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Performance analysis of Ethernet Powerlink protocol: Application to a new lift system generation

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Abstract—To ensure control, present lifts use the Controller Area Network (CAN) bus for transmitting commands between components. Although it is largely adopted in the industrial process, CAN is not able to guarantee a sufficient throughput to transmit multimedia data or to meet the requirements of some safety standards. In this paper, we present a transition case from electrical/electromechanical components to a networked control system. The main element we focus on in the lift system is the safety chain. We propose to build the lift communication system around real-time Ethernet for more efficiency, smartness and safety. Furthermore, the use of the openSAFETY protocol as a safety layer over the real-time Ethernet allows the achievement of the required Safety Integrity Level (SIL). This adopted solution should meet the adopted standard IEC 61508 requirements.

I. Introduction

Nowadays, Ethernet is commonly used for the home and office environment. Ethernet allows connecting any type of device due to its fast and easy installation, and interoperability. In addition, Ethernet has a large potential to become an ideal solution for automation technology. However, it is known that classic Ethernet is not suitable for industrial networking because of the Carrier Sense Multiple Access with Collision Detection (CSMA-CD) mechanism. Modern industrial automation systems consist of multiple devices exchanging information through communication networks. Traditionally, these local networks are restrained to an industrial plant, but recently the trend is to interconnect them remotely through Internet. This allows the collect of available supervisory and control data to apply maintenance and diagnosis operations on the running devices [1]. In [2], authors explain that Industrial Control System (ICS) is a general term that refers to a set of interconnected systems that include Programmable Logic Controllers (PLC), Distributed Control Systems (DCS) and Supervisory Control and Data Acquisition (SCADA). They allow automation and control of industrial processes. They include industrial processes for Power Generation, Gas Transportation, Aero-Space Industry, Food Industry, Automotive, etc.. The adoption of Ethernet technology cannot be accepted if the field area loses its principal features:

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

Industrial Ethernet must fully retain the office Ethernet communication capability. Using Ethernet for industrial communication brings some advantages; Solutions, that uses unified physical layer leading to lower prices and vast choice of network components. In this paper, we detail the development of an experimental test bed dedicated to industrial systems (lift control system). The test bed is built on real hardware (STM32 cards). We designed and implemented a networked process control system using an Ethernet-based protocol in their communication layer: the Powerlink + OpenSAFETY. Using the developed experimental process, we analyze Ethernet Powerlink protocol (EPL) and its safety extension (OpenSAFETY) to reach a minimum cycle time in industrial networked architecture around a real-time operating system. This solution allows to meet a safety standard requirements for the lift system. The remainder of the paper is organized as follows. In section II, we present the state of the art for deterministic industrial communication based on Ethernet. After the state of art, we justify our choice for the Real-Time Ethernet (RTE) protocol. Then, we detail the classification of RTE. In section III, we describe the adopted protocol for our project and we compare its model with the model of a classical communication (OSI model). Our adopted approach and results are presented in section IV and V. In fact, section IV shows our architecture for the lift control system. In this section we explain how we do integrate RTE in our networked industrial system and we will present the theoretical analysis and experimental measures. In Section V, we focus on new concept in the lift control system: the safety over RTE in lift control system, so we will interpret the obtained results and discussing it. Finally, in Section VI we make our conclusions.

II. Classes of Real-time Ethernet

In modern lift architectures, sensors and actuators are connected through the CAN bus [3]. The integration and system management are declared in the CANopen framework. The CAN in Automation group (CiA) adjusts and refines the CANopen dictionary to have a new suitable CANopen called CANopen-Lift [3]. This kind of frameworks gives the designer full variables access in the lift control system. For the future lift management in buildings, it is imperative to ensure data video, multimedia support, etc.. Despite the growth up to 10 Mbits/s of the last draft of CAN, stakeholders aim for a global solution supporting IP connection for web services, remote maintenance, etc.. Stakeholders are looking for a unique interface for the control and services. In our contribution we make a survey of the real time Ethernet and reuse the CANopen communication in the head of IP networks. We can classify different approaches of Real-Time Ethernet (RTE) realization into 3 classes [4] as shown in Fig.1. All RTE approaches use identical physical layers. Non real-time applications use of the Ethernet protocols as defined in ISO 8802-3 and the TCP/UDP/IP protocol suite.

