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Decision-support framework to evaluate the practicality of 5G for intralogistics use cases in standalone non-public networks

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Abstract

In the context of Industry 4.0, intralogistics faces an increasingly complex and dynamic environment driven by a high level of product customisation and complex manufacturing processes. One approach to deal with these changing conditions is the decentralised and intelligent connectivity of intralogistics systems. However, wireless connectivity presents a major challenge in the industry due to strict requirements such as safety and real-time data transmission. In this context, the fifth generation of mobile communications (5G) is a promising technology to meet the requirements of safety-critical applications. Particularly, since 5G offers the possibility of establishing private 5G networks, also referred to as standalone non-public networks. Through their isolation from public networks, private 5G networks provide exclusive coverage for private organisations offering them high intrinsic network control and data security. However, 5G is still under development and is being gradually introduced in a continuous release process. This process lacks transparency regarding the performance of 5G in individual releases, complicating the successful adoption of 5G as an industrial communication. Additionally, the evaluation of 5G against the specified target performance is insufficient due to the impact of the environment and external interfering factors on 5G in the industrial environment. Therefore, this paper aims to develop a technical decision-support framework that takes a holistic approach to evaluate the practicality of 5G for intralogistics use cases by considering two fundamental stages. The first of these analyses technical parameters and characteristics of the use case to evaluate the theoretical feasibility of 5G. The second stage investigates the application's environment, which substantially impacts the practicality of 5G, for instance, the influence of surrounding materials. Finally, a case study validates the proposed framework by means of an autonomous mobile robot. As a result, the validation proves the proposed framework's applicability and shows the practicality of the autonomous mobile robot, when integrating it into a private 5G network testbed.

Keywords: Decision-support framework; 5G; intralogistics; use cases; non-public networks; private 5G networks; practicality;

1. Introduction

Due to the globalisation of businesses, the complexity of value chain networks increases [1,2]. Additionally, shorter product life cycles and a rising individualisation of products with small batch sizes further increase the complexity of production processes [1], resulting in dynamic and volatile markets [3]. Thus, intralogistics faces increasing dynamics and must continuously adapt to changing conditions within manufacturing processes [4–5]. One approach to deal with these changing conditions is the decentralised and wireless connectivity of intralogistics systems [4,6]. However, wireless communication presents a current challenge in the industry, especially for time-critical applications such as autonomous mobile robots, due to the interplay of strict requirements such as safety, security, reliability and real-time data transmission

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[6,7]. In this context, the 3rd generation partnership project (3GPP) standardises the fifth generation of mobile communication (5G) to fill the gap in reliable, wireless communication. 3GPP plans four major 5G releases (2017: Release 15, 2020: Release 16, 2022: Release 17, 2024: Release 18) consisting of documents specifying the upcoming 5G, while the latest is Release 17 [8]. 5G provides three primary core services [6,9]: enhanced mobile broadband (eMBB) up to 10 Gb/s, massive machine-type communication (mMTC) of up to 1 million devices per square kilometer in public networks and ultra-reliable low-latency communication (uRLLC) in the millisecond range [5]. Additionally, 5G enables standalone (SA) non-public networks (NPN) purely established by 5G components [6,10]. NPNs offer private organisations to deploy their dedicated 5G network within a restricted area using licensed or sub-leased frequencies, leading to high network control and security through isolation from public networks [10]. However, 5G is currently still in its development process and, thus, cannot yet offer the promised performance. Further, 5G promises to establish services such as positioning, network slicing and vehicle-to-vehicle communication based on other standards, increasing the release process's complexity. In addition, the release process is not separated into non-public and public networks. Thus, the performance of NPN lacks transparency of individual releases and depends on the implementation in the infrastructure under responsibility of network providers. This frequently leads to a distorted picture when evaluating 5G for applications. In this context, this paper aims to develop a generic framework to overcome the lack of transparency of 5G's performance in the real-world. After providing a general topic overview in Section 1, Section 2 reviews the relevant literature and describes the rationale of the paper. Section 3 specifies the framework's methodology based on the development approach of Jabareen. Section 4 represents the proposed framework, and Section 5 framework's validation. Finally, Section 6 presents a conclusion and future research recommendations based on this study.

