Real-Time Ethernet—Industry Prospective

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Invited Paper

After more than ten years of experience with applications of fieldbus in automation technology, the industry has started to develop and adopt Real-Time Ethernet (RTE) solutions. There already exists now more than ten proposed solutions. International Electrotechnical Commission standards are trying to give a guideline and selection criteria based on recognized indicators for the user.

Keywords*—*Field buses, industrial networks, Real-Time Ethernet (RTE), standardization.

I. Introduction

International fieldbus standardization has always been a difficult endeavor. 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 [1]. What followed was a protracted struggle inside the European Committee for Electrotechnical Standardization (CENELEC)[1] and the International Electrotechnical Commission (IEC)[2] 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 multivolume standards compiled from specifications of proven fieldbus systems. On a worldwide scale, IEC defined a matrix of protocol modules, so-called types [2], together with guidelines on how to combine the various modules in to actually working fieldbus specifications [3]. With the adoption of the IEC 61 158 standard [2] on the memorable date of 31 December 2000, the fieldbus war seemed to be settled just in time for the new millennium.

At the same time, in the office world, we see the penetration of the networks based on Ethernet and TCP/IP. The costs of the network infrastructure in the office world are steadily going down, and it is becoming possible to connect almost anything with everything, anywhere, with the help of the Internet technology. But in the field of automation technology, dedicated fieldbuses are used. The only barrier to access devices in the field of the automation world, from the Internet over a network connection, are the fieldbuses. Therefore, the question is: why is it not possible to use Ethernet also in automation technology?

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) (see below for a definition);
- 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 RTE is a fieldbus specification using Ethernet for the lower two layers.

As a matter of fact, industrial RTE 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 [7]. To cope with these limitations, many research projects proposed solutions for the introduction of quality of service, modifications to

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[1]See http://www.cenelec.org
[2]See http://www.iec.ch

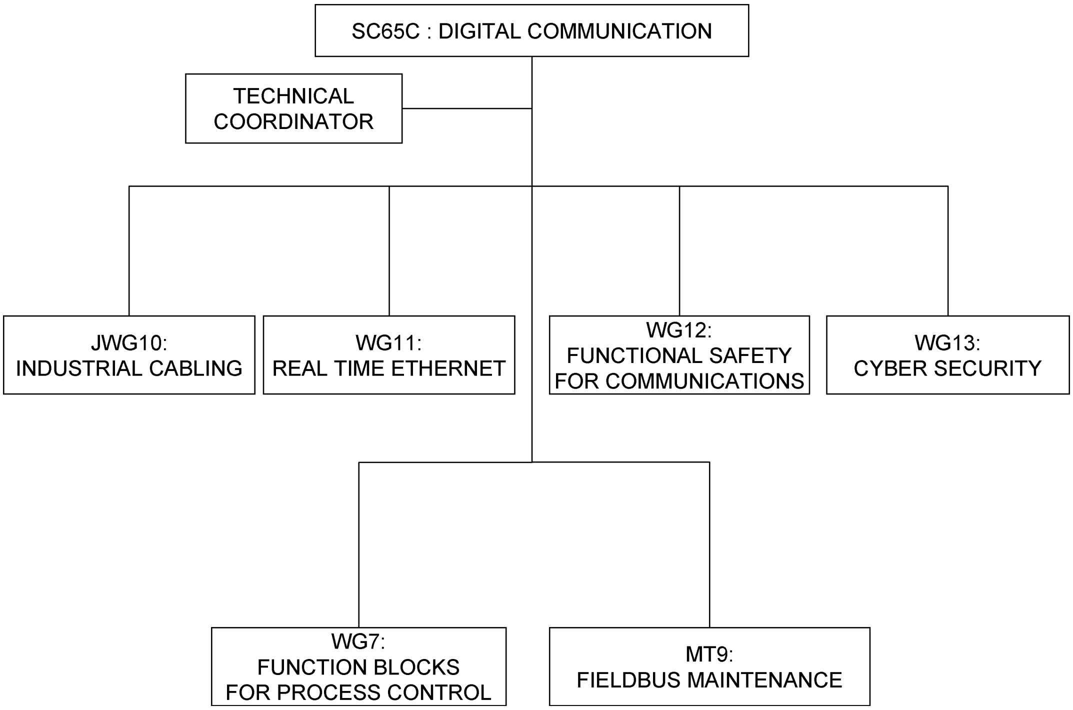

Fig. 1. Organizational structure of IEC SC65C.

packet processing in switches, or synchronization between devices.

The IEC is organized in Technical Committees (TC) and Subcommittees (SC); TC65 deals with industrial-process measurement and control and SC65C with digital communication and has the scope to prepare standards on digital data communications subsystems for industrial-process measurement and control as well as on instrumentation systems used for research, development, and testing purposes. The IEC/SC65C committee, in addition to the maintenance of the international fieldbus and its profile, has started a new standardization project with new work items including the aim to define additional aspects of RTE. And as in the case of the fieldbus, there are several competing solutions and their proponents represented in the working groups (WGs).

This paper will give an outline of this new working item and the requirements specified for the RTE standardization. All solutions proposed for this international standard will be presented with their key technical features.

II. IEC Standardization

Previously, the technical standardization work in the fieldbus area was done in WG 1 of the IEC/SC65C committee. However, the new standardization projects contain several aspects that can, to a large extent, be treated more efficiently in parallel. In order to distribute the workload evenly and still maintain close cooperation, a new structure of the SC65C was suggested and adopted. Cooperation is required so that all new working groups will build on the fieldbus standards of the IEC 61 158 [2] series and their unifying set of profiles, IEC 61 784-1 [3]. Apart from a larger number of WGs, the new structure (Fig. 1) essentially consists in the establishment of the new position of a Technical Coordinator, who is subordinate to the Chairman and Secretary and serving a primarily advisory role for WGs 10 through 13 and Maintenance Team 9.

