Feasibility and Performance Case Study of a Private Mobile Cell in the Smart Factory Context

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Abstract. Industrial applications in the era of Industry 4.0 require more flexibility for the integration of new sensors and actuators and also demand high mobility for which wired communication is unsuitable. For the integration of wireless communication systems in an industrial application, guaranteed high Quality of Service (QoS) is a premise that is not fully covered by wireless systems such as WiFi, Bluetooth, ZigBee or LTE. For the latter, the evolution to 5G systems as private or public networks is a currently ongoing process.

This paper examines the legal and technical requirements to operate a private mobile cell in a smart factory and presents measurements on latency and bandwidth performance of current state of the art hardware as well as the integration in an industrial Layer 2 communication system. The system in use is ready for only low demanding industrial real-time applications but, nevertheless, the advantages of a licensed frequency range for private use become visible. Furthermore, some concepts defined by the 3GPP, e.g. mini-slots and grant free transmission, are pointed out that are expected to enhance the QoS guarantees for industrial traffic.

1 Introduction

The upcoming changes on the road to Industry 4.0 arise new demands for the communication technologies. Nowadays, there is a heterogeneity of communication technologies with a diversity that is expected to even further increase in the future [14]. 5G is a promising technology to serve the requirements for high data rates, low latencies and real-time capabilities, especially for scenarios in which wired technologies are unsuitable.

While Release 15 sets a basis for future 5G developments and guarantees upward and downward compatibility for following specifications, the recently finalized Release 16 (June 2020) and future Release 17 (September 2021) target the service requirements for Industrial IoT, Ultra-reliable low latency communication (URLLC), Positioning and many more. In particular, Release 16 incorporates periodic and deterministic communication with stringent capabilities of timeliness and availability, mixed traffic, or precise clock synchronization of user-specific time clocks over the network as described in TS22.104 [1].

In order to use 5G systems in industrial applications in a reasonable way, it has to be integrated alongside various wired and wireless communication systems. Currently, most of the real time demanding industrial applications communicate over wired technologies on a layer 2 protocol base. The integration of 5G into Time Sensitive Network (TSN) or real time Ethernet (RTE) protocols, such as PROFINET has been studied in [8, 11, 10]. However, so far, there is no translation from the results pointed out theoretically in an evaluation of a real world test scenario. The aim of this work is to benchmark the QoS of current state of the art solutions and to pinpoint their bottlenecks.

Therefore, a setup with a private LTE cell operating as a 3GPP Non-Public Network (NPN) within the 3.7-3.8 Ghz frequency range inside the SmartFactoryOWL was designed. As depicted in Fig. 1, the Core Network (CN) hosted by a Mobile Edge Computing (MEC) system is connected to the factory's local subnet and Customer Premises Equipments (CPEs) integrate machines via Radio Access Network (RAN).

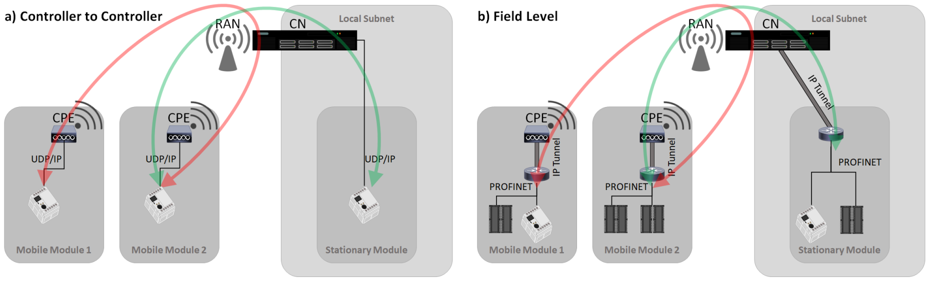


Fig. 1: Use Cases for a Mobile Network in the SmartFactoryOWL

In the first use case, the small cell network will be used to interconnect the modules of a modular production system via their control units according to part a) of Fig. 1. The module controllers use a UDP/IP based protocol for the exchange of information, such as discrete process status values. Here, the small cell network can be integrated directly since it supports the function of an IP router. This use case corresponds to the Control-to-Control communication in the application area of Factory Automation of the vertical domain Factories of the Future in [1]. Part b) of Fig. 1 shows the principal setup of the second use case in which decentralized I/O-System of the modular process plant in the SmartFactoryOWL is connected via the CPE to the RAN. The process module consists of a controller and I/O-stations. The cyclic process data exchange is transmitted via PROFINET RT protocol. The available NPN does not allow

