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Precise Time Distribution and Time Synchronized Transmission Aspects in the Industrial Ethernet Networks

***Abstract**. In the article the main principles of transmissions in the Industrial Ethernet are described with the special attention to the real time transmission implementations. The requirements for transmissions in automation and control systems and the possibility of their realization using synthesized TCP/IP and Ethernet protocols are discussed. Additionally some practical aspects of ultra-precise clock signal distribution are presented.*

***Streszczenie.** W artykule przedstawiono główne zasady transmisji w przemysłowych sieciach Ethernet, ze szczególnym uwzględnieniem transmisji realizowanych w czasie rzeczywistym. Omówiono wymagania stawiane procesowi transmisji w systemach automatyki i układach kontrolno-sterujących oraz dokonano analizy możliwości ich realizacji przy wykorzystaniu stosu protokołów TCP/IP oraz sieci Ethernet. Ponadto przedstawiono w zarysie metody dystrybucji ultra-precyzyjnego sygnału zegarowego. (**Dystrybucja precyzyjnego sygnału zegarowego oraz synchronizacja transmisji w przemysłowych sieciach Ethernet**).*

Keywords: clock distribution system; industrial Ethernet; real time transmissions.
Słowa kluczowe: systemy dystrybucji sygnału zegarowego, Ethernet przemysłowy, transmisje czasu rzeczywistego.

Introduction

Ethernet protocol is currently the most popular local area networking method of data transmission in the home and office environment. Very high transmission speed (100Mb/s, 1Gb/s) and possibility of cheap implementation (computer devices usually have built-in Ethernet interface) are the reasons for its use not only in computer networking but also for data transmission in automatic control and sensor networks. However Ethernet protocol does not guarantee possibility of real-time transmission, which is often required for this type of network. In order to solve this problem a number of improvements to Ethernet time restricted transmission have been proposed in recent years [1][2]. Depending on the real time requirements, proposed modifications differ principles approaches. They were divided into three classes, depending on the method of transfer implementation (Fig. 1) [3]:

- Class A - uses the classical, unmodified Ethernet and TCP/IP transmission. The real time performance is limited by the unpredictable delays arising from the protocol and network devices features (“best effort” transmission).
- Class B - uses standard Ethernet protocol with unmodified hardware, but does not use TCP/IP protocols. The transmission is performed by the special, dedicated protocols which are transported directly in the Ethernet frame.
- Class C - for increasing the productivity and performance of real time transmissions, dedicated hardware is used (usually the special real-time Ethernet controllers and special switch devices). The TCP/IP protocols can be used for data transfer.

Newly defined family of transmission protocols, named Common Industrial Protocol (CIP) offers differential possibilities for variety of manufacturing automation applications, including control, safety, synchronization, motion, and configuration. As fully media independent protocols provide users with a unified communication architecture throughout the network. The most popular implementation of CIP are EtherNet/IP and Profinet [4][5].

One of the important advantages of these protocols are the possibility of real time transmission realization and time synchronization of the transmission process.

