Simulation Study of Wired/Wireless Fieldbus Systems Using Store and Forward Mode

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Abstract

Fieldbus is a specific class of LAN technology, through which the communication process in industrial applications is integrated. The extent of using the wireless communications in most applications, leading to design hybrid wired/wireless fieldbus systems is based on standard PROFIBUS protocol. Because of the difference in physical media such as bit rate and/or frame format between wired domain and wireless domain, there is a need to use a method to overcome traffic congestion that may occur in the intermediate systems as a result of the heterogeneity in the physical media. Within this work the intermediate systems (repeaters) are suggested to work as store-and-forward mode. The main objectives of this work is to develop simulation tools for the hybrid wired/wireless PROFIBUS architectures in order to perform behavioral study of such network protocols. The use of our developed simulation tools has indeed enabled us to test different network configurations and different parameters settings more easily, cheaper, and faster than in a real application.

Keywords: Fieldbus, PROFIBUS, Simulation Tools, Store and Forward Mode, Wired/Wireless Systems.

محاكاة لدراسة أنظمة النواقل الحقلية السلكية واللاسلكية باستخدام نمط الخزن والإرسال

الخلاصة

الناقل الحقلي هو صنف معين من تقنيات شبكات الاتصال المحلية والذي من خلاله تتكامل عملية الاتصال في التطبيقات الصناعية. إن الاستخدام الواسع للاتصالات اللاسلكية في كثير من التطبيقات قادنا إلى تصميم أنظمة نواقل حقلية سلكية و لاسلكية استنادا على معيار البروفيبس. هذا وبناء على الاختلاف الموجود في وسائط الاتصال مثل معدل نقل البيانات أو شكل الإرسال بين المجالين السلكي واللاسلكي، فإن هناك حاجة ملحة لاستخدام طريقة للتغلب على ازدحام حركة المرور التي قد تحدث في الأنظمة الوسطية نتيجة للتباين الحاصل بين المجالين. وقد اقترح في هذا العمل أن تقوم الأنظمة الوسطية بالعمل بنمط الخزن ثم الإرسال. إن الهدف الرئيسي لهذا العمل هو تطوير وبناء أدوات محاكاة حاسوبية لمعماريات هجينة سلكية ولاسلكية لمعيار البروفيبس بغرض دراسات سلوكيات وبروتوكولات هذه الشبكات. وقد مكننا استخدام أدوات المحاكاة هذه من اختبار أشكال مختلفة لهذه الشبكات وكذلك اختيار قيم مختلفة للمتغيرات ذات العلاقة بأسلوب أسرع وأرخص وأكثر سهولة من التطبيق الواقعي.

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1. Introduction

Fieldbus is a digital communication system for field devices. There are many types of fieldbus systems that allow us to connect many devices together into a network. Fieldbus communication is a two-way so that devices can receive information from controlling stations and also can send information to controlling stations.

PROFIBUS is one famous type of Fieldbus. PROFIBUS is a multi-master system that makes possible the mutual operation of several automating masters. Masters, also designated as active devices, define the data traffic on the bus. When in possession of the access permission (token), they can send data without external requests. The slaves, designated as passive devices, have no bus access permission. They can only confirm received messages or send messages when requested by a master [1].

PROFIBUS supports baud rate varies from 9.6kb/s up to 12Mb/s. A maximum of 127 devices can be operated at the bus. PROFIBUS also supports broadcast and multicast communication. It supports high-priority and low priority messages. The PROFIBUS MAC protocol is depends on the measurement of the token rotation time and it is based on token passing between master nodes [2, 3].

The objective of this work is to develop simulation software for studying and analysis of hybrid wired/wireless fieldbus networks based on the PROFIBUS standard. The remaining of the paper is organized as follows:

Section 2 contains theoretical background about PROFIBUS. Section 3 presents various components of related communication network components. Section 4 starts the presentation of some basic mathematical analysis required to model PROFIBUS hybrid networks. Issues like congestion control and system turnaround time are analyzed. Section 5 continues the mathematical analysis of queuing delays and duration of message streams. To explain the developed simulation software, a case study is described in Section 6. Some important points of discussion are explained in Section 7. Finally, the paper in concluded in Section 8.

2. PROFIBUS Relevant Details

PROFIBUS as one of the Fieldbus solutions of the General-Purpose Fieldbus Communication System was standardized in 1996 as a European standard [4]. It is based on the International Standards Organization (ISO) Open System Interconnection (OSI) reference model, however collapsed to just three layers: Physical Layer (PhL), Data Link Layer (DLL) and Application Layer (AL) [5]. The PROFIBUS PhL can use the RS-485 standard over twisted pair or coaxial cable for the transfer of data, with bit rates up to 12 Mbit/s [1, 6]. The basic unit of the physical topology is called *segment* and has a bus structure, i.e. all stations attached to a segment see the same signals. The maximum numbers of stations on a single segment are 32. Segments can be coupled using repeaters, a maximum of three repeaters are allowed between any pair of stations. The PROFIBUS addressing scheme

restricts the number of stations in a single PROFIBUS LAN with multiple segments to 127.