2. Literature review and rationale of the paper

Numerous studies have already been published on the technical aspects of 5G SA NPN. In contrast, only minor publications deal with the assessment, implementation and prototyping of industrial 5G. Often, publications address the topic of use cases and required key performance indicators (KPIs) theoretically, based on 5G's promised future target performance [11,13]. For example, the study by Ordonez-Lucena et al. [11] investigates the use of 5G NPNs to support Industry 4.0 scenarios. This study derives guidelines to select an appropriate network deployment. However, [11] does not consider applications' requirements and does not provide a reference structure of steps that must be considered to integrate 5G as communication. The publication from the 5G Alliance for Connected Industries and Automation (5G-ACIA) identifies seven use cases and classifies them into hard and soft real-time [12]. 5G-ACIA also highlights key requirements of wireless communication. Nevertheless, environmental analysis is not included in [12]. O'Connell, Moore and Newe [13] examine challenges associated with implementing 5G. They detect the need for a detailed understanding of use cases and their specific requirements to adopt 5G. Furthermore, [13] recommend investigating 5G in the factory environment.

Only Rodriguez et al. [14] propose a similar approach in their experimental framework for 5G wireless system integration into Industry 4.0 applications. This framework is structured in three parts: Operational flow, experiments in an industrial research lab, and 5G hardware and software tools used for their 5G prototype. The operational flowchart consists of six generic steps to integrate 5G in industrial applications. Furthermore, Rodriguez et al. [14] recommend analysing the environment but do not incorporate generic steps to investigate influencing factors. However, 5G SA NPN measurements indicate network internal and external influences interfering with 5G [15,16]. For example, the measurements in [16] show that 5G devices with different chipsets, interfaces and software versions impact the performance of 5G. In conclusion, existing literature lacks a generic framework to assist decision-makers when evaluating the technical practicality of 5G for intralogistics indoor use cases in SA NPNs. Therefore, this paper aims to develop a framework guiding decision-makers through evaluating 5G in chronological order by considering the use case and its environment. For the sake of clarity, this paper defines the term practicality as follows:

Practicality refers to the usefulness of technology in real-world scenarios. Therefore, the term practicality combines the theoretical feasibility and environmental influencing factors (see Fig. 1.).

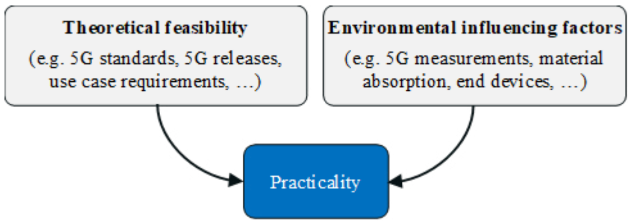

Fig. 1. Definition of the term practicality

3. Methodology of the framework development

This paper aims to develop a framework. Jabareen [17] defines a framework as a "network, or 'a plane,' of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena." Initially, a semi-systematic review adopted from [18] collects intralogistics use cases requiring wireless communication. Here, the databases IEEE Xplore and Elsevier Scopus are searched using the keywords 'wireless communication', '5G', 'intralogistics', 'use case', and 'application'. The search strategy includes the backward and forward snowballing adopted from [19] to reveal literature beyond the predefined databases. After collecting potential use cases, a morphological analysis, according to [20], identifies the most critical applications serving as a reference for the framework to ensure a generic design. Here, the most critical use cases possess the maximum intersection with less critical ones. For the morphological analysis, the eight applications from the literature review are translated into a matrix on the y-axis. The corresponding requirements are plotted on the x-axis.

Marking the strictest values per requirement and going through the marked values, identifies the most critical use cases. As a result, the reference applications for the framework are: Augmented reality representing eMBB, remote control of autonomous mobile robots (AMRs) representing uRLLC and, finally, condition monitoring using Internet of Things (IoT) sensors on intralogistics machines representing mMTC.

4. Proposed framework

The proposed meta-level of the framework to evaluate 5G's practicality consists of a vertical process flow connecting two generic stages with sub-steps in chronological order. Fig 2. shows the vertical process flow and links the interrelationships between individual sub-steps.

