Performance aspects of PROFIBUS segments interconnected through ATM

O. Kunert, M. Zitterbart
Technical University of Braunschweig , Institute of Operating Systems and Computer Networks
Bueltenweg 74/75, D-38106 Braunschweig, Germany
email: [kunert | zit]@ibr.cs.tu-bs.de, http://www.ibr.cs.tu-bs.de/hm

ABSTRACT

Field buses have been developed to fulfill real-time requirements of applications related to factory automation. However, they are limited in their extension, and can only cover geographical areas such as factory halls or buildings. In order to reduce this drawback a possible solution is to connect field bus segments using interworking devices and a backbone network. This backbone could be an ATM network. Within this paper we concentrate on the interworking of PROFIBUS segments. The main topic is to investigate performance aspects of such an interworking concept. From PROFIBUS point of view the impact on the parameterization of the PROFIBUS system is of special interest. Simulations of an example PROFIBUS system were performed in order to cover this aspect, to evaluate the feasibility of the presented approach and to show its limitations concerning the range of PROFIBUS applications it is suited for. Another main topic in this concern is the choice of appropriate QoS parameters for the ATM connections.

Keywords: field bus, PROFIBUS, ATM

1 Introduction

Networks in the area of factory automation have been developed with the specific requirement of tight real-time capabilities. These so-called field buses are typically used in industrial environment. Many different types of field buses coexist, 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.

A common restriction of all field buses is their limited extension. E.g., PROFIBUS, as part of the European standard, only allows a maximum extension of 200 m at 500 kbit/s data rate.[2, 3] 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. ATM as a promising technology could be used as a backbone network in order to connect PROFIBUS segments. ATM is especially interesting, since it provides a variety of services and is able to guarantee distinguished QoS. Another fact which makes ATM a suited technology is its scalability in terms of extension and performance capabilities. In [4] the authors proposed two interworking scenarios:

- interconnecting segments of a single PROFIBUS
- interconnecting independent PROFIBUSes

This work focuses on the first scenario. Its intention is to discuss the implications a connection of PROFIBUS segments has for PROFIBUS itself. Another topic is to investigate the overall system performance and its dependabilities in order to determine which applications the concept is suited for. Characteristics of ATM and PROFIBUS relevant for the interworking of both can be found in.[4]

Section 2 introduces an example of a PROFIBUS application in an industrial environment and introduces QoS requirements. In section 3 a possible topology for connecting PROFIBUS segments through ATM based on the example application is presented. Furthermore, implications on the system performance of the PROFIBUS example application caused by ATM are the main discussion topic. Section 4 gives a summary and an outlook on future work.

2 PROFIBUS

2.1 General characteristics

Real-time traffic requires deterministic media access. Thus, the use of field buses under real-time conditions implies the provision of maximum waiting times for applications, even in worst-case scenarios.[5, 6, 7, 8] Therefore special attention has to be paid to quality-of-service parameters, such as transmission delay and response time. As opposed to traditional data networks, PROFIBUS is parameterized according to its operational configuration. A system designer analyses the pur-

pose the field bus is intended for and determines the number of master and slave devices and their interaction. Dynamic changes in the configuration are unusual and require re-parameterization if they take place. Before a PROFIBUS system will be installed its devices are initialized with global parameters, i.e., station address, token target rotation time and several control timers. A connection list, residing in each master station, contains its pre-defined communication relations to other devices, including both masters and slaves. This more or 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.
PROFIBUS uses 4 services to transfer data: Send Data with no Acknowledge (SDN), Send Data with Acknowledge (SDA), Send and Receive Data (SRD), Cyclic Send and Receive Data (CSRD). Most data transfers are defined as SRD. A SRD service is a message cycle consisting of a request packet and an immediate response. A response can occur as a one byte acknowledgment or a data packet. During a message cycle an addressed station has to respond within a bounded time interval. Thus, PROFIBUS behavior is comparable to a stop-and-wait protocol.

