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

by
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Abstract

In the context of Industry 4.0, intralogistics is exposed to 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, security and real-time data transmission and processing. Furthermore, this is becoming increasingly important with the mass adoption of technologies used for time-critical applications, such as autonomous mobile robots.

The fifth generation of mobile communications (5G) is a promising telecommunication technique to fill this gap and meet the requirements of safety-critical and time-critical applications. In addition, 5G offers the possibility of establishing private 5G networks. Private 5G networks, referred to as standalone non-public networks, provide exclusive coverage for private organisations and offer high intrinsic network control and data security through isolation from public networks and the dedicated use of pure 5G components. However, at the present time 5G is still in the development process and is being gradually introduced in a continuous series of releases. In this context, the release process of 5G lacks transparency regarding the performance of 5G in individual releases, complicating the successful adoption of 5G as an industrial communication technique. 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.

The proposed framework takes a holistic approach to evaluate the practicality of 5G for intralogistics use cases by considering two fundamental perspectives. The first of these considers the use case and analyses technical parameters and characteristics of the use case to evaluate the feasibility of 5G. The second perspective investigates the application's environment, which has a substantial impact on the practicality of 5G, for instance, the influence of surrounding materials. By adopting both perspectives, a holistic conclusion on the practicality of 5G can be drawn. A case study validates the proposed framework, in which an autonomous mobile robot use case is evaluated for the practicality of 5G. Subsequently, empirical measurements and the integration into the 5G standalone non-public network are carried out.

Keywords: *5G; mobile communications; standalone non-public networks; intralogistics; use cases;*

Opsomming

In die konteks van Industrie 4.0 word intralogistiek blootgestel aan 'n toenemend komplekse en dinamiese omgewing. Hierdie word gedryf deur 'n hoë vlak van produkaanpassing en komplekse vervaardigingsprosesse. Een benadering om hierdie veranderende toestande te hanteer, is die gedesentraliseerde en intelligente konnektiwiteit van intralogistieke stelsels. Draadlose konnektiwiteit bied egter 'n groot uitdaging in industriële omgewings, as gevolg van die wisselwerking van streng vereistes soos veiligheid, sekuriteit en intydse data-oordrag en -verwerking. Verder word dit al hoe belangriker met die massa-opneming van tegnologieë wat vir tyd-kritiese toepassings gebruik word, soos outonome mobiele robotte.

Die vyfde generasie van mobiele kommunikasie (5G) word gesien as 'n belowende telekommunikasietegniek om hierdie gaping te vul en aan die vereistes van tyd-kritiese toepassings te voldoen. Boonop bied 5G ook die moontlikheid om private 5G netwerke te vestig. Private 5G netwerke, waarna verwys word as selfstandige en nie-openbare netwerke, bied eksklusiewe dekking vir private organisasies en bied hoë intrinsieke netwerkbeheer en datasekuriteit deur isolasie van publieke netwerke. Op die oomblik is 5G egter steeds in die ontwikkelingsproses en word geleidelik in vrystellings bekendgestel. In hierdie konteks het die vrystellingsproses van 5G nie deursigtigheid oor die prestasie van 5G in individuele vrystellings nie, wat dus die suksesvolle aanvaarding van 5G as 'n industriële kommunikasie tegniek belemmer. Boonop is die evaluering van 5G teenoor die gespesifiseerde teikenprestasie onvoldoende as gevolg van die impak van die omgewing en eksterne steurende faktore op 5G.

Die voorgestelde raamwerk neem 'n holistiese benadering om die praktiese toepassing van 5G vir intralogistieke gebruiksgevalle te evalueer deur twee fundamentele perspektiewe te oorweeg. Die eerste perspektief beskou die gebruiksgeval en analiseer tegniese parameters en kenmerke van die gebruiksgeval om die praktiese toepassing van 5G te evalueer. Die tweede perspektief ondersoek die omgewing van die toepassing, wat 'n wesenlike impak kan hê op die praktiese toepassing van 5G, byvoorbeeld soos deur materiale wat die kwaliteit van die sein belemmer. Deur beide perspektiewe te ondersoek, kan 'n holistiese gevolgtrekking oor die praktiese toepassing van 5G as 'n draadlose kommunikasie tegniek gemaak word. 'n Outonome mobiele robotgevallestudie dien om die voorgestelde raamwerk te valideer, waarin die outonome mobiele robotgebruiksgeval eers geëvalueer word vir die praktiese toepassing van 5G, waarna empiriese metings en die integrasie in die 5G-selfstandige nie-openbare netwerk uitgevoer word.

Sleutelwoorde: *5G; mobiele kommunikasie; selfstandige nie-openbare netwerke; intralogistiek; gebruiksgevalle;*

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List of acronyms

1G	First generation of mobile communications
2G	Second generation of mobile communications
3G	Third generation of mobile communications
3GPP	Third Generation Partnership Project
4G	Fourth generation of mobile communications
5G	Fifth generation of mobile communications
AGV	Automated Guided Vehicle
AMR	Autonomous Mobile Robots
AR	Augmented Reality
CM	Condition Monitoring
CN	Core Network
CP	Control Plane
CPS	Cyber-Physical System
DSR	Design Science Research
EC	Exclusion Criteria
EDGE	Enhanced Data Rates for GSM Evolution
eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B
EPC	Evolved Packet Core
FDD	Frequency Division Duplex
FFLM	Flexible Factory Layout Monitoring
gNB	Next Generation Node B
GSM	Global System for Mobile
HSPA	High-Speed Packet Access
IC	Inclusion Criteria
ICT	Information and Communication Technologies
IIoT	Industrial Internet of Things
IMT-Vision	International Mobile Telecommunication Vision
ITU	International Telecommunication Union
ITU-R	Radiocommunication Sector of the International Telecommunication Union
LAN	Local Area Network
LTE	Long Term Evolution
LTE-A	Long-Term Evolution Advanced
mMTC	Massive Machine Type Communication

MNO	Mobile Network Operator
MTU	Maximum Transmission Unit
NFV	Network Function Virtualisation
NPN	Non-public Network
NR	New Radio
NSA	Non-Standalone
PN	Public Network
PRQ	Primary Research Question
RAN	Radio Access Network
RMC	Robot Motion Control
RO	Research Objective
RT	Real-time
SA	Standalone
SDN	Software Defined Networking
SIM	Subscriber Identity Module
SMS	Short Message Service
SRQ	Subsequent Research Question
SSLR	Semi-systematic Literature Review
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TI	Tactile Internet
TR	Technical Report
TS	Technical Specification
UAV	Unmanned Aerial Vehicle
UMTS	Universal Mobil Telecommunications System
UP	User Plane
uRLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle-2-Everything
VR	Virtual Reality
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

1 Introduction to the research

This chapter introduces the research and formally defines the objectives of the thesis. Furthermore, within this chapter the problem statement and the research questions are outlined, and the scope of the research is discussed. Subsequently, this chapter addresses the research design and methodology that underlies the research and closes with a brief outline of the thesis.

1.1 Background and rationale of the research

Today's manufacturers in supply chains are facing increasing challenges. In the course of the globalisation of businesses, the complexity of value chains increases and the manufacturing depth of single supply chain participants continuously decreases (Aelker, Bauernhansl and Ehm, 2013, p. 79). Additionally, factors such as shorter product life cycles, increasing product variance and individualisation of products with small batch sizes further increase the complexity of production processes (Aelker, Bauernhansl and Ehm, 2013, p. 80; Windt, Philipp and Böse, 2008, p. 195). This results in dynamic and volatile markets (Wilding, 1998, p. 599). Due to these developments, intralogistics systems are also exposed to increasing dynamics and complexity and must constantly adapt to changing conditions (Fottner et al., 2021, p. 2; Windt, Philipp and Böse, 2008, p. 195). Thus, various automation approaches are being pursued in research and practice to control processes more efficiently using data and information to adapt to the increasingly flexible environment.

One approach to deal with these changing conditions is the decentralised connectivity of intralogistics systems. However, wireless connectivity presents a major 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 and real-time data transmission and processing (Rao and Prasad, 2018, p. 149). Existing industrial wireless communication systems, such as Wi-Fi, Bluetooth or ZigBee, use public frequencies for signal transmission. As a result, any mobile device located within the transmission range of the sender can log into the network and use these frequencies. This leads to an overload of the frequencies (Aijaz, 2020, p. 141; VDMA, 2020, p. 24) and does not protect the network from intrusion and attacks. In particular, ultra-reliable and low-latency communication is seen as an enabler for industrial time-critical applications requiring wireless real-time data transmission (Oyekanlu et al., 2020, 202312). For example, applications such as autonomous mobile robots or robot motion control based on tactile internet have strict requirements regarding communication systems due to their time or safety-critical mission. These requirements often cannot be entirely covered by established wireless communication technologies (Rao and Prasad, 2018, p. 149; Temesvári, Maros and Kádár, 2019a, p. 601). For these reasons, wired communication technologies are mainly used for time-critical industrial applications (Jonsson and Kunert, 2009, p. 429; VDE, 2017, p. 12).

The fifth generation of mobile communications (5G) has been specified and developed since 2017 by a consortium of seven organisations known as the 3rd Generation Partnership Project, called 3GPP

(3GPP, 2022a). 5G was specifically developed for industrial purposes for the first time in mobile communication history, to fill the gaps in reliable industrial real-time communication. Therefore, the Radiocommunication sector of the International Telecommunication Union (ITU-R) has defined three service categories for 5G in their International Mobile Telecommunication Vision (IMT-Vision) in coordination with 3GPP, shown in Figure 1.1.

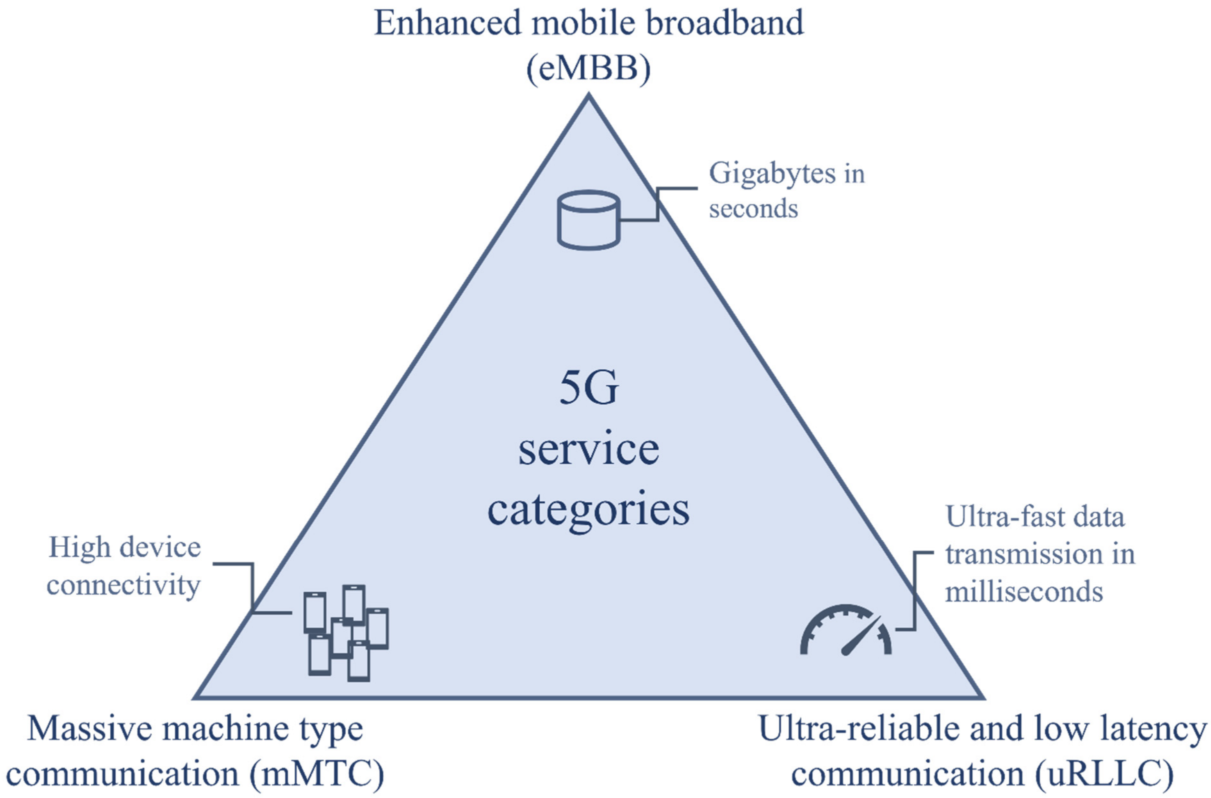


Figure 1.1: IMT-Vision beyond 2020 and 5G service categories
(based on ITU-R, 2015b, p. 12)

As shown in Figure 1.1, the 5G service categories are called enhanced mobile broadband (eMBB) enabling peak-download rates of up to 20 gigabits per second and peak-upload rates of up to 10 gigabits per second. Ultra-reliable low-latency communication (uRLLC) enables latencies in the range of 1 millisecond and minimum reliability of 99.999% and massive machine-type communication (mMTC) connects up to 1 million devices per square kilometre (ITU-R, 2015b).

Furthermore, 5G provides the deployment of standalone (SA) non-public networks (NPNs). SA networks operate on their dedicated core network without using 4G/ LTE infrastructure. Therefore, the SA architecture is a pure 5G-based system enabling the full performance capabilities and services of 5G by guaranteeing a definite quality of service (Aijaz, 2020, p. 138). For industrial purposes, 5G networks based on the SA architecture are particularly interesting in combination with the deployment of NPNs (Aijaz, 2020, pp. 136–137; Rostami, 2019, p. 433). In contrast to public networks, NPNs use locally restricted and licensed frequencies that guarantee a high level of data security and privacy due to their full isolation from public networks. Moreover, NPNs enable the operator to control and fully coordinate the network with the requirements of industrial applications (Aijaz, 2020, pp. 138–139; J. Ordonez-Lucena et al., 2019, p. 6).

The defined service categories of 5G with their performances and the possibility to establish SA NPNs increase the expectations of 5G for industrial usage. For example, Gartner's Hype Cycle for Emerging Technologies from 2020 and Gartner's Networking Hype Cycle from 2021 lists private 5G networks as innovation triggers that will reach the plateau of productivity in five to ten years (Gartner, 2020, 2021). Accordingly, a recent study from 2021 expects that private networks for industrial markets will reach a compound annual growth rate of US$208 billion in 2025 (HarborResearch, 2021, p. 11).

However, the high expectations of private 5G are based on the target performance defined by ITU-R and 3GPP. The specification and development of 5G takes place in *releases*. These *releases* are published in a continuous release process. In 2018, 3GPP provided the first complete set of 5G standards supporting SA NPNs with Release 15, followed in 2020 by Release 16 with enhanced 5G functionality. Releases 17 and 18 contain enhanced 5G services announced for 2022 and 2024 (3GPP, 2022d). Therefore, the standardisation of 5G has not been completed and is still an ongoing process that will be continued until the defined performance targets for the 5G service categories by ITU-R and 3GPP are achieved. Thus, it is essential at this early stage of 5G to investigate the expectations of SA NPNs and assist companies in establishing 5G as a wireless technology for industrial use cases.

1.2 Research problem statement and questions

5G is a promising technology to meet the growing demand for wireless communications in the intralogistics and to fill gaps in reliable and wireless real-time communication. However, 5G is still in development, and further releases of 5G are needed until it reaches the defined target performance. 3GPP plans four major 5G releases consisting of many documents specifying the upcoming 5G. For example, Release 16 consists of more than 83 studies (3GPP, 2022k) which increases the complexity of the 5G release process.

Additionally, 5G promises to offer various services such as the positioning service or the vehicle-to-everything communication raising the interest in 5G for intralogistics applications. These services, in turn, are based on various other standards and further increase the complexity. However, the 5G release process is not separated into non-public and public networks and, therefore, it lacks transparency regarding the available performance of 5G in non-public networks within respective releases.

Furthermore, *practicality* combines theoretical feasibility with environmental influences, further complicating the evaluation process. This results in a distorted picture regarding the performance of SA NPNs in respective releases regarding the *practicality* of intralogistics applications, which leads to the following problem:

The intransparent practicality of 5G applications in intralogistics results in decision-makers in companies not knowing whether use cases can be implemented with available 5G releases, what use case requirements must be considered, and what factors in the industrial environment must be taken into account to evaluate the practicality of 5G. Against this background, introducing a 5G standalone non-public network in industrial facilities at this early phase of 5G is associated with a complex setup process, performance and feasibility uncertainties.

To solve this problem, current academic literature is lacking at the level of a generic framework to assist decision-makers when evaluating the *practicality* of 5G for intralogistics use cases in SA NPNs. Therefore, the derived primary research question (PRQ) of this thesis is:

PRQ	*How can a framework assist the decision-making process of companies in evaluating the practicality when adopting 5G for intralogistics use cases in standalone non-public networks?*

To address the PRQ, subsequent research questions (SRQ) are defined and must be answered first. Examining the SRQ leads to an understanding and theory building, resulting in answering the PRQ. Therefore, the following four SRQs are defined:

SRQ 1	*What performances and services in 5G standalone non-public networks are required to evaluate the practicality, and in what 5G releases are these performances and services available?*
SRQ 2	*What influencing factors occur in the intralogistics that can impact the practicality of wireless communication?*
SRQ 3	*What wireless indoor use cases and their critical requirements regarding wireless communications occur in the intralogistics?*
SRQ 4	*What intralogistics use cases can be used as reference use cases for the framework development to ensure a generic design?*

To answer the research questions, research objectives are defined for each question. The research objectives are presented in the following section.

1.3 Research aim and objectives

This research aims to develop a framework that assists the decision-making process for evaluating the *practicality* of 5G for intralogistics use cases in SA NPN. To achieve this aim, the following research objectives (RO) are defined:

1. Conducting a thorough literature review to gain knowledge of relevant subjects for this research:
    a. Intralogistics
        i. Fundamentals and definitions of intralogistics
        ii. Automation in intralogistics
    b. Mobile communication:
        i. Fundamentals and definitions of mobile communications
        ii. Fundamentals of 5G technology
    c. Influencing factors on wireless communication
    d. Intralogistics related to wireless communication
        i. Collection of intralogistics use cases requiring wireless communication
        ii. Real-time communication concepts for industrial use cases
2. Use case classification and analysis
    a. Use case classification
    b. Identification of critical use cases
3. Framework development
4. Validation of the proposed framework
    a. Conducting a case study
    b. Empirical measurements

1.4 Research contribution

The research contribution of this thesis is divided into theoretical and practical parts.

1. Theoretical research contribution:
    - Developing and providing a holistic framework that enables the evaluation of the *practicality* of 5G for intralogistics use cases based on the use case and based on the use case environment
    - Providing a consolidated summary of all specified performances of 5G SA NPNs for each 5G release in the form of tables
    - Identifying intralogistics use cases requiring wireless communication and mapping their respective requirements with the individual 5G releases

2. Practical research contribution:
    - Minimising the technical uncertainties that decision-makers are faced with in the context of introducing 5G for intralogistics use cases
    - Performing initial measurements of different SA capable end devices in 5G SA NPN for a first performance benchmark

1.5 Research design and methodology

According to Creswell and Creswell, 2018, a research approach consists of three elements that interact (see Figure 1.2): The philosophical worldview, research design and research methods (Creswell and Creswell, 2018, p. 43).

