Limits of Increasing the Performance of Industrial Ethernet Protocols

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Abstract

The evolution of industrial communication inexorably moves to Industrial Ethernet networks. One important reason for using Ethernet at the shop floor is to participate on the continuous advancements of standard Ethernet. Thus it seems to be the logical next step to change the bit rate from Fast Ethernet to Gigabit Ethernet to achieve better performance. The question is, how the cycle time as a relevant performance metrics of industrial automation systems can profit from increasing the bit rate to 1 Gbps. Because of its importance for the industrial automation domain this paper focuses on line topology. The analysis is based on EtherCAT and PROFINET, which are two popular representatives of different architectures for high performance Industrial Ethernet networks.

1. Introduction

The evolution of industrial communication moves to Industrial Ethernet networks, which are now in the phase of market launch. An introduction to Industrial Ethernet and the standardisation process can be found in [1, 6, 5]. At the field level of industrial automation systems, the line topology is very important [21]. In difference to the office communication, the wiring structures in the industrial automation domain must follow mechanical conditions and cabling channels of machines and plants. This mostly leads to a structure of a line topology with some trunks. When using Ethernet, an industrial control system may have tens or even up to hundreds of active nodes or switches cascaded.

Today, Industrial Ethernet protocols can be classified into three main categories which are shown in Figure 1. The protocols are becoming more powerful from category 1 to category 3, while additional functionality at the data link layer becomes necessary simultaneously. ModBus/IDA [18], Ethernet/IP [3] and FF HSE [7] are representatives of the first category. The protocols are using Ethernet as it is, only adding an industrial-automation-specific application layer on top of TCP/IP. Because of using the whole TCP/IP protocol stack, they are lacking performance in realtime transfer. Data transfer times of about 100 milliseconds can be achieved, typically. Industrial communication systems, which use protocols of the second category are perceived as a compromise between native Ethernet standard and achievable performance for realtime data transfer. An example for this category is given by PROFINET RT [4, 12, 9]. These protocols are using the priority scheme at the Ethernet MAC layer according to IEEE802.1D/Q [14, 15]. For an additional optimisation the transport and the network layer has to be bypassed for realtime data. Implementing this optimisation, a data transfer in the range of 10 milliseconds can be achieved.

Further enhancements are only possible by interventing into the scheduling procedure of the MAC layer. Protocols which are changing the original MAC scheme of Ethernet are part of category 3. In order to use those protocols, specific hardware or software is necessary. For example, Ethernet Powerlink [19] uses a Master/Slave support, while EtherCAT [2, 10, 11] organises the whole cyclic realtime data exchange using a so-called summation frame. This means that EtherCAT uses only one single frame for mes-

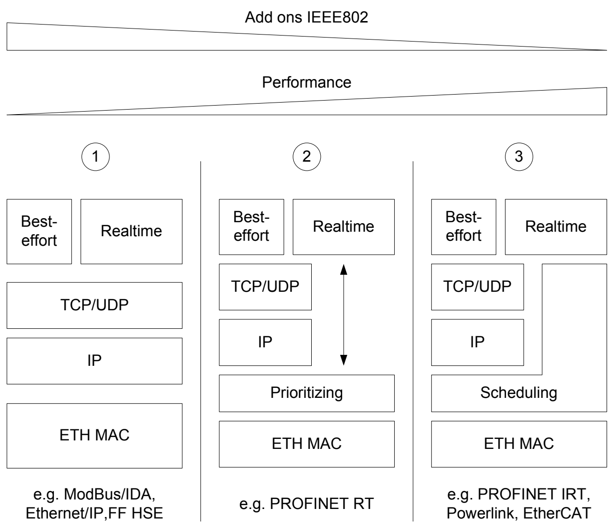

Figure 1. Classification of industrial-Ethernet Protocols

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sages from and to all devices. The devices which are involved in the cyclic real time communication, receive their data at a predefined position of the total frame. This basic concept is well-known from fieldbus systems like INTERBUS [8].

On the other hand PROFINET IRT utilises individual frames for every node and schedules the whole real time traffic a priori [20]. In the startup phase every PROFINET IRT node receives its individual timetable from an engineering station for dealing with incoming frames, making the real time traffic completely predictable. Category 3 based protocols support data transfer times in the range below milliseconds.