Class 1: *Realization on top of TCP/IP:*

The TCP/UDP/IP protocol stack is used here without any modification [5]. To achieve a cycle time equal to 100 ms, the protocol stack needs reasonable resources in processing power and memory which introduces non-deterministic delays in the communication [3].

- Class 1 protocols: ModBus/TCP [6][7], Ethernet/IP [8][9], etc..

Class 2: *Realization on top of Ethernet:*

These realizations are required by PLCs and they do not change the Ethernet communication principle (i.e. the data link layer). Their own protocol stack replaces TCP/UDP/IP protocol stack to obtain a cycle time $<$ 10 ms.

- Class 2 protocols: Profinet RT [10][11], Ethernet Powerlink [12][13], EtherCAT class B [14], etc..

Class 3: *Realization with modified Ethernet:*

The data link layer is modified within this approach to achieve a cycle time $<$ 1 ms. This class offers a high synchronization precision. These realizations are required by Motion Control. They implement specific hardware to reduce the classic stack.

- Class 3 protocols: Profinet IRT [5] [10], SERCOS [15], EtherCAT class A [5][14][16], TTEthernet [17][18][19], etc..

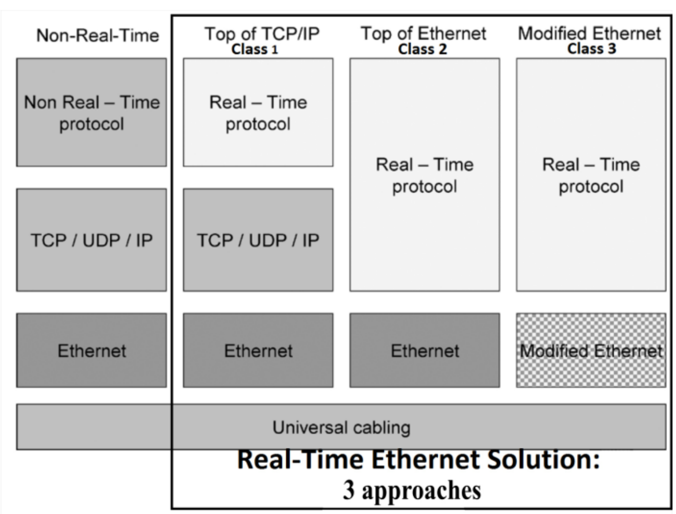

Fig. 1. Classification of industrial Ethernet protocols.

III. Ethernet Powerlink protocol

Ethernet Powerlink (EPL) was originally developed to transfer the CANopen framework over IP stack. Some german companies like B&R GmbH support the EPL developer for industrial control application on real time Ethernet. Supported by Ethernet Powerlink Standardization Group (EPSG), this protocol was certified ISO in 2004 and IEC 61784 (Communication Profile Families CPF-13) [12]. This standard, managed by the EPSG, is still opened in order to be specified for industrial control [20].

A. *Model of Ethernet Powerlink*

EPL is considered as a class 2 protocol i.e over a Mac 802.3 standard (with *88AB* Ethetype value). It could achieve a cycle time less than 10 ms. As shown in Fig. ??, EPL network uses standard Ethernet interface (all Ethernet usual port will support EPL network). The Data Link Layer (EPL DLL) is specified over the Ethernet Medium Access Control (MAC). The application layer offers the process data support with an Object Dictionary (OD) inherited from the CANopen stack. Regarding IEEE 802.3 Protocol Data Unit (PDU), EPL add five additional fields allocated in the three bytes of the Ethernet data field. The *"MessageType"* field is used to identify the different exchanges in an EPL network. It is used in our approach to calculate the cycle time in our industrial network (used in sniffing with wireshark). At least, with the EPL, Ethernet protocol was not hardware modified. Therefore a standard communication over TCP/IP is still possible.

