Ethernet-based Real-Time Communications with PROFINET IO

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Abstract: The fieldbus systems have been successfully introduced in the industrial automation. Nowadays, a large community is inventing the usage of Ethernet-based local communication systems in this domain ensuring the real-time behaviour of these systems. Profinet IO provides the service definition and protocol specification for real-time communication based on Ethernet, IP, and UDP for the field area. It defines services and protocols mainly for communication between IO controllers (e.g. a PLC) and IO devices (e.g. Remote IO). It includes a QoS architecture for real time control and alarm messages taking precedence over parameter, diagnosis, or infrastructure messages including other TCP or UDP based protocols. High message priorities in combination with a time division multiplexing approach with direct data link layer access provide short cycle times and low jitter.

Key-Words: Communication Systems, Decentralised Control Systems, Industry Automation, Real-time, industrial Ethernet, IP-based control networks, real time aspects and QoS of control networks.

1 Introduction

The development of distributed computer control systems has been strongly influenced by digital communications for the last 25 years. At the same time, Ethernet won the battle as the most used communication technology within the office domain resulting in low component prices caused by the mass production of these components. The proprietary communication systems within SCADA systems were supplemented and partially displaced by the fieldbus systems and sensorbus systems etc. For the last five years and nowadays, there is a large community inventing the usage of Ethernet based communication systems to be used in the industrial automation domain, e. g. in the real-time and safety-critical world, e.g. [8, 31, 33, 34]. [29, 30, 32] contain an overview regarding the real-time aspects. However, opposite to that, fieldbus systems are the most important communication systems used in commercial control installations. In the future, both the fieldbus systems and Ethernet-based real-time communication systems will co-existent over a mid-term period. Thus, concepts for migration of standardised fieldbus systems into Ethernet-based real-time communication systems becomes important.

2 Recent situation and activities in Ethernet-based real-time communications

There are three real-time classes guaranteeing response time:

- Class 1: soft real-time (scheduling on top of UDP/TCP): scalable cycle time; used in factory floor and process automation
- Class 2: hard real-time (scheduling on top of MAC): cycle time 1…10ms. Used for control
- Class 3: isochronous real-time (with time/clock synchronisation and routing with time schedule): cycle time 250µs…1ms; jitter less than 1 µs. Used for motion control.

Additionally, there is a class "non real-time" not considered here.
Investigations have shown that at present the (switched) Ethernet itself is not the bottle neck of data transmission within local automation networks (for star topology as well as for line topology – this means each control device assesses its own switch, and all traffic has to pass through many or all switches). The present bottle neck is the communication stack within the end devices [1].
Regarding class 1, there are many investigations regarding temporal behaviour related to Ethernet-TCP/IP based local networks. They include mainly the response aspect of data packet transmission, which is very important within the industrial automation domain. The synchronous video or audio stream

transmission is of secondary interest. But the infrastructure of LAN, e. g. switches, offers a high priority to stream transmission. In contrast to that in the industrial automation application, the data packet transmission has to have the highest priority.
The systems which are using Ethernet-TCP/IP offer response time in the Millisecond range. The data transmission is based on the best effort principle. To use these systems within the automation domain, mechanisms are needed to monitor time limits, to use substitution values, to optimise the transmission (using records of many values within one MAC-PDU) as well as time- and event-triggered data transmission.
Examples are:
Ethernet/ IP (Rockwell, ControlNet International, Open DeviceNet Association) uses a Control and Information Protocol CIP [2]. CIP represents a common application layer for all physical networks of Ethernet/ IP, ControlNet and DeviceNet. Data packets are transmitted via CIP router between the networks. The application process is based on a Producer/ Consumer model.
High Speed Ethernet HSE (Fieldbus Foundation). A Field Device Agent represents a specific Foundation Fieldbus application layer function (including Fieldbus Message Specification, originally specified by the PROFINET user organisation). Additionally, there are HSE communication profiles to support the different device categories: host device, linking device, I/O gateway, field device. These devices share the tasks of the system using distributed Function Block applications.
Interface for Distributed Automation IDA (MODBUS-IDA Group., Schneider, Phoenix Contact). The layer functions allow three types of communication channels: Client/ Server Messaging for Engineering data exchange for real-time traffic using Real-time Publish Subscribe middleware RTPS from RTI (Real-Time Innovations, 2002), Modbus/ TCP as a widely spread protocol.
PROFINET CBA (PROFINET user organisation, Siemens) uses the DCOM Wire Protocol with the Remote Procedure Call mechanisms (DCE RPC) to transmit the soft real-time data. An open source code and various exemplary implementations/portations for different operating systems are available on the PNO Website.

