (using the IDMP). Station S7 is referred as Domain Resident Wireless Master/Slave Station since it is stationary in a single domain. These wireless stations are standard PROFIBUS stations equipped with a radio front-end containing specific wireless extensions (as defined in RFieldbus [1]). Three bridge devices are considered: B1, B2 and B3. Each includes two modified PROFIBUS masters (denoted as Bridge Masters (BM)) implementing the required protocol extensions. In our system, the network has a tree-like topology, and bridges perform routing based on MAC addresses.

All wireless communications are relayed through base stations (BS), operating in cut-through mode. Each BS uses two channels to communicate with the wireless stations, one to receive data from the wireless stations (the uplink channel) and another to transmit data to the wireless stations (the downlink channel). Each adjacent BS (e.g. BS1 and BS2) must use a different set of radio channels. In the example each wired/wireless domain has its own logical ring, four different logical rings exist: {(M5 → M3), (M1 → M4 → M6), (M7 → M9), (M8→M2)}.

2.3 The Inter-Domain Protocol (IDP)

A consequence of the MLR approach is that when a master makes a PROFIBUS standard request addressed to a station in another domain (an Inter-Domain Request), it will not receive an "immediate" response from the responder. The IDP [4] proposes some protocol extensions suitable for handling such kind of transactions – Inter-Domain Transactions (IDT).

The IDP protocol specifies that when an initiator makes an Inter-Domain Request, only one of the BMs belonging to the initiator's domain – denoted as BM 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 Inter-Domain Request frame 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-DP station. The response (referred as IDT Response frame) is again coded using the IDP and routed back until reaching BM BM_i, where it will be decoded and stored. The IDP assumes that the initiator Application Layer (AL) periodically repeats the same request until receiving the related response. During this period we refer to the state of the IDT in BM_i as a pending or open IDT. In Fig. 2, we illustrate this behaviour for a transaction between M3 and S7 in the example illustrated in Fig. 1.

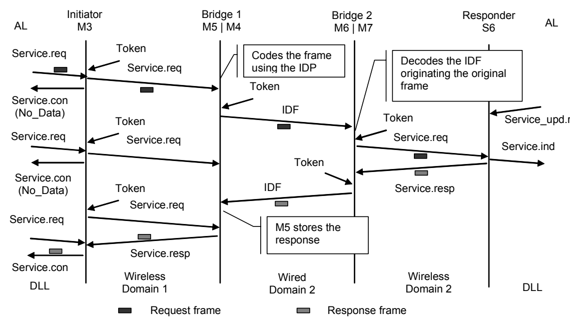

Fig. 2 – Inter-Domain Transaction (IDT) example

Note in Fig. 2 the several AL repetitions made by M3. Additionally, it is assumed that slaves read their inputs periodically, updating data structures in their DLLs, using the PROFIBUS *Service_upd.req* primitive.

2.4 Inter-Domain Mobility Procedure (IDMP)

The main objective of the inter-domain mobility procedure (IDMP) is to ensure that a wireless mobile station is able to change from one wireless domain to another, whenever it detects an adjacent wireless domain with a better signal quality. The IDMP is a hierarchically managed procedure, where one master in the system (the *Global Mobility Manager* (GMM)) is responsible for periodically starting the IDMP and controlling some of its phases. 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. For the network example depicted in Fig.1, M6 can assume both the role of GMM and DMM for its domain. M5, M7 and M8 can assume the role of DMM for domain D^1, D^3 and D^4, respectively.

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

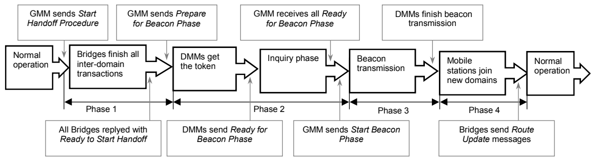

Fig. 3 – Phases of the IDMP

The GMM initiates the IDMP by sending the `Start_Mobility_Procedure` (`SMP`) message, which commands the system BMs to finish all pending IDTs (for which they are responsible). After receiving the confirmation that all BMs had finished their IDTs (by the `Ready_to_Start_Mobility_Procedure` (`RSMP`) message) the GMM starts phase 2. During this phase, all DMMs are commanded, using the `Prepare_for_Beacon_Transmission (PBT)` 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 and the DMMs, thus allowing a closer synchronization of the start of the beacon emission during Phase 3. When a DMM enters into the inquiry mode it transmits a `Ready_for_Beacon_Transmission (RBT)` message. The beacon transmission, by the DMMs, is triggered by the `Start_Beacon_Transmission` (`SBT`) message, sent by the GMM. This sub-phase is used by the wireless mobile stations to evaluate the quality of adjacent wireless channels and handoff if required. During phase 4, the DMMs of wireless domains try to detect which mobile stations are present on their domains. If stations are found, the DMMs inform the system BMs about the location of the mobile stations, using `Route_Update (RU)` messages.

