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USEFUL EFFICIENCY IN CYCLIC TRANSACTIONS OF PROFINET IO

Summary. In this article the subject matter of using Ethernet network in industrial computer systems is considered. In this kind of systems it is required that the access to medium is determined in time and the time of network transaction execution should be finite and specified in range. There are numerous attempts of adaptation and standardization of various network technologies which fulfill such a kind of requirements for these type of applications. One of the most interesting is Profinet IO. Disclosure of useful efficiency value for key transactions such as cyclic ones is important to objective comparison of time features of fieldbus protocols, also those based on Ethernet.

Keywords: Profinet, fieldbus, useful efficiency, Ethernet

SPRAWNOŚĆ UŻYTECZNA TRANSAKCJI CYKLICZNYCH W PROFINET IO

Streszczenie. W niniejszym artykule poruszono tematykę wykorzystania sieci Ethernet w informatycznych systemach przemysłowych. W systemach tych wymaga się, aby dostęp do medium był zdeterminowany w czasie, a co za tym idzie czas realizacji transakcji sieciowych był skończony i określony w przedziale. Istnieje wiele prób adaptacji i standaryzacji różnych technologii sieciowych spełniających takie wymagania dla tego typu zastosowań. Jedną z ciekawszych jest Profinet IO. Poznanie wartości sprawności użytecznej dla kluczowych transakcji, jakimi są transakcje cykliczne, jest ważne dla obiektywnego porównania właściwości czasowych protokołów, w tym również opartych na Ethernecie.

Słowa kluczowe: Profinet, sieci polowe, sprawność użyteczna, Ethernet

1. Introduction

The basic kind of computer networks designed for distributed control with real time constraints is a fieldbus idea. The big variety of the solutions have been developed and have got known well since the 80's and have been constantly used in industry till now. Nevertheless, the new branch of real time networking was born at the end of the 90's – based on Ethernet. Nowadays, there exist several dozen communication solutions used in industrial computer systems based on the Ethernet standard.

The main problem related to industrial application is to ensure the time-limited processing during the whole process of data passing between system components and into itself. Generally, the Ethernet network does not serve any mechanisms which could deterministic access control to medium make possible. Activity of the link layer is based on line monitoring mechanisms and collision detection CSMA/CD [1]. One can think that using the TCP/IP together with Ethernet is a universal remedy for all communication problems. Regrettably, using the TCP/IP stack in higher level of network interface does not eliminate the problem because TCP/IP does not contain any protocols to control access to medium by default. [1, 2, 3, 6, 7].

However, thanks to that, that TCP/IP protocol is an open standard, creating a new constituent protocol which provides exchange execution according to rules known from industrial networks seems natural [1, 2]. The solution like that does not boil down only to design and implementation suitable protocol. Since the 90's many companies have tried to bring their own propositions in the global market trying to bring everybody round to the correctness of their ideas. Unfortunately, mutual competition to clients did not allow building one coherent standard. In the open market, there exist series of industrial networks, using various sets of communication protocols, both specialized solutions and ones based on Ethernet and TCP/IP standards [6, 9].

Currently, there are many industrial Ethernet solutions. The existence of at last 22 protocols is acknowledged by author. Some of the protocols are also subsumed into international standards. One of them is Profinet [4, 9, 10]. In the next part of the article a concise description of Profinet/Profinet IO mechanisms as well as the analysis of useful efficiency for its cyclic transactions is presented.

2. Profinet

The beginning of the Profinet was in 2002 when various companies started to develop fieldbuses in order to use the Ethernet standard as a physical and link layer. Nowadays, the

Profinet is an open platform supported by specially founded PI (*Profibus & Profinet International*) organization. The competition problems and followed applicability limitations previously mentioned are decreased by the fact that the Profinet IO is such an open network. Additionally, it became a part of international norms or it is liable to them (IEC 61158, IEC 61784, IEC61588, IEEE802.3, IEEE802.1Q). The standardization concerns the Ethernet frames, its addressing, unique identifiers, priority tagging, and a general concept of network activity.