All the mentioned approaches are able to support the office domain protocols, e. g., SMTP, SNMP, HTTP, some of them BOOTP, DHCP, for Web access and/ or for Engineering data exchange. [3] compares these approaches.

Regarding class 2, a lot of research activities deal with a middleware on top of the MAC layer of Ethernet scheduling the hard real-time and soft real-time/ non real-time traffic, see e.g. [4-9]. [10-13] deal with the usage of Switched Ethernet in the automation domain.
In academic and industrial research, different scheduling strategies and smoothing concepts are investigated [7-9]
An industrial example is **PROFINET RT.**

Regarding class 3, there are the following main examples:

- Powerlink (Ethernet PowerLink Standardisation Group EPSG, Bernecker & Rainer), developed for Motion Control
- EtherCAT (Beckhoff) developed as a fast backplane communication system
- PROFINET V2 (PROFINET user organisation, Siemens) developed for any industrial applications.

Powerlink uses a proprietary real-time protocol on top of the shared Ethernet. The scheduling mechanism is a time-division scheme. Every node uses its own time slot (Slot Communication Network Management SCNM) to send its data. This mechanism avoids the collisions on the Ethernet. Using 100 Mbps Ethernet Powerlink allows real cycle times of 400 microseconds or less in applications. The network jitter has been proven to be below 1 microsecond. The drives (less than 50 with cycle times in the range of 2 ms) can communicate synchronously with each other using broadcast services. Remarkable is that only hubs can be used for such real-time requirements. Switches do not meet these demands.
EtherCAT uses Bus Terminal Controllers to support active (event-driven) sending and receiving of data via Ethernet. This enables a lateral communication independent of a higher-level master, supported by Function Blocks. The routing functionality ADS (Automation Device Specification) enables local and remote communication via any connection route. The Bus Terminal Controllers can exchange data between themselves, with PLCs or with bus couplers of Fieldbus systems. The IP sockets can be opened and closed at runtime in order to communicate with additional devices.
PROFINET IRT uses a middleware on top of Ethernet MAC layer to enable high-performance transfer, cyclic data exchange and event-controlled signal transmission. The layer 7 functionality is directly linked to that middleware. The middleware itself contains the scheduling and smoothing functions. This means: the PDU structure is not influenced by TCP/IP. A special ethertype is used to identify real-time PDUs (only one PDU type for real-time communication). That enables an easy hardware support for the real-time PDUs. The technical background is a 100 Mbps full duplex Ethernet

(switched Ethernet). PROFINET IRT adds a isochronous real-time channel to the RT channels of class 2 option channels. This IRT channel enables a high-performance transfer of cyclic data in an isochronous mode [28]. The time synchronisation and node scheduling mechanism is located within and on top of the Ethernet MAC Layer. The offered bandwidth is separated in bandwidth for cyclic hard real-time and soft/non real-time traffic. This means, within a cycle there are separate time domains for cyclic hard real-time, for soft /non real-time over TCP/IP traffic, and for the synchronisation mechanism. The cycle time should be in the range of 250 µsec (35 nodes) to 1 msec (150 nodes) when simultaneously TCP/IP traffic of about 6 Mbps is transmitted. The jitter will be less than 1 µsec. PROFINET IRT uses switched Ethernet (full duplex). Special 4 Port (followed by 2 Port) switch ASICS are under development and will allow the integration of the switches into the devices (nodes) substituting the legacy communication controllers of the Fieldbus systems. Distances of 100 m per segment (electrical) and 3 km per segment (fibre-optical) will be bridged.