The WG 7 Function Block group develops specification, architecture, as well as description and communication mapping onto a fieldbus of the function blocks for process control. The MT9 Fieldbus Maintenance group develops a revised edition of and amendments to IEC 61 158. Both groups have been in existence for some time. WG10 to WG13 are new WGs with activities focused on industrial communication including Ethernet, fieldbus, and Internet technologies, and will tackle new domains of standardization for the automation technology.

The task of the new SC65C/JWG10 joint WG (JWG) between the International Organization for Standardization (ISO) and the IEC is to define the wiring and cabling of Ethernet in the industrial environment. This was traditionally the realm of ISO/IEC Joint Technical Committee (JTC) 1/SC25 of ISO, which deals with information technology and Subcommittee (SC) 25, which deals with interconnection of information technology equipment which defined standards for generic wiring in office and similar environments. ISO/IEC JTC1/SC25 has already requested that this new work be coordinated with them to have clear boundaries of responsibility. It was therefore agreed that the development of cabling to support fieldbus installation beyond (outside) the machinery network interface in the ISO/IEC JTC1/SC25 model (derived from CLC EN 50173) will be entirely the responsibility of ISO/IEC JTC1/SC25. Nevertheless, there is a certain amount of overlap, and it is clear that the work to address new environments cannot proceed properly unless the work is truly done jointly. The minimum level of cooperation are mutual comments;[3] however, the existence of a JWG is more promising.

The new SC65C WG11 WG has the task to refine a classification scheme for RTE requirements, to define profiles and related network components based on international standards ISO/IEC 8802-3 [6] and IEC 61 784-1 [3], and to cover the aspects of referencing these and other existing standards. Part 1 of IEC 61 784 already meets the industrial automation market objective of identifying the RTE communication networks coexisting with the ISO/IEC 8802 series,[4] providing more predictable and reliable real-time data transfer and means for support of precise synchronization of automation equipment according to IEEE 1588 [8].

There is a common understanding that WG11 will not define new standards, but refer to existing ones. It has been agreed that the different existing RTE solutions will be published first as Public Available Specifications[5] (PASs) and referenced inside the new IEC 61 784-2 [5] list of profiles for RTE. In the next maintenance cycle[6] of the IEC 61 158 fieldbus document, these RTE protocols will be integrated into the fieldbus document, to have all solutions listed in one document.

A new proposal [4] defined the topics of communication for functional safety and security aspects of communication. Originally combined in one new work proposal, it was split into two separate activities. 65C/WG12 will address communications for functional safety, and 65C/WG13 will address cybersecurity.

III. RTE Requirements

In the existing communication profile (CP) families for fieldbuses (in IEC 61 784-1 [3]), some solutions for Ethernet in industrial applications are already defined. The new RTE CP families (CPFs) (in IEC 61 784-2 [5]) are therefore considered as extensions of the fieldbus profiles.

SC65C/WG11 has already published a first working draft document [5] for IEC 61 784-2. This document is called "Additional profiles for ISO/IEC 8802-3 based communication networks in real-time applications." The document defines different CPs which are grouped into CPFs. The CP does not specify the protocol, but it refers to external communication specifications for communication services and protocols. In the first phase, these external documents are mainly the PASs provided by the different technology groups and the existing IEC 61 158 document. In a second phase, all of these PASs will also be integrated in the fieldbus standard IEC 61 158 [2].

Table 1
Possible RTE Topologies

Basic network topologie	CP
Hierarchical star	CP m/1
Ring (loop)	CP m/2
Daisy-chain	CP m/3

Note: a real topology could be any combination of the three basic topologies.

To use the advantages of the Internet technology and protocols like the Hyper-Text Transfer Protocol (HTTP) for using Web servers for device engineering or the File Transfer Protocol (FTP) for up- or downloading files to field devices, it is important that the new RTE solutions maintain the compatibility with Ethernet and the TCP/IP protocols. They must permit coexistence of Ethernet and RTE on the same cabling infrastructure. They may, in some cases, amend those widely used standards for RTE behaviors like IEEE 1588 [7].

Users of an RTE 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 CP has to define which performance indicators it fulfils in what conditions.

A. *The Different Performance Indicators*

The following performance indicators are proposed in the new list of CPs for RTE (IEC 61 784-2):

— delivery time;
— number of end nodes;
— basic network topology;
— number of switches between end nodes;
— throughput RTE;
— non-RTE bandwith;
— time synchronization accuracy;
— 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 end nodes states the maximum number of RTE end devices supported by a CP. The basic network topology supported by a CP is stated out of the topologies listed in Table 1, or as a combination of these topologies. The number of switches between end nodes supported by a CP defines the possible network layout and is also an important indicator. The throughput RTE is the total amount of application process object (APO) 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. Time synchronization

[3]The cooperation of ISO and IEC can have five different modes: informative, contributive, subcontracting, collaborative, and integrated relation. A JWG is an integrated relation and gives the highest level of cooperation.

[4]ISO copies under the number 8802 the corresponding standards from IEEE 802 named "Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks."

[5]A PAS may be an intermediate specification, published prior to the development of a full International Standard, or a publication published in collaboration with an external organization of IEC. It is a document not fulfilling the requirements for a standard. A PAS shall remain valid for an initial maximum period of 3 years. The validity may be extended for a single 3-year period, following which it shall be revised to become another type of normative document, or shall be withdrawn.

[6]To maintain the quality of a standard on every document, a maintenance time is defined. After this time, the specification may be reconfirmed, withdrawn, or amended. The maintenance cycle of IEC 61 158 is 2007, so this is the first date where an amendment for RTE is possible.