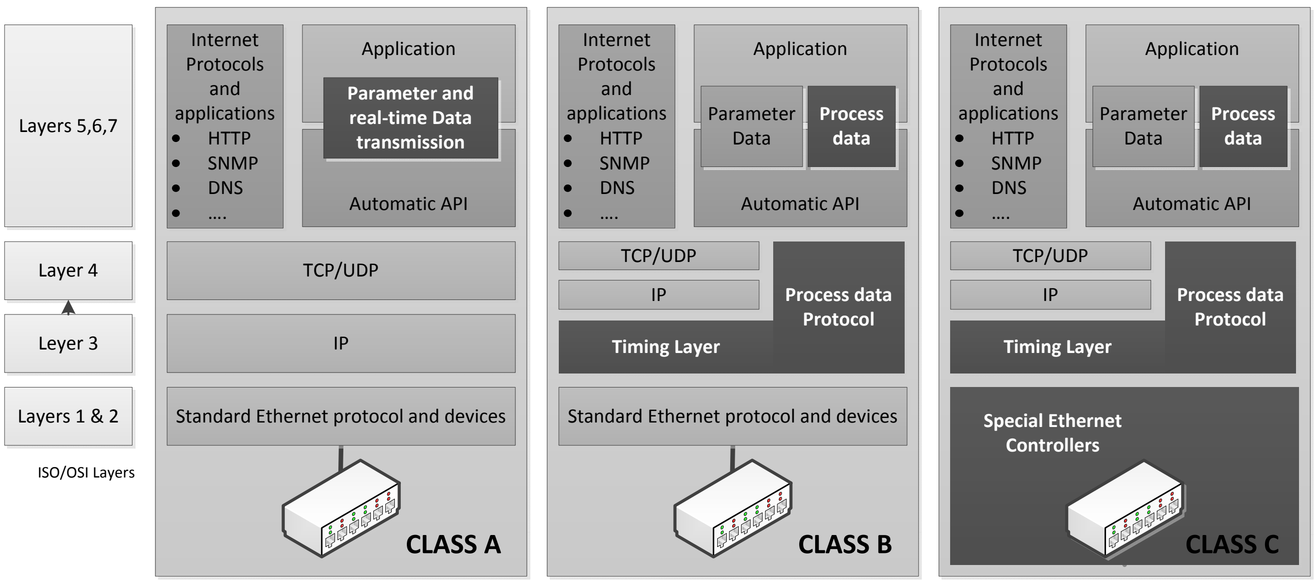

Fig. 1. Class of the automation objects

For soft real-time transmission they reserve dedicated traffic class (Real Time Control) supported by special rules.

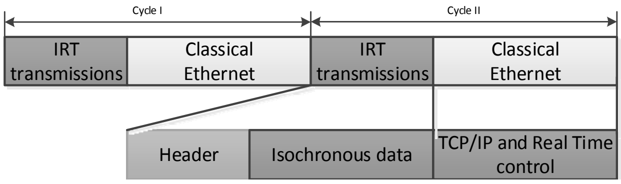

Fig. 2. CIP real time transmission implementation

For hard real-time transmissions the implementation of the time division multiplex is realized (Isochronous Real-Time) and special class of Ethernet switches must be used. The diagram of the transmission process is presented in Fig. 2.

In the standard, devices are modeled as a collection of objects. Each class of objects is a collection of related services (procedures that an object performs), attributes (characteristics of objects represented by values) and behaviors (indication of how the object responds to particular events) [4].

Access to precise time and frequency signals are necessary for proper transmission with time restriction and very important for many group of users like scientific and research communities, business or government users. Devices, which can provide such a signal (e.g. atomic clock) are very expensive and not all group of users have access to such sophisticated equipment. To ensure access to high-accuracy signals other methods as satellites systems (GPS, GALILEO, GLONAS) must be used.

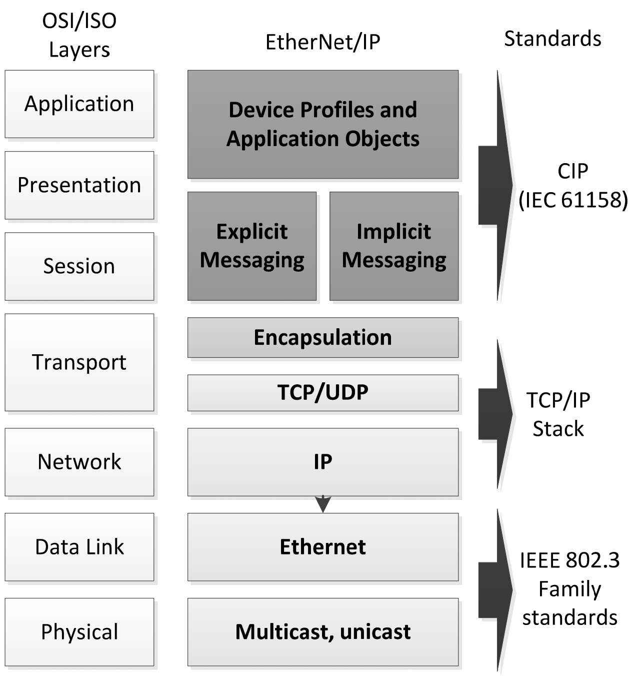

Fig. 3. Ethernet/IP architecture [4]

No less important than transfers time and frequency signals to end-users is comparisons of remote clocks. There are only a few methods (Two-Way, PPP, L2T2) with the expected results in terms of accuracy. One of them is a comparison by a fiber optical network. Its main advantages is an almost immediate receiving of measurement results.

Industrial Ethernet

At the upper layers EtherNet/IP implements the Common Industrial Protocol, which defines a library of messages and services for a variety of automation applications (this library can be used by other protocols: ControlNet, DeviceNet, CompoNet) and provides a unified communication architecture [4].