Layer 2-based integration and one approach to overcome this is to tunnel the Layer-2 traffic through the network, see [9]. This use case corresponds to the closed-loop control in the application area of process automation of the vertical domain factories of the future in [1].

2 5G Non Public Networks (NPN) in Industry

NPN is the designation of 3GPP for a private local area network with dedicated equipment and settings. It supports industrial players to run one or more industrial applications with diverse requirements by providing dedicated coverage, exclusive network capacity which is crucial for high availability even at remote locations and intrinsic control for adjusting appropriate security policies and optimal settings for traffic treatment, see also [6]. From a functional perspective, four different basic deployments of a private network are possible, according to [4]. First, in a standalone deployment, the network is fully separate from any public network and all the data flows and network functions remain in the premises of the site owner. Second, in a shared RAN deployment, the private and the public networks share the RAN, where an own identity of the private network confines the user data of the private network at the industrial site. The network control functions remain completely separated. Third, in a fully shared deployment, also the network control functions are handled by the public network. And fourth, a NPN can be hosted by a public network, for example by means of network slicing. In this case the user data are not confined to private premises but access to public network services and the ability to roam can be implemented easily. Furthermore, the usage of 5G in an industrial environment can be classified depending on the level of its integration, as described in [13]. The integration can be realized either based on a CPE as an additional device that provides 5G access to one or more networked devices typically as an IP router or based on radio modules that are typically pre-certified and connected to networked device by an internal bus such as PCI Express or based on chipsets to be supplemented and attached to a printed circuit board of a networked device. In the afore mentioned succession, both the level of effort and complexity and the possible effectiveness are increasing.

In this work a standalone deployment is used for the investigations. With respect to the operator model, the system is owner-operated with an option for remote monitoring and maintenance by the supplier. CPEs are utilized for integration of 5G to the industrial equipment.

3 System Application in the Smart Factory

3.1 Setup and configuration

The installed mobile edge cloud system consists of a MEC server which can run applications in virtual machines and has reasonably powerful memory and CPU hardware. The server is connected to the base station subnet with the base stations operating in different frequency ranges located between 3700 and 3800 MHz in the B43 frequency band. In Germany, this range can be licensed by the federal network agency (Bundesnetzagentur) for local campus networks independent from a mobile network operator and allows the usage of Time Division Duplex (TDD) within the licensed area. In the current setup two base stations are available, both providing a 20 MHz bandwidth and allowing to double the bandwidth by activating a carrier aggregation mode. Another opportunity for adapting the RAN to the application requirements is given with the TDD subframe configuration. With respect to [3], ten subframes build a frame of 10 ms duration. Here, the time slots can be allocated to privilege uplink traffic or downlink traffic or to balance both directions. This setting affects the number of uplink and downlink subframes and is statically applied to the whole network. Furthermore, QoS differentiation can be configured. The present network supports two QoS classes called default (according to 3GPP QoS Class Indicator (QCI) 9: non-guaranteed bit-rate, Packet Delay Budget (PDB) 300 ms) and real-time (according to 3GPP QCI 3: guaranteed bit-rate, PDB 50 ms). Currently, the QoS is associated to a CPE, i.e., all uplink and downlink traffic of a CPE will be mapped to the same bearer getting the same priority. In addition to this setup, CPEs of two fabricators are in use. They are differing in the processing unit, the radio module and the Multiple Input Multiple Output (MIMO) capabilities. Each device in use supports a 20 MHz bandwidth. Static conditions of radio propagation ensuring line of sight are realized throughout the measurements.