2.5 Previous work on timing analysis

Related to the timing analysis approach presented in [5], the WCRT for a high priority message stream i from a master k, in a SLR network ($Rslr_i^k$), or in the case of the bridge-based approach referred as an Intra-Domain Transaction (IADT), can be computed by:

$$Rslr_i^k = nh^k \times T_{cycle}^k + Ch_i^k \tag{1}$$

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}, the worst-case token rotation time can be computed as presented in [5].

In [8], 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:

$$Rmlr_i^k = A_i^k \times T_i^k + Rslr_i^k \tag{2}$$

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 $\lceil (Rslr_i^k + Rbmi_i^k - C_i^k) / T_i^k \rceil$. $Rbmi_i^k$ can be obtained as follows:

$$Rbmi_i^k = \sum_{f=2}^{b+1} \left(Rslr_i^k\right)^{\Omega_{req}[f]} + \sum_{f=2}^{b} \left(Rslr_i^k\right)^{\Omega_{res}[f]} + 2 \times b \times \phi \tag{3}$$

b is the number of bridges between the initiator and the responder. Ω_{req} represents the set of BMs which relay the IDT request frame in the path from the initiator to the responder. Ω_{res} represents the set of BMs which relay the IDT response frame in the path from the initiator to the responder. The network domains are numbered from 1 to $b + 1$.

The mobility-related messages are transmitted using the PROFIBUS DLL Send Data without Acknowledge (SDN) service, which only involves the transmission of a request message. The worst-case time required by a request from a message stream i, to go from a master k to another station w ($Ru_i^{k\to w}$), can be obtained by:

$$Ru_i^{k\to w} = Rslr_i^{k'} + \sum_{f=1}^{b} Rslr_i^{\Omega_{req}[f]} + (b + di + df) \times \phi \tag{4}$$

k' is the first BM to transmit the request, which can be master k itself, when it is directly connected to the first domain in the path (in this case di is equal to 0), or can be the BM on the other side of the bridge if master k is a BM not directly connected to the first domain in the path (in this case di is equal to 1). df is equal to 0 if the destination station is a master, a slave or a BM directly connected to the last domain in the IDT Communication Path. df is equal to 1 if the destination station is a BM not directly connected to the last domain where the message is transmitted. ϕ is the internal relaying delay of the bridges in the path.

3 INTER-DOMAIN MOBILITY PROCEDURE TIMINGS

3.1 Phase 1

The IDMP starts with the transmission, by the GMM, of the `SMP` message, which must be received by all BMs in the system. Fig. 4, illustrates phases 1 and 2 events, assuming the network scenario in Fig. 1.

The worst-case time span for the `SMP` message to reach a BM bm (t_{SMP}^{bm}), can be calculated considering an unicast IDT (Eq. (4)): $t_{SMP}^{bm} = Ru_{SMP}^{GMM\to bm}$.

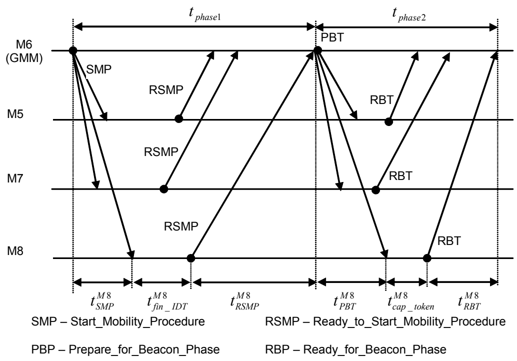

Fig. 4 – Phase 1 and Phase 2 main events timings

After receiving the `SMP` 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. The following equation gives the worst-case time until all IDTs are completed for a particular BM *bm*.

$$t^{bm}_{fin\_IDT} = \max_{S_i^k \in \Psi_{IDT}} \left\{ Rbmi_i^k + T_i^k + Rslr_i^k \right\} \tag{5}$$

Ψ_{IDT} refers to the set of message streams which are also IDTs served by BM *bm*. *k* represents a master which belongs to the domain where the BM *bm* is connected, and uses BM *bm* as the first BM in the path (BM_{ini}). $Rbmi_i^k$ can be calculated using Eq. (3).

After completing all pending IDTs, the bridges signal their new state by sending to the GMM a `RSMP` message. The worst-case time needed by the `RSMP` message to go from a BM *bm* to the GMM (t_{RSMP}^{bm}) can also be calculated using Eq. (4): $Ru_{RSMP}^{bm \rightarrow GMM}$.

Phase 1 only stops when all `RSMP` messages (coming from all DMMs) have been received by the GMM. Therefore, the following equation allows computing the worst-case time span of Phase 1.

$$t_{phase1} = \max_{\forall bm} \left\{ t^{bm}_{SMP} + t^{bm}_{fin\_IDT} + t^{bm}_{RSMP} \right\} \tag{6}$$

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

3.2 Phase 2

Phase 2 starts when the the GMM sends the `PBT` message. The worst-case time required for the `PBT` message (time span denoted as t_{PBT}^{dmm}) to reach DMM *dmm* is given by $Ru_{PBT}^{GMM \rightarrow dmm}$. Additionally, the DMM clears all its routing table entries related to mobile wireless stations.