The PROFIBUS DLL uses a token passing procedure to grant bus access to masters, and a master-slave procedure used by masters to communicate with slaves (or other masters). Slaves do not have communication initiative. They are only capable of transmitting a response (or an acknowledgement) upon master request. The token is passed between masters in ascending Medium Access Control (MAC) address order, thus the masters organize network access in a logical ring fashion. The PROFIBUS standard considers three different types of Application Layer profiles [7, 8]:

- PROFIBUS-Fieldbus Message Specification (FMS)
- PROFIBUS-Decentralized Peripherals (DP)
- PROFIBUS- Process Automation (PA)

Some issues related to PROFIBUS DLL are briefly described below.

a. Message Cycle: In PROFIBUS, only master stations may initiate transactions, whereas slave stations do not transmit on their own initiative, but only upon (master) requests. The station that sends an *Action Frame* (the first frame transmitted in each transaction) is the *initiator* of the transaction, while the addressed one is the *responder*. A transaction (or message cycle) consists of the request or a send/request frame from the initiator (always a master station) and the associated acknowledgement or response frame from the responder (either a master station or a slave station, but typically a slave station) [6].

b. Token Passing: The token is passed between masters in ascending address order. The only exception is that in order to close the logical ring, the master with the highest address must pass the token to the master with the lowest one as shown in Figure 1. Each master knows the address of the previous station (PS – *Previous Station* address), the address of the following station (NS – *Next Station* address) and, obviously, its own address (TS – *This Station* address) [1, 7].

c. Token Cycle: After receiving the token, a master station is allowed to execute message cycles during *Token Holding Time*. T_{TH} is equal to the difference between the *Target Rotation Time* (T_{TR}) and the *Real Rotation Time* (T_{RR}) of the token. T_{TR} is a parameter common to all masters in the network, which must be set to the expected time for the token cycle. T_{RR} is the time measured between two consecutive token receptions – the token cycle.

d. (Re) Initializing the Logical Ring: The logical ring of PROFIBUS is supported by two tables: the *GAP List* (GAPL) and the LAS. It may also optionally maintain a *Live List* (LL) table. The GAPL contains the address range from address TS to NS. This includes all possible addresses. Initialization is primarily a special case of updating the LAS and the GAPL. If after power is on a master station in the LISTEN_TOKEN state a time-out is encountered, i.e., no bus activity within *Time-Out Time* (T_{TO}), it shall claim the token is in CLAIM_TOKEN state and it starts initializing the logical ring. The master station with the lowest station address starts initialization by transmitting two token frames addressed

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to itself (*Destination Address* (DA) = SA = TS) it informs any other master stations (entering a NS into the LAS) that it is now the only station in the logical token ring. Then it transmits an *FDL_Request_Status* frame to each station in an incrementing address sequence, in order to register other stations. The first master station to answer with *Ready_to_Enter_Logical_ Ring* is registered as NS in the LAS and thus closes the GAP range of the token holder. Then the token holder passes the token to its NS.

e. Ring Maintenance: The ring maintenance mechanism is distributed by all master stations. As mentioned, each PROFIBUS master maintains two tables: the GAPL and the LAS. Each master station when holding the token frame checks its GAP addresses every time its *Gap Update Timer* (T_{GUD}) expires. If a station acknowledges positively to the GAP request (an *FDL_Request_Status* frame), with the state

Not_Ready_to_Enter_Logical_Ring or *Slave_ Station*, it is accordingly marked in the GAPL and the next address is checked. If a station answers with the state *Ready_to_Enter_Logical_Ring*, the token holder changes its GAPL and passes the token to the new NS. This (master) station, which has newly been admitted to the logical ring, has already built up its LAS when it was in the LISTEN_TOKEN state, so it is able to determine its GAPL and its NS. This mechanism allows masters to track changes in the logical ring due to the addition (joining) and removal (leaving) of stations. This is accomplished by examining (at most) one GAP address per token visit, using an

FDL_Request_Status frame after the execution of all high-priority transactions, and if the value of T_{TH}, is still positive [9].

f. Error Handling: Additionally, in order to enhance the communication system's reliability, PROFIBUS handles some operational or error states, concerning logical ring management. References [10] and [11] indicate which fault-tolerant mechanisms are activated and their effects on the network behavior. The most important error situations are the lost token, "heardback removal" and error skipping.

g. Frame Formats: In the asynchronous (RS-485) version of the PROFIBUS PhL, each frame is coded in UART characters. Each UART character comprises eleven bits: one start bit (binary 0), eight data bits (octet), one (even) parity bit and one stop bit (binary 1). Indeed, PROFIBUS DLL defines three types of request/response frames, which are the *fixed length with no data field*, the *fixed length with data field* and the *variable data field length* [1 and 7].

h. Data Link Layer Services: PROFIBUS defines 4 types of data transfer services: *Send Data with Acknowledge* (SDA); *Send Data with No acknowledge* (SDN); *Send and Request Data* (SRD) and *Cyclic Send and Request Data* (CSRD). The SDA service allows a user to transmit data to another station and receive a *Short Acknowledge* confirming its reception by the responder station. The SDN service permits transferring data to a single station, to a group of stations (multicast) or to all stations (broadcast). The SRD service allows the transmission of a message to another station and the retrieval of a response. This service can

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be used, for example, to send the output settings for an I/O device and retrieve the state of the device's input ports. The CSRD builds upon the SRD service adding the capability of transferring data periodically, according to the user requirements [12].

3. Network Components

The communication network is composed of End Systems (Master or Slave) and Intermediate Systems that connect the End Systems either via wired physical medium and this is called Wired Domain (WRD) or via wireless physical medium and this is called Wireless Domain (WLD). The End Systems either connect directly with Intermediate Systems and this procedure is called Ad-hoc Radio Cell (ARC) or indirectly and this procedure is called Structured Radio Cell (SRC). Therefore, the Radio Cell can be defined as a common radio coverage area of Wireless End Systems and Intermediate Systems. The main classes of Intermediate Systems in the realm of fieldbus systems are Repeater, Bridge and Router [1, 14].

