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Supporting digital transformation: real-time monitoring of private 5G networks to educate future connectivity experts by means of learning factories

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Abstract

The fifth generation of mobile communication (5G) is a wireless technology developed to provide reliable, fast data transmission for industrial applications, such as autonomous mobile robots and connect cyber-physical systems using Internet of Things (IoT) sensors. In this context, private 5G networks enable the full performance of industrial applications built on dedicated 5G infrastructures. However, emerging wireless communication technologies such as 5G are a complex and challenging topic for training in learning factories, often lacking physical or visual interaction. Therefore, this paper aims to develop a real-time performance monitoring system of private 5G networks and different industrial 5G devices to visualise the performance and impact factors influencing 5G for students and future connectivity experts. Additionally, this paper presents the first long-term measurements of private 5G networks and shows the performance gap between the actual and targeted performance of private 5G networks.

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1. Introduction

In the course of Industry 4.0 and cyber-physical systems (CPS) using Internet of Things (IoT) sensors, wireless connectivity plays an increasingly important role [1]. In this context, the 3rd generation partnership project (3GPP) standardises the fifth generation of mobile communication (5G) to meet this growing demand for reliable and fast wireless communication [1,2]. In 2015, 3GPP defined three core services of 5G together with the International Telecommunication Union [2,3]: (1) enhanced broadband for data rates of up to 10 Gbit/s in download and 1 Gbit/s in upload, (2) ultra-reliable and low-latency communication for time-critical applications in the range of 1 millisecond, and (3) massive connectivity for industrial IoT applications of up to 1 million devices per square kilometre. Based on these core services, 3GPP plans four releases of the 5G standard in a parallel development process [4]. The parallel release process enables the development of 5G features optimised with enhanced functionality in subsequent releases [4]. The first 5G release is Release 15, which is available since 2018. Release 16 was specified in 2020, and Release 17 is being finalised. Release 18 is the last planned 5G release and is expected to be available in 2024 [4]. Furthermore, 5G enables the establishment of private 5G networks. Private 5G networks utilise dedicated 5G components [2], making 5G a promising wireless communication technology for private organisations.

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Unlike public 5G, private 5G networks use the standalone architecture, which does not require 4G components [2]. Further, private 5G networks enable complete isolation from public networks guaranteeing sovereignty and providing high data security to the network's owner. This also includes acquiring licensed frequencies for private 5G networks. In Germany, frequencies for private 5G networks are between 3.7-3.8 GHz and 24.25-27.5 GHz [5]. Due to 3GPP's ongoing release process, 5G is still in the development process, and further development is needed to achieve the target performance of 5G. In addition, 5G integrates various services, such as the positioning, deployment of multiple virtual networks over one physical infrastructure (network slicing), and vehicle-to-vehicle communication. The development of these services follows individual timelines, adding additional complexity to the release process. Moreover, the 5G standards for public and private networks are not separated in the release roadmap, further complicating the derivation of the performance of private 5G networks in individual releases. In addition, external interfering factors such as material absorption and interferences can limit the performance in production environments. Therefore, assessing the real-world performance of 5G is complex and lacks transparency. In this respect, long-term measurements in industrial environments of learning factories can support evaluating 5G for industrial applications. Here, learning factories play a critical role by testing 5G's performance on a small scale before implementing 5G in the industry [6]. Therefore, the purpose of learning factories is to design courses allowing students to proactively participate in the wireless communication experiments and gaining experience-based knowledge about influencing factors of 5G. After providing a general overview in section 1, section 2 serves as a literature review of the field of interest and states this paper's rationale. Section 3 presents the proposed 5G real-time monitoring consisting of the 5G network, the 5G devices, and the 5G monitoring to visualise the key performance indicators (KPIs) for future wireless communication experts and to conduct long-term measurements of 5G. Section 4 discusses the conducted results using the proposed monitoring. Finally, section 5 concludes the research and provides an outlook of future research activities.

