Real Time Ethernet: standardization and implementations

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***Abstract* - The International Electrotechnical Commission (IEC) failed to define one standard Real Time Ethernet (RTE) solution. The actual set of standards defines more than a dozen of technical different solutions. This paper tries to give an overview and indication of differences between these specifications.**

I. INTRODUCTION

The adoption of Ethernet technology for industrial communication between controllers, and even for communication with field devices, supports direct Internet capability, for instance, remote user interfaces via web browser, in the field area. But, it would be unacceptable if the adoption of the Ethernet technology would cause loss of features required in the field area, namely:

- Time deterministic communication.
- Time-synchronized actions between field devices like drives.
- Efficient and frequent exchange of very small data records.

An implicit but essential requirement is that the office Ethernet communication capability is fully retained so that the entire communication software involved remains usable.

This results in the following requirements:

- Support for migration of the office Ethernet to Real-Time Ethernet (RTE)
- Use of standard components: bridges, Ethernet controllers, and protocol stacks as far as possible.

To achieve the required higher quality of data transmission with limited jitter and disturbances due to TCP/IP data traffic, it may be necessary to develop further network components. In short, the Real-Time Ethernet (RTE) is a fieldbus specification using Ethernet for the lower two layers.

As a matter of fact, industrial Real-Time Ethernet devices can neither be as cheap as in the office world (limited by the scale of industrial deployment), nor can plain Ethernet be applied to control applications demanding some sort of hard real-time behavior; for details of the argument see [1]. To cope with these limitations, many research projects proposed solutions for the introduction of quality of service, modifications to packet processing in switches, or synchronization between devices.

The IEC SC65C committee, in addition to the maintenance of the international fieldbus and its profile, finished a standardization project and defined additional aspects of Real-Time Ethernet. And as in the case of the fieldbus, there are several competing solutions and their proponents represented.

This paper will give an outline of this document and the requirements specified for the Real-Time Ethernet standardization. All solutions in this standard able to handle real-time requirements will be presented with their key technical features.

II. RTE STANDARDIZATION OF THE IEC

After a short summary of the history of this standard we outline the structure and give an introduction the listed performance indicators.

A. *Short summary of the history*

International fieldbus standardization has always been a difficult endeavour. After a timely start in 1985 and a few enthusiastic years of development, the quest for the one and only comprehensive international fieldbus gradually became entangled in a web of company politics and marketing interests [2]. What followed was a protracted struggle inside CENELEC and IEC committees that finally ended up in the complete abandonment of the original idea. Instead of a single fieldbus, a collection of established systems was standardized. In Europe, CENELEC adopted a series of multi-volume standards compiled from specifications of proven fieldbus systems. On a worldwide scale, IEC defined a matrix of protocol modules, so-called “types”, together with guidelines how to combine the various modules in to actually working fieldbus specifications. With the adoption of the IEC 61158 standard [3] on the memorable date of Dec. 31st, 2000, the fieldbus ware seemed to be settled just in time for the new millennium.

After a first revision of this standard, a new edition was issued already three years later. In this second edition already several Ethernet based solution were incorporated in the set of standards. In an additional project, a complete set of Real Time Ethernet (RTE) solutions was added in IEC 61784-2 [5] and published end of 2007. This is the actual structure we have today valid for the next five years.

B. *Structure of the IEC Standards*

All industrial protocols are defined in IEC 61158 [3]. This document is structured according to the Open System Interface (OSI) reference model in seven parts. Inside the parts 2 to 6 all networks are identified by types. So there exist 22 different types of networks in six different parts.

In the IEC 61784 standard, different sets of profiles are collected. In IEC 61784-1 [4] the profile sets for continues and discrete manufacturing relative to fieldbus use in industrial control systems are defined. Inside this first profile definitions also some version based on Ethernet technology are defined. In the second standard IEC 61784-2 [5] additional profiles for ISO/IEC 8802.3 (Ethernet) [6] based communication networks in real-time applications are defined. To identify all these profile a classification with Communication Profile Families (CPF) is introduced. Every CPF is free to define a set of communication profiles. The complete set of Communication Profiles (CP) and the related types are listed in [7].