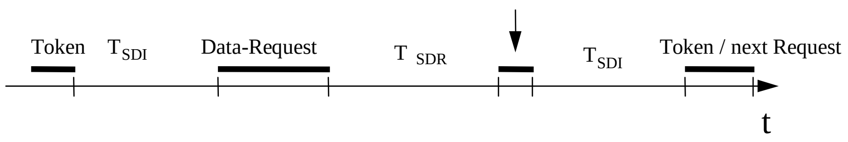

Figure 1: Activity on the bus during a message cycle

Fig. 1 shows the activity on the bus during an arbitrary time interval. A master station received the token. T_{SDI} (station delay initiator) is the processing time the station needs to initialize the data request packet. After sending a request packet the station waits T_{SDR} (station delay responder), the time the addressed station needs to process the request packet and to initialize the transmission of the response frame. After that either the token will be forwarded to the next master or another message cycle begins. Based on that a message cycle covers the time interval between the sending the first bit of a request frame and sending the first bit of the next response frame. In order to ensure system stability PROFIBUS uses control timers. The most important is the slot-time. It represents the maximum time that the requesting station waits for the response during a message cycle before initializing a retransmission.

2.2 PROFIBUS example

The range of PROFIBUS implementations is so versatile that there is no general model for a PROFIBUS application or even a benchmark. Despite of this, to illustrate the communication behavior and to discuss the system performance a PROFIBUS example can be used. This section describes a PROFIBUS implementation controlling a production plant. The considered PROFIBUS consists of 6 components: 2 personal computers and 4 controller units, as depicted in figure 2.

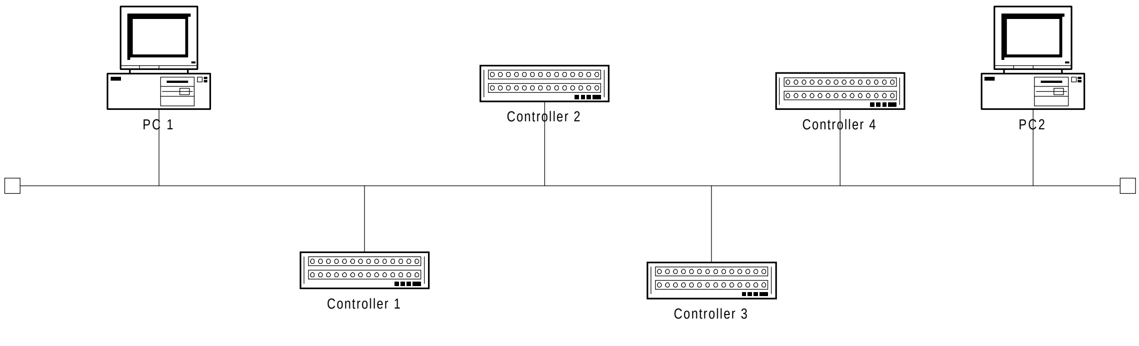

Figure 2: PROFIBUS example

The system is organized in two logical parts in which each PC has the coordinating function. It manages both controller units assigned. Furthermore, the PCs are used to visualize the process states and to collect statistical data. One of the controller units of each part controls the subprocesses within its part. As a result of the design phase the communication relations between the components were determined. According to the needs of the application process the frequency of occurrence of each message has to be estimated. Table 1 shows the communication matrix that contains the messages to be exchanged and table 2 represents the length, the interval and the deadline of each message.

	PC 1	PC 2	Controller 1	Controller 2	Controller 3	Controller 4
PC 1		n2	n3	n3		
PC 2	n2				n3	n3
Controller 1	n1			n4	n4	
Controller 2	n1		n4			n4
Controller 3		n1	n4			
Controller 4		n1			n4	

Table 1: Communication matrix

Message	Length [Byte]	Interval [s]	Deadline [s]
n1	64	0.2	0.2
n2	64	1	0.2
n3	32	0.2	0.2
n4	38	0.1	0.1

Table 2: Messages

Data Rate	500 kbit/s
Token Rotation Time	0,06 s
min T_{SDR}	0,0001 s
Slot Time	0,004 s