The reception of the `PBT` message commands the system DMMs to enter into inquiry sub-phase, after which the DMMs will retain the token. The worst-case time required until capturing the token (denoted as $t_{\text{cap\_token}}^{\text{dmm}}$) is equal to the worst-case token rotation time of the domain where the DMM *dmm* is located, T_{cycle}^{dmm}. Following that, the DMMs send a `RBT` message to the GMM and enter into the inquiry sub-phase. In this sub-phase, the domain DMMs inquire, in sequence, their domain BMs, whether they have any `RBT` message available.

With the network operating in inquiry mode, the worst-case time required for the `RBT` message to go from the DMM *dmm* to the GMM can be computed as follows:

$$t^{dmm}_{RBT} = \sum_{x=0}^{b-1} (Rinq^{2x \rightarrow (2x+1)}_{RBT} + \phi) \tag{7}$$

where $Rinq^{x \rightarrow (x+1)}_{RBT}$ is the worst-case delay experienced by the `RBT` 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 GMM are numbered as: {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. For further details on the reasoning on the timing analysis when the network is inquiry mode, the reader is referred to [10].

To obtain the worst-case time span for Phase 2, the following analytical formulation may then be applied:

$$t_{phase2} = \max\left\{ t^{dmm}_{PBT} + t^{dmm}_{cap\_token} + t^{dmm}_{RBT} \right\}, \forall \text{ dmm} \tag{8}$$

3.3 Phase 3

After collecting all `RBT` messages from all the DMMs, the GMM starts the `Beacon` transmission sub-phase, by broadcasting the `SBT` message. Fig. 5, depicts a timeline for the sequence of events during Phases 3 and 4. The worst-case time required by the `SBT` message to reach a DMM *dmm* is given by:

$$t^{dmm}_{SBT} = \sum_{x=0}^{b} Rinq^{2x \rightarrow 2x+1}_{SBT} + \phi \tag{9}$$

where *x* represents the list of BMs in the IDT Communication Path, from the GMM to a DMM *dmm*, which relay the `SBT` message, similar to the formulation in Eq. (7). *b* is the number of bridges between the GMM and DMM *dmm*. Upon receiving this message, the DMMs start emitting `Beacons`. In wired domains no `Beacons` are transmitted, and therefore stations in these domains may resume IADTs.

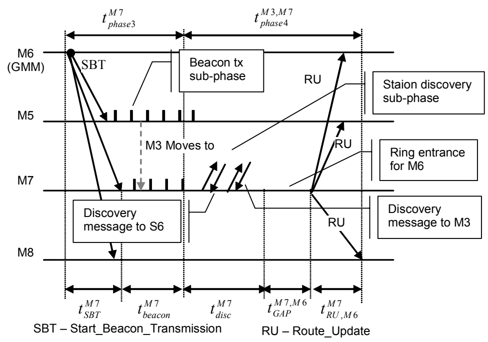

Fig. 5 – Timeline for Phases 3 and 4

The duration of the `Beacon` transmission sub-phase (t_{beacon}^{dmm}) is a parameter that is setup individually on every domain, according to the condition proposed in [1]. Thus, the worst-case duration of Phase 3, calculated for every wireless domain d (represented in the equation by its DMM), is given by:

$$t_{phase3}^{dmm} = t_{SBT}^{dmm} + C_{beacon} \times n_{beacon}^{dmm} \quad \textbf{(10)}$$

where, C_{beacon} is the worst-case latency associated with the transmission of a `Beacon` frame and $n_{beacon}{}^{dmm}$ is the number of `Beacon` frames to be transmitted by DMM *dmm*.

3.4 Phase 4

After the end of the `Beacon` transmission sub-phase, every wireless DMM (still holding the token) inquires all mobile wireless stations, using the `Discovery` message, in order to detect if they still belong to its domain or to detect new "entries" on its domain.

The worst-case duration of the station discovery sub-phase can be computed by:

$$t_{disc}^{dmm} = n_{mob\_stations} \times C_{dic}^{dmm} \quad \textbf{(11)}$$

where $n_{mob\_stations}$ is the number of mobile wireless stations (including masters and slaves), and $C_{disc}{}^{dmm}$ is the worst-case latency associated with the `Discovery` message on the domain represented by *dmm*, including the response from the addressed station. After this, mobile wireless slaves are capable of answering requests, but new mobile wireless masters must still enter the logical ring using the standard PROFIBUS Gap Update mechanisms (briefly described in Section 2.1).

The worst-case time for a master station j entering the ring, after master k ($t_{master\_entry}{}^{k,j}$) can be computed as described in [10].

