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Real-Time Ethernet for Automation Applications

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21.1 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 [2]. What followed was a protracted struggle inside European Committee for Electrotechnical Standardization (CENELEC, see www.cenelec.org) and International Electrotechnical Commission (IEC, see www.iec.ch) 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, the so-called types [3], together with guidelines how to combine the various modules into actually working fieldbus specifications [4]. With the adoption of the IEC 61158 standard [3] on the memorable date of December 31, 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, is the fieldbuses. Therefore, the question is why is it not possible to use Ethernet also in the automation technology?

The adoption of Ethernet technology for industrial communication between controllers, and even for communication with field devices, supports direct Internet capability in the field area, for instance, remote user interfaces via Web browser. 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 such as 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 such as 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 that uses 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 [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 RTE. And as in the case of the fieldbus, there are several competing solutions and their proponents represented.

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

21.2 Structure of the IEC Standardization

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 according to Table 21.1. In parts 2–6 all networks are identified by types. So there exist 16 different types of networks in six different parts.

In the IEC 61784 standard, different sets of profiles are collected as listed in Table 21.2. In IEC 61784-1 [4] the profile sets for continuous and discrete manufacturing relative to fieldbus use in industrial control systems are defined. Inside this first profile some version based on Ethernet technology are also defined. In the second standard IEC 61784-2 [5], additional profiles for ISO/IEC 8802.3 (Ethernet) based communication networks in real-time applications are defined. To identify all these profiles a classification with communication profile families (CPF) according to Table 21.3

* 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.

TABLE 21.1 Structure of IEC 61158

IEC 61158-1	Introduction
IEC 61158-2-x	PhL: Physical Layer
IEC 61158-3-x	DLL: Data Link Layer Service
IEC 61158-4-x	DLL: Data Link Layer Protocols
IEC 61158-5-x	AL: Application Layer Services
IEC 61158-6-x	AL: Application Layers Protocol
IEC 61158-7	Network Management

Note: x indicates the related CPF.

TABLE 21.2 Standards Related with Profiles

IEC 61784-1	Profile sets for continuous and discrete manufacturing relative to fieldbus use in industrial control systems
IEC 61784-2	Additional profiles for ISO/IEC 8802 3 based communication networks in real-time applications
IEC 61784-3-x	Profiles for functional safe communications in industrial networks
IEC 61784-4-x	Profiles for secure communications in industrial networks
IEC 61784-5-x	Installation profiles for communication networks in industrial control systems

Note: x indicates the related CPF

TABLE 21.3 List of CPF

CPF1	FOUNDATION® Fieldbus
CPF2	ControlNet™
CPF3	PROFIBUS
CPF4	P-NET®
CPF5	WorldFIP®
CPF6	INTERBUS®
CPF7	SwiftNet
CPF8	CC-Link
CPF9	HART
CPF10	VNET/IP
CPF11	TCnet
CPF12	EtherCAT
CPF13	EPL
CPF14	EPA
CPF15	Modbus
CPF16	SERCOS

is introduced. Every CPF is free to define a set of communication profiles (CPs). The complete set of CP and the related types are listed in Table 21.4.

Additional profiles listed in Table 21.2 cover functional safe communications, secure communications, and installation profiles for communication networks. These profiles are also separated according the same CPF, but are not discussed any further in this chapter.

21.3 Real-Time Requirements

Users of a 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 fulfills in what conditions.

21.3.1 User-Application Requirements

Users of a RTE network have different requirements for different applications. One possible classification structure could be based on the delivery time:

- A low-speed class, i.e., the first 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 (10 pictures/s can already be seen as a low-quality movie), for engineering,