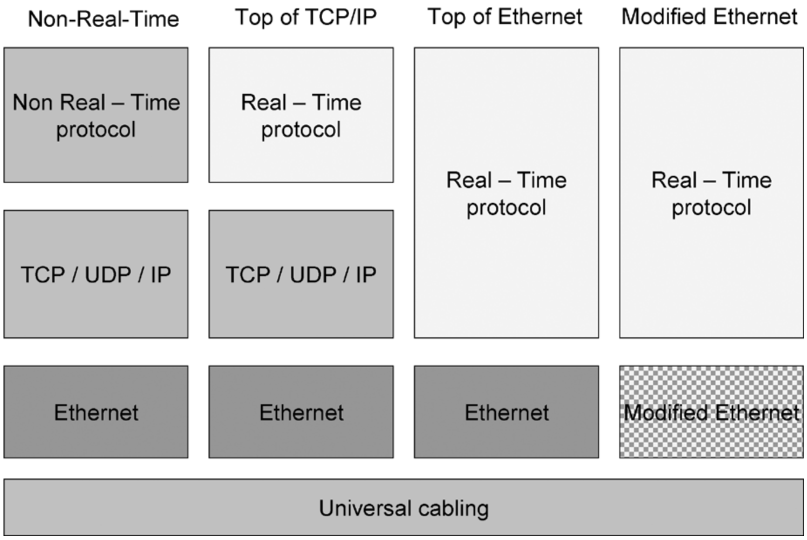

Fig. 2. Possible structures for RTE.

accuracy shall indicate the maximum deviation between any two node clocks. Redundancy recovery time shall indicate the maximum recovery time in case of a single permanent failure. Delivery time with permanent failures but not with transient failures is replaced in that case by the recovery time.

B. User Application Requirements

Users of an RTE network have different requirements for different applications. It is the intention of the document with CPs for RTE [5] to define different performance classes for different classes of applications. These classes are at the time of writing of this paper still under discussion.

One possible classification structure could be based on the delivery time.

— A low-speed class for human control with delivery times around 100 ms. This timing requirement is typical for the case of humans involved in the system observation (ten pictures per second can already be seen as a low-quality movie), for engineering, and for process monitoring. Most processes in process automation and building control fall into this class. This requirement may be fulfilled with a standard system with TCP/IP communication channel without many problems.

— In a second class, for process control, the requirement is a delivery time below 10 ms. This is the requirement for most tooling machine control system like programmable logic controllers (PLCs) or PC-based control. To reach this timing behavior, special effort has to be taken in the RTE equipment: powerful and expensive computer resources are needed to handle the TCP/IP protocol in real time, or the protocol stack must be simplified and reduced to get these reaction times on simple, cheap resources.

— The third and most demanding class is imposed by the requirements of motion control: to synchronize several axes over a network, a cycle time less than 1 ms is needed with a jitter of not more than 1 μs. This can only be reached with Ethernet network with a minimal bit rate of 100 MB/s, if both protocol medium access and hardware structure are modified.

IV. Practical Realizations

Standard Ethernet is not able to reach the requirements of the RTE. There exist different propositions to modify the Ethernet technology by the research community [7]. The market has adopted also additional technical solutions. All the solutions proposed for the standardization are presented here in a short description.

Communication interfaces are structured in different layers. In Fig. 2, a simplified structure of a communication protocol is described. Common to all Ethernet networks is the universal cabling infrastructure. Non-real-time applications make use of the Ethernet protocols as defined in ISO 8802-3 and the TCP/UDP/IP protocol suite. They use typical Internet protocols like HTTP or FTP for the non-real-time applications. To build an RTE solution, there are in principle three different approaches, as shown in Fig. 2. The first is to keep the TCP/UDP/IP protocols unchanged and concentrate all real-time modification in the top layer; here, this solution is called "on top of TCP/IP." In the second approach, the TCP/UDP/IP protocols are bypassed and the Ethernet functionality is accessed directly ("on top of Ethernet"). In the third approach, the Ethernet mechanism and infrastructure itself is modified to make it more real-time performed (Modified Ethernet).

A. Realization on Top of TCP/IP Protocols

Several RTE solutions use the TCP/UDP/IP protocol stack without any modification. With this protocol stack, it is possible to communicate over network boundaries transparently, also trough routers. Therefore, it is possible to build automation networks reaching almost every point of the world in the same way as the Internet technology. However, the handling of this communication protocol stack requires reasonable resources in processing power and memory and introduces nondeterministic delays in the communication.

1) Modbus/TCP: Modbus/TCP, defined by Schneider Electric and supported by Modbus-IDA, uses the well-known MODBUS—the industrial *de facto* standard since 1979—over a TCP/IP network [9], [10], using port 502. This is probably one of the most widely used Ethernet solution in industrial applications today and fulfils the requirements of the lowest class of applications which we call human control.

a) Description of Protocol and Application Model: MODBUS is a request/reply protocol (send a request frame and get a reply frame back) and offers services specified by function codes to read or write data objects which could be discrete inputs, coils,[7] input registers, or holding registers. In fact, this protocol is very simple and the actual definition must be extended with service definitions for the integration in international standards.

In additional to the historical MODBUS protocol, new real-time extensions have been defined. These real-time extensions use the Real-Time Publisher Subscriber (RTPS) protocol [10]. The RTPS protocol provides two main communication models: the publish–subscribe protocol, which transfers data from publishers to subscribers; and the Composite State Transfer (CST) protocol, which transfers state information from a writer to a reader.

In the CST protocol, a CST writer publishes state information as a variable (VAR) which is subscribed by CST readers. The user data transmitted in the RTPS protocol from the publisher to one or several subscribers is called an issue. The attributes of the publication service object describe the contents (the topic), the type of the issue, and the quality (e.g., time interval) of the stream of issues that is published on the network. A subscriber defines a minimum separation time between two consecutive issues. It defines the maximum rate at which the subscription is prepared to receive issues. The persistence indicates how long the issue is valid. The strength is the precedence of the issue sent by the publication. Strength and persistence allow the receiver to arbitrate if issues are received from several matching publications. Publication relation may be best effort (as fast as possible but not faster as the minimum separation) or strict. In the case of the strict publisher–subscriber relation, the timing is ensured with a heartbeat message sent from the publisher to the subscriber (exact timing is middleware dependent) and a replied acknowledge message. The RTPS protocol is designed to run over an unreliable transport such as UDP/IP and a message is the contents (payload) of exactly one UDP/IP datagram.