3 PROFINET – an overview

PROFINET specification and technical realisation has been driven by by the PROFINET user organisation PNO (PI). It should be classified into

- PROFINET CBA (including PROFINET RT)
- PROFINET IO (hard real-time; including PROFINET RT)

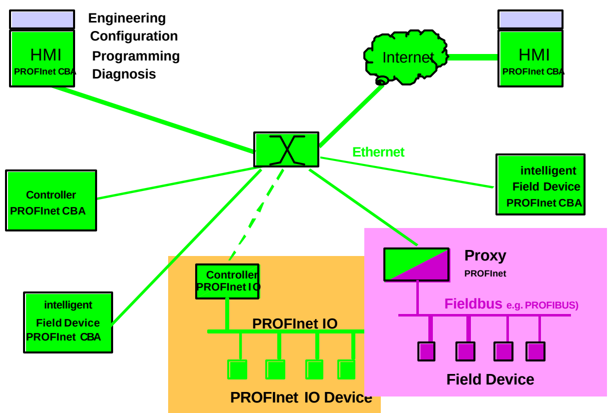

Figure 1. PROFINET system topology

Figure 1 shows the system topology, figure 2 the stack architecture.

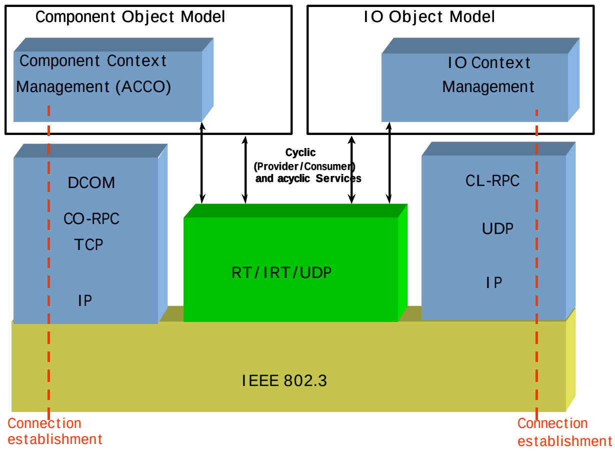

Figure 2. PROFINET stack architecture

As shown in figure1, there are two opportunities to integrate a fieldbus into the Ethernet-based PROFINET:

- using a PROFINET proxy (realised for PROFINET)
- using a PROFINET IO controller (actually developed for PROFINET and Interbus, the worldwide leading fieldbus systems)

On the other hand, the PROFINET IO allows a mid-term substitution of any fieldbus by PROFINET IO, because the PROFINET IO specification includes the potential features of the fieldbus systems.

4 PROFINET IO

4.1 System Overview

The system definition includes the following main capabilities:

- Very short reaction time supporting cyclic exchange of more than 1000 inputs and outputs with 32 field devices in less than 1 ms by means of a provider/consumer protocol mechanism.
- Supporting automation system consisting of one or several programmable controllers by means of mono-controller or multi-controller operation on one associated field device.
- Using an enhanced diagnosis and alarm object model for field devices.
- Support of smart field devices by means of common read and write services, which provides a flexible and enhanced addressing scheme of generic data within field devices.
- Unified PROFINET protocols by using the same real-time transport protocol mechanism for different PROFINET application models.
- Concurrent support of UDP/TCP based applications without functional restrictions over the same network.