2. Problem outline

PROFINET is a representative of protocols, which are based on a message-related method for realtime data exchange, while EtherCAT is a representative of systems using the summation frame method. Thus in this paper we take EtherCAT and PROFINET and address the issue of the cycle time as an important performance metrics of industrial automation systems and whether it can profit from increasing the bit rate to 1 Gbps. Because of its importance in the industrial automation domain we focus on realtime communication using the line topology.

IP communication in combination with realtime communication may require more attention in the future. While EtherCAT requires a master to handle IP communication, which limits this type of communication, PROFINET allows unlimited IP communication in the interval with no RT communication.

This paper is organised as follows: Section 3 gives a brief introduction to EtherCAT and PROFINET, and analyses both Industrial Ethernet Protocols. In section 4 we discuss the potential of PROFINET and EtherCAT when the bit rate is changed from 100 Mbps to 1 Gbps. The paper ends with the conclusions in section 5.

3. Analysis of EtherCAT's and PROFINET's Performance

This chapter gives a brief introduction to EtherCAT and PROFINET taking the used frame structure into regard. Afterwards, we present the analysis of the cycle time for both systems.

3.1. Frame structure

3.1.1 Standard Ethernet frame

Obviously, all Industrial Ethernet Protocols are using a native Ethernet Frame as a carrier, shown in figure 2 [16]. It starts with a 7 bytes long preamble and an 1 byte long Start-of-Frame Delimiter (SFD). These 8 bytes are used to synchronise the physical layer (PHY) of the receiver. The following 12 bytes are the destination and the source addresses. The next 2 bytes are reserved for the Ethertype

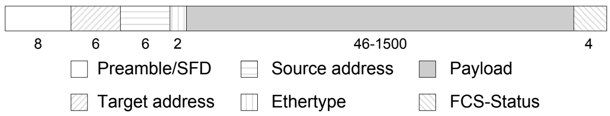

Figure 2. Structure of a native Ethernet-Frame

which marks the encapsulated higher layer protocol (e.g. IPv4: 0x0800, EtherCAT: 0x88A4, PROFINET: 0x8892). Hereafter the payload of the frame follows. The frame ends with a 4 bytes-long Frame Check Sequence (FCS) to guarantee the integrity of the received data.

3.1.2 Frame structure of EtherCAT

EtherCAT uses a standard Ethernet frame with an Ethertype of 0x88A4. The EtherCAT-specific data is embedded in the payload of the Ethernet Frame. As shown in Figure 3, the EtherCAT-specific information starts with the EtherCAT-header which is 2 bytes long. The device user data is exchanged by so-called EtherCAT telegrams. These are starting with a 10 bytes telegram header and close with a working counter, which requires another 2 bytes. The working counter is automatically incremented by all devices, that process the associated telegram. It provides an effective diagnostic tool. In order to reduce the overhead of EtherCAT, it is possible, that all telegrams share solely one telegram header and working counter. The main advantage of EtherCAT is based on the possibility to pack the individual data of several devices into one single summation frame.

The potential of merging EtherCAT telegrams in one single frame reduces the overhead of EtherCAT. The output data to the device sent by the controller will be replaced by the input data of the device on the fly. Because of this method, the reserved space in the telegram has to be determined by the controller or the device data, depending on their size. In the case of the amount of controller data exceeding the amount of device data, the controller determines the telegram size and vice versa.

3.1.3 Structure of a PROFINET frame

The basic structure of a PROFINET frame is similar to an EtherCAT frame (cf. Fig. 4). The PROFINET-specific