Contrary to the standard MODBUS protocol, the RTPS protocol is not used very much in practical industrial applications today, and therefore it is not known exactly what sort of performance this protocol really has to offer. Simulations in [11] showed that the required performance of the "process application class," which was introduced earlier, may be reached with this system.

[7]In MODBUS, for the representation of binary values, the term coil is used. This originates from the ladder logic where the coil of a relay is used to store binary information.

2) EtherNet/IP: EtherNet/IP,[8] defined by Rockwell and supported by the Open DeviceNet Vendor Association (ODVA)[9] and ControlNet International,[10] makes use of the Common Interface Protocol (CIP) which is common to the networks EtherNet/IP, ControlNet, and DeviceNet [12].

b) Description of Protocol: The EtherNet/IP communication technology, standardized in IEC 61 784-1 as CP 2/2 (using Type 2 specifications in IEC 61 158), already provides ISO/IEC 8802-3 based real-time communication. In full-duplex switched Ethernet, there is no possibility to get delays due to collisions. But in the switching device, the different Ethernet frames may be delayed, if an output port is already busy with the transmission of another Ethernet frame. This may lead to nondeterministic delays which are not suitable for real-time applications. To reduce these delays, a priority mechanism is defined in IEEE 802.3 [6] which allows the sender of a frame to assign a priority to an Ethernet frame. A virtual bridged LAN (VLAN) tag is added into the Ethernet frame containing a VLAN-ID and a priority level 0 to 7 of the message. The EtherNet/IP real-time messages get the highest priority and are transmitted by the switches before other non-real-time frames, which results in better accuracy for the real-time constraints.

c) Topology and Performance: In the CIPsync [13] extensions, the clocks of the devices are synchronized with the IEEE 1588 [8] protocol (accuracy of 0.5 μs). The only problem is that delays may be introduced in the software protocol stack. Based on this time synchronization, the actions in the distributed system are executed based on the planned timing, e.g., a device sets its outputs to a defined value not based on the moment a message is received, but on the scheduled time. With this principle, the timing of the application is independent of the delay introduced in the communication network and relies only on the accuracy of the time synchronization. When these guidelines are strictly applied, EtherNet/IP is a real-time solution usable even for the best class of applications, but it is still not deterministic as a communication network.

d) Application Protocol Model: CIP defines objects—an object in CIP provides an abstract representation of a particular component within a product—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.

3) P-NET: The P-NET on IP specification [14] has been proposed by the Danish national committee and is designed for use in an IP environment. P-NET on IP enables use of P-NET (type 4 in IEC 61 158) real-time communication wrapped into UDP/IP packages.

a) Description of Protocol: P-NET packages can be routed through IP networks in exactly the same way as they

[8]EtherNet/IP is a trade name of ControlNet International, Ltd. and Open DeviceNet Vendor Association, Inc. IP stands here for Industrial Protocol.

[9]See http://www.odva.org

[10]See http://www.controlnet.org

can be routed through non-IP networks. Routing can be through any type of P-NET network and in any order.

A P-NET frame has always two P-NET-route elements constructed as a table of destination and source addresses. In the simple case of a fieldbus solution, these two addresses are the node addresses of the fieldbus network. To allow routing over IP-based networks, these P-NET-route tables are now extended to include also IP addresses in the P-NET-route element. For a fieldbus based P-NET node, these IP addresses are just another format of addresses. This means that any P-NET client can access servers on an IP network without knowing anything about IP addresses.

b) Application Protocol Model: In fact, this P-NET on IP specification just specifies how the existing P-NET is tunnelled over UDP/IP networks without any special measures to ensure real-time behavior on the Ethernet network.

4) Vnet/IP: Vnet/IP[11] has been developed by Yokogawa. 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 the Real-Time and Reliable Datagram Protocol (RTP) [15].

a) Description of Protocol: The Vnet/IP is in fact not an RTE 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 behavior. 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 communication relations are used.

b) Topology and Performance: The minimum cycle-time of scheduling of real-time traffic is 10 ms [15, p. 137] which fulfils the application class of process control. This specification does not cover the limiting of other traffic using the available bandwidth, e.g., HTTP or TCP transfer on the same network, which could slow down the real-time behavior.

c) Application Protocol Model: On the application layer, different objects like variables, events, regions, time and network, and the corresponding services are defined. As an example, the variable object may be accessed over client–server relations with read or write services or publisher–subscriber relations with push or pull mode of operation. In the pull model, the publisher distributes the variable data periodically by multicasting as requested by a remote subscriber. In the push model, the request is generated locally by the publisher itself.

B. Realization on Top of Ethernet

These RTE realizations do not alter the Ethernet communication hardware in any way, but are realized by specifying a special protocol type (Ethertype) in the Ethernet frame. The standard protocol type for IP is Ethertype $= 0 \times 0800$. These RTE protocols do use beside the standard IP protocol stack their own protocol stack identified with their own protocol type. Table 2 lists the different values assigned to this Ethertype for these protocols.

[11]Vnet/IP is a trade name of Yokogawa Electric Corporation.