TABLE 21.4 Relation between CPF, CP, and Type of Protocol

	IEC 61784		IEC 61158 Services and Protocols			
Family	Part 1	Part 2	Phy	DLL	AL	Brand Names
Family 1						**Foundation Fieldbus (FF)**
	Profile 1/1		Type 1	Type 1	Type 9	FF-H1
	Profile 1/2		8802-3	TCP/UDP/IP	Type 5	FF-HSE
	Profile 1/3		Type 1	Type 1	Type 9	FF-H2
Family 2						**CIP**
	Profile 2/1		Type 2	Type 2	Type 2	ControlNet
	Profile 2/2	Profile 2/2	8802-3	TCP/UDP/IP	Type 2	EtherNet/IP
		Profile 2/2.1	8802-3	TCP/UDP/IP	Type 2	EtherNet/IP with time synchronization
	Profile 3/3		Type 2	Type 2	Type 2	DeviceNet
Family 3						**PROFIBUS and PROFINET**
	Profile 3/1		Type 3	Type 3	Type 3	PROFIBUS DP
	Profile 3/2		Type 1	Type 3	Type 3	PROFIBUS PA
	Profile 3/3		8802-3	TCP/IP	Type 10	PROFINET CBA
		Profile 3/4	8802-3	Type 10	Type 10	PROFINET IO Class A
		Profile 3/5	8802-3	Type 10	Type 10	PROFINET IO Class B
		Profile 3/6	8802-3	Type 10	Type 10	PROFINET IO Class C
Family 4						**P-NET**
	Profile 4/1		Type 4	Type 4	Type 4	P-NET RS-485
	Profile 4/2		Type 4	Type 4	Type 4	P-NET RS-232
		Profile 4/3				P-NET on IP
Family 5						**WorldFIP**
	Profile 5/1		Type 1	Type 7	Type 7	WorldFIP (MPS,MCS)
	Profile 5/2		Type 1	Type 7	Type 7	WorldFIP (MPS,MCS,SubMMS)
	Profile 5/3		Type 1	Type 7	Type 7	WorldFIP (MPS)
Family 6						**INTERBUS**
	Profile 6/1		Type 8	Type 8	Type 8	INTERBUS
	Profile 6/2		Type 8	Type 8	Type 8	INTERBUS TCP/IP
	Profile 6/3		Type 8	Type 8	Type 8	INTERBUS Subset
		Profile 3/4			Type 8/10	Link 3/4 to 6/1
		Profile 3/5			Type 8/10	Link 4/5 to 6/1
		Profile 3/6			Type 8/10	Link 4/6 to 6/1
Family 7						**Swiftnet** (not in the standard anymore)
Family 8						**CC-Link**
	Profile 8/1		Type 18	Type 18	Type 18	CC-Link/V1
	Profile 8/2		Type 18	Type 18	Type 18	CC-Link/V2
	Profile 8/3		Type 18	Type 18	Type 18	CC-Link/LT (Bus powered—low cost)
Family 9						**HART**
	Profile 9/1		—	—	Type 20	Universal Command (HART 6)
Family 10						**Vnet/IP**
		Profile 10/1	8802-3	UDP/IP	Type 17	Vnet/IP
Family 11						**TCnet**
		Profile 11/1	8802-3	Type 11	Type 11	TCnet
Family 12						**EtherCAT**
		Profile 12/1	Type 12	Type 12	Type 12	Simple IO
		Profile 12/2	Type 12	Type 12	Type 12	Mailbox and time synchronization
Family 13						**ETHERNET Powerlink**
		Profile 13/1	8802-3	Type 13	Type 13	
Family 14						**Ethernet for Plant Automation EPA**
		Profile 14/1	8802-3	UDP/TCP/IP	Type 14	EPA master to bridge
		Profile 14/2	8802-3	Type 14	Type 14	EPA bridge to device
Family 15						**MODBUS-RTPS**
		Profile 15/1	8802-3	TCP/IP	Type 15	MODBUS TCP
		Profile 15/2	8802-3	TCP/IP	Type 15	RTPS
Family 16						**SERCOS**
	Profile 16/1		Type 16	Type 16	Type 16	SERCOS I
	Profile 16/2		Type 16	Type 16	Type 16	SERCOS II
		Profile 16/3	8802-3	Type 16	Type 16	SERCOS III

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 the second class, for *process control*, the requirement is a delivery time below 10 ms. This is a requirement for most tooling machine control system like 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 and 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 Mbps, if both protocol medium access and hardware structure are modified.

21.3.2 Performance Indicators of the IEC Standard

The following performance indicators are defined in the CPs for RTE (IEC 61784-2):

- Delivery time
- Number of RTE end-stations
- Basic network topology
- Number of switches between RTE end-stations
- Throughput RTE
- Non-RTE bandwidth
- Time synchronization accuracy
- Non-time based 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 RTE end-stations* states the maximum number of RTE end-stations supported by a CP.