3.1. Repeater Operation

One of the solutions to interconnect wired and wireless stations is using the Repeater to broadcast message throughout the overall network. The Repeater receives frames from the wired domain and then transmits it to the wireless domain and vice versa. In repeaters and certain types of bridges, packets are forwarded from one port to another with no modifications to their contents. The forwarding delay can be defined as the time difference between the time instant at which the last bit of a packet is received on the input port and the time instant at which the last bit of

the packet was transmitted on the output port. The forwarding delay depends on the implementation of the forwarding operation [15]:

- In cut-through forwarding, the transmission of packet on the output port can start before the packet has been fully received by the input port.

- In store-and-forward forwarding, the transmission of packet on the output port is start after full received of packet by the input port.

3.2. Bridge Operation

A bridge interconnects two Communication Domains with different DLL and PhL protocols. A bridge performs routing functionality according to DLL (MAC) addresses. Reference [16] introduces a type of bridge called "transparent bridge", where all the incoming packets are relayed, regardless of the DLL destination address.

Bridges can be classified according to its content or not for medium access. The use of no-contention Bridge is not useful because the relaying latencies in it are higher than in repeater. The contention bridges cannot be used in PROFIBUS because the bridges may enter in a deadlock state. When there are two communication domains and everyone has token (two logical rings) and one of the stations in the first domain sends requests to station in the second domain and at the same time station in the second domain sends requests to station in the first domain and this case leads the bridge to enter in a deadlock state [1, 17 and 18].

3.3. Router Operation

A router is capable of relaying packet according to their Network Layer addresses. The routing operation can be implemented according to the extended

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addresses, but there is a problem because only fixed and variable data field have extended addresses. The stations that are associated with the same communication domain have the same extended addresses. Also, the extended address of a mobile station should be changed when the mobile station moves from domain to another, but in fact the extended address remains the same [1, 17].

4. Traffic Congestion

The congestion occurs when the demands are greater than the available resources. These resources include bandwidths of links, buffer space (memory), and processing capacity at intermediate systems. Therefore the congestion happens in these cases:

1. Buffer space shortage.
2. Slow links.
3. Slow processors.

The traffic congestion can be avoided through the insertion of additional idle time before issuing message request [1, 19]. The congestion problems depend on the type of Intermediate Systems (ISs), particularly if (ISs) act as Repeater (R), traffic congestion may occur as a result of heterogeneity in bit rates and in PhL PDU formats. There are many congestion control and avoidance schemes which have been proposed in the last two decades [20, 21], but they are unsuitable for fieldbus networks. The timing diagram depicted in Figure 2, illustrates a sequence of message cycles between the Initiator and Responder.

From Figure 2, it can be noted that the Intermediate System (Repeater) interconnects two Communication Domains (Domain 1 & Domain 2) that are different in bit rate, where Domain 1 is faster than Domain 2. Therefore the PhL PDU duration in Domain 2 is large than the PhL PDU duration. The idle times separate the consecutive PDUs in the Communication network. As a result of the different physical media between the two communication domains, the queuing delay (q) is increased with the time. The system turnaround time of message cycle 3 will be affected by the cumulative queuing delay in the Intermediate Systems (ISs).

Traffic congestion avoiding is done through the insertion of additional idle time before issuing message request where queuing delay is zero for all message cycles in the first Intermediate System. The advantages of additional idle time are: avoiding traffic congestion, better responsiveness to failure, and bounded worst-case message response times. The disadvantage of this technique is reducing the number of message cycles per time unit.

To compute the proper value of additional idle time, one must take into account all cases that are related to computation of additional idle time. The relevant cases are discussed in the following three subsections. Later, the issue of system turnaround time is to be considered. For more details on mathematical derivations and modeling assumptions, the reader is advised to refer to [22] and [23].

4.1. After Receiving the Token

Each Master station (M) must insert additional idle time $t_{ID1+(1)}$ after reception of token. Assuming that the master transmits the token and receives the token in the same Communication Domain (Domain i), the $t_{Mesg.req.}^{ready(token)}$ is

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defined as the time elapsed from the beginning of transmission of the token until the moment when the message request is ready to be transmitted in Communication Domain (Domain j). Also the $t_{IS.req.}^{ready(token)}$ is defined as the time elapsed from the beginning of transmission of the token until the moment when the Intermediate system (Repeater) is ready to start relaying the message request from Communication Domain (Domain i) to Communication Domain (Domain j).

It can be shown that:

$$t_{Mesg.req}^{ready(token)} = C_{token}^i + t_{ID1m}^j + t_{ID1(1)}^{j \to j} + C_{req.1}^i + t_{rd} \quad (1)$$

Also the $t_{IS.req.}^{ready(token)}$ can be computed using the following equation:

$$t_{IS.req}^{ready(token)} = C_{token}^i + t_{rd} + C_{token}^j + t_{ID1m}^j \quad …(2)$$

The condition of inserting additional idle time after receiving the token is to guarantee that $t_{Mesg.req.}^{ready(token)}$ must be equal to or larger than $t_{IS.req.}^{ready(token)}$. Thus, the additional idle time $t_{ID1+(1)}^{i \to j}$ can be computed using the following equation:

$$\therefore t_{ID1+(1)}^{i \to j} = C_{token}^j - C_{req.1}^i + t_{ID1m}^j - t_{ID1m}^i \quad …(3)$$

In order to compute the worst-case, it is possible to maximize the $t_{ID1+(1)}^{i \to j}$ by deriving equation (3) for $L_{req.1}$ and L_{token}.

