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Interconnection of Autonomous PROFIBUS Segments through IEEE 802.16 WMAN

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***Abstract*—**PROFIBUS (PROcess FIeld BUS) which is defined with international standarts (IEC61158, EN50170) is the most popular fieldbus, and provides a communication between industrial applications which are located in different control environment and location in manufacturing, process and building automation. Its communication speed is from 9.6 Kbps to 12 Mbps over distances from 100 to 1200 meters, and so it is to be often necessary to interconnect them in order to break these limits. Unfortunately this interconnection raises several issues and the solutions found so far are not very satisfactory. In this paper, we propose a new solution to interconnect PROFIBUS segments, which uses a wireless MAN based on the IEEE 802.16 standard as a backbone system. Also, the solution which is described a model for internetworking unit integrates the traffic generated by PROFIBUS segments into IEEE 802.16 wireless MAN using encapsulation technique.

***Keywords*—**Internetworking Unit, PROFIBUS, WiMAX, WMAN, 802.16.

I. Introduction

COMMUNICATION networks are used for very different purposes. Networks in the area of factory automation have been developed with the specific requirement of tight real-time capabilities. Those networks are typically used in industrial environment. They have been named field-buses. Generally, field-buses can be categorized as local area networks. However, many different types of field-buses co-exist, ranging from very small and primitive networks that are usually installed in cars (e.g., CAN [1]) to more sophisticated networks used for factory communication (e.g., PROFIBUS [2]). This results in a wide diversity of applications that are served by field-buses. However, they share the requirement of very tight timing conditions. [1]

With respect to factory communication, field-buses must be capable of covering a physical area, such as a medium to large factory hall or a complete factory building. Field-buses have to handle deterministic response times for time critical processes being part of factory and building automation and production technology. An example is the PROFIBUS. Recently, an increasing demand for additional services (e.g. management) on field-buses can be observed. Furthermore, the interconnection of different field-bus-islands is required. [1] A typical example can be seen in Traffic Control System (TCS) communicating with a Central Management Unit (CMU) at highways or within cities. [2]

The extension of Field-Bus systems is generally limited - varying from a few tens to a few hundreds of meters. They are, therefore, not capable of covering the vast areas typical of modern industrial plants. In addition, the number of control devices that can be interconnected by a Field-Bus is generally limited. The number of devices in an area of a plant may therefore be so high as to require more than one Field-Bus to interconnect them [3]. For an example, PROFIBUS only allows a maximum extension of 200 m at 500 kbps data rate. This aspect implies the existence of field bus islands, especially in larger installations. An increasing demand for breaking these limitations emerged. One step towards this is the interconnection of field bus islands.[4]

The main limit of this topological solution is that several field-buses have to be crossed for information to be transmitted between two field-buses which are not directly connected. In some time-critical applications, the time this takes may be quite unacceptable. In order to reduce this time, a backbone is often used; each Field-Bus is connected to it and all the traffic exchanged between field-buses is conveyed on it. This solution drastically reduces delivery times as long as the backbone has a large amount of bandwidth.[3]

There are industrial scenarios where the use of a wired backbone is extremely difficult. This happens, for instance, when communication systems have to be installed in existing plants, where cable laying would be quite difficult. In some cases, the use of a wired backbone may be impossible for long distances, for example traffic flow management at highways or within cities. In this scenario, each traffic signal location is a PROFIBUS segment that interconnecting the local actuators and sensors. These segments can evidently not be interconnected using traditional wired systems. In such scenarios it would be a great advantage to be able to use an IEEE 802.16 wireless backbone to interconnect the autonomous PROFIBUS segments [3]. In this research work a new Interworking Unit architecture is proposed to build autonomously interconnected PROFIBUS segments through IEEE 802.16 and a timing analysis for the system is presented. The paper describes PROFIBUS and IEEE 802.16 briefly in Section II. Section III. introduces the proposed approach for interconnection of the autonomous PROFIBUS segments, using IEEE 802.16 WMAN over radio links. Section IV presents timing requirements of the proposed system.