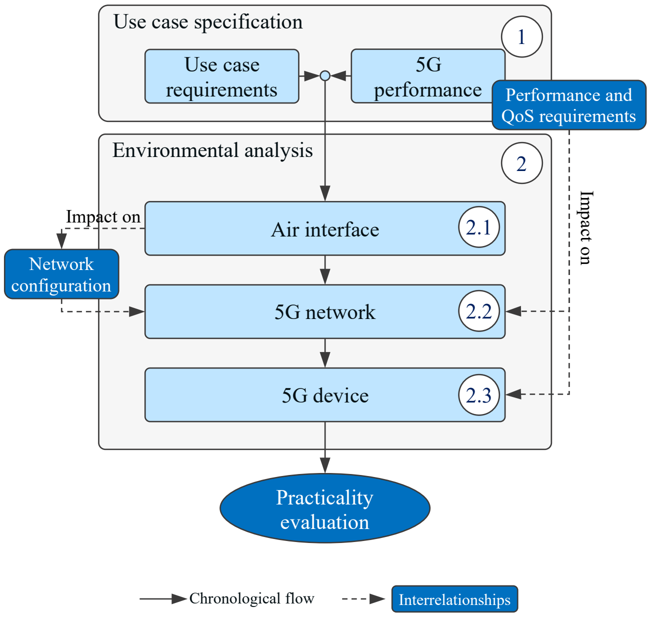

Fig. 2. Proposed vertical process flow of the decision-support framework

The use case specification stage (1) evaluates the theoretical feasibility of 5G for the use case by matching the use case's requirements to the specified performance of individual 5G releases. The environmental analysis stage (2) represents the second stage consisting of three chronological sub-steps evaluating the use cases' environment and its impact on 5G. Combining both stages provide a holistic decision-support regarding the practicality of 5G for the intralogistics use case.

4.1. Use case specification

The use case specification adopts an application-centered perspective and evaluates the theoretical feasibility of 5G. First, the user must create a use case profile by defining requirements that must be met by 5G during active operation. Generally, these requirements are classified into two groups:

- *Quantifiable*. KPIs with measurable thresholds to be met by wireless communication. 3GPP specifies accuracy, latency, data rate, reliability, availability, speed and density as relevant KPIs for industrial 5G use cases [21,22].
- *Non-quantifiable*. Descriptive features of use cases with at least two feature attributes where the use case can only be assigned to precisely one attribute, such as real-time with its attributes hard/ soft or mobility with mobile/ stationary.

The requirements above are essential to specify the use case profile. In the first step, this framework proposes to define the non-quantifiable requirements since, firstly, they can serve to derive performance thresholds for quantifiable requirements. Secondly, the non-quantifiable requirements serve as an initial decision-making criterion regarding the general usability of wireless communication. Wireless technologies must be used when use cases can be classified as 'mobile'. However, when the use case is classified as 'stationary', meaning the use case does not move during active operation, wired industrial fieldbus standards such as Ethernet and Profinet provide higher security and reliability [23]. In the second step, the quantifiable requirements must be defined by measurable performance thresholds. When all requirements are defined, the quantifiable requirements can be mapped to the specified performance of individual releases. Mapping use cases' requirements with the specified performance enable the identification of the required 5G release. For this purpose, the spider chart in Fig. 2 shows the specified performance of individual 5G releases in SA NPNs, which can be used to identify the required 5G release. Identifying the required 5G release indicates the time horizon for implementing the application using 5G due to 3GPP's release process and leads to interrelationships between the 5G network and 5G device. The interrelationships of the use case specification with the following stages are Quality of Service (QoS) and performance requirements considered as strict preconditions for the 5G network and 5G device. For example, when applying the framework and identifying Release 16 for implementing the intralogistics use case, the 5G network and device must support the identified release and the QoS and 5G services. Therefore, the use case specification impacts the subsequent environmental analysis by revealing preconditions strictly required for the 5G network and device.