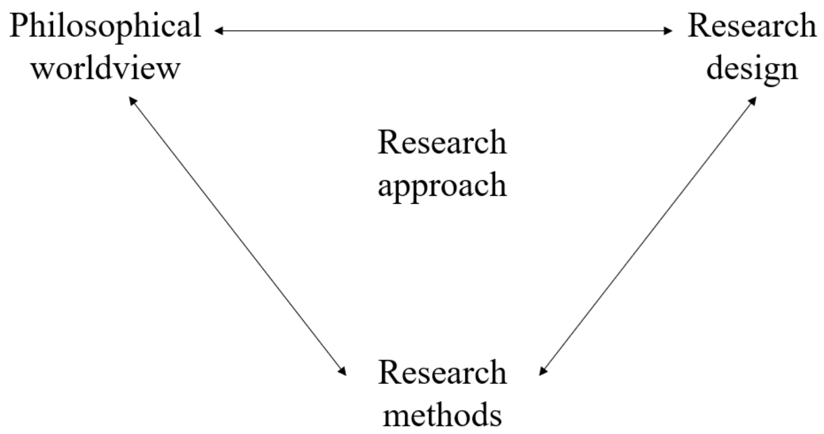


Figure 1.2: Research framework
(Creswell and Creswell, 2018, p. 43)

For this purpose, this section contextualises pragmatism as the philosophical perspective of the author to establish an understanding of how this research claims to gain knowledge. Subsequently, the design science research (DSR) is highlighted as the underlying research design, and finally, the methodology and process steps for developing the framework will be discussed. The philosophical perspective is the foundation of how a researcher seeks to build theories and create knowledge. The belief and pre-existing assumptions influence the research and must thus be presented (Fink, 2018, p. 23). Furthermore, presenting the philosophical view provides a good foundation for an intersubjective understanding of the research and the comprehensibility of results (Fink, 2018, pp. 50–51; Helfrich, 2016, p. 90). The literature commonly highlights five philosophical perspectives and movements – realism, empiricism, constructivism, interpretivism and pragmatism. The perspective adopted for this research is pragmatism. Pragmatism is grounded in the assumption that a single point of view is often insufficient to form theories, but rather that problems the researcher seeks to solve must be approached from different perspectives. This allows the researcher the freedom to adopt different methods and approaches.

In the context of methods, Creswell and Creswell fundamentally consider the qualitative, quantitative and mixed methods as approaches to research (Creswell and Creswell, 2018, p. 41). However, the freedom to use different pragmatism methods does not imply that research requires multiple methods. It instead means that the data collection techniques can be adapted to the research questions and the prevailing circumstances (Saunders and Tosey, 2011, p. 58).

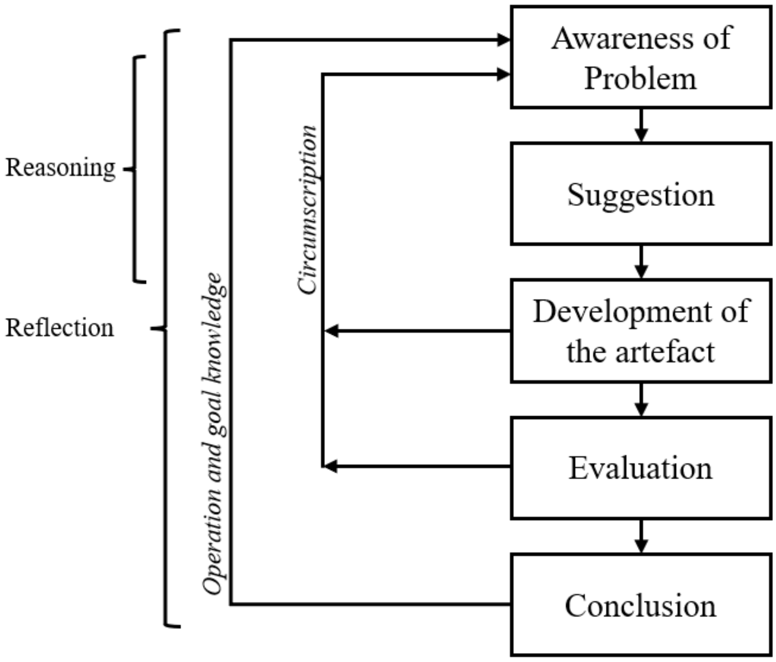


Figure 1.3: Design science research theory development framework
(William Kuechler and Vijay Vaishnavi, 2015, p. 406)

The Design Science Research (DSR) was chosen as the research design. Figure 1.3 represents the DSR theory development framework followed in iterative process loops to acquire the knowledge needed and build theories. DSR is a design approach focusing on developing an artefact that solves real-world problems (Dresch, Lacerda and Antunes, 2015, p. 2). In the context of this project, the artefact is represented by the proposed framework. The DSR framework consists of five major phases. The first phase serves to identify and raise awareness of the problem. In this phase, the research problem is defined, questions are formulated, and the underlying research design is selected according to how the researcher seeks to solve the problem. Once problem awareness has been established, possible solutions are studied in the suggestion phase. Approaches, explanations and theories for solving the problem can be formed by examining core theories from literature, the experience-based intuition of the researcher, and experiments (William Kuechler and Vijay Vaishnavi, 2015, p. 407). The suggestion phase involves problem-specific approaches and explicit concepts to solve the underlying problem. The selected concepts are mapped and linked together in the development phase to generate an initial artefact. The artefact, in this case, the developed framework, can subsequently be improved and refined in several loops. After each development phase, the artefact is re-evaluated and adapted as needed. Finally, the artefact as the researcher's construct can be communicated and discussed in the conclusion phase after validating the framework. In addition, the researcher may identify recommendations and improvements for future research activities.

In terms of methodology, the research aims to develop a framework. Jabareen (2009, p. 51) defines a framework as a "network, or 'a plane,' of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena." Jabareen (2009) proposes collecting data from multidisciplinary literature such as books, articles, or practices. The outcome of discipline-oriented theories becomes the conceptual framework's empirical data, which "uses grounded theory methodology rather than a description of the data and the targeted phenomenon". As Jabareen (2009) suggests, qualitative methods are used for fundamental concepts. To summarise, Table 1.1 provides an overview of the underlying methods for this project assigned to the individual DSR steps.

Table 1.1: Research process steps and methods used for this thesis

DSR process step	Method	Chapter
Awareness of problem	Research definition	1. Introduction
Suggestions	Qualitative data collection	2. Literature review
Suggestions and reasoning	Qualitative data collection	3. Use case analysis
Development of the artefact	Qualitative data analysis	4. Framework development
Evaluation	Quantitative case study	5. Framework validation
Conclusion	Critical review, reflection	6. Conclusion

1.6 Delimitations and limitations

The scope of the research contains delimitations as well as limitations. Delimitations are boundaries set by the scientist, while limitations are external constraints that cannot be explicitly influenced.

Regarding the delimitations, this research project aims to develop a framework to evaluate the *practicality* of 5G for intralogistics use cases. As the aim indicates, the focus is on intralogistics use cases and their requirements. The use cases are collected solely through a literature review concerning the methodology. Furthermore, only indoor intralogistics use cases requiring wireless communication are considered. However, the framework aims to adopt an industry-independent and generic approach. With respect to the intralogistics indoor environment, factors influencing 5G are often situation-dependent variables. Therefore, this framework cannot provide a quantification of these variables. However, the framework is intended to provide the user with indications of all influencing factors to be considered when adopting 5G. Regarding the 5G network, the research only considers 5G SA NPNs as relevant deployments for industrial use. Concerning 5G releases that have been specified but are not yet available, the theoretically specified performances must serve as a benchmark.

Moreover, the framework focuses on the technical *practicality* of 5G and does not, therefore, consider costs and other economic perspectives.

1.7 Thesis outline

Chapter 1. Chapter 1 formally defines and introduces the research undertaken. The background of the research, as well as the research questions and the objectives are presented. Furthermore, the chapter includes the research design and methodology and closes with a thesis outline.

Chapter 2. Chapter 2 is part of the data collection process and reviews relevant literature focusing on the intralogistics and fundamentals of 5G. Chapter 2 also includes a semi-systematic literature review of intralogistics use cases related to wireless communication.

Chapter 3. Chapter 3 includes a use case analysis to examine their requirements and characteristics based on the identified use cases from Chapter 2. Additionally, this chapter aims to derive critical use cases that can serve as reference use cases for the framework.

Chapter 4. A framework to evaluate the *practicality* of 5G for intralogistics use cases is developed based on the data collected. The outcome is the proposed framework that answers the PRQ.

Chapter 5. The framework validation is carried out through a case study using an autonomous mobile robot in the learning factory *Werk150* at Reutlingen University. The case study is supplemented with empirical measurements of the 5G network.

Chapter 6. Chapter 6 summarises and concludes the research. Furthermore, the chapter reviews the research contribution and limitations retrospectively. Finally, recommendations for further research activities are discussed.

The thesis outline is shown in the following Figure 1.4.

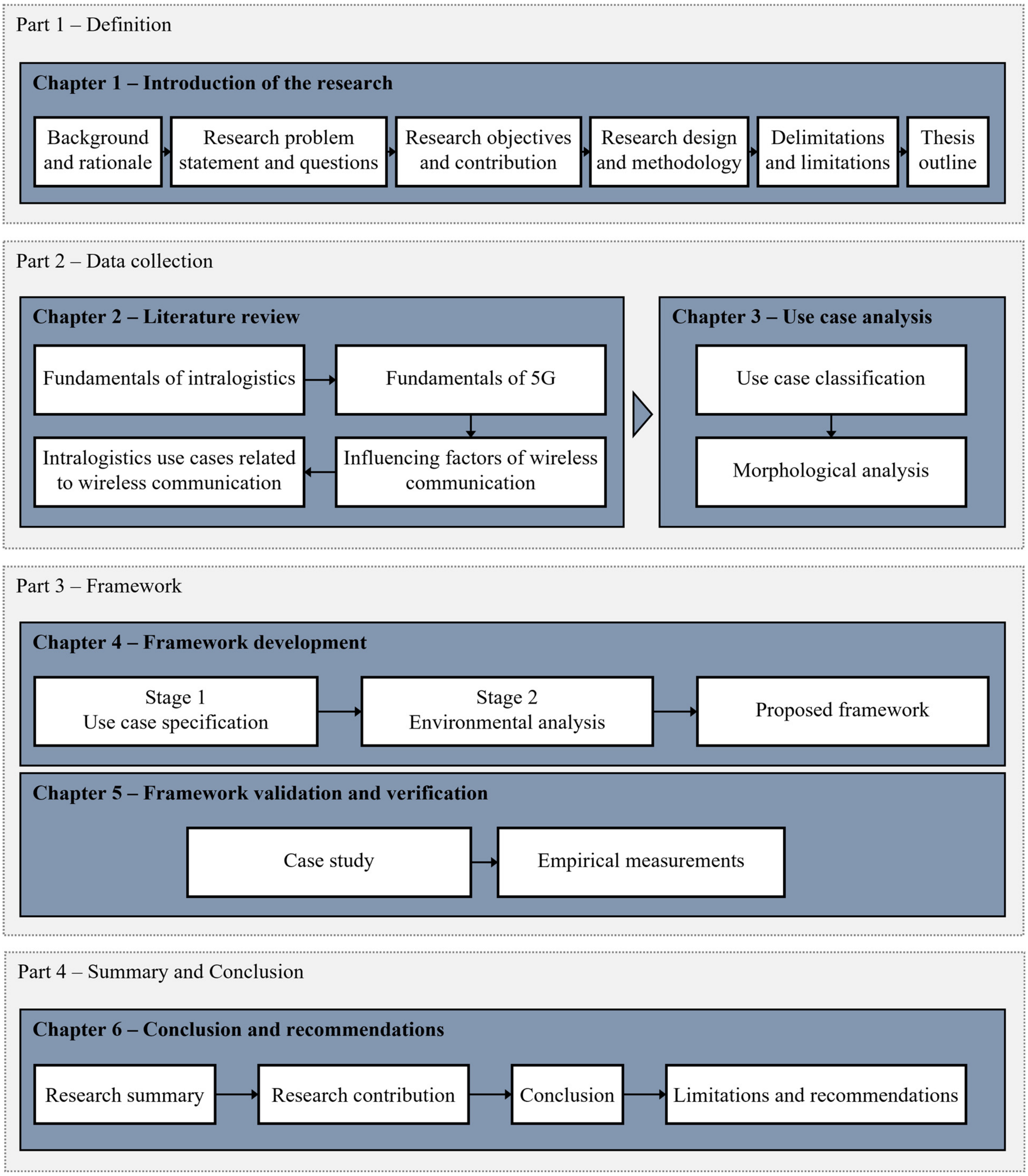


Figure 1.4: Thesis outline

1.8 Concluding summary

Chapter 1 defines the research and introduces the background and motivation to investigate 5G for intralogistics use cases. The presented problem statement, research questions and objectives, and the research design and methodology equip the author with the required tools to develop the framework. The preliminary literature review indicates an existing need for decision support in evaluating the *practicality* of 5G for intralogistics use cases. In particular, a holistic investigation of the applications' requirements and environmental factors is essential to support companies' decisions to adopt 5G.

2 Literature review

Chapter 2 covers the literature review of this thesis. Section 2.1 defines intralogistics and distinguishes the term from the concept of logistics. Subsequently, intralogistics challenges are presented, and the resulting automation is outlined. In Section 2.2, the fundamentals and core elements of 5G are introduced. Concerning 5G, the section focuses on standalone non-public networks, their performance and services. Section 2.3 investigates influencing factors of wireless communication with the focus of industrial environments. Therefore, this section aims to answer SRQ 2. In Section 2.4, wireless intralogistics use cases are semi-systematically identified. Thus, Section 2.4 provides answers to SRQ 3. This section also includes a review of industrial real-time systems to identify characteristics of use cases requiring real-time data transmission and, thus, must be met by 5G. The structure of this chapter is shown in Figure 2.1.

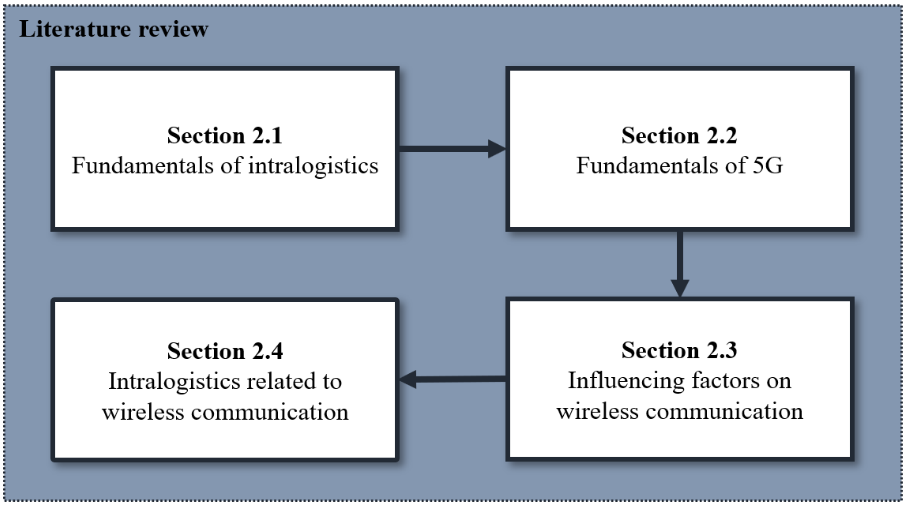


Figure 2.1: Structure of the literature review

Regarding the research method, the literature review forms the qualitative part of the data collection (see Table 1.1). An inherent part of scientific work is the presentation of the methodology and the sources and databases for the comprehensibility of the theories formed. Different types of sources were used for the literature review. Concerning 5G, relevant journal articles, books, white papers and reports from industry-related organisations and mainly the technical specifications of 5G were studied. For the literature review, various databases and search engines are used. Regarding 5G specifications, 3GPP's database (www.portal.3gpp.org) is consulted. In addition, the database IEEE Xplore (ieeexplore.ieee.org) and the search engines from Google Scholar (scholar.google.com) and Elsevier Scopus (www.scopus.com) are consulted for the literature review.

2.1 Fundamentals of intralogistics

This section focuses on the fundamentals of intralogistics. First, intralogistics is defined and distinguished from logistics by describing intralogistics tasks. Second, the section reviews centralised and decentralised intralogistics systems. In conclusion, this section defines important fundamentals of intralogistics and provides the required knowledge for Section 2.4 on identifying use cases in intralogistics requiring wireless communication.

2.1.1 Definition and tasks of intralogistics

The term *intralogistics* was first introduced by the association of mechanical and plant engineering, called VDMA, in 2003. According to VDMA, intralogistics is a subdiscipline of logistics and is defined as “the organisation, control, implementation and optimisation of internal material flows, information flows and goods handling in industry, commerce and public institutions” (Arnold, 2006, p. 1; VDMA, 2021). In this context, the *internal flow* includes all parts of self-contained company sites, for example, factories, warehouses, distribution centres or harbours (Fottner et al., 2021, p. 2). Thus, all indoor and outdoor processes and flows of goods on the company’s site are included in the term *intralogistics*. Based on Rixe and Augustin’s (2020) reference model (Figure 2.2), intralogistics tasks include planning and controlling these processes.

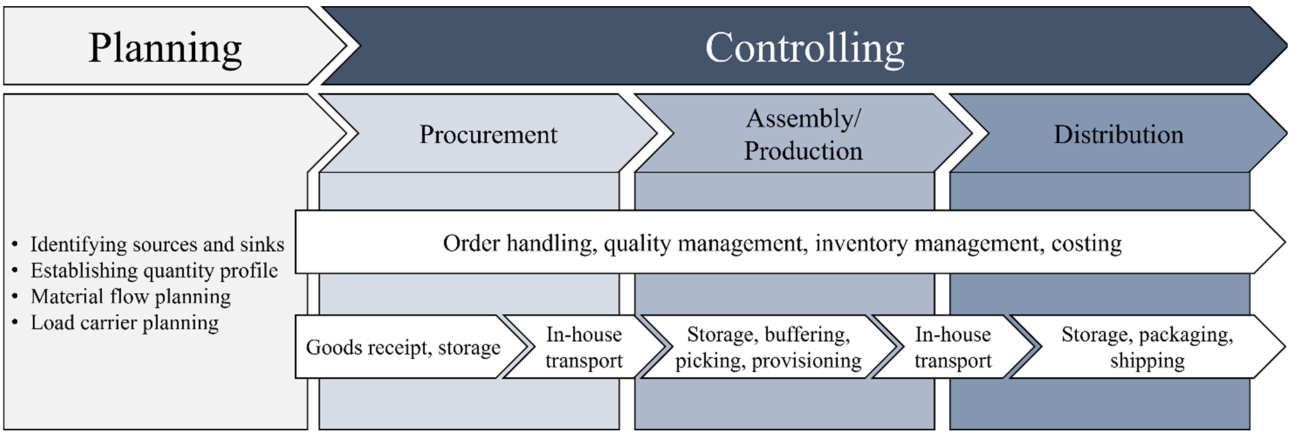


Figure 2.2: Reference model for intralogistics tasks
(Rixe and Augustin, 2020, p. 894)

According to Rixe and Augustin (2020, p. 894), the planning phase includes identifying sources and sinks, determining a quantity structure and planning the material flow, resources and load carriers. The controlling phase starts once the goods or information are on the company site. The controlling phase is divided into three divisions (Rixe and Augustin, 2020, p. 894):

- Procurement
- Assembly & Production
- Distribution

In the controlling phase, additional tasks are carried out across all three divisions, such as order handling, quality management, inventory management, and costing. As shown in Figure 2.2, the different divisions have different process steps and tasks. Between each of the process steps, an in-house transport takes place. Machines and transport systems, storage systems, and software systems are required to enable the various material and information flow tasks in intralogistics. In this context, Arnold (2006, p. 6) identifies eight product groups that can be understood as core elements to execute intralogistics tasks within the controlling stage:

- Continuous conveyors (unit load/bulk material)
- Storage systems
- Industrial trucks
- Logistics software
- Forklifts and lifting equipment
- Crane systems
- Operating equipment/packaging technology
- Industrial communication system providers, system integrators

The product groups are integrated into the intralogistics material flow and perform various subtasks in the internal value stream. Data about the individual process steps and their progress is required to control and coordinate the internal flow of goods and information. In this context, different approaches to data acquisition in intralogistics systems are described in the following section.