Additional profiles cover functional safe communications, secure communications or installation profiles for communication networks. These profiles are also separated according the same CPF, but are not discussed any further in this paper.

C. *Performance Indicators (PI)*

Users of a Real-Time Ethernet network have different requirements for different applications. These requirements are defined in [5] as performance indicators. A list of performance indicators defines the requirements for a class of applications. Every performance indicator has its limits or ranges and there exists interdependence between these performance indicators. Every Communication Profile (CP) has to define which performance indicators it fulfils in what conditions. The following performance indicators are defined in the communication profiles for Real-Time Ethernet (IEC 61784-2):

- delivery time
- number of RTE end-stations
- basic network topology
- number of switches between RTE end-stations
- throughput RTE
- non-RTE bandwith
- Time synchronization accuracy
- Non-time based synchronization accurancy
- Redundancy recovery time

Delivery time is the time needed to convey a Service Data Unit (SDU, message payload) from one node (source) to another node (destination). The delivery time is measured at the Application Layer interface. The maximum delivery time shall be stated for the two cases of no transmission errors, and one lost frame with recovery. The Number of RTE end-stations states the maximum number of RTE end-stations supported by a CP. The basic network topology supported by a CP is stated out of the topologies hierarchical star, ring or loop and daisy-chain or as a combination of these topologies. The Number of switches between RTE end-stations supported by a CP defines the possible network layout and is also an important indicator. The Throughput RTE is the total amount of application data by octet length on one link received per second. Non-RTE bandwidth is the percentage of bandwidth, which can be used for non-RTE communication on one link. Time synchronization accuracy shall indicate the maximum deviation between any two node clocks. Non-time-based synchronization accuracy indicates the maximum jitter of the cyclic behaviour of any two nodes, using triggering by periodic events over the network for establishing cyclic behaviour. Redundancy recovery time indicates the maximum from a single permanent failure to become fully operational again. In this case of a permanent failure, the delivery time of a message is replaced by the redundancy recovery time.

In the international standard IEC 61784-2 [5] all communication profiles have to list also at least one typical set of performance indicators as defined in the standard. This allows the end user an easier selection of an appropriate network for his application.

III. PRACTICAL REALIZATIONS

Not all CPF available in IEC 61784-2 list all the required values in consistent sets of performance indicators. So we list here only the solutions, which provide this information. The values are summarised in tables 1 to 3. To provide a better overview, the performance indicators are grouped in sets for data capacity (table 1), topology (table 2) and timing (table 3).

A. *EtherNet/IP (Profile 2/2 & 2/2.1)*

EtherNet/IP , defined by Rockwell and supported by the Open DeviceNet Vendor Association (ODVA) and ControlNet International, makes use of the Common Interface Protocol (CIP) which is common to the networks EtherNet/IP, ControlNet, and DeviceNet.

The EtherNet/IP communication technology, standardized in IEC 61784-1 as Profile 2/2 (using Type 2 specifications in IEC 61158), already provides ISO/IEC 8802-3 based real time communication.

In the CIPsync [8] extensions the clocks of the devices are synchronized with the IEEE 1588 [9] protocol (accuracy of 0.5 µs).

CIP defines objects to transport control-oriented data associated with I/O devices and other information which are related to the system being controlled, such as configuration parameters and diagnostics. The CIP communication objects and application objects are grouped in classes. Profiles for different types of applications define the objects to be implemented and their relations.

D. *PROFINET IO (Profile 3/4, 3/5, 3/6)*

PROFINET is defined by several manufacturers (including Siemens) and supported by PROFIBUS International [10]. A second step after the PROFINET CBA (profile 3/3 in IEC 61784-1) definition was the definition of an application model for PROFINET IO based on the well proven PROFIBUS DP (type 3 of IEC 61158, profile 3/1). The devices are IO Controllers to control IO Devices with cyclic, buffered data communication. An IO Supervisor is used to manage the IO Devices and IO Controllers in a system.