Table 2
RTE Profiles Defined in IEC 61784

IEC 61784 Profile	Brand names	Ethertypes
CPF-2	ControlNet (Ethernet/IP)	(0x0800 IP)
CPF-3	PROFIBUS / PROFINET	0x8892
CPF-4	P-Net	(0x0800 IP)
CPF-10	Vnet/IP	(0x0800 IP)
CPF-11	TCnet	0x888B
CPF-12	EtherCAT	0x88A4
CPF-13	Ethernet POWERLINK (EPL)	0x88AB
CPF-14	EPA	0x88BC
CPF-15	MODBUS – RTPS	(0x0800 IP)
CPF-16	SERCOS	0x88CD

1) Ethernet Powerlink (EPL): EPL was defined by Bernecker + Rainer (B&R), and is now supported by the EPL Standardization Group (EPSG).[12]

a) Description of Protocol: It is based on the principle of using a master–slave scheduling system on a shared Ethernet segment called Slot Communication Network Management (SCNM) [16]. The master, called the managing node (MN), ensures real-time access to the cyclic data and lets non-real-time TCP/IP frames pass through only in time slots reserved for this purpose. All other nodes are called controlled nodes (CNs) 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 periods exist within one cycle: Start period, Isochronous[13] period, Asynchronous[14] 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 (compare also Fig. 3). Thus, transmission of isochronous and asynchronous data will never interfere, and precise communication timing is guaranteed.

b) Topology and Performance: An EPL network is a "protected Ethernet" defined with one controller acting as the MN and several field devices implemented as CNs. In order to protect the SCNM access mechanism of the MN, non-EPL nodes are not permitted within the "protected Ethernet" itself, as they would corrupt the SCNM access mechanism.

Messages exchanged between MNs of different "protected Ethernet" segments are synchronized based on distributed

[12]See http://www.ethernet-powerlink.org

[13]From the Latin for *iso* (the same) and *chronous* (time based), thus, communication at the same time interval.

[14]Asynchronous is without any synchronization to a reference.

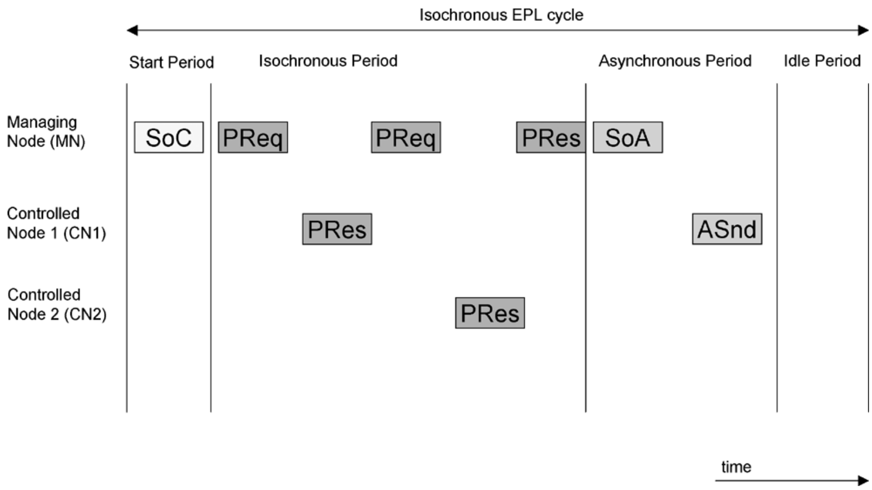

Fig. 3. EPL timing.

clock. With the IEEE 1588 protocol in every MN, a clock is synchronized and the messages between the different machine networks are sent based on the synchronized time in the MNs. The MN includes the routing functionality, including the IP address translation from the machine network to the outside world. With this synchronization mechanism, RTE communication is also possible among different machine networks.

c) Application Protocol Model: The application layer of the EPL is taken from the CANopen standards provided by the CAN in Automation (CiA)[15] organization [17]. CANopen standards define widely deployed CPs, device profiles, and application profiles. Integration of EPL with CANopen combines profiles, high-performance data exchange, and open, transparent communication with TCP/UDP/IP protocols. These CANopen profiles define process data objects (PDOs) to control the physical process and service data objects (SDOs) which are used to define the behavior of the device as parameters or configuration data. The PDOs are transmitted with the isochronous EPL communication, and the SDOs are transmitted with the UDP/IP protocol. Based on this CP, a variety of CANopen device profiles can be used in an EPL environment without changes.

2) Time-Critical Control Network (TCnet): The TCnet is a proposal from Toshiba [18]. Like EPL, the TCnet interface goes between the Physical and the Data Link layer; the standard Media Access Control (MAC) access Carrier Sense Multiple Access With Collision Detection (CSMA/CD) of Ethernet is modified.

a) Description of Protocol: 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[16] on preestablished point-to-multipoint connections on the same local link separated by routers, whereas the sporadic message 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 one 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 (see CMP1 in Fig. 4). 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 sent 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.

b) Topology and Performance: TCnet is able to handle redundant transmission mediums. The RTE-TCnet stack manages the selection of two redundant inputs of received frames and two outputs to two redundant transmission mediums. In the case of collision on one of the mediums, the transmission is continued on the other. The RTE-TCnet accepts the first incoming frame without transmission error from one of the redundant transmission media.

c) Application Protocol Model: The RTE-TCnet application layer service defines the common memory system. The common memory is a virtual memory shared over the RTE-TCnet network by the participating application

[15]See http://www.can-cia.org

[16]In a buffered transfer, a new message overwrites the old value of the previous message in the receiving buffer. This is in contrast to the (standard) queued transfer, where the messages are kept in the receiver in the same order they are sent. Buffered transfer is more suited for control applications than queued: the control application is interested in the actual buffered value and not in the sequence of values.