At lower layers it performs the encapsulation of messages and uses TCP/IP stack and Ethernet protocol for transmission. The protocol is a synthesis of Ethernet standard and TCP/IP technology, used for proper transport CIP communications packets. The network architecture is shown in Fig. 3.

EtherNet/IP provides a client/server mechanism for the exchange of time-critical control data. It allows the exchange of application information between a server and many clients (receivers) without the need to send the data multiple times to multiple destinations. For EtherNet/IP, this is realized by transmission with IP Multicast technology. All receivers can obtain the same application information from a single device.

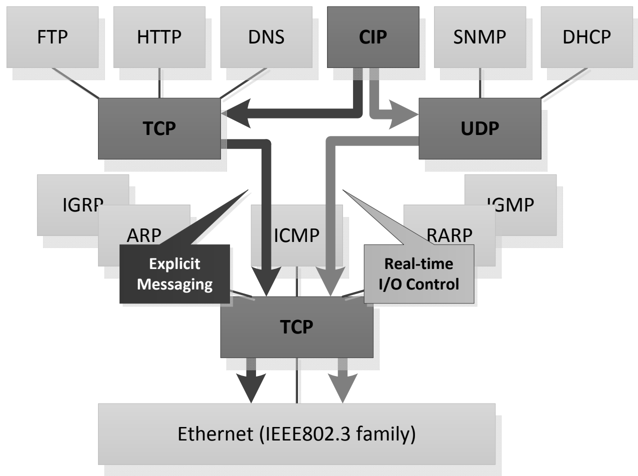

Fig. 4. Realization of the transmission process [5]

The encapsulation protocol defines a dedicated port number for transport layer protocols, that shall be supported by all EtherNet/IP devices (for TCP port 0xAF12, for UDP port 0xAF12) [6] .

EtherNet/IP supports two different types of messages (Fig. 4):

- I/O or implicit messages - typically contain no protocol information, only real-time I/O data,
- Explicit messages - carries protocol information, configuration, diagnostic and event data.

Implicit connections are instituted to move application-specific, periodic I/O data. It typically uses UDP/IP to make multicast data transfers over Ethernet with real-time rigors.

Explicit messaging connections are point-to-point transmissions, that are established to make the possibility for request-response transactions between two nodes. Explicit messaging connections uses TCP/IP protocols for messages sending.

One of the most common arguments that traditionally have been used against the use of Ethernet for control is that Ethernet is non-deterministic. EtherNet/IP uses standard IEEE 802.3 technology. It does not apply any additional, non-standard mechanisms to improve the transmission determinism. It recommends the use of commercial switch technology, with 100Mbps speed of transmission and full-duplex operation. For this reason, the protocol has limited feasibility of real-time transmission. In order to achieve good results hardware timestamping (implemented in MAC or physical layer) is required.

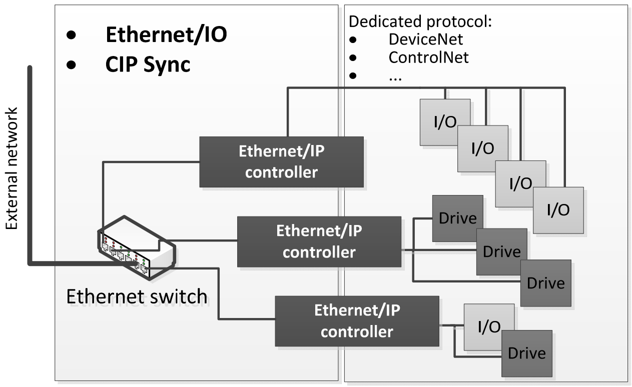

Fig. 5. Structure of network with time synchronization

The special, additional time synchronization protocols (CIP Sync) should be used (and supported by the network equipments). The structure of this type of network is shown in Fig. 5.

Time Synchronization

In distributed data-processing systems, as well as in control networks, the synchronization of precise events detection is required. Time and frequency technologies with microsecond accuracy are also implemented in management equipment of Smart Grid substations. Specifically they are used in supervising operations, such as wide area measurement systems, traveling wave fault locators and sampled value recorders. Design of accurate, secure and reliable timing and synchronization units of mission-critical processing will be able to mitigate outages with real-time monitoring for grid stress, frequency instability, voltage instability and reliability margins. Power units and their data networks are changing from simple, responsive control and reporting to proactive, real-time management. Thus, advanced synchronization and timing are more critical than earlier, enabling power systems to operate more efficiently and closer to its operational limits. For example, microsecond accuracy is required by the phasor measurement unit (PMU) for real-time network situational awareness and overall operational efficiency. Without accurate time stamps, PMU data has incorrect value [7], so the Smart Grid architecture and related standards require a new method to timing dissemination across the whole network. Many companies outside the field of power technology are also working on the evaluation and implementation of time synchronization protocols. In Motion Control application high time precision helps to synchronize drives inside a robot or, for example, actuators in a paper processing machine. In case of cooperating machines (robots), which are linked to each other through really exact clocks or installations are closely connected over timing protocols, the running processes are coordinated accurately with each other chronologically. Synchronous clocks in each working together module make it possible to create distributed structure and decouple the completion of the processes from the communication and processing it only by command-control procedures [8]. Time coordination mechanism is always requested in automation technology when precise synchronization is required.