Two types of communication are distinguished in the Profinet standard:

- PROFINET CBA (Component Base Automation),
- PROFINET IO (Input Output service).

The structure of communication layers of Profinet is shown in figure 1. There are three types of network activity, Profinet becomes quite adaptable to various system requirements and its scope. There can be distinguished communication without time limitations NRT (*Non-Real Time communications*), with limitations RT (*Real Time communications*) as well as isochronous mode IRT (*Isochronous Real Time communications*). The last one needs to use specialized hardware support (so-called ASIC – application-specific integrated circuit).

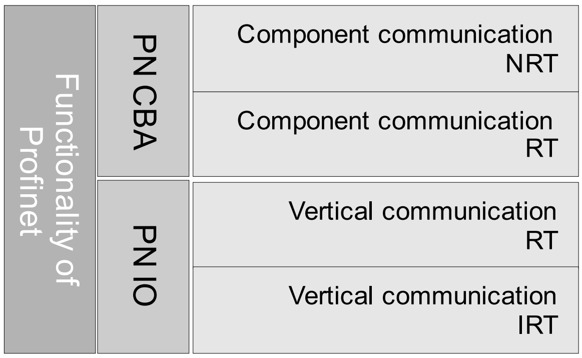

Fig. 1. Genaral functionalities of Profinet
Rys. 1. Ogólne funkcjonalności Profinet

Only Profinet IO standard designed to fieldbus domain, concisely described before, is the subject of this article. In the next figure (fig. 2) one can find the Profinet layers cooperation according to reference ISO/OSI model. In the Profinet IO the RT mode transmissions occur only in the application and Ethernet layers. Thus, the idea of Profinet IO work is based on a special managing protocol located in application layer of multilayer communication model.

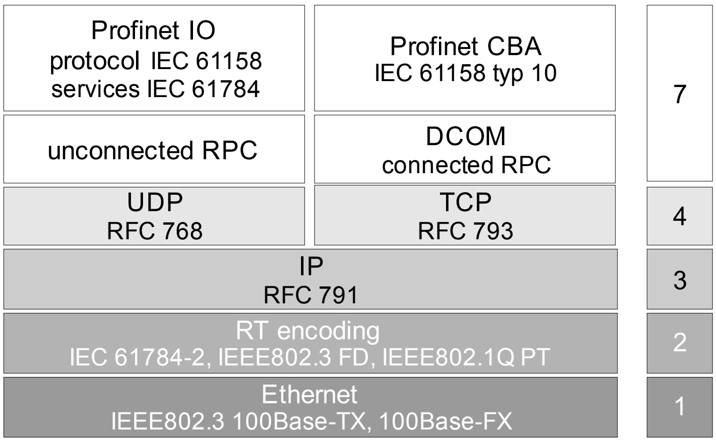

Fig. 2. Profinet network according to ISO model
Rys. 2. Sieć Profinet względem modelu ISO

The activity of this layer is based on a specific token model, where no special marker, passed from a station to a station, exists. Instead of this, time slides are created, in which the type of passing information and its order is well-known in advance (TDMA model – time division multiple access). In order to transmit data in the Ethernet, the standard IEEE 802.1Q is used. Type of VLAN header was specified in norm to value 0x8100. Thus, it does not interfere with other VLAN standards. Using the VLAN header is necessary only with older Ethernet switches when priority control is needed. Normally, the Ethertype assignment to RT (0x8892) is enough to properly distinguish the priority control.

The general protocol idea and data passing with TDMA mechanism differs from other solutions and could be better than useful efficiency and useful throughput point of view.

2.1. Profinet IO

In the NRT mode, there are possible nondeterministic transmissions of data with using typical network hardware together with other subscribers not involved in exchanges connected with Profinet IO system. The values of time cycle for this type of transmission are above 100ms with jitter of cycle of rank 100% [10].

