Costa-Requena, Jose; Estevan, Carlos Barjau; Borenius, Seppo

# Transport layer and synchronization for smart grid and industrial internet in 5G Networks

*Published in:*
2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids, SmartGridComm 2019

*DOI:*
10.1109/SmartGridComm.2019.8909744

Published: 01/10/2019

*Document Version*
Peer reviewed version

*Please cite the original version:*
Costa-Requena, J., Estevan, C. B., & Borenius, S. (2019). Transport layer and synchronization for smart grid and industrial internet in 5G Networks. In *2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids, SmartGridComm 2019* [8909744] IEEE. https://doi.org/10.1109/SmartGridComm.2019.8909744

# Transport layer and Synchronization for Smart Grid and Industrial Internet in 5G Networks

Jose Costa-Requena
Department of Communications and Networking, Aalto University
Espoo, FINLAND
jose.costa@aalto.fi

Carlos Barjau Estevan
iTEAM Research Institute, UPV
Valencia, SPAIN
carbare1@iteam.upv.es

Seppo Borenius
Department of Communications and Networking, Aalto University
Espoo, FINLAND
seppo.borenius@aalto.fi

***Abstract*- Industrial internet is the main customer for 5G networks. However, mobile networks cannot deliver currently the required reliability and transport infrastructure. In the past mobile networks were designed for personal communications optimized for downlink data transfer. A new transport that provides seamless connectivity between mobile and fixed devices is required. Moreover, reliable timing information has to be delivered to both cellular and fixed devices with predictable delay to enable synchronous communications. This paper studies limitations of utilizing the current transport in mobile networks for smart grid and industrial communications. A new transport layer is proposed and the solution to deliver accurate timing information. Finally, the paper studies capabilities of deploying the proposed transport in both 4G but also in emerging 5G cellular networks.**

***Keywords—Industrial Internet, 4G, 5G, Smart Grids.***

## I. INTRODUCTION

5G networks are key enablers to deliver carrier grade transport for smart grids and industrial internet applications. However, industrial environment and smart grids demand a reliable transport as well as seamless connectivity of sensors, actuators and controlling devices distributed in both cellular and fixed infrastructure. This introduces the challenge of precise timing information as well as symmetric transport between fixed and mobile devices.

The current cellular networks have been designed mainly for personal communications and specifically for downlink data transfer i.e. asymmetric transport. The cellular networks support higher bandwidth for downlink data transfer.

This paper studies the limitations of current technologies for delivering a transport that resembles Ethernet which would be used between fixed and cellular devices.

The remaining of the paper is structured as follows. Chapter II provides background by introducing Industrial Internet transport technologies used currently. This chapter analyses how is being provided timing using NTP over cellular networks. Chapter III discusses the limitations cellular networks to provide carrier grade transport. Chapter IV introduces a new transport solution based on NB-IOT [1] and eMBMS [2] as well as a novel mechanism to delivery accurate timing information to devices both in cellular and fixed networks. Thereafter, chapter V provides a summary and conclusions, and discusses options for future work.

## II. INDUSTRIAL INTERNET TRANSPORT

Industrial applications where smart grids is a concrete scenario, require a reliable transport as well as accurate time information for synchronous communications. Devices in industrial environments require a robust and reliable transport. Over time there has been several solutions, but Ethernet-based networks have become the most widely adopted solutions. The usage of Ethernet in Local Area Networks has even Wide Area Networks facilitates the mass-production of devices and network devices. The fact that Ethernet has been standardised and is de-facto transport for TCP/IP communications facilitates its proliferation in industrial environments as well. This makes industrial Ethernet becoming more established across industry.