The exchange of data between the devices may be in different classes of communication service like Isochronous

TABLE 1

EXAMPLES OF CONSISTENT SETS FOR DATA CAPACITY

CPF	Trade name	Delivery time	Troughput RTE	Non-RTE bandwith
CP 2/2	EtherNet/IP	0,13 to 20,4 ms	3,44 Mbyte/s	0-100 %
CP 2/2.1	EtherNet/IP with Time Synchronization	0,13 to 0,19 ms	3,44 Mbyte/s	0-100 %
CP 3/4	PROFINET IO Class A cycle of 120 ms	128 ms	3,32 Mbyte/s	23,5 %
CP 3/6	PROFINET IO Class C IRT with cycle of 1 ms	1 ms	3,32 Mbyte/s	23,5 %
CP 4/3	P-NET on IP	0,564 to 6,3 ms	5 – 64 Kbyte/s	75 %
CP 10/1	VNET/IP different domain	50 to 200 ms	10 Mbyte/s	< 50 %
CP 10/1	VNET/IP same domain	20 to 60 ms	10 Mbyte/s	< 50 %
CP 11/1	TCnet-star only RT	2ms / 20ms / 200ms	7,3 Mbyte/s	0 %
CP 11/2	TCnet-loop mixed RT and NRT	2ms / 20ms	4,8 Mbyte/s	< 20 %
CP 12/1	EtherCAT Simple I/O small system cycle of 60 µs	0,15 ms	10,75 Mbyte/s	50,6 %
CP 12/2	EtherCAT Mailbox / Synchronization cycle 200 µs	< 0,519 ms	10,5 Mbyte/s	55,9 %
CP 13/1	Ethernet Powerlink small system cycle of 150 µs	0,4 ms	1,9 Mbyte/s	19,6 %
CP 13/1	Ethernet Powerlink medium system cycle of 500 µs	1,1 ms	2,5 Mbyte/s	11,5 %
CP 13/1	Ethernet Powerlink large system with cycle of 2700 µs	5,5 ms	4 Mbyte/s	4,4 %
CP 14/1	EPA master to bridges	5 ms	1,5 Mbyte/s	85 %
CP 14/2	EPA field devices to bridges	0,1 ms	1,538 Mbyte/s	85 %
CP 14/3	EPA master to field devices	0,1 ms / 0,2 ms	3,84 Mbyte/s	0 %
CP 16/3	SERCOS III small cycle of 31,25 µs	0,0398 ms	11,52 Mbyte/s	0 %
CP 16/3	SERCOS III medium cycle of 500 µs with NRT	0,513 ms	9,248 Mbyte/s	25 %

Real-Time (IRT), Real-Time (RT), or non-Real-Time (NRT). NRT traffic is standard TCP/UDP/IP and may also be PROFIBUS CBA traffic. In a system with high isochronous cycle requirements, only special PROFINET switching devices are allowed. The Ethernet communication is split in to send clock cycles each with different time phases. In the first time phase called Isochronous Phase all Isochronous Real-Time (IRT) frames are transmitted. These frames are passed through the switching device without any interpretation of the address information in the Ethernet frame. The switches are set according to a predefined and configured timetable: on every offset time, the planned frame is send from one port to the other one without interpretation of the address. In the next time phase called Real-Time Phase, the switching devices change to address based communication and behave as standard Ethernet switches. In this addresses based phases, Real-Time (RT) frames are transmitted followed by non-Real-Time (NRT) Ethernet frames. All PROFINET switching devices are synchronised by means of a modified IEEE1588v2 mechanism with “transparent clock” stamping [11], to have their cycles and IRT timetables synchronized with one microsecond jitter.

E. P-NET (Profile 4/3)

The P-NET on IP specification has been proposed by the Danish national committee and is designed for use in an IP-environment as profile 4/3. P-NET on IP enables use of P-NET (type 4 in IEC 61158) real-time communication wrapped into UDP/IP packages.