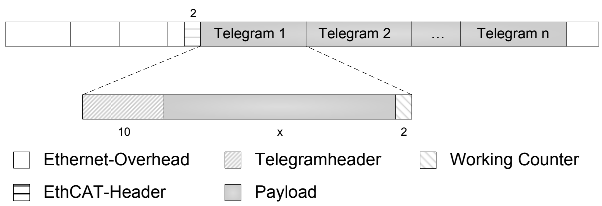

Figure 3. Structure of an EtherCAT-Frame

overhead is also embedded in the payload of a standard Ethernet frame and starts after the ethertype 0x8892 with a 2 byte Frame-ID, which defines the type of PROFINET IO messages. Afterwards the payload of the PROFINET device follows. The payload will be finalised by one byte IOPS (IO-Data Object Producer Status) and one byte IOCS (IO-Data Object Consumer Status) for every submodule in the device. The IOCS and IOPS show the validity of the cyclic data transfer. A PROFINET telegram is completed by the APDU-status (Application Layer Protocol Data Units). The APDU status comprises a 2 byte cycle counter to control the timeliness of a frame in a redundant wired system and an 1 byte data-status, which shows whether the data is valid. The APDU-Status is completed by an 1 byte Transfer-Status.

3.2 Cycle time

Common industrial control applications are typically based on controller units, which require fixed sampling rates. Therefore the cycle time is an important performance metrics for industrial communication systems. The cycle time is defined as the time necessary to exchange the input/output data between the controller and all networked devices once. The following chapter analyses the minimum of possible cycle times of EtherCAT and PROFINET.

3.2.1 Cycle time of EtherCAT

The minimal cycle time of an industrial communication system based on EtherCAT depends on several terms. The first term is the delay $t_{Ethernet}$, which covers the overhead generated by a standard Ethernet-frame itself. In Figure 2 the overhead consists of 24 bytes for protocol control information and the FCS ($d_{Ethernet}$), and 12 bytes for the interframe gap (d_{IFG}). The delay $t_{Ethernet}$ could be calculated by dividing the number of bytes over the given bit rate b:

$$t_{Ethernet} = \frac{d_{Ethernet} + d_{IFG}}{b} \quad (1)$$

The delay t_{ecat_fwd} describes the time necessary for an individual EtherCAT device for forwarding the frames from the incoming interface to the outgoing interface and vice

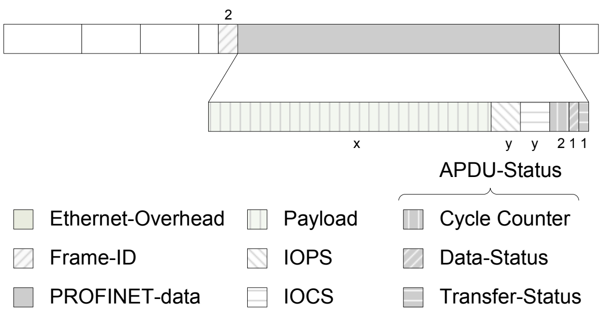

Figure 4. Structure of an PROFINET-Frame

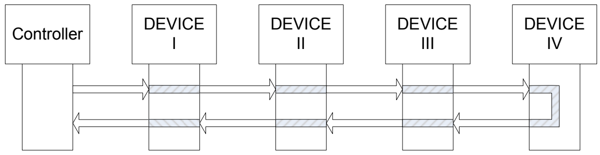

Figure 5. EtherCAT uses a ring structure

versa (see Figure 5). The delay t_{medium} defines the average medium delay.

t_{data} is caused by the payload. It can easily be calculated considering the d_{data} in bytes and the bit rate b:

$$t_{data} = \frac{d_{data}}{b} \quad (2)$$

The recent relevant delay component t_{ecat_ov} is introduced through the overhead of every EtherCAT telegram. It includes the 10 byte EtherCAT telegram header $d_{ecat\_teleg\_Hd}$ and a 2 byte working counter d_{wc}.

An additional overhead of two bytes is caused by the EtherCAT header $d_{ecat\_teleg\_Hd}$ for every EtherCAT frame. The maximum EtherCAT payload $d_{max\_ecat\_payload}$ will be introduced for the sake of clarity . It consists of the maximum Ethernet payload $d_{ethernet\_max\_payload}$ (cf. Fig. 2) minus the additional EtherCAT overhead.