4.2. After Receiving a Response

Each Master station (M) must insert additional idle time $t_{ID1+(2)}$ after receiving a response. Assuming that the first message cycle is done at Communication Domain (Domain i), the

$t_{Mesg.req.}^{ready(resp.)}$ is defined as the time elapsed from the beginning of transmission of a request for message cycle 1 (Req.1) in (Domain i) until the moment when the request of message cycle 2 (Req.2) is ready to be transmitted in (Domain j). Also $t_{IS.req.}^{ready(resp.)}$ is defined as the time elapsed from the beginning of transmission of a request of message cycle 1 (Req.1) in Communication Domain (Domain i) until the moment when the Intermediate System (Repeater) is ready to start relaying the request of message cycle 2 (Req.2) from (Domain i) to (Domain j).

The $t_{Mesg.resp.}^{ready(resp.)}$ can be defined as the time elapsed from the beginning of transmission of a request of message cycle 1 (Req.1) in Communication Domain (Domain i) until the moment when the response of message cycle 1 (Resp.1) is ready to be transmitted in Communication Domain (j). Also $t_{IS.resp.}^{ready(resp.)}$ is defined as the time elapsed from the beginning of transmission of a request of message cycle 1 (Req.1) in Communication Domain (i) until the moment when the Intermediate System (Repeater) is ready to start relaying the response of message cycle 1 (Resp.1) from Communication Domain (i) to Communication Domain (j). One can compute all necessary parameters that are used to find the value of $t_{ID1+(2)}^{i \to j}$ as follows:

$$t_{ISresp}^{ready(resp)} = C_{req.1}^i + t_{rd} + C_{req.1}^j + t_{ID1m}^j \quad ….(4)$$

The value of $t_{Mesg.resp.}^{ready(resp.)}$ may be larger or smaller than $t_{IS.resp.}^{ready(resp.)}$.

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,therefore the max value can be computed as follows:

$$t_{ID1+(2)}^{i\to j} = C_{req1}^{j} - C_{req2}^{i} + C_{resp1}^{j} - C_{resp1}^{i} + 2\times t_{ID1m}^{j} - t_{ID1m}^{i} - t_{rt1}(5)$$
$$+\max(C_{resp1}^{i} - C_{req1}^{j} - t_{ID1m}^{j} + t_{rt1}, 0)$$

In order to compute the worst-case, it is possible to maximize the $t_{ID1+(2)}^{i\to j}$ by deriving equation (5) for $L_{req.1}, L_{req.2}$ and $L_{resp.1}$.

After computing of $t_{ID1+(1)}^{i\to j}$ and $t_{ID1+(2)}^{i\to j}$, one needs to find the maximum value between $t_{ID1+(1)}^{i\to j}$ and $t_{ID1+(2)}^{i\to j}$.

$$\therefore t_{ID1+}^{i\to j} = \max(t_{ID1+(1)}^{i\to j}, t_{ID1+(2)}^{i\to j}) \qquad (6)$$

To compute the total value of idle time:

$$t_{ID1}^{total} = t_{ID1m} + t_{ID1+} \qquad (7)$$

$$T_{ID1}^{i} = t_{ID1}^{total} \times r^{i} \qquad (8)$$

4.3. After Sending an Unacknowledged Request

Each Master station (M) must insert additional idle time t_{ID2+} after unacknowledged request. The $t_{Mesg.req.}^{ready(unack.req.)}$ can be defined as the time elapsed from the beginning of transmission of the unacknowledged request (Req.1) until the moment when the message request (Req.2) is ready to be transmitted in Communication Domain (j). Also, the $t_{IS.req.}^{ready(unack.req.)}$ is defined as the time elapsed from the beginning of transmission of the unacknowledged request (Req.1) until the moment when the Intermediate System (Repeater) is ready to start relaying the message request (Req.2) from Communication Domain (i) to Communication Domain (j).

Then, the $t_{Mesg.req.}^{ready(unack.req.)}$ can be computed as:

$$t_{Mesgreq}^{read(unackreq)} = C_{req1}^{i} + t_{ID2m}^{i} + t_{ID2+}^{i\to j} + C_{req2}^{j} + t_{rd}(9)$$

Also the $t_{IS.req.}^{ready(unack.req.)}$ can be computed as:

$$t_{IS.req.}^{ready(unack.req.)} = C_{req.1}^{i} + t_{rd} + C_{req.1}^{j} + t_{ID2m}^{j} \quad (10)$$

The condition of inserting additional idle time after receiving the token is to guarantee that $t_{Mesg.req.}^{ready(unack.req.)}$ must be equal to or larger than $t_{IS.req.}^{ready(unack.req.)}$. The additional idle time can be computed using the following equation:

$$\therefore t_{ID2+}^{i\to j} = C_{req.1}^{j} - C_{req.2}^{i} + t_{ID2m}^{j} - t_{ID2m}^{i}(11)$$

In order to compute the worst-case, the $t_{ID2+}^{i\to j}$ must be maximized by deriving the equation (11) for $L_{req.1}$ and $L_{req.2}$.

To compute the total value of idle time:

$$t_{ID2}^{total} = t_{ID2m} + t_{ID2+} \qquad (12)$$

$$T_{ID2}^{i} = t_{ID2}^{total} \times r^{i} \qquad (13)$$

4.4. System Turnaround Time

The system turnaround time can be defined as the time interval between the end of the request transmission and the beginning of the response reception. The computation of the system turnaround time is necessary to evaluate the duration of message cycle. To clarify this definition, consider Figure 3.