- Compatible but enhanced application model to PROFINET DP to make it easy to adapt existing device or controller applications to the new network technology.
- Compatible but enhanced generic station description GSD model using an XML based scheme. The defined GSDML follows the same basic principle that is used for PROFINET DP network configurations.

The PROFINET IO service definition [14] and protocol specification [15] was released by the Technical Committee TC3 Working Group WG14 of the PROFINET User Organization. The dedicated application area is the same as applied for today's fieldbus systems. It covers the communication between programmable logical controller PLC systems, supervisor systems, and field devices or remote input and output IO devices. The PROFINET IO specification complies with IEC 61158 [16, 17].

In general, PROFINET IO distinguishes between three device types:

- An **IO controller**, which represents mainly a PLC or scanner. An IO controller is responsible for its associated field devices including IP address assignment, configuration, parameterisation, alarm handling and in most cases also the destination for inputs and source for outputs.
- An **IO device**, which represents mainly field devices or remote IO devices. An IO device is the source for process input data and the destination for process output data. It provides diagnosis and alarm information for protocol, device and process events. It may receive large blocks of parameter data, alarm or warning limits, and many others. Furthermore, each IO device has to support an enhanced identification and maintenance data set to support e.g. asset management functions.
- An **IO supervisor**, which represents a diagnosis, HMI or commissioning tool. An IO supervisor supports client functions to remote control, inspect, maintain, or parameterise an IO device. It may also temporarily force process output values by disabling the associated IO controller.

Real devices may be composed of several instances of the above mentioned basic device types.

The PROFINET IO specification complies with the structure and services of the IEC Fieldbus Application Layer FAL. It is specified in conformance with the OSI Basic Reference Model (ISO/IEC 7498) [18,19] and the OSI Application Layer Structure (ISO/IEC 9545) [20].

PROFINET IO defines its own layers and uses several other standards. On top, the PROFINET IO application process PROFINET IO AP is defined. The PROFINET IO application layer providing the PROFINET IO specific services and protocol follows it. PROFINET IO uses IETF and OSF standards for the OSI Middle Layer's, which were empty in most known fieldbus architectures. PROFINET IO uses the Internet Standards IP [21] and UDP [22] defined by the Internet Engineering Task Force IETF. Furthermore, the connectionless distributed communication environment remote procedure call CL DCE RPC [23] available from the Open Software Foundation OSF defines the basis for context management and generic read or write services. Between the application layer and data link layer a glue layer for hard real-time scheduling referred to as PROFINET IO link layer mapping protocol machine PNIO LMPM is specified. It is responsible for the precedence and timeliness of provider / consumer IO data and alarm data, which bypass the OSI Middle Layers. The lower layers comply to the IEEE standards [23, 24] with different physical media.

The advantages of the chosen architecture including CL DCE RPC are as follows:

- The reuse of existing standards prevents from inventing the wheel again and supports interoperability with office systems. In fact, CL DCE RPC is also a built in standard API for MS Windows, which can easily be used to set up IO supervisor clients.
- UDP in combination with CL DCE RPC provides a "better" TCP in case of retransmissions and a lean implementation for field devices. It must also be considered that only a small well-defined subset of CL DCE RPC is used.
- Many investigations have pointed out that the "standard stack" is the main source for delays and non-determinism. The bypass for opened connections addresses this issue and opens the possibility for hardware implementations with ASICs to reduce the jitter.

4.2 Protocol

4.2.1 Protocol Machines

The PROFINET IO protocol is defined by a set of protocol machines. Together with the coding section the behaviour on the wire is fixed. Fig. 3 depicts the protocol machines (gray boxes) within an IO device providing the behaviour of the AR ASE (Application Relationship Application Service Element). Furthermore, the main interactions between the protocol machines are shown.