$$\begin{aligned} d_{max\_ecat\_payload} &= \lceil d_{max\_ethernet\_payload} \rceil \cdot \\ &- d_{ecat\_Hd} - k * (d_{ecat\_teleg\_Hd} + d_{wc}) \end{aligned} \quad (3)$$

where k represents the number of EtherCAT telegrams per frame. The whole EtherCAT overhead t_{ecat_ov} can be calculated with the following equation:

$$\begin{aligned} t_{ecat\_ov} &= \left\lceil \frac{n_{devices} \cdot d_{data}}{d_{max\_ecat\_payload})} \right\rceil \cdot \\ &\frac{d_{ecat\_Hd}}{b} + \frac{(d_{ecat\_teleg\_Hd} + d_{wc}) * k}{b} \end{aligned} \quad (4)$$

If the total sum of the desired user payload exceeds $d_{max\_ecat\_payload}$, the data has to be segmented, whereby every frame creates an additional overhead. To be more definite the delay t_{frame} is established. It consists of the data transfer time t_{data}, the overhead caused by Ethernet $t_{ethernet}$ and the protocol-specific overhead t_{ecat_ov}:

$$t_{frame} = t_{data} + t_{ethernet} + t_{ecat\_ov} \quad (5)$$

The minimum possible cycle time t_{ecat} of EtherCAT consists of the sum of the delay components mentioned before.

$$t_{ecat} = n_{devices}(t_{ecat\_fwd} + t_{medium} + t_{frame}) \quad (6)$$

As shown in equations (2) and (4) t_{ecat_ov} and t_{data} are affected by the payload size and the bit rate, while the forwarding delay t_{ecat_fwd} and the medium delay t_{medium} are independent from these parameters. Figure 5 shows an example of a EtherCAT topology, with one controller and four devices.

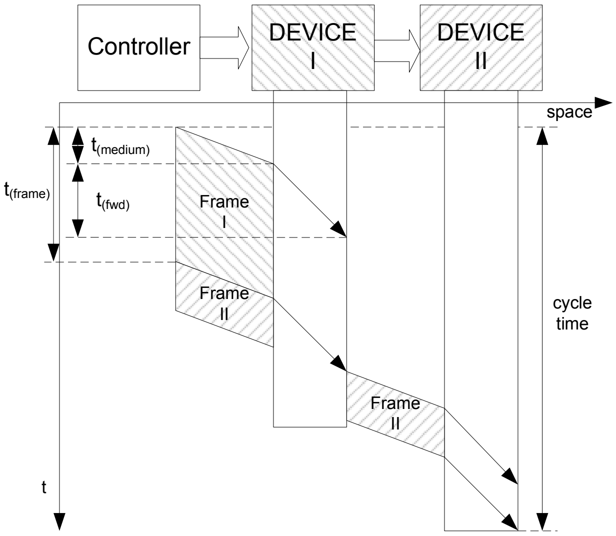

Figure 6. Space-time Diagram

3.2.2 Cycle time of PROFINET

In order to calculate the cycle time of PROFINET the forwarding delay t_{pn_fwd}, the medium delay t_{medium}, the payload delay t_{data}, the PROFINET overhead t_{pn_ov} and the delay $t_{Ethernet}$ introduced by the Ethernet frame itself must be taken into account. PROFINET uses the full-duplex feature of Ethernet [13]. Therefore, the data exchange between controller and devices, can occur simultaneously in both directions. For this reason only the way from the controller to the devices has to be considered for the calculation of the cycle time. Because PROFINET uses individual frames for every device, a higher amount of overhead is produced in comparison to EtherCAT.

With Figure 6 we introduce a space-time diagram. This presents the position of objects as a function of time. Usual time runs down the diagram, so that the bottom represents the future, or late times, and the top represents the past, or early times. A point on this graph describes both, a position (the horizontal or x coordinate) and a time (the vertical or t coordinate). This diagram type is very appealing for visualising the physical propagation of frames through the topology. Figure 6 presents a space-time diagram for a communication system based on a message-related principle like PROFINET with one controller and two devices arranged in a line topology. It represents a situation, where the controller is sending the frames in the order of the arranged devices. The cycle time spans the time period from sending the first bit of frame I until receiving the last bit by the furthest right arranged device. In order to reach a minimum cycle time, it is necessary, that the controller sends the frame for the last device at first. This type of sending, utilising the slipstream-effect, is shown in figure 7. The positive characteristics of the slipstream-effect can be used, if $t_{frame} \geq (t_{medium} + t_{pn\_fwd})$ is valid.