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II. The PROFIBUS, The IEEE 802.16 WMAN and the WiMAX

PROFIBUS protocol is one of the most popular fieldbus defined with international standards (IEC61158, EN50170). PROFIBUS defines the technical characteristics of a serial fieldbus system with distributed digital programmable controllers can be networked, from field level to cell level of CIM (Computer Integrated Manufacturing) architecture. PROFIBUS offers functionally graduated communication protocols (communication profiles): DP (Decentralize Periphery) and FMS (Fieldbus Message Specification). DP is the most frequently used communication profile of PROFIBUS, and permits mono-master or multi-master systems. This provides a high degree of flexibility during system configuration. FMS is designed for communication of programmable controllers (PLCs and PCs) – master devices-with each other [5-7].

PROFIBUS communication profiles use a uniform medium access protocol. PROFIBUS medium access control is based on a token-passing procedure used by master stations to grant the bus access to each one of them, and a master–slave procedure used by master stations to communicate with slave stations. These MAC mechanisms are implemented at the layer 2 of the open systems interconnection (OSI) reference model, which, in PROFIBUS, is called field-bus data link. In addition to controlling the bus access and the token cycle time, the field-bus Data Link Layer (FDL) is also responsible for the provision of data transmission services for FDL user. PROFIBUS supports four data transmission services:

- Send data with no acknowledge (SDN);
- Send data with acknowledge (SDA);
- Send and request data with reply (SRD); and
- Cyclic send and request data with reply (CSRD).

Most data transfers are defined as SRD. The SRD is based on a real dual relationship between the initiator (master station holding the token) and the responder (slave or master station not holding the token). A SRD service is a message cycle consisting of a request packet and an immediate response. A response can occur as a one byte acknowledgement or a data packet. During a message cycle an addressed station has to respond within a bounded time interval

PROFIBUS frame format includes 0-246 bytes of variable data and 3-9-bytes of protocol control information (i.e. Start Delimiter Length, Source and Destination Addresses, Frame Control and CRC data) as shown Fig. 1. More detail about PROFIBUS can be found in [5].

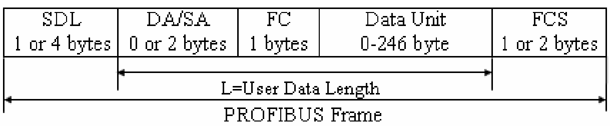

Fig. 1 PROFIBUS Frame Format

IEEE Standard 802.16-2001, is completed in October 2001 and published on 8 April 2002, defines the WirelessMAN air interface specification for wireless metropolitan area Networks (MANs). The completion of this standard heralds the entry of broadband wireless access as a major new tool in the effort to link homes and businesses to core telecommunications Networks worldwide [8].

WiMAX is a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL. WiMAX will provide fixed, nomadic, portable, and, eventually, mobile wireless broadband connectivity without the need for direct line-of-sight to a base station. In a typical cell radius deployment of three to 10 kilometers, systems can be expected to deliver capacity of up to 40 Mbps per channel, for fixed and portable access applications. This is enough bandwidth to simultaneously support hundreds of businesses with T-1 speed connectivity and thousands of residences with DSL speed connectivity. Mobile network deployments are expected to provide up to 15 Mbps of capacity within a typical cell radius deployment of up to three kilometers. It is expected that WiMAX technology will be incorporated in notebook computers and PDAs by 2007, allowing for urban areas and cities to become “metro zones” for portable outdoor broadband wireless access [9]

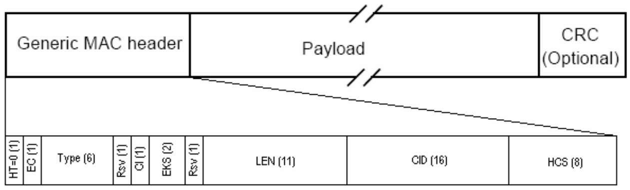

Fig. 2 IEEE 802.16 WMAN MAC PDU format

In Fig. 2 LEN is the length of MAC PDU in bytes that includes the MAC header and the CRC if present [10]. It can be seen that MAC PDU format is 2048 byte totally.

III. Interconnecting PROFIBUS Segments through IEEE 802.16

IEEE 802.16 could be used as a backbone network for a new generation of field-buses. Moreover, it could be used to interconnect different field-buses. The basic scenario of interconnected PROFIBUS segments is depicted in Fig. 3. It shows a IEEE 802.16 network with multiple internetworking units attached to it. Autonomously interconnected PROFIBUS segments operate completely independent from each other. So every field-buses have own token and own token handling time. The approach more or less complies to traditional bridged networks [1,12].