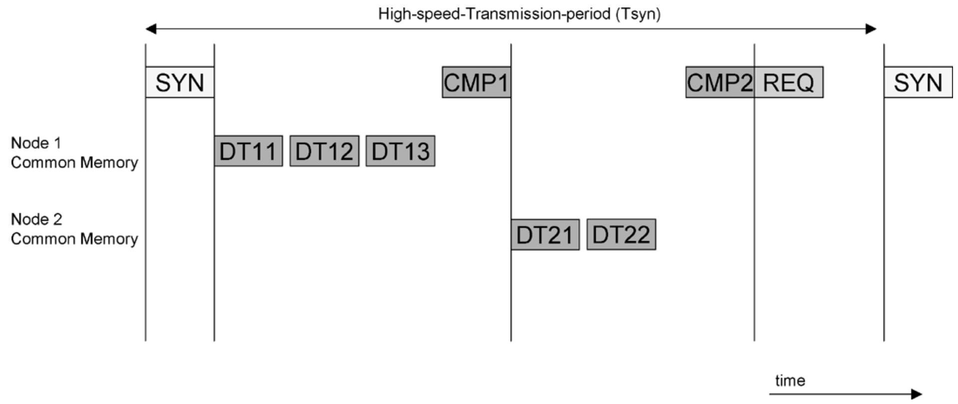

Fig. 4. TCnet timing.

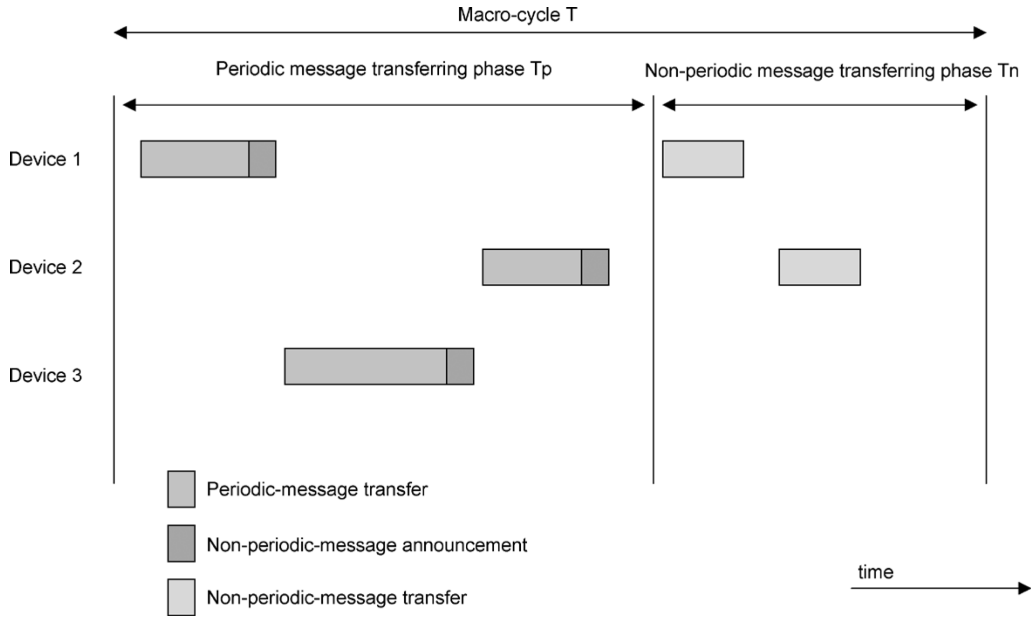

Fig. 5. EPA timing.

processes running on each node. The common memory is divided into numbers of blocks with different sizes. One node is the publisher of a block of data and broadcasts this data block to all the others by means of cyclic data service. Each node receives the data block as a subscriber and updates its local copy of the common memory. By this means, each controller can quickly access each other's data by accessing its local copy of the common memory.

3) Ethernet for Plant Automation (EPA): The EPA[17] protocol is a Chinese proposal [19].

a) Description of Protocol: 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 and marked as T. Fig. 5 illustrates that each communication macrocycle (T) is divided into two phases, the periodic message transferring phase (Tp) and the nonperiodic message transferring phase (Tn) The last part of each device's periodic message contains a nonperiodic message announcement which indicates whether the device also has a nonperiodic message to transmit or not. Once the periodic message transferring phase is completed, the nonperiodic message transferring phase begins. All devices which announced (during the periodic message transfer phase) that they have a nonperiodic message to send are allowed to transmit their nonperiodic messages in this phase.

b) Application Protocol Model: In EPA systems, there are two kinds of application processes, the EPA function block[18] application processes and non-real-time application processes, which may run in parallel in one EPA system. Non-real-time application processes are those based on regular Ethernet and TCP/IP. The interoperation between two function blocks is modeled as connecting the input/output parameters between two function blocks using EPA application services.

4) PROFINET CBA: PROFINET is defined by several manufacturers (including Siemens) and supported by

[17]EPA is a trade name of Zhejiang Supcon Co. Ltd.

[18]A function block is an algorithm with its own associated static memory. Function blocks can be instantiated with another copy of the function block's memory. Function blocks are only accessed via input and output variables.

PROFIBUS International[19] [26]. The first version was based on component-based automation (CBA) and is included in IEC 61 784-1 (type 10 in IEC 61 158).

a) Description of Protocol: The mechanical, electrical, and functional elements of an automation device are grouped together in to components. Components have inputs and outputs. The values of the input and output variables of the components are transmitted over the standard TCP/IP connection using the remote procedure call (RPC)[20] and the Distributed Component Object Model (DCOM) [21] protocol from the office world.

b) Topology and Performance: With this RPC and DCOM protocol, it is possible to reach cycle times for what we call the human control application class. If cycle times of less than 100 ms are required, the Real-Time (RT) protocol is used. The RT protocol is based on a special Ethertype (see Table 2) and frame prioritization (see Section IV-A2). In this case, the TCP/IP stack is bypassed, and cycle times of less than 10 ms become possible.

c) Application Protocol Model: With the PROFINET CBA, the end user defines his automation components with the traditional programming and configuration tool for the PLC he is used to. These components are represented by one controller in a machine, a fieldbus network, or any device on the fieldbus itself. For the planning of the installation, logical connections between the different components are defined. These connections specify the data type and the cycle time of the transmission. The supported RT or non-RT protocols by the components define the possible cycle time which can be selected in the planning.

