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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.

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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 \(T_{ST}\), 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 \rightarrow M3), (M1 \rightarrow M4 \rightarrow M6), (M7 \rightarrow M9), (M8 \rightarrow 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_{Bi}, 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_{M}, (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}, 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_{M} 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 D3, D4 and D5, respectively.

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

![Fig. 3 – Phases of the IDMP](image)

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 destination station). 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 (by the Master) and the DMMs, which commands the system BMs to finish all pending IDTs.

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. Consequently, the WCRT for a message stream i from master k on a MLR network (Rmlk), can be formulated as follows:

$$Rmlk^i = A^k_i \times Tml^i + Rslk^i$$  \hspace{1cm} (2)

$$A^k_i$$ 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, until the arrival of the respective response to BMi (Rbmi). Therefore, $$A^k_i$$ can be obtained by computing $$\left(\frac{(Rslk^i + Rbmi^k - C_m)}{Tml^i}\right)$$. Rsmpk can be obtained as follows:

$$Rbmi^k = \sum_{i=1}^{b} \left(Rsl_{i,\text{req}} \cdot \frac{T_{\text{req}}}{\phi} \right) + \sum_{f=1}^{\bar{f}} \left[Rsl_{f,\text{req}} \cdot \frac{T_{\text{req}}}{\phi} \right] + 2 \times b \times \phi$$  \hspace{1cm} (3)

In the worst-case analysis of the IDP, the WCRT for a high-priority message stream i from a master k in an MLR network (Rslk), or in the case of the bridge-based approach referred to as an Intra-Domain Transaction (IADT), can be computed using Eq. (4):

$$Rslk^i = nh^k \times T_{\text{sl,req}} + Ch^k_i$$  \hspace{1cm} (4)

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 (Rslk), or in the case of the bridge-based approach referred to as an Intra-Domain Transaction (IADT), can be computed using Eq. (4):

$$Rslk^i = nh^k \times T_{\text{sl,req}} + Ch^k_i$$  \hspace{1cm} (1)

where $$nh^k$$ is the number of synchronous high-priority messages streams generated in master k and $$Ch^k_i$$ is the worst-case duration of a synchronous message cycle i issued by master k. $$T_{\text{cycle}}$$, the worst-case token rotation time can be computed as presented in [5].

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 (Istampbm), can be calculated considering an unicast IDT (Eq. (4)): $I_{\text{stamp}} = R_{\text{SMP}} \times \text{GMM-bm}$. soften

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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 \( bm \).

\[
I_{\text{fin, dmm}} = \max_{i \in \mathcal{Q}_{\text{dmm}}} \{ R_{\text{dmm}i} + T_{\text{i}} + \text{Retr} \} \tag{5}
\]

\( \mathcal{Q}_{\text{dmm}} \) 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\(_{\text{init}}\)). \( R_{\text{dmm}i} \) can be calculated using Eq. (3).

After completing all pending IDTs, the bridges signal the GMM to proceed to Phase 2. Only at this point in time the GMM can proceed to Phase 2.

### 3.2 Phase 2

Phase 2 starts when the GMM sends the PBT message. The worst-case time required for the PBT message (time span denoted as \( I_{\text{PBT}} \)) to reach DMM \( dmm \) is given by \( R_{\text{PBT}} \text{GMM-}dmm \). 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 \( I_{\text{cap, token}} \)) is equal to the worst-case token rotation time of the domain where the DMM \( dmm \) is located, \( T_{\text{cycle}} \). 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:

\[
I_{\text{RBT}} = \sum_{i=x}^{2} (R_{\text{BMI}i} + \psi) + \phi \tag{7}
\]

where \( R_{\text{BMI}i} \) 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: \( 0, 1, 2, \ldots, 2\times b-1 \), where 0 refers to DMM \( dmm \) and \( 2\times b-1 \) 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:

\[
I_{\text{phase2}} = \max_{i \in \mathcal{Q}_{\text{dmm}}} \{ I_{\text{PBT}} + I_{\text{cap, token}} + I_{\text{RBT}} \} \tag{8}
\]

### 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:

\[
I_{\text{SBT}} = \sum_{i=x}^{2} (R_{\text{SBT}i} + \phi) \tag{9}
\]