Once the discovery of stations is complete, or a new master has entered into a different domain, the domain DMM sends a `RU` message, which will be used by the bridges to update their routing tables. The worst-case time span that the `RU` 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 $Ru_{RU,s}{}^{dmm \to bm}$ (using Eq. (4)).

To summarize, the time required before a BM *bm* knows that a station s is again operational in a wireless domain, the duration of Phase 4, is given by:

$$t_{phase4}^{s,bm} = \begin{cases} t_{disc}^{dmm} + t_{RU,s}^{bm}, s \in \Pi_{slave} \\ t_{dis}^{dmm} + 3 \times t_{cycle}^{dmm} + t_{m\_master\_entry}^{k,j} + t_{RU,s}^{bm}, s \in \Pi_{master} \end{cases} \quad \textbf{(12)}$$

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 wireless slaves and mobile wireless masters in the system, respectively.

4 INCORPORATING THE LATENCIES OF THE IDMP INTO MESSAGE TRANSACTIONS

When the IDMP mechanism is active, it is responsible for additional delays on the response time of the system message streams.

4.1 Intra-Domain Transactions

The period of time in which the transactions between stations belonging to the same domain are not possible, comprises the inquiry sub-phase, the beacon emission sub-phase and the identification sub-phase. Therefore, Eq. (1) must be updated by considering the period of time during which IADTs are disabled in a domain.

A worst-case condition occurs when master k queues a request related to message stream S_i^k, just before the start of the period of time during which IADTs are disabled. The following equation updates the WCRT for IADTs under these circumstances.

$$Rslr\_m_i^k = \begin{cases} Rslr_i^k + t_{IADT\_dis\_wr}^{dmm}, \text{in wired domains} \\ Rslr_i^k + t_{IADT\_dis\_wl}^{dmm}, \text{in wireless domains} \end{cases} \quad \textbf{(13)}$$

where $t_{IADT\_dis\_wr}{}^{dmm}$ and $t_{IADT\_dis\_wl}{}^{dmm}$ are the time during which IADTs are disabled in a wired and in a wireless domain (defined by its DMM), respectively. These time spans be calculated by:

$$\begin{aligned} t_{IADT\_dis\_wr}^{dmm} &= t_{phase2} - t_{PBP}^{dmm} - t_{cap\_token}^{dmm} + t_{SB}^{dmm} \\ t_{IADT\_dis\_wl}^{dmm} &= t_{phase2} - t_{PBP}^{dmm} - t_{cap\_token}^{dmm} + t_{phase3}^{dmm} + t_{disc} \end{aligned} \quad \textbf{(14)}$$

4.2 Inter-Domain Transactions (involving Domain Resident Wireless Stations or Wired Stations)

The IDMP requires disabling IDTs during its evolution. IDTs are disabled, on BMs, from the reception of the `SMP` message until the end of the identification sub-phase or the reception of the `SBT` message, for wireless and wired domains, respectively. IDTs involving mobile wireless stations are only enabled again at the reception of a `RU` message regarding the responder station. Therefore, in relation to transactions involving Domain Resident Wireless Stations or Wired Stations, the time during which IDTs are disabled in a BM belonging to a wired ($t_{IDT\_dis\_wr}{}^{dmm}$) or wireless ($t_{IDT\_dis\_wl}{}^{dmm}$) domain can be obtained by:

$$\begin{aligned} t_{IDT\_dis\_wl}^{bm} &= t_{phase1} - t_{SMP}^{bm} + t_{phase2} + t_{SB}^{dmm} \\ t_{IDT\_dis\_wr}^{bm} &= t_{phase1} - t_{SMP}^{bm} + t_{phase2} + t_{phase3}^{dmm} + t_{disc}^{dmm} \end{aligned} \quad \textbf{(15)}$$

To obtain the WCRT of an IDT related to message stream S_i^k, involving domain resident wireless stations or wired stations, the following situations must be analysed separately:

1. $T_i^k > t_{IADT\_dis}{}^{bm} > t_{IDT\_dis}{}^{bm}$
2. $t_{IADT\_dis}{}^{bm} < T_i^k \leq t_{IDT\_dis}{}^{bm}$
3. $T_i^k \leq t_{IADT\_dis}{}^{bm} < t_{IDT\_dis}{}^{bm}$

where $t_{IADT\_dis}{}^{bm}$ represents either $t_{IADT\_dis\_wr}{}^{dmm}$ or $t_{IADT\_dis\_wl}{}^{dmm}$ on the initiator domain, in the case when the domain is wired or wireless, respectively. *bm* represents the BM on master k domain, which is used as BM_{ini} by the message stream S_i^k, and *dmm* is the DMM in the domain to which master k belongs.