In the RT mode, data is transmitted along with time windows according to TDMA model (*Time Division Multiple Access)*. Each subscriber of communication subsystem has a selected window in which it could execute a frame transfer. This solution guarantees lack of logical collision inside a switch provided that no additional traffic from the outside of a given system appears. Additionally, the prioritization of packets is used and makes the control of its traffic on a switch level possible. It is specified that for this type of work the cycle period of data exchanges might be from a few milliseconds. The jitter of the cycle is below 15% [10].

In the IRT mode along with TDMA transmission the synchronization of subscriber's local timers protocol is added based on IEC 61588 standard. It is specified that data exchange cycle could be above 250µs for this kind of work along with jitter below 0,4%. On the other hand, the deviation value is on maximum level of 1μs for time values of the cycle below 1 ms [9, 10].

In this paper, the main focus is on the RT mode. In this mode the schema of a general idea of cyclic transactions is presented in the figure below.

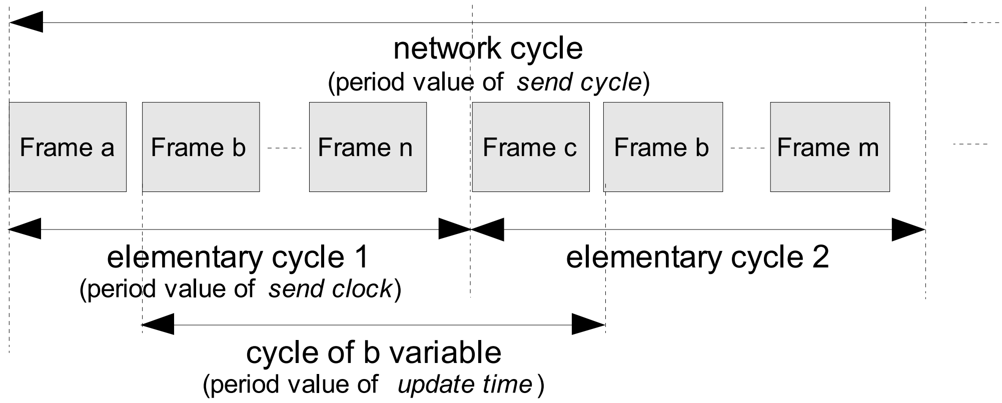

Fig. 3. The data exchange cycle in Profinet IO RT mode
Rys. 3. Cykl wymiany informacji w Profinet IO w trybie RT

In each of the elementary cycles various frames could be transmitted according to period of value update for a given frame. The period of elementary cycle results from the *send clock* parameter appointed and fixed for the whole subsystem of Profinet IO. The special time for frame transmission of IRT, RT and NRT is reserved in each elementary cycle. The cycle of the whole network is followed from subscribers assignment definition. The period of network cycle described by the *send cycle* parameter is a multiplication of elementary cycle period, but its value depends on requested transmission periods of given frames. Appearances of the given frames in the cycles arise from the *update time* parameter defined for each subscriber.

2.2. Analysis of cyclic transactions

Efficiency and throughput are the most important work parameters of any network. However, calculation of such parameters for the whole network activity or for the whole protocol stack is impossible. Therefore, the good determinant of a characteristic of network work could be a calculation of useful efficiency and useful throughput which are defined for a given, specific type of transaction. The definition of useful efficiency and throughput states that [8]:

efficiency: $\eta = \frac{T_U}{T_T}$, (undimensional, as factor 0-1), (1)

throughput: $P = \frac{L_U}{T_T}$ [b/s], (2)

where T_U is the time of useful data transaction, L_U is a number of useful data, T_T is the duration time of the whole transaction.

In further considerations, one fixates cyclic transactions as a key for functionality of field networks. The analysis was executed in order to compare useful efficiency of Profinet IO with values from other Ethernet solution, field networks protocols as well as theoretical protocol based on UDP [6].