2. Rationale of the paper

Wireless technology presents a challenging teaching topic due to the multidisciplinary fundamental knowledge and the lack of visual or haptic interfaces between the technology and students. Here, graphic real-time dashboards help to transfer the subject visually and provide a practice-oriented understanding of various influencing factors and configurations impacting the performance of wireless technology. The 5G real-time monitoring platform proposed in this paper serves two main objectives in this context. On the one hand, the system provides a visual interface for students, and on the other hand, different 5G devices and configurations undergo long-term endurance tests in an industrial environment. However, the literature lacks long-term measurements of 5G to conclude the suitability of standalone-capable 5G devices for industrial applications regarding critical KPIs such as data rate, round-trip time (RTT), reliability and availability. Rischke et al. [7] present a first measurement study of private 5G standalone networks in 2021. They provide one-way download and upload delays and losses in a private 5G network. Moreover, Rischke et al. [7] compare their results to measurements conducted in non-standalone networks. A study by Turkka et al. [8] measures the reliability and availability as requirements of industrial applications based on short-interval RTTs. Turkka et al. conclude that both 5G devices and networks need to be further optimised to achieve the industrial suitability of 5G. A study by Lackner et al. [9] presents data rate and RTT measurements of five different 5G devices in a private 5G network using licensed frequencies. Their results show that 5G currently lacks behind its targeted performance, especially for low latency-based industrial applications. Dietrich et al. [6] present an implementation framework for 5G use cases (see Fig. 1) in which learning factories play an important role in testing 5G prototypes in the early stages of 5G.

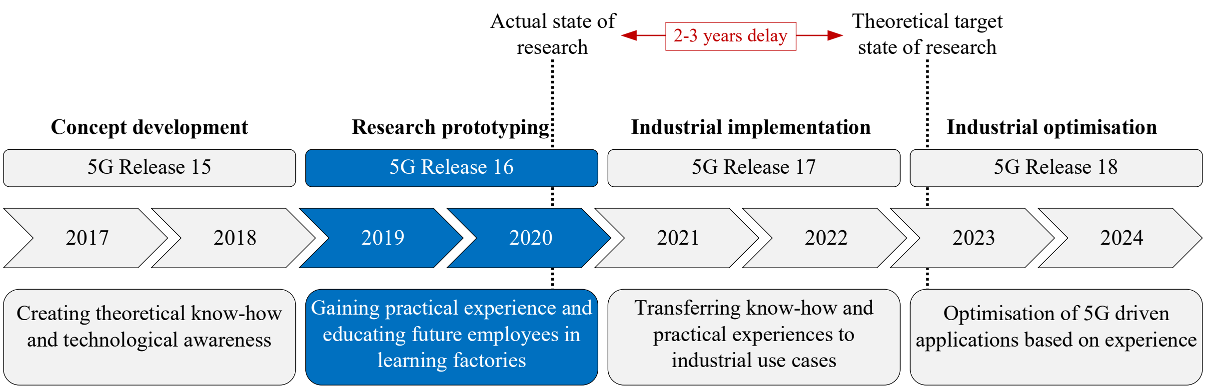

Fig. 1. Role of learning factories in implementing 5G (based on [6]).

In [6], possible 5G applications in the context of learning factories are reviewed and assessed regarding their technical feasibility. According to [6], learning factories should focus on gaining practical experience and educating future wireless technology experts with Release 16 before transferring the know-how to industrial use cases with 5G Release 17. Additionally, their implementation framework shows that the introduction of 5G lacks two to three years behind the theoretical target state of research. Considering these initial findings, this paper aims to present a 5G real-time monitoring system of different 5G devices that visualises the performance of 5G and the impact of different device configurations to conduct the first long-term endurance measurements of critical KPIs.

3. Proposed 5G real-time monitoring

The 5G real-time monitoring measures the performance of the 5G devices and the private 5G network in the learning factory Werk150 at Reutlingen University. The teaching and research centre Werk150 is 800 square meters large and offers students a small-scale industrial environment equipped with mobile assembly lines, shelf storages, logistics systems and mobile robots. The long-term measurements enable evaluating the usability for industrial use cases demanding different communication requirements. Fig. 2 shows the overall architecture of the 5G real-time monitoring system divided into three main parts described in detail in the following subsections.