2.1.2 From centralised to decentralised intralogistics

Today's manufacturers in supply chains are facing increasing challenges. In the course of the globalisation of businesses, the complexity of value chains increases and the manufacturing depth of single supply chain participants continuously decreases (Aelker, Bauernhansl and Ehm, 2013, p. 79). Additionally, factors such as shorter product life cycles, increasing product variance and individualisation of products with small batch sizes further increase the complexity of production processes (Aelker, Bauernhansl and Ehm, 2013, p. 80; Windt, Philipp and Böse, 2008, p. 195). This results in dynamic and volatile markets (Wilding, 1998, p. 599). Due to these developments, intralogistics systems are also exposed to increasing dynamics and complexity and must constantly adapt to changing conditions (Fottner et al., 2021, p. 2; Windt, Philipp and Böse, 2008, p. 195). For this reason, various automation approaches are being pursued in research and practice to control processes more efficiently using data and information to better adapt to the increasingly flexible environment.

According to VDI, the most common approach to intralogistics is still a centralised automation model (VDI, 2013, p. 4). Centralised intralogistics systems are primarily characterised by their hierarchical design (VDI, 2013, p. 4). In this context, the automation pyramid is widely adopted as a reference model to visualise the different material flow control levels in intralogistics and their respective tasks (Fottner et al., 2021, p. 3; Sohrt et al., 2020, p. 29).

The five-level automation pyramid in centralised intralogistics systems is explained below (Fottner et al., 2021, pp. 3–4):

- **Level 0 (Physical process):** This level represents the physical processes. According to the intralogistics reference model (Figure 2.2) from Rixe and Augustin's research (2020), the physical process level includes tasks such as receiving goods, storage, transport, picking, provisioning, packaging and shipping (Rixe and Augustin, 2020, p. 894). Sensors and actuators are integrated to control and monitor these processes. Sensors and actuators can be physical, mechanical, or electrical and form the interface between the physical process and device control.
- **Level 1 (Device control):** The device control represents the level of embedded sensors and actuators within the physical processes. Sensors collect and provide data, whereas actuators execute commands passed from the device control stage to the physical process. The tasks of the device control level include data collection and processing and actuator control.
- **Level 2 (Process control):** Process control forms the second level. The information and data from the device level are processed to coordinate the physical process on Level 0. This includes, for example, the routing of vehicles on the shop floor and synchronising successive process steps.
- **Level 3 (Operations control):** The operations control represents tactical planning with a short-term horizon, such as the tasks of order management and quality management in intralogistics. The top-down tactical planning in this stage is based on data provided from lower levels.
- **Level 4 (Overall planning):** The top level reflects medium-term and long-term planning. In intralogistics, for example, raw material and resource planning, factory layout planning or planning of assembly lines occur at this level.

The automation pyramid representing a centralised and hierarchical intralogistics system linked to its respective intralogistics tasks is shown in Figure 2.3.

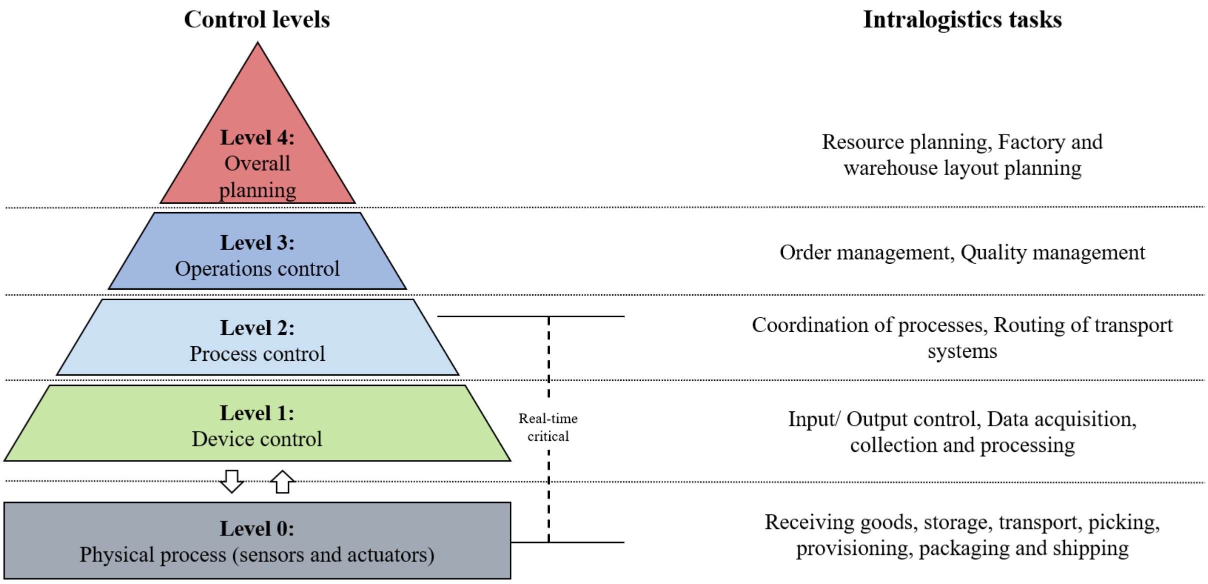


Figure 2.3: Automation pyramid in hierarchical intralogistics and its intralogistics tasks (based on Fottner et al., 2021, p. 3; VDI, 2013, p. 4)

Figure 2.3 illustrates that communication interfaces exist only between the individual control levels in centralised systems. Each control level is linked to predefined intralogistics tasks (Fottner et al., 2021, pp. 3–4). This leads to vertical integration of systems in which data is collected from physical processes and shared with upper levels. The planning takes place top-down based on the data and information provided by lower levels. Due to the strict vertical integration of systems, data is stored and processed in a central storage unit. However, the centralised approach to automation limits the performance of data transmission and processing (Siepmann, 2016, p. 51).

Additionally, the hierarchical levels separate the real object and the information (virtual object). Due to the limitations of centralised systems and the challenges mentioned above of increasing complexity and flexibility in intralogistics, in the last few decades a shift has started toward decentralised and autonomous automation systems (Windt, Philipp and Böse, 2008, p. 195). The transformation from centralised intralogistics toward Cyber-Physical Systems (CPS) is shown in Figure 2.4.

Decentralised intralogistics is based on the principle of CPS, illustrated in Figure 2.4 (b). According to the integrated research agenda of CPS of the Academy of Science and Engineering in Germany, a CPS is characterised by “a linking of real (physical) objects and processes with information-processing (virtual) objects and processes” (acatech, 2012). This leads to a non-hierarchical network of interconnected entities sharing data and services with each entity (Bauernhansl, 2014, pp. 15–16). Therefore, decentralised systems shift the storage, processing and ultimately the decision-making directly or close to the physical process by equipping the entities with embedded smart Industrial Internet of Things (IIoT) sensors (Günthner and Hompel, 2010, p. 45). Each control unit possesses a so-called ‘agent’. The agents are background information clouds in which the data not actively involved in the physical process step is processed and stored (Sohrt et al., 2020, pp. 32–33).

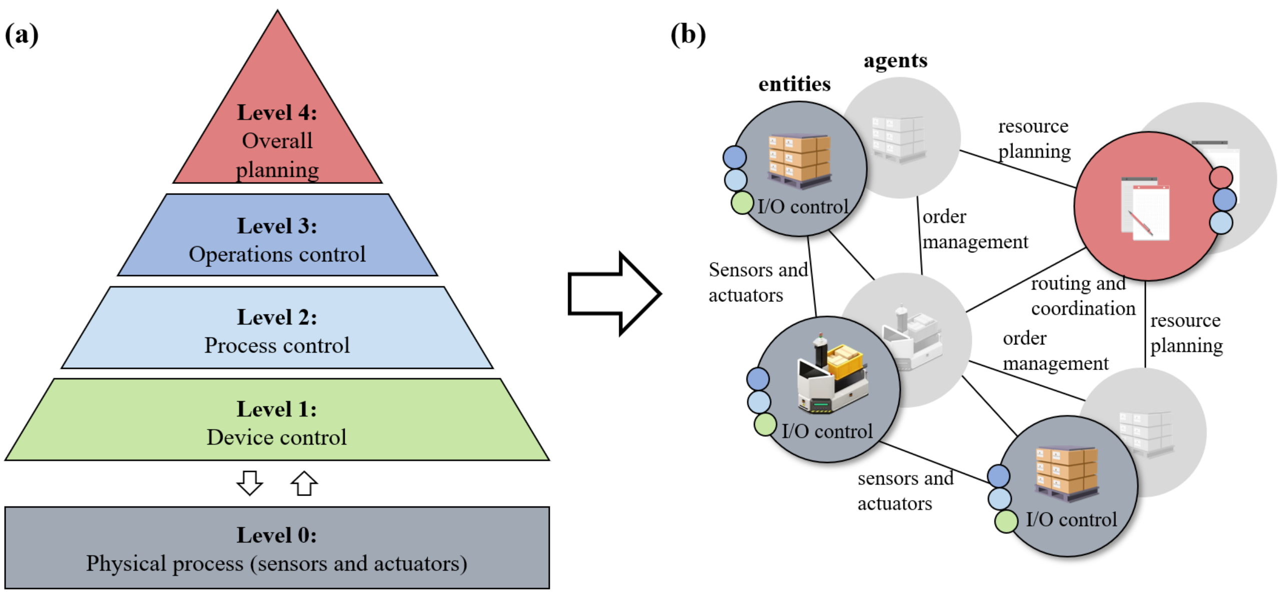


Figure 2.4: Transformation from (a) centralised to (b) decentralised, autonomous systems in intralogistics (based on Fottner et al., 2021, p. 3; VDI, 2013, p. 4)

As shown in Figure 2.4 (b), agents perform tasks such as resource management, routing, and order management in interaction with other agents. Thus, decentralised systems enable fast adaptation to dynamic changes in the environment or to changes in the systems' state (Fragapane et al., 2021a, p. 405).

In intralogistics, in particular, decentralisation is an evolving area of research. However, the decentralisation and introduction of CPS in intralogistics are associated with critical success factors. In this context, the interplay and mutual influence of security, safety, and real-time requirements are reported as relevant (VDI, 2013, p. 7). Due to increases in networking, the potential of security threats likewise increases, resulting in risks to the functional safety of applications (VDI, 2013, p. 7).

Furthermore, intralogistics systems are typically mobile and require strict requirements since they often interact with humans, for example, when humans and machines operate on the shop floor (Sohrt et al., 2020, p. 30). However, the realisation of decentralised systems in intralogistics still faces technological challenges (Sohrt et al., 2020, p. 30). For example, one factor is the lack of intelligent networking due to the lack of uniform communication interfaces (Sohrt et al., 2020, p. 30). Another factor is the required simultaneous data security in wireless communication systems by a highly reliable data transmission (VDI, 2013, p. 7).

In this context, 5G promises mobile communications offering high-performance, low latencies and high data security with the simultaneous deployment of standalone non-public networks (Aijaz, 2020, pp. 136–137). Therefore, 5G is seen as a promising enabler technology for mobile intralogistics systems (Günthner and Hompel, 2010, pp. 258–259).

2.2 Fundamentals of 5G New Radio

This literature review section introduces the fundamentals of mobile communication and, in particular, the 5G New Radio (NR) technology. First, this section places 5G into the ecosystem of communication technologies and provides an overview of the evolution of mobile communications. Second, the release process of 5G is presented, and the individual scope of each release regarding the specified performance is investigated. The third part introduces the architecture of 5G standalone non-public networks. Both the second and third parts collectively provide answers to SRQ1.

2.2.1 The ecosystem of communication technologies

This section aims to place 5G as mobile communications in the industrial communication technologies ecosystem. As shown in Figure 2.5, communication technologies can be fundamentally categorised into wired and wireless technologies (Scanzio, Wisniewski and Gaj, 2021, p. 4). In the ecosystem of wireless communication technologies are various standards such as Bluetooth (IEEE 802.15.1), Wi-Fi (IEEE 802.11/ac/ax) or ZigBee (IEEE 802.15.4) that have different characteristics and are thus used for different purposes. The latest generation of mobile communications, 5G, belongs to wireless communication (Scanzio, Wisniewski and Gaj, 2021, p. 4), shown in Figure 2.5.

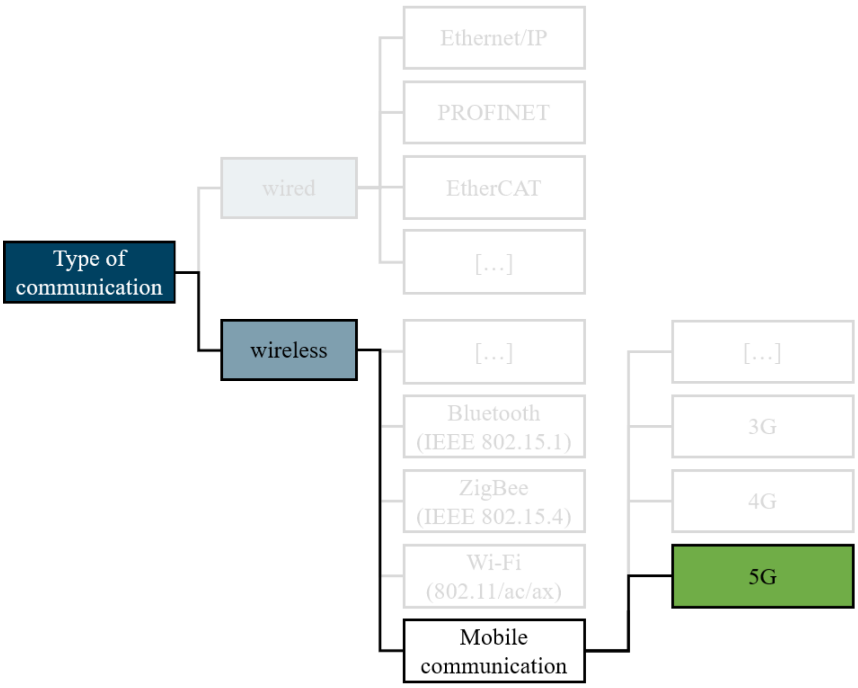


Figure 2.5: Classification of communication technologies
(Scanzio, Wisniewski and Gaj, 2021, p. 4)

In the following sections, the evolution of mobile communication as part of wireless communication technologies and, in particular, 5G is introduced in detail.

2.2.2 Evolution of mobile communications

The roots of wireless communication can be found in the invention of the wireless telegraph in 1896 by Guglielmo Marconi. Marconi's telegraph enabled signals to be sent over 3200 kilometres for the first time, decoded in analogue form as alphanumeric characters (Nitesh and Kakkar, 2016, p. 320). In the early twentieth century, telecommunications technology was researched primarily for use in military and intelligence agencies operations.

In the late 1950s, research organisations, particularly in the United States, developed the first ideas and concepts for realising a conventional mobile communication system based on the principles and fundamental theories of wireless signal transmission (Salih et al., 2020, 2140). The following sections briefly summarise the evolution up to the present fifth generation. Figure 2.6 provides a timeline overview and services of the generation of each mobile communication.

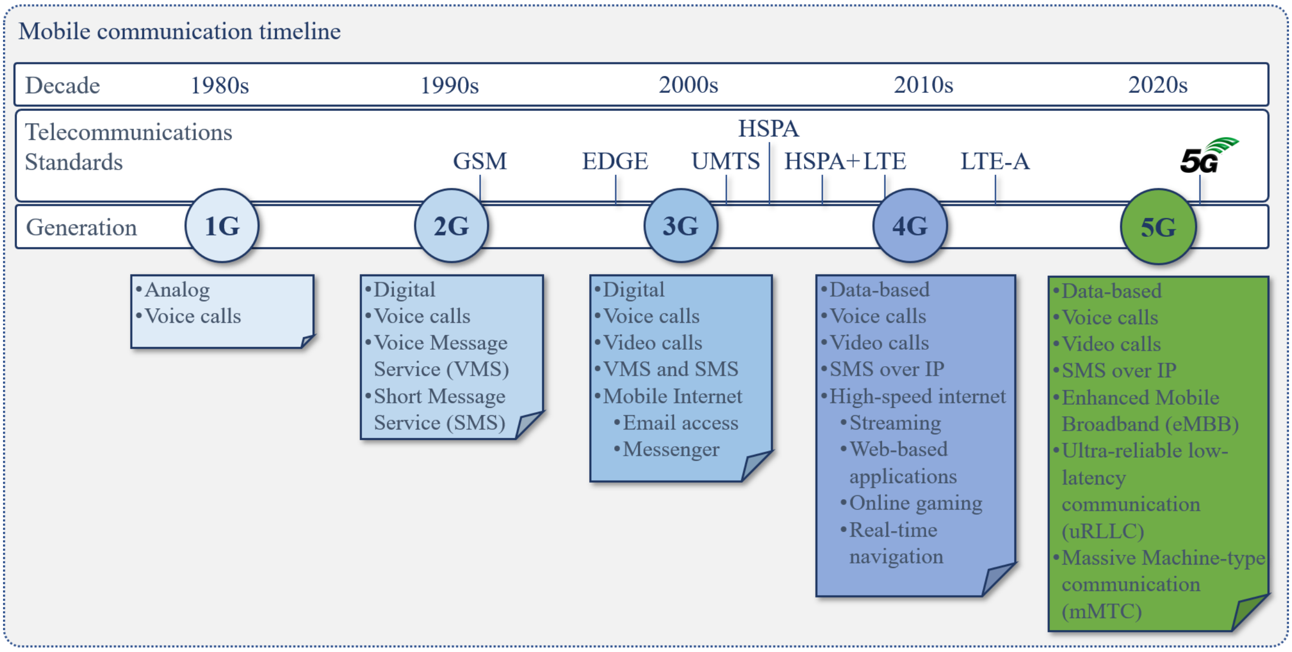


Figure 2.6: Evolution of mobile communications
(based on Shetty, 2021, p. 2)

First generation (1G)

The first mobile communication generation was a purely analogue system which could be used only for voice transmission. Maximum data rates for 1G were typically 2.4 kilobits per second (Nitesh and Kakkar, 2016, pp. 321–323). As a successor to 1G, the 1990s brought the decade of 2G.

Second generation (2G)

In contrast to the first generation, 2G is based on the Global System for Mobile (GSM) standard, entirely on digital signal processing. In addition to voice transmission, 2G enables further services such as the Voice Mail Service or the Short Message Service (Shetty, 2021, p. 2). As a further development of 2G, the Enhanced Data rates for GSM Evolution (EDGE) was introduced.

Third generation (3G)

The third generation (3G) was developed in the 2000s under the International Mobile Telecommunications-2000. A single global network protocol known as Universal Mobile Telecommunications System (UMTS) was designed to increase data transmission efficiency, (see Figure 2.6). The later-developed High-Speed Packet Access (HSPA) protocol enabled data rates up to the Megabit range (Dunnewijk and Hultén, 2007, p. 172). In addition to voice communication, 3G also enabled services such as video calls, internet access, and navigation (Shetty, 2021, p. 2).