However, industrial protocols require real-time communication transport for interconnecting devices and control systems. In the early days those connections were based on serial interfaces e.g. RS-232/485 using direct physical connections. Over time this transport has evolved to operate over Ethernet to provide easy integration of application and services built on top of TCP/IP and UDP/IP. However, industrial Ethernet is used as default transport for Time Sensitive Networks (TSN) [3], which require some fine-tuning in terms of reliability and timing media delivery which lead to protocols such as PROFINET [4]. There are other protocols used in industrial environments such as Common Industrial Protocol (CIP) [5], Highway Addressable Remote Transducer (HART) [6], Process Field Bus (PROFIBUS) [4] but we would focus in PROFINET that is gaining momentum across major industry players.

PROFINET consists of a family of protocols or channels depending on the communication requirements. One channel consists of standard TCP/IP to exchange data without timing constrains. Another channel is used for real time communications where alarms and other critical information is exchanged between devices in the factory floor. Finally, Isochronous Real Time (IRT) requires a very precise high-speed communications channel between controlling devices.

Thus, PROFINET include own devices and scheduling solutions to ensure both cyclic or scheduled and repetitive communications as well as acyclic or unscheduled, on demand communications. The different types of channels or communications will be identified by the frame ID, which is a two-byte field in the standard Ethernet frame.

Moreover, PROFINET provides a device discovery mechanism as well as device description language. In detail, there are three types of devices i.e. IO-Controllers, IO-Devices and IO-Supervisors. The IO-Controllers exchange data with IO-Devices that are distributed over the industry floor connected between them over Ethernet. The IO-Supervisors devices performing system monitoring or diagnosis. The devices are assigned an IP address that is stored by the device in persistent memory and can retrieved from the IO-Supervisor device in the network or the device can be configured to retrieve the IP address from DHCP server.

The PROFINET IO devices are configured from IO-Supervisor which provide Generic Station Description Markup Language (GSDML). The configuration is transferred from the IO-Supervisor to the IO-device using the Record Data Object (RDO) services. The PROFINET IO device uses a number of constant values listed in Table 1.

TABLE I. PROFINET IO DEVICE VALUES

| **VALUE** | **DESCRIPTION** |
|---|---|
| Vendor ID | Unique value identifying an authorized PROFINET IO Vendor. |
| Device ID | Unique value identifying a PROFINET IO device. |
| Module ID | Unique value identifying a specific module type. This value is assigned by the device manufacturer. When the PROFINET IO device plugs in a module, the module id must agree with the module id specified in the GSDML file. |
| Submodule ID | Unique value identifying a specific submodule type. This value is assigned by the device manufacturer. When the PROFINET IO device plugs in a submodule, the submodule id must agree with the submodule id specified in the GSDML file. |
| Product Family | A manufacturer specific text string describing the product family. |
| Station Name | A text string describing the function of the station in the application. The PROFINET IO device is delivered with a default station name. An IO-Supervisor or IO-Controller can send a new station name to the PROFINET IO device. |
| IP Address | The IP Address of the device. The IP Address can be changed by an IO-Controller or IO-Supervisor or by a DHCP server. Every PROFINET IO device is shipped with a default IP Address. |

Based on the requirements from PROFINET a transport network that provides acquire timing for assigning slots to the PROFINET IO devices is required.

To enable consistent system wide functionality, distributed sensors, actuators and controlling devices need to be time synchronised. PROFINET utilizes Precision Transparent Clock Protocol (PTCP), a modified version of IEEE 1588-2008 [7]. IEEE 1588 Precision Time Protocol (PTP) allows an up-to sub-microsecond level accuracy in an Ethernet network [8]. PTP estimates the downlink latency from the timing source to the client device by measuring the roundtrip time and then diving this roundtrip time by two. This estimation of the downlink latency is then added to the time stamp sent by the timing source [8] Thus the fundamental assumption in PTP is that latencies from the timing source to the client device (downlink) and from the client device to the timing source (uplink) are equal. If this is not the case, the timing error will be half of the difference between the real downlink and uplink latencies. The asymmetry in latencies could be attributable e.g. to asymmetric routing of traffic downlink and uplink or an inherently asymmetric cellular channel. The widely used Network Timing Protocol (NTP) utilizes similar principal than PTP when estimating downlink latency from the timing source to the client device [9]. As a consequence, it shares the same challenge with asymmetric links as PTP. NTP allows a timing accuracy of about 1ms in fixed Ethernet networks [9].