The angle α in the figure 7 represents the actual bottleneck of a system and can be calculated with the following formula:

$$\tan\alpha = \frac{|t_{medium} + t_{pn\_fwd} - t_{frame}|}{n_{devices}} \tag{7}$$

If the value of the angle α becomes negative, the system does not profit from a increasing bit rate b. Depending on t_{frame} the relevant bottleneck of PROFINET changes. Thus, we need two formulas for calculating the cycle time of PROFINET.

If $\alpha \geq 0$ the minimum cyclic time t_{pn1} will be calculated with the following equation:

$$t_{pn1} = t_{medium} + t_{pn\_fwd} + n_{devices}(t_{frame}) \tag{8}$$

If $\alpha \leq 0$ the minimum cycle time t_{pn2} will be calculated as follows:

$$t_{pn2} = n_{devices}(t_{medium} + t_{pn\_fwd}) + t_{frame} \tag{9}$$

4 Potential of EtherCAT and PROFINET

In the following chapter we take a look at the performance potential of EtherCAT and PROFINET, when using a bit rate of $b = 1Gbps$. The results in this chapter are based on the equations of Chapter 3.2.

4.1 Advantage of an increased bit rate

First we would like to discuss the cycle time for PROFINET using a bit rate b of 100 Mbps and 1 Gbps. The following assumptions are applied:

- the forwarding delay inside a PROFINET device t_{pn_fwd} is set to 3 μs when using Fast Ethernet. This is a typical value of cut-through switches [17].

  By using Gigabit Ethernet the PHY delay was set to 250 ns, which is typical for modern gigabit PHYs.

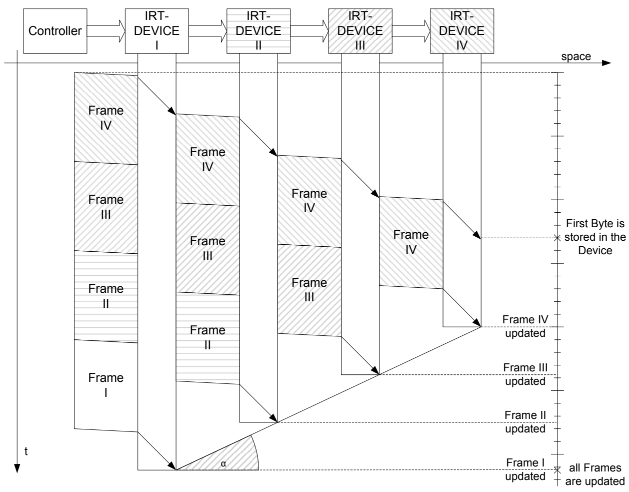

Figure 7. Space-time diagram for PROFINET (100Mbps) using the slipstream-effect

Because of the increased bit rate the delay to forwarding data is divided by the factor 10. The clockrate of a gigabit switch exceeds the Fast Ethernet clockrate by the factor 5. Because of the increased clockrate, the forwarding logic should also gain a speedup. Under the given conditions the forwarding delay t_{pn_fwd} in a gigabit network is set to 0.6 μs.

- only minimum sized frames are considered.
- the length of a copper-based segment between two devices is set to 50 meters. This leads to a medium delay of $t_{medium} = 227ns$.

Figure 8 presents the same configuration as figure 7, but with a bit rate of 1 Gbps. Because of the raised bit rate the time for sending all frames is reduced by the factor 10. By reducing t_{frame}, a new bottleneck appears. Figure 8 shows that the bottleneck is caused by the forwarding delay t_{pn_fwd} and the medium delay t_{medium} now. The maximum gain of an increased bit rate is reached, when $t_{medium} + t_{pn\_fwd}$ is equal to t_{frame}.