A. Internetworking Unit Architecture

The expected functionality of the internetworking unit is to transparently deliver data between the PROFIBUS segments. Since PROFIBUS lack layer 3 functionality, routers cannot be directly applied. Proposed method to interconnect the PROFIBUSs over the IEEE 802.16 networks is to use a bridge that is capable of translation of the two networks. It contains the worst-case translation that requires creation or loss of fields representing unmatched services as follows:

- Having different frame format and size.

- Having different medium access control technique and topology.
- Role of the port/unit that located at the PROFIBUS side

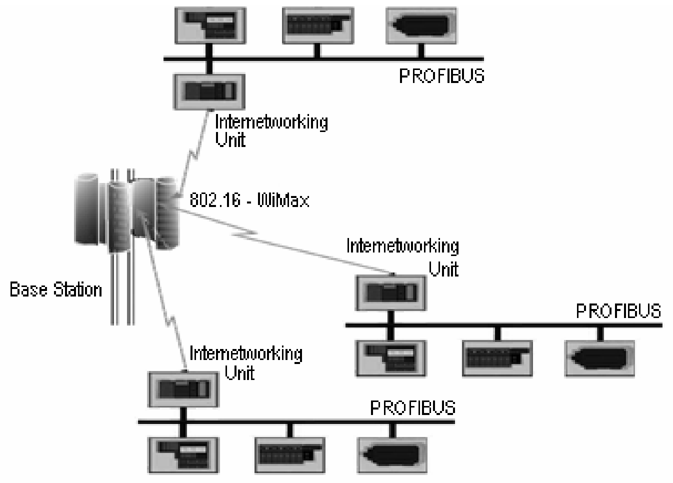

Fig. 3 Interconnecting PROFIBUS Segments through IEEE 802.16 WMAN

The unmatched services can be solved by a transparent–translating remote bridge used to interconnect to LANs in different locations. The layered protocol architecture of the transparent-translating bridge is as in Fig. 4. One port of the bridge is on field-bus and acts as a field-bus station. The other is connected to CPE (Customer Premises Equipment) and acts as a SS (Subscriber Station).

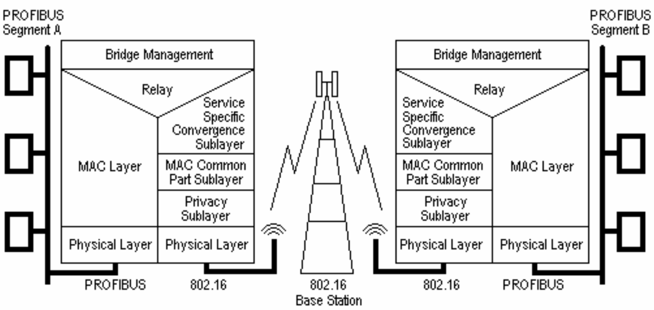

Fig. 4 Internetworking Unit Protocol Architecture

B. The PROFIBUS/IEEE 802.16 Wireless Internetworking Unit Model

In this section interconnection of two independent PROFIBUS segments is discussed. This means, the IEEE 802.16 interconnection is not an extension of a PROFIBUS segment, but interconnects completely autonomous operating PROFIBUS segments (A and B), as shown in Fig. 4. As mentioned above, there are unmatched services for communication between PROFIBUS and WMAN. It can be solved by WIU (Wireless Internetworking Unit) having a transparent–translating local bridge attributes.

While planning the PROFIBUS application the desired connections between distant PROFIBUS networks have to be determined. As depicted in Fig. 4, according to the application PROFIBUS segment A needs to get in contact with B. Therefore connections between these are established. The WIU in A has to know the IEEE 802.16 addresses of other WIU.

The modeling of the WIU may differ depending on the implementation point of view. However, in general, the processes to be performed on the frames and the desired services in a PROFIBUS / IEEE 802.16 WIU will be the same. The number of bridge elements, their domain of operations, and their relations with each other should be such that they are able to perform the required processes and to provide the necessary services. Thus, there are two concepts that should be considered to model the bridge: the unmatched services listed above and the implementation point of view. Fig. 5 shows functional block diagram of the designed bridge depending upon assumptions made above.