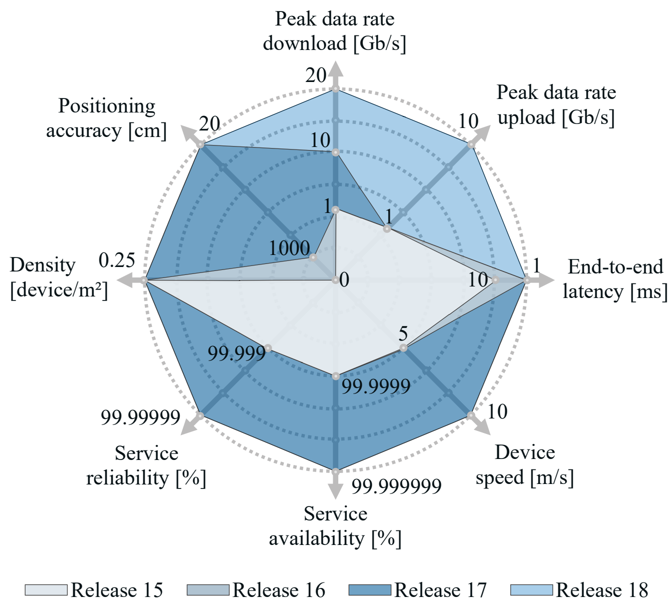

Fig. 3. Specified performance of standalone non-public networks for each 5G release (based on [21,24,25])

4.2. Environmental analysis

This stage aims to analyse environmental interfering factors on 5G. The environmental analysis follows a chronological process to identify external influencing factors systematically. However, the environmental analysis stage does not provide a quantification of interferences, as they are situation-specific and depend on numerous variables, such as the factory layout, surrounding materials, network deployments and 5G devices. Therefore, this stage is structured as a step-by-step guideline.

Fundamentally, 5G networks consist of three parts: (1) air interface, (2) 5G network (backbone) and (3) 5G device (shown in Fig. 4). Considering environmental influences and network-internal bottlenecks on each part from end-to-end ensures covering all potential influences on the 5G communication. Therefore, the environmental analysis stage is developed along the fundamental architecture of an industrial 5G network.

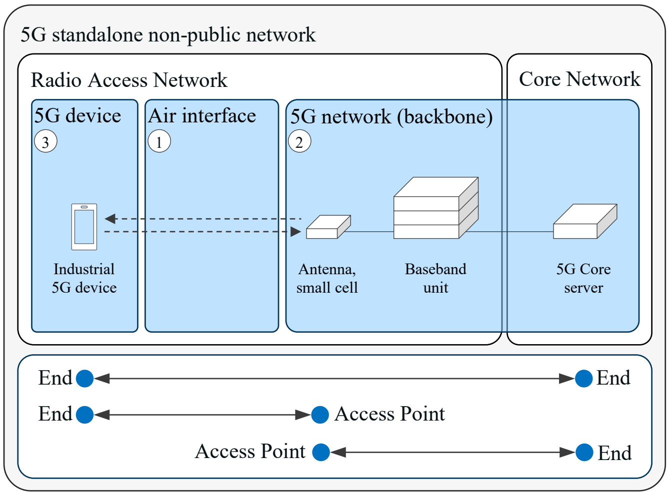

Fig. 4. Simplified architecture of an industrial 5G standalone non-public network from end-to-end

As illustrated in Fig. 4, this paper recommends investigating the air interface first, followed by the 5G network (backbone) and, finally, the 5G device. The following sections *4.2.1*, *4.2.2* and *4.2.3* describe the environmental analysis for all three parts of the 5G network in detail.

4.2.1. Air interface

The air interface is mainly affected by the intralogistics shop floor layout due to facilities' equipment, materials encircling the intralogistics application and existing wireless technologies, additionally stressing the air interface and potentially provoking interferences. Therefore, this framework proposes analysing influencing factors on the air interface first.

In the first step, the applications' operational area needs to be defined to delimit the area where external influencing factors must be analysed. After defining the operational area, this framework proposes identifying materials in the applications' environment absorbing electromagnetic waves in non-line-of-sight (NLOS) scenarios. NLOS exist when at least one obstacle is between the transmitter and receiver. In this context, metal, concrete and aluminum are reported as critical materials absorbing in 5G's frequency range [26]. Preventive actions should be considered when critical zones are identified in which materials such as autonomous mobile robots (AMRs) move between metallic high-bay warehouses or robots in metallic cells interfere with the transmission. For example, the systematic installation of additional 5G small cell antennas in detected locations can guarantee 5G coverage in critical zones. In this case, LOS connections replace NLOS connections. Otherwise, redesigning the shop floor should be considered.

