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Measurement and comparison of data rate and time delay of end-devices in licensed sub-6 GHz 5G standalone non-public networks

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Abstract

The fifth mobile communications generation (5G) offers the deployment scenario of licensed 5G standalone non-public networks (NPNs). Standalone NPNs are locally restricted 5G networks based on 5G New Radio technology which are fully isolated from public networks. NPNs operate on their dedicated core network and offer organizations high data security and customizability for intrinsic network control. Especially in networked and cloud manufacturing, 5G is seen as a promising enabler for delay-sensitive applications such as autonomous mobile robots and robot motion control based on the tactile internet that requires wireless communication with deterministic traffic and strict cycling times. However, currently available industrial standalone NPNs do not meet the performance parameters defined in the 5G specification and standardization process. Current research lacks in performance measurements of download, upload, and time delays of 5G standalone-capable end-devices in NPNs with currently available software and hardware in industrial settings. Therefore, this paper presents initial measurements of the data rate and the round-trip delay in standalone NPNs with various end-devices to generate a first performance benchmark for 5G-based applications. In addition, five end-devices are compared to gain insights into the performance of currently available standalone-capable 5G chipsets. To validate the data rate, three locally hosted measurement methods, namely iPerf3, LibreSpeed and OpenSpeedTest, are used. Locally hosted Ping and LibreSpeed have been executed to validate the time delay. The 5G standalone NPN of Reutlingen University uses licensed frequencies between 3.7-3.8 GHz and serves as the testbed for this study.

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Keywords: 5G; standalone non-public network; measurements; end-devices; download; upload; data rate; time delay;

1. Introduction

The fifth mobile communications generation (5G) is seen as an enabler technology for various industrial applications in manufacturing, such as autonomous mobile robots and robot motion control based on tactile internet [1–3]. 5G focuses on ultra-reliable low-latency communication (uRLLC) for reliable real-time data transmission, enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC) for Internet of Things (IoT) scenarios that require a mass end-device density. The defined target capabilities of 5G promises to offer a theoretical download speed up to 20 Gbit/s, latencies in the millisecond (ms) range down to 1 ms round-trip time (RTT) and a density of one million devices per square kilometer [4,5]. However, the 5G telecommunication standard is still in the development phase and yet cannot deliver the targeted performance [6]. The 5G standard is specified in releases within a continuous release process by a consortium of seven organizations called the 3rd generation partnership

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project (3GPP). In 2018, 3GPP provided the first full set of 5G standards with Release 15 (Rel-15). While previous releases focussed on Non-Standalone (NSA) networks, Rel-15 introduced the possibility of Standalone (SA) networks [7]. In contrast to NSA networks which leverage existing Long-Term Evolution (LTE) core networks and only carry out the communication between the terminal and the antenna based on 5G protocols [5], SA networks operate on their own dedicated 5G Core (5GC) [8]. Furthermore, the deployment of Non-Public Networks (NPN) enables setting up a customizable, local and high-security network mainly required by industry for safe data transmission [9]. NPNs are locally restricted and operate on licensed frequencies in a restricted area. In Germany, for example, frequencies between 3.7-3.8 GHz are available for NPN [10]. Since the development process of 5G continues until 5G reaches its full capacity for industrial operations, it is essential to investigate the technology early to provide an initial assessment for future realizations in the industry.

2. Literature review and contribution of the paper

Academic publications on measurements of 5G SA NPNs and SA-capable end-devices in non-laboratory environments are currently not present. Available literature focuses on measurements under laboratory conditions or simulations [11,12]. Some studies extend their research on 5G wave propagation in different outdoor and indoor scenarios [13–17] and wave propagation at different frequencies [18–20]. For example, with the focus on mm-Wave frequencies for the 5G technology [21–24]. Regarding different deployment scenarios of 5G networks, most of the literature researches NSA networks [25–28]. For example, a study from Zayas et al. [25] proposes an experimentation methodology for testing 5G and their key performance indicators (KPIs). The methodology is validated by measuring the data rate and the RTT in line-of-sight (LOS) and no-line-of-sight (NLOS) scenarios in a NSA network. Xu et al. [28] measure similar KPIs such as the RTT, the coverage, signal strength and throughput in a NSA network. In contrast, Huang et al. [29] adopt an Artificial Intelligent (AI) supported outdoor SA network purely based on 5G NR to measure the data rate and the time delay. Nonetheless, the study does not investigate an indoor SA NPN within a typical industrial facility and scenario. A recent study from 2021 by Rischke et al. [9] provides one-way download and upload packet delays and losses measured in a licensed indoor SA NPN. Additionally, Rischke et al. [9] compare the results to measurements conducted in a NSA network. The presented one-way download delays in the SA testbed are in 95% of the measurements between 4-10 ms. However, the deployment of licensed SA NPN is still in an early stage, and a time lag exists between the specification of releases and the implementation in end-devices. Thus, SA NPNs have not been widely adopted yet, resulting in a lack of academic literature on measurements, especially on the data packet level. Efforts have been made to fill this gap on 5G measurements before components are commercially available through laboratory experiments and simulations. In contrast, this paper presents measurements of end-devices conducted in a SA NPN within a typical industrial facility equipped with a commercially available 5G network infrastructure in which influencing factors are not eliminated.