The *basic network topology* supported by a CP comprises the topologies listed in Table 21.5, 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 nodes' clocks.

Non-time-based synchronization accuracy indicates the maximum jitter of the cyclic behavior of any two nodes, triggered by periodic events over the network for establishing cyclic behavior.

TABLE 21.5 Possible RTE Topologies

Basic Network Topology	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.

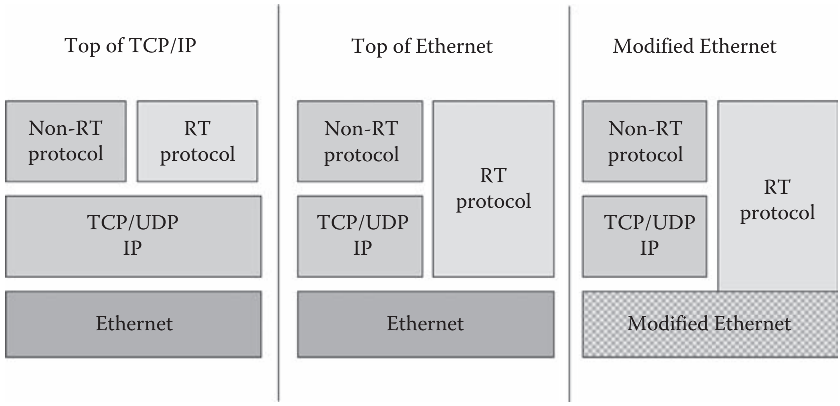

FIGURE 21.1 Possible structures for real-time (RT) Ethernet.

Redundancy recovery time indicates the maximum time from a single permanent failure to the network becoming fully operational again. In this case of a permanent failure, the delivery time of a message is replaced by the redundancy recovery time.

21.4 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 [1]. The market has adopted also additional technical solutions. All the solutions included in the standardization are presented here in a short description.

Communication interfaces are structured in different layers. In Figure 21.1, a simplified structure of a communication protocol is described. Common to all Ethernet network 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, e.g., HTTP or FTP for the non-real-time applications. To build a RTE solution, there are in principle three different approaches as shown in Figure 21.1. 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 are modified to ensure real-time performance ("modified Ethernet").

21.4.1 Realization of the "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.

In the international standard IEC 61784-2 [5], all CPs 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.

21.4.1.1 Modbus/TCP (Profiles 15/1 and 15/2)

Modbus/TCP, defined by Schneider Electric uses the well-known MODBUS* over a TCP/IP network [8], using port 502 and defined as profile 15/1. This is probably one of the most widely used Ethernet solutions in industrial applications today and fulfills the requirements of the lowest class of applications which we called human control.

MODBUS is a request/reply protocol (send a request frame and get back a reply frame) and offers services specified by function codes to read or write data objects. These data objects can be discrete inputs, coils,† 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 as profile 15/2. These real-time extensions use the real-time publisher subscriber (RTPS) protocol [9]. 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 CTS protocol, a CTS writer publishes state information as a variable (VAR) which is subscribed by the CTS 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.

In the standard, any concrete indication for values for the performance indicators is missing. They depend very strongly on the performance and implementation of the UDP/IP communication stack. So it is not possible to define an implementation independent message delivery time, for instance.

21.4.1.2 EtherNet/IP (Profiles 2/2 and 2/2.1)

EtherNet/IP,‡ defined by Rockwell and supported by the Open DeviceNet Vendor Association (ODVA, see www.odva.org) and ControlNet International (see www.controlnet.org), makes use of the common interface protocol (CIP) which is common to the following networks: EtherNet/IP, ControlNet, and DeviceNet [10].

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 full-duplex switched Ethernet, there is no possibility to get delays due to collisions. But in the switching device, Ethernet frames may be delayed, if an output port is busy with the

* Industrial de facto standard since 1979.

† In MODBUS, for the representation of binary values, the term coil is used. This is originating from the ladder-logic where the coil of a relay is used to store binary information.

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

TABLE 21.6 Performance Indicators for Ethernet/IP

Performance Indicator	Profile 2/2	Profile 2/2.1
Delivery time	130 μs to 20.4 ms	130–190 μs
Number of end-stations	2–1024	2–90
Number of switches between end-stations	1–1024	1–4
Throughput RTE	0–3.44 M octets/s	0–3.44 M octets/s
Non-RTE bandwidth	0% to 100%	0% to 100%
Time synchronization accuracy	—	≤1 μs
Non-time-based synchronization accuracy	—	—
Redundancy recovery time	—	—

transmission of an 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 which allows the sender of a frame to assign a priority to an Ethernet frame. A virtual bridged local area network (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.