P-NET packages can be routed through IP-networks in exactly the same way as they can be routed through non-IP-networks. Routing can be through any type of P-NET network and in any order.

F. Vnet/IP (Profile 10/1)

Vnet/IP has been developed by Yokogawa and is included in the IEC document as profile 10/1. The Vnet/IP protocol uses standard TCP/IP protocols for the integration of HTTP or other internet protocols over the network and special real-time extension protocols called RTP (Real-time & Reliable Datagram Protocol) .

The Vnet/IP is in fact not a real-time Ethernet protocol. It just uses the UDP/IP protocol suite to transport the RTP application protocol. No special measures are taken to get a deterministic or even real-time behaviour. A Vnet/IP network consists of one or more domains connected to each other by routers. The IP unicast and multicast addresses are used as addresses of the Data-Link protocol and queued

G. TCnet (Profile 11/1)

TCnet (Time-critical Control Network) is a proposal from Toshiba. Like Ethernet Powerlink, the TCnet interface goes between the Physical and the Data Link layer; the standard MAC access CSMA/CD of Ethernet is modified.

In this proposal, there exists a High-speed-Transmission period composed of a real-time (in TCnet called “time-critical”) cyclic data service and an asynchronous (in TCnet called “sporadic”) message data service. The time-critical cyclic data service is a connection oriented buffer transfer on pre-established point-to-multipoint connections on the same local link separated by routers, whereas the sporadic message

TABLE 2
EXAMPLES OF CONSISTENT SETS FOR TOPOLOGY

CPF	Trade name	Basic network topology	Number of end-stations	Number of switches between end-stations
CP 2/2	EtherNet/IP	Star	2 to 1024	1 to 1024
CP 2/2.1	EtherNet/IP with Time Synchronization	Star	2 to 90	1 to 4
CP 3/4	PROFINET IO Class A	Star, Line, Ring	60	10
CP 3/6	PROFINET IO Class C (IRT)	Line	60	20
CP 4/3	P-NET on IP	Star, Line, Ring	30	4
CP 10/1	VNET/IP different domain	Tree	4096	39
CP 10/1	VNET/IP same domain	Tree	64	7
CP 11/1	TCnet-star only RT	Star	24	0 (3 Hubs)
CP 11/2	TCnet-loop mixed RT and NRT	Loop (Ring)	13	0 (5 Hubs)
CP 12/1	EtherCAT Simple I/O	Ring	180	n.a.
CP 12/2	EtherCAT Mailbox & Synchronization	Ring	650	n.a.
CP 13/1	Ethernet Powerlink small system	Star	4	0 (1 Repeater)
CP 13/1	Ethernet Powerlink medium system	Star & Linear	20	0 (7 Repeaters)
CP 13/1	Ethernet Powerlink large system	Star	150	0 (3 Repeaters)
CP 14/1	EPA master to bridges	Star	32	4
CP 14/2	EPA field devices to bridges	Star	64	4
CP 14/3	EPA master to field devices	Star / Line	6	0 / 1
CP 16/3	SERCOS III short cycle	Ring	≤ 9	n.a.
CP 16/3	SERCOS III medium cycle	Ring	≤ 139	n.a.

services are unacknowledged messages on an extended link allowed to go through routers.

At the start of the High-speed-Transmission-period a special SYN message is broadcasted to all RTE-TCnet nodes. After receiving the SYN-Frame, the node with the number 1 starts sending its data frames as planned during the system configuration. After completion of the transmission of its data frames, it broadcasts a frame called Completed Message. Node n upon receiving the CMP (n-1) Completed Message can send out its own data frames. Each node can hold the transmission right for a preset time and must transfer the transmission right to the next node within this time. The node holding the transmission right can send cyclic data and sporadic messages. The cyclic data transmission is divided into High, Medium and Low-Speed cyclic data transmission. Each node sends at least the High-speed cyclic data when it receives the transmission right. The other, lower priority, data is send only depending on the circumstances. Thus, the cycle time for the High-speed cycle is the cycle of the SYN frame, and the cycle time of the Medium-speed or Low-speed cyclic data is a multiple of the SYN frame cycle.