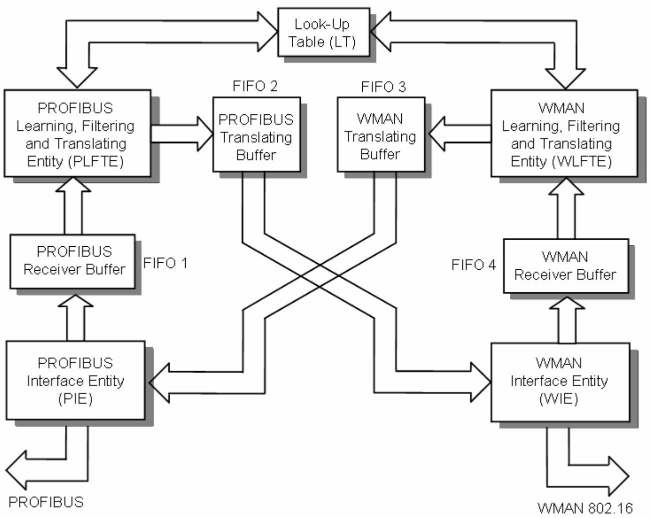

Fig. 5 Functional block diagram of the PROFIBUS/IEEE 802.16 WIU

The functional model of the WIU shown in Fig.5 contains nine entities. The first is the PROFIBUS Interface Entity (PIE) that provides the means for communication with PROFIBUS and has a bus receiver and a bus transmitter

The second is the WMAN Interface Entity (WIE) that provides the necessary functions for communication over wireless medium and has a wireless receiver and a wireless transmitter.

The third is the PROFIBUS Receiver is a buffer storing PROFIBUS messages delivered from the PIE. Similarly, the fourth is the WMAN Receiver that is a buffer storing WMAN IEEE 802.16 frames delivered from the WIE.

The fifth is the Look-up Table (LT) that is the most important part of a WIU. It is built up during a Learning Process (LP) in which every WIU finds out its own attached PROFIBUS nodes' local messages and remote messages destined from/to any other PROFIBUS segment. After that the messages with certain priorities are associated with the address of the relevant WIU connected to the destination PROFIBUS segment.

The sixth is the PROFIBUS Learning, Filtering, and Translating Entity (PLFTE) that contains the PROFIBUS-LP. It also compares identifiers of the messages received from the

PROFIBUS with the ones in the LT to realize whether the messages are local or remote. If the PROFIBUS message identifier has a match in the LT (i.e., it is destined to another PROFIBUS segment) then it is converted to WMAN frame format and sent to PROFIBUS Translating Buffer. Otherwise the PROFIBUS message is filtered as it is a local message.

The seventh is the WMAN Learning, Filtering and Translating Entity (WLFTE) that contains the WMAN-LP. It is also used to realize if any WMAN frame received is destined to the WIU. If so, the PROFIBUS message is extracted from the WMAN frame delivered from the WIE, and it is sent to the WMAN Translating Buffer. Otherwise it is filtered as not destined to this WIU.

The eighth and the last are the FIFO2 and FIFO3 that are the PROFIBUS Translating and the WMAN Translating buffers, respectively.

C. The PROFIBUS / IEEE 802.16 Wireless Internetworking Unit Operations

The operation of the PROFIBUS/WMAN WIU is explained in two phases; the way in which the processes are performed and the structure of each element (called as entity) in the bridge. In the proposed WIU model, each port has a different protocol with a different frame and message format, and a different frame and message reception/transmission mechanism. Thus, the processes to be performed at each port of the WIU are different. So, the process at each side should be detailed individually. The two processes mentioned above, i.e. PROFIBUS to WMAN and WMAN to PROFIBUS, have different algorithms. The flowcharts of PROFIBUS to WMAN and WMAN to PROFIBUS data transfer processes of the proposed WIU are shown in Fig.6 and in Fig.7, respectively.

Both processes contain Learning and Transferring sub-processes. Learning process is used to determine remote messages in every PROFIBUS segment and it works in conjunction with the LT. LT is created in learning process time and used for filtering PROFIBUS messages and WMAN frames. It is updated when either a new PROFIBUS node or WIU is introduced to the network as this is a very common case in an industrial process control environment.