After identifying critical materials in NLOS, this paper proposes to analyse possible critical scenarios. Critical scenarios are worst-case situations in which 5G must ensure failure-free communications to avoid endangering the environment. For example, 5G enables a so-called seamless handover between radio cells. In this case, the handover areas must be defined as critical scenarios and coordinated to ensure seamless communication. Additional critical scenarios can include areas where the application interacts with humans or carries out critical tasks. These scenarios must be included in the practicality evaluation and must be considered for the configuration of the 5G network. As shown in Fig. 2, the influencing factors on the air interface can impact the 5G network and its setup, for example, when additional antennas are required. Thus, the air interface possesses interrelations with the following 5G network (backbone) section.

4.2.2. 5G network (backbone)

In this sub-step, the framework user performs bottleneck analyses of the 5G network and its configurations to ensure the performance, services and resources required for the respective use case. This includes radio access network components such as small cell antennas, the baseband unit, and the core network server providing the 5G functions and services. In this context, virtual and physical bottlenecks can occur. For example, hardware components and cabling materials can limit the transmission throughput resulting in physical bottlenecks. Based on Patounas et al. [27], four typical physical network bottlenecks exist besides interferences:

- Packet losses
- Congestions
- Computational resources
- Time delays/ latencies

A further division allows to classify the physical bottlenecks into causes and effects. Here, only data congestions and computational resources represent causes, triggering effects such as packet losses and time delays/ latencies. Therefore, investigating data congestions and computational resource bottlenecks with the support of IT specialists might be sufficient to identify physical bottlenecks in 5G networks.

In contrast, virtual bottlenecks are software-driven and located on the network function and service layer of the 5G core network. Since the network functions and their availability is strictly linked to the 5G releases, the 5G core network functionality needs to be aligned with the required 5G release identified within the use case specification (Section 4.1) to ensure the availability of critical network functions. After analysing physical and virtual bottlenecks, the final step is to perform stress tests and measurements. Regarding stress tests, different simulation tools exist to emulate defined worst-case scenarios. In this regard, worst-case scenarios are given by the identified thresholds defined in the use case specification (Section 4.1). Simulated data packets are sent over the 5G network to subject the network to the stress test. iPerf3 [28] and the Linux-based network emulator netem [29] are example tools to simulate network tests. After the 5G network passes the simulated stress tests, the final step considers investigating the 5G device.

4.2.3. 5G device

The 5G device is located at the applications' site and represents the hardware interface between the application and the 5G network. Additionally, the 5G device is reported as a bottleneck having a decisive impact on the performance [30]. Therefore, the 5G device is considered the final critical sub-step for practicality evaluation. Firstly, decision-makers must identify the required device type. In this context, different types in various designs, sizes, antenna shapes and interfaces are currently available, for example, 5G routers, modems, modules and IoT devices. Essentially, the 5G device must support the SA mode and the frequency band of the 5G network. For example, Germany reserves the n78 band for SA NPNs; thus, only 5G devices supporting the n78 band are compatible. Secondly, this paper proposes to analyse the interface of applications' main board, which must be coordinated with the devices' interface. Importantly, investigating the performance limitations of 5G devices and the interface/ protocol is critical to ensure the required data throughput. For example, standard industrial interfaces such as Ethernet (Cat6) can provide up to 10 Gb/s [31] and USB 3.0 up to 5 Gb/s [32]. Finally, the devices' driver software needs to be checked for compatibility with the underlying operating system of the intralogistics application.

5. Framework validation

An autonomous mobile robot (AMR) case study validates the proposed framework. First, the case study applies the proposed framework step-by-step to evaluate the practicality of 5G. After, the AMR is implemented into the 5G network to demonstrate the framework's correctness in practice.

In this case study, the AMR uses 5G to send position data to the global planning system and to receive orders, start and stop commands and waypoints from the superordinated fleet management. The AMR manufacturer defined thresholds for each quantifiable requirement as proposed in the use case specification. After defining all quantifiable KPIs with their corresponding thresholds, the requirement profile of the AMR is transferred to the spider chart to identify the 5G release for successful implementation of the AMR using 5G. Fig. 5 shows the requirement profile of the AMR (dark blue) mapped to the developed spider chart, resulting in the finding that at least Release 15 is required. Concerning the interrelationships shown in Fig. 2, the 5G network and device must also support Release 15 to realise the AMR use case successfully.