The analysis of EtherCAT, by using a bitrate of 100 Mbps and 1 Gbps, is based on the following assumptions:

- the forwarding delay t_{ecat_fwd} in an EtherCAT device is given by the PHYs (forward and reverse channel). Additionally, a delay for the forwarding logic of the downstream channel, and a delay for the forwarding logic of the upstream channel were assumed. The sum of the delays build up the forwarding delay of EtherCAT in a fast Ethenet network. It consists of 1.35 μs. By using a gigabit network, EtherCAT also gains a performance benefit of the modern technology. Thus the forwarding delay of EtherCAT in a gigabit network is decreased to $0.85\mu s$.
- the length of a copper-based segment between two devices is set to 50 meters. Because of the used forward and reverse channel the delay caused by the medium has to be counted twice. This leads to a medium delay of $t_{medium} = 454ns$.
- for better system diagnosis the number of EtherCAT telegrams per frame is set to $k = \frac{n_{devices}}{10}$.

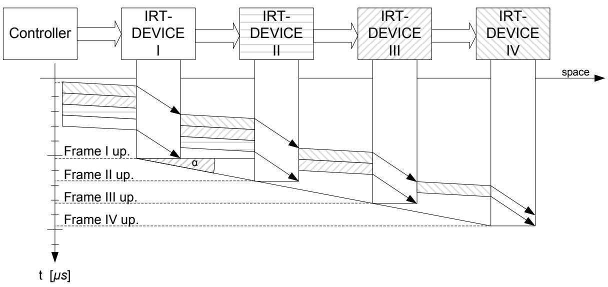

Figure 8. Space-Time Diagram for PROFINET with a bit rate of 1Gbps

Figure 9 and Figure 10 shows the real time data transfer using EtherCAT. It can be concluded that EtherCAT does not profit as strongly from the increase of the bit rate as PROFINET.

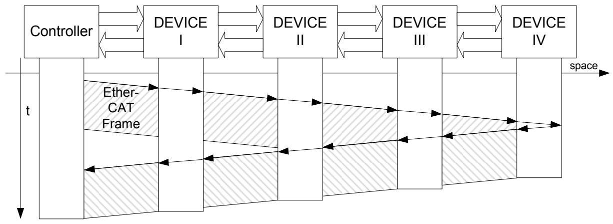

Figure 9. EtherCAT with 100 Mbps

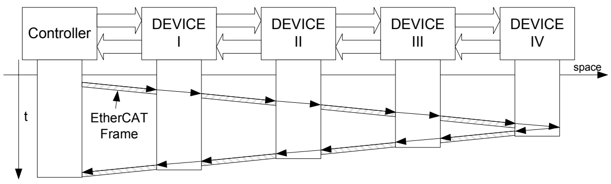

Figure 10. EtherCAT with 1 Gbps

4.2 Analysis of EtherCAT's and PROFINET's Performance

Firstly we calculate the minimum cycle time as a function of the number of devices. Figure 11 shows the minimum cycle time of EtherCAT and PROFINET, using a Fast Ethernet network. The number of devices solely effect the minimum cycle time in a linear function. Using a Fast Ethernet network EtherCAT inhibits a significant performance advantage in comparison to PROFINET. Figure 12 presents the minimal cycle time of EtherCAT and PROFINET in a gigabit network. Comparing figures 11 and 12, you see that EtherCAT profits less strongly from increasing the bit rate than PROFINET. Both systems are unable to convert the increase of the bit rate to an appropriate reduction of cycle time. The reason for this is, that an increasing bit rate has an influence on the data transfer time but not on the medium delay and the forwarding delay.

Figure 13 shows a diagram, which compares the cycle times of EtherCAT and PROFINET as a function of the payload per device. We assume a moderately sized network with 50 devices connected through Fast Ethernet. The figure shows, that EtherCAT receives a magnificent performance gain for small payloads per device. The reason for this is, that PROFINET demands at least a minimum sized frame of 64 bytes. If the payload per device exceeds 36 bytes, this lack of PROFINET is compensated (36 bytes payload + 28 bytes overhead). The small skips in the curve of EtherCAT find their cause in the fact that with higher payloads per device further frames are necessary. Figure 14 shows the same scenario as in Figure 13 using Gigabit Ethernet. The maximum performance of PROFINET in comparison to EtherCAT is reached at a payload of 55 bytes per device. This value represents the point, where the bottleneck moves from the propagation time $t_{pn\_fwd} + t_{medium}$ to the frame transfer time t_{frame}. This point can be calculated by equate (8) and (9), where α is zero. The following equation shows the result of the conversion to t_{data} :