Fourth generation (4G)

The further evolution of 3G is called Long Term Evolution (LTE) and is considered the early phase of 4G, also known as LTE-Advanced (LTE-A). 4G then became popular in the 2010s and is regarded as the first generation built on a pure data-based network. LTE-A can achieve peak data rates of up to 1 Gbit/s (Manam, P.V. and Telluri, 2019, p. 272). This enables, for example, high-speed internet access, high-resolution video streaming or internet-based real-time navigation (Shetty, 2021, p. 2).

Fifth generation (5G)

The 3rd generation partnership project (3GPP) has been developing 5G since 2017. 3GPP has agreed on three core elements in coordination with the International Telecommunications Union, namely, enhanced Mobile Broadband (eMBB), ultra-reliable low-latency communications (uRLLC) and massive machine-type communication (mMTC) representing a massive end device connectivity (ITU-R, 2015b). 3GPP is developing an entirely new mobile communications system to meet these core elements, known as 5G.

2.2.3 3GPP: 5G development process and release content

5G is defined and developed by a consortium of seven global telecommunications standard development organisations called the 3GPP. This consortium first came together as a project to define the third mobile communications standard (3G) in 1998.

The organisation aims to work with mobile service providers, the International Telecommunication Union (ITU) and research and development experts to provide a complete system description for mobile communications that covers all levels of mobile communications (3GPP, 2022a). The levels include the Radio Access Network (RAN), Core Network (CN), the terminal hardware (end devices), the software functions and the definition of services (Service & System Aspects). For this purpose, 3GPP is divided into three primary technical specification groups, which define the following levels of mobile communications (3GPP, 2022a):

- Radio Access Network
- Service & System Aspects
- Core Network & Terminals

Subsequently, the system description is published as Technical Specifications (TS) or Technical Reports (TR). Accordingly, the TS and TR of 5G are made publicly available, and hardware manufacturers and mobile phone service providers can align their network infrastructure development (3GPP, 2022a).

2.2.3.1 Release process overview

3GPP uses a system of parallel releases. Individual releases contain the specifications and functional scopes of the 5G standard to be developed. The releases are numbered in ascending order (e.g. Release 15, Release 16, Release 17, and Release 18). A release timeline is divided into different stages (see Figure 2.7). The beginning of each release, Stage 1, is called package approval, in which the scope of the release is defined. The working groups listed in Section 2.2.3 then develop the specific 5G functions. In Stage 2, the functions are frozen (functional freeze). Stage 3 forms the release freeze, in which no additional functions and specifications can be added. Subsequently, the protocols for implementing the defined functions are completed in Stage 4, called protocol coding freeze (3GPP, 2022d).

The first 5G release was Release 15 (Rel-15). Rel-15 was specified from 2017 to 2019 and focused on basic functionality (5G System Phase 1). The specifications of Release 16 were completed in 2020 and focused on completing the basic functionalities of 5G (5G System Phase 2). According to 3GPP, Rel-17 and Rel-18 are announced for 2022 and 2024, focusing on further developments of basic functionalities and achieving the predefined performances and service capabilities (3GPP, 2022d). The timeline (see Figure 2.7) shows that the development of 5G is still an ongoing process. Therefore, the performances and services of 5G as defined by the ITU-R cannot yet be fully achieved.

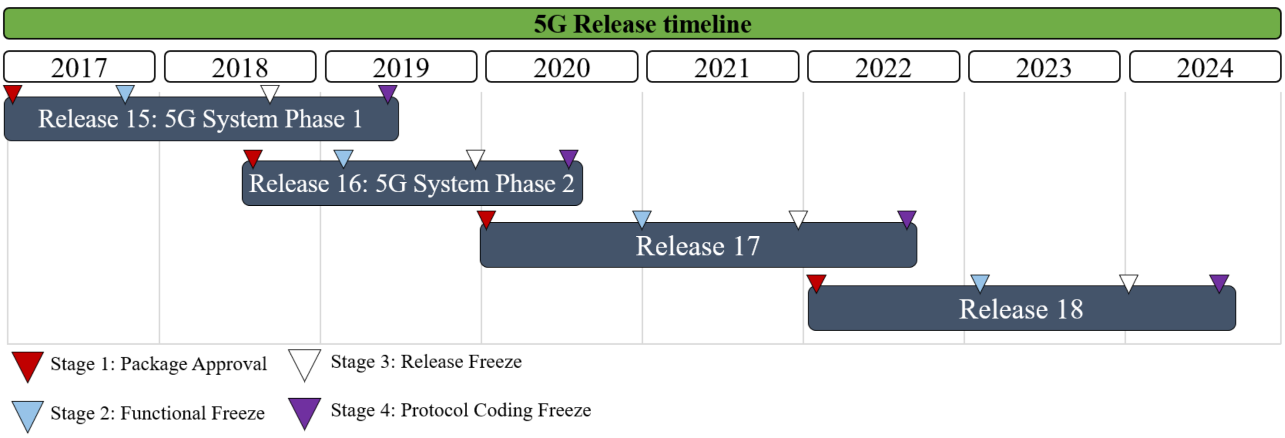


Figure 2.7: 5G release process timeline
(based on 3GPP, 2022g, 2022h, 2022i, 2022j)

Each release within the release process includes definitions, basic functionalities, Key Performance Indicators (KPIs) and 5G services for both public and non-public networks. In this context, 3GPP subdivides the release content of each release into three main categories, as shown in Figure 2.8.

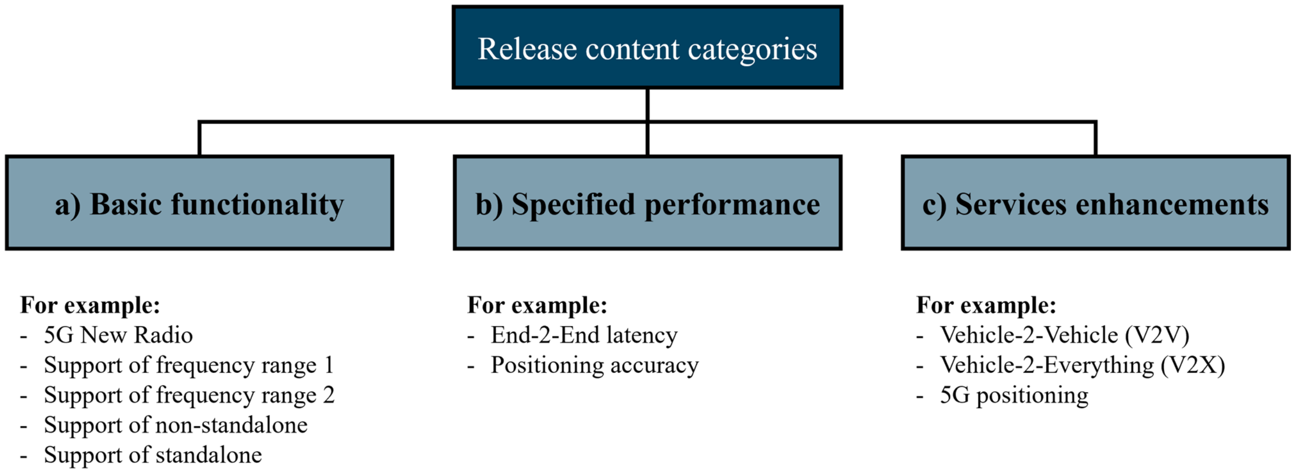


Figure 2.8: 5G release content categories
(3GPP, 2022c)

In the following section, each release content category is described in detail. The release-specific sections (Sections 2.2.3.2; 2.2.3.3; 2.2.3.4 and 2.2.3.5) follow the same structure, with the following three content categories:

a) Basic functionality

The basic functionality covers all technical aspects of the 5G system, enabling the basic communication between network and end device (3GPP, 2022c), such as the technical definition and system design of 5G New Radio (NR).

b) Specified performance

The specified performance includes defining target values to be achieved by predefined KPIs. In this context, 3GPP itself defines a set of KPIs relevant for industrial applications, defined below:

- **Positioning accuracy:** Unit of length defined as the "closeness of the measured position of the object to its true position value" (3GPP, 2018, p. 10).

- **End-to-End latency:** "Time that takes to transfer a given piece of information from a source to a destination, measured from the moment it is transmitted by the source to the moment it is successfully received at the destination" (3GPP, 2021a, p. 9).

- **Maximum end device speed:** "Maximum velocity of the object to which the communication service needs to be delivered" (3GPP, 2018, p. 12).

- **User experienced data rate:** "Minimum data rate required to achieve a sufficient quality experience" per user per second (3GPP, 2021a, p. 10).

- **End device density:** The end device density defines the number of end devices per unit of area, typically in square metres or square kilometres (3GPP, 2018, p. 12).

- **Communication service availability:** "Amount of time the communication service is delivered, divided by the time the system is expected to deliver the service" (3GPP, 2021a, p. 9).

- **Communication service reliability:** "Ability of the communication service to perform as required for a given time interval, under given conditions, where given conditions would include aspects that affect communication service reliability, such as mode of operation, stress levels, and environmental conditions. Communication service reliability may be quantified using appropriate measures such as mean time to failure, or the probability of no failure within a specified period" (3GPP, 2020a, p. 8; IEC 61907:2009, 2009).

c) Service enhancements

Furthermore, 5G releases include so-called service enhancements. This category defines all services that are unlocked with the respective release. Examples of services are the 5G positioning service and the vehicle-to-everything (V2X) communication (see Figure 2.8). However, a prerequisite for any service enhancement is the basic functionality required for the respective service.

The release content categories are divided into various documents and specifications. To provide an overview, the specification documents for all categories are listed in Table 2.1. In the following, Rel-15, Rel-16, Rel-17 and Rel-18 are presented according to 3GPP's release content categories.

Table 2.1: Release content categories and the associated specifications

Release content category	Specification	Title
a) Basic Functionality	TR 21.915	5G Release description (Release 15)
	TR 21.916	5G Release description (Release 16)
	TS 23.501	System architecture for the 5G System
b) Specified Performance	TS 22.261	5G Service requirements for next generation
c) Service Enhancements	TS 22.104	5G Service requirements for cyber-physical control applications in vertical domains

2.2.3.2 Release 15 – 5G system Phase 1

Rel-15 provides the first complete set of 5G standards and thus, forms the initial phase of the 5G (3GPP, 2022g). 3GPP's focus in Rel-15 is the requirements definition and implementation as a system architecture (3GPP, 2019b, p. 9). The entire system definition follows in Phase 2 with Rel-16 (3GPP, 2019b, p. 9).

a) Basic functionality

Regarding basic functionality, Rel-15 defines both the non-standalone architecture and the standalone architecture (3GPP, 2019b, pp. 11–12, 2022g). This includes the definitions of the 5G Core Network and the Radio Access Network. Furthermore, Rel-15 focuses on implementing eMBB capabilities.

b) Specified performance

The specified performance for standalone networks is based on the performance requirements from TS 22.261 for indoor hotspots of a 5G system and is shown in Table 2.2 (3GPP, 2019c, pp. 28–30).

Table 2.2: Specified performance of Release 15
(3GPP, 2019c, pp. 28–30)

Performance Parameter	**Specified Performance (Release 15)**	
Positioning accuracy (cm)	Positioning service is not available	
Communication service availability (%)	99.9-99.9999	
Communication service reliability (%)	99.9-99.999	
End-to-End latency (ms)	> 10	
End device speed	Pedestrian (< 5 m/s)	
User experienced data rate (Gbit/s)	Download: 1	Upload: 0.5
End device density (end device/m²)	0.25	

The positioning service is not provided for Rel-15 regarding the positioning accuracy. Concerning availability, a range between 99.9-99.9999% is given, as this is influenced by situation-dependent factors, such as the internal network interfaces or the speed at which a receiver terminal moves (3GPP, 2019c, p. 30). Depending on the availability, maximum reliability of only up to 99.999% can be guaranteed in Rel-15. With regard to the time delay, the latency is considerably higher than 10 ms. Depending on specific conditions, the 10 ms latency limit can only be reached in some instances. Typically, latencies between 100 ms and 10 ms are specified within Rel-15 (3GPP, 2019c, p. 30).

Regarding latency, Table 2.2 indicates the optimum lower threshold. The download rates depend on the density of the end device. Assuming 0.25 end devices per square metre, a maximum of 1 Gbit/s in download and 0.5 Gbit/s in upload can theoretically be achieved.

c) Service enhancements

Due to the focus on the basic functionality of 5G, service enhancements are not explicitly foreseen in Rel-15. Rel-15 includes a set of two services. The first service supports high data rates (3GPP, 2022g). The second service supports V2X communication. However, V2X in Rel-15 is defined for 4G and will be adapted for 5G in the subsequent releases (3GPP, 2019c, 2022g). The following lists both services:

- eMBB
- V2X communication (Phase 2)

2.2.3.3 Release 16 – 5G system Phase 2

Rel-16 forms Phase 2 of 5G (3GPP, 2022g) and offers for the first time, in conjunction with Rel-15, a complete 5G system definition (3GPP, 2022h). Rel-16 is based on more than 83 studies and is seen as the major release of the 5G system (3GPP, 2022g).

a) Basic functionality

The basic functionality is primarily comprised of system enhancements completing 5G. In this context, the focus is on providing ultra-reliable and low-latency communication (URLLC) for non-public networks (3GPP, 2022h). In addition, Rel-16 offers additional functionalities in the radio access network, especially concerning end devices, such as the power saving mode (3GPP, 2022h).

b) Specified performance

The specified performance for standalone architectures is based on the performance requirements from TS 22.261 for indoor hotspots of a 5G system and is shown in Table 2.3 (3GPP, 2021b, pp. 41–46). The positioning service is available in Rel-16 and provides horizontal accuracy of 1000 cm and vertical positioning accuracy of 300 cm in indoor environments (3GPP, 2021b, p. 46). The communication service availability and reliability remain the same as in Rel-15. Rel-16 offers significant improvements down to 1 ms end-to-end latencies in cases where high data rates are not required. As shown in Table 2.3, the remaining values are equal to those in Rel-15.

Table 2.3: Specified performance of Release 16
(3GPP, 2021b, pp. 41–46)

Performance Parameter	**Specified Performance (Release 16)**	
Positioning accuracy (cm)	Horizontal: 1000	Vertical: 300
Communication service availability (%)	99.99-99.9999	
Communication service reliability (%)	99.9-99.999	
End-to-End latency (ms)	> 1	
End device speed	Pedestrian (< 5 m/s)	
User experienced data rate (Gbit/s)	Download: 1	Upload: 0.5
End device density (end device/m²)	0.25	

c) Service enhancements

The introduction of the 5G positioning represents the major service enhancement of Rel-16 (3GPP, 2022e, p. 66). Furthermore, the V2X communication is adapted from 4G to 5G. To enable uRLLC, the network slicing is partly introduced. A list of relevant services for standalone non-public networks is given below:

- 5G positioning (Phase 1): Phase 1 serves to define the performance for horizontal and vertical positioning (3GPP, 2021b, p. 46). Table 2.4 shows the defined service levels for indoor scenarios. In Rel-16, only positioning service level 1 should be achieved (3GPP, 2021b, p. 45).

Table 2.4: Positioning service levels for indoor hotspots
(3GPP, 2021b, p. 46)

Level	**Positioning accuracy [cm]**		**Latency [ms]**	**Speed of end devices (up to) [m/s]**
	Horizontal	**Vertical**		
1	1000	300	1000	8
2	300	300	1000	8
3	100	200	1000	8
4	100	200	15	8
5	30	200	1000	8
6	30	200	10	8
7	20	20	1000	8

- 5G NR V2X communication (Phase 1): Regarding V2X, Rel-16 includes the exchange of parameters from the vehicle-to-everything, such as machines or platforms. For example, in case of a packet error in the vehicle, the error can be passed on to a V2X platooning platform, and the vehicles can adapt inter-vehicle distance automatically (3GPP, 2022e, p. 24).

- Network slicing service (Phase 1)

2.2.3.4 Release 17 – Beyond 5G system Phases 1 and 2

Rel-17 is currently under development, and therefore, agreed specifications are yet not available. However, 3GPP provides insights into draft documents about the specifications. According to 3GPP, 2022f, Rel-17 focuses on 5G's quality of service (QoS), improvements regarding performance and an extensive service enhancement (3GPP, 2022f).

a) Basic functionality

Basic functionalities are implemented. Rel-15 and Rel-16 provide the complete basic functionalities for the 5G system.

b) Specified performance

Table 2.5 provides an overview of performance specifications within Rel-17. As shown in Table 2.5, the positioning can reach an accuracy of up to 20 cm horizontally and vertically.

Table 2.5: Specified performance of release 17
(3GPP, 2022f, pp. 42–59)

Performance Parameter	**Specified Performance (Release 17)**	
Positioning accuracy (cm)	Horizontal: 300-20	Vertical: 20
Communication service availability (%)	99.99-99.999999	
Communication service reliability (%)	99.99-99.99999	
End-to-End latency (ms)	<1	
End device speed (m/s)	up to 10	
User experienced data rate (Gbit/s)	Download: 10	Upload: 1
End device density (end device/m²)	0.25	

Furthermore, indoor vehicles, flying objects and wearables are supported using 5G positioning (3GPP, 2022f, p. 65). The availability depends on specific network interfaces and applications with an improved upper limit of 99.999999%. In terms of latency, delays below 1 ms for critical applications can be achieved with Rel-17. The end device speed increases by 10 m/s to support flying objects. In terms of data rate, up to 10 Gbit/s is specified for downloads and up to 1 Gbit/s for uploads.

c) Service enhancements

The list below provides information on the releases planned for standalone non-public networks. In addition to the extended 5G positioning, Rel-17 focuses on services for flying objects, extended reality support and edge computing in the core network (3GPP, 2022i).

- 5G NR positioning service. Levels 2-7 are targeted to be achieved (see Table 2.4)
- Network slicing service and radio access network slicing (Phase 2)
- Unmanned aerial systems (Phase 1)
- Enhanced 5G NR V2X communication (Phase 2)

2.2.3.5 Release 18 – 5G advanced

Release 18 (Rel-18), called 5G-Advanced, is expected to be finally standardised by 2024. (3GPP, 2022b). However, Rel-18 is not yet the focus of development. 3GPP has only published a preliminary list of extensions defined for Rel-18, giving a superficial idea of the upcoming Rel-18 (3GPP, 2022b).

a) Basic functionalities

- Edge computing (Phase 2)
- Enhanced support for non-public networks (Phase 2)
- Network slicing (Phase 3)

b) Specified performance

- not specified yet

c) Service enhancements

- Enhancements for V2X communication
- Enhanced management of non-public networks
- Enhancements for network slicing on radio access network and core network
- Unmanned aerial services and unmanned aerial vehicle support (Phase 2)

2.2.4 5G network deployments: An overview

Mobile communication networks and their architecture are being further developed and adapted to new requirements with each generation. However, the fundamental structure of mobile networks is based on core elements that remain the same regardless of the generation (Langmann, 2021, p. 196). Figure 2.9 shows the fundamental structure of mobile communication networks.