The Profinet network combines connections between application layers of subscribers during startup. All exchanges involved in this process arrive in the NRT mode with part of TCP/IP, ARP etc., and occur only during startup. The time of such boot-up measured in practice is set from several to several dozen seconds. Assuming stable structure of physical and logical connections we can also assume that after finish of this process and during execution of cyclic exchanges in RT mode, the startup exchanges won't have occur yet. It comes from the fact that for the execution of functional tasks of useful data transmission, these kinds of NRT exchanges are unnecessary.

During cyclic transactions in Profinet IO, the Ethernet frames of type II are used. Additionally, the Ethernet frame could be used along with code of virtual network protocol (VLAN) according to IEEE 802.1Q (frame code in hex: 0x8100). However, there is an optional field and for the RT and IRT modes this field can be omitted. For the RT mode the frame type code 0x8892 is set, but for cyclic transactions the frame identifier 0xC0xx is used. The fragments of frames for the NRT and RT modes are presented in figure 4, with and without VLAN header.

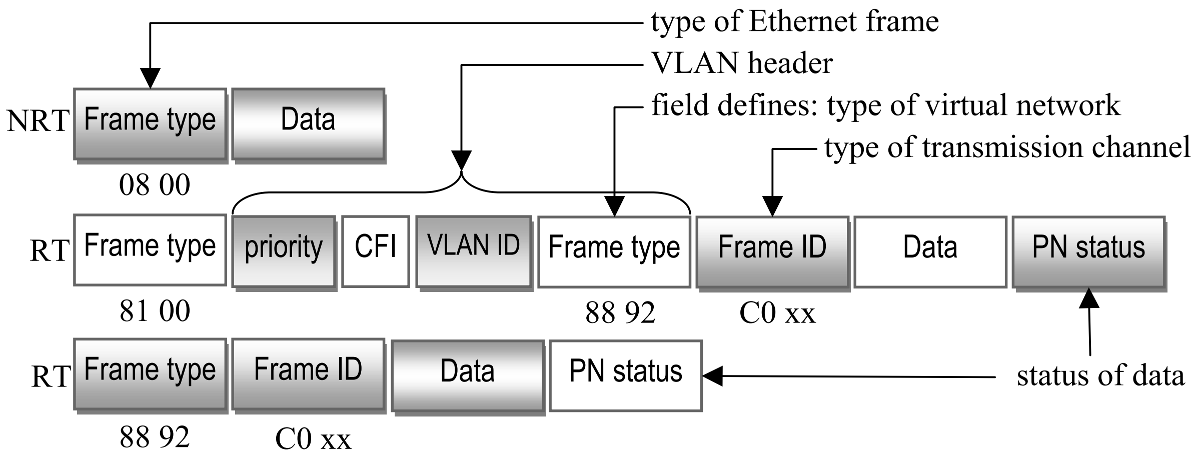

Fig. 4. Profinet frames (field sizes are not according to their real size)
Rys. 4. Ramki sieci Profinet (rozmiar pól nie oddaje ich rzeczywistej wielkości)

There is a part of sample frame along with VLAN header presented below. This frame was captured from test system (see 2.3) with working Profinet IO network during execution of cyclic transactions between controller and remote IO module.

Destination MAC	Source MAC	Frame type
08 00 06 99 43 5c	08 00 06 99 0a a0	81 00
Header VLAN	*Frame ID*	*Useful data*
C0 00 88 92	c0 80	00 00 00 00 00 ...
Control data (cycle counter, data and transfer status)		
d5 40 35 00		

The part of frame without VLAN fields is presented below.

Destination MAC	Source MAC	Frame type
08 00 06 99 43 5c	08 00 06 99 0a a0	88 92
Frame ID	*Useful data*	
c0 00	60 60 60 60 00 ...	
Control data (cycle counter, data and transfer status)		
F9 20 25 00		

The cyclic transactions are not confirmed as well as there do not exist any queries and other elements causing the necessity of additional exchanges execution in order to finish transactions. Cycle transaction contains single transmission of Ethernet frame coded as RT Profinet IO frame of cyclic transactions (fig. 4). Calculations of useful efficiency have been made due to equation 1, assuming the following:

- Ethernet 100 Mb/s,
- small packets of useful data of 1-128 bytes, typical for fieldbus application,
- Ethernet header size of 16 or 20 bytes subject to VLAN header,
- 4 control data bytes of Profinet and 4 bytes of FCS,
- minimal size of frame being 64 bytes,
- 8 bytes of preamble and SFD and 12 bytes of silence which should be taken into consideration because they have to occur after transmission of every frame,
- minimal size of useful data the size of 36 or 40 bytes,
- 100% of cycle time for Profinet IO, 0% for CBA.

