Towards Integration of Industrial Ethernet with 5G Mobile Networks

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***Abstract*—In contrast to the predecessors, the fifth generation of mobile networks (5G) will particularly address communication in production systems by providing machine-type communication and matching requirements regarding reliability and latency. However, 3GPP 5G will not be the one and only network technology that can be used to fulfill all the requirements raising from industrial applications at reasonable costs. It is more likely, that it complements other wired and wireless technologies, rather than replacing them. This paper presents different scenarios to combine 5G and Industrial Ethernet to a hybrid topology, it explains the characteristics and possible use cases for these scenarios and it sketches approaches to engineer and configure the hybrid network.**

***Index Terms*—industrial communication; hybrid networks; 5G; industrial Ethernet; TSN; network configuration**

I. Introduction

Industrial communication has been evolved from specific fieldbus systems over Industrial Ethernet to industrial wireless networks in three generations [1]. The ongoing digitalization of the production systems often referred to as the fourth industrial revolution or simply Industry 4.0 [2], increases the demand for connectivity between people, products and machines along the complete value chain in the manufacturing and process industry. Here, the 3GPP mobile networks [3] come into the scope of industrial communication because with Releases 15 and the next Release 16 of the technical specification, they do not only provide expanded broadband capabilities, such as increased peak data rate, 3Gbps (downlink) and 1.5Gbps (uplink), but also aim to support a wide range of vertical industries including manufacturing and process automation [4].

On the other hand, connectivity requirements are very diverse regarding spatial extent, mobility, energy consumption, data throughput, timeliness, reliability and other characteristics. As a consequence, several wired and wireless network technologies have to be combined to provide the required QoS for the communication. This trend towards hybrid communication network systems has been observed in the past and it will continue in the future [5]. In order to achieve sufficient end-to-end (E2E) QoS in hybrid networks, an efficient coupling of the different network technologies is essential. In addition, a holistic concept for engineering, monitoring and configuration of hybrid networks is required. It is to keep the E2E perspective and to confine the efforts of users in the phase of engineering, and to avoid performance losses at the network transitions.

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The paper targets on forming and handling a hybrid network comprising Industrial Ethernet/Time Sensitive Networking (TSN) and 5G, as the key communication system representatives of operational technology (OT) and information and communication technology (ICT) industry. It is organized as follows, the subsections below introduce 5G mobile networks, Industrial Ethernet and TSN, section II describes scenarios to combine both communication technologies, section III describes approaches to model and configure hybrid networks and their transitions, and section IV concludes the paper.

A. 5G Mobile Networks

While the provision of enhanced mobile broadband (eMBB) is already in the focus of 4G mobile networks, two new types of communication are considered for 5G: massive machine-type communication (mMTC) and ultra-reliable low-latency communication (URLLC). According to the ITU-R [6], the target performance indicators of 5G include data rates up to several Gb/s, wide-area coverage and deep indoor penetration for up to a million nodes per square kilometer, E2E latency close to 1 ms and a reliability of 99,999 % of packets. By fulfilling these characteristics, 5G becomes an important candidate to provide mobile connectivity for a wide range of applications in the manufacturing and process industry. In order to fulfill the above mentioned requirements, 5G systems become more complex compared to previous generations, e.g, new spectrum paradigms including higher frequency at millimeter wave bands, and cutting- edge air-interface technologies such as massive antenna arrays [7].

B. Industrial Ethernet and TSN

Industrial Ethernet communication merges the application layer functionality coming from the well established fieldbus protocols with the standard IEEE 802.1 Ethernet technology for the lower protocol layers. It utilizes the opportunities of IEEE 802.1Q to assign dedicated priorities to messages.

However, in order to fulfill real-time requirements, additional functionalities such as Time Division Multiple Access (TDMA), summation frame communication, or polling based communication have been introduced. These extensions provide stringent real-time capabilities, but require modifications of the original IEEE Ethernet MAC [8]. As a consequence, the several Industrial Ethernet protocols specified in IEC 61158 and IEC 61784 like Profinet, Ethercat, Ethernet/IP and Powerlink are compliant with the Ethernet standard only at the physical layer and differ at medium access layer and upwards.