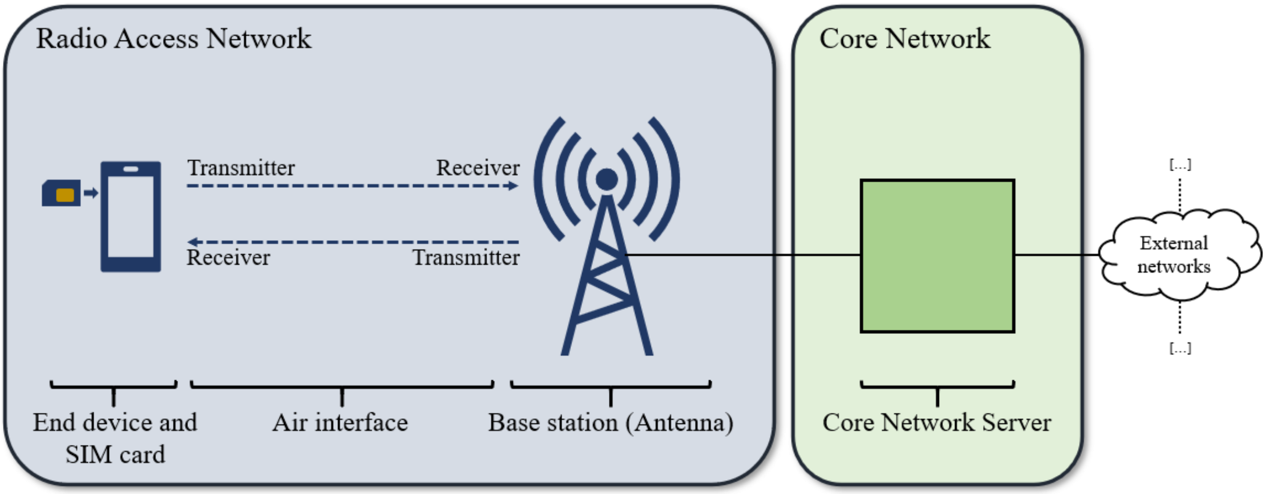


Figure 2.9: Fundamental structure and core elements of a mobile communications network (based on Langmann, 2021, p. 196)

The network consists of a Radio Access Network (RAN) and a Core Network (CN). The RAN includes mobile end devices with a Subscriber Identity Module (SIM), the air interface and the antenna, also called a base station. The base station is connected via a physical link to the CN, on which the services and functions are made available, and data processing takes place (Langmann, 2021, pp. 196–197).

3GPP (2019a) classifies 5G networks into two types, referred to as Public Networks (PN) and Non-Public Networks (NPN). PN are networks available publicly with 5G-capable end devices. In contrast, NPNs are private networks for the sole use of private organisations (Aijaz, 2020, pp. 139–140).

In addition to the classification into PN and NPN, 3GPP distinguishes networks further into their specific architecture. According to 3GPP (2019a, pp. 11–12), two different architectures exist, namely non-standalone (NSA) and standalone (SA). The NSA architecture describes a network consisting of 4G and 5G infrastructure. In contrast, SA networks are purely based on 5G. Figure 2.10 shows that combining the types and architectures results in four fundamentally different 5G network deployments.

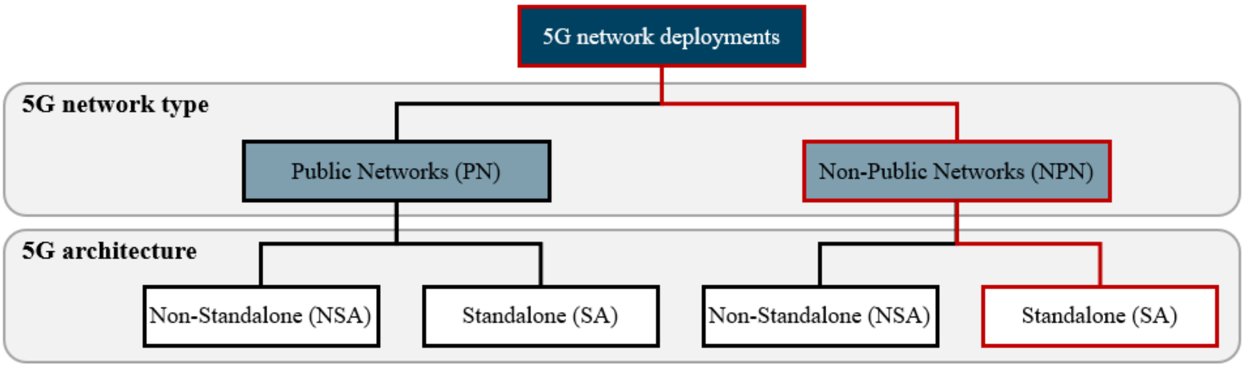


Figure 2.10: 5G network deployments

Each network deployment (shown in Figure 2.10) is being discussed among researchers for various purposes. However, a common consensus is that standalone non-public networks are appropriate deployments for industrial applications (Aijaz, 2020, pp. 139–140; J. Ordonez-Lucena et al., 2019, pp. 4–6; Rostami, 2019, p. 434). This is due to the pure 5G architecture and the purely private access. Table 2.6 summarises all network deployments, their architecture and access.

Table 2.6: Summary of 5G network deployments

Network deployment	**Architecture**		**Access**
	RAN	**CN**	
Non-Standalone Public Networks	4G/5G	4G	public
Standalone Public Networks	5G	5G	public
Non-Standalone Non-Public Networks	4G/5G	4G	private
Standalone Non-Public Networks	5G	5G	private

2.2.5 5G standalone non-public networks

5G standalone non-public networks are defined as local area networks for the sole use of a private entity, such as a private organisation, that are solely built on 5G NR infrastructure and exclusively provide dedicated connectivity and 5G services to a geographically restricted area (3GPP, 2021b, p. 34; Aijaz, 2020, p. 138; J. Ordonez-Lucena et al., 2019, p. 1). Moreover, the NPN is protected from public access by unauthorised subscribers to the network's resources, thus guaranteeing a high level of security (3GPP, 2021b, pp. 34–35).

2.2.5.1 Standalone architecture

The standalone (SA) architecture represents a network based solely on 5G NR infrastructure in terms of their core network (CN) and radio access network (RAN). In this context 4G components are not required for the 5G standalone mode. However, two general definitions must first be made regarding the Control Plan (CP) and the User Plan (UP). The UP is responsible for forwarding and processing the data from the source to the destination, whereas the CP consists of a set of functions to control, check, and verify the UP (Arnold et al., 2017, p. 1). In the following section, the standalone (SA) architecture is described in detail regarding the CN and the RAN. Initially, the non-standalone architecture (NSA) is also briefly described to illustrate the main differences between SA and NSA. Figure 2.11 presents the SA and NSA architecture.

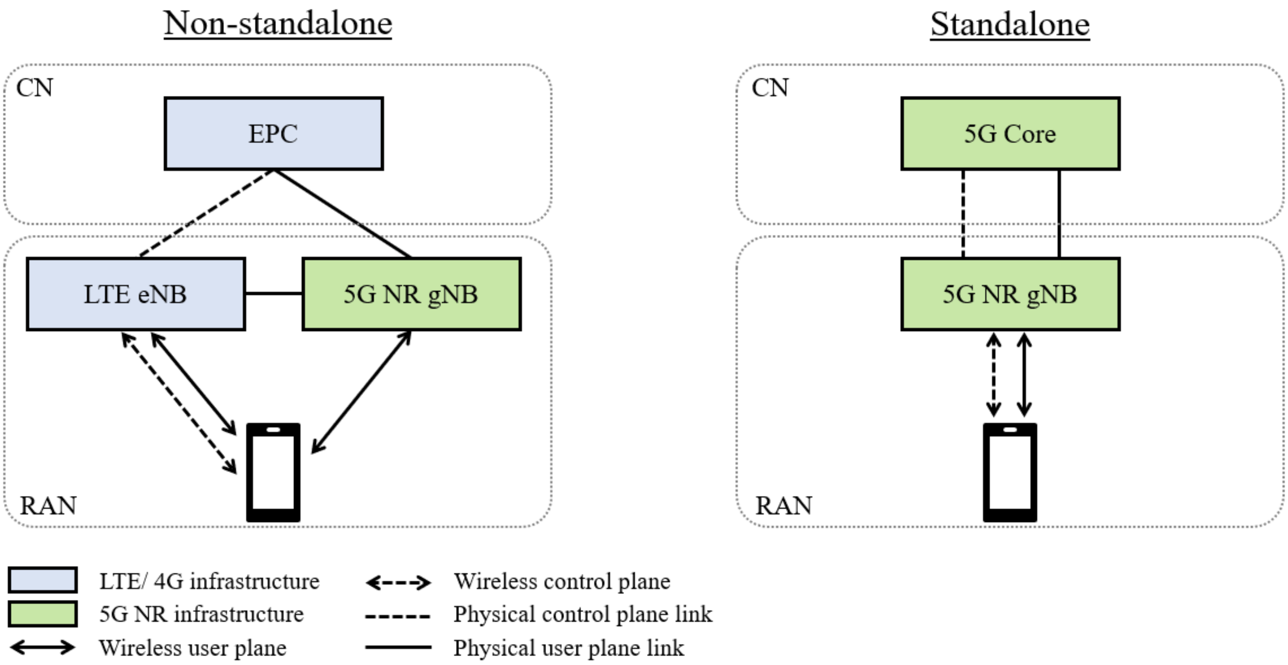


Figure 2.11: Non-standalone versus standalone architecture
(based on 3GPP, 2019a, pp. 11–12; Morais, 2022, p. 234)

The NSA architecture, shown in Figure 2.11, is primarily developed for public networks due to the use of 4G and 5G infrastructure in conjunction (3GPP, 2019a, p. 11). This leads to backwards compatibility with previous technologies, ensuring access to the network for users with end devices using 4G technology (3GPP, 2019a, pp. 11–12). Additionally, NSA networks accelerate the 5G roll-out without upgrading the entire network (Farah Salah and Mika Rinne, 2018, p. 1). As can be seen in Figure 2.11, the existing 4G RAN is only upgraded and extended with a 5G base station called Next Generations NodeB (gNB). The gNB is linked to the 4G base station (LTE eNB). However, the NSA architecture uses the entire 4G core network, called Evolved Packet Core (EPC). For communication, the end device can communicate by wireless UP with the eNB and the gNB.

In contrast, the CP is only provided by the eNB base station. As a result, an end device can transmit data to the core network via the 5G UP with the advantages of 5G, such as faster data rates or lower latency, but also necessarily requires a 4G base station to handle the CP. Since both 4G and 5G technology are required for the NSA architecture, this is also referred to as 4G-5G dual connectivity (Farah Salah and Mika Rinne, 2018, p. 1).

The SA architecture is shown in Figure 2.11. The CN and RAN regarding the physical layer and the network functions in an SA network are entirely based on 5G NR. Furthermore, the 5G CN and 5G RAN provide the UP and CP functions without requiring a 4G base station. The CN and RAN of the SA architecture are explained in detail in the following sections.

2.2.5.2 5G core network

The main task of the CN is to provide connectivity to active mobile end devices logged into the network. Therefore, the CN needs to coordinate and provide service requests to all mobile end devices (Peterson and Sunay, 2020, p. 22). The 5G CN is specifically designed to meet industrial needs, namely eMBB, uRLLC and mMTC (3GPP, 2019a, p. 12). The 5G CN is a service-based architecture characterised by interconnected network functions (3GPP, 2019a, p. 12). Figure 2.12 shows the service-based architecture of the 5G CN with its primary functions, divided into two superordinated groups (blue and orange).

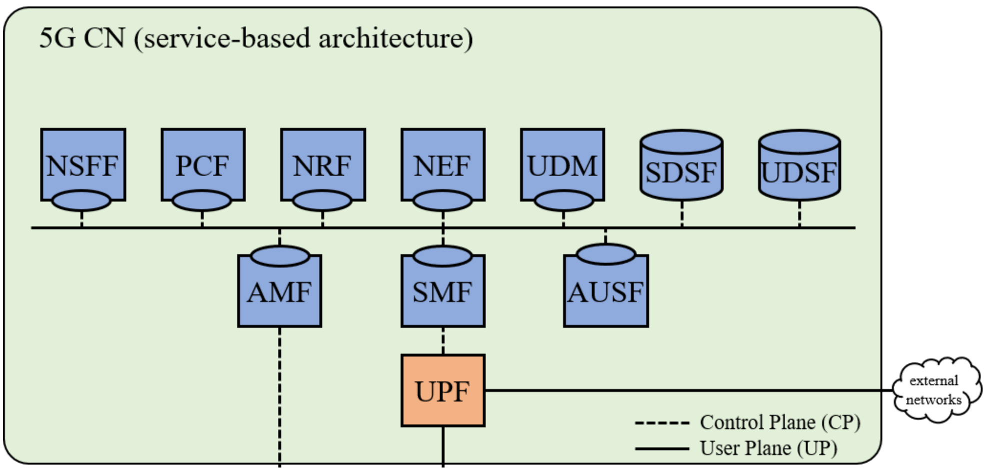


Figure 2.12: 5G core network – service-based architecture
(based on 3GPP, 2019b, p. 14; Peterson and Sunay, 2020, p. 24)

Each network function provides a service to all other authorised CN-internal functions or CN-external authorised ‘consumers’, such as mobile end devices (3GPP, 2019a, p. 12). However, the availability of network function services depends on the respective 5G release (3GPP, 2019a, p. 12).

The blue functions represent group one and run on the CP. The following descriptions of individual network functions are adopted from Peterson and Sunay, 2020, pp. 24–25:

- **AMF** (Core Access and Mobility Management Function): The AMF manages all mobility-related aspects of subscribers (end devices). Additionally, the AMF is responsible for connection, mobility management, access authentication, authorisation and location service.

- **SMF** (Session Management Function): The SMF manages the session with the end device, including the IP address allocation, the selection of CN functions, and control functions regarding the Quality of Service and UP routing.

- **PCF** (Policy Control Function): PCF manages the policy rules enforced by other CP functions.

- **UDM** (Unified Data Management): UDM manages the user identity and stores all user-related information.

- **AUSF** (Authenticate Server Function): The authentication server manages the authentication of users of the network together with the UDM.

- **SDSF** (Structured Data Storage Network Function): SDSF is used to store data structured.

- **UDSF** (Unstructured Data Storage Network Function): UDSF stores data unstructured. The USDF can be compared with a random access memory (RAM).

- **NEF** (Network Exposure Function): NEF provides an interface to expose selected capabilities to third-party services. The NEF also includes the translation between external and network internal data.

- **NFR** (NF Repository Function): NRF discovers available services.

- **NSSF** (Network Slicing Selector Function): NSSF selects network slices (see Section 2.2.5.5) for active end devices.

The orange function represents group two and runs on the UP. The following description of the UPF is adopted from Peterson and Sunay, 2020, pp. 24–25:

- **UPF** (User Plane Function): The UPF forwards and processes traffic between the RAN and CN. The UPF is also responsible for policy enforcement, lawful interception, traffic usage reporting and Quality of Service policing.

Furthermore, the service-based architecture enables the virtualised provision of all network functions by creating *instances* which can be shared with other functions' *instances* (3GPP, 2019a, p. 12). Figure 2.13 represents the creation of network function *instances* schematically.

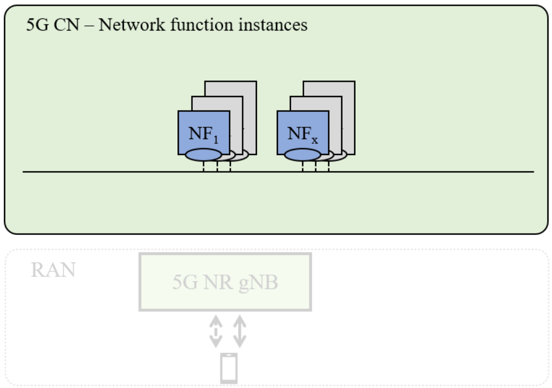


Figure 2.13: Core network – network function instances
(based on 3GPP, 2019a, p. 12)

As can be seen in Figure 2.13, the network functions $NF_1 \ldots NF_x$ possess virtual *instances*, highlighted in grey. The virtualising of network functions within the CN is called Network Function Virtualisation (NFV), enabling network slicing on the core network layer (Sama et al., 2016, p. 2). For creating network slices, the interaction between CN and RAN is needed. Therefore, the network slicing concept is described in Section 2.2.5.5 after introducing the 5G RAN.

2.2.5.3 5G radio access network

The 5G radio access network (RAN) forms the second part of the SA architecture. The RAN consists of at least one 5G base station, called 5G gNB, the air interface, and end devices with the respective Subscriber Identity Module referred to as SIM (3GPP, 2019a, pp. 11–12; Morais, 2022, p. 234). From a component perspective, the RAN includes the base station and a base band unit where the central unit and the distributed unit are located (Peterson and Sunay, 2020, p. 33). The 5G radio access network is shown in Figure 2.14. In the following section, all parts of the 5G RAN are described.

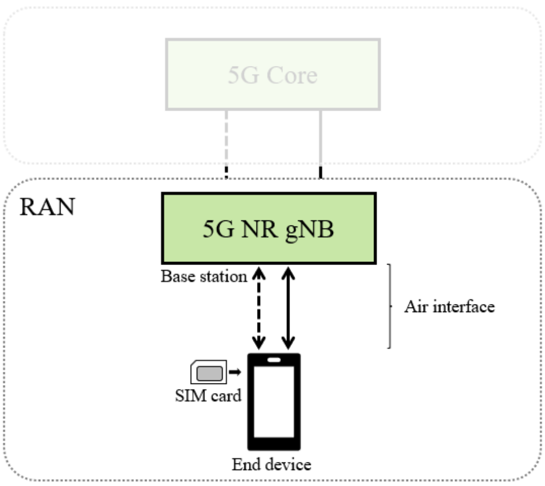


Figure 2.14: 5G radio access network
(based on 3GPP, 2019a, pp. 11–12; Morais, 2022, p. 234)

Base station

The 5G base station is called 5G NR gNB (3GPP, 2019a, pp. 11–12). The gNB represents the Radio Unit (RU) of the RAN and transmits and receives radio frequencies (Temesvári, Maros and Kádár, 2019b, p. 601). The gNB is physically linked via the distributed unit (DU) to the central unit (CU) (Peterson and Sunay, 2020, p. 33). The DU and CU are often located within the base band unit (BBU), which is responsible for the modulation of the signals (Peterson and Sunay, 2020, p. 33).

For indoor environments such as industrial facilities, small cell base stations called pico radio heads are typically used (Temesvári, Maros and Kádár, 2019b, p. 601). To ensure coverage and signal quality within the industrial facility, the pico radio head can be adjusted in terms of range and transmitting power (Temesvári, Maros and Kádár, 2019b, p. 601). The capacity and the design of an indoor pico radio head depends on the network operator and the hardware manufacturer. Figure 2.15 shows two representative examples of indoor pico radio heads.

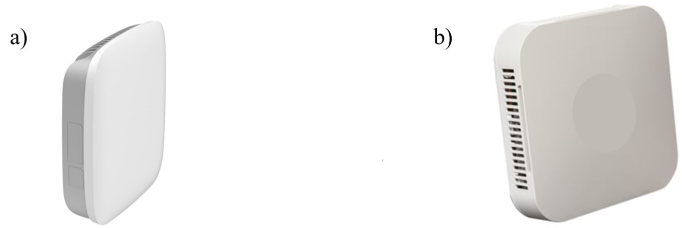


Figure 2.15: Different types of pico radio heads typically used in indoor scenarios

New Radio air interface and radio access principles

The air interface varies between generations and determines the method for sending and receiving signals (Asif, 2019, p. 46). The end device and the base station can receive and transmit signals in two-way communication, called full-duplex communication (Chang and Hsing, 1995). The corresponding technique is called duplexing, describing the resource allocation between sending (upload) and receiving (download) signals. Regarding duplexing, two general approaches can be used to allocate the download and upload in a 5G network. First, the time-division duplex (TDD) method uses different time slots to separate upload and download (Esswie and Pedersen, 2020, p. 1). Another approach is to rather separate the frequency than the time, called frequency-division duplex (FDD). This approach allocates the resources by using slightly different frequencies for upload and download (Esswie and Pedersen, 2020, p. 1). If multiple end devices access the network, the multiplexing method must be used (Asif, 2019, p. 47). A time-frequency matrix is defined for incoming electromagnetic waves called 5G frame (Takeda, Harada and Osawa, 2019, p. 50). The 5G frame consists of ten sub-frames, each with a length of one millisecond. Each sub-frame can be divided into one or more time slots depending on the carrier frequency. Each time slot contains 14 symbols or a multiple of 14 symbols, depending on the frequency used for transmission. The 5G frame and the possible carrier frequencies are shown below in Figure 2.16.