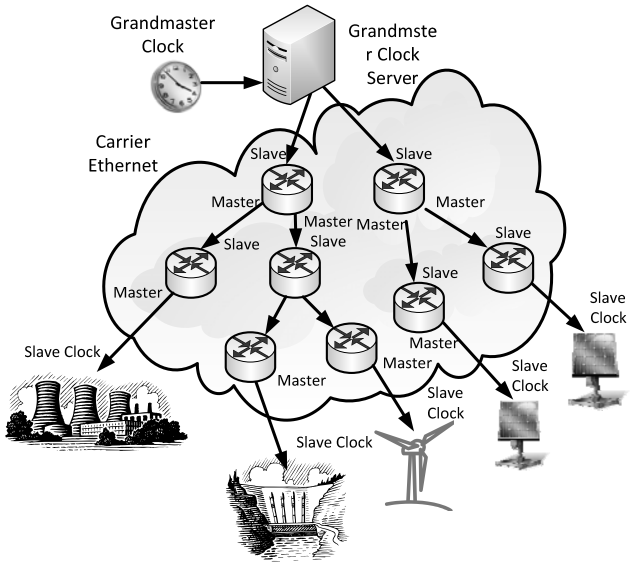

Fig. 6. Timing over Packet Protocols using Precise Time Protocol (IEEE-1588) in Smart Grid application

Determination of the event occurrence related to "common time" can be implemented indirectly, without real time clock, on the basis of action, depending on the time sequence or on the consequence steps of executed program. This type of synchronization is typical in small and closed systems.

Direct implementation of the “common time” in spread system requires a transmission of the clock signal to all cooperating nodes. In the last few years three general research areas of time and frequency dissemination have been observed: time transfer over radio systems (satellite-GPS systems), frequency and time transfer via fiber-optic links (eg.: OPTIME [9]) or time synchronization based on the classic data networks and defined protocols, such as NTP/SNTP (Network Time Protocol-RFC1305/Simple Network Time Protocol-RFC2030, PTP (Precise Time Protocol-IEEE 1588) [10][11], White Rabbit [12]. To holdover the clock in the incident of GPS or network (LAN, fiber optic backbone) transmission interruption the additional atomic clock is required, but this results in a highly cost.

Table 1. Comparison of public methods of time synchronization

	NTP / SNTP	GPS	PTP
Distribution range	Very large	Very large	Several subnets
Signal Distribution Channel	Internet	Radio Satellite Systems	LAN
Accuracy	Several ms	Better then μs	Better then μs
Management	Configurable	Does not apply	Inside the subnet
Dedicated equipment	Not required	Dedicated receiver	Depending on the required precision: yes or not

In command-control systems the communication is realized by packet protocols, mainly Ethernet-based protocol, and it is natural to use packet for time synchronization. NTP and SNTP protocols are used to send real time with a few milliseconds accuracy [11].

For applications to determine the actual time (date, hour) they are sufficient, when the application requires better events synchronization (at the level of the microseconds), it is possible to use White Rabbit (WR) methods or PTP. Developing technology based on the active propagation of compensation packages in Ethernet, which is the backbone of White Rabbit, is now in the test phase and it is still under developing by the CERN scientific community. Comparison of public methods of time synchronization shows Table.1

WR time transfer method requires the use of special network devices, which, in addition, deliver typical data transfer services, but only PTP works with standard network configuration and allows achieving microseconds accuracy (Fig. 6). This protocol exchanges messages that are sent across the network as data packets, and therefore its application is not limited only to the Ethernet. Standard Ethernet switches and routers introduce time varying delay of packets that limits the measurement accuracy of packet round-trip delay. Thus improving the clock distribution imposes modifications to the network infrastructure, associated with measurements of delay and its correction [13]. Switches use a transparent clock method that minimizes latency and delays in the network by providing a local clock for network nodes rather than letting instruments rely on the IEEE master clock [14]. Synchronization with less precision can be achieved by averaging the propagation time in nodes only by means of dedicated software. Although the PTP can be used in each packet network, the main objective of the development was UDP/IPv4 (User Datagram Protocol over Internet Protocol version 4), but it has been extended to IPv6. If two devices are networked together and use the IEEE 1588, they could all be set to same time, typically within 100 nanoseconds of each other [14].