Where the Initiator belongs to Domain 1 and the Responder belongs to Domain 3. Both Domain 1 and Domain 3 have the same type of physical layer (Wireless Domain) while Domain 2 has another type of physical layer (Wired Domain). It can be shown that:

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$$t_{stn}^{1-3}=t_{rd}+C_{req1}^{2}+t_{rd}+C_{req1}^{3}+t_{rt}+C_{resp}^{3}+t_{rd}+C_{resp}^{2}+t_{rd}$$
$$\dots(14)$$

where t_{stn} represents the system turnaround with no queuing delay. For general equation t_{stn} can be computed as follows:

$$t_{stn(a)}^{1-n} = \sum_{i=2}^{n}(C_{req(a)}^{i} +t_{rd})+t_{rt}+ \sum_{i=n}^{2}(C_{resp(a)}^{i} +t_{rd}) \quad (15)$$

To compute the worst-case system turnaround time t_{st}, one needs to compute the worst-case total queuing delay (Q) and sum it with the system turnaround time with no queuing delay t_{stn}.

$$t_{st} = Q + t_{stn} \qquad (16)$$

5. The Queuing Delay

As mentioned before, a Master (M) must receive the response to a request within the slot time (T_{SL}). If a timeout occurs, the Master retries the request or aborts the transmission. In a Network composed of several heterogeneous domains (different physical layer frame formats and different bit rates) interconnected by Intermediate Systems (Repeaters), the message turnaround times will increase, due to relaying latencies in the Repeaters. These latencies result from the fact that the Repeaters must relay frames between domains with different physical layer frame formats and different bit rates [12]. The request frame of message cycle may be affected by queuing delays in the Intermediate Systems (Repeaters) due to a previous message cycle. The previous message cycle may be acknowledged or unacknowledged.

Therefore, the queuing delay must be computed for these two cases.

At first, for the case of acknowledged message cycle, the queuing delay in every Intermediate System (Repeater) between the Initiator and the Responder where the Initiator and the Responder are in the same Communication Domain can be calculated as follows (for a general case of ith number of Intermediate Systems):

$$t_{Mesgeq}^{(i)ready}=\max(t_{Mesgeq}^{(i-1)ready},t_{IS}^{(i-1)ready})+C_{req2}^{i}+t_{rd} \quad (17)$$

$$t_{IS}^{(i)ready}=\max\begin{Bmatrix} t_{IS}^{(i-1)ready}-t_{ID1m}^{i-1}+t_{rd} \\ \sum_{j=1}^{i}(C_{req1}^{j} +t_{rd})+C_{req1}^{i+1}+t_{ID1m}^{i+1} \end{Bmatrix}+C_{resp1}^{i+1}+t_{ID1m}^{i+1} \quad (18)$$

To compute the queuing delay (q_1) in each Intermediate System (Repeater) between two domains in case the previous message cycle is acknowledged, one must use:

$$q_{1}^{i} = \max(t_{IS}^{(i)ready} - t_{Mesg.req.}^{(i)ready},0) \qquad (19)$$

The total queuing delay of a number Communication Domains (nds) can be computed as follows:

$$Q_{1} = \sum_{j=1}^{nd-1}(q_{1}^{j}) \qquad (20)$$

Secondly, to compute the queuing delay in every Intermediate System (Repeater) between the Initiator and the Responder when the previous message cycle is unacknowledged, it can be shown that for the general case of (i) number of Intermediate Systems:

$$t_{Mesgeq}^{(i)ready}=\max(t_{Mesgeq}^{(i-1)ready},t_{IS}^{(i-1)ready})+C_{req2}^{i}+t_{rd} \quad (21)$$

$$t_{IS}^{(i)ready}=\sum_{j=1}^{i}(C_{req1}^{j} +t_{rd})+C_{req1}^{i+1}+t_{ID2m}^{i+1} \qquad (22)$$

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To compute the queuing delay (q_2) in each Intermediate System (Repeater) between two domains in case the previous message cycle is unacknowledged, one must use:

$$q_2^i = \max(t_{IS}^{(i)ready} - t_{Mesg.req.}^{(i)ready}, 0)$$

(23)

The total queuing delay of a number of communication domains (nd) can be computed as follows:

$$Q_2 = \sum_{j=1}^{nd-1}(q_2^j)$$

(24)

Then, after computing the queuing delay for two cases (when the previous message cycle is acknowledged (Q_1) and when the previous message cycle is unacknowledged (Q_2)), the maximum value between them needs to be found is:

$$Q_M = \max(Q_1, Q_2)$$

(25)

Furthermore, in order to guarantee the real time behavior of PROFIBUS network, there is the need to compute the duration of every message stream. It can be shown that the duration of acknowledged message cycle (C_{ack}) is:

$$C_{ack} = C_{req1}^1 + t_{st} + C_{resp1}^1 + t_{ID1m}^1 + t_{ID1+}^1$$

(26)

Also the duration of an unacknowledged message cycle (C_{unack}) can be computed as follows:

$$C_{unack} = C_{req.1}^1 + t_{ID2m}^1 + t_{ID2+}^1$$

(27)