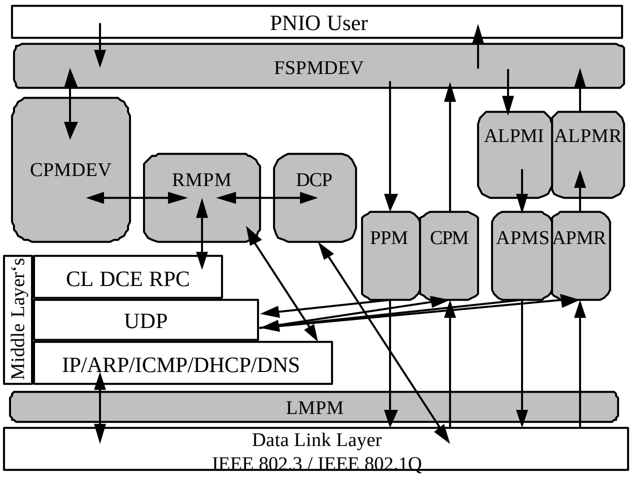

Fig. 3. IO device protocol machine architecture.

The PROFINET IO user issues or receives service primitives via the Fieldbus Service Protocol Mapping Machines for an IO device FSPMDEV. The FSPMDEV maps the service to the underlying protocol machines and provides a means for cross communication and synchronization. The Context Protocol Machine for an IO device CPMDEV controls the establishment of an AR and starts and stops other protocol machines. Furthermore, it may receive errors from other protocol machines and logs them by means of the Logbook ASE. The CMDEV is closed coupled with the Resource Manager Protocol Machine RMPM. The RMPM maps and encapsulated all CL DCE RPC related services and deals with the address assignment issues. The Discovery and Basic Configuration Protocol DCP [25] is a protocol definition within the PROFINET context. It is a Data Link Layer based protocol to configure station names and IP addresses. It is restricted to one subnet and mainly used in small and medium applications without an installed DHCP server. The Provider Protocol Machine PPM and the Consumer Protocol Machine CPM support the IO data transfer and monitor the IO and Supervisor AR. The conveyance of IO data can be configured. The alternatives are direct conveyance over the Data Link Layer or via UDP if the destination is in another IP subnet.

The conveyance of alarms is supported by following protocol machines:

- The Acyclic Protocol Machine Receiver APMR receives and acknowledges acyclic messages at transport level.
- The Acyclic Protocol Machine Sender APMS sends acyclic messages at transport level.
- The Alarm Protocol Machine Receiver ALPMR receives alarm notifications and acknowledges alarm messages at user level.
- The Alarm Protocol Machine Initiator ALPMI sends alarm notifications and receives alarm acknowledgements at user level.

The Link Layer Protocol Mapping Machine LMPM is responsible for the scheduling and the precedence of real-time data. It is required that the LMPM lies between the Data Link Layer and higher layers. Therefore, it should be implemented in hardware or as a device driver to fulfil this requirement.
In the same manner the protocol machines for an IO controller are defined, which play the counterpart for an IO device.

4.2.2 APDU Format

PROFINET IO defines a certain number of Application Protocol Data Units APDUs. Besides the CL DCE RPC based APDUs for the Context ASE, Record Data ASE, Logbook ASE and Diagnoses ASE Data Link Layer based APDUs for the IO Data ASE and Alarm ASE are defined. Fig. 4 depicts the PDU structure for the IO Data ASE.

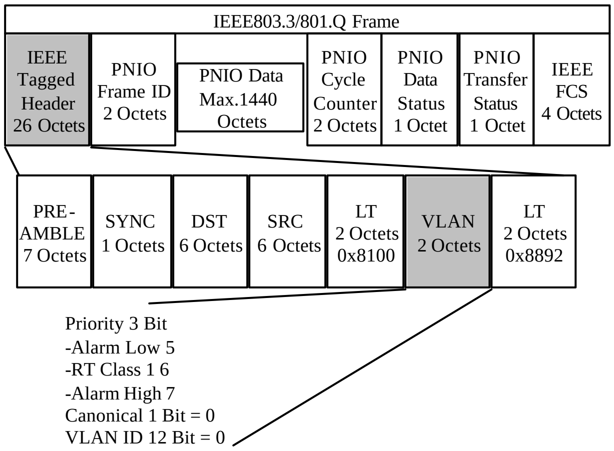

Fig. 4. Real-time PDU structure for IO Data ASE.