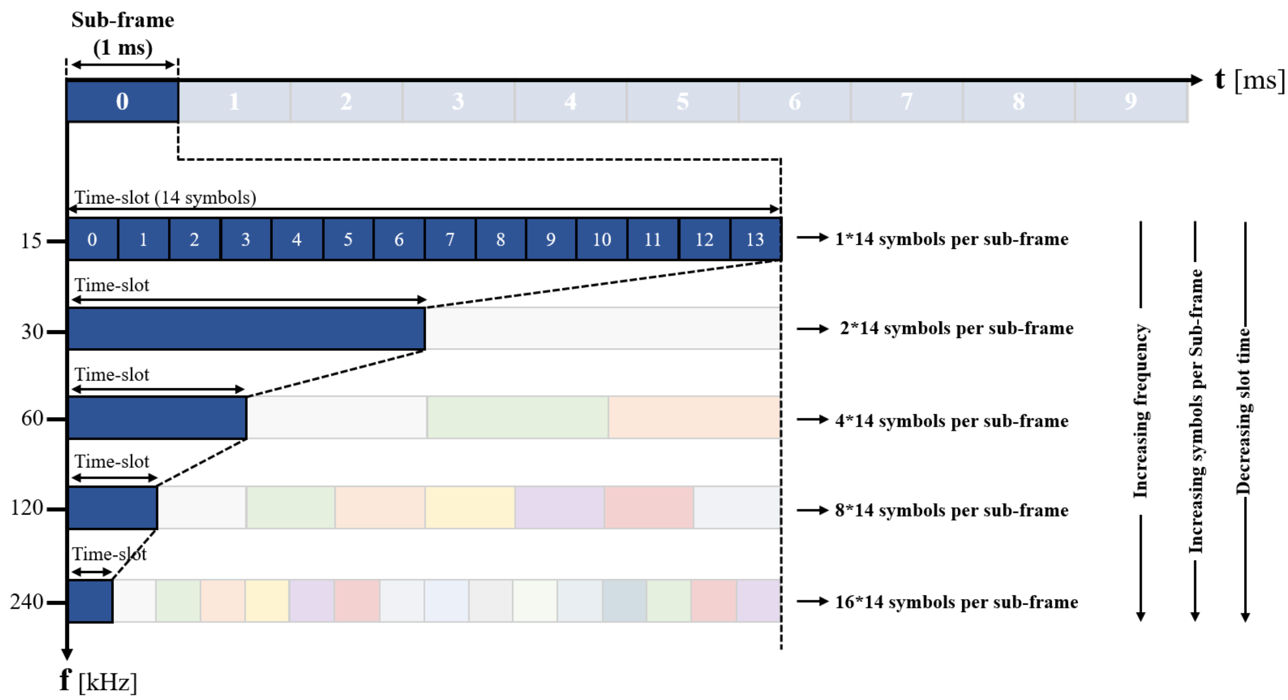


Figure 2.16: 5G NR frame
(based on 3GPP, 2019b, p. 26; Takeda, Harada and Osawa, 2019, p. 51)

As shown in Figure 2.16, depending on the carrier frequency, the sub-frame can contain 1/2/4/8/16 time-slots in which 14 symbols can be transmitted (3GPP, 2019b, p. 25). This results in a highly flexible frame structure needed to transmit a higher number of symbols within shorter time cycles for high-priority applications (3GPP, 2019b, p. 25). The symbols transmitted depend on the frequency (sub-carrier spacing) and corresponding time-slots are called numerologies. Table 2.7 provides information on the 5G NR numerologies.

Table 2.7: 5G NR numerologies
(3GPP, 2019b, p. 26)

Sub-carrier spacing	Symbols per time-slot	Time-slot	Frequency range
15 kHz	14	1 ms	FR1
30 kHz	14	0.5 ms	FR1
60 kHz	14/12	0.25 ms	FR1/FR2
120 kHz	14	0.125 ms	FR2
240 kHz	14	62.5 µs	FR2

5G industrial end devices

The end devices consist of hardware and software components, building a logical architecture (Asif, 2019, p. 217). An end device's mobile communications core elements are a radio frequency module with one or multiple antennas, a base band unit and a software platform including an application and signal processor, and a power supply (Asif, 2019, p. 217). The Subscriber Identity Modules (SIM) card slot provides a socket for the SIM card to function as an authentication bridge between the network and the end device. The compatibility of the SIM card with the respective mobile communication generation is essential for establishing a connection with the mobile network (Deepu George Koshy and Sethuraman N. Rao, 2018, p. 4). For example, since the end device requires a SIM card as authentication and connection bridge to the network, each end device needs a specific SIM card for the associated non-public network. Consequently, users without a SIM card for the specific non-public network do not have access to the network.

Furthermore, industrial 5G end devices have different characteristics, shapes, and functionalities and are used for different cases (5G ACIA, 2022, p. 7). However, the logical architecture of industrial 5G end devices remains the same, as illustrated in Figure 2.17.

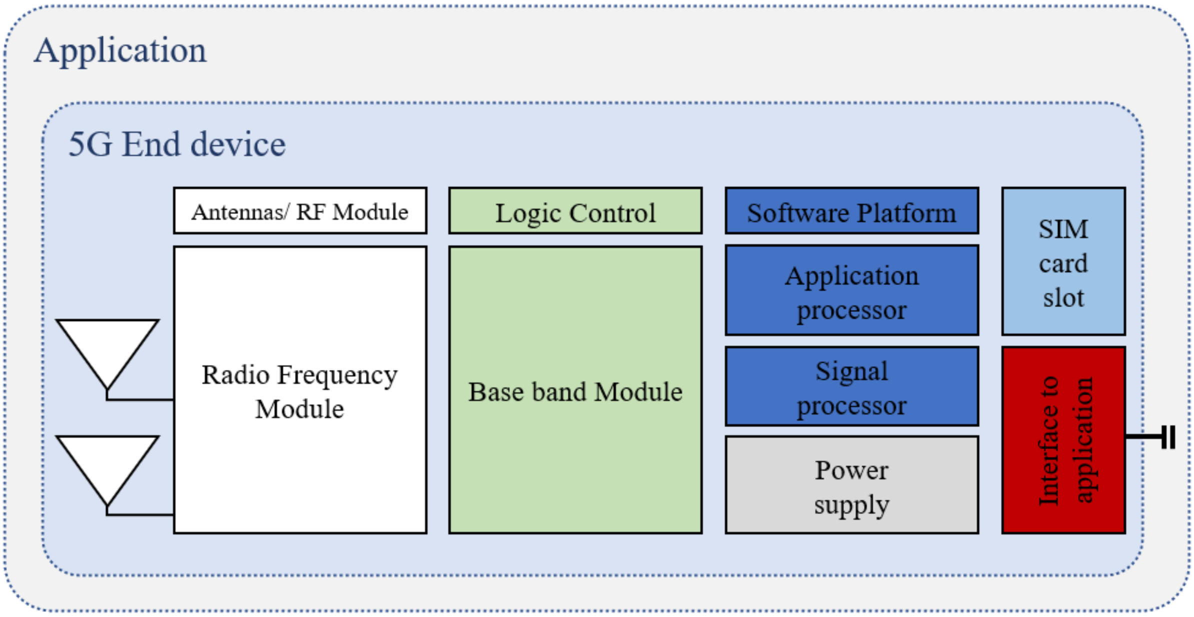


Figure 2.17: Logical architecture of industrial 5G end devices as part of an application (based on 5G ACIA, 2022, p. 7; Asif, 2019, p. 218)

According to 5G ACIA (2022, pp. 16–24), the following classifications of 5G standalone capable end device types are currently available:

- **5G Smart Sensors and IIoT sensors.** Smart sensors have an embedded microcontroller and their unit for signal processing. Due to their miniaturisation, 5G-enabled smart sensors are particularly suitable for mass integration on assets or machines for condition monitoring of physical parameters.

- **5G Ethernet bridge.** An Ethernet bridge is typically used to integrate Ethernet devices into the 5G network. Since Ethernet devices are often used for time-critical use cases requiring high availability and low latency communication, the 5G Ethernet bridge focuses on fast data transmission of smaller data packets.
- **5G wireless industrial router.** A Wireless 5G router is typically used for mobile machine and robot connectivity because an industrial wireless router combines high reliability and low latency communication with an accurate time synchronisation for safety-critical protocols.
- **5G industrial gateway.** A 5G gateway can be seen as an interface between the 5G module and the 5G network and connects devices with different network protocols. Therefore, the gateway does not have a processing unit but is only used to forward data over 5G with different protocols.
- **5G mobile trackers.** A mobile tracker device contains a battery-powered tracker with its own 5G module, and integrated sensors. In particular, the 5G mobile tracker is suitable for positioning use cases. The mobile tracker must support the required 5G positioning service level with its corresponding accuracy.
- **5G controller (remote I/O).** The 5G controller for remote I/O pre-processes data between sensors and actuators and is typically located close to the physical process. This enables remote access to peripherals, like remotely controlling flexible machine parts such as a robot arm.

RAN session cycle

According to Peterson and Sunay, 2020, establishing a connection and session between an end device and base station in the RAN can be described in a six-step cycle (shown in Figure 2.18). In step one, the base station detects the active end device. After detecting the end device, in step two the gNB establishes a CP connectivity between the end device and the 5G Core. Within the third step, the gNB establishes one or multiple dedicated tunnels for the data traffic between the 5G Core and the end device. In step four, the gNB receives the end devices' requests and forwards them via Stream Control Transport Protocol (SCTP) and General Packet Radio Service Tunnelling Protocol (GTP). If a mobile end device changes location (step five), the active gNB holds the connection until the end device receives a signal from another gNB.

This process is called 'soft handover' and is coordinated between two gNBs via a direct linkage (Peterson and Sunay, 2020, p. 21). Soft handover describes how an end device communicates between two base stations during the handover from one cell to another until the signal strength of the target base station is sufficiently strong (Kassar, Kervella and Pujolle, 2008, p. 2609). For this reason, soft handover is also called *seamless* handover. The hard handover is defined as the process in which the signal from the target base station cannot be received until the signal from the source radio cell is interrupted. This is also referred to as the 'break before make' handover (Kassar, Kervella and Pujolle, 2008, p. 2609). Therefore, as offered by 5G, a soft handover can guarantee a seamless transition between two base stations. In the sixth step, the gNBs coordinate a wireless multipath transmission until the decoupling process of the source gNB is complete, followed by step one again.

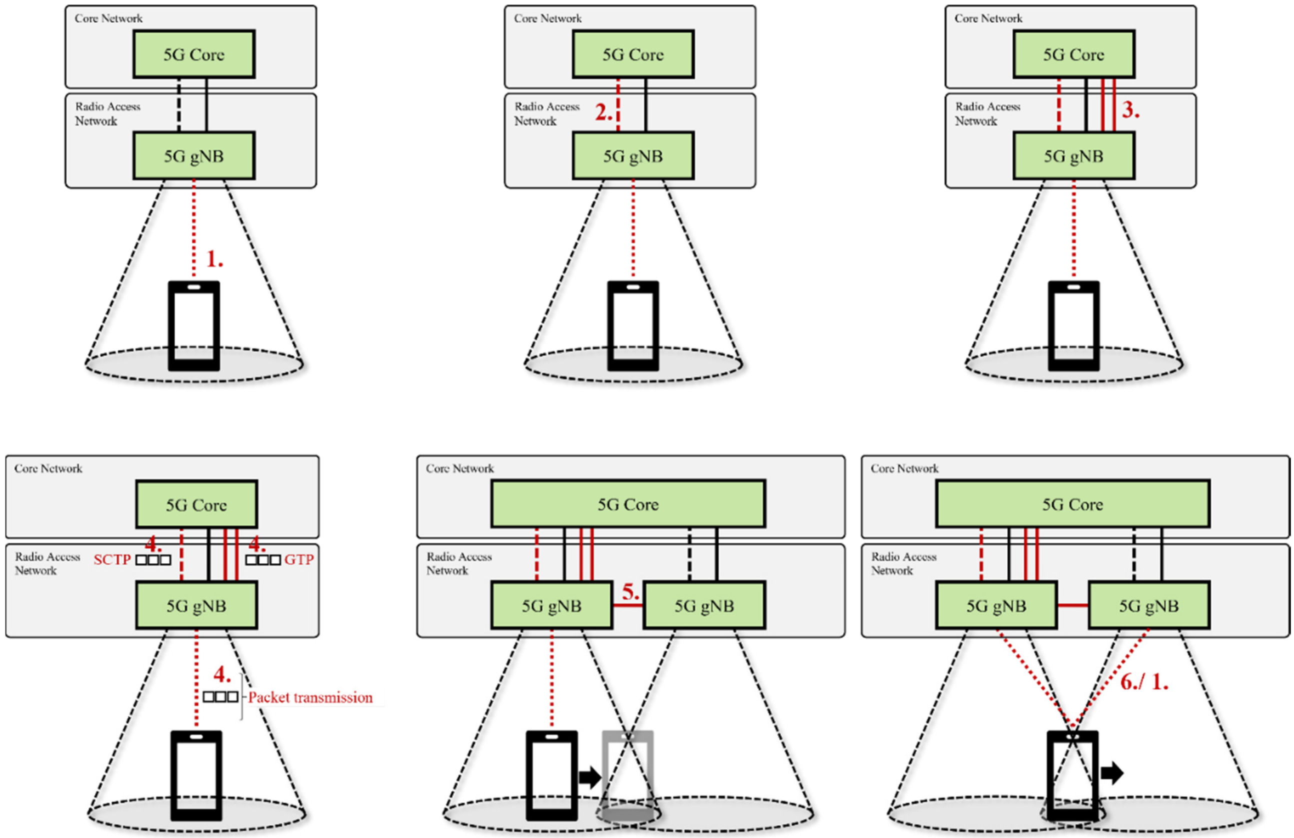


Figure 2.18: Six-step 5G RAN session cycle
(own representation, based on Peterson and Sunay, 2020, pp. 20–22)

2.2.5.4 Multi-user multiple-input multiple-output

Multi-user multiple-input multiple-output (MU-MIMO) represents a technological extension of 5G enabling the simultaneous sending and receiving of signals with multiple end devices (Oughton et al., 2021, p. 5). The efficient use of antennas primarily achieves this technical upgrade. Theoretically, MU-MIMO of up to 128 end devices for download and upload (128x128 MU-MIMO) can be achieved with 5G (Oughton et al., 2021, p. 9). However, it also depends on the base station's capability. 4x4 MU-MIMO to 16x16 MU-MIMO are typically available for pico radio heads for indoor networks.

2.2.5.5 Network slicing

The previous generations of mobile communications are designed as a 'one-size-fits-all' solution and, consequently, deliver identical performance to each end device within a network (Zhang, 2019, p. 111). This results in a lack of customisability and flexibility in the communication services (Zhang, 2019, p. 111). However, 5G and future cellular networks require a high level of flexibility and customisability to meet various industrial requirements regarding services, performance and security (Zhang, 2019, p. 111).

In this respect, the 5G standalone architecture offers the possibility of network slicing for the first time in mobile communications, providing optimally tailored network resources for each application individually. Network slicing offers the possibility of establishing several software-defined networks and virtual networks over one physical infrastructure (3GPP, 2019a, p. 13; Zhang, 2019, p. 112). The virtual networks, called 'slices', can then be customised and optimised for specific applications' requirements. Therefore, the network slicing concept enables unrestricted scalability and flexibility of the 5G network (3GPP, 2019a, p. 13; Kaloxylos, 2018, p. 60). According to the Next Generation Mobile Networks Alliance (2016, p. 5), the generic network slicing concept consists of three layers, including the CN and the RAN:

- **Service Instance Layer:** This layer represents all 'third-party' services represented as service instances within the virtual network. The service instances are created using a so-called 'network slice blueprint' by the network operator.

- **Network Slice Instance Layer:** The network slice instance layer includes the set of network function instances on the core network level. All network functions within a network slice are isolated from another instance slice.

- **Resource Layer:** The resource layer consists of the physical resources required to compute, store, and transmit the data within a network slice.

Technically, the slices can be customised on all three layers (NGMN Alliance, 2016, pp. 6–7). For example, the study by Zhou et al. (2016) shows the three fundamentally different architectures of network slicing.

The first network slicing architecture is solely built on the CN. In the *CN-only architecture*, the network slices consist of a set of network function instances only existing in the CN. This set of customised network instances can then be provided to the use case (Zhou et al., 2016, p. 148).

The second architecture is called *RAN-only architecture* in which the slices are configured only on RAN components, for example, on radio hardware, the base station and the base band unit. In this architecture, the slices are built on technical parameters such as carrier-spacing frequency, cell selection or handover threshold, and specific radio resources within the 5G NR Frame (Zhou et al., 2016, p. 148).

The third network slicing architecture is based on both the CN and RAN. In this scenario, each RAN slice is connected to a CN slice. Therefore, physical resources within the RAN slice are connected to a specific set of network functions representing a CN slice. This enables the complete customisation, resource and service allocation to specific use cases in the factory (Zhou et al., 2016, pp. 148–149). Figure 2.19 exemplifies the partitioning of one physical network into three virtual network slices by representing the three different architectures.

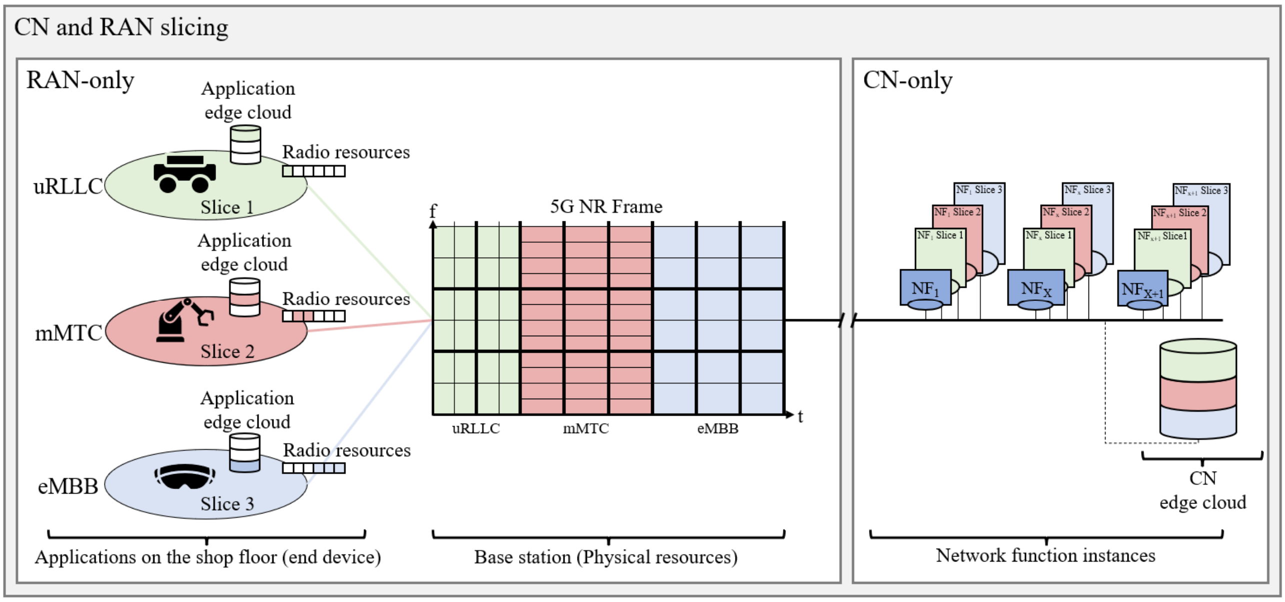


Figure 2.19: Network slicing on RAN and CN layer
(based on Garcia-Morales, Lucas-Estan and Gozalvez, 2019, p. 143141; Zhou et al., 2016, p. 148)

As Figure 2.19 shows, three virtual network slices for three application scenarios possess different requirements. Slice 1 (green) requires an ultra-reliable low-latency communication (uRLLC), Slice 2 (red) requires mass connectivity (mMTC), and Slice 3 (light blue) represents a virtual reality application requiring enhanced mobile broadband (eMBB) for high data rates. The 5G NR frame within the RAN-only architecture provides the physical resources such as the time slots for sending and receiving signals which can be customised in 5G (see Figure 2.16). The 5G NR frame can reserve various resources depending on the carrier frequency for each slice (Garcia-Morales, Lucas-Estan and Gozalvez, 2019, p. 143140). Furthermore, an edge cloud can optionally be implemented directly at the application, on which data and information can be stored and exchanged with other applications' edge clouds and edge clouds on the CN layer.