Learning process consists of a PROFIBUS-LP and a WMAN-LP. In the former, any PROFIBUS node informs its WIU about the remote and local PROFIBUS message to be received and sent when the initialization process takes place. After that both WIUs build their local LTs that are used to form a networking environment with fully connected independent PROFIBUS segments. On the other hand, the latter is used to match any remote PROFIBUS message with the relevant WIU. Both processes are repeated if a new PROFIBUS node or WIU is introduced to (or excluded from) the interworking system.

In the PROFIBUS to WMAN data process, all PROFIBUS messages received from the PROFIBUS bus through the CIE is checked for a match in the LT. If there is a match with this PROFIBUS message then it is converted into the WMAN frame format using the encapsulation method, and it is sent to the FIFO2. Otherwise, the PROFIBUS message is discarded as it is destined to a local PROFIBUS node. Meanwhile, when the FIFO3 is full, meaning that it contains a PROFIBUS message delivered from the WFTE, the PROFIBUS message is passed to the PROFIBUS (Fig. 6).

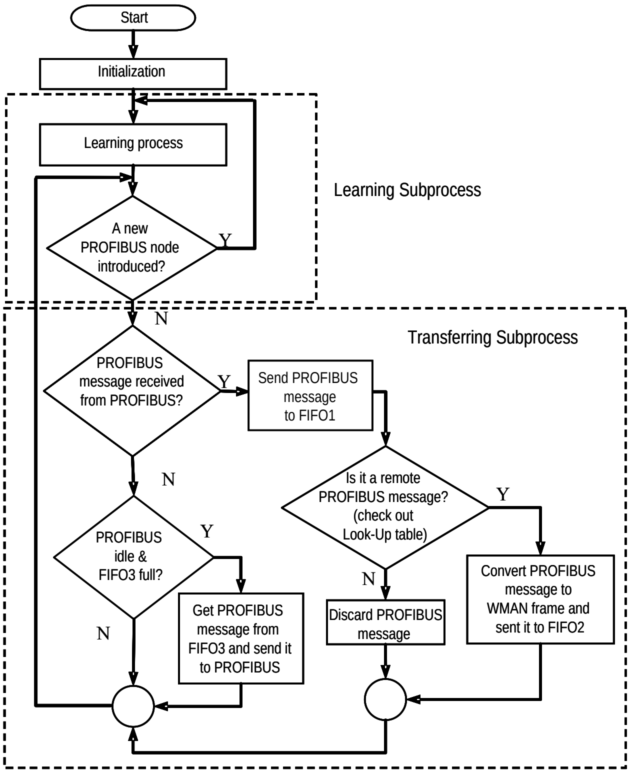

Fig. 6 Flowchart of the WIU – PROFIBUS to WMAN data transfer process

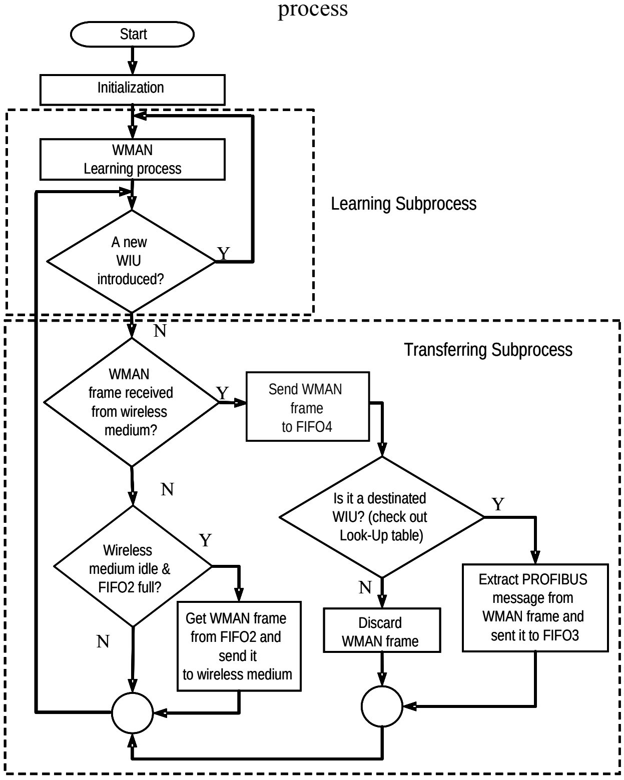

Fig. 7 Flowchart of the WIU – WMAN to PROFIBUS data transfer process

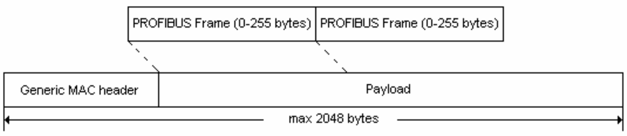

Fig. 8 Encapsulation of a PROFIBUS frame into an IEEE 802.16 MAC PDU

IV. Timing Requirements

A. Timing Requirements of PROFIBUS

As opposed to traditional data networks, PROFIBUS is parameterized according to its operational configuration. Dynamic changes in the configuration are unusual and require reparameterization. Before a PROFIBUS system will be implemented its devices are initialized with global parameters, i.e., station address, token target rotation time and control timers, based on the application purpose. A connection list, residing in each station, contains its pre-defined communication relations to other devices, including both masters and slaves. This more ore less static configuration allows for a deterministic behavior of a PROFIBUS network. Moreover, either forecasting the duration of message cycles consisting of a request from a master and the immediate response from the requested slave device or fast reactions to alarms become available.

In the following we describe some timing aspects of PROFIBUS that are relevant to further considerations [1,5]. During a message cycle T_{MC} an addressed station has to respond within a bounded time interval.

$$T_{MC}=T_{S/R} + T_{SDR} +T_{A/R} + T_{ID} + 2.T_{TD} \quad (1)$$

$T_{S/R}$: Send/Request frame time, $T_{A/R}$: Acknowledgment/ Response frame time, T_{SDR} : Station delay responder, T_{TD} : Transfer delay, T_{ID} : Idle time