Case One. In the first case, it is obvious that at most one request related to an IDT may be lost due to the IDMP. The following equation incorporates these conditions by adding another retry on the WCRT calculation for IDTs:

$$Rmlr\_m_i^k = \left(A_i^k + 1\right)\times T_i^k + Rslr_i^k \tag{16}$$

Case Two. In the second case, several requests related to message stream S_i^k can be lost during the evolution of the IDMP. Also, since $T_i^k \geq t_{IADT\_dis}^{bm}$, it is not possible to guarantee that a request is queued on the initiator transmission queue at some point in the period of inaccessibility during which IADT are disabled. Fig. 6 depicts such kind of scenario, assuming the network depicted in Fig. 1, and an IDT between master M2 and slave S7.

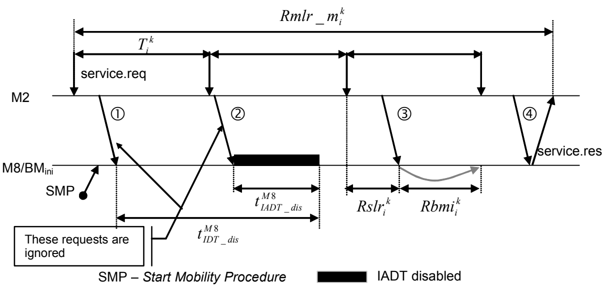

Fig. 6 – Case when $t_{IADT\_dis}^{bm} < T_i^k \leq t_{IDT\_dis}^{bm}$

In the depicted scenario, the first and the second requests arriving at M8/BM_{ini} are ignored, since M8/BM_{ini} had previously received a `SMP` message, and stopped accepting new IDTs. M8/BM_{ini} only opens an IDT on the third request.

To obtain the effect of IDMP on the IDT response time, when $t_{IADT\_dis}^{bm} < T_i^k \leq t_{IDT\_dis}^{bm}$, the following worst-case assumptions are made: the first request issued by master k, related to message stream S_i^k, arrives at BM_{ini} just after it had received the `SMP` message; another request, which initialises an IDT on the BM_{ini}, arrives after the end of the period of time during which IADTs are disabled in master k domain.

Under these conditions, the following equation accounts for the effect of the IDMP on IDTs if $t_{IADT\_dis}^{bm} < T_i^k \leq t_{IDT\_dis}^{bm}$:

$$Rmlr\_m_i^k = Rslr_i^k + t_{IDT\_dis}^{bm} + T_i^k + Rmlr_i^k \tag{17}$$

Case Three. In this case, since $T_i^k < t_{IADT\_dis}^{bm}$, master k is able to queue at least one retry related to message stream S_i^k, at some point in the period of inaccessibility during which IADTs are disabled. Fig. 7 depicts such kind of scenario.

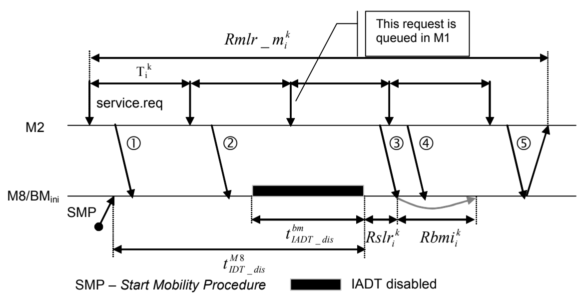

Fig. 7 – Case when $T_i^k \leq t_{IADT\_dis}^{bm} < t_{IDT\_dis}^{bm}$

In this example, the first two requests are ignored since M8/BM_{ini} previously has received the `SMP` message. The third request is queued on the M2 output queue at some stage in the period of time during which IADTs are disabled. As soon as this period ends, and M2 is able to contend for the medium, the request is transmitted, initialising an IDT in M8/BM_{ini}. The fourth request is ignored by M8/BM_{ini}, since it does not have any response available. Finally, only on the fifth request a response is transmitted back to M2.

To obtain the effect of the IDMP on the IDT response time, when $T_i^k \leq t_{IADT\_dis}^{bm} < t_{IDT\_dis}^{bm}$, the following assumptions are made: the first request issued by master k related to message stream S_i^k, arrives at BM_{ini} just after it had received the `SMP` message; another request related to the same message stream is received by BM_{ini} at some stages in the period of time during which IADTs are disabled. Therefore, the following equation holds:

$$Rmlr\_m_i^k = \begin{cases} Rslr_i^k + t_{IDT\_wr\_dis}^{bm} + Rmlr_i^k & \text{, wired domains} \\ Rslr_i^k + t_{IDT\_wl\_dis}^{bm} + Rmlr_i^k & \text{, wireless domains} \end{cases} \tag{18}$$

Accounting for the effects of the IDMP on the calculation of $Rbmi_i^k$

The analysis presented above only takes into consideration the state in the initiator domain. Nonetheless, there are no guarantees if the remaining BMs which belong to the IDT Communication Path have its IDTs enabled. In such cases, when an Inter-Domain Request frame arrives at a bridge, having one of its BMs with IDTs disabled, the IDF must wait on the BM output queue until being transmitted by the BM.