Based on (1) the equations describing the useful efficiency are created and presented below, where n is a number of useful bytes.

$$\eta = \frac{\frac{8n}{V}}{\frac{8*(16+8+8+12+n)}{V}} = \frac{n}{44+n}, n \geq 20 \qquad (3)$$

$$\eta = \frac{n}{64}, n < 20 \qquad (4)$$

In figure 5 there are graphs of useful efficiency resulting from calculations with assumptions and equations above. Useful throughput changes in range from 1,2 Mb/s to 72,7 Mb/s according to efficiency characteristic, thus appropriate graphs are not presented.

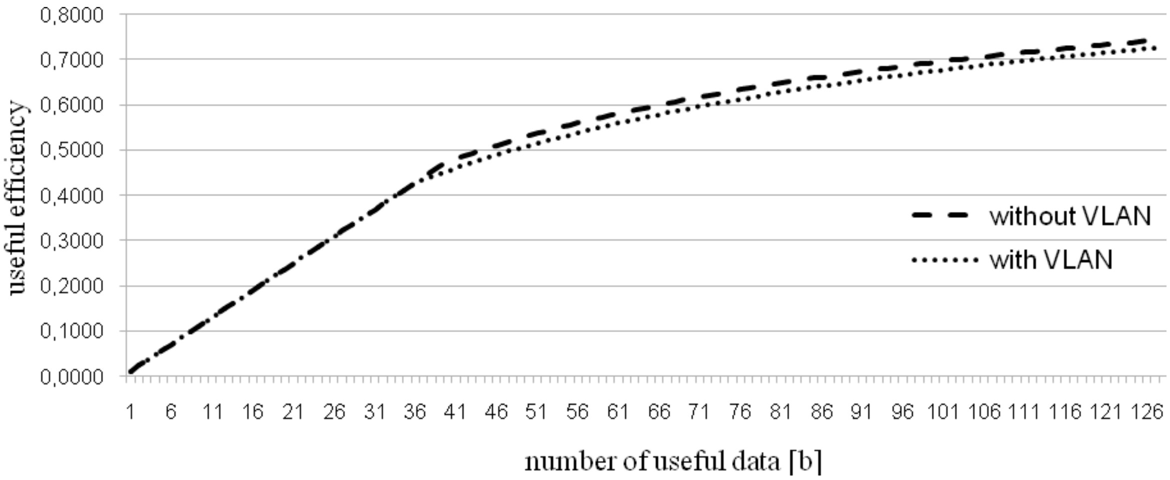

Fig. 5. The useful efficiency graph for packets of 1-128 bytes with and without VLAN header
Rys. 5. Wykres sprawności użytecznej dla pakietów 1-128 bajtów z nagłówkiem VLAN oraz bez nagłówka VLAN

The characteristic bend of linear growth of graph near the number of about 40 bytes of useful data results from minimum length of Ethernet frame and follow that, from minimal size of useful data field. Influence of removing VLAN header is visible just above the boundary of minimum size of data field. However, for frame without this header the boundary is shifted by 4 bytes forward. Next the efficiencies for both cases tend to 1. The conclusion is: for packets of useful data containing up to 36 bytes, the existence of VLAN header does not impact useful efficiency. Above this size the lack of header improves efficiency imperceptibly. This is presented in figure 6.