3. Testbed and measurement setup

This chapter is divided into four parts. Part one describes the network specification, part two the data traffic generation tools, part three the end-devices, and part four finally describes the measurement procedure.

3.1. Testbed and network configurations

The 5G SA NPN of Reutlingen University serves as the testbed for the measurements. The network architecture and the measurement setup are shown in Fig. 1.

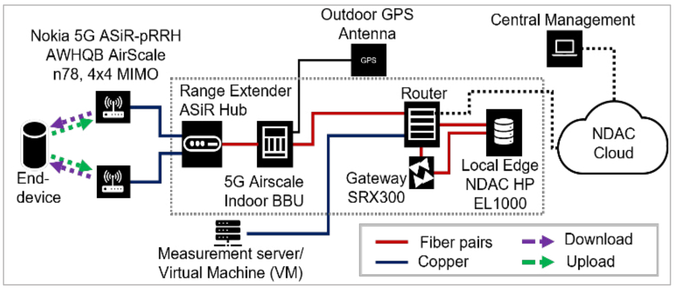


Fig. 1. Network architecture of the testbed.

The radio access network (RAN) is based on the indoor AirScale system module from Nokia and operates on licensed frequencies between 3.7-3.8 GHz. The RAN is equipped with two ASiR-pRRH (AWHQB) AirScale antennas with 4*4 multiple-input multiple-output (MIMO) transmission operating on the n78-band and maximum transmission power of 250 mW. The baseband unit (BBU) is based on ASIK and ABIL components (gNodeB). The 5G core network (CN) runs on the local NDAC Edge HP EL1000. For clock master synchronization, a GPS antenna is installed outside the building connected to the BBU. The radio uses the time division duplex (TDD) method with a download-to-upload ratio of 70% to 30%. At the time of the measurements, Rel-15 based on 3GPP's releases is implemented. To run the traffic generation tools, a Linux-based virtual machine (VM) on a locally hosted edge-server is used equipped with an Intel (R) Xeon (R) Silver 4116 Central Processing Unit (CPU) at 2.1 GHz. The VM has eight virtual CPUs and 8-gigabyte Random Access Memory. An overview of the network configurations is shown in Table 1.

Table 1. Network configurations set up for the measurements.

Characteristics	Network configuration
Radio Access Technology	5G New Radio (2 Radio Heads in total)
5G Network Deployment	Standalone
Frequency spectrum	3.7-3.8 GHz
Bandwidth	100 MHz
Band	n78
5G Core Network Version	6.2021.35.2974
gNB/ BBU Version	5G20A
Software release	Release 15 (according to 3GPP releases)
Transmitting power	50 mW (~17 dBm)
Transmission mode	Time Division Duplex (TDD)
Download-to-Upload Ratio	70% to 30%
Subcarrier spacing	30 kHz

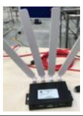
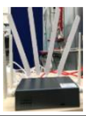
3.2. Data traffic generating tools

For the data traffic generation, open-source tools, namely iPerf3, LibreSpeed and OpenSpeedTest, were selected. The source codes are available on GitHub [30–32]. iPerf3 served as the reference tool identified in a conducted pre-analysis based on existing studies [33,34]. OpenSpeedTest and LibreSpeed validated the measurements. All three methods only used the transmission control protocol (TCP) for communication, and the maximum transmission unit (MTU) was set up to 1500 bytes for all testing series to ensure comparability of the measurements. The tools are implemented and executed locally only on a network-internal server without connection to public networks. The download and upload are measured with iPerf3, LibreSpeed and OpenSpeedTest. Regarding the time delay, the RTT is measured by the *Ping*-command and LibreSpeed on the CN side. For the measurements, the data packets are sent from the end-device via the air interface to the AirScale antennas, then to the 5G backend and finally to the speed test server (see Fig. 1.). OpenSpeedTest and LibreSpeed are both web-based speed tests where each measurement is triggered manually. In order to be able to perform several measurements in series, the web pages are modified to enable automatic repetition of the measurements after a specific time and an export function. For the tests, the end-devices were connected to a Linux notebook except for the Waveshare 5G module, which can currently only be used with a Raspberry Pi and its released driver.