Independent of the activities about industrial field level communication, in 2006 the IEEE became active in enhancing the real-time capabilities of the Ethernet standard, initially driven by the entertainment sector due to evolutions in high quality audio and video streaming. The corresponding Audio Video Bridging (AVB) working group gained interest of the manufacturing and automotive sector. Consequently the group extended the focus to cover industrial application requirements [9] and was renamed to TSN. TSN targets a variety of particular aspects [10], among them timing and synchronization aspects, quality of service aspects and resource reservation, forwarding and queuing mechanisms and reliability. TSN as an integral part of the standard IEEE Ethernet MAC allows for utilizing IP as well as TCP or UDP at the upper communication layers which enables the harmonization of industrial real-time field level networks.

II. Integration Scenarios

Several opportunities exist to combine Industrial Ethernet and 5G mobile networks. Each scenario is able to provide a benefit to specific user applications. Three of them are discussed in this section in more detail.

The first scenario is characterized by production islands of a production site, containing sensors, actuators and controllers. In this scenario all islands are equipped with the same Industrial Ethernet technology, hence all communication endpoints provide network interfaces according to the same standard. Information exchange among the islands becomes necessary in the context of Industry 4.0 and digitization. This can be

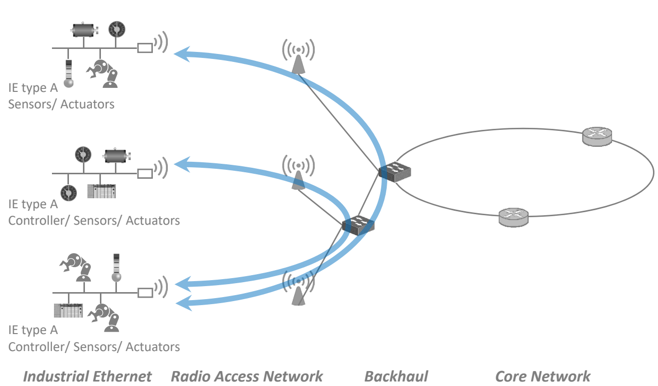

Fig. 1. Scenario 1: Connected homogeneous islands

advantageously realized by a 5G system, for example if the islands are mobile or electrically isolated. Figure 1 shows, that this scenario affects the Radio Access Network (RAN) and the backhaul of the 5G system, while its Core Network (CN) is not concerned. The QoS requirements can be challenging when the 5G system is involved in the closed loop control, i. e., when a controller is connected to sensor and actuator signals of a remote island, or more relaxed, when only controller to controller communication happens via 5G.

In the second scenario, the physical entity of the controller is moved from a dedicated device at the production line to a virtualized entity in the 5G network. Thereby this scenario corresponds to the approach of cloud based control as described in [11]. The virtualized controller is connected to the core

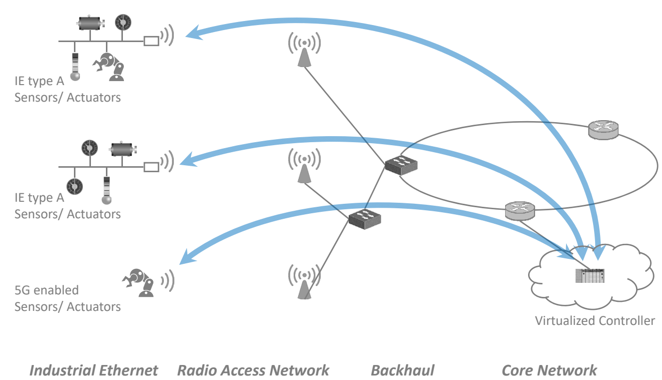

Fig. 2. Scenario 2: Virtualized controller

network, thus the entire 5G system is involved in this scenario, see Figure 2. The communication endpoints in this scenario provide different network interfaces: the sensors and actuators at the production line may provide either Industrial Ethernet or native 5G radio access, while the virtualized controller more likely provides standard Ethernet IP based communication. The scenario imposes high demands on the QoS since the entire network topology is included in the control loop.

The third scenario is the most versatile one. It extends the second scenario by a remote production site, which is connected to the 5G CN, see Figure 3. The interfaces of the

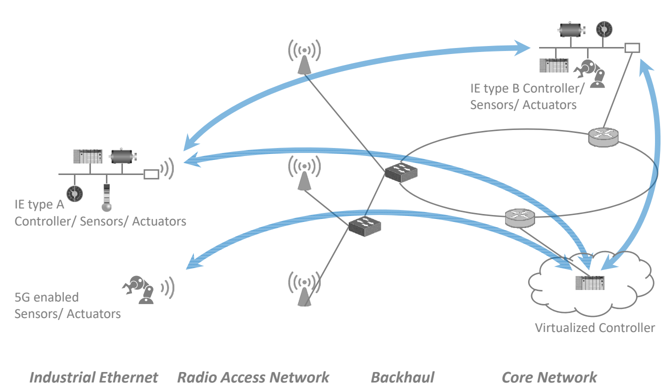

Fig. 3. Scenario 3: Versatility with virtualization and remote site

communication endpoints can be diverse and include standard Ethernet IP based protocols, 5G radio and various Industrial Ethernet protocols.