Fig. 8 depicts an example regarding an IDT between master M2 and slave S1.

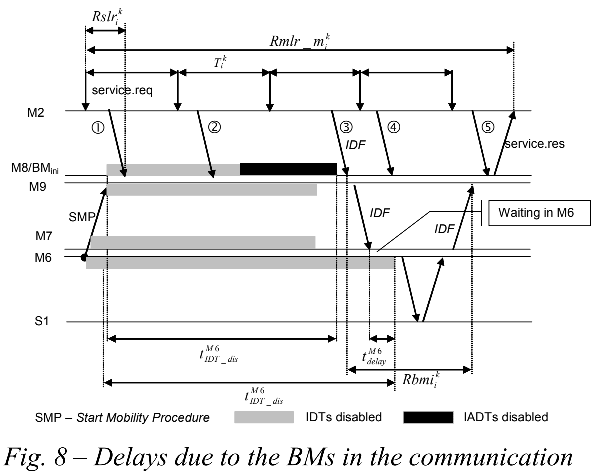

Fig. 8 – Delays due to the BMs in the communication path set not having its IDTs enabled

In this example, the two first requests transmitted by M2 are ignored, since M8/BM_{ini} has its IDTs disabled. The third request is accepted by M8/BM_{ini} opening an IDT at M8/BM_{ini}. M8/BM_{ini} receives the request and transforms it into an IDF using the rules defined by the IDP, then this frame is relayed until M6, which does not have its IDTs enabled. Consequently, the IDF has to wait (t_{delay}^{M6}) until the IDTs are again enabled in M6.

The following equation provides a new formulation to $Rbmi_i^k$, including the effects of the IDMP:

$$Rbmi\_m_i^k = \max\left\{Rbmi_i^k + pos(t^{bm}_{IDT\_dis\_GMM} - t^{BM_{ini}}_{IDT\_dis\_GMM})\right\}, \quad \forall bm \in \Omega_{req}(S_i^k) \tag{19}$$

where, $t_{IDT\_dis\_GMM}{}^{BM_{ini}}$ is equal to the time during which IDTs are disabled on the BM which is the BM_{ini} for message stream S_i^k, plus the time required for the `SMP` message to reach that BM, $t_{IDT\_dis\_GMM}{}^{BM_{ini}} = t_{IDT\_dis}{}^{BM_{ini}} + t_{SMP}{}^{BM_{ini}}$. Similarly, $t_{IDT\_dis\_GMM}{}^{bm}$ refers to the time during which IDTs are disabled on a BM bm which belongs to the BMs which relay the IDT request frame in the path from the initiator to the responder related to message stream S_i^k, plus the time required for the `SMP` message to reach BM bm, $t_{IDT\_BM}{}^{bm} = t_{IDT\_dis}{}^{bm} + t_{SMP}{}^{bm}$. In the equations, the inclusion of the time spans $t_{SMP}{}^{BM_{ini}}$ and $t_{SMP}{}^{bm}$ is required in order for $t_{IDT\_dis\_GMM}{}^{BM_{ini}}$ and $t_{IDT\_dis\_BM}{}^{bm}$ to have the same starting reference – the start of the IDMP by the system GMM. $pos(a)$ is a function that returns a when $a \geq 0$ and 0 otherwise.

4.3 Transactions Involving Mobile Wireless Stations

The problem of providing a worst-case bound for the response time of IDTs related to a message stream S_i^k involving mobile wireless stations is, in practice, similar to the scenario described in the Sections 4.2 and 4.3.

Three main sub-cases must be considered: 1 – IDTs between a wired or domain resident wireless master and a mobile wireless slave/master; 2 – IDTs between a wireless mobile master and a wired or domain resident wireless slave/master; 3 – IDTs involving two mobile wireless stations.

Case One. IDTs involving a mobile wireless station are disabled, on the BM_{ini}, from the reception of the `SMP` message until the reception of a `RU` message regarding the responder station s – $t_{IDT\_mob\_dis}{}^{BM_{ini},s}$. For the case of a wireless mobile master this time span can be calculated by:

$$\begin{aligned} t^{bm,s}_{IDT\_MM\_dis} &= t_{phase1} + t_{phase2} + \\ &\max(t^{wldmm}_{phase3} + t^{wldmm}_{dics} + t^{s,i}_{m\_master\_entry} + t^{bm}_{RU,s}) - t^{bm}_{SMP}, \forall wldmm \end{aligned} \tag{20}$$

where j is the address of the station that will be the predecessor of station s, when s moves into a new domain. For the case of wireless mobile slave, this time span can be calculated by:

$$\begin{aligned} t^{bm,s}_{IDT\_MS\_dis} &= t_{phase1} + t_{phase2} + \\ &\max(t^{wldmm}_{phase3} + t^{wldmm}_{disc} + t^{bm}_{RU,s}) - t^{bm}_{SMP}, \forall wldmm \end{aligned} \tag{21}$$

In both cases, *wldmm* represents the set of DMMs which belong to all possible domains where station s is capable of belonging.