In the CIPsync extensions, the clocks of the devices are synchronized with the IEEE 1588 [7] 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. This is defined as profile 2/2.1. When these guidelines are strictly applied, Ethernet/IP is a real-time solution usable even for the most demanding classes of applications—compare the range of values in Table 21.6—but it is still not deterministic as a communication network.

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.

21.4.1.3 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.

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.

In fact, the P-NET on IP specification just defines how the existing P-NET package is tunneled over UDP/IP networks without any special measures to ensure real-time behavior on the Ethernet network. The performance indicators are listed in Table 21.7.

* An object in CIP provides an abstract representation of a particular component within a product.

TABLE 21.7 Performance Indicators for P-NET

Performance Indicator	Profile 4/3
Delivery time	0.564–6.3 ms
Number of end-stations	30
Number of switches between end-stations	4
Throughput RTE	0–3.44 M octets/s
Non-RTE bandwidth	75%
Time synchronization accuracy	—
Non-time-based synchronization accuracy	5.7 ms
Redundancy recovery time	1 s

TABLE 21.8 Performance Indicators for Vnet/IP

Performance Indicator	Profile 10/1[a]	Profile 10/1[b]
Delivery time	20 ms	200 ms
Number of end-stations	64	4096
Number of switches between end-stations	7	39
Throughput RTE	10 M octets/s	10 M octets/s
Non-RTE bandwidth	0%–50%	0%–50%
Time synchronization accuracy	<1 ms	<5 ms
Non-time-based synchronization accuracy	—	—
Redundancy recovery time	<200 ms	<600 ms

[a] For two end-stations belonging to the same domain.
[b] For two end-stations belonging to different domains with one lost frame.

21.4.1.4 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 and reliable datagram protocol).

The Vnet/IP is in fact not a 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.

The minimum cycle-time of scheduling of real-time traffic is 10 ms, which fulfills 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. The performance indicators as indicated in the IEC standard are listed in Table 21.8.

At 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.

21.4.2 Realization of the "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

* Vnet/IP is the trade name of Yokogawa Electric Corporation.

TABLE 21.9 Protocol Types for Different RTE Profiles Defined in IEC 61784

IEC 61784 Profile	Brand Name	Protocol Type
Family 3	PROFIBUS/PROFINET	0x8892
Family 11	TCnet	0x888B
Family 12	EtherCAT	0x88A4
Family 13	Ethernet POWERLINK (EPL)	0x88AB
Family 14	EPA	0x88BC
Family 16	SERCOS	0x88CD

for IP is Ethertype = 0×0800. These RTE protocols do use, beside the standard IP protocol stack, their own protocol stack identified with their own protocol type. Table 21.9 lists the different values assigned to this Ethertype for these protocols.

21.4.2.1 Ethernet Powerlink (Profile 13/1)

Ethernet Powerlink (EPL) was defined by Bernecker and Rainer (B&R), and is now supported by the Ethernet Powerlink Standardisation Group (EPSG, see www.ethernet-powerlink.org).

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 (compare also Figure 21.2). Thus the transmission of isochronous and asynchronous data will never interfere and precise communication timing is guaranteed.

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 MN of different "protected Ethernet" segments are synchronized based on distributed clock. With the IEEE 1588 [7] protocol in every MN, a clock is synchronized and the messages between the different networks are sent based on the synchronized time in the MNs. The MN includes the routing functionality, including the IP address translation from the network to the outside world. With this synchronization mechanism, RTE communication is also possible among different networks. Performance indicators for a small- and a large-size automation system within a "protected Ethernet" are listed in Table 21.10.

* From Latin for iso = the same and chronous = time based, so communication at the same time interval.

† Asynchronous is without any synchronization to a reference.