In a PROFIBUS system the token-cycle-time T_{TC} calculates as follows:

$$T_{TC} = T_{TF}+T_{TD}+T_{ID} \quad (2)$$

T_{TF}: Frame time, T_{TD}: Transmission delay, T_{ID} : Idle time

The token-target-rotation-time is one of the parameters defined during the design phase of the PROFIBUS-application. It equals the system response time and is determined by

$$T_{TR}=na.(T_{TC}+highT_{MC})+ k.\ low\ T_{MC} +mt.T_{MC} \quad (3)$$

na: Number of active stations (masters), mt : Number of retransmissions, k : Number of message-cycles with low priority, T_{TC} : Token-cycle-time, T_{MC} : Message-cycle time,

In order to ensure system stability, PROFIBUS uses control timers. The most important is the slot-time T_{SL}: the maximum time the requester waits for the response during a message cycle before initializing a retransmission. (T_{SM}: safety margin)

$$T_{SL} = 2.T_{TD} + max\ T_{SDR} + 11\ Bit + T_{SM} \quad (4)$$

A second control time taken into account is the time-outtime, which is derived from slot time. If the time-outtime is reached, the bus is assumed to be inactive and the system has to be restarted.

Fig. 9 shows the activity on the bus during an arbitrary time interval. In Fig. 1, While T_{SDI} (station delay initiator) is the processing time the station needs to initialize the data request packet, T_{SDR} (station delay responder) is the time the addressed station needs to process the request packet and to initialize the transmission of the response frame. A requesting station receives the token and begins to send after a station delay caused by protocol processing. A second station delay caused by protocol processing within the responding station occurs. After that the responder sends an acknowledgment, after which the initiator needs another time to process the acknowledgment and prepare the next request or token forwarding.

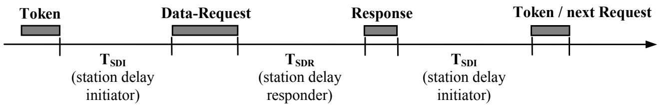

Fig. 9 Activity on the bus during a message cycle

B. Timing Requirements of 802.16

Timing requirements for the 802.16 standard are defined in terms of bearer services that the systems must support. Separate bearer service requirements have been defined for 802.16.1. The 802.16.1 spec is designed to support three types of bearer services: circuit-based, variable packet, and fixed-length cell/packet. Requirements for these services are grouped into three categories. The first category is the data rate that must be supported. The second category refers to error performance. For most services an upper limit on the bit error ratio (BER) is defined. The final category is maximum one-way delay. This delay can be defined as medium-access delay, transmit delay, and end-to-end delay.