Table 3: PROFIBUS system parameters

PROFIBUS provides a number of parameters that have to be adjusted prior to implement the system. However, only the 4 parameters shown in table 3 are relevant for performance aspects. The data rate has to be chosen according to the expected communication effort, that has to be summarized over all messages exchanged between any two stations. The maximum data rate PROFIBUS allows is 12 Mbit/s. Token rotation time is responsible for ensuring the required system response time. It has to provide that under normal conditions each station is able to handle all its message cycles during one token interval. It is difficult to determine a lower bound for the token rotation time due to the fact that the number and the length of the messages are varying during a full token rotation. Furthermore, it has to take into account, that message retransmission because of errors can occur. A much too long token rotation time has only few implications on the system performance. In case of a master station has no more communication requests it forwards the token despite of the fact that it still has token holding time. MinT_{SDR} is the time the responding station needs for protocol processing and to assemble the response packet. The parameter equals the minimum amount of all stations. The fastest station is only allowed to send after min T_{SDR} is elapsed, i.e. this timer ensures that each station on the bus has received the packet before the addressed station sends the response frame. It further ensures that after receiving the token a master waits for minT_{SDR} counter to expire until it sends its first request frame. The choice of this timer value is of particular importance because a too long minT_{SDR} leads to unnecessary delays in the message cycle. But a too small value for minT_{SDR} injures system stability. The value of the slot timer determines the maximum time the requesting station waits for a reaction from the addressed station.

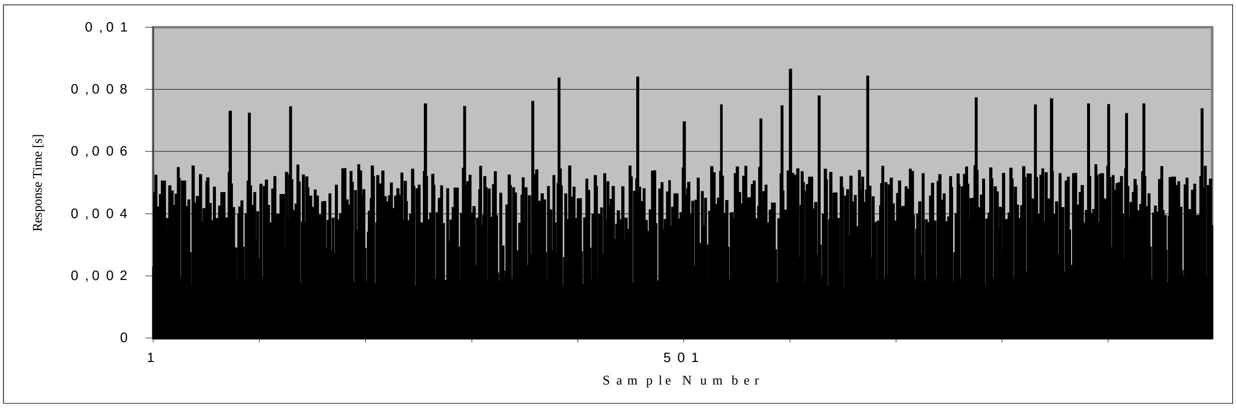

Fig. 3: Response times of message n4

Otherwise it supposes a transmission error and retransmits the packet. For all the discussed timers the PROFIBUS standard suggests default values, which ensure system stability. To tune a PROFIBUS system they can be optimized. In order to study the system behavior, especially the PROFIBUS layer 2 characteristics, a simulation model of PROFIBUS layer 2 was developed and applied to the PROFIBUS example system. In this model each PROFIBUS station provides a service access point to the application layer. Requests from the application layer arrive according to the intervals defined in table 2. The most interesting result expected from the simulation is to know whether the deadlines of all messages can be kept. In place of all messages fig. 3 shows the response times for all messages n4 occurring during the simulation phase of 60 seconds. As can be seen the response times of the most crucial message with a deadline of 100 ms never even exceeds 10 ms. The measurement of the response time of each message starts when the request from the application layer passes the service access point of layer 2 and ends after the service primitive signals the arrival of the corresponding response to the application layer. Therefore the response time includes not only the message cycle time but the time the request spends in the queue before it will be send out.

3 Interworking PROFIBUS segments through ATM

3.1 Concept

One possible solution to allow a PROFIBUS system to span longer distances is to use PROFIBUS / ATM bridges to interconnect PROFIBUS segments through an ATM network.[4] The basic fact that determined the design of the concept was the following. In order to use existing PROFIBUS devices the concept has to be in accordance with the PROFIBUS standard.