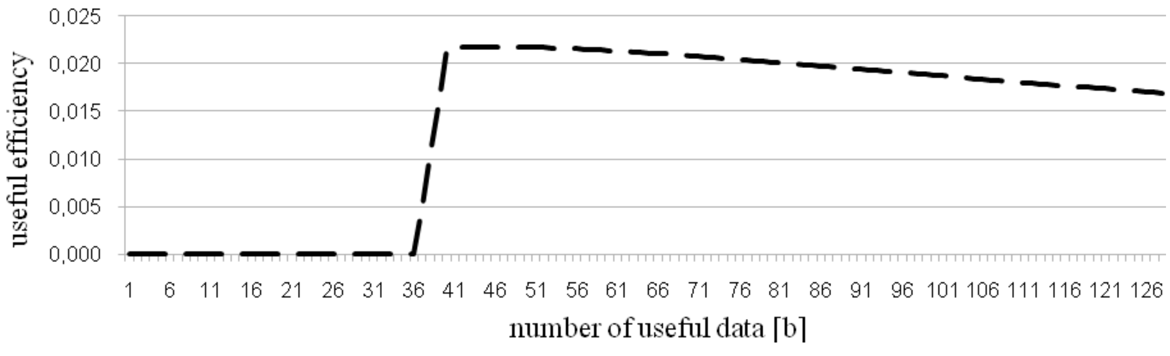

Fig. 6. Difference of efficiency value for frame with and without VLAN header
Rys. 6. Różnica wartości sprawności dla ramki z nagłówkiem VLAN i bez

In figure 7 efficiencies of others solutions are presented, included cyclic transactions of selected fieldbus protocols [8] and theoretical protocols based on Ethernet and UDP/IP [6].

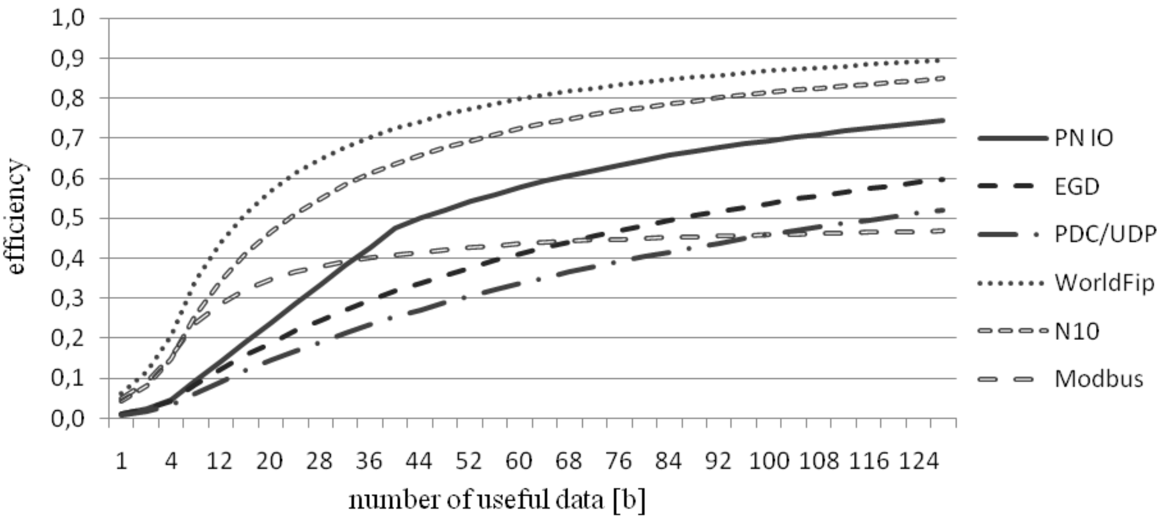

Fig. 7. Useful efficiency of cyclic transactions in other solutions
Rys. 7. Sprawności użyteczne transakcji cyklicznych w innych rozwiązaniach

It is possible to infer from the graph above that efficiency of cyclic transactions in Profinet network is quite big. It is increasing following the increase of sending useful data number. For the maximum Ethernet frame size it achieves value of 0,97. Nevertheless, the typical data size of frame in fieldbus systems is in a range from a few to several dozen bytes, but transmission of large packets of data is very rare. For a small amount of sent data the useful efficiency of Profinet IO cyclic transactions is comparable with cyclic transactions of Modbus protocol, though the efficiency firmly grows for sizes of already tens bytes.