C. Realization With Modified Ethernet

Typical cabling topology of Ethernet is the star topology: all devices are connected to a central switching device. With the introduction of the fieldbuses over ten years ago in the automation applications, this star topology was replaced by bus or ring topologies to reduce the cabling cost. Likewise, the RTE solutions should allow for bus or ring topologies with reduced cabling effort. To permit this daisy-chained bus topology with switched Ethernet, a switch is needed in every connected device.

Most solutions providing hard real-time services are based on modifications in the hardware of the device or the network infrastructure (switch or bridge). To allow cabling according to the bus or ring topology and to avoid the star topology, the switching functionality is integrated inside the field device. The modifications are mandatory for all devices inside the real-time segment, but allow non-RTE traffic to be transmitted without modifications.

1) SERCOS: Currently its own standard IEC 61 491 [20] is the SEriell Real time COmmunication System Interface (SERCOS),[22] well known for its Computer(ized) Numerical(ly) Control(led) (CNC) control optical ring interface. In the following years, this standard will be split into an application part and a communication part [21], and the communication part will be integrated into the IEC 61 158/IEC 61 784 set. The SERCOS standard will be extended to feature an Ethernet-based solution. It is currently under development and is titled SERCOS III [22], [23].

a) Description of Protocol: 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 real-time channel (RT channel) and the non-real-time channel (IP 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 (ATs)[23]) in the RT channel and the IP channel. MDTs are transmitted by the master and received by each slave (see Fig. 6). 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 data fields allocated to it 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.

The number and the lengths of the RT data telegrams (MDT and AT) are fixed according to a configuration that is also determined during the initialization.

IP telegrams are standard, non-real-time IP telegrams that can be used for any purpose and can even be omitted. The IP channel length has a fixed duration and determines the maximum number of IP telegrams that can be sent during this duration.

b) Topology and Performance: This sequence of transmitting synchronization, RT data telegrams, and IP telegrams is repeated every communication cycle. Defined values for a communication cycle are 31.25, 62.5, 125, 250, and integer multiples of 250 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 field-programmable gate array (FPGA) (a gate array is a prefabricated circuit with transistors and standard logic gates) will be needed which separates the RT channel from the IP channel.

[19]See http://www.profibus.org

[20]An RPC is a protocol that allows a computer program running on one host to cause code to be executed on another host without the programmer needing to explicitly code for this (see http://wikipedia.org).

[21]DCOM is a Microsoft proprietary technology for software components distributed across several networked computers (see http://wikipedia.org).

[22]See also http://www.sercos.org

[23]Abbreviated from "device (acknowledge) telegram" as AT for historical reasons.

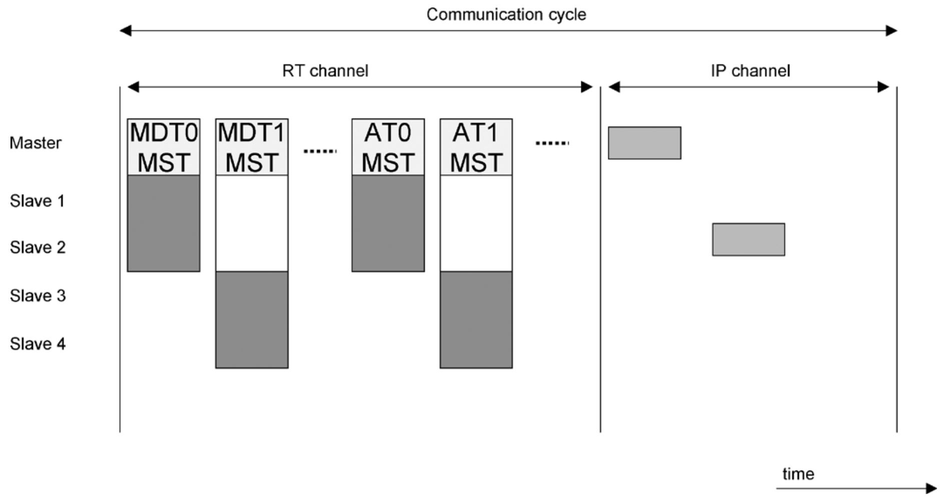

Fig. 6. SERCOS timing.

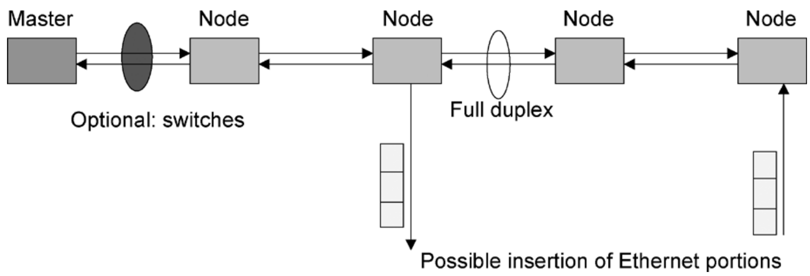

Fig. 7. EtherCAT topology.

c) Application Protocol Model: The application model of SERCOS is based on the drive model consist of a controller and one or several drives (e.g., motors, servos) with a cyclic data exchange. This exchange includes status and actual values transmitted from the drive to the controller and commands and set points from the controller to the drive. The functionality of the drive device is determined by setting different parameters in the model.

2) EtherCAT: EtherCAT,[24] defined by Beckhoff and supported by the EtherCat Technology Group (ETG),[25] uses the Ethernet frames and sends them in a special ring topology [24], [25].

a) Description of Protocol: 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.

From an Ethernet point of view, an EtherCAT segment is a single Ethernet device, which receives and sends standard ISO/IEC 8802-3 Ethernet frames. However, this Ethernet device is not limited to a single Ethernet controller with a downstream microprocessor, but may consist of a large number of EtherCAT slave devices. These devices process the incoming frames directly and extract the relevant user data, or insert data and transfer the frame to the next EtherCAT slave device. The last EtherCAT slave device within the segment sends the fully processed frame back, so that it is returned by the first slave device to the master as the response frame.