## III. LIMITATIONS OF CELLULAR NETWORKS TRANSPORT

The cellular networks have been designed to deliver optimal transport for end customers to download content from fixed networks. Video streaming and web access are the most used applications and services in mobile devices. Thus, cellular network by default have been defined for asymmetric communications where downlink have allocated most of the radio resources compared to uplink communications. This affects the clock synchronization distribution based on PTP/NTP as described in previous section. This also limits the uplink communications from devices in industrial environments.

Moreover, the cellular networks allocate uplink and downlink tunnels to the mobile devices, which are identified by Tunnel End Points ID (TEID). These tunnels encapsulate the user data from the mobile devices all the way to the mobile core where the tunnels are terminated in the packet GW that connects the mobile devices to fixed networks (e.g. public Internet or private LAN) as shown in the Figure 1.

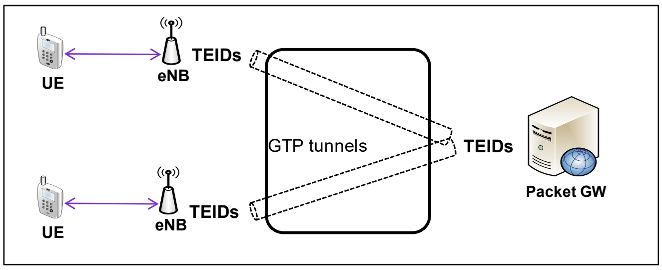

Fig.1. Transport between mobile devices and packet GW

The transport provided by cellular networks consist of IP based communications which are encapsulated over GTP/UDP/IP tunnels. However, the cellular networks do not provide plain Ethernet transport to mobile devices.

In order to enable the connectivity of machine type of communications 3GPP, which is the standardisation body for mobile communications, has specified two radio interfaces, Narrowband Internet of Things (NB-IoT), optimized for low-end machine type traffic, with very high robustness in order to reach deep indoor sensors. It is kept as simple as possible in order to reduce device costs and to minimize battery consumption. The other Air Interface is named LTE-M, with higher bandwidth, throughput and better latency. LTE-M targets high-end IoT devices.

Regarding NB-IoT specifications, 3GPP has defined a new transport which allows to encapsulate non-IP frames inside the signalling messages exchanged between the IoT devices and the Packet GW. This transport allows the devices to send Ethernet frames which will be encapsulated into the signalling messages and decapsulated and sent as Ethernet frames after the Packet GW, which in this case is named Service Capability Exposure Function (SCEF). In this case still the devices cannot send directly Ethernet frames which are then delivered as such to the fixed industrial network. Another limitation is that packet size and delay is limited in NB-IoT because the encapsulation into signalling messages. Note that, even LTE-M has this limitation, since it uses IP transport which is encapsulated as any other mobile devices using GTP tunnels, as Fig.1 shows. Another limitation of NB-IoT is downlink transfer of large amount of data, which in case of PROFINET when sending device configuration or diagnosis information to IO-Supervisors might be problematic.

Industrial internet requires a seamless connectivity between wireless distributed across the floor plant and wired devices connected in the factory private network. The wireless link should be symmetric to both uplink and downlink have the same latency and bandwidth.

Moreover, the wireless connection needs to support unicast and broadcast transport since the devices either wired or wireless have to discover each other using broadcast messages e.g. Ethernet ARP or PROFINET DCP messages.