3.3. End-devices

Five end-devices for the data collection are selected to enable insights into SA-capable chipsets and their performance. Table 2 provides an overview of the end-devices and their specifications in detail.

Table 2. Specifications of SA-capable end-devices used for the measurement.

End-device	Nokia SRS621 Router 	Huawei P40 Pro+ 	Quectel USB Modem 	M2M SIMCom 5G Module 	Waveshare 5G Module 
5G Module	FM150-AE(M2)	Kirin 990 5G	RM500Q-GL(M2)	SIM8200 EA-M2	SIM8200E A-M2
5G Chipset	SDX55	Balong5000	SDX55	SDX55	SDX55
Max. download	2.1 Gbit/s	2.3 Gbit/s	2.1 Gbit/s	4 Gbit/s	2.4 Gbit/s
Max. upload	900 Mbit/s	1.25 Gbit/s	900 Mbit/s	500 Mbit/s	500 Mbit/s
External interface	Ethernet (CAT6)	USB-C 3.1	USB 3.0	Ethernet (CAT6)	USB 2.0
Software version	SQM06 _V1.1.5	11.0.0.193(C432E3R5 P3)	RM500QG LABR11A 03M4G	V1.4.4	SIM8200 M44A-M2_V1.20

A different 5G module based on a 5G chipset is used for each end-device. The chipsets are mostly Qualcomm's Snapdragon X55 5G Modem-RF System (SDX55) with a transmission rate of up to 7.5 Gbit/s [35]. In contrast, Huawei's 5G module integrates the Balong5000 chipset with a maximum transmission rate of 4.6 Gbit/s [36]. Thus, the modules' performance differs due to the architecture of the 5G module and the provided external interfaces. For example, USB2.0 has a theoretical maximum data transmission of 480 Mbit/s [37]. This limiting factor needs to be considered for the Waveshare 5G module, as this module is installed on a Raspberry Pi3. A Raspberry Pi3 was used despite the limitations of 480 Mbit/s of the external USB2.0 interfaces, as the supply shortages and the lack of chips prevented the availability of Raspberry Pi4. In contrast, USB3.0 can transmit data with a speed of up to 5 Gbit/s [38]. USB3.1 and Ethernet (Cat6) up to 10 Gbit/s [39,40]. As a result, the manufacturers' specifications for maximum download and upload rates vary.

3.4. Measurement execution and scenario

The indoor 5G SA NPN at the learning factory of Reutlingen University serves as the measurement environment. The 5G SA NPN is managed by a third-party provider via the NDAC cloud in terms of services and central management. The shop floor at the learning factory is 775 m² large with a ceiling height of 8 m. The 5G infrastructure, in contrast to numerous laboratory studies, is set up in a typical industrial facility in which influencing factors on the 5G communication are not eliminated to recreate industrial circumstances. The end-devices are surrounded by assembly lines, machines, robots and warehouse racks. Moreover, metallic and concrete materials encircle the end-devices. Industrial equipment and materials can impact wireless communication by absorbing, reflecting, diffracting or scattering the waves [41], which can provoke interferences and additionally stress the air interface. Therefore, other wireless technologies such as Bluetooth, Wi-Fi, ZigBee and various localization technologies transmit data during the tests. In contrast to simulations, data packet modifications and performance-based network optimizations were not carried. Furthermore, this study mainly addresses uRLLC and eMBB scenarios rather than mMTC scenarios in which multiple end-devices transmit data simultaneously. Therefore, only the end-device that was used to measure the performance was logged in to the 5G SA NPN.