Numerous use cases for the integration of 5G mobile networks in the factories of the future are collected in [4]. The presented scenarios are able to support these use cases. In detail, scenario 1 can be applied for mobile robots, mobile control panels, connectivity for the factory floor, closed loop control in process automation, or modular assembly areas. Scenario 2 is applicable to massive sensor networks, control-to-control communication, plant asset management, or process monitoring. Scenario 3 is suitable for remote access and maintenance, or inbound logistics.

A crucial point for all of the scenarios is, to which extend the performance indicators of the 5G network, such as the latency of 1 ms, can be transferred to the performance of the overall hybrid network. At a first sight, scenario 1 might provide advantage over the others since the CN is excluded , but in the 5G architecture the RAN protocols, i.e. the bearers, are terminated in instances of the CN. Nevertheless, a deployment of this termination function at an edge cloud can keep a benefit in performance. But this is only a narrow once-over about performance consideration. In general, the performance evaluation of the proposed scenarios is an item of future work.

III. Integration Concepts

A. Non-native integration

In hybrid networks, industrial services or protocols may not natively be supported by all network technologies. However, there are several concepts to realize this support. Tunneling protocols are an option to use protocols over a network that does not support this particular protocol by repackaging the frames into the payload. Tunneling, however, requires the same protocol at the communication endpoints which is only given in Scenario 1 outlined in section II. In other cases, the utilization of gateways is possible. Gateways translate between different protocols at a specific communication layer transparently to the communication endpoints. If for example only the physical layer of the protocols differ, the gateway works at the MAC layer and it is called a bridge. Utilizing proxies is an alternative to gateways. A proxy represents all nodes of a foreign network and thereby provides encapsulation.

B. 5G integration into TSN configuration approach

Tunneling, gateways, and proxies provide a non-transparent way of integrating 5G and industrial networks. However, in order to facilitate the migration towards a 5G supported industrial deployment, a transparent integration is necessary, where E2E protocols are not affected by the use of 5G technology. This is exemplified in the following, using the fully centralized model of Ethernet TSN as defined in IEEE 802.1Qcc.

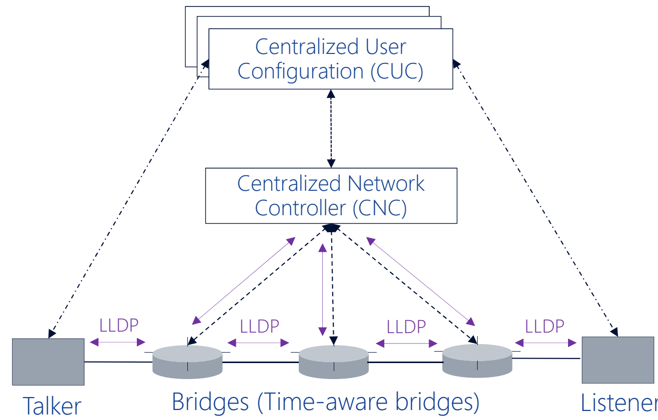

Fig. 4. Centralized model of IEEE 802.1Qcc

1) Fully centralized configuration of IEEE 802.1Qcc: Figure 4 shows the fully centralized model of the TSN network described in IEEE 802.1Qcc. The talker end stations are devices that generate information (sensors); the listener end stations are devices that consume information, e.g., controller or monitoring device [12]. The network has a set of time-aware bridges. These bridges and the end stations are synchronized to a master clock in the system and hence, are aware of the global absolute time. The end stations are proprietary devices and communicate their stream requirements through the Centralized User Configuration (CUC). The CUC translates the stream requirements into corresponding communication requests towards the network. While there may be several CUCs in one TSN domain, each TSN domain has a single entity called Centralized Network Controller (CNC). The CNC gets the E2E stream request from the CUC through the user/network configuration interface. This interface is standardized in TSN. CNC has a complete view of the network and can compute the schedule and configure each of the bridges so that the E2E communication with the required QoS can be established.