$$t_{data} = \frac{t_{medium}+t_{pn\_fwd}-(t_{pn\_ov}+t_{ethernet})}{1-\frac{1}{n_{devices}}} + \frac{\frac{t_{pn\_ov}+t_{ethernet}-(t_{medium}+t_{pn\_fwd})}{n_{devices}}}{1-\frac{1}{n_{devices}}} \quad (10)$$

In order to calculate the optimum payload d_{opt}, t_{data} must be multiplied with the used bit rate b:

$$d_{opt} = t_{data} \cdot b \quad (11)$$

Figure 15 shows an analysis, which compares EtherCAT and PROFINET depending on the given bit rate. The optimal bit rate b_{opt} of PROFINET is given when α equals zero. In the following calculations t_{frame} is replaced by: $t_{frame} = \frac{d_{frame}}{b}$. After the conversion of t_{frame} equations (8) and (9) have to be equated and converted to b.

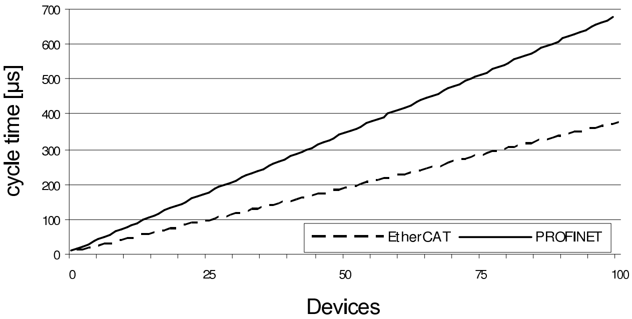

Figure 11. Cycle time as a function of the number of devices with a constant payload of 16 byte per device and a bit rate of 100Mbps

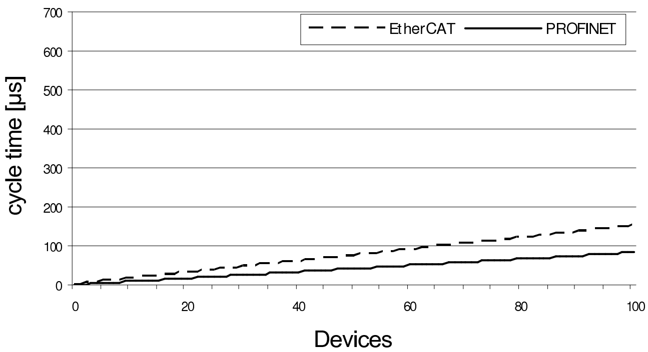

Figure 12. Cycle time as a function of the number of devices with a constant payload of 16 byte per device and a bit rate of 1Gbps

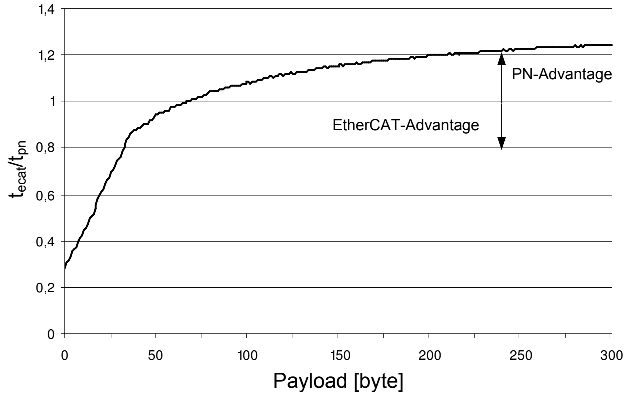

Figure 13. PROFINET vs. EtherCAT as a function of the payload per device and a bit rate of 100 Mbps