H. EtherCAT (Profile 12/1 & 12/2)

EtherCAT defined by Beckhoff and supported by the EtherCat Technology Group (ETG) uses the Ethernet frames and sends them in a special ring topology [12].

Medium access control employs the Master/Slave principle, where the master node (typically the control system) sends the Ethernet frames to the slave nodes, which extract data from and insert data into these frames.

The EtherCAT slave node arrangement represents an open ring bus. The controller is connected to one of the open ends, either directly to the device, or via Ethernet switches utilizing the full duplex capabilities of Ethernet, the resulting topology is a physical line. All frames are relayed from the first node to the next ones. The last node returns the telegram back to the first node, via the nodes in between.

The nodes have an addressable memory that can be accessed with read or write services, either each node consecutively or several nodes simultaneously. Several EtherCAT telegrams can be embedded within an Ethernet frame, each telegram addressing a data section. The EtherCAT telegrams are either transported directly in the data area of the Ethernet frame or within the data section of an UDP datagram transported via IP. The first variant is limited to one Ethernet subnet, since associated frames are not relayed by routers. For machine control applications, this usually does not represent a constraint. Multiple EtherCAT segments can be connected to one or several switches. The Ethernet MAC address of the first node within the segment is used for addressing the EtherCAT segment. The second variant via UDP/IP generates a slightly larger overhead (IP and UDP header), but for less time-critical applications, such as building automation, it allows using IP routing. On the master side, any standard UDP/IP implementation can be used on the EtherCAT devices.

TABLE 3
EXAMPLES OF CONSISTENT SETS FOR TIMING

CPF	Trade name	Time synchronization accuracy	Non-time-based synchronization accuracy	Redundancy recovery time
CP 2/2	EtherNet/IP	-	-	-
CP 2/2.1	EtherNet/IP with Time Synchronization	≤ 1 µs	-	-
CP 3/4	PROFINET IO Class A	≤ 1 ms (local time) ≤ 1 µs (applications)	-	< 200ms
CP 3/6	PROFINET IO Class C (IRT)	≤ 1 ms (local time) ≤ 1 µs (applications)	-	< 3ms
CP 4/3	P-NET on IP	5,7 ms	-	1s
CP 10/1	VNET/IP different domain	< 5 ms	-	< 600ms
CP 10/1	VNET/IP same domain	< 1 ms	-	< 200ms
CP 11/1	TCnet-star only RT	-	< 10 µs	0 s
CP 11/2	TCnet-loop mixed RT and NRT	-	< 10 µs	0 s
CP 12/1	EtherCAT Simple I/O	-	10 µs	60 µs
CP 12/2	EtherCAT Mailbox & Synchronization	< 200 ms	10 µs	200 µs
CP 13/1	Ethernet Powerlink small system	< 1 s	< 200 ns	150 µs
CP 13/1	Ethernet Powerlink medium system	< 1 s	< 440 ns	< 500 µs
CP 13/1	Ethernet Powerlink large system	< 1 s	< 280 ns	< 2,7 ms
CP 14/1	EPA master to bridges	< 10 µs	-	< 300 ms
CP 14/2	EPA field devices to bridges	< 1 µs	-	< 300 ms
CP 14/3	EPA master to field devices	< 1 µs	-	0 (Ring)
CP 16/3	SERCOS III short cycle	-	< 1 µs	0 s
CP 16/3	SERCOS III medium cycle with NRT	-	< 1 µs	0 s

I. *Ethernet Powerlink (Profile 13/1)*

Ethernet Powerlink (EPL) was defined by Bernecker + Rainer (B&R), and is now supported by the Ethernet Powerlink Standardisation Group (EPSG).