2) Transparent integration of 5G and TSN networks: Figure 5 depicts the functional view of integrating a 3GPP 5G mobile network within a TSN network. In addition to 3GPP Release 15, two new functional entities, namely TSN translator (Txl) and an adaptation interface (AIF), are introduced. These two entities encapsulate the 5G network as a virtual bridge in the TSN network. Hence, from the perspective of the TSN network, the complete 5G network will appear as a TSN bridge. The TSN Txl and the AIF translate the TSN commands into corresponding actions in the 3GPP network and vice versa. They are involved in procedures such as Link Layer Discovery Protocol (LLDP) and Precision Time Protocol (PTP) to be compatible with the TSN network. In the following, the interactions of the TSN Txl and the AIF with the TSN network and the 5G network are described.

First, when the end station is plugged in, the AIF triggers the User Equipment (UE) to establish a wireless connection to the network. After this, the Txl and the AIF can communicate

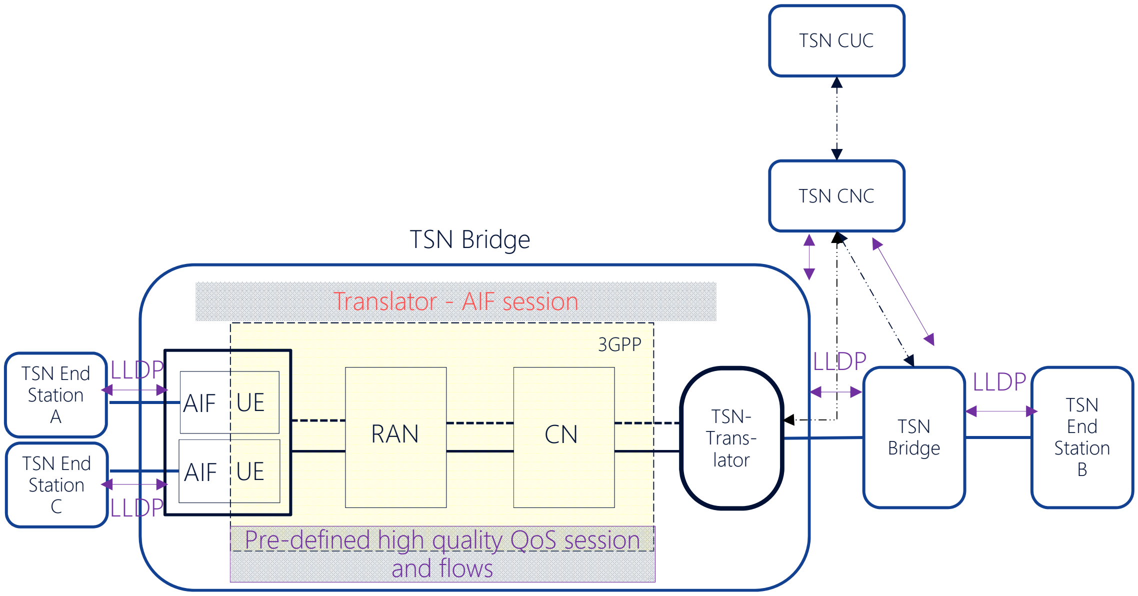

Fig. 5. Transparent integration of 3GPP network into TSN network

with each other. During the network discovery, CNC will send requests to all bridges to read the bridge managed objects containing the bridge capabilities. On receiving such request, the TSN Txl will trigger establishment of a set of pre-defined high quality session. Afterwards, the TSN Txl maps the 5G QoS Class Indicator (QCI) of the Protocol Data Unit (PDU) sessions to the corresponding QoS of the TSN network and reports them to the CNC. Finally, when the CNC distributes the bridge configurations, the TSN Txl also informs the AIF about the configuration parameters in order to handle the TSN traffic properly.

IV. Conclusion

This paper introduced three potential integration scenarios of industrial network technologies and 5G mobile networks. Key differences of these scenarios as well as specific ways to transparently integrate TSN/Industrial Ethernet with 3GPP 5G have been discussed. Due to the adaptive system architecture of 3GPP 5G, it is possible to provide interface towards industrial networks in order to transparently integrate them with the 5G mobile networks. This is an important requirement to enable a successful migration towards 5G enabled industrial networks. Especially in brownfield deployments, the concept of transparent integration may be beneficial. Nevertheless, its performance and usability still have to be investigated, such as the impact of a 5G bridge on an overall TSN network.

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