Regarding time-critical applications, the antenna's position is essential and typically coordinated with the application's operational area to guarantee direct LOS communication. For this reason, the end-device transmit data in direct LOS 8 m below the second antenna in this study. The antennas are installed under the ceiling and surrounded by wood and steel girders, as they are often found in industrial buildings. iPerf3 has been selected as the reference tool in analyzing existing studies [33,34]. LibreSpeed and OpenSpeedTest measurements serve as validation. The measurement tools were performed for each of the five end-devices in sequence to execute data rate tests. Concerning the RTT, only the Ping-command and LibreSpeed provided data. 50 data points were collected per measurement in a 10-second interval. In sub-experiments, 50 data points proved to be suitable, as the median showed almost no change from this point on.

4. Measurement results and end-device comparison

The following sections present the measured results of data rate and time delay KPIs and compare the performance of the measured end-devices. A detailed summary closes this chapter.

4.1. Data rate results and comparison

The Nokia SRS621 Router, the Huawei P40 Pro+ and the Quectel USB Modem have a comparatively high download rate than the M2M SIMCom 5G Module and the Waveshare 5G Module. The Nokia SRS621 Router has a download value range of 646.4 Mbit/s to 768.4 Mbit/s depending on the measurement tool. Huawei's P40 Pro+ does perform slightly better in download with 657.1 Mbit/s measured with OpenSpeedTest and 830.4 Mbit/s with LibreSpeed. The Quectel USB Modem shows almost identical performances in download with a median of 748.4 Mbit/s measured with OpenSpeedTest and a median value of 751.2 Mbit/s measured with LibreSpeed. The M2M SIMCom 5G Module shows similar measurement results with OpenSpeedTest, LibreSpeed and iPerf3 with under 200 Mbit/s. The boxplots for the download rate of the end-devices are shown in Fig. 2.

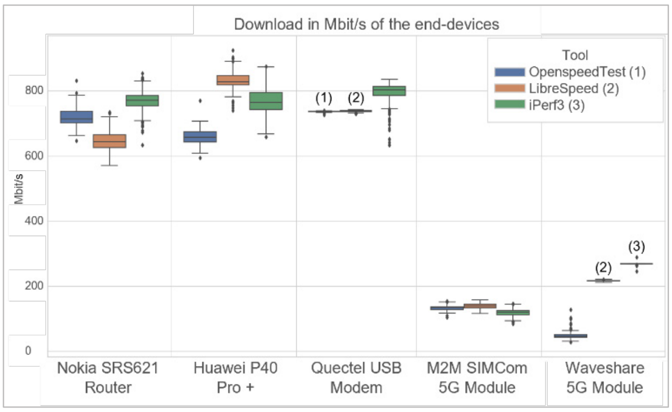


Fig. 2. Boxplot diagram of the download in Mbit/s per end-device and tool.

Regarding SIMCom's M2M 5G Module, LibreSpeed shows the maximum median download rate of 139.2 Mbit/s from the three measurement tools used. The measured data rate in the download of the Waveshare 5G Module is significantly below 300 Mbit/s with the values of 50.9 Mbit/s measured with OpenSpeedTest, 215.9 Mbit/s (LibreSpeed) and 267.7 Mbit/s with iPerf3. The external USB2.0 interface of the Raspberry Pi3 used for the Waveshare 5G Module is limited to 480 Mbit/s. Despite using a Raspberry Pi3 due to the supply shortage of available Raspberry Pi4's, the measured download with a USB2.0 interface is still below its theoretically limited capacity of 480 Mbit/s. In general, all end-devices do not reach the download performance that is limited by their hardware. The boxplot diagram for the upload data rate in Mbit/s per end-device is shown in Fig. 3. The upload per end-device varies, ranging from a median value of 83.1 Mbit/s measured with iPerf3 for the Waveshare Module to a median of 181.2 Mbit/s for the Huawei P40 Pro+ Smartphone measured with LibreSpeed. The Nokia SRS621 Router show a stable and comparatively high upload range from 171.2 to 180.6 Mbit/s. In particular, the Huawei P40 Pro+ and the Quectel USB Modem have an unstable upload with large oscillations.

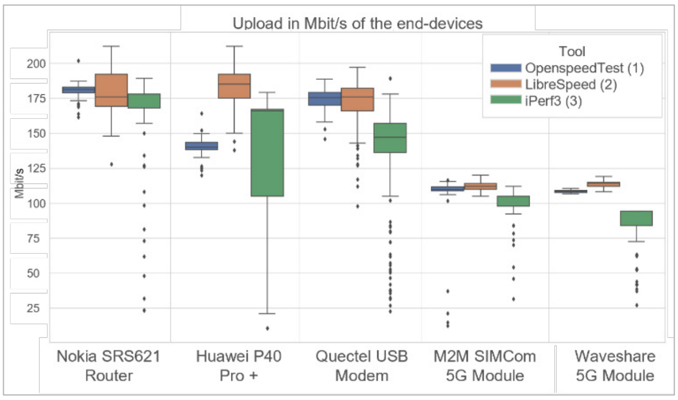


Fig. 3. Boxplot diagram of the upload in Mbit/s per end-device and tool.