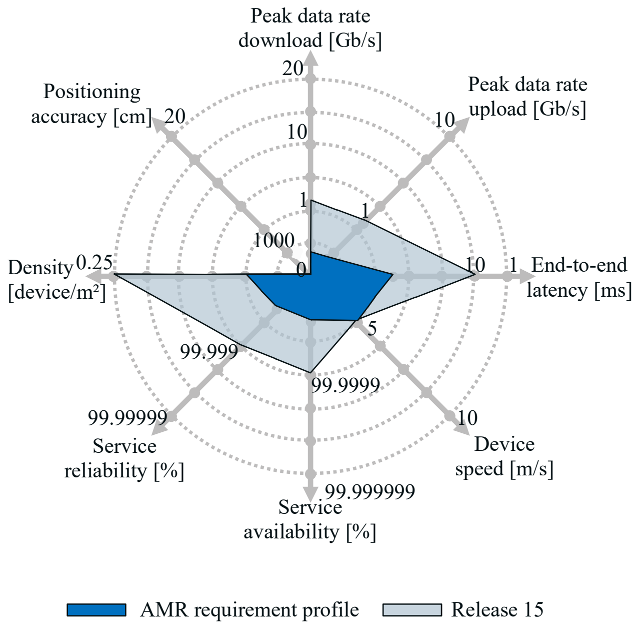

Fig. 5. AMR requirement profile mapped to the specified 5G performance

Regarding environmental analysis, the learning factory at Reutlingen University serves as the 5G testing environment. The learning factory is 800 m² large and equipped with flexible assembly lines, workstations, robots, warehouse shelves and machines. The 5G SA NPN in the learning factory operates on licensed frequencies between 3.7-3.8 GHz (sub-6 GHz) and is based on the indoor AirScale system from Nokia. The network uses two small cells with a transmission power of 50mW. And the 5G core network runs on a local edge cloud (NDAC Edge HP EL1000).

Concerning influences on the air interface, other wireless technologies such as Wi-Fi using 2,4 GHz and 5 GHz and Bluetooth transmit in the sub-6 GHz band and potentially lead to interferences. To investigate network bottlenecks and interferences resulting from competing wireless technologies, measurements are conducted and published in [16]. As a result, various 5G devices performed differently. However, the required performance values for the AMR are achieved by all 5G devices.

A second measurement series serves to ensure the signal quality in NLOS worst-case scenarios where the 5G device is encased by aluminum (1mm), concrete (50mm) and stainless steel (1.5mm). As a finding, all 5G devices still reach a sufficient signal strength ranging from -65 dBm (very good) to -95 dBm (normal) according to the reference classification from [33]. Both measurement series demonstrate that potential external influencing factors do not limit 5G in the learning factory. Frameworks' output results in the finding that 5G represents a technically practical communication technology for the AMR within the learning factory.

The final step of this case study covers the upgrade of the AMR to a 5G prototype. Therefore, the AMR is equipped with a 5G router and reconfigured by installing the routers' driver on AMR's operating system. Repeatedly performing the defined commands demonstrate that the AMR can execute the tasks within the thresholds using 5G.

6. Conclusion and recommendations for future research

This paper proposes a holistic, technical decision-support framework to evaluate the practicality of 5G for intralogistics use cases in SA NPNs. The framework consists of the use case specification stage aiming to evaluate the theoretical feasibility of 5G and the environmental analysis stage to analyse external influencing factors. The proposed framework is structured as a vertical process flow and guides decision-makers through the evaluation in chronological order. Finally, the AMR case study exemplifies the framework's applicability in a real-world scenario. Regarding the study's scope, the framework only considers evaluating one single use case. Therefore, future investigations of mutual influences between various 5G applications are recommended. One approach might be to apply this framework to complex industrial setups to evaluate multiple use cases and their mutual influences. Furthermore, an economic analysis of 5G is beyond the study's scope but needs to be considered by decision-makers when evaluating 5G as communication for intralogistics applications. Concluding this research, the commercial readiness of industrial 5G largely depends on network providers and the coherent availability of networks' performances and services. In this context, there is still a gap between the high expectations of industrial 5G and their actual performance and service availability in commercial 5G infrastructures.

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