B. *Slot Communication network Management*

Powerlink Ethernet is based on the principle of using a master-slave scheduling system on a shared Ethernet segment called Slot Communication Network Management (SCNM) [21]. EPL defines two types of stations: Managing Node (MN) and Controlled Node (CNs). The master (MN which is unique) ensures the real-time access to the cyclic data and lets standard TCP/IP frame pass through, only in specific time-slots. The unique MN in the network is responsible for traffic scheduling and executes regular polls of several CNs (up to 240). It allocates time slot of data transmission for each node in a cyclic manner within a guaranteed cycle. The master-slave relationship is established by means of a continuously repeated sequence of operations namely cycle shown in Fig. 2. Generally, we can split the EPL cycle into 4 sections as shown in Fig. 2. Effectively, the cycle is composed of two different periods: the *Isochronous* and the *Asynchronous* period. At the beginning of each cycle, the unique MN in the network broadcasts a "Start of Cycle" (*SoC*) frame to synchronize all the CNs. Then, the isochronous period is started. During this period, the MN polls each CN in sequence by means of "Poll

Request" (*PReq*) frame to transfer output data. When a CN gets the *PReq* frame, it should broadcast "Poll Response" (*PRes*) frame to the network to transfer input data. Then every node (MN or CN) can detect this *PRes* frame. At the end of an isochronous period, the MN broadcasts the *PRes* frame to all CNs. Only the MN can start and finish the isochronous period. The MN broadcasts the "Start of Asynchronous" (*SoA*) frame to notify the beginning of the acyclic period to all the CNs. Via the SoA frame, the MN grants a unique CN to send an acyclic message. Then, the designed CN uses the "Asynchronous Send" (*ASnd*) frame to transmit its acyclic data. When CN finishes sending its acyclic message, an idle phase starts. The MN waits for the remaining time before starting a new EPL cycle. The SCNM mechanism ensures that only one network device can access to the network and there are no collisions, thus providing deterministic communication and real-time network transmission. The CNs may be accessed every cycle or every nth cycle. It shall send back a *PRes* frame to MN. The duration of the asynchronous phase may vary from one cycle to the next. If a CN is assigned to send and there is no information about the length of the expected asynchronous frame available at the MN, the next reduced Powerlink cycle shall not start until at least the timeout given by the length of a maximum size Ethernet frame.

IV. Principle and Realization: Safety Chain in Lift System

A. Adopted approach: New lift safety architecture

In this part, we describe our target networked industrial system. As shown in Fig. 3, the lift system is composed essentially of a car, a safety chain, a controller and a motor [22]. To move the lift car, the controller checks that all contacts of the safety chain are closed and then controls the motor. Communication between components is ensured through industrial protocols (fieldbus). The safety chain is composed of serial contacts range that controls the power of a dedicated Input. The displacement of the car is possible only if all contacts are closed. Currently, this is the solution adopted by all lift constructors. So, making the safety chain smarter is a business need. To facilitate the control and automation of the safety chain lift, we proposed a new approach using an industrial network to replace the contact in the existing safety chain with smarter devices identifiable and controlled by a programmable logic controller (PLC). To improve the

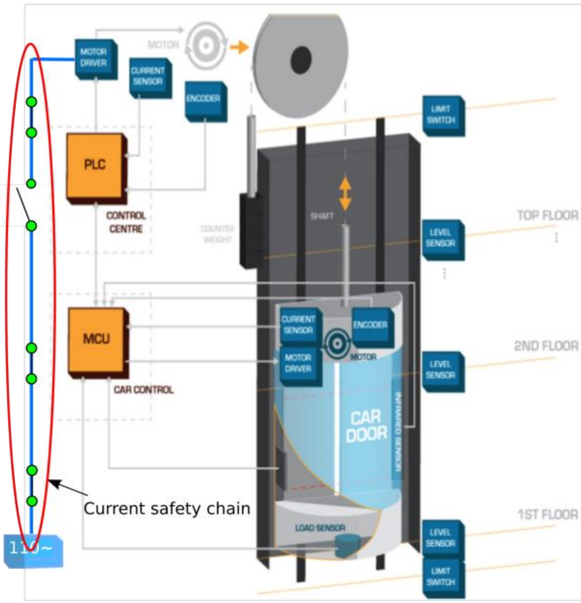

Fig. 3. Current safety chain in the lift architecture.