Fig. 9, depicts an example which illustrates an IDT between a master M2 and S6. In this example, the requests transmitted by M2 and received by M8/BM_{ini} are ignored from the reception of the `SMP` message until the reception of a `RU` message regarding slave S6. The third retry is successful, and opens an IDT on M8/BM_{ini}.

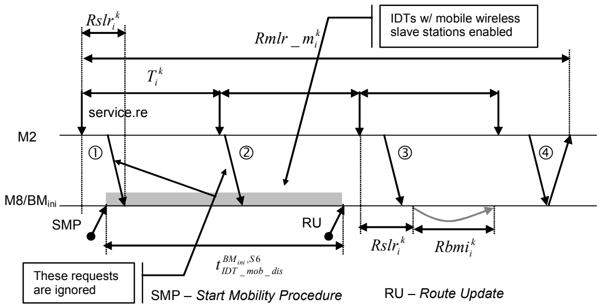

Fig. 9 – IDT example with a mobile wireless station

In this situation the WCRT for an IDT regarding a message stream S_i^k can be calculated assuming the following worst-case conditions: the first request is received by BM_{ini} just after the reception of the `SMP` message; no IDT request is accepted by BM_{ini} during $t_{IDT\_mob\_dis}{}^{BM_{ini},s}$, i.e. from the reception of the `SMP` message until the reception of a `RU` message regarding station s; a request arrives at BM_{ini} just before it receives the `RU` message concerning the responder station.

The following formulation gives the WCRT for IDTs between a wired or domain resident wireless master k and a mobile wireless station s:

$$Rmlr\_m_i^k = Rslr_i^k + t^{BM_{ini},s}_{IDT\_mob\_dis} + T_i^k + Rmlr_i^k \tag{22}$$

$t_{IDT\_mob\_dis}{}^{BM_{ini},s}$ can be calculated by Eq. (20) or (21), in the case when the mobile wireless station is a master or a slave, respectively.

Case Two. The IDT initiator is a mobile wireless master and the responder is a wired or domain resident wireless station.

Fig. 10 shows a timeline depicting an IDT between master M3 and slave S1, where master M3 moves from the original domain (D^1) to a destination domain (D^3), during the execution of an IDT with S1. After the reception of the `SMP` message by the IDT $(BM_{ini})^{orig}$, on the original domain (the domain D^1, to which M5/$(BM_{ini})^{D1}$ belongs to), M3 is no longer able to complete IDTs with S1. Only after entering the logical ring on the destination domain, M3 is capable of completing the transaction, using BM M7/$(BM_{ini})^{D3}$ on the destination domain.

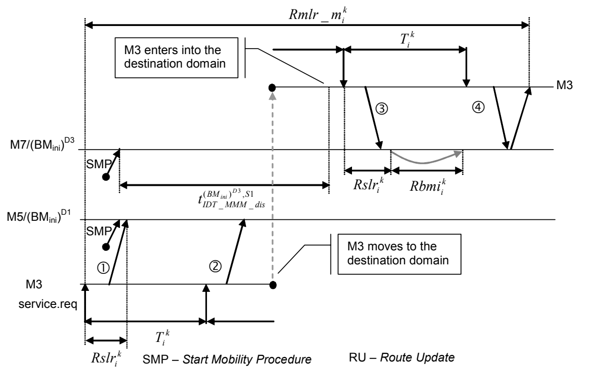

Fig. 10 – IDT example between a mobile wireless master and slave S1

To obtain the WCRT for an IDT related to message stream S_i^k, the following conditions are assumed: the first request is received by $(BM_{ini})^{orig}$ just after the reception of the SMP message; the first request made on the destination domain is delayed by T_i^k after master k has entered the domain.

Under these conditions, the following equation updates Eq. (13) for the case when the transaction is made between a wireless mobile master and a wired or domain resident wireless station:

$$Rmlr\_m_i^k = (Rslr_i^k)^{orig} + (t_{IDT\_MMM\_dis}^k)^{orig \to dest} + T_i^k + (Rmlr_i^k)^{dest} \quad \textbf{(23)}$$

$(y)^d$ represents the value for time span y in domain d. $(t_{IDT\_MMM\_dis}{}^k)^{orig \to dest}$ represents the time during which master k has its IDTs disabled when moving between the original domain and the destination domain, which can be calculated as follows:

$$(t_{IDT\_MMM\_dis}^k)^{orig \to dest} = t_{phase1} + t_{phase2} + t_{phase3}^{dest} + (t_{m\_master\_entry}^{k,j})^{dest} - t_{SMP}^{(BM_{ini})^{orig}} \quad \textbf{(24)}$$

Case Three. Finally, the third case occurs when the two stations move during the execution of an IDT. In this case, it is also necessary to consider two sub-cases: the RU message, regarding the responder station, arrives at the destination domain **before** the initiator has entered into the domain; the RU message, regarding the responder station, arrives at the destination domain **after** the initiator has entered into the domain.