Figure 2.19 also shows the network slice instance layer within the CN, representing the CN slice. The CN contains the set of required function instances for the respective slice. Additionally, a factory edge cloud can be optionally connected to the core network at the edge of the factory. In principle, network slicing is a technology-independent concept. However, 5G is currently the only technology that offers network slicing. Therefore, the literature consensually considers network slicing to be a unique selling point in addition to the performance of 5G, as it makes the network highly flexible and configurable (Garcia-Morales, Lucas-Estan and Gozalvez, 2019, p. 143141).

Another study by Ordonez-Lucena et al. (2019) investigates further benefits of standalone non-public networks based on key attributes of wireless networks (see Table 2.8).

Table 2.8: Attributes of 5G standalone non-public networks
(J. Ordonez-Lucena et al., 2019, p. 6)

Attribute	**5G Standalone non-public networks**
Quality of Service customisation	Full customisation
Autonomy	Full autonomy
Isolation	Nothing is shared. Non-public network end device, control and user plane confined within the factory
Security	High security due to isolation between non-public and public networks
Service continuity	Dependent on the Mobile Network Operator
NPN management for verticals	Complete control (for example, due to network slicing)
Entry barriers	Very high

2.2.5.6 Spectrum for 5G standalone non-public networks

In addition to the architecture, a further aspect of 5G standalone non-public networks concerns utilising their exclusive frequency spectrum (J. Ordonez-Lucena et al., 2019, p. 4). Regarding global spectrum sharing, the telecommunications sector of the International Telecommunication Union (ITU-R) reserves specific frequencies for public protection and disaster relief (ITU-R, 2015a). The ITU-R divides the world into three regions ensuring regionally harmonised frequency bands (Figure 2.20). The remaining available frequencies are coordinated independently by the nations concerned.

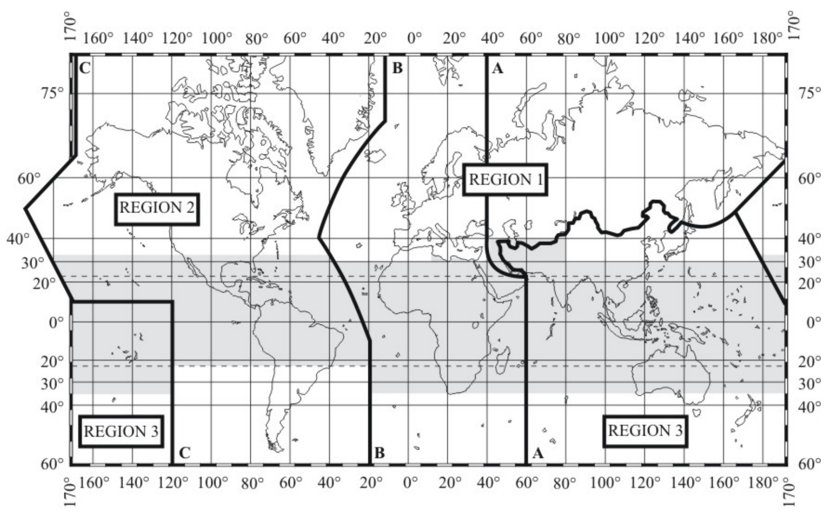


Figure 2.20: ITU-R regions for harmonised frequency bands
(ITU, 2022)

Concerning 5G, 3GPP and ITU-R have defined specific frequency ranges (FR) technically supported by 5G. According to 3GPP, the supported FR are (3GPP, 2020b, p. 17):

- FR1: 410 MHz - 7.125 GHz (cm-Wavelength)
- FR2: 24.25 GHz - 52.6 GHz (mm-Wavelength)

Within FR1 and FR2, the spectrum allocation and the specific bandwidth are under the responsibility of each country. Another aspect depending on the country, is the existing option for obtaining licensed frequencies. Some countries, such as Germany, offer to directly acquire licensed frequencies for private networks from the responsible governmental authority (BNetzA, 2019). Alternatively, in countries where obtaining licensed frequencies directly from governmental authorities is not available, licensed frequencies can be acquired as so-called 'sub-leases' from Mobile phone Network Operators (MNOs) (J. Ordonez-Lucena et al., 2019, p. 4). As outlined above, the frequency allocation of 5G is a country-specific task. Since this thesis is being written at Reutlingen University, Germany and Stellenbosch University, South Africa, the following section only focuses on frequencies of standalone non-public networks in Germany and South Africa.

The responsible authority for frequency allocations in Germany is the Federal Network Agency (Bundesnetzagentur; BNetzA). For non-public networks, obtaining licensed frequencies directly from the Federal Network Agency independent of MNOs is available. In this respect, licensed frequencies in the range between 3.7-3.8 GHz and 24,25-27,5 GHz are available for local use in Germany (BNetzA, 2019, 2021).

In South Africa, the Independent Communications Authority of South Africa (ICASA) is responsible for frequency allocation. As shown in Figure 2.20, both Germany and South Africa are part of the ITU-R region 1 (ITU, 2022). Therefore, according to Ngcaba, Pie and Venkatesh (2020), the allocation of 5G frequencies in South Africa is to be coordinated with those of European countries to enable economies of scale for network infrastructure. According to ICASA's annual 5G report from 2021, the option of directly obtaining licensed frequencies from ICASA itself is not yet available (ICASA, 2021). Thus, the frequencies must be sub-leased from MNOs. According to Ajao (2019) and (2020), available 5G frequencies in South Africa are currently 3.6 GHz (MNO: Rain SA) and 3.5 GHz (MNOs: Liquid Telecom SA, Vodacom SA 5G, MTN). Table 2.9 summarises the available 5G frequencies for standalone non-public networks in South Africa and Germany.

Table 2.9: 5G frequencies in Germany and South Africa for private use
(based on Ajao, 2019, 2020; BNetzA, 2019; ICASA, 2021)

Country	Frequencies	Business Model	Wavelength
Germany	3.7 - 3.8 GHz	Licensed	cm
	24.25 - 27.5 GHz	Licensed	mm
South Africa	3.5 - 3.6 GHz	Sub-leasing from MNO	cm

2.3 Influencing factors of wireless communication

The concept of 5G standalone non-public networks is introduced in the previous section. In addition, potential intralogistics use cases for wireless communication are semi-systematically identified. Since 5G, as a mobile communication system, belongs to the group of wireless communication, certain influencing factors can occur in industrial environments and can, therefore, impact the performance of 5G. Performance losses can ultimately affect the *practicality* of 5G for intralogistics use cases. For this reason, the following section investigates influencing factors in more detail. This section qualitatively investigates SRQ 2.

2.3.1 Wave propagation paths

Electromagnetic wave propagation can be classified into two categories described in the literature (Galiotto et al., 2017; Wollert and Gebhardt, 2010, p. 64). In ideal wave propagation, a direct line-of-sight (LOS) exists between the transmitter and receiver and the electromagnetic waves can be transmitted over the air interface. In LOS, the air interface as a medium causes negligible signal attenuation, and the occurrence of interfering factors is unlikely (Wollert and Gebhardt, 2010, p. 62). The second category describes the case of non-line-of-sight (NLOS) propagation. In this case, at least one obstacle exists between the transmitter and receiver, preventing electromagnetic waves from being transmitted in direct LOS. However, in real-world environments, the idealised conditions of a LOS connection are rarely present (Wollert and Gebhardt, 2010, p. 64). Especially in the context of mobile applications in intralogistics, the wave propagation is often a combination of LOS and NLOS scenarios depending on the location of the end device and the base station. In this context, NLOS connections, for example, due to high-bay warehouses, assembly lines, humans or robot cells, can significantly impact data transmission performance (Galiotto et al., 2017, p. 126).

Figure 2.21 represents an example shop floor scenario of LOS and NLOS connections between the base station and end device from a bird’s eye view.

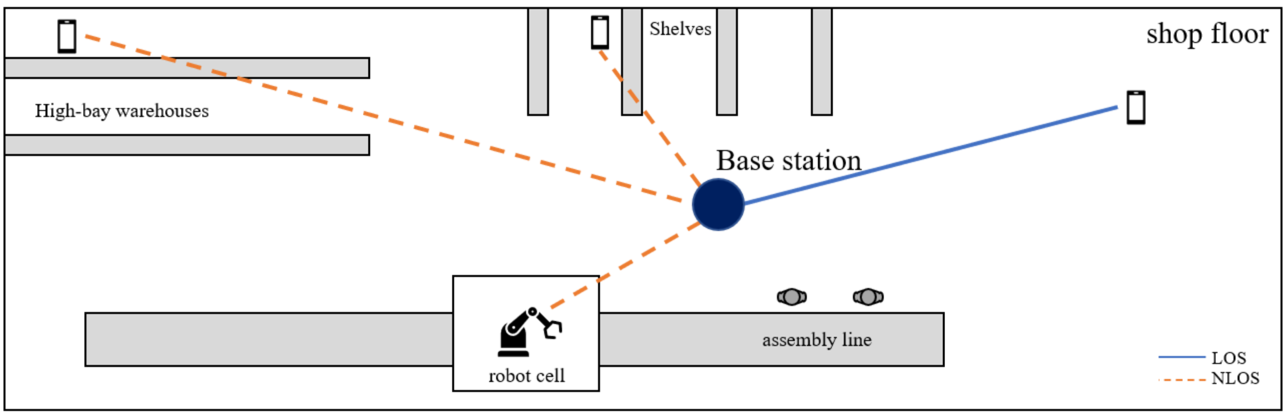


Figure 2.21: Exemplary LOS and NLOS connections in a shop floor scenario (own representation, based on Galiotto et al., 2017, p. 128)

The electromagnetic waves are exposed to six fundamental physical effects in the NLOS connection between the end device and the base station. Figure 2.22 provides an overview of all possible physical effects of electromagnetic waves. The following section defines each of the physical effects.

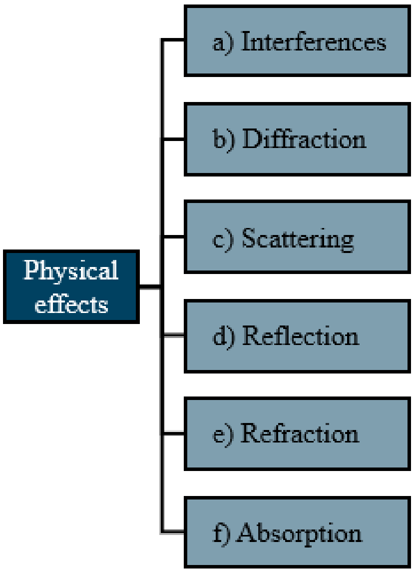


Figure 2.22: Physical effects influencing wireless communication
(Wollert and Gebhardt, 2010, pp. 62–63)

a) Interferences are superpositions of two waves. In the case of a superposition, the waves can either eliminate (destructive interference) or amplify (constructive interference) one another (Wollert and Gebhardt, 2010, p. 62). Interference can be divided into two types: 1) interferences caused by diffraction, scattering, reflection or refraction in NLOS scenarios, and 2) interference caused by communication technologies transmitting on similar frequencies. If several wireless technologies are present in a shared environment, they are referred to as heterogeneous networks. Different wireless technologies can interfere with neighbouring technologies. In the case of licensed 5G frequencies, interferences caused by other wireless technologies are unlikely (Figure 2.23a).

b) Diffraction refers to the phenomena of waves subtending an obstacle in circular patterns within obstacle's shadow (Figure 2.23b). Diffraction can produce multiple waves that can constructively or destructively superpose and initiate interferences (Wollert and Gebhardt, 2010, p. 62).

c) Scattering occurs when electromagnetic waves encounter objects that diffract or reflect the wave (illustrated in Figure 2.23c). Depending on the surface of the scattering object, forward and backward scattering can occur (Wollert and Gebhardt, 2010, p. 62).

d) Reflection of electromagnetic waves occurs on plane surfaces. The angle of arrival equals the angle of reflection (shown in Figure 2.23d). In general, the wave is reflected partially, and the other part of the wave propagates through the reflecting medium. Since reflections only occur when an electromagnetic wave impinges between two different media, the wave is also refracted in the penetrated medium (Wollert and Gebhardt, 2010, p. 62).

e) **Refraction** describes the angular change of a wave when passing from one medium to another (see Figure 2.23e). Each medium possesses its specific incident index (Wollert and Gebhardt, 2010, p. 62; Zang and Mascarenhans, 2005, p. 21).

f) **Absorption** is shown in Figure 2.23f and it is the decrease in field strength of an electromagnetic wave due to the penetration of a solid medium or material. The decrease in field strength is called attenuation (BSI, 2008, p. 12).

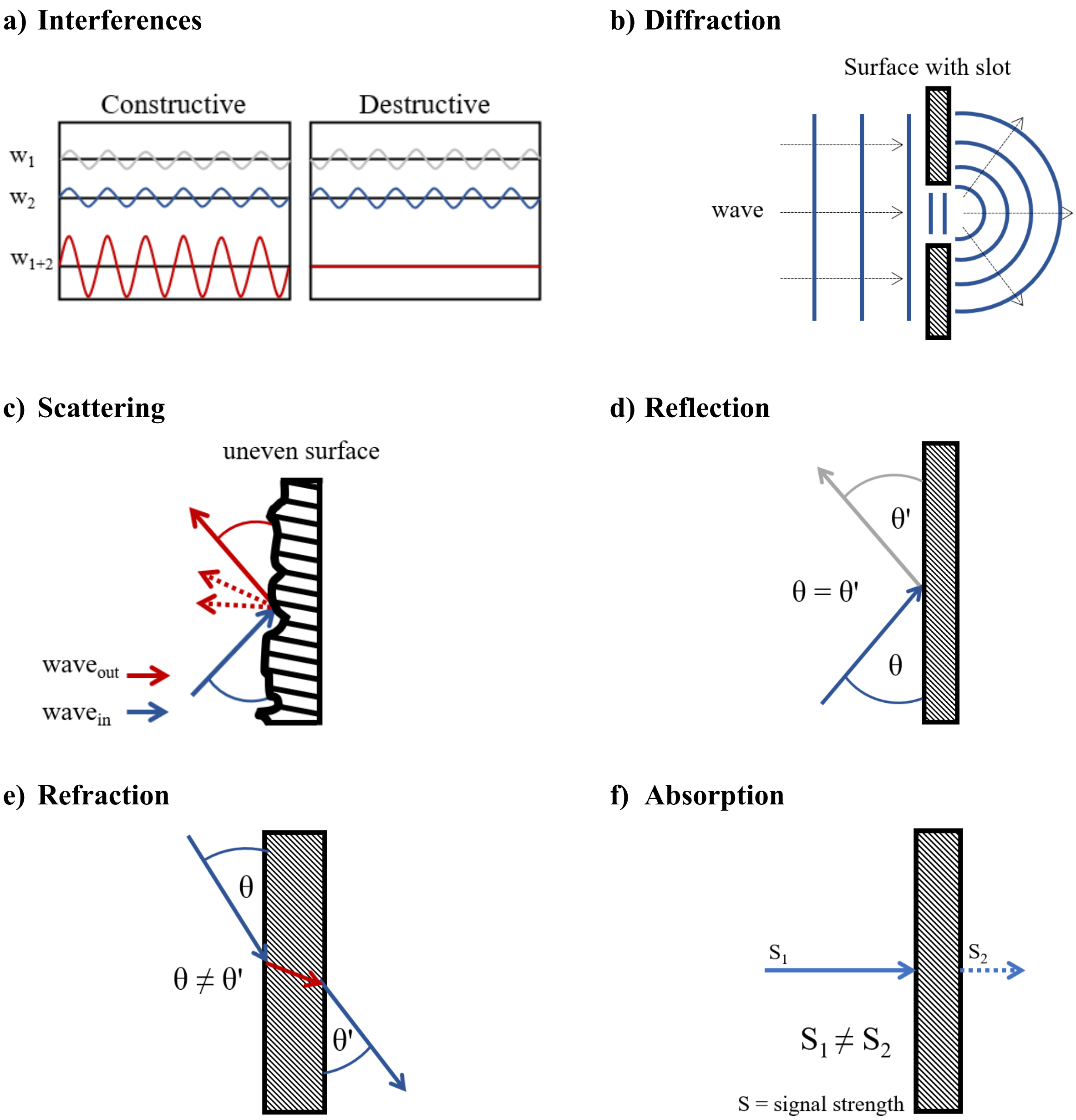


Figure 2.23: Fundamental physical effects on waves
(own representation, based on Petosa, 2018, p. 479; Wollert and Gebhardt, 2010)

The effects mentioned above on electromagnetic waves in an NLOS scenario only occur independently in an ideal environment, such as a laboratory. Multiple effects coincide in the case of materials typically used for buildings, such as production and warehouse facilities (Wollert and Gebhardt, 2010, p. 64). Figure 2.24 represents multiple effects when electromagnetic waves impinge simultaneously on materials. Simultaneous occurrence of multiple effects results in emitted waves repeatedly arriving at the receiver over multiple paths, known as multipath fading error.

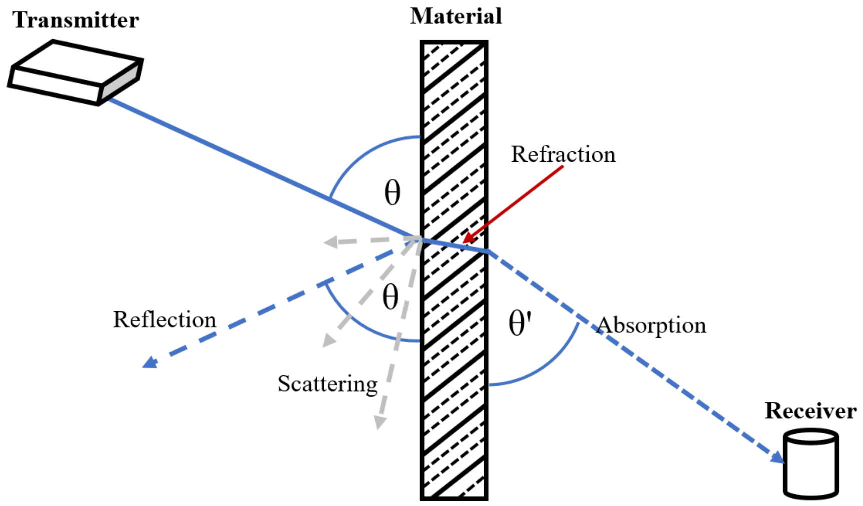


Figure 2.24: Simultaneous occurrence of multiple effects on electromagnetic waves in NLOS

2.3.2 Multipath fading error

The multipath fading error is caused by scattering, diffraction, reflection or refraction of electromagnetic waves on materials. In a real-world environment, such as industrial shop floors, the multipath error appears and is unavoidable (Wollert and Gebhardt, 2010, p. 64). The multipath fading error is a phenomenon in which a signal sent by the transmitter is received by the receiver multiple times with different propagation times. This is referred to as a propagation time shift of signals (Wollert and Gebhardt, 2010, p. 64).