The bridges provide two ports. One is connected to the PROFIBUS segment and the other is connected to the ATM network. A PROFIBUS / ATM bridge has to perform the following tasks. An arriving packet on the PROFIBUS side will be segmented, if necessary, and encapsulated in ATM cells. That happens within the AAL layer of the ATM part of the bridge. The cells are transmitted over an ATM link to the distant bridges. If only two segments comprise the "virtual" PROFIBUS only one bi-directional connection has to be established. If more than two segments are involved the ATM cells have to be delivered to all corresponding bridges. To support this ATM provides point-to-multipoint connections. In this concept neither bridge performs any filtering task. The bridge on the remote segment decapsulates, reassembles the cells to a PROFIBUS packet and sends it on the attached PROFIBUS segment, immediately. The transport through the ATM network happens transparently, with respect to the devices on the PROFIBUS segments. They are not aware of the situation that the field bus segments are interconnected through an ATM network.

The PROFIBUS part of a remote bridge deals with reading and writing functions of the field bus. It neither functions as slave nor as master and is not involved in the token passing mechanism. However, not only data packets but also the token has to be carried across the ATM connections. This means according to the standard that each sent packet including the token has to reach each station in the "virtual" PROFIBUS. This has to happen independent of the location of the communicating devices with respect to PROFIBUS segments.

Generally, it is conceivable to connect several PROFIBUS segments through an ATM network consisting of multiple switches whose structure is unknown. However, the basic approach discussed within this paper is to connect only two PROFIBUS segments, and a situation is envisioned where only a single ATM switch exists to connect both segments. Thus, all bridging devices attach the PROFIBUS segments to the same switch.

3.2 Mapping the timing constraints of PROFIBUS to ATM service parameters

In order to interconnect field buses through an ATM network, proper service categories of ATM [9, 10] need to be identified together with a suited mapping of QoS parameters. Especially the high timing requirements associated with field buses need to be considered.

To map the traffic characteristics of field buses to ATM service categories and their QoS parameters one of the main aspects is the investigation for suitable traffic descriptors. The load behavior of field bus applications is a key aspect. PROFIBUS traffic mainly takes place in cycles (Fig. 1) consisting of a request and an immediate response or an acknowledgment. It is a stop and wait protocol. The resulting traffic pattern can be characterized as bursty with a maximum burst length of 255 bytes, the maximum length of a PROFIBUS packet. Additional characteristics strongly depend on the configuration of the PROFIBUS that is determined by the application, e.g., token rotation time, slot time, station delays, and data rate.

With respect to ATM service categories ABR and UBR can be disqualified due to the fact that field bus applications require tight timing conditions. Both are intended for non-real-time applications. CBR provides a static amount of bandwidth and a bounded delay that are continuously available during connection lifetime. However, due to the bursty

nature of field bus traffic, CBR may lead to low link utilization which could get a cost issue if leased lines or public ATM networks are involved. Therefore CBR is not chosen. The service category rtVBR appears to be better suited. Its parameters are peak cell rate, sustainable cell rate, maximum burst size, cell transfer delay and cell loss ratio. The peak cell rate (PCR) specifies an upper bound on the rate at which traffic can be submitted to an ATM connection, whereas the sustainable cell rate (SCR) is an upper bound on the average rate. This bound allows the network to allocate sufficient resources, but less than those based on PCR and still ensures that the performance objectives can be achieved. The maximum burst size is coded as a number of cells.
In the following the choice of the service parameters is discussed. On major fact for the choice of PCR is that the mainly short PROFIBUS packets lead to a massive overhead if the only one byte long acknowledgment or the 3 byte long token have to be packed into a single cell of 53 byte length. This results not only in a waste of bandwidth but also in an unacceptable delay if the data rate of the ATM connection is not appropriately higher than the data rate of PROFIBUS. The transport of a token packet with a length of 3 bytes in an ATM cell produces an overhead of 50 bytes. Therefore, in order to not further delay the token packet the bandwidth within ATM has to be 17 times higher than in PROFIBUS. PROFIBUS packets with a multiple of 48 byte length will experience the least delay. To find a compromise the length and the frequency of each packet have to be considered. A pragmatic approach is to take care of the length of each packet weighted with its frequency of occurrence during a certain time interval and set the data rate of the ATM connection accordingly. During the design phase the number of PROFIBUS devices and their message exchange among each other is determined. The design phase also includes the determination of the packet length, the deadline and the frequency of each message. Token and acknowledgments have to be taken into account, as well. These data can be used according to (1) to derive PCR.