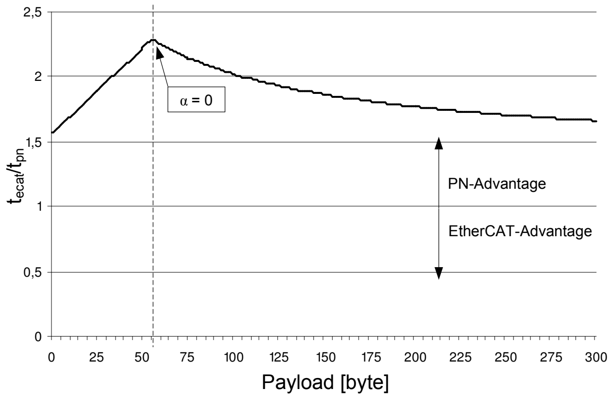

Figure 14. PROFINET vs. EtherCAT as a function of the payload per device and a bit rate of 1 Gbps

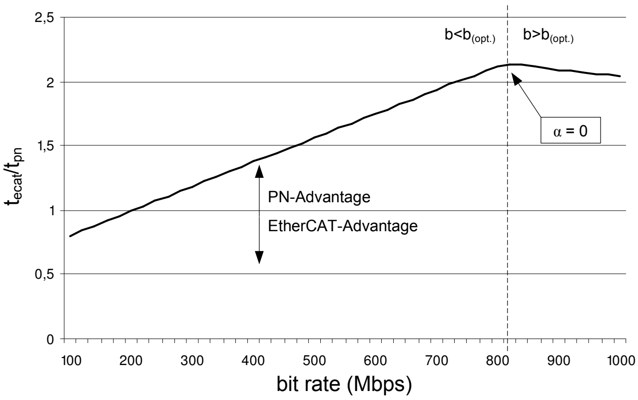

Figure 15. PROFINET vs. EtherCAT as a function of the bit rate and a fixed payload of 36 bytes per device

b_{opt} could yet be calculated as follows:

$$b_{opt} = \frac{d_{frame}}{t_{medium} + t_{pn\_fwd}} \quad (12)$$

With the given delays, the optimal bit rate for PROFINET is reached at 813 Mbps. An additional increase of the bit rate does not have a perceivable influence on the performance of PROFINET.

5. Conclusions

Today high performance networks in industrial automation systems offer cycle times of below 1 millisecond. Typical representatives of this class of Industrial Ethernet protocols are EtherCAT and PROFINET. Both systems are using different technological approaches to fulfill the named requirements. EtherCAT uses a summation frame approach, while PROFINET uses a message-related approach with individual frames for every device. In regard of further decrease of the cycle time of future industrial communication systems, the usage of gigabit Ethernet is discussed as a reasonable solution. This paper tries to give an answer to the question how the cycle time of Industrial Ethernet protocols can profit of increasing the bit rate to 1 Gbps with a focus on line topologies.

The two most important parameters are the propagation delay through the line topology and the data transfer time. The propagation delay consists of a time component for forwarding a frame and the medium delay. It is independent to the amount of data, which must be exchanged between the involved devices. The data transfer time depends on the necessary number of frames and its payload sizes as well as the used wire speed. With exception of the medium delay, these parameters are specified directly by the used architecture of the particular Industrial Ethernet protocol.

Our analysis shows, that EtherCAT is twice as fast as PROFINET when using small payload sizes and the line topology. However it must be noticed, that a line topology represents a best case situation for EtherCAT. In real plants more complex wiring structures with branches are required. These structures are shifting the performance quickly in favour of PROFINET.

Due to the summation frame approach, which has to go through all nodes of the network twice, EtherCAT can not profit significantly from increasing the bit rate from 100 Mbps to 1 Gbps. However the cycle time of PROFINET can be reduced by the factor 8.13 in a line topology. Thus PROFINET becomes 50% faster than EtherCAT when using Gigabit Ethernet.

Reliability is another important requirement of real-time communication. A summation frame traveling to all stations twice (as done by EtherCAT) is much more subject to transmission errors than individual frames forwarding directly (PROFINET principle).

Because of these benchmarks, it seems that a message-related principle (e.g. PROFINET) is more suitable than a purly summation-frame (e.g. EtherCAT) orientated system.

The presented results express the necessity of new concepts for efficient utilisation of higher bit rates in order to decrease cycle times of future networks.

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