3.2 Initial measurements

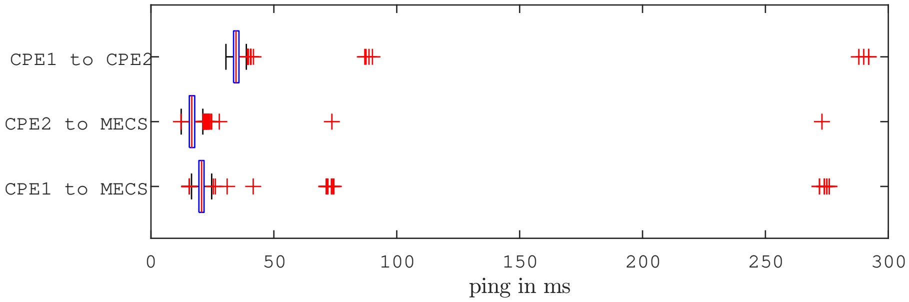


Fig. 2: Ping measurement results

In Fig. 2 and 3 the system was evaluated by means of plain ping and iperf measurments to determine the round trip time and the throughput of the system, respectively. All measurements have been performed both way round and the position of the CPE was chosen to have a short distance line of side connection to the base station. The tested CPEs were the only active devices while all other

CPEs have been switched off, i.e. at maximum two CPE were connected to the base station.

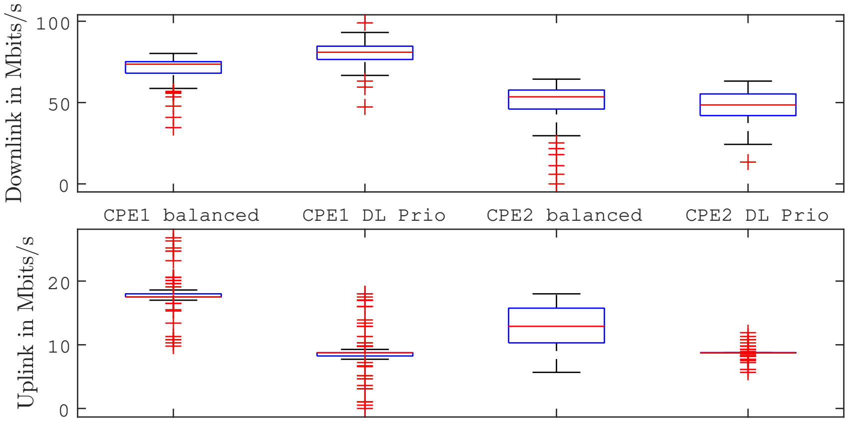


Fig. 3: Iperf measurement results

Fig. 2 shows the results of three different ping measurements between one of each CPEs and a VM running on the MECS as well as the ping times between one CPE and another. It can be seen that the CPEs have different ping performances. The median of CPE1 is 20.7 ms whereas CPE2 decreases the round trip delay to a median of 16.6 ms. The ping between both CPEs is slightly below the sum of the two other measurements. The retransmission intervals of the system can be seen with a look at the outliers of the boxplots that are approximately 50, and 250 ms delayed compared to the quartile borders of the corresponding boxplots. Another outlier which is delayed about 450 ms is not shown due to better visibility.

The downlink and uplink bandwidth measurements depicted in Fig. 3 have been performed with the test tool iperf3 using 1 ms intervals. At first, CPE1 has been tested with two different TDD frame structures according to [3]. The first frame structure has an equal number of uplink and downlink subframes per frame whereas the second one has a higher number of downlink subframes and thus the downlink-rate rises while the uplink-rate decreases. In comparison, the measurements of CPE2 do not show a significant increase of the downlink throughput. Note that the uplink measurement of CPE1 has a high amount of outliers. These appeared in all repetitions of the experiment and can be reffered to the iperf measurement since each lower outlier was followed by an upper outlier. The theoretical limitations given by the fabricator are 19 and 9 Mbits/s of the uplink as well as 71 and 101 Mbits/s for the downlink with the balanced and downlink priorized frame structure, respectively. Due to active works on the synchronization of the base stations with the precision time protocol, the measurements could not reach the bounds given in theory.