## IV. PROPOSED TRANSPORT FOR INDUSTRIAL 5G NETWORKS

5G networks have introduced non-IP transport targeting sensors and industrial networks with Ethernet based devices. However, the current transport in cellular networks (See upper part in Fig. 2) encapsulate the IP packets from mobile devices and after reaching the mobile core or S/PGW the packets are decapsulated and sent to fixed data networks. 3GPP Release 13 proposes that the non-IP data can be transferred encapsulated in the signalling xmessages and it is also decapsulated in the SCEF. Thus, in order to provide seamless communications between wireless and wired industrial devices a transport that delivers non-IP data is required (See lower part in Fig.2).

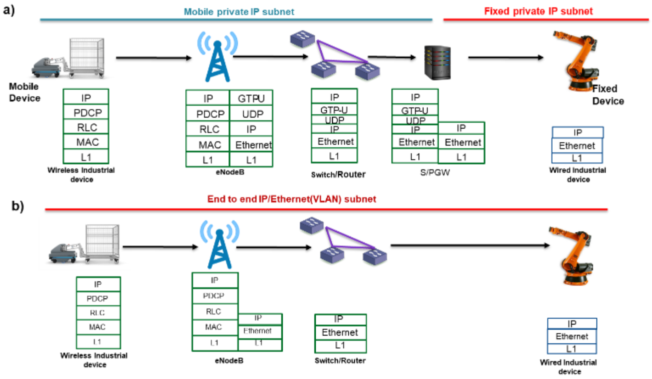

Fig.2. a) Current transport between mobile and fixed devices, b) new proposed seamless transport mobile and fixed devices.

The proposed transport should provide broadcast or multicast message delivery between wireless and wired devices discover each other before they have been assigned an IP address. Moreover, this communication might be non-IP if used when the proposed solution to enable this transport network is based on using NB-IoT for the wireless devices to send their non-IP message uplink and then using eMBMS to broadcast the received message to other devices in the cellular and fixed network as shown in Fig.3.

The proposed solution consists of integrating the SCEF functionality in the gNB or first switch where the gNB is connected. The current design of the SCEF will receive the signalling messages including the sensor Ethernet frames from the AMF. Instead, the SCEF or a new industrial UPF will receive the signalling with the NB-IoT messages or the GTP tunnels from the eNB. These messages will be encapsulated directly on top of Ethernet or MPLS to be delivered to the switches connecting the fixed devices.

5G Service Based Architecture (SBA) allows the default AMF configured in the gNB to redirect the device registration process to a new AMF. This process allows to bind the devices with the closest AMF that receives the non-IP data in the signalling and forwards it to the SCEF.

In this architecture the SCEF forwards all the Ethernet frames received from the devices connected to the cellular network to the fixed Ethernet segment. The SCEF includes the functionality to 1) encapsulate/decapsulate the signalling messages from the cellular network and 2) Ethernet bridge connecting the fixed Ethernet network. Moreover, SCEF can incorporate SDN functionality to assign the traffic to different VLAN based on the timing requirements of the different traffic.

Therefore, the 5G SBA with the new architecture allows to locate network functions such as AMF and SCEF in different parts of the network. The introduction of non-IP data inside signalling used in NB-IOT sensors allows to transfer Ethernet frames between cellular and fixed networks. Thus, 5G networks facilitates the deployment of seamless transport based on Ethernet such as PROFINET used in industrial environments with enhanced SCEF that bridges cellular and fixed Ethernet network segments.

In addition to proper transport that supports non-IP data between wireless and wired devices, accurate timing information is required.

## V. PROPOSED SYNCHRONIZATION FOR INDUSTRIAL 5G DEVICES

In section III we showed the asymmetry of mobile networks leads to inaccurate timing information when using NTP or PTP protocol. Instead, we propose using the fact that eNB are synchronized to send Timing information i.e. Timestamps to both wired and wireless devices to get all of them in sync. This proposal is applied to 4G since there is no available broadcast mechanisms in 5G.

eMBMS is used to broadcast the downlink timing information periodically to each IoT device simultaneously. The use for MBMS in IoT was already proposed in [11], but only covered the use of broadcast to provide software updates to a massive number of users. We propose the use of Transparent delivery method, introduced in Release 14, to provide a modified version of PTP to all wireless devices located inside a Smart Factory to support the usage of PROFINET. The transmission is sent in Multicast/Broadcast Single Frequency Network (MBSFN) mode, turning the interference between cells into constructive diversity. Devices which attach to the network can decode this signal to correct the drift in their internal clocks and get the current date in case of a reboot in a spectrally efficient way.