Finally, it is important to compute the slot time parameter (T_{SL}). On one hand, it must be set large enough to cope with the extra latencies introduced by the Intermediate System (Repeater). On the other hand, it must be set as small as possible because the Master station (M) must detect a message/token loss or a node failure

within an acceptable time interval. The computation of the worst-case system turnaround time (t_{st}) for every message cycle in the network permits computing one of the components of the PROFIBUS Slot Time parameter (T_{SL1}).

$$t_{SL1} = \max\{t_{st}\}$$

(28)

$$T_{SL1}^i = \left| t_{SL1} \times r^i \right|$$

(29)

The second component of the PROFIBUS Slot Time parameter (T_{SL2}), is based on the worst-case system turnaround time after token passing. It can be shown that:

$$t_{st\_token} = \sum_{i=2}^{nd}(C_{token}^i + t_{rd}) + Q + t_{ID1m}^{nd} + t_{ID1+}^{nd} + \sum_{i=2}^{nd}(C_{req.}^i + t_{rd})$$

(30)

$$t_{SL2} = \max\{t_{st\_token}\}$$

(31)

$$T_{SL2}^i = \left| t_{SL2} \times r^i \right|$$

(32)

6. Simulation Case Study

As a case study, this section presents the simulation run procedure and results of PROFIBUS communication network composed of two Master stations (M1, M2), four Slave stations (S1, S2, S3, and S4), three Intermediate Systems (IS1, IS2, and IS3), two Wired Domains (WRD1, WRD2) and two Wireless Domains (WLD1, WLD2), as shown in Figure 4. The computation of all relevant parameters for putting the Hybrid Wired/Wireless network into operation is quite complex, time-consuming and error-prone. Therefore, we have developed simulation software using Visual Basic Language to compute all necessary parameters and simulate the network behavior such a way system performance behavioral study can be performed more easily. For this case study, it was assumed that the

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Wireless Domain Based on IEEE 802.11b Physical Medium.

The frame format for specific physical media parameters of wireless domain is shown in Figure 5. where (l_H) is the header of frame and its value is equal to 120 bit (15 byte), (l_T) is the tail of frame and its value is equal to 32 bit (4 byte), *Offset* (*O*) represents the number of bits from beginning of frame until the instant at which the length of data field is known and it is equal to 104 bit (13 byte). The range of bit rates that are supported by IEEE 802.11b is (1, 2, 5.5 and 11) Mb/s and the bit rate that is used in this case study is 2 Mb/s (r = 2). Finally, the overhead per each character is equal to (k=0). All these parameters can be set as shown in Figure 6. The most relevant issues of this simulation are discussed in the following subsections.

6.1. Physical Media Parameters of Wired Domain

Figure 7 illustrates the physical medium parameters of wired domain, where (r) is the bit rate and the value of it that is supported by RS-485 is varying between 9.6kb/s and 12Mb/s (9 cases) and within this work we will take all these cases. (l_H) represents the frame header and its value is equal to 77 bits because the frame head has 7 bytes and each byte adds overhead per each character (k=3) and so the (l_H = 7×11=77). (l_T) represents the frame tail and its value is equal to 22 bits because the frame tail has 2 bytes and each byte adds overhead per each character (k=3) and so (l_T = 2×11=22). Finally, the offset (o) is equal to 33 bits because the length of data field is known after three bytes and so (o=3×11=33).

6.2. Communication Network Parameters

In this work, it is assumed that the number of data bit per character is eight (d=8). The maximum length of request and response frames is equal to ($L_{req}^{\max} = L_{resp}^{\max} = 255 byte$), also the minimum length of request and response frame is equal to ($L_{req}^{\min} = L_{resp}^{\min} = 6 byte$).

The length of the token frame is equal to (L_{token}=3). According to, it is assumed that the Intermediate Systems have internal relaying delay equal to 25 μs. The minimum responder turnaround time ($t_{rt}^{\min}$) is equal to 10 μs and the maximum responder turnaround time ($t_{rt}^{\max}$) is equal to 50 μs and the minimum idle time (T_{IDm}) is equal to 100 bit. All these parameters can be set as shown in Figure 8.

There are additional communication network parameters that are used in Mobility Management Mechanism and can be set as shown in Figure 9, where (BTLen) is the length of beacon trigger and it is equal to (10 chars). The number of radio channel is represented as (nch) and it is equal to 2 according to the model described previously. The duration of beacon (C_{beacon}) is equal to (100) μs. The time of beacon gap (t_{bgap}) is equal to (25) μs. Finally, the channel switching delay is equal to (100) μs.

6.3. Simulation Results

After completing the entry of physical media parameters for both domains (Wired & Wireless) and all communication network parameters, a window appears and through it we can insert the Message Stream (M.S) parameters (step 1), Token Passing (T.P)

parameters (step 2) and Intermediate System (I.S) parameters (step 3). After all necessary parameters in step 1, 2 and 3 are entered; the project results can be obtained.

Figure 10 represents a sample of simulation results. The idle time that must be inserted by each Master station (M) in wired domain and wireless domain is shown in this figure. Where ($t_{ID1plus}$) represents the additional idle time in two cases: after receiving the token and after receiving the response. (T_{ID1}) represents the total idle time and it is equal to ($t_{ID1plus}$ in bit times) plus the minimum idle time (T_{ID1m}). ($t_{ID2plus}$) represents the additional idle after sending an unacknowledged request. (T_{ID2}) represents the total idle time and it is equal to ($t_{ID2plus}$ in bit times) plus the minimum idle time (T_{ID2m}). The slot time parameter (t_{SL1}) represents the timeout for receiving acknowledged/response frame after sending request frame. The slot time parameter (t_{SL2}) represents the timeout for listening activity in the bus after sending token frame, and (t_{SL}) is the maximum between (t_{SL1}) and (t_{SL2}).