3.3 Measurements under industrial conditions

In order to investigate the performance of the system in an industrial application with the variety of different communication types, Deterministic Traffic (DT) and Burst Traffic (BT) according to [5] have been generated. DT patterns, e.g. sensor data or control messages require a low latency communications since the receiver needs to process the data. The most characteristic metrics of DT are transfer interval and message size. The DT is either periodic due to a sample frequency or PLC cycle time or can be aperiodic if the messages are triggered by a process. Depending on the application itself and the integration level of the 5G system, the message size varies. On the other hand, BT usually consists of one or more large data packets, e.g. high resolution cameras inducing uplink traffic or firmware updates inducing downlink traffic, that use the highest available data rate without stringent latency requirements. Its most characteristic metrics are average and peak data rate.

For testing purposes, two CPEs have been connected to a base station without carrier aggregation and thus they mutually impact the communication of each other due to the limited availability of transmission slots. To both CPEs clients are attached that generate uplink traffic. One of these clients, connected to CPE1, generates a BT with iperf to simulate a video upstream and the other, connected to CPE2, is periodically sending a UDP packet including Ethernet frame with the minimum size of 64 bytes to simulate sensor data, respectively. A sampling frequency of 100 Hz is assumed for the sensor and thus the messages are sent with 10 ms intervals.

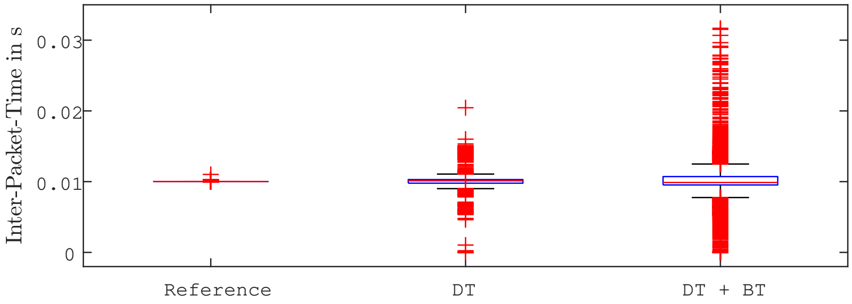


Fig. 4: Deterministic Traffic Jitter

The relevant measures for the DT is the latency jitter. In most closed loop controls, the PLC processes the incoming sensor data in the order of arrival. Delays of 50 or 250 ms and more due to retransmissions in the system make old measurement results appear in between more recent values. Thus, outdated measurement values might be treated disturb the closed loop control in fast changing processes. In Fig. 4, the latency jitter of the DT is displayed. A reference value was measured at the network interface of the transmitting client. With no other CPEs online the DT has a higher jitter due to the TDD slot alignment and the unsynchronized times between the packet generation and the time of the 5G system. If less uplink slots are allocated to the device, the jitter further increases as seen on the right hand side of Fig. 4 where the BT occupies uplink slots. Thus, the jitter increases to a maximum of 30 ms meaning that two consecutive packets have not been received properly in time.

For the BT which are not latency-critical, the measurements concentrate on the reached throughput as a key performance indicator (KPI). As depicted in Fig. 5, a drop of the data rate can be seen for the uplink and downlink measurement results.