(1) $$PCR = \frac{D*53}{n} \sum_{i=1}^{n} \frac{1}{L_i}$$

n: Number of PROFIBUS packets including token and acknowledgment during a certain time interval
D: PROFIBUS data rate
L_i: Length of packet i

The maximum burst size is limited by the longest packet of PROFIBUS which is 255 byte. Thus, the MBS is 6 cells if there are packets with 255 bytes transferred. Over a longer interval, the average rate at which a source is permitted to send is the SCR (2), which is derived from MBS, the minimum time interval between two bursts, and the PCR.

(2) $$SCR = \frac{MBS}{I + (MBS-1) * \frac{1}{PCR}}$$

I: Minimum interval between two bursts

An ATM parameter related to SCR is the burst tolerance (BT). It makes use of the leaky bucket algorithm to limit the maximum burst size which may be transmitted at the PCR. All cells entering the network are placed in this bucket, which is drained at the SCR. The BT (3) is the depth of this bucket, and is related to the MBS at the PCR by the following formula:

(3) $$BT = (MBS - 1) * \left(\frac{1}{SCR} - \frac{1}{PCR}\right) \quad [s]$$

With respect to the loss rate (CLR) ATM is expected to provide the lowest cell loss ratio it can guarantee. CTD is determined by the number of switches the cell stream has to cross and the propagation delay.

The cell transfer delay is the sum of the total inter-ATM node transmission delay and the total ATM node processing delay. For end-to-end delay parameter objectives CTV and CTD are negotiated. Both are accumulated QoS parameters.[10, 11] During the connection establishment process each switch involved adds its contribution to the CDV and CTD. The CLR parameter is the value of CLR that the network agrees to offer as an objective over the lifetime of the connection. CLR is not explicitly accumulated. Each switch accepts or rejects the call based on a comparison between the rate supported and the rate requested. [12]

3.3 PROFIBUS example with ATM

As described in section 2 communication on the PROFIBUS is subject to tight timing requirements. The scenario depicted in Fig. 4 serves as an example in order to study system behavior. The considered system is based on the example described in section 2.2 with the same communication relations between the devices and the same messages and corresponding deadline requirements. The main difference is that the existing PROFIBUS application was split up into two parts which are now connected through an ATM switch using two PROFIBUS / ATM interworking units.

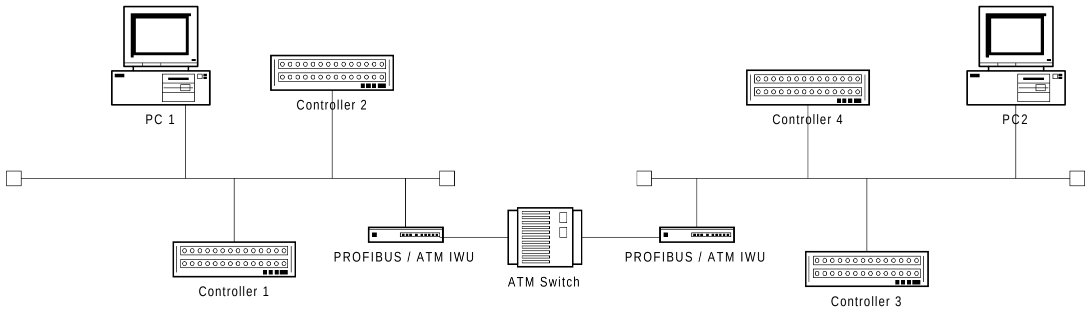

Fig. 4: Example: PROFIBUS segments connected through ATM

The duration of a message cycle in a PROFIBUS system calculates according to equation 4.

(4) $$T_{MC}= minT_{SDR} + T_R + T_{SDR} + T_A$$

T_{MC}: Message Cycle Time
$minT_{SDR}$: minimum station delay
T_R: Transmission Time of Request Packet
T_{SDR}: Station Delay Responder
T_A: Transmission Time Response Packet

In the PROFIBUS example shown in fig. 4 the message cycle calculates based on the equation (5).