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.
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:

\[ t_{\text{dec}} = n_{\text{mobile}} \times C_{\text{dec}} \]  

(11)

where \( n_{\text{mobile}} \) is the number of mobile wireless stations (including masters and slaves), and \( C_{\text{dec}} \) 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 \( k \) \((t_{\text{master_entry}})^k\) 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 \( t_{\text{RU}} \)) can be calculated by \( R_{\text{GUS}} \) (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:

\[ t_{\text{phases}} = t_{\text{dec}} + t_{\text{bm}} + t_{\text{master}} + t_{\text{sent}} + t_{\text{entry}} + t_{\text{master_entry}} + t_{\text{mac}} \]

(12)

where, \( dmm \) represents DMM of the domain in which station \( s \) is, or to where it has entered. \( \Pi_{\text{slave}} \) and \( \Pi_{\text{master}} \) 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 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 \( S_k^i \), 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.

\[
R_{\text{IADT}}^{\text{in}} = \begin{cases} 
\frac{t_{\text{dec}}}{2} + t_{\text{w} \text{IADT}}, \text{in wired domains} \\
\frac{t_{\text{dec}}}{2} + t_{\text{IADT}}, \text{in wireless domains}
\end{cases}
\]

(13)

where \( t_{\text{IADT}_{\text{w} \text{IADT}}} \) and \( t_{\text{IADT}_{\text{w} \text{IADT}}} \) are the time during which IADTs are disabled in a wired and in a wireless domain (defined by its DMM), respectively. These time spans can be calculated by:

\[
t_{\text{IADT}_{\text{w} \text{IADT}}} = t_{\text{phw}} - t_{\text{phw}} + t_{\text{token}} + t_{\text{phw}}
\]

(14)

\[
t_{\text{IADT}_{\text{w} \text{IADT}}} = t_{\text{phw}} - t_{\text{phw}} + t_{\text{token}} - t_{\text{phw}}
\]

(15)

To obtain the WCRT of an IDT related to message stream \( S_k^i \), involving domain resident wireless stations or wired stations, the following situations must be analysed separately:

1. \( T_{\text{IADT}}^{\text{in}} > t_{\text{IADT}_{\text{dis}}} \)
2. \( t_{\text{IADT}_{\text{dis}}} < T_{\text{IADT}}^{\text{in}} < t_{\text{IADT}} \)
3. \( T_{\text{IADT}}^{\text{in}} < t_{\text{IADT}_{\text{dis}}} \)

where \( t_{\text{IADT}_{\text{dis}}} \) represents either \( t_{\text{IADT}_{\text{dis}} \text{IADT}} \) or \( t_{\text{IADT}_{\text{dis}} \text{IADT}} \) 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 \( BM_{\text{dis}} \) by the message stream \( S_k^i \) 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:

\[ R_{\text{m}t} = (A_t + 1) \times T_i + R_{\text{slr}} \]  

(16)

**Case Two.** In the second case, several requests related to message stream \( S_i \) can be lost during the evolution of the IDMP. Also, since \( T_i \geq t_{\text{IADT_dis}} \), 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 IADTs 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 \( t_{\text{IADT_dis}} < T_i \leq t_{\text{IDT_dis}} \)](image)

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

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

\[ R_{\text{m}t} = R_{\text{slr}} + T_{\text{init}} + R_{\text{m}r} \]  

(17)

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

![Fig. 7 – Case when \( T_i < t_{\text{IADT_dis}} \)](image)

In this example, the first two requests are ignored since M8/BMini 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/BMini. The fourth request is ignored by M8/BMini since it does not have any response available. Finally, on the fifth request a response is transmitted back to M2.