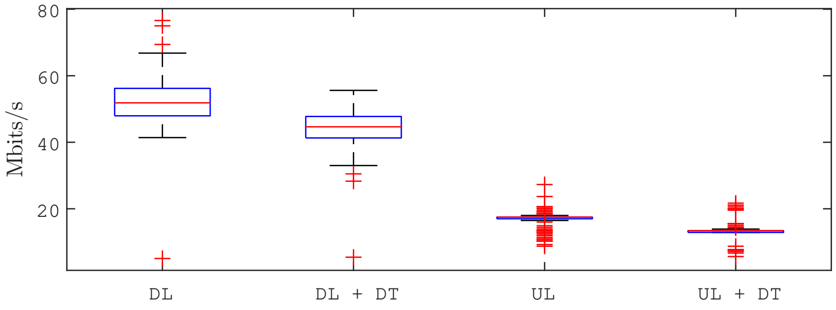


Fig. 5: Burst Traffic available data rate

4 Layer 2 Tunnel Integration

4.1 Setup

Industrial Ethernet Protocols use OSI layer 2 functions to make deterministic real-time communication possible. PROFINET I/O uses layer 2 techniques like VLAN priority tagging (802.1Q) or TSN (Time Sensitive Networking). Therefore basic router respectively IP communication does not fulfill these requirements. For this reason a layer 2 tunnel is necessary to send the traffic through the networks. Tunneling means the data is encapsulated in another protocol e.g. L2TP, OpenVPN, GRE or PPTP are only some of the protocols. The tunneling can be done with a client-server model or a site-to-site connection. With a client-server model the clients are responsible to connect to the server, encapsulate and encrypt the data which means the client needs to have a VPN Client (software) and the resources to handle the VPN traffic. A Site-to-site tunnel connects two independent networks together and can provide the same subnet on both endpoints. The clients in the VPN network can send and receive data as usual in this subnet. The connection, the encapsulation and the encryption of the data is handled by additional hardware usually a router or a gateway.

In this use case the layer 2 tunneling is implemented in a quality control demonstrator in the SmartFactoryOWL. This demonstrator inspects corn and sorts out defective corns or some impurities. The corn is stored in a tank and drops on a conveyor. A camera inspects these corns and if the algorithm detects a defective corn a blast pipe blows the corn through a small gap down to another tank.

The model is controlled by a Hilscher PLC with Codesys Control and uses decentralized Phoenix Contact I/O system for analog and digital Inputs and Outputs. According to the Profinet system description the I/O update cycle times can individually set for each component. The cycle times depend on the protocol (Profinet RT or Profinet IRT) and can range from 250 µs to 512 ms. The devices communicate via PROFINET RT and I/O-update cycle time is configured to 16 ms. In this use case the PLC is connected via wired network to the Service Network Interface. The decentralized I/O is connected wireless via a Sercomm CPE to the base station. Since the decentralized I/O cannot provide a layer 2 tunnel, the VPN tunnel has to be implemented via additional hardware as a site-to-site connection. One cost-effective solution is the Ubuquitos Unifi EdgeRouterX. The EdgeRouterX provides two possibilities to implement site-to-site layer 2 tunnel OpenVPN or EoGRE (over IPSec). The setup is shown in Figure 6.

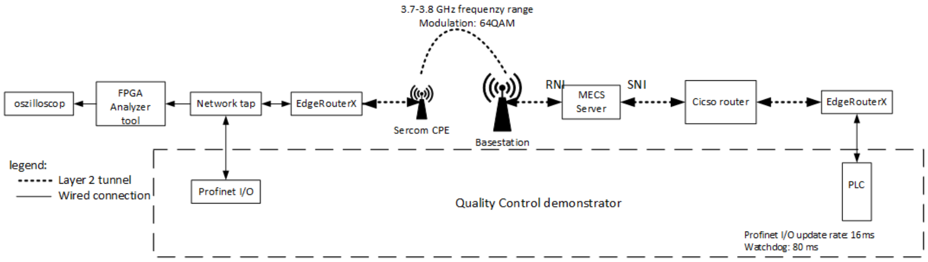
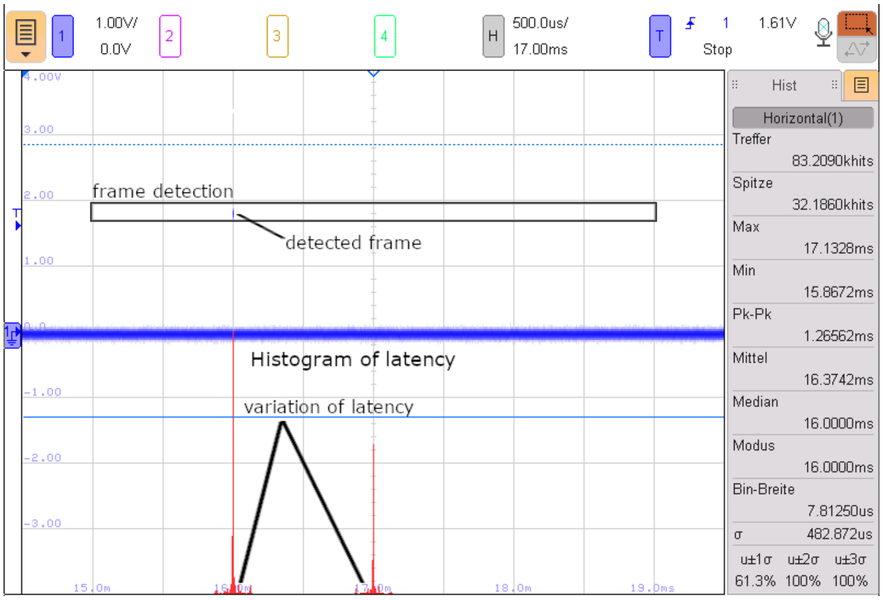