The time that is required to reach the beacon trigger from Mobility Master to the last Structured Intermediate System is known as (t_{bt}). The operation of assessment radio channels and switching to the best one is known as handoff procedure (t_{ho}). The duration of mobility management mechanism after computing integer number of beacons is known as (t_{mob}).

($t_{ID2plus}$) represents the additional idle after sending beacon trigger and it corresponds to the additional idle after sending an unacknowledged request. (T_{ID2}) represents the total idle time and it

is equal to ($t_{ID2plus}$ in bit times) plus the minimum idle time (T_{ID2m}). From Figure 10, if the Message Streams Table button is clicked, then a window similar to that shown in Figure 11 will appear.

As explained previously, M is the Master station and S is the Slave station. (L_{req}) represents the length of request frame and (L_{resp}) represents the length of response frame and we take the (L_{req} & L_{resp}) values as minimum, medium and maximum values.

The path represents the number of communication domains between Initiator and Responder. "1" symbolizes the wired domain and "2" symbolize wireless domain. The system turnaround time with no queuing delay is represented as (t_{stn}) and (Q) is the queuing delay that may occur in the Intermediate System. The system turnaround time (t_{st}) is equal to (t_{stn}) plus (Q). And finally (C_{ack}) represents the message cycle duration.

From Figure 10, if the Token Passing Table button is clicked, a window similar to that shown in Figure 12 will appear, where (Sum_C_{Ltoken}) is the sum of token duration in the path between two Master stations.

The (Que.delay) is the queuing delay that may occur in the Intermediate Systems. (t_{ID1_ndp}) is the additional idle time that is inserted by Master Station after receiving the token. (Sum_C_{Lreq}) is the sum of request duration in the path. (C_{token_ndp}) represents the token duration in the last domain and (C_{token_1}) represents the token duration in the first domain. And finally (t_{st_token}) is the system turnaround time after token passing.

From Figure 10, if the Intermediate Systems Table button is clicked, a

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window similar to that shown in Figure 13 will appear, where (t_{btn}) is the time required for the beacon trigger frame to arrive to the most distant wireless station assuming no queuing delay and (t_{bt}) is the time required for the beacon trigger frame to arrive to the most distant wireless station with queuing delay. (t'_{bp}) is the preliminary value of duration for the beacon period and (t_{bp}) is the actual duration of beacon period. (nb) is the number of beacons that are transmitted by a base station. And finally (t_{mob}) is the mobility management duration.

7. Discussions

After testing of different case studies using the proposed simulation software, one can emphasize some points of discussion on the results obtained. At first, By inserting adequate value of additional idle time, the queuing delay can be avoided in the first Intermediate System. The additional idle time that is inserted after sending an unacknowledged request frame is always smaller than the additional idle time that is inserted after receiving a response or token frame because the queuing delay that may occurs after receiving a response or token is larger than the queuing delay that may occurs after sending unacknowledged request and this is a result that the length of unacknowledged frame is shorter than the token or response frame. The additional idle time of wired master station is increased when the baud rate of wired physical medium is increased. The additional idle time of wireless master station is decreased when the baud rate of wired physical medium is increased.

Another issue is that the ratio of additional idle time in wireless Master station is larger than it is in wired Master station because of the larger difference in baud rate between them. Furthermore, The maximum duration of the handoff procedure (t_{ho}) is constant when the baud rate of wired physical layer is changed for all cases (9.6kb, 19.2kb, 93.75kb,………, 12Mb) since the (t_{ho}) doesn't depend on wired baud rate, but it depends on wireless baud rate and the last is constant for all cases.

One can also note that if the results that are obtained using repeater working as store and forward mode are compared with the results that are obtained using repeater working as cut through mode, we will find that the message duration of store and forward mode is greater than the message duration of cut through mode, which mean that the cut through mode is faster than the store and forward mode. The cut through mode has disadvantage: It cannot always send useful packet because the cut through mode does not allow the switch to read the Frame Check Sequence (FCS) before it begins transmitting, it cannot verify data integrity in that way. While the store and forward has advantage: It allows low priority pass traffic to be stored while high priority add is admitted.

Finally, the number of beacons that are transmitted by a Base Station (BS) is decreased whenever the baud rate of data transmission is increased. The number of beacons that are transmitted by a Base Station (BS) is inversely proportional to the number of communication domains in the path between the Mobility Master (MobM)

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and the Structured Intermediate System (SIS).

8. Conclusions

The simulation software tools which are presented turned out to be very important to compute all relevant parameters for putting the hybrid network into operation. Obviously, its advantages increase as networks get more complex. After studying the whole system, one can conclude that guarantee is assumed that no Queuing delay occurs in the first Intermediate System (Repeater) when the frame is relaying from (wired to wireless) domain or from (wireless to wired) domain because of the inserted additional idle time. Also, the additional idle time (t_{ID2+}) that is inserted after sending an unacknowledged request is always smaller than the additional idle time (t_{ID1+}) that is inserted after receiving a response or token. Finally, it can be noted that the Queuing delay is decreased whenever the baud rate of data transmission is increased whatever is the number of domains between Master station and Slave station.