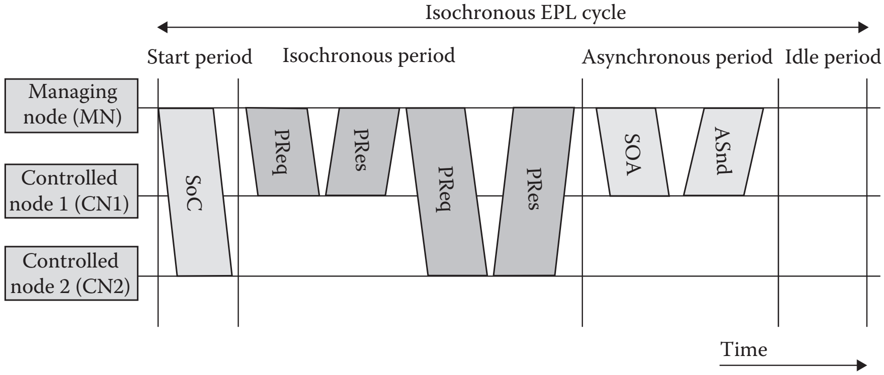

FIGURE 21.2 Ethernet Powerlink timing.

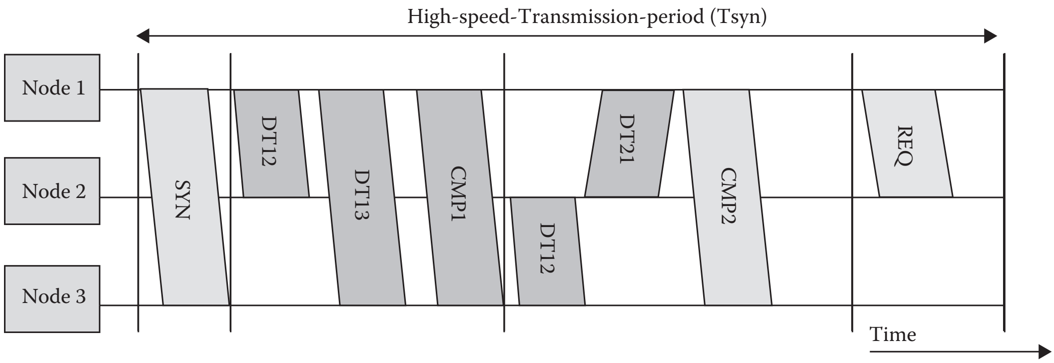

FIGURE 21.3 TCnet timing.

TABLE 21.10 Performance Indicators for Ethernet Powerlink

Performance Indicator	Profile 13/1[a]	Profile 13/1[b]
Delivery time	400 µs	5.5 ms
Number of end-stations	4	150
Number of switches between end-stations	0 (1 Repeater)	0 (3 Repeaters)
Throughput RTE	1.9 M octets/s	4 M octets/s
Non-RTE bandwidth	19.6%	4.4%
Time synchronization accuracy	<1 s	<1 s
Non-time-based synchronization accuracy	<200 ns	<280 ns
Redundancy recovery time	150 µs	2.7 ms

[a] Small size automation system.
[b] Large size automation system.

The Application layer of the EPL is taken from the CANopen standards provided by the CAN in Automation (CiA, see www.can-cia.org) organization [11]. 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.

21.4.2.2 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 media access control (MAC) access carrier sense multiple access with collision detection (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 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 (see CMP1 in Figure 21.4). 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 send only depending on the circumstances. Thus, the cycle

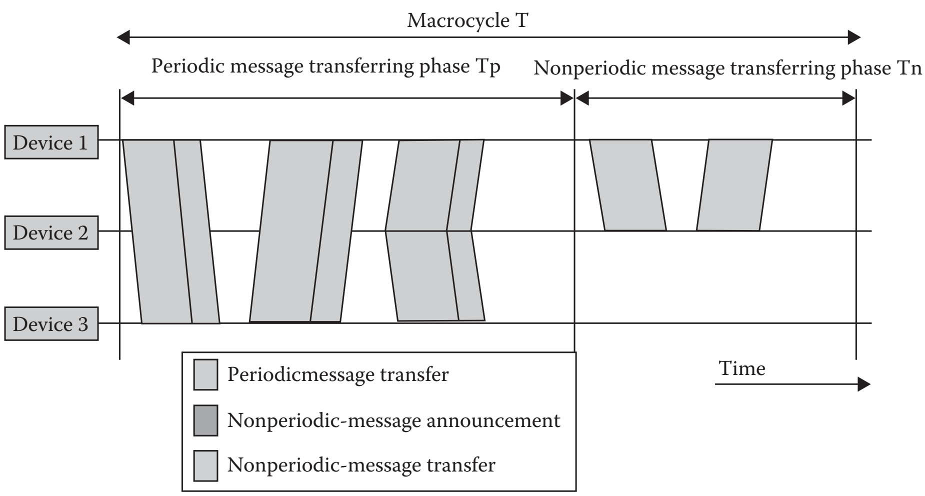

FIGURE 21.4 EPA timing.