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 (see Fig. 7). 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.

In order to achieve maximum performance, the Ethernet frames should be processed "on the fly." This means that the node processes and relays the message to the next node in the line as the message is being received, rather than the other (slower) option of waiting until the message is fully received. If the "on the fly" method of processing is implemented, the slave node recognizes relevant commands and executes them accordingly while the frames are passed on to the next node. To realize such a node, a special application-specific IC (ASIC) is needed for medium access which integrates a two-port switch into the actual device.

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 as a set of memory variables (e.g., inputs or outputs). 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

[24]EtherCAT is a registered trade name of Beckhoff, Verl.

[25]See also http://www.ethercat.org

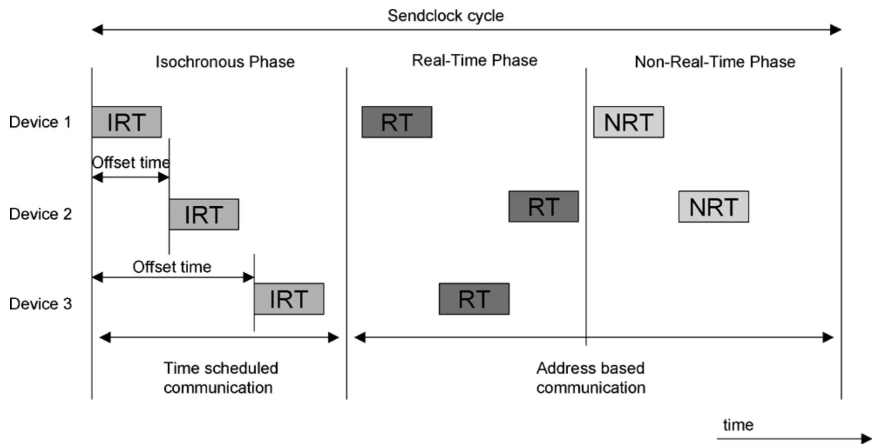

Fig. 8. PROFINET timing.

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.

For messages, a mailbox mechanism with read and write services is used; for process data output and input, buffered data services are defined.

b) Topology and Performance: The performance of the EtherCAT system (when configured to run "on the fly") is very good: it may reach cycle times of 30 μs if no standard (non-RTE) traffic is added. The maximum transmission unit (MTU) of Ethernet with 1514 B corresponding to approximately 125 μs at 100 MBd in the non-RTE phase would enlarge the EtherCAT cycle to approximately 200–250 μs. But in EtherCAT, Ethernet telegrams are divided into pieces and reassembled at the destination node, before being relayed as complete Ethernet telegrams to the device connected to the node (see Fig. 7). This procedure does not restrict the achievable cycle time, since the size of the fragments can be optimized according to the available bandwidth (EtherCAT instead of IP fragmentation). This method permits any EtherCAT device to participate in the normal Ethernet traffic and still have a cycle time for RTE with less than 100 μs.

c) Application Protocol Model: Similar to EPL, EtherCAT uses the CANopen application layer. The PDOs are mapped to the input and output buffer transfer, which is the same as what is used for EPL. The SDOs, however, are mapped to the mailbox messaging mechanism, rather than the IP protocol which EPL uses.

3) PROFINET IO: PROFINET is defined by several manufacturers (including Siemens) and supported by PROFIBUS International[26] [26]. A second step after the PROFINET CBA definition was the definition of an application model for PROFINET IO [27] based on the well-proven PROFIBUS DP (type 3 of IEC 61 158). 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.

a) Description of Protocol: The exchange of data between the devices may be in different classes of communication service like Isochronous RT (IRT), RT, or Non-RT (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 into send clock cycles each with different time phases as presented in Fig. 8. In the first time phase, called the isochronous phase, all 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 (see Fig. 8), the planned frame is sent from one port to the other one without interpretation of the address. In the next time phase, called the real-time phase, the switching devices change to address-based communication and behave as standard Ethernet switches. In this address-based phase, RT frames are transmitted, followed by NRT Ethernet frames (see also Fig. 8). All PROFINET switching devices are synchronized by means of a modified IEEE 1588 mechanism with "on the fly" stamping [28], to have their cycles and IRT timetables synchronized with 1-ms jitter.

b) Topology and Performance: PROFINET CBA and IO do not need any special hardware for RT communication. To ensure good performance, PROFINET IO needs a 100-Mb/s switched full duplex Ethernet network. For IRT, a special PROFINET-Ethernet switch is needed. It is recommended to integrate this special PROFINET-Ethernet switch in every device to allow all possible Ethernet network topologies as listed in Table 1.

c) Application Protocol Model: The PROFINET specification includes a concept allowing one to integrate existing fieldbuses with proxy devices. A proxy device represents a

[26]See http://www.profibus.org

field device or a fieldbus with several field devices, on the PROFINET network. The user of the PROFINET does not see any difference if the device is connected to Ethernet or to the fieldbus. This proxy technology is very important to allow for a migration of the existing fieldbus installations to new Ethernet solutions with PROFINET. Initially, proxies are defined for INTERBUS (type 8 in IEC 61 158) and PROFIBUS (type 3 in IEC61158).

V. Conclusion

The automation technology user would like to see just one standard solution for industrial Ethernet. At the moment, it looks as if there will be one standard document, IEC 61 784-2, which specifies at least ten different and most of them incompatible technical solutions for RTE (see Table 2). Some of the proposed protocols are just defined, and no products exist at the moment. With others, there are already products and applications available. There is in fact no technical reason to have so many different realizations for RTE. Reducing the number of solutions for the convenience and benefit of end users is a focus of ongoing discussions.

At the time of writing this paper, the definitions of different classes of applications and possible CPs are not finished. As presented in this paper, in principle, one could live with a set of about three different solutions for all possible applications. Is it up to the end user and the market to decide which one of the proposed solutions fulfils the requirements of the automation applications and will end up in real applications?

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