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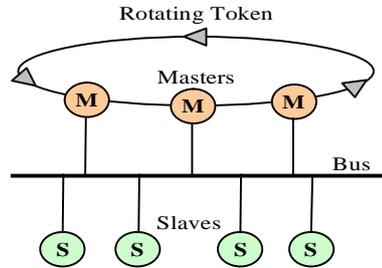
Figure (1) PROFIBUS Token Passing.
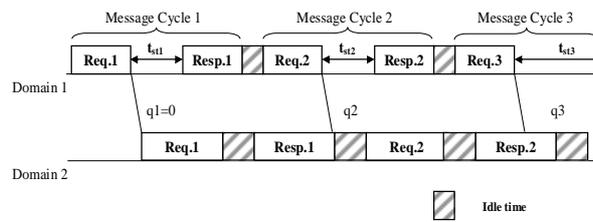
Figure (2) Timing Diagram Illustrating the Queuing Delay
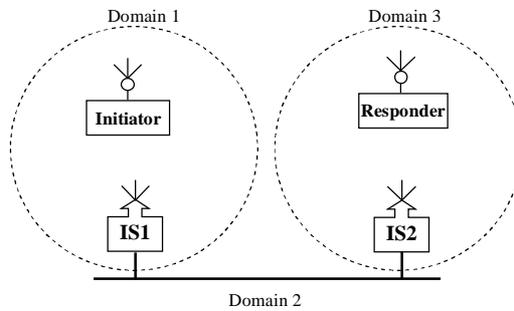
Figure (3) Communication Network.

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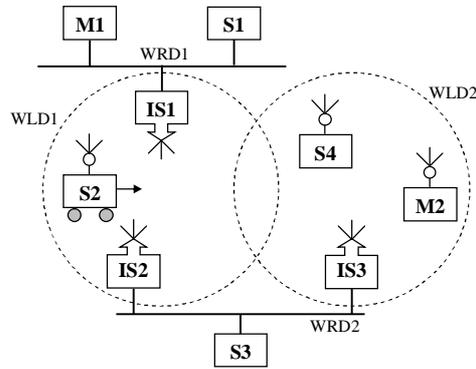
Figure (4) PROFIBUS Communication Network Example.
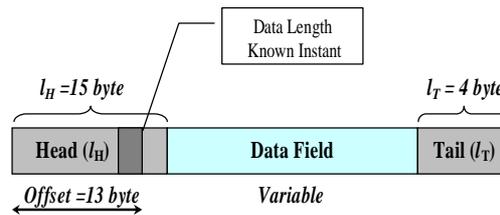
Figure (5) Frame Format.
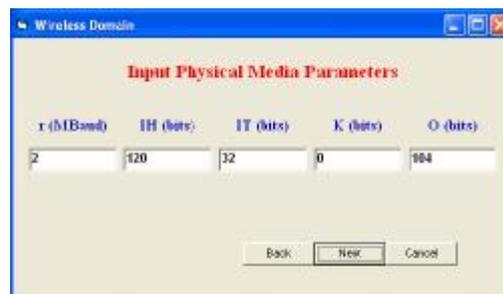
Figure (6) Physical Media Parameters of Wireless Domain.

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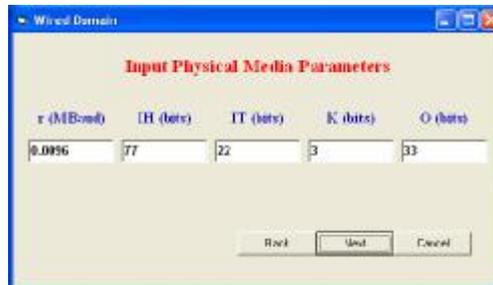
Figure (7) Physical Media Parameters of Wired Domain.
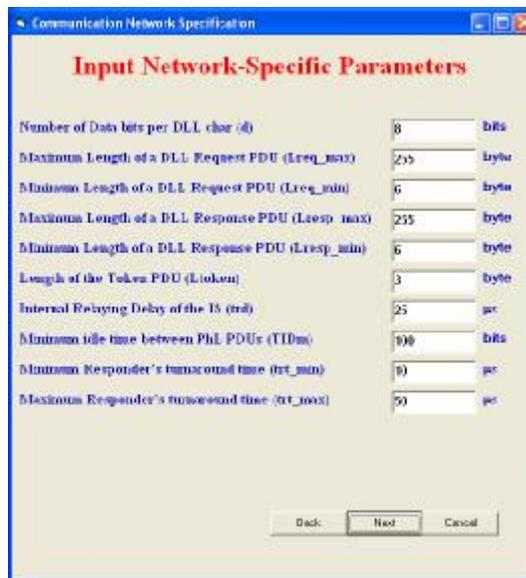
Figure (8) Network Parameters.

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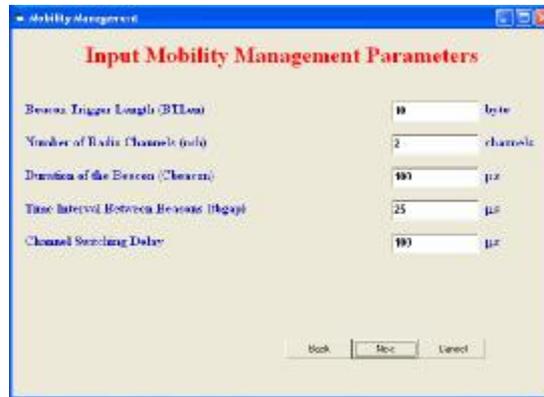
Figure (9) Mobility Management Parameters.

Figure (10) Sample of Simulation Results.

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Figure(11) Table of Message Streams.

Figure (12) Table of Token Passing.

Figure (13) Table of Intermediate Systems.

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