Medium-access delay measures the amount of time that the station, once the transmitter is turned on, must wait before it can transmit. Transmit delay; on the other hand, refers to delay from SNI to BNI or BNI to SNI. It includes the medium access delay plus the processing at the MAC layer for preparing transmission (from the subscriber transceiver station [STS] or base transceiver station [BTS]) and at the MAC layer for reception (at the BTS or STS). End-to-end delay is characterized as the total delay between a terminal in the subscriber network and the ultimate service beyond the core network. This includes the transit delay [11].

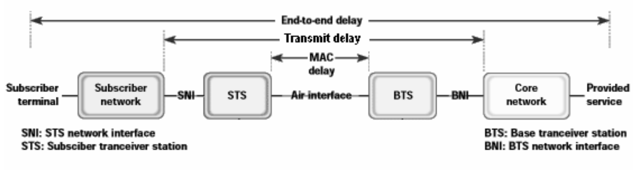

Fig. 10 The 802.16 system reference model's typical operating conditions and specifications

C. Timing Requirements of the Designed Systems

Timing requirements for PROFIBUS and 802.16 are mentioned in subsections *IV.A.* and *IV.B.,* separately. In Fig. 11, an overall system that interconnects autonomous PROFIBUS segments through IEEE 802.16can be seen.

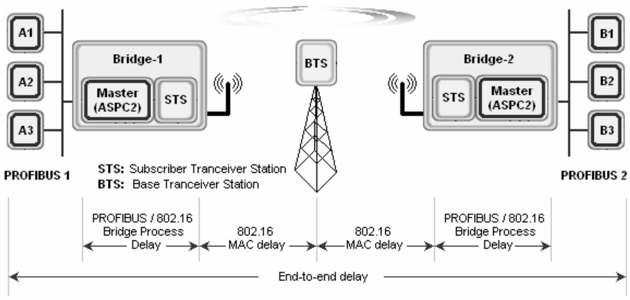

Fig. 11 The designed system characteristics

In the system, for a message that is generated for the same segment, the timing requirements of PROFIBUS can be used only. For example, the message generated from A1 to A2 or B1 to B2. For a message that is generated for one of the other segments (the message generated from A1 to B1 or B2 to A3), timing requirements includes a number of parameters as follows:

T_{CS} : Connection setup time (=Transmit delay [11])
$T_{MC\text{-}A}$: Message cycle from A to B
T_{BD} : Bridge delay
T_{MAC} : MAC delay
$T_{MC\text{-}B}$: Message cycle from B to A
$T_{BD\text{-}ACK}$: Bridge delay for ACK
$T_{MAC\text{-}ACK}$: MAC delay for ACK

$T_{MC\text{-}A}$ and $T_{MC\text{-}B}$ are message cycle times that are given in Equation 1. So end-to-end delay of the system is,

$$T_{MC}=T_{CS}+T_{MC\text{-}A}+2.T_{BD}+2.T_{MAC}+T_{MC\text{-}B}+2.T_{BD\text{-}ACK}+2.T_{MAC\text{-}ACK} \quad (5)$$

V. Conclusion

An interworking unit must provide a selective frame retransmission function and interface operation allowing communication between similar and/or dissimilar systems. In this research a new interworking unit architecture has been proposed to build autonomously interconnected PROFIBUS segments. By means of the architecture, PROFIBUS networks will be connected to an IEEE 802.16 wireless backbone, and so it will be coped with physical and wired limitations. The internetworking unit has to a transparent-translating remote bridge for solved of the unmatched services. The bridge has used encapsulation technique to integrate the traffic generated by PROFIBUS segments into IEEE 802.16 wireless MAN. In addition, this paper has defined the end-to-end delay parameters of the overall system. Considering their easy usage in many industrial areas, PROFIBUS nodes emerge inevitably to need this type of wireless interworking for greater flexibility for their applications to be controlled and/or programmed remotely.

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