2.3. Verification

In order to demonstrate samples of real frames and do further research, the special stand was made. The system contained Siematic S7-300 (CPU315-2 PN/DP) PLC, module IO (IM151-3PN), switch SCALANCE (X208) and PC. The selected port of the switch was configured as a port with mirroring feature of PLC port. It allows to observe the in and out traffic related to PLC. This test system was used to verify the theoretical analysis.

To catch the real frames flowing in the network we used the WinPcap drivers of version 4.0.2 and Broadcom NetLink (TM) Gigabit Ethernet. Initially we used Windows operating system platform, but after a few measurement an anomaly in period of cycle appeared. This problem disappeared on platform of Linux operating system. In our opinion the reason of the anomaly is a delay on network drivers level. However, to become convinced it is necessary to use a specialist equipment to computer network analysis.

During capture of the real frames of double transactions of 40 useful bytes (it means total 84 bytes per each frame), the efficiency of cyclic transactions was 0,006402 while the theoretical value is about 0,6452.

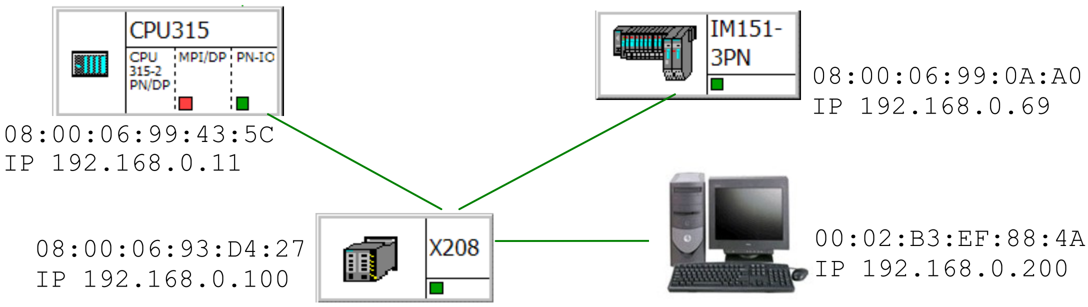

Fig. 8. Schema of testing set
Rys. 8. Schemat zestawu testowego

It confuses the presented above time analysis of cyclic transactions. The reason of the situation is the fact that cyclic frames cannot be sent in the cycle with a period value inherited from time of frame transmission (fig. 3). The period of elementary cycle is a global network parameter and its minimum value is 1 ms. Thus, during cyclic transmission of 2 frames of size of 40 useful bytes the wasted time during the one cycle phase is on level of above 99%. The useful efficiency of a network cycle can be calculated with formula 5, where T_{CW} is a period value and V is a network speed rate.

$$\eta = \frac{T_U}{T_T} = \frac{\frac{8n}{V}}{T_{CW}} \tag{5}$$

For network cycle which contains one transaction of useful data in range 1-128 bytes, the efficiency is presented in figure 9 (assumptions: $V = 100Mb/s$, $T_{CW} = const$).