To distinguish between the two sub-cases, the following equations allow determining the time when the initiator is operational (i.e. when it is capable of making transactions) on its destination domain ($dest_i$):

$$\left(t_{ini\_op}\right)^{dest_i} = t_{phase1} + t_{phase2} + t_{phase3}^{dest_i} + (t_{disc})^{dest_i} + (t_{m\_master\_entry}^{k,j})^{dest_i} \quad \textbf{(25)}$$

and when the RU message regarding the entry of responder (r) in its destination domain ($dest_r$) has reached the BM_{ini} on the destination domain of the initiator:

$$\left(t_{resp\_op}\right)^{dest_r} = t_{phase1} + t_{phase2} + t_{phase3}^{dest_r} + t_{phase4}^{r,BM_{ini}} \quad \textbf{(26)}$$

In the first sub-case, the RU message arrives at the destination domain BM_{ini} before master k is ready to make the request. Therefore, the conditions are similar to case two (i.e. when the IDT responder is a domain resident master/slave) and the WCRT can be given by Eq. (23).

In the second sub-case, the initiator has to wait until the reception of a RU message before being capable of completing a transaction with the responder. Therefore the WCRT can be calculated based partially on Eq. (22), in order to account for the mobility of the initiator station as follows:

$$Rmlr\_m_i^k = (Rslr_i^k)^{orig} + t_{phase1} + t_{phase2} + t_{phase3}^{dest_i} + (t_{disc})^{dest_i} + (t_{m\_master\_entry}^{k,j})^{dest_i} - t_{SMP}^{orig} + T_i^k + (Rmlr_i^k)^{dest} \quad \textbf{(27)}$$

5 CONCLUSION

In this paper we presented a worst-case timing analysis for transactions occurring between stations in a hybrid wired/wireless PROFIBUS network, where the interconnection between different wireless media is supported by intermediate systems operating as bridges. The presented analysis evolved from previous works which had proposed a timing analysis for the IDP [8] and for the latencies involved in the IDMP [10], to provide a complete analysis considering inter-domain mobility.

REFERENCES

1. Alves, M., Tovar, E., Vasques, F., Roether, K., Hammer, G., "Real-Time Communications over Hybrid Wired/Wireless PROFIBUS-based Networks", Proceedings of the 14th Euromicro Conference on Real-Time Systems, Vienna, Austria, pp. 142-151 June 2002.
2. Ferreira, L., Alves, M., Tovar, E., "Hybrid Wired/Wireless PROFIBUS Networks Supported by Bridges/Routers", Proceedings of the 2002 IEEE International Workshop on Factory Communication Systems, Vasteras, Sweden, pp. 193-202August 2002.
3. Ferreira, L., Tovar, E., Alves, M., "PROFIBUS Protocol Extensions for Enabling Inter-Cell Mobility in Bridge-based Hybrid Wired/Wireless Networks", Proceedings of the 5th IFAC International Conference on Fieldbus Systems and their Applications, Aveiro, Portugal, pp. 283-290, July 2003.
4. Ferreira, L., Tovar, E., Alves, M., "Enabling Inter-Domain Transactions in Bridge-Based Hybrid Wired/Wireless PROFIBUS Networks", Proceedings of the 9th IEEE International Conference on Emerging Technologies and Factory Automation - ETFA2003, Lisbon, Portugal, pp. 15-22, July 2002.
5. Tovar, E. and Vasques, F., "Cycle Time Properties of the PROFIBUS Timed-Token Protocol", Computer Communications 22 (1999), pp. 1206-1216, Elsevier.
6. Lee K., Lee S., "Integrated Network of PROFIBUS-DP and IEEE 802.11 Wireless LAN with Hard Real-Time Requirement", Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE'01), Pusan, Korea, pp. 1484-1489, 2001.
7. Willig, A., "Investigations on MAC and Link Layer for a Wireless PROFIBUS over 802.11", PhD Dissertation, University of Berlin, 2002.
8. Ferreira, L., Tovar, L., "Timing Analysis of a Multiple Logical Ring Wired/Wireless PROFIBUS Network", Proceeding of the 5th IEEE International Workshop on Factory Communication Systems – WFCS'2004, pp. 81 – 90, September 2004.
9. Aslanis, S., Koulamas, C., Koubias, S., Papadopoulos, G., "Architectures for an Integrated Hybrid (Wired/Wireless) Fieldbus", EFT Journal of Electrical Engineering, October 2001.
10. Ferreira, L., Tovar, E. "Timing Analysis of an Inter-Cell Mobility Procedure for a Wired/Wireless PROFIBUS Network" Proceedings of the 10th International Conference on Real-Time and Embedded Computing Systems and Applications - RTCSA04, Gothenburg, Sweden, pp. 591 – 609, 2004