components behavior we used a real-time operating system in this smart device to achieve the temporal requirement as shown in Fig. 4. Respecting Fig. 4, the lift control system becomes able to collect information from the safety chain by means of slaves, make the decision to move the car, control the PLC from the master and give orders to the motor. The adopted architecture must model the communication in the safety chain. The automation of the safety chain has to ensure a communication through a protocol based on Ethernet and deterministic real time among the different nodes of the network. The following networked safety chain uses the Ethernet Powerlink as communication protocol. This Powerlink network, consisted of one MN and two CNs is established for the purpose of explaining the realization process of safety chain. In Fig. 6, as soon as MN starts the EPL communications by broadcasting the *SoC* frame to all nodes in the network.

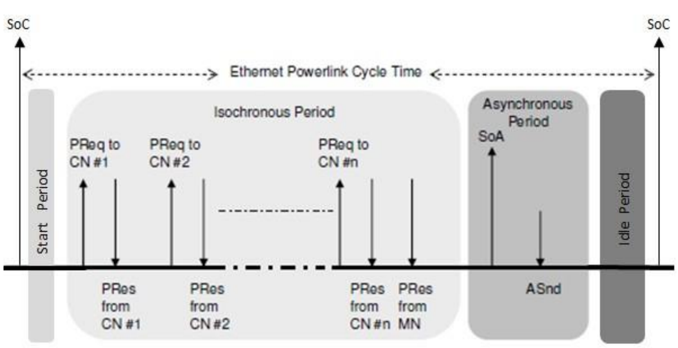

Fig. 2. Ethernet Powerlink cycle.

B. Configuration of parameters of protocols stack

Ethernet Powerlink introduces object-oriented communication. Indeed, in application Layer, EPL uses the Objects Dictionary (OD). It defines all the objects that can be exchanged in the network. The OD may contain a maximum of 65536 (2^{16}) inputs which are addressed through a 16-bit index. The communication profile area at indices 1000 through 1FFF contains the communication specific parameters for the Powerlink network. These inputs are common to all devices. The setting of configuration parameters of protocols stack is the key to enable the network to transmit information in accordance with the user agreement. In addition, the configuration parameters are stored in object index of OD. For instance, to control the timing behavior of the Powerlink network traffic, we store our configuration in object index 1006. This object defines the communication cycle time interval in µs. The 1F9C object assigns nodes to a particular isochronous slot, and the 1F8B object defines the *PReq* payload data size in octet for each configured node. The 1F8D object configures the *PRes* payload data. There are two types of Process Data Object (PDO) for the critical data transfer in real time. There is the Transmitted Process Data Objects (TPDO) which is configured at the sending node and stored in object index from 1800 to 1AFF. While, in the receiver node, there is the Received Process Data Objects (RPDO) stored in object index from 1400 to 16FF. To reduce the cycle time, users need to pay much more attention to the definition of the following object indexes (payload size, frame timeout, etc.).

C. Theoretical analysis and experimental measurements

In order to determine the optimized cycle time of our Powerlink network, we shall choose the appropriate network variables configuration. We have made some measurements on the cycle time in our EPL network with two slaves. The results are inserted in Table I.