(5) $$T_{MC\text{-}ATM} = T_{MC} + 4{*}T_{BD} + minT_{SDR\text{-}ext} + T_{STD} + T_{R\text{-}ATM} + T_{A\text{-}ATM} + T_R + T_A$$

$T_{MC\text{-}ATM}$: Message Cycle Time with ATM
T_{BD} : Bridge Processing delay
$minT_{SDR\text{-}ext}$: Extension for $minT_{SDR}$
T_{STD} : Switch Transit Delay
$T_{R\text{-}ATM}$: Transmission Time for ATM cells containing the PROFIBUS request packet
$T_{A\text{-}ATM}$: Transmission Time for ATM cells containing the PROFIBUS response packet
$CTD = T_{STD} + T_{R\text{-}ATM}$

To make the timing relations more transparent the following scenario is considered. If PC1 in the example sends a packet to controller 2. The packet reaches controller 2 much earlier than it reaches the stations on the remote segment. However, to keep the system stable controller 2 has to wait until the packet arrives on the remote segment. The parameter $minT_{SDR\text{-}ext}$ is responsible to ensure that. $MinT_{SDR\text{-}ext}$ strongly depends on the ATM network, the delay caused by the PROFIBUS / ATM IWUs, and the number of cells to be transmitted. On one hand the delay caused by the interworking units has a static nature and can be measured. On the other hand the CTD, as an ATM QoS parameter, is given by the ATM network and depends on the data rate, the number of switches and the distance between them. Possible cell loss is not considered. CTD as one of the parameters which can be negotiated during connection establishment is given by the ATM network and cannot be freely chosen. Once the ATM network agrees to a CTD it will be guaranteed over the lifetime of the connection. Thus, twice the bridge processing delay and CTD together comprise $minT_{SDR\text{-}ext}$. The considered aspect subsequently affects the values of token rotation time and slot time which have to be adjusted as well.

In order to evaluate the proposed concept the introduced PROFIBUS example was again implemented in the simulation system. The following parameters were used during the simulation sessions.

ATM data rate = PCR = 2.5 Mbit/s
Tsl = 0,05 s
T_{TR} = 0,5 s
min T_{SDR} = 0,0001 s
$T_{STD\,=}$ 0,0001 s
T_{BD} = 0,0001 s
min$T_{SDR\text{-}ext}$ = 0,0015 s
PROFIBUS data rate = 500 Kbit/s

At first min$T_{SDR\text{-}ext}$ has to be determined. It is equal to the time that is needed to transfer the longest PROFIBUS packet between the PROFIBUS segments. The bridge processing delays have to be included in the calculation. In case of the ATM network is unknown the parameter CTD resulting from the negotiation process has to be used. The slot time was not changed. Because of the fact that transmission errors are neglected the simulation is not affected by the slot time. Finally, the token rotation time was adjusted.

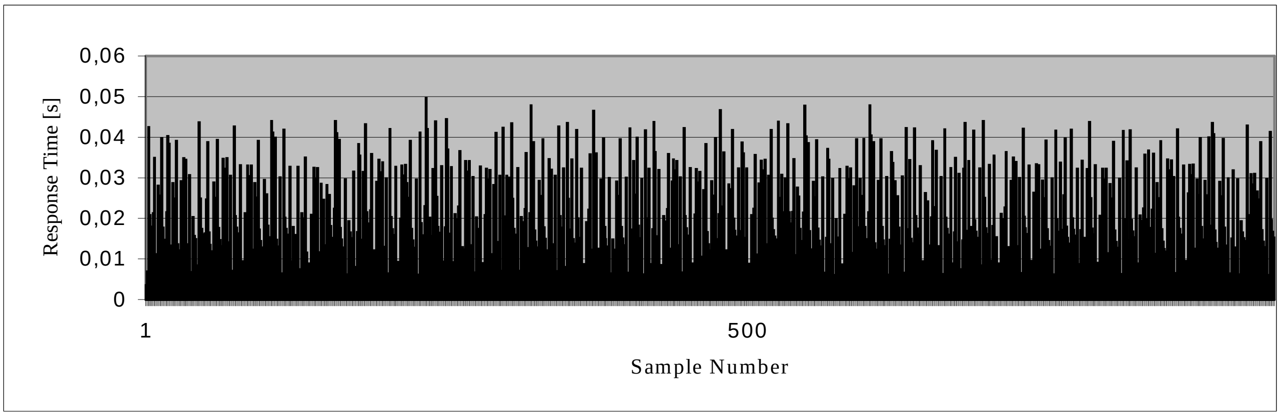

Fig. 5: Response times of message n4 with ATM backbone

Fig. 5: shows the response times of message n4 if the segments of the example system are connected as depicted in fig. 4. Obviously, in this case all response packets arrived without exceeding the deadline of 100ms. The chosen parameter combination enables a consistent implementation of this considered PROFIBUS application.