A priority tagged Ethernet frame is used for real-time data. The chosen priority for alarm messages is 5 and 7. IO data for real-time class 1 are conveyed with priority 6. Real-time classes 1 to 3 are defined by the protocol specification to distinguish between different real-time requirements. Class 1 requires no network synchronized clocks and the jitter may vary. Whereas class 3 requires network synchronized clocks and a jitter of less than one microsecond. Destination DST and Source SRC MAC address fields contain the Ethernet addresses. The second Length Type LT field contains a special for PROFINET assigned number. By means of this field the frame can be distinguished from IP or ARP [26] frames and filtered by LMPM. The field Frame ID contains a configured number that represents the data in a unique manner. Different areas are defined to distinguish e.g. between real-time class 1 IO data and alarm data. The Frame IDs are

distributed during the establishment of the AR by means of the Context Management ASE. The subsequent user data count up to 1440 octets. These number of octets fit also in one UDP based frame. The field Cycle Counter contains the send clock value with a 31,25 microseconds time base. The counter value is used to evaluate the timeliness of the frame at the receiver. The subsequent status fields inform about the validity of the user data.
The frame structure is optimised for real-time data and hardware support.

4.2.3 LMPM MAC Access

PROFINET IO provides a mean for soft real-time communication referred to as real-time class 1. It is aimed to control the usage of the bandwidth within the system. However, real-time class 1 uses local unsynchronised clock scheduling at the sending DTE interface. Therefore no special tolerance parameter for the jitter within the system is defined.

PROFINET IO devices shall use a data rate of 100 Mbit/s and full duplex mode. In theory, each device could always use wired speed for sending frames. Such behaviour applied over a certain amount of time would bring the system out of operation. Therefore, PROFINET IO provides a fair mechanism to restrict the transmission performance of each device.

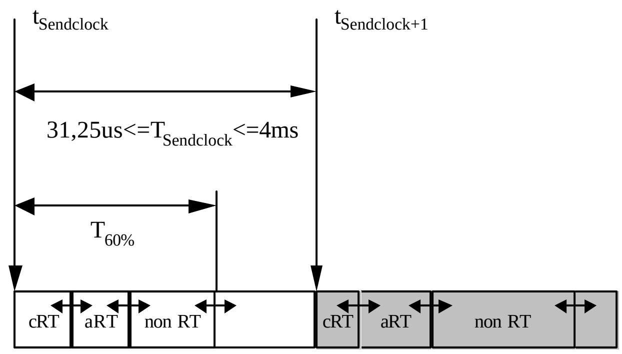

Fig. 5. LMPM MAC access.

As shown in Fig. 5, the transmission of frames is divided into different cycles at the local interface. Each cycle is defined by TSendclock which can be configured between 31,25 microseconds and 4 milliseconds. A typical value is one millisecond. At the beginning of cycle at tSendclock the cyclic real-time frames cRT are scheduled that are related to the IO Data ASE. The number of frames depends on the scheduled frames for the current phase and may be also zero. The time for cRT frames should not exceed about 50 percent of the bandwidth for each cycle. Subsequently, possible aRT (acyclic real-time) of the Alarm Data ASE will be sent. The time for aRT frames should not exceed about 10 percent of the bandwidth for each cycle. Then non real-time frames (e.g. UDP/TCP) will be sent during the rest of available time minus a safety margin (T60%).

4.3 Application Service Elements

FAL services and protocols are provided by FAL application-entities AE contained within the application processes. The FAL AE is composed of a set of object-oriented Application Service Elements ASEs. The ASEs provide communication services that operate on a set of related application process object APO classes.