TABLE I
RESULTS OF POWERLINK PROTOCOL TESTS FOR TWO SLAVES (ms)

Soc$\rightarrow$ P_{Req}	P_{Req} $\rightarrow$ P_{Res}	*Soc*$\rightarrow$*SoA*	*SoA*$\rightarrow$*ASnd*	Cycle time
0.1	10	50	30	100
0.1	08	40	20	80
0.1	05	25	15	50
0.1	03	15	10	30
0.1	01	05	03	10

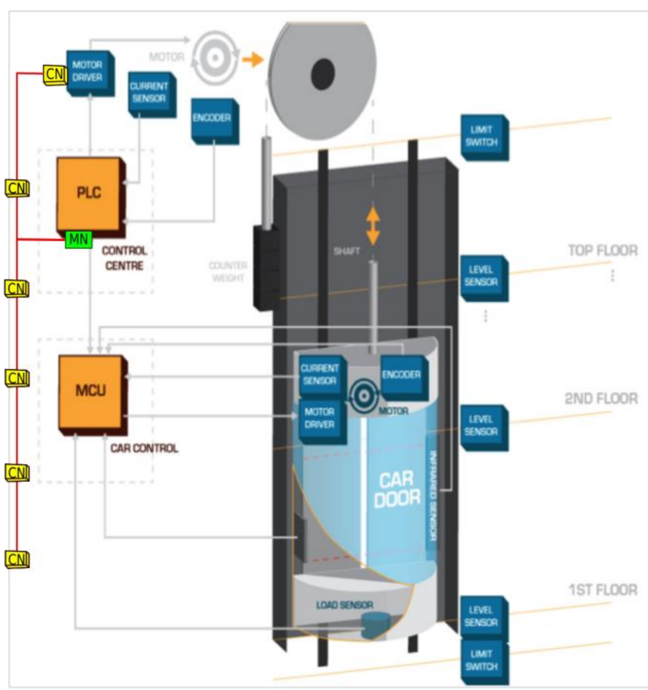

Fig. 4. Modified safety chain in lift control system.

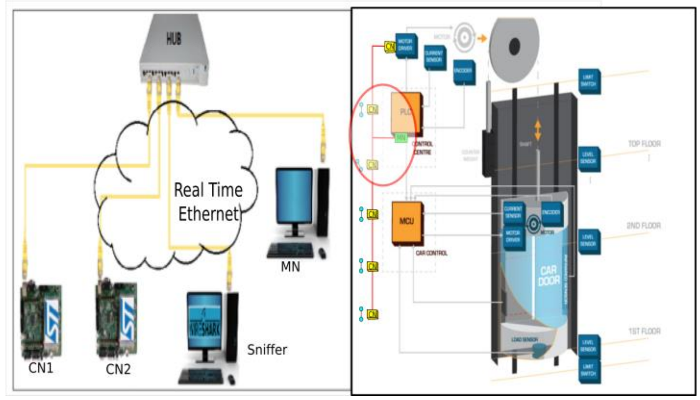

Fig. 5. Realization process of safety chain.

- *Soc*$\rightarrow$ P_{Req}: The time between the SoC frame and the first frame PReq.
- P_{Req} $\rightarrow$ P_{Res}: The maximum time required by CN to reply to PReq frame.
- *Soc*$\rightarrow$*SoA*: The maximum time of the isochronous period.
- *SoA*$\rightarrow$*Asnd* The maximum time required by the CN to issue ASnd frame.