4.2. Round-trip time results and comparison

Regarding the RTT, upward outliers can be observed in all measurements with Ping and LibreSpeed. These outliers occur at the beginning of each measurement series because the tools adaptively adjust the data packets over the measurement time. The results of the RTT are presented in Fig. 4.

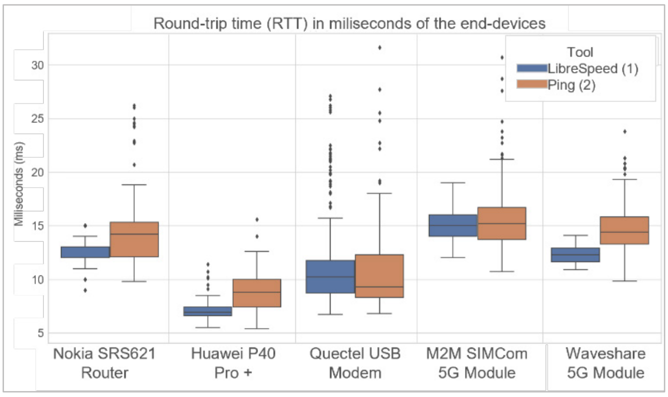


Fig. 4. Boxplot diagram of the RTT in ms per end-device and tool.

Huawei's P40 Pro+ smartphone has performed the lowest average RTT of all end-devices of 7.2 ms with LibreSpeed and 8.8 ms with *Ping*. The Quectel USB Modem achieves an average of 10.5 ms and 9.4 ms. The other end-devices are, on average, substantially above the 10 ms threshold.

All end-devices show values almost twice as high as the average RTT regarding the maximum RTT. The Huawei P40 Pro+ with the Balong5000 chipset achieves a maximum RTT of 15.6 ms with *Ping* and 11.4 ms with LibreSpeed. In addition, the 50 measurement points with a standard deviation of 1.7 ms and 1.1 ms in both measurement series are close to the median compared to the other end-devices. In the *Ping* measurement series, except for the Huawei P40 Pro+, all end devices are close to 30 ms for maximum RTT. The LibreSpeed measurement series displays lower maximum RTTs in total. In this respect, both the Nokia SRS621 Router and the Waveshare 5G module are close to the minimum values achieved by Huawei. The standard deviation for LibreSpeed is considerably lower for each end-device than the *Ping* measurements. Here, the Waveshare 5G module achieves 0.9 ms, followed by the Huawei P40 Pro+ with 1.1 ms. Compared to the other end devices measured with LibreSpeed, the Quectel USB modem records the highest maximum RTT of 27.5 ms with a standard deviation of 3.5 ms.

4.3. Summary of the measurements

A detailed summary of the results is presented in Table 3. Both data rate and time delay KPIs are shown for each tool and end-device, respectively.

Table 3. Summary of data rate and time delay KPIs per end-device and tool.

		Data rate		Time delay			
	End-device	Avg. download (Mbit/s)	Avg. upload (Mbit/s)	Avg. RTT (ms)	Max. RTT (ms)	Std. Dev. (ms)	Packet loss (%)
iPerf3/ Ping	Nokia SRS621 Router	768.4	171.2	14.4	27.2	3.2	0.33
	Huawei P40 Pro+	767.9	143.0	8.7	15.6	1.7	0
	Quectel USB Modem	791.9	141.6	10.5	32.6	5.6	0
	M2M SIMCom 5G	118.2	101.4	15.6	30.7	2.6	0
	Waveshare 5G Module	267.7	83.1	14.8	28.8	2.4	0
LibreSpeed	Nokia SRS621 Router	646.4	179.0	12.6	15.0	1.4	-
	Huawei P40 Pro+	830.4	181.2	7.2	11.4	1.1	-
	Quectel USB Modem	751.2	171.6	10.5	27.5	3.5	-
	M2M SIMCom 5G	139.2	112.1	15.2	19.0	1.5	-
	Waveshare 5G Module	215.9	113.2	12.5	14.1	0.9	-
OpenSpeedTest	Nokia SRS621 Router	720.4	180.6	-	-	-	-
	Huawei P40 Pro+	657.1	140.3	-	-	-	-
	Quectel USB Modem	748.4	173.9	-	-	-	-
	M2M SIMCom 5G	132.8	106.6	-	-	-	-
	Waveshare 5G Module	50.9	108.4	-	-	-	-