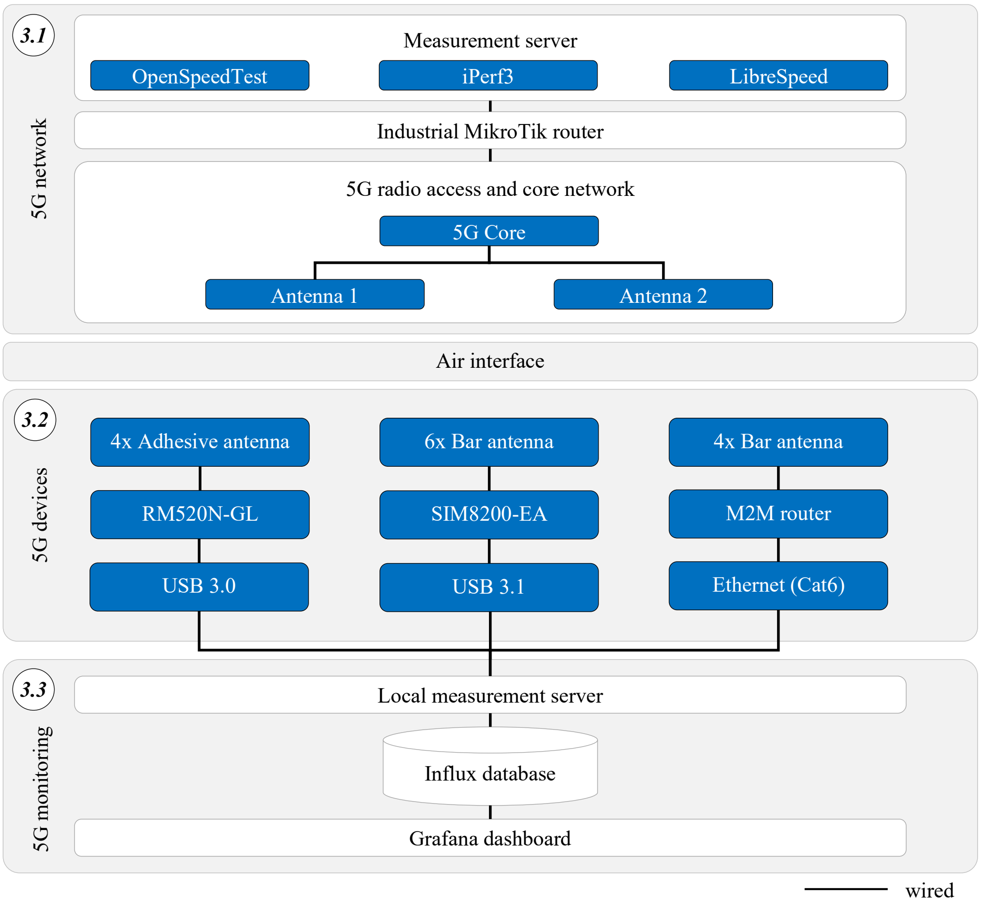

Fig. 2. Architecture of the real-time private 5G network performance monitoring system.

3.1. 5G network

The private 5G network consists of a core network and a radio access network and is set up locally in the learning factory Werk150. The network uses licensed frequencies at a bandwidth of 100 MHz between 3.7 and 3.8 GHz (sub-6 GHz). Additionally, the learning factory is equipped with two omnidirectional indoor antennas, sending with a transmission power of 50 mW respectively. The transmission power is comparable to Wi-Fi, which typically transmits between 50 and 100 mW. The 5G core runs with the 5G release 16 software and a configured download-to-upload ratio of 60:40. Consequently, the theoretical data rate is 1 Gbit/s, distributed into 600 Mbit/s in download and 400 Mbit/s in upload. The 5G network is connected to the server through an industrial MikroTik router, serving as the backend measurement server. The speed tests OpenSpeedTest, iPerf3 and LibreSpeed are running on the server. The monitoring system uses iPerf3 as open source software to test the data throughput to determine the download and upload. The RTT measurements use the ping command.

3.2. 5G devices

The monitoring uses three commercially available sub-6 GHz 5G devices. The devices consist of a 5G module with an M2 interface, a motherboard and connectors for the antennas. The Quectel RM520N-GL module has a USB 3.0 interface and works with Release 16. The maximum download speed is 2.4 Gbit/s and 900 Mbit/s in the upload. The SIMcom SIM8200 module has a USB 3.1 interface and works with Release 15. The maximum download speed is 2.4 Gbit/s and 500 Mbit/s in the upload. The SIMcom M2M router has an Ethernet CAT6 interface and works with Release 15. The maximum download speed is 4 Gbit/s and 500 Mbit/s in the upload. The devices were explicitly selected to conduct manufacturer-independent tests and identify the influence of interfaces, design, antennas and releases. The 5G devices are connected to the local measurement server as part of the 5G monitoring system, which triggers the measurements.

3.3. 5G monitoring

The measurement server is connected to the 5G devices, the Influx time-series database, and the Grafana dashboard, forming the 5G monitoring system. A local script triggers continuous measurements for each 5G device consecutively in sequential order on the local server. During the measurement, the local measurement server sends data packets to the 5G network infrastructure via a 5G device over their internal interface (USB/Ethernet). The backend measurement server, connected to the MikroTik router, receives and measures the data packets to determine the maximum data rate. In the case of the round-trip time (RTT), the backend measurement server returns the data packets to the local measurement server of the 5G monitoring system. The values obtained from the measurements are stored in an Influx database. Finally, the Grafana dashboard pulls the data from the Influx database and displays the values.