Fig. 6: LTE testsetup

The configuration of the EdgerouterX works via the webinterface or the command line. The EdgeRouterX is configured as a OpenVPN Site-to-site layer 2 tunnel as describe in [12]. Only the IP address are adjusted for this use case. In this configuration OpenVPN communicates via UDP.

4.2 Measurements

One critical system parameter in a deterministic PROFINET communication is the variation of latency from data packets (jitter). To inspect the frames a PROFINET TAP is connected between the Profinet I/O and the EdgeRouterX as seen in Figure 6. To measure the jitter one of the incoming frames is used as a trigger. The black frame in figure 7 determines an observation space and within in this space the oscilloscope measures the time until the next Profinet RT frame appears. The vertical blue line shows a detected frame. The red bars show the histogram of the latency. Every red bar illustrates a measured frame. The higher a red bar is the more frames were detected with this latency. In an ideal network there would only be one red graph in the histogram.The more red bars are spread in the histogram the more variation in latency (jitter) is in the system. Figure 7 shows the direct connection between the PLC and the Profinet I/O with a layer 2 tunnel without LTE connection.



Hist
Horizontal(1)
Treffer 83.2090khits
Spitze 32.1860khits
Max 17.1328ms
Min 15.8672ms
Pk-Pk 1.26562ms
Mittel 16.3742ms
Median 16.0000ms
Modus 16.0000ms
Bin-Breite 7.81250us
σ 482.872us