A consistent trend concerning data rate KPIs between the measurement series and the end-devices is present. Nokia's SRS621 Router, the Huawei P40 Pro+ smartphone and the Quectel USB Modem have similar average download speeds between 750 and 800 Mbit/s measured with the iPerf3 tool. Regarding the upload, the results are also similar between the three end-devices, with values ranging from 140 to 180 Mbit/s on average. In contrast, SIMCom's M2M 5G Module and the Waveshare 5G Module lag far behind these data rates in both download and upload. Depending on the tool, the measured average download oscillates between 50.9 and 267.7 Mbit/s but do not come close to the 300 Mbit/s thresholds. In upload, the M2M 5G module and the Waveshare 5G module achieve 83.1 to 113.2 Mbit/s, which are also far behind the achieved values by Nokia's SRS621 Router, the P40 Pro+ and Quectel's USB Modem. OpenSpeedTest and LibreSpeed validate these results with similar average data rates in download and upload.

Regarding the time delay, Table 3 shows the average RTT, the maximum RTT, the standard deviation of the RTT and the packet losses. Especially the maximum RTT and packet loss are considered critical parameters regarding time-sensitive applications, as the maximum RTT determines the critical upper threshold, and the packet loss determines the failed transmission of data. In time-sensitive applications, hard requirements such as maximum RTT and packet losses can cause catastrophes when not met. The Huawei P40 Pro+ Smartphone with its Balong5000 chipset reaches the best and most stable RTT values. The average RTT ranges from 7.2 ms (LibreSpeed) to 8.7 ms (iPerf3) with a maximum RTT of 11.4 ms for LibreSpeed and 15.6 ms for iPerf3. The standard deviation of 1.1 ms (LibreSpeed) and 1.7 ms (iPerf3) shows that the RTT for the Balong500 chipset is relatively low in both measurements in comparison to other measured end-devices. The maximum RTT in combination with a low standard deviation is particularly relevant for realizing low-latency applications. In addition, the packet loss is surprisingly low for all end-devices. Only the Nokia SRS621 Router records one packet loss out of 300 sent packets (0.33%).

In general, the results show that differences between various end-devices currently exist regarding their performance. Unexpectedly, the results demonstrate that identical chipsets (SDX55) perform differently. The 5G module's architecture on which the chipset is implemented can affect the conversion of protocols between internal interfaces and therefore influence the end-device performance. Additionally, the different performance of identical chipsets with respect to USB modules can be caused by the available driver software versions.

5. Conclusion and further research activities

This paper presents data rate and time delay measurements as critical KPIs of industrial wireless communication. The measurements enable an initial performance assessment of available 5G SA NPNs and various 5G end-devices in a typical industrial facility. All five tested end-devices do not yet reach the maximum performance parameters specified by the end-device providers. This performance gap is caused by missing software updates provided by both end-devices manufacturers and network providers. The first 5G release Rel-15 was initiated in 2018, and the measurements in this paper were carried out with the first commercially available 5G SA-capable end-devices in 2021. Therefore, real-world measurements are approximately three years behind the 5G standardization process of 3GPP, whereas the latest published release would be Rel-16 [42]. To implement industrial applications with a reliable wireless 5G, selecting an appropriate 5G chipset is crucial and must be coordinated with the respective application's requirements. This limits, in particular, latency-based industrial applications such as autonomous robots that are frequently associated with 5G technology [43]. Further improvements can be expected with network and end-device performance releases. Only a download-to-upload ratio of up to 70% to 30% was available for the measurements. The download-to-upload ratio controls the allocation of time slots between download and upload and thus also influences the performance. The download-to-upload ratio can be adjusted individually to improve the data rate with further releases. Significantly, the upload is essential for the realization of industrial applications such as, for example, cyber-physical systems that transmit data to an edge cloud via the 5G network. Thus, further research activities are necessary to configure and test the upload of deterministic data packets within a strict cycling time. Moreover, the measurements should be extended to NLOS communication and mMTC scenarios. Based on these results, further research is currently being conducted to develop a framework evaluating the practicality of 5G-enabled industrial applications in private networks, considering influencing factors on the wireless 5G in industry.

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