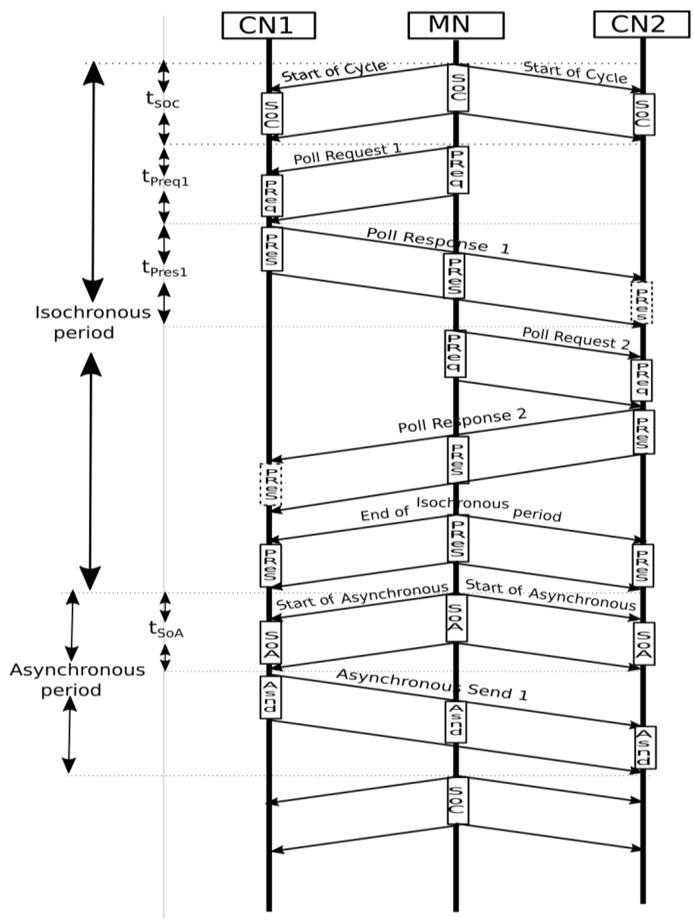

Fig. 6. Sequence Diagram of EPL Communication.

In EPL network containing n CNs, we can identify in each cycle the following messages:

- 1 *SoC* frame sized 64 bytes for all network.
- n *PReq* frames (for each CN one *PReq* frame). Each frame sized 64 (minimum)-1518 (maximum) bytes.
- n *PRes* frames (from each CN). Each frame sized 64-1518 bytes.
- 1 *PRes* frame (broadcasting by MN to declare the isochronous period end). It sized 64-1518 bytes
- 1 *SoA* frame sized 64 bytes for all network.
- 1 *ASnd* frame sized 318-1518 bytes (at least).

The theoretical cycle time depends on the size of the messages and the number of slaves in the network. The formula computation of the minimum cycle time is as follows (1)

$$\text{Minimum cycle} = \frac{((2n+3)\times 64+318)\times 8}{\text{Real rate}} + 2\times(n+2)\times IFG + \text{Jitter start}$$

n: Slave number,
IFG: Inter Frame Gap (default value = 960n s)
Jitter start: 20n s

Fast Ethernet has a theoretical speed of 100 Mbits/sec. In our case (with only two slaves and one master, e.g n=2), we have to reach 100 µs.
Based on the diagram of sequences shown in Fig. 6, we can deduce in another way the formula of the cycle time in the EPL network:

$$\text{Cycle time} = t_{SoC} + \sum_{k=1}^{n}(t_{Preq_k} + t_{Pres_k}) + t_{Pres} + t_{SoA} + t_{ASnd}$$

Theoretically, a PowerLink cycle may reach values less than 1 ms (around 400 µs [4]). But in theory, theory and practice are the same. In practice, they are not. These values (400 µs) can be achieved by using a specific hardware in the network components (MN or CN) as FPGA (Field Programmable Gate Array) or ASIC (Application Specific Integrated circuit) allowing very fast data processing.

In our implementation, using STM32 cards, the minimum cycle time that we have achieved is 10 ms as shown in Table I. we wanted to refine the configuration of the network by acting on the objects of the EPL in order to reach a cycle time less than 10 ms. Unfortunately, under 10 ms the nodes neither interconnect nor exchange messages. This phenomenon refers to the integrated clock in each node (MN or CN) of the network.