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

\[ R_{\text{m}t} = \begin{cases} R_{\text{slr}} + T_{\text{init}} + R_{\text{m}r} \quad \text{wired domains} \\ R_{\text{slr}} + T_{\text{init}} + R_{\text{m}r} \quad \text{wireless domains} \end{cases} \]  

(18)

**Accounting for the effects of the IDMP on the calculation of \( R_{\text{m}t} \).**

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](image)
The following equation provides a new formulation to \( Rbmi_i \), including the effects of the IDMP:

\[
Rbmi_i = max\{Rbmi_i + pos(t_{IDT,\_i}^{\_BM}, \_BM) \; \forall \; \BM \in \Omega_{BM}(S_i^k) \} 
\]  

(19)

where, \( IDT\_dis\_GMM_{BM} \) is equal to the time during which IDTs are disabled on the BM which is the \( BM_{\text{Init}} \) for message stream \( S_i^k \), plus the time required for the \( SMP \) message to reach that BM, \( IDT\_dis\_GMM_{BM} = IDT\_dis\_BM \). Similarly, \( IDT\_dis\_GMM_{BM} \) 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 \( bm \), \( IDT\_dis\_BM_{bm} = IDT\_dis\_BM_{BM} + t_{SMP}^{BM} \). In the equations, the inclusion of the time spans \( t_{SMP}^{BM} \) and \( t_{SMP}^{BM} \) is required for \( IDT\_dis\_GMM_{BM} \) and \( IDT\_dis\_BM_{BM} \) 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 \( BM_{\text{Init}} \) from the reception of the \( SMP \) message until the reception of a \( RU \) message regarding the responder station \( s \). The following worst-case conditions: the first request is received by \( BM_{\text{Init}} \) just after the reception of the \( SMP \) message; no IDT request is accepted by \( BM_{\text{Init}} \) during \( IDT\_mob\_dis_{BM} \), i.e. from the reception of the \( SMP \) message until the reception of a \( RU \) message regarding station \( s \); a request arrives at \( BM_{\text{Init}} \) 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 \( s \):

\[
Rm_{\_i} = Rbmi_i + t_{IDT\_dis\_GM}^{BM_{\text{Init}}} + t_{IDT\_mob\_dis}^{BM_{\text{Init}}} + t_{SMP}^{BM_{\text{Init}}} + t_{RU}^{BM_{\text{Init}}} \]  

(22)

\( IDT\_mob\_dis_{BM}^{BM_{\text{Init}}} \) 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 (\( D^2 \)), during the execution of an IDT with S1. After the reception of the \( SMP \) message by the IDT (\( BM_{\text{Init}} \)), on the original domain (the domain \( D^1 \), to which \( M3/\_\_BM_{\text{Init}} \) 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 \( M7/\_\_BM_{\text{Init}} \) on the destination domain.

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 \( BM_{\text{Init}} \) just after the reception of the \( SMP \) message; no IDT request is accepted by \( BM_{\text{Init}} \) during \( IDT\_mob\_dis_{BM}^{BM_{\text{Init}}} \), i.e. from the reception of the \( SMP \) message until the reception of a \( RU \) message regarding station \( s \); a request arrives at \( BM_{\text{Init}} \) just before it receives the \( RU \) message concerning the responder station.

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 \(T^i_{f}\) 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:

\[
RM_{m}^{d} = (RM_{r})^{res} + (t_{dest \to orig})^{orig \to dest} + T^i_{f} + (RM_{f})^{dest}
\]

\((y)^{d}\) represents the value for time span \(y\) in domain \(d\). \((t_{dest \to orig})^{orig \to dest}\) 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:

\[
(t_{dest \to orig})^{orig \to dest} = t_{phase1} + t_{phase2} + t_{dest}
\]

\((t_{phase})^{dest}\) denotes the time during which the responder \(r\) is ready to make transactions (i.e. when it is capable of making transactions) on its destination domain \((dest)_d\):

\[
(t_{phase})^{dest} = t_{phase1} + t_{phase2} + t_{dest} + (t_{dest \to orig})^{orig \to dest}
\]

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 \((dest)_d\):

\[
(l_{m}^{orig \to dest})^{orig \to dest} = t_{phase1} + t_{phase2} + t_{dest} + (t_{dest \to orig})^{orig \to dest}
\]

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

\[
(l_{r}^{orig \to dest})^{orig \to dest} = t_{phase1} + t_{phase2} + t_{dest}
\]

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:

\[
RM_{m}^{d} = (RM_{r})^{res} + (t_{orig \to dest})^{orig \to dest} + t_{dest} + (RM_{f})^{dest}
\]