* 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 send. 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.

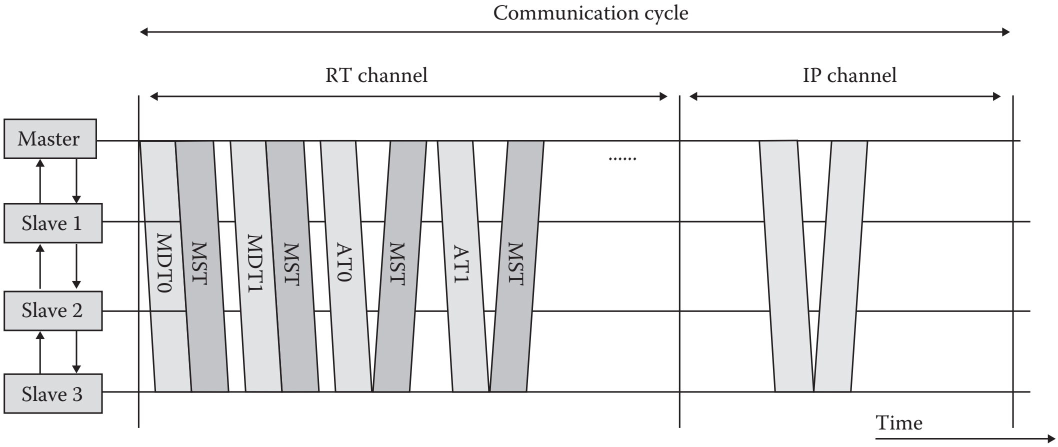

FIGURE 21.5 SERCOS timing.

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.

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. This is the reason why in Table 21.11 the recovery time is set to 0.

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 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.

21.4.2.3 EPA (Profiles 14/1 and 14/2)

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

TABLE 21.11 Performance Indicators for TCnet

Performance Indicator	Profile 11/1[a]	Profile 11/1
Delivery time	2 ms/20 ms/200 ms	2 ms/20 ms/200 ms
Number of end-stations	24	13
Number of switches between end-stations	0 (3 Repeater)	0 (5 Repeaters)
Throughput RTE	7.3/6.4/0.9 M octets/s	5.7/5.1/0.6 M octets/s
Non-RTE bandwidth	0%	< 20%
Time synchronization accuracy	—	—
Non-time-based synchronization accuracy	<10 µs	<10 µs
Redundancy recovery time	0 s	0 ms

[a] With no non-RTE bandwidth.
[b] With allocated non-RTE bandwidth.

* EPA is the trade name of Zhejiang SUPCON Co. Ltd.

TABLE 21.12 Performance Indicators for EPA

Performance Indicator	Profile 14/1	Profile 14/2
Delivery time	5 ms	100 μs
Number of end-stations	32	64
Number of switches between end-stations	4	4
Throughput RTE	1.536 M octets/s	1.536 M octets/s
Non-RTE bandwidth	85%	85%
Time synchronization accuracy	<10 μs	<1 μs
Non-time-based synchronization accuracy	—	—
Redundancy recovery time	<300 ms	<300 ms

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. Figure 21.4 illustrates that each communication macrocycle (T) is divided into two phases, periodic message transferring phase (Tp) and 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. Two sets of consistent performance indicators are listed in Table 21.12.

In EPA systems, there are two kinds of application processes, EPA function block* 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.

21.4.2.4 PROFINET CBA (Profile 3/3)

PROFINET is defined by several manufacturers (including Siemens) and supported by PROFIBUS International (see www.profibus.org) [17]. The first version was based on component-based automation (CBA) and is included in IEC 61784-1 (type 10 in IEC 61158) as profile 3/3.

The mechanical, electrical, and functional elements of an automation device are grouped together into 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)† and distributed component object model (DCOM)‡ protocol from the office world.