4. Measurement results

Table 1 shows the measurement results from a three-month endurance test of the 5G monitoring system. The results show that the selection of the device and its configuration impacts the performance of 5G. Furthermore, there is a gap between the current state and the theoretically specified target state of private 5G networks regarding their performance. Considering the interfaces, the 5G devices with a USB 3.x interface have a mean download three times faster than the M2M router equipped with an Ethernet port. The difference in upload between the devices with USB 3.x interface and Ethernet port is a factor of 1.5 due to the limitation of the router-internal ethernet interface to 100 Mbit/s. As a result, the M2M router cannot fully utilise the performance of the private 5G network. In contrast to the device interface, the device's 5G release does not impact the data rate. Comparing the maximum and mean download of the 5G devices with USB 3.x interface, Release 16 and Release 15 devices are in the same range. However, a difference can be observed in the upload. The average upload speed is 1.25 times greater for the end device with Release 16 than for Release 15. When considering the maximum value, the upload speed is 1.75 times greater. The maximum RTT value for Release 16 is twice as high as for Release 15. Thus, the release of the end devices mainly affects the upload and the RTT.

Table 1. Measurement results of the private 5G network (current state) compared to the defined target state.

		Current state			Target state			
Specification	5G device	RM520N-GL	SIM8200-EA	M2M-router	Release 15	Release 16	Release 17	Release 18
	5G release	16	15	15				
	Interface	USB 3.0	USB 3.1	Ethernet Cat6				
Download [Mbit/s]	Max.	512	540	147	up to 600 Mbit/s[1]	up to 600 Mbit/s[1]	up to 6 Gbit/s[1]	up to 6 Gbit/s[1]
	Mean	408	412	112				
	Min.	259	233	21				
Upload [Mbit/s]	Max.	297	171	171	up to 400 Mbit/s[1]	up to 400 Mbit/s[1]	up to 4 Gbit/s[1]	up to 4 Gbit/s[1]
	Mean	187	149	122				
	Min.	19	51	25				
Round-trip time [ms]	Max.	368	161	131	up to 10 ms	up to 1 ms	up to 1 ms	below 1 ms
	Mean	11.2	9.9	9.3				
	Min.	6.2	5.2	5.4				

[1]Download-to-Upload-Ratio of 60:40

The measurements show that the 5G infrastructure does not fully utilise the maximum bandwidth of 1 Gbit/s possible in Release 16. Due to the download-upload ratio, a data rate of 540 Mbit/s achieved approximately 90% of the maximum possible bandwidth, and a transfer rate of 297 Mbit/s achieved 75% in the upload. The RTT of an average of 9.3 seconds is a factor of 10 higher than the target value of 1 ms.

5. Conclusion

The implementation of a real-time monitoring system of private 5G networks in learning factories serves to train future connectivity experts. With the increasing demand for high-speed connectivity and the deployment of 5G networks in the industry, it is important to prepare the workforce to handle the complexity of these networks. By visualising and monitoring the performance of 5G in real-time, learners can gain practical experience and develop the skills needed to design, operate, and maintain these networks effectively. Here, learning factories allow for a simulated environment that closely resembles a real-world scenario, allowing students to work with actual equipment and experience the challenges arising in this field. Furthermore, a 5G real-time monitoring system in learning factories provides learners with immediate feedback and a closer understanding of the underlying principles of 5G. This allows to tangibly experience the impact of 5G devices and interfaces on transmission performance and influencing factors of 5G. In addition, the real-time monitoring system enables long-term measurements required before implementing specific applications to ensure that 5G fully covers the application's requirements. Additionally, latency and throughput tests can act as a starting point to further derive specific industrial test scenarios such as high-frequency IoT-sensor data transmission concerning about packet losses, jitter and interferences on wireless signals. The latency and data rate measurements show that the target performance defined by 3GPP for private 5G networks currently cannot be achieved in real production environments. On average, the 5G network achieves a maximum of 69% in the download and only 47% in the upload of the target performance. The RTT is also above the theoretically specified performance of 1 ms. Data packets can achieve an RTT of 10 ms. This performance difference in field trials is due to the delay between the theoretical 3GPP release and the actual availability of the release functionality in the 5G network infrastructure. Here, development delays exist between the 5G standard and the implementation in the 5G infrastructure under the responsibility of hardware manufacturers. Network manufacturers will have to conduct further development to overcome this delay and achieve the target performance of 5G. The current performance gap of 5G shows that particularly learning factories are a suitable environment to implement small-scale prototypes and to prepare both students and the industry for the imminent market maturity of 5G.

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