Conclusions

Popularity of the Internet, which uses the Ethernet protocol in the local area, led to increased interest in the possibility of using this network for transmissions in the time-restricted automation and controls systems.

For less demanding systems it is possible to use these protocols directly, with some additional functionality at the application layer. For systems with larger requirements, it is necessary to use additional protocol for distribution and synchronization of transmission clocks, which in conjunction with the timestamp technique allows for the implementation of real-time transmission.

When in our live the clocks aren't synchronize, bad things happen: we are always too late or too early. If this occurs in collaborate machines the consequence is much worse, therefore the command-control networks with data transmission and time synchronization must be used. Ethernet became a carrier-grade technology in WANs, and with some main technologies for transport of timing and synchronization over packet networks: e.g.: synchronous Ethernet and precision time protocol (PTP, IEEE 1588) may be used in distributed command-control network. Selection and verification of the suitable technology needs careful analysis, included the characterization of jitter/wander performance of Ethernet interfaces in different background network traffic rate.

Acknowledgments

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REFERENCES

[1] Decotignie J.D., Ethernet-based real-time and industrial Communications, Proc. IEEE, 93(6):1102–1117, June 2005.

[2] Felser M., Real-Time Ethernet - Industry Prospective, Proc. IEEE, 93(6):1118–1129, June 2005

[3] Rostan M., Ethernet Technology Introduction, Industrial Ethernet Seminar Series, 2011

[4] ODVA, Inc. Common Industrial Protocol (CIP) (PUB122), 2006. http://www.odva.org/Portals/0/Library/Publications _Numbered/PUB00122R0_CIP_Brochure_ENGLISH.pdf

[5] ODVA, Inc. The Common Industrial Protocol (CIP) and the Family of CIP Networks (PUB122), 2006. http://www.odva.org/Portals/0/Library/Publications_Numbered/ PUB00123R0_CommonIndustrial_Protocol_and_Family_of_CIP_Netw.pdf.

[6] ODVA, Inc. EtherNet/IP Quick Start for Vendors Handbook: A Guide for EtherNet/IP Developers (PUB213R0), 2008. http://www.odva.org/Portals/0/Library/Publications_Numbered/ PUB00213R0_EtherNetIP_Developers_Guide.pdf.

[7] Liam R., Symmetricom Delivers Precise Time to the Next Generation Smart Grid, 2013. [Online]. Available: http://www.edn.com/electronics-products/electronic-product-releases/communications-design/4405806/Symmetricom-Delivers-Precise-Time-to-the-Next-Generation-Smart-Grid.

[8] Precision Time Protocol, 2013. [Online]. Available: http://www.hirschmann.com/en/Hirschmann_Produkte/Industrial_Ethernet/Technologies/Precision_Time_Protocol/index.phtml.

[9] OPTIME Consortium, 2013. [Online]. Available: www.optime.org.pl.

[10] IEEE Unapproved Draft Std P1588/D2.2, Draft Standard for a Precision Clock Synchronization Protocol for Net- worked Measurement and Control Systems. IEEE Unapproved Draft Std P1588/D2.2, March 2008.

[11] IEEE Std. 1588 - 2002 IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, p. i–144, 2002.

[12] White Rabbit, [Online]. Available: http://www.ohwr.org/projects/white-rabbit .

[13] Rowe M., Transparent clock improves network timing, 2010. [Online]. Available: www.edn.com.

[14] Han J. and Deog-Kyoon J., A Practical Implementation of IEEE 1588–2008 ransparent Clock for Distributed Measurement and Control Systems, IEEE Transactions on Instrumentation and Measurement, p. p. 433., Feb. 2010.

[15] http://www.optime.org.pl/, [Online].

[16] Dopplinger J. A., Using IEEE 1588 for synchronization of network-connected devices, 2007. [Online]. Available: http://www.embedded.com/design/embedded/4007059/Using-IEEE-1588-for-synchronization-of-network-connected-devices#.

[17] Marais A., IEEE 1588-2008 perspectives and opportunities, EDN, Oct 2010.

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