V. THE SAFETY OVER REAL-TIME ETHERNET

The industrial communication in deterministic networks is far from being secure, it guarantees perfect synchronization among devices, and meets the temporal requirements (section 3) imposed by the deterministic kernel, and the standard but not all safety requirements. To ensure these requirements, we need to add safety measures at the top of the application layer. OpenSAFETY is such an application layer communication protocol. In Section 3, we discuss the requirement of minimum cycle time equal to 10ms. The implementation of openSAFETY protocol over EPL as shown in Fig. 7 duplicates the cycle time calculated in the section 3. It will be 20ms. These results meet the temporal requirements of the safety standard for lift control system; Programmable Electronic components and Systems in Safety Related Applications for Lifts (PESSRAL). In fact, in case of danger, the PESSRAL requires an immediate and necessary stop of the lift car regardless its speed. After an outbreak, the maximum tolerated margin for the movement of the lift car is 1.2 meter [23]. Furthermore, we assume that the maximum speed of lift car is 2.5 meters per second, so the system will take:
$\frac{1.2}{2.5} = 0.48$ second to react.
The mechanical actuators require 0.4 second to perform efficiently [23]. It remains to the communication systems to react within a maximum time of 80 ms (sensor, controller, actuators). The sensors require 30 ms to update their information. The actuators require 30 ms to process orders from the controller. With a cycle time equal to 20 ms we meet the requirements of the PESSRAL standard because: 20+30+30=80ms. This seems satisfactory for our project. OpenSAFETY allows creating communication systems requiring SIL 3 (Safety Integrity Level) according to PESSRAL

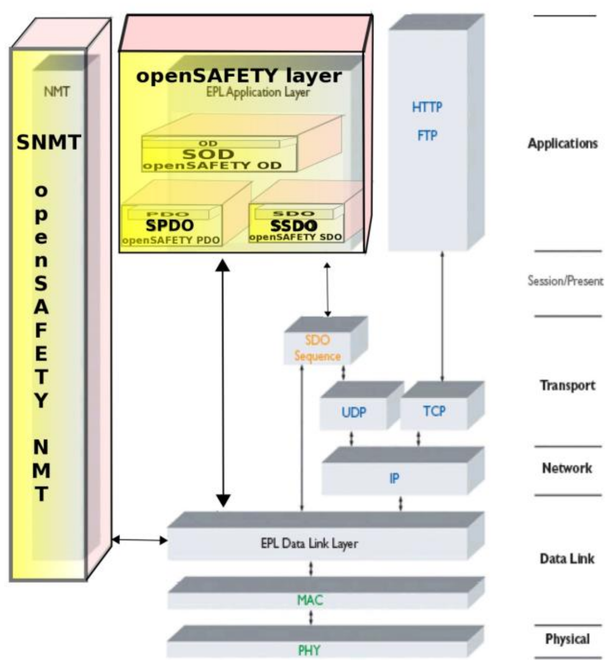

Fig. 7. OpenSAFETY over real-time Ethernet.

[24]. It is a set of components offering services and security mechanisms for secure data exchange via networks unsecured [25]. For example:

- Time stamp: This timestamp mechanism allows associating with each frame the time and date of transmission in order to avoid duplication of frames.
- Time monitoring: This time monitoring can predict moments of frame arrival and thus can detect losses and delays.
- Identification: Each frame is identified by a unique identifier to prevent and detect any kind of integration.
- Cyclic Redundancy Check (CRC): To ensure the integrity of messages sent and to avoid the alteration and modification of data, OpenSAFETY uses the CRC.
- Frame format: Using different frame format allows the distinction between the standard frame and the Open SAFETY frames.

VI. Conclusion

The innovative aspect of this collaborative project is the capacity to replace the classical safety chain composed of electromechanical components (serial electric contacts) by dedicated fieldbus networks. In this research project, we identified an adapted IP protocol to support dependability constraints for lift applications control. The mixed methodology allows integrating the communication architecture in the development in order to ensure the time performances based on deterministic operating system and safety by construction. Currently, the safety chain is not possible to diagnose. Indeed, our contribution will allow to perform a safety chain analysis. As a perspective, we can study the possibility to guarantee SIL3 in the worst-case scenario.The next task will be devoted to the modeling of a safe communication. This generic model will be included in the modeling of a deterministic core used in the ADN4SE project.

Acknowledgment

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