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 21.9) and frame prioritization (see explanation in Section 21.4.1.2). In this case, the TCP/IP stack is bypassed and cycle times of less than 10 ms become possible.

With PROFINET CBA, the end user defines his automation components with the traditional programming and configuration tool for programming logic controller (PLC). 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.

* 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.

† A 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 (source: wikipedia.org).

‡ DCOM is a Microsoft proprietary technology for software components distributed across several networked computers (source: wikipedia.org).

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. As PROFIBUS CBA is defined in the first part of IEC61784; there are no performance indicators published.

21.4.3 Realizations of the "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 10 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.

21.4.3.1 SERCOS (Profile 16/3)

The former IEC 61491 [12] standard SERCOS (SEriell Real time COmmunication System Interface, see also www.sercos.org) is well known for its CNC (computer(ized) numerical(ly) control(led)) optical ring interface. This standard is now split into an application part and a communication part [21]; 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 [13] 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 (see Figure 21.6). 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 the 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 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.

* Abbreviated from device (acknowledge) telegram as AT for historical reasons.

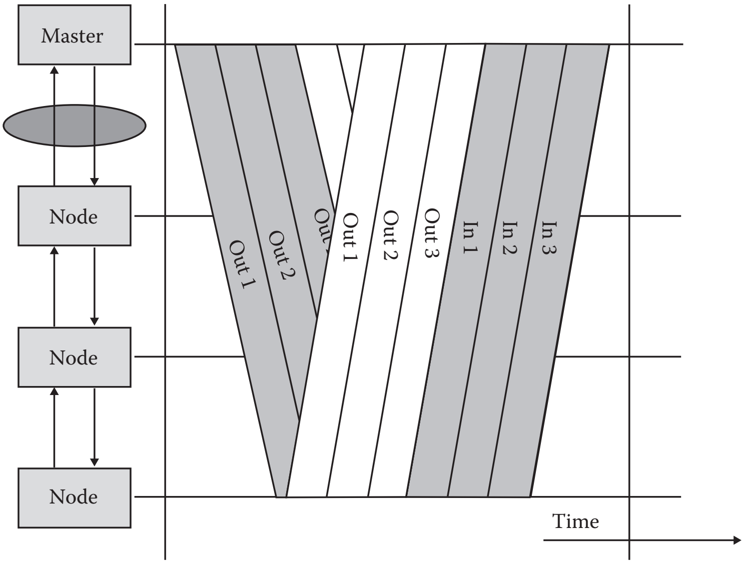

FIGURE 21.6 EtherCAT timing.

TABLE 21.13 Performance Indicators for SERCOS

Performance indicator	Profile 16/3[a]	Profile 16/3[b]
Delivery time	<39.8 μs	<513 μs
Number of end-stations	≤9	≤139
Number of switches between end-stations	0	0
Throughput RTE	11.2 M octets/s	≤9.248 M octets/s
Non-RTE bandwidth	0%	25%
Time synchronization accuracy	—	—
Non-time-based synchronization accuracy	<1 μs	<50 μs
Redundancy recovery time	0	0

[a] Scenario with minimum cycle time and high-performance synchronization
[b] Scenario with non-RTE bandwidth and low-performance synchronization.

This sequence of transmitting synchronization, RT-data telegrams, and IP telegrams is repeated every communication cycle. 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 field-programmable gate array (FPGA),* will be needed which separates the RT channel from the IP channel. Performance indicators for two typical setups are listed in Table 21.13.

The application model of SERCOS is based on the drive model† 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.

* FPGA, a gate array is a prefabricated circuit, with transistors and standard logic gates.
† A drive model consists of a controller and one or several drives (e.g., motors, servos).

21.4.3.2 EtherCAT (Profiles 12/1 and 12/2)

EtherCAT* defined by Beckhoff and supported by the EtherCat Technology Group (ETG, see also www.ethercat.org) uses the Ethernet frames and sends them in a special ring topology [14].