In detail, the proposed methodology to reach high accuracy in wireless connected industrial devices consist of using a periodic eMBMS subframe in a NB-IoT transmission. The overall architecture is shown in Fig 4. The wireless system is composed by a NTP or PTP server depending on the accuracy required, one BM-SC alongside a SGW with Transparent Delivery Mode functionalities, one NB-IoT capable MME, several eNB with MBSFN and NB-IoT RAT, and an arbitrary number of IoT devices.

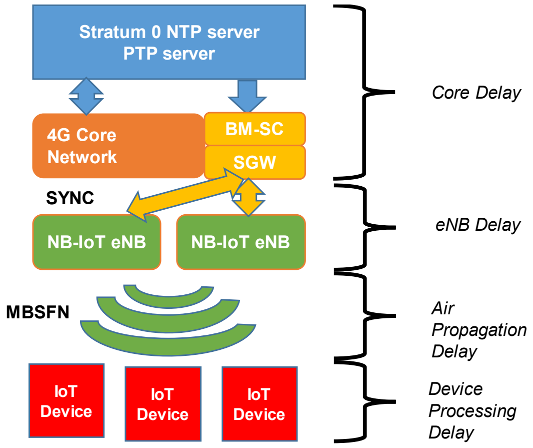

Fig.3. Synchronization architecture proposed with delay overview

The NTP or PTP server operates in broadcast and server/client mode. Each packet is routed inside the network differently thanks to SDN and header inspection. A stratum 0 timing source can be obtained from a GPS signal.

Moving to the BM-SC, the newly introduced transparent delivery mode in Release 14 is leveraged. In this mode, the source packets (usually multimedia data, but in our case, NTP timing packets) are forwarded to the Serving Gateway without any re-encoding. Note that, SYNC protocol is mandatory and encapsulates the NTP packets, adding packet sequence and Time To Air (TTA) headers. This protocol is needed to guarantee Single Frequency Network operation at RAN level. SYNC works by defining a synchronization period, synchronization sequence, and timestamps. Detailed explanation of SYNC procedures can be found in [13] and [14].

3GPP has defined Service Based Architecture (SBA) for 5G which we propose to use for delivering accurate timing information based on SYNC procedures. The SBA allows to utilize local deployments of the mobile core right in the industrial plant. When the mobile device attach to the network the default AMF can be located in the cloud but SBA allows to redirect the attach to another AMF that will handle the network slice associated to the device. The network slices allow to isolate network resources for selected devices. This means an industrial floor could have different slices with own AMF to ensure low latency or reliability. This approach enables multiple 5G packet cores inside the industrial floor. The objective is to avoid sending CIoT to the 5G core on the cloud and d instead have a Industrial UPF or SCEF right in the gNB or first switch where the gNB is connected as shown in Fig 4. Considering a manufacturing plant where all the devices are connected to each other through Ethernet, some mobile devices will connect to the gNB in the plan and those devices would be immediately connected to the fixed Ethernet in the same plant.

The RAN is formed by one or several eNB, depending on the deployment chosen. Each eNB incorporates the Multicast Coordination Entity or MCE, a logical entity part of the eMBMS architecture, forming a distributed MCE deployment. The MCE role is to choose the radio parameters of the MBSFN based on the QoS Class Identifier (QCI) mapped to each multicast flow, and this decision must be consistent across all eNB in order to fulfil the MBSFN requirements. Operator must manually setup this allocation using Orchestration and Management (O&M) interfaces for every eNB involved in the transmission.