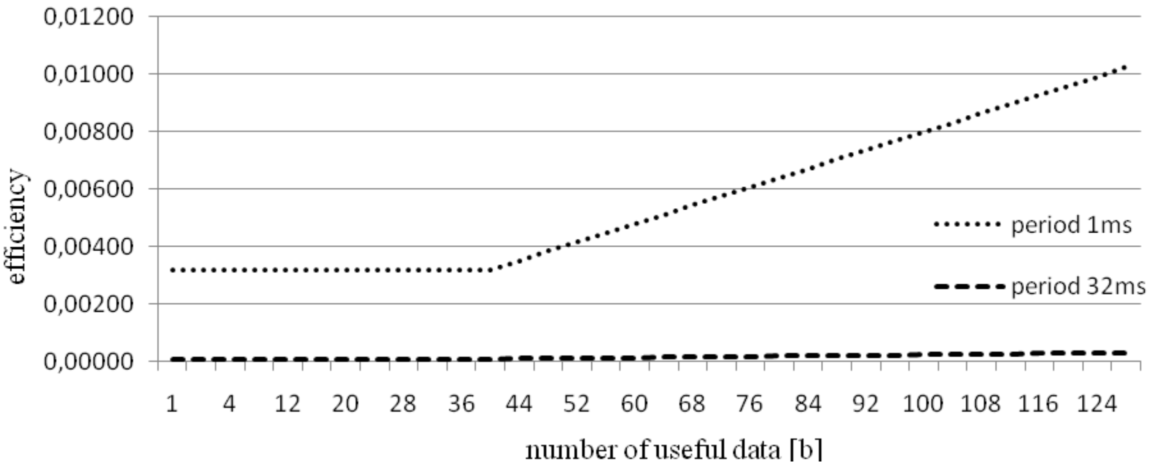

Fig. 9. Useful efficiency of network cycle
Rys. 9. Sprawność użyteczna cyklu sieci

The growth is linearly because of constant time of T_{CW}. The maximum number of frames with 40 useful bytes, during one 1ms period is 148. It gives a maximum value of useful efficiency of about 0,47.

3. Conclusions

The usage of Ethernet as industrial computer network is still growing, including a field-bus utility in control process level.

Research of existing solutions could help in selection of appropriate technology for system requirement. The Profinet is a standard suitable for various using domains and to be applied with various level of data exchange. Nevertheless, the solutions like this are currently available on the market in a very big amount. Thus, the familiarity of basic work features could be an advantage for system designers with correct choosing of network protocol.

By using the TDMA model as well as by working on low network level during execution of cyclic transactions, there is a possibility to obtain a high efficiency of these transactions. For a network based on the Ethernet technology and other model, such efficiency is difficult to achieve. However, the presented analysis of cyclic transaction does not suit the real behavior of protocol. In order to achieve reliable results, there is a necessity to analyze the whole cycle of all cyclic data.

There is a general conclusion regarding the efficiency of Industrial Ethernet. In fieldbus technologies the protocols are specialized for passing a low number of data, thus they can obtain a higher factor of useful efficiency than protocols based on the Ethernet. The reason of that comes from the fact that the Ethernet's frame overhead, related to transmission a small amount of useful bytes, is significant.

The time of establishing connections between network subscribers, before starting the RT mode transmission, is considerable. It could be a problem in case of a necessity of a quick start of a system. The sequence of exchanges executed to init interapplication connections does not impact cyclic exchanges work of the RT type, except the case when network addresses or network logical structure are changed.

Using the VLAN header has a small influence on useful efficiency of cyclic transaction, but only when data size is above 36 bytes.

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Omówienie

W niniejszym artykule poruszono tematykę wykorzystania sieci Ethernet w informatycznych systemach przemysłowych na bazie protokołu Profinet IO. W systemach tych wymaga się, aby dostęp do medium był zdeterminowany w czasie, a co za tym idzie czas realizacji transakcji sieciowych był skończony i określony w przedziale. W protokołach Profinet IO, dzięki zastosowaniu modelu TDMA oraz pracy w najniższych możliwych warstwach przy transakcjach cyklicznych trybu IO, możliwe jest osiągnięcie wysokiej sprawności tych transakcji. Sprawność taka dla sieci opartej na Ethernecie i innych modelach wymian jest trudna do osiągnięcia. Jednak stały okres cyklu sieci powoduje, że sprawność pojedynczej transakcji jest zdecydowanie niemiarodajna dla określenia sprawności użytecznej dla całego cyklu. Ponadto, narzut czasowy związany z transmisją niewielkiej liczby bajtów informacji użytecznej przy użyciu ramki Ethernet jest znaczący, przez co sieci specjalizowane mogą osiągać wyższy współczynnik sprawności użytecznej niż sieci oparte na Ethernecie.

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