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 Figure 21.7). 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 integrated circuit (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.† The EtherCAT telegrams are either transported directly in the data area of the Ethernet frame or within the data section of an

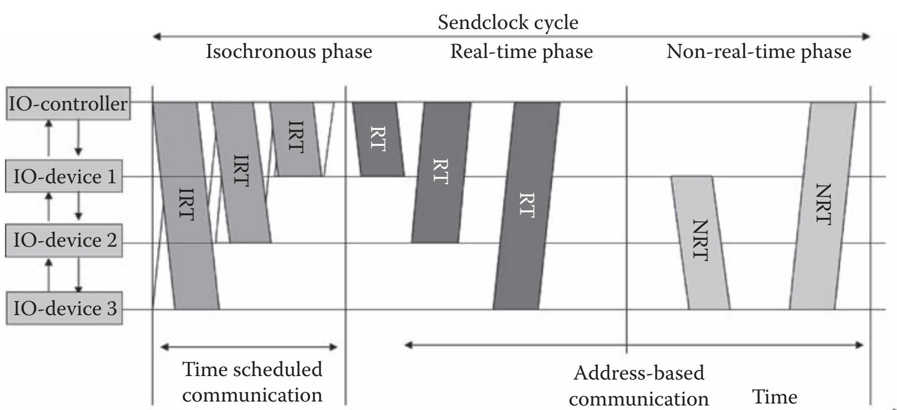

FIGURE 21.7 PROFINET timing.

* EtherCAT™ is the registered trade name of Beckhoff, Verl.
† A data section is a set of memory variables (e.g., inputs or outputs).

TABLE 21.14 Performance Indicators for EtherCAT

Performance Indicator	Profile 12/1	Profile 12/2
Delivery time	<150 µs	<519 µs
Number of end-stations	180	650
Number of switches between end-stations	NA	NA
Throughput RTE	10.75 M octets/s	10.5 M octets/s
Non-RTE bandwidth	50.6%	55.9%
Time synchronization accuracy	—	<<1 µs
Non-time-based synchronization accuracy	10 µs	10 µs
Redundancy recovery time	60 µs	200 µs

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.

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

The performance of the EtherCAT system (when configured to run "on the fly") may reach cycle times of 30 µs if no standard (non-RTE) traffic is added. The maximum transmission unit (MTU) of Ethernet with 1514 bytes corresponding to approximately 125 µs at 100 MBd in the non-RTE phase would enlarge the EtherCAT cycle. Two examples of consistent sets of performance indicators are shown in Table 21.14. 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 Figure 21.6). 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.

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.

21.4.3.3 PROFINET IO (Profiles 3/4, 3/5, and 3/6)

PROFINET is defined by several manufacturers (including Siemens) and supported by PROFIBUS International (see www.profibus.org) [15]. A second step after the PROFINET CBA 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 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 into send clock cycles each with different time phases as presented in Figure 21.7. In the first time-phase called 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 Figure 21.7), the planned frame is send from one port to the other without interpretation of the address. In the next time phase called real-time phase, the switching devices change to address-based

TABLE 21.15 Performance Indicators for PROFINET IO

Performance Indicator	Profiles 3/4 and 3/5	Profile 3/6
Delivery time	128 ms	1 ms
Number of end-stations	60	60
Number of switches between end-stations	10	20
Throughput RTE	2.324 M octets/s	3.324 M octets/s
Non-RTE bandwidth	23.5%	23.5%
Time synchronization accuracy	<1 ms	<1 μs
Non-time-based synchronization accuracy	—	—
Redundancy recovery time	<200 ms	0 ms

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 (see also Figure 21.7). All PROFINET switching devices are synchronized by means of a modified IEEE 1588 mechanism with "on the fly" stamping [16], to have their cycles and IRT timetables synchronized with 1 μs jitter.

PROFINET CBA and IO do not need any special hardware for real-time communication. To ensure good performance, PROFINET IO needs a 100 Mbps 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 21.15.

The PROFINET specification includes a concept allowing one to integrate existing fieldbuses with proxy devices. A proxy device represents a 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 61158) and PROFIBUS (type 3 in IEC61158) but today proxies are also defined for DeviceNet, AS-Interface, and other networks in the field.

21.5 Summary: Conclusions

During the standardization process there was a long discussion on why is it not possible to reduce the number of technical solutions to three or four RTE profiles. But there was a common understanding from the manufacturers that it is not up to the engineers in the standardization groups to take such decisions. It is agreed, that the market should decide which system will be successful in the field. So the problem of selecting a good solution is finally moved to the end user. We will see which of the RTE systems in the international standard will still be in large usage in the next 10 to 15 years.

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