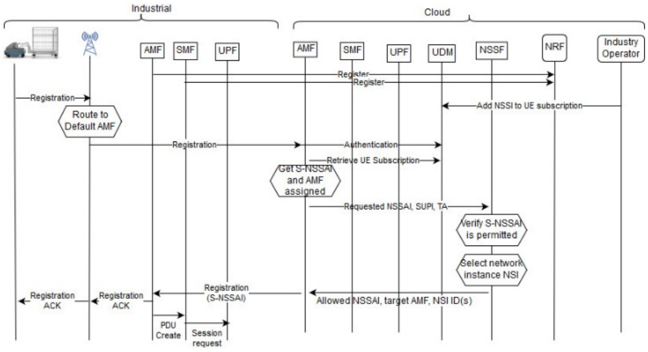

Fig.4. SBA for selecting 5G core in industrial floor.

Not all NB-IoT radio resources are needed to be allocated to eMBMS. In fact, NTP requires very little bandwidth to carry each multicast packet. The resource allocation of the radio frames dedicated to MBSFN can be found in the System Information Block 2 (SIB-2), where 3 parameters configure the allocation of the MBSFN subframes: *radioframeAllocationPeriod*, *radioframeAllocationOffset* and *subframeAllocation*.

The first parameter defines the interval between frames until a new MBSFN subframe is allocated, the second parameter indicates the starting frame relative to the System Frame Number 0, and the third parameter indicates which subframe inside the frame is the one carrying multicast data. Given existing value ranges of these parameters, the maximum period of multicast timing transmission is 1 MBSFN subframe every 32 NB-IoT frames. Choosing these values provide the least bandwidth consumption used for timing delivery, which is a very scarce resource in NB-IoT systems.

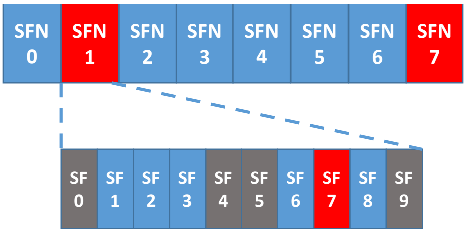

Fig.5. Frame structure showing System Frame Numbers (in blue) with embedded MBSFN subframes (in red). In this example, radioframeAllocationOffset is 1, radioframeAllocationPeriod is 6 and subframeAllocation is 000010.

Target receivers are IoT devices. IoT devices can cover from simple temperature, pressure, etc… sensors to complex precise equipment like production machinery, video surveillance and many other several applications. For this timing proposal system to work, all of the IoT devices must incorporate eMBMS capabilities. Low-end, simple devices restrained by memory and processing capabilities can make use of the multicast NTP to correct their internal clocks. High-end, precise devices can obtain PTP sync packets from the eMBMS transmissions and feed them to the dedicated PTP hardware in order to obtain more accurate timing information than NTP.

The delay experimented by the source NTP packets until they reach the IoT devices can be divided in: Core Network delay, eNB delay, Air Propagation delay and Receiver Processing delay. Core Network delay contains the transmission delay from the NTP source server and the NTP packet processing inside the BM-SC, basically, SYNC encapsulation. eNB delay comprises the transmission delay from the SGW, the required buffering time of the SYNC protocol and any internal processing time required by the eNB.

In order to successfully build end to end TSN network including both fixed and cellular links, requires having delay lower than 1ms. with cellular Air Propagation delay is the time taken by the radiated timing packets by the eNB to reach the IoT device. Finally, the Receiver Processing time is totally dependent on the device capabilities, alongside the time required to undo the eMBMS Physical Layer and deliver the packet to the device OS.