Figure 2.25 shows the multipath fading error schematically. The primary signal (blue arrow) is received in direct LOS, while reflected signals (orange, dashed arrows) access the receiver at later times in NLOS. Due to the so-called multipath scheduling and Multiple-Input Multiple-Output (MIMO), several signals can be received and transmitted by 5G base stations, depending on the MIMO capability (Morais, 2022, pp. 197–200). However, the multiple receptions of the same signals at different time slots cause signal variations and subtract the signal strength, referred to as fading (Wollert and Gebhardt, 2010, p. 62). Furthermore, the multipathing of signals blocks resources for other signals during the reception process.

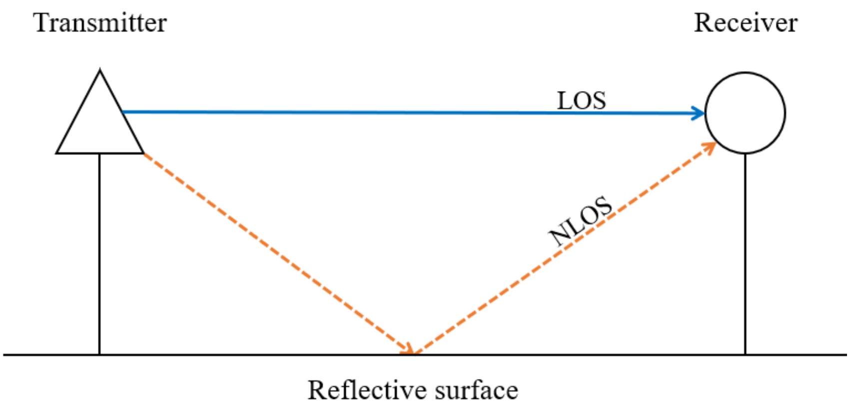


Figure 2.25: Multipath fading error
(Bevelacqua, 2021)

In particular, for time-based localisation methods such as those used by the 5G positioning services, the precise time of arrival (ToA) and the angle of arrival (AoA) at the base station is essential to ensure high accuracy (Sen et al., 2013, pp. 249–250). Additionally, different propagation times of a single signal can cause interference at the receiver and ultimately lead to amplification or elimination of the waves. Thus, the multipath error can also increase the data packet losses.

2.3.3 Absorption

Absorption is defined as the decrease in the field strength of an electromagnetic wave due to the penetration of a solid medium or material (BSI, 2008, p. 12). Materials possess different electromagnetic shielding characteristics resulting in attenuation of the signal strength, also referred to as signal loss (Morais, 2022, p. 62). The absorption rate can measure absorption. The absorption rate is the difference between the signal strength in an LOS connection and the signal strength in an NLOS connection under stable conditions measured in decibels (dB). Especially in industrial indoor networks, the penetration loss of a signal caused by different materials is considered significantly high (Morais, 2022, p. 62). In this context, signal losses can play a critical role in influencing the design of the network; for example, the number and location of the base stations (Morais, 2022, p. 62). However, the absorption by materials is difficult to predict since it depends on various situation-specific variables. Figure 2.26 illustrates these affecting variables.

As shown in Figure 2.26, waves' frequencies, the AoA of the wave on the material and the material itself influence the absorption rate. The density, surface texture, and thickness of the material influence the degree of attenuation (Wollert and Gebhardt, 2010, p. 65). Due to these variables, it is difficult to explicitly determine a material's absorption rate. However, as a general principle, low frequencies experience a lower absorption by materials than high frequencies.

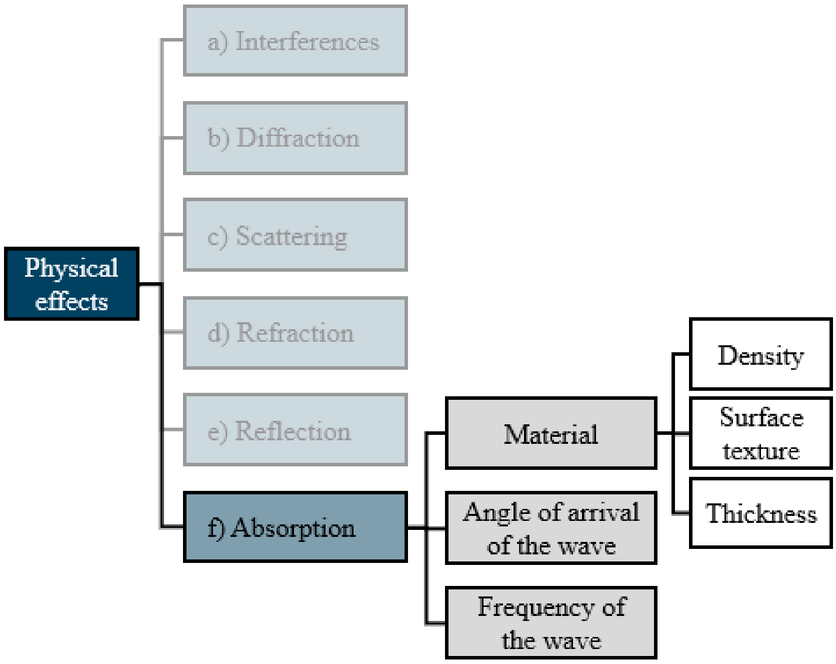


Figure 2.26: Variables affecting the absorption rate
(Wollert and Gebhardt, 2010, p. 65)

A study conducted by the Federal Department for Security and Information Security (BSI) in Germany in 2008 thoroughly investigated the absorption rate of various materials under different frequencies (BSI, 2008). Table 2.16 shows the estimated reference attenuation values for materials determined by the BSI for frequencies below 10 GHz. Currently, frequencies in the sub-6 GHz range are used for 5G standalone non-public networks. The attenuation of materials in Table 2.10 can serve as a preliminary assessment. Table 2.10 shows that reinforced concrete, metal and aluminium can impact the signal by an attenuation of between 30 to 90 percent.

Table 2.10: Estimated attenuation of materials below 10 GHz
(based on BSI, 2008; Wollert and Gebhardt, 2010, p. 65)

Material	**Thickness (cm)**	**Attenuation (%)**
Wood	< 30	1-10
Gypsum (cardboard)	< 10	1-10
Glass (uncoated)	< 5	1-10
Pressboard	< 30	30
Pumice stone	< 30	10
Concrete	< 30	20
Brick	< 30	35
Reinforced concrete	< 30	30-90
Metal mesh	< 1	90-100
Metal, aluminium lamination	< 1	60-90

2.4 Intralogistics related to wireless communication

After reviewing the background for the increasing need for wireless communication in intralogistics in Section 2.1, 5G as industrial communication in standalone non-public networks in Section 2.2 and influencing factors of wireless communication in 2.3, this section of the literature review aims to identify use cases in intralogistics requiring wireless communication semi-systematically. First, the literature review design is described, and subsequently, the literature review is conducted. Finally, the found documents are qualitatively analysed for the use cases. The output of this section is a collection of intralogistics use cases requiring wireless communication and, therefore, they are potential use cases to adopt 5G. Thus, this section provides answers to SRQ 3.

2.4.1 Related works regarding the practicality of 5G in intralogistics

An increase in publications on 5G can be observed since 3GPP announced the first 5G release in 2017. Numerous studies have already been published on technical aspects of 5G standalone non-public networks. In contrast, only minor publications deal with the assessment, implementation and prototyping of industrial use cases. In this early phase of 5G, these publications often address the topic of use cases theoretically, based on the promised future target performance of 5G. However, 5G is specified in releases, and the target performance can only be reached with further releases in years to come. Here, research lacks consideration of the 5G releases and their performances. A summary of related research efforts is given below.

The study by Ordonez-Lucena et al. (2019) investigates the use of 5G non-public networks to support Industry 4.0 scenarios. First, Ordonez-Lucena et al. (2019) map application areas with use cases in the Industry 4.0 ecosystem to understand where private 5G networks can be applied. Second, an analysis of different private network deployment scenarios is conducted. The study derives guidelines that companies can use to select appropriate network deployments. The proposed guideline to select network deployments addresses attributes including economics, security, customisation, entry barriers, autonomy and 5G service continuity. However, the guideline does not include application-oriented attributes.

The research by Varga et al. (2020) investigates challenges, solutions and research gaps in 5G supporting Industrial Internet of Things (IIoT) applications. This publication is structured into an overview of 5G, followed by fundamentals of 5G network architecture and a description of underlying concepts of 5G to support industrial scenarios such as network slicing, software-defined networking (SDN) and network function virtualisation (NFV). Varga et al. (2020) regard research gaps in proving that metrics such as latency, jitter, loss, throughput, availability, and reliability meet the defined performance in real life and an investigation of 5G in the real world using prototypes.

O'Connell, Moore and Newe (2020) examine challenges associated with implementing 5G in manufacturing. They state that a 'plethora of engineering-related questions' needs to be considered before 5G can be the 'all-conquering panacea' for the industry (O'Connell, Moore and Newe, 2020, p. 64). There is especially a need for a detailed understanding of use cases and their specific requirements in order to adopt use cases using 5G. Furthermore, the investigation of 5G within the factory environment should be considered in further research (O'Connell, Moore and Newe, 2020, p. 64; Varga et al., 2020, p. 35).

Rodriguez et al. (2021) propose an experimental framework for 5G wireless system integration into Industry 4.0 applications. The framework is structured in three parts: An operational flow, experiments in an industrial research lab, and 5G hardware and software tools used for the 5G prototype. The operational flow consists of six generic steps: 1) Understanding the needs of the factory and its current level of digitalisation; 2) Understanding the exact communication requirements of the wired setup; 3) Selection of the appropriate wireless technology and dimensioning of the solution; 4) Deployment; 5) Performance analysis; and 6) Optimisation. The steps are supplemented with a description and exemplified by the use case of autonomous mobile robots. This study provides a generic reference procedure but does not follow an application-oriented approach. Here, the framework is not equipped with a straightforward process that non-experts can apply without prior knowledge about 5G and the use case. In addition, the framework indicates that an analysis of the use case environment should be carried out, but possible influencing factors have not been investigated.

In conclusion, 5G in standalone non-public networks is not yet a thoroughly researched area. Regarding the implementation of intralogistics use cases, the need for a broad range of research is evident. Assessments of 5G for industrial use cases are often grounded on the theoretical target state of 5G that has yet not been reached. For this reason, mainly theoretical feasibility studies have been carried out in research based on the defined target performance. Furthermore, 5G has not yet been widely tested in real-world environments. The testing of specific critical performance parameters and prototyping of 5G use cases are largely unexplored fields, especially in non-laboratory environments. In addition, existing studies have not included the environment of the use case including influencing factors, such as surrounding materials in the applications' environment or different 5G end devices that can impact the data transmission. However, without considering the environment in which the use case is to be implemented, it is not possible to draw conclusions about 5G's *practicality* (Rodriguez et al., 2021, p. 2).

Therefore, *practicality* in this thesis combines the theoretical feasibility and usefulness of 5G with external influencing factors. Regarding the theoretical feasibility, the performance of 5G needs to be evaluated against the requirements of the use case, and characteristics must be elaborated to ensure that 5G makes sense as communication from a technical point of view. The external influencing factors consist of the intralogistics environment, where obstacles made of different materials can interfere with 5G communication, as well as the 5G network and the 5G end device, which can also have a limiting influence on 5G depending on the hardware, software and configuration options.

The literature review thus offers the opportunity to pursue further research in developing a framework to evaluate the *practicality* of 5G for intralogistics use cases.

2.4.2 Identification of intralogistics use cases requiring wireless communication

Snyder (2019) proposes to use a semi-systematic literature review (SSLR) methodology to detect and synthesise topics within a broad research area (Snyder, 2019, p. 335). The methods used to analyse and synthesise the findings of an SSLR are often qualitative approaches (Snyder, 2019, p. 335). However, the SSLR should be transparent and follow a replicable strategy. Therefore, Snyder (2019) suggests structuring the literature review into different phases, as shown in Figure 2.27 (Snyder, 2019, p. 335). The following section presents each of the phases in detail.

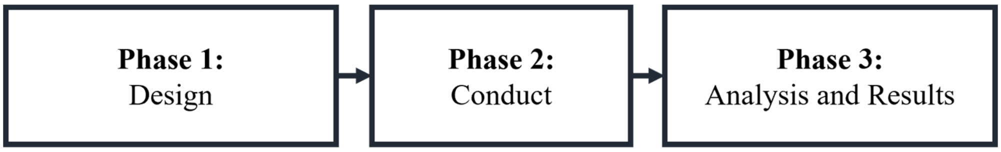


Figure 2.27: Phases of the SSLR
(Snyder, 2019)

2.4.2.1 Phase 1 – Designing the semi-systematic literature review

The design of the SSLR forms the initial phase. Following Snyder (2019), the design serves to define the specific purpose of the SSLR, leading to the answering of underlying research questions. In addition, this phase reveals the search strategy, including the databases, keywords, and inclusion and exclusion criteria (Snyder, 2019, p. 336). The specific purpose of the SSLR is to identify use cases in intralogistics that require wireless communication. In this respect, the research limitations constrain the literature collection by including only indoor use cases related to intralogistics. Regarding the research question, the SSLR is conducted to address the SRQ 3:

SRQ 3	*What wireless indoor use cases and their critical requirements regarding wireless communications occur in the intralogistics?*

With regard to the search strategy, both databases and the search string consisting of keywords are to be defined. The databases for the search are IEEE Xplore (www.ieeexplore.ieee.org) and Elsevier ScienceDirect (www.sciencedirect.com). In these databases, the following keywords were defined:

- wireless communication; mobile communication; 5G
- intralogistics; use case; application

Using the keywords, the search string (“wireless communication” OR “mobile communication” OR “5G”) AND (“intralogistics”) AND (“use case” OR “application”) is formed, which can be applied directly to the databases. Finally, after defining the databases and the search string, Snyder (2019) suggests defining inclusion criteria (IC) and exclusion criteria (EC). The following IC and EC are defined for the SSLR:

Inclusion criteria:

IC1: The document presents at least one indoor use case in intralogistics based on wireless communications and describes all critical requirements

Exclusion criteria:

EC1: Document is not written in English or German

EC2: Documents published before the beginning of the 5G standardisation process (2017)

EC3: Duplicates

EC4: Document does not belong to the subject area of engineering

EC5: Title or Abstract do not provide explicit information about the use case

EC6: Document does not describe an indoor use case

2.4.2.2 Phase 2 – Conducting the literature review

Conducting the literature review acts as the second phase of the SSLR. In this phase, the defined search string is applied to the databases. To limit the search to the relevant literature from the beginning, the filter function of IEEE Xplore and Elsevier ScienceDirect is used. Thus, EC1 and EC2 were applied directly to the search function. Furthermore, the language of the publications was restricted to English or German and the publication period within the range from 2017 to the date of the latest update of the review.

The command search function is used to apply search strings to IEEE Xplore. The amount of hits per database is shown in Table 2.11.

Table 2.11: Found documents

Database	**Hits**	**Last updated**
IEEE Xplore	7	16.03.2022
Elsevier ScienceDirect	76	16.03.2022
Total	82	

Table 2.11 shows 82 documents found after applying EC1 and EC2 directly within the databases. IEEE Xplore only returned seven articles. Elsevier ScienceDirect returned 76 documents. Table 2.12

displays the exclusion criteria filter on the documents found. Since EC1 and EC2 are applied directly to the search, these exclusion criteria are not shown in Table 2.12.

Table 2.12: Exclusion criteria filter

Documents after applying…	Excluded documents	Included documents
…EC3	0	82
…EC4	19	63
…EC5	39	24
…EC6	9	15
Total	67	15

After applying all filters, 67 documents were filtered out, resulting in 15 remaining documents. For comprehensibility and transparency, an important observation has to be stated regarding the documents found.

After analysing the documents' references, the use cases described in the found publications often did not represent the primary source. Comparing the documents and following the references using the snowballing principle resulted in the observation that intralogistics use cases were either adopted directly from 5G specifications (TS 22.104) or white papers from industry-related organisations, namely 5G Alliance for Connected Industries and Automation (5G ACIA) and from the Association for Electrical, Electronic & Information Technologies (VDE).

Table 2.13: Primary sources additionally included in the SSLR

	Title	Source, Year
1	Wireless Technologies for Industrie 4.0	VDE, 2017
2	Key 5G Use Cases and Requirements	5G ACIA, 2020
3	Technical Specification 22.104 – 5G Service requirements for cyber-physical control applications in vertical domains	3GPP, 2020a

For this reason, these documents are added to the use cases collection. The sources additionally included are shown in Table 2.13. Finally, a total of 18 documents are thus included in the qualitative analysis to identify intralogistics use cases requiring wireless communication.

2.4.2.3 Phase 3 – Results of the qualitative content analysis

For overview and transparency, Table 2.14 presents all 18 sources used for the use case identification. In general, the documents found can be divided into two types.

Some of the documents present a collection of several intralogistics use cases, while other documents only present a single use case in detail. For this reason, some documents may appear several times in different use case descriptions.

Table 2.15 represents the results of the SSLR by listing the identified intralogistics use cases, the frequency of their occurrence and the source. As shown in Table 2.15, the use cases can be thematically clustered into eight intralogistics areas. The most frequently mentioned use case is an automated guided vehicle (AGV) and an autonomous mobile robot (AMR), described in nine sources. Augmented reality and virtual reality applications follow with a total of seven sources. The condition monitoring application in intralogistics is mentioned in five sources. This is followed by robot motion control with four documents. Flexible factory layout and asset tracking are each described in two documents. The crane system use case is specified in a single source.

Table 2.14: Documents included for the use case identification using the SSRL

	Title	Source, Year
[1]	Wireless Technologies for Industrie 4.0	VDE, 2017
[2]	Key 5G Use Cases and Requirements	5G ACIA, 2020
[3]	Technical Specification 22.104 – 5G Service requirements for cyber-physical control applications in vertical domains	3GPP, 2020a
[4]	The potentials of augmented reality in supply chain management: a state-of-the-art review	Rejeb et al., 2021
[5]	The Acceptance of Augmented Reality as a Determining Factor in Intralogistics Planning	Rohacz and Strassburger, 2021
[6]	Augmented reality in support of intelligent manufacturing – A systematic literature review	Egger and Masood, 2020
[7]	Digital Manufacturing for Smart Small Satellites Systems	Krauß et al., 2021
[8]	A Review of Recent Advances in Automated Guided Vehicle Technologies: Integration Challenges and Research Areas for 5G-Based Smart Manufacturing Applications	Oyekanlu et al., 2020
[9]	Centralized Robotic Fleet Coordination and Control	Berndt et al., 2021
[10]	Cloud-Controlled Autonomous Mobile Robot Platform	Balogh et al., 2021
[11]	5G as Enabler for Industrie 4.0 Use Cases: Challenges and Concepts	Gundall et al., 2018
[12]	Enabling Communication Technologies for Automated Unmanned Vehicles in Industry 4.0	Fellan et al., 2018
[13]	Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda	Fragapane et al., 2021b
[14]	Opportunities