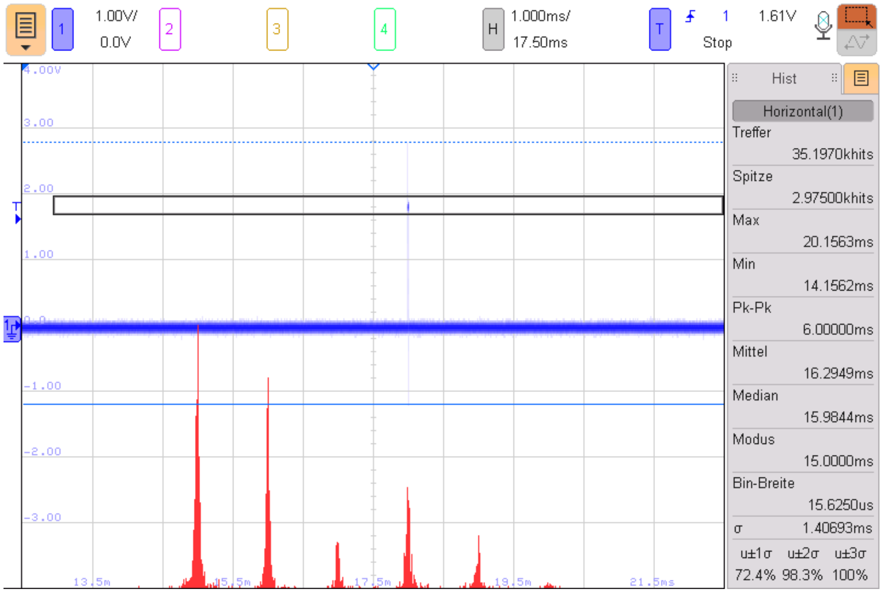
u±1σ	u±2σ	u±3σ
61.3%	100%	100%

Fig. 7: Layer 2 Tunnel cable connection

Figure 7 shows that there is a jitter in the system. 68.7 % of the Frames are within a deviation of ±493 µs where 99.6% are within a deviation of ±987 µs. Figure 8 shows the wireless connection between the PLC and Profinet I/O as shown in Figure 6. The dispersion of the red bars indicate that there is more jitter from the wireless connection in the system. 68,7 % of the latency values are within ±1.4 ms. 98.3 % are within ±2.8 ms deviation.

5 Outlook on future 5G mechanisms

With the ongoing 3GPP specification work in view, further desirable developments will increase the QoS of an NPN in industrial applications. In terms of URLLC, the key to reduce the latencies in a TDD communication system is an



Horizontal(1)
Treffer 35.1970khits
Spitze 2.97500khits
Max 20.1563ms
Min 14.1562ms
Pk-Pk 6.00000ms
Mittel 16.2949ms
Median 15.9844ms
Modus 15.0000ms
Bin-Breite 15.6250us
σ 1.40693ms
u±1σ 72.4%
u±2σ 98.3%
u±3σ 100%

Fig. 8: Layer 2 Tunnel wireless connection

optimal usage of the available slots to shorten the time until the packet is transmitted. This time depends on the processing time, the scheduling policy and the minimal available Transmission Time Interval (TTI). Whereas the current setup allows TTIs of 1 ms, i.e. a subframe, with a static subframe assignment, the TTIs can be reduced with wider subcarrier spacing or by means of mini-slots that allow uplink/downlink slot assignments down to the length of one Orthogonal Frequency Division Multiplexing (OFDM) symbol in 5G NR systems as introduced by 3GPP in TR38.912 [2]. The reduction of the TTI impacts the latency if the scheduler allows immediate mini-slot scheduling without the necessity to schedule the complete subframe or frame before the start of its transmission. To reach low latencies for the uplink, grant free transmission support and configured grants are effective approaches. In particular, DT suffers from obsolete handshakes that can be avoided in deployments similar to Section 3.3 if the periodic transmission is granted once and each frame has a reserved uplink slot for the sensor data. Further concepts for latency and reliability improvements are discussed in [7]. As 3GPP Release 16 was recently finalized in June 2020, the specified mechanisms still need to be implemented by the manufacturers to achieve a 5G NPN that guarantees high QoS.

The afore mentioned improvements will be seized by the fabricator of the investigated NPN by adopting upcomming 3GPP releases. In addition, further QoS differentiation is in preparation by using source address and port, destination address and port and protocol type (also known as 5-tuple) as a determinant for QCI assignment as well as implementing new QCI values designated for industrial type traffic. With respect to the integration of the NPN into the industrial setup, an improvement of the efficiency by utilizing radio modules internal to industrial devices is considered to replace CPEs.

6 Conclusion and Future Work

The paper shows how a private mobile network can be configured to transport data between mobile equipment at the factory shop floor. Measurement results of the basic performance characteristics of the the concrete setup of a NPN are provided as a step towards the implementation of two use cases at the in a close to the real environment which is SmartFactoryOWL. The measurement results show a gap between the theoretical results for the datarate and the measurement results. Opportunities and limits of nowadays available 3GPP small cells with respect to their integration into industrial Ethernet based communication technologies are discussed. Figures for the KPIs of different integration approaches are presented which allow an outlook to the next level of 5G mobile network integration towards isochronous real-time behavior as given with TSN. The overview over upcoming changes in 3GPP systems in Section 5 gives a brief summary about what might be possible with future deployments.

In the future, an integration of the private network into real industrial applications is planned evaluate the system as part of a heterogeneous system such as a demonstrator for a versatile production. With regard to the future 5G developments, the measurements carried out in this paper will be used as KPIs.

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