3.4 Consequences for PROFIBUS applications

This section discusses the conclusions for PROFIBUS systems that can be drawn from the simulations results. The main purpose field buses have been designed for is to provide very short deterministic response times. It is essential still to provide this functionality if PROFIBUS segments are connected through an ATM backbone. The first aspect that has to be mentioned is that due to the wide variety of PROFIBUS applications there can be no general criteria that decides whether a PROFIBUS system is feasible or not. However, applying the simulation model provides certainty.
Obviously, the main drawback concerning the discussed interconnection concept is the PROFIBUS immanent demand that each station has to receive each packet. To be in accordance to the standard the drawback has to be taken as is. To overcome this is a topic for further studies. A second disadvantage the stop-and-wait nature of the PROFIBUS protocol could be encountered. The number of simulations we performed leads to the result that min$T_{SDR\text{-}ext}$ should be considered as the parameter most significant in terms of the overall system performance. Generally, the delay caused by the interworking units is not that significant. However, if mainly very short packets (< 10 Byte) have to be transmitted the bridging delay will be a performance issue, too. Using a much higher ATM data rate than calculated with equation (1) only leads to slightly better response times and should be considered as the least opportunity to improve the performance.
If it is intended to implement a system based on the concept discussed within this paper the design phase should be directed to the exchange of small data units, since the length of the packets to transfer directly affects the parameter min$T_{SDR\text{-}ext}$. If necessary the data units should be segmented to achieve this.

4 Summary and outlook

Using an interworking unit to connect field bus segments through an ATM backbone network can overcome current limitations of field bus systems in terms of the maximum extension between controller unit and the components close to the technical process. By means of a PROFIBUS example system it was discussed, that an existing field bus system may be separated in two or more parts transparently connected through ATM comprising a "virtual" PROFIBUS system. There are important implications to the parameterization of the PROFIBUS system, that have to be considered during the design phase of the PROFIBUS. The main PROFIBUS parameters station delay, slot time and token rotation time have to be adjusted to the new conditions. Within this paper it was further outlined that the PROFIBUS standard has inherent drawbacks for the considered connection concept.
Moreover, it was underlined that the choice of the appropriate QoS parameters is an important fact in order not to bind too many resources, but still to ensure acceptable response times.

The second concept proposed in [4], the interworking of autonomous operating PROFIBUSes, was not discussed within this paper. Generally, for this concept the drawn conclusions in terms of the implications for the PROFIBUS system parameters caused by the ATM network are applicable, too. However, to study the particular system behavior will be one of the next tasks to perform.

REFERENCES

1. CAN, Controller Area Network, ISO/DIS 11898, 11519-1
2. German standardization office DIN 19245 - PROFIBUS Specification
3. Solvie, M.: Time management and multimedia support in field buses, University Erlangen-Nuremberg, Ph.D. thesis (in German). 1995
4. Kunert, O., Zitterbart, M.: Interconnecting field buses through ATM, Proceedings of the 22nd Conference on Local Computer Networks, LCN, Minneapolis, 1997
5. Bender, K. PROFIBUS- the field bus for industrial automation, Hanser, Munich 1993
6. Rembold/Levi: Real-time systems in process automation, Hanser, 1994
7. Hoyer, Robert: Performance analysis of field buses under heavy load, Ph.D. thesis (in German), Magdeburg, 1994
8. Funke, Axel: Feasibility analysis of field bus applications, Ph.D. thesis (in German), VDI, Karlsruhe, 1992
9. de Prycker, Martin.: Asynchronous Transfer Mode, Prentice Hall, 1995
10. ATM Forum: Traffic Management Specification, Version 4.0, 1996
11. ATM User Network Interface, Signaling Specification 4.0, ATM-Forum 1996
12. Onvural, R., Cherukuri, R.; Signaling in ATM networks, 1997, Artech House