However, the use of SYNC protocol at the BM-SC can turn the Core and eNB delay into a deterministic delay. Since SYNC forces the eNB to put into air determined eMBMS packets, the overall delay from the NTP source server and the packets are radiated is contained inside the SYNC TTA headers. By adding the SYNC delay to the NTP timestamps as they cross the BM-SC, Core and eNB delay can be compensated. For the Air Propagation delay, the Timing Advancement procedure at Uplink used in LTE and NR can be exploited. When a terminal attach to the network using the RACH (Random Access Channel), the eNB evaluates the arrival time to the frame timing and tells the device to advance their transmission by an amount specified in the Timing Advancement Control Elements to avoid interference with other users. For example, in LTE [TS 36.213], this value is a 16 times multiple of the basic time unit $T_s$ (0,0325 µs) which provides a maximum timing range of $1282 * 16 * T_s = 666{,}64$ µs. If the IoT device OS has access to the Timing Advancement signalling used by the RF modem, the Air Propagation delay can be corrected by the upper layers. Finally, the Receiver Processing time, unless specific hardware is used for the timing correction, can be considered random.

## VI. CONCLUSIONS AND FUTURE WORK

The industrial Internet network requires a new transport to seamless connect mobile and fixed devices. Accurate timing to synchronize the devices is also required for manufacturing process. In this paper we propose 5G networks enhanced with the proposed transport based on non-IP and usage of eMBMS to delivery accurate timing information to the mobile devices. The next step consists of prototyping the delivery of timing information using eMBMS to measure the accuracy to correct clock offsets in mobile devices. This solution provides all the required enablers for industrial Internet connecting both mobile and fixed devices.

## ACKNOWLEDGMENTS

This work was supported in part by the Finnish public funding agency for research, Business Finland under the project 5G-FORCE part of 5G Test Network Finland (5GTNF).

## REFERENCES

[1] IoT specifications (https://www.3gpp.org/images/PDF/R13_IOT_rev3.pdf)

[2] eMBMS 3GPP TS 36.743 "Enhanced Multimedia Broadcast/Multicast (eMBMS) enhancements for LTE"

[3] Time Sensitive Networking IEE working group (https://1.ieee802.org/tsn/ )

[4] Profinet/Profibus (https://www.profibus.com/index.php?eID=dumpFile&t=f&f=51714&token=4ea5554cbb80a066e805a879116ead2a759c23c3)

[5] Common Industrial Protocol (https://www.odva.org/Technology-Standards/Common-Industrial-Protocol-CIP/Overview)

[6] Highway Addressable Remote Transducer (- SMART Communications Protocol, Common Tables Document, Revision: 9.0, Version:A Nov/15/96 (HCF_SPEC-183)

[7] Xuepei Wu, Lihua Xie: Performance evaluation of industrial Ethernet protocols for networked control application, Control Engineering Practice 84 (2019) 208–217.

[8] Mingyu Hana, Hao Guob, Peter Crossleya: IEEE 1588 time synchronisation performance for IEC 61850 transmission substations, Electrical Power and Energy Systems 107 (2019) 264–272.

[9] D. Mills, J.Martin, J. Burbank, W. Kasch:" Network Time Protocol Version 4: Protocols and Algorithm Specification", Internet Engineering Task Force, Request for Comments (RFC) 5095, June 2010.

[10] Andrew N. Novick, Michael A. Lombardi: "Practical Limitations of NTP Time Transfer", Joint Conference of the IEEE International Frequency Control Symposium & the European Frequency and Time Forum, 2015.

[11] 3GPP TR 26.850 v16.0.0 "MBMS for IoT" September 2018.

[12] Hong Wang, H. Vandervelde and S. Kim, "LTE MBMS SYNC protocol for support synchronisation of content," *2009 IEEE International Conference on Communications Technology and Applications*, Beijing, 2009, pp. 392-395.

[13] 3GPP TS 25.446 v15.0.0 "MBMS Synchronization Protocol SYNC" July 2018.

[14] 3GPP TS 25.436 v15.0.0 "Introduction of the Multimedia Broadcast/Multicast Service (MBMS) in the Radio Access Network (RAN); Stage 2" June 2018.

[15] 3GPP TS 36.213 v15.0.0 "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures" March 2019.