Fig. 6 depicts the ASEs defined by PROFINET IO version 1.0. (2004). The Application Relationship AR ASE defines the conveyance characteristics used by other ASEs.

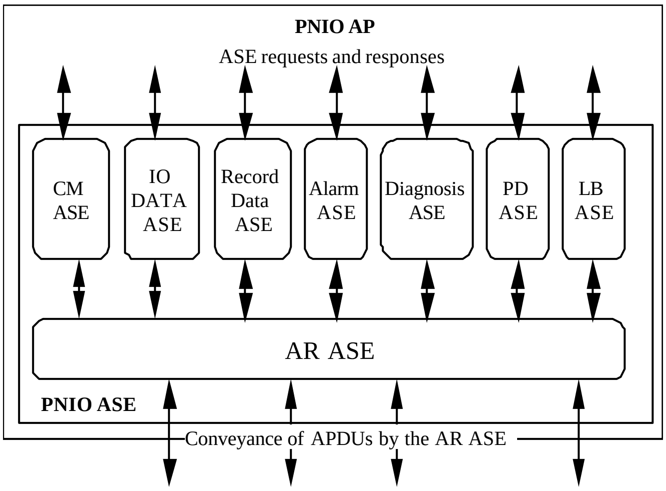

Fig. 6. PROFINET IO ASEs.

Details of the ASE description: see [27].

4.4 Addressing

The PROFINET IO addressing scheme supports hardware or functional modular devices very well. The basic model of IEC1168 type 3 was refined and enhanced. Fig. 7 shows an example of the basic addressing scheme for PROFINET IO for record data. An incoming Application Layer Protocol Data Unit APDU is decoded according to the protocol and delivered to an AREP. The service itself selects the appropriated ASE. The Record Data ASE in the example.
The PROFINET IO specification just defines APOs, which is the network view of a real object. How the real objects are mapped to an APO is manufacturer specific or part of dedicated profile specifications.

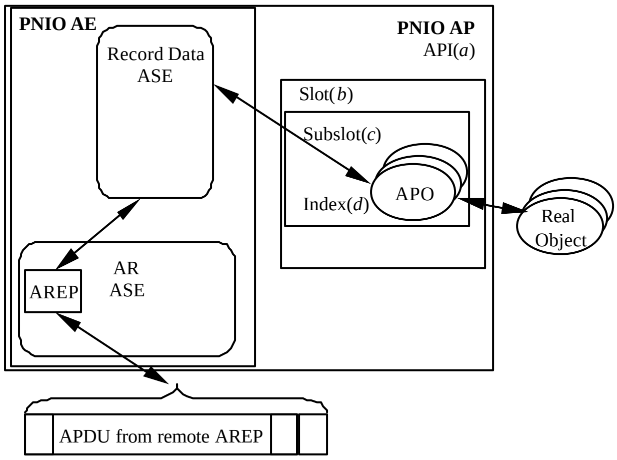

Fig. 7. PROFINET IO addressing scheme for record data.

5 Conclusions

The use of industrial communication systems in distributed computer control systems requires a guaranty of scalable real-time behaviour. The necessary QoS depends of the automation tasks and differ from soft real-time to isochronous hard real-time.

PROFINET IO can be used for all three real-time classes. It offers the mid-term substitution of fieldbus systems and short-term integration of different fieldbus system into one application. The protocol mechanisms, addressing schemes and service definitions contain a large potential for future system design. The scheduling mechanisms and synchronisation protocols are tailored also for line topologies (preferred within the automation domain).

The specification uses many results of the past academic research (especially regarding the scheduling mechanisms on top of MAV layer). An ASIC implementation will support an efficient market access. Furthermore, the functionality could be a basis for the development of Virtual Automation Networks including wireless, safety and security issues for geographically distributed automation.

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