It is based on the principle of using a master-slave scheduling system on a shared Ethernet segment called Slot Communication Network Management (SCNM). The master, called Managing Node (MN) ensures real-time access to the cyclic data and lets non real-time TCP/IP frame pass through only in time-slots reserved for this purpose. All other nodes are called Controlled Nodes (CN) and are only allowed to send on request by the MN. The MN sends a multicast Start-of-Cycle (SoC) frame to signal the beginning of a cycle. The send and receive time of this frame is the basis for the common timing of all the nodes. It is important to keep the start time of an EPL cycle as exact (jitter-free) as possible. The following time periods exist within one cycle: Start period, isochronous period, asynchronous period and an additional idle period. The length of individual periods can vary within the preset period of an EPL cycle. In the Isochronous period of the cycle, a Poll-Request (PReq) frame is sent unicast to every configured and active node. The accessed node responds with a multicast Poll-Response (Pres) frame. In the Asynchronous period of the cycle, access to the EPL network segment may be granted to one CN or to the MN for the transfer of a single asynchronous message only. The preferred protocol for asynchronous messages is UDP/IP. The Start-of-Asynchronous (SoA) frame is the first frame in the asynchronous period and is a signal for all CNs that all isochronous data has been exchanged during the isochronous period. Thus transmission of isochronous and asynchronous data will never interfere and precise communication timing is guaranteed.

J. *EPA (Profile 14/1 & 14/2)*

The EPA protocol (Ethernet for Plant Automation) profile 14 is a Chinese proposal.

It is a distributed approach to realize deterministic communication based on a time slicing mechanism inside the MAC layer. The time to complete a communication procedure is called communication macrocycle (named as T) and illustrates that each communication macrocycle T is divided into two phases, periodic message transferring phase (Tp) and non-periodic message transferring phase (Tn). The last part of each device's periodic message contains a non-periodic message announcement which indicates whether the device also has a non-periodic message to transmit or not. Once the periodic message transferring phase is completed, the non-periodic message transferring phase begins. All devices which announced (during the periodic message transfer phase) that they have a non-periodic message to send are allowed to transmit their non-periodic messages in this phase.

K. *SERCOS (Profile 16/3)*

The former IEC 61491 [13] standard SERCOS is well known for its CNC control optical ring interface. This standard is now split in an application part and a communication part, and the communication part is integrated in to the IEC 61158/ IEC 61784 set. The SERCOS standard is extended to feature an Ethernet based solution with the name SERCOS III [14] as profile 16/3.

In a SERCOS system, there is always a master station as a controlling device and one or up to 254 slave devices as axis controllers each with two Ethernet ports. The basic network topology can be either a daisy-chain (line structure) or a ring (ring structure). General use switches are not permitted between any two participants. Only the free port of the last slave in a line structure may be connected to a switch if required by the configuration, e.g., for communication with devices via TCP/IP or UDP/UDP.

SERCOS III communication consists of two different logical communication channels: the RT channel (real-time channel) and the IP channel (non real-time channel).

The communication cycle is initiated by the master and consists of up to four Master Data Telegrams (MDT) and up to four Device Telegrams (AT) in the RT channel and the IP channel. MDTs are transmitted by the master and received by each slave. They contain synchronization information and a data record for each slave containing control information, service channel data and command values sent from the master to the slaves. The ATs are transmitted by the master as an empty frame with predefined fields but without information. Each slave inserts its data into allocated to it data fields in the ATs. Within their data fields in the telegram, the slaves transmit status information, service channel data and actual values to the master and to other slaves.

Defined values a for a communication cycle are 31,25 µs, 62,5 µs, 125 µs, 250 µs and integer multiples of 250 µs up to 65 000 µs. The time-slots for the RT channel, the IP channel, and the transmission time of the AT are transmitted during initialization and are therefore known to each slave. In every device, a special software, or for a higher performance a FPGA, will be needed which separates the RT channel from the IP channel.

IV. Closing remark

The performance indicators give a first possibility for a user to evaluate the different technical solutions for Real Time Ethernet (RTE) defined in the standard.

The values collected in the different tables in this overview paper are taken from the IEC 61784-2 as provided by the different consortia. There is no proving or verification by calculation or measurement of these values involved yet. It is not sure, that all consortia providing PI values for the different profile families have the same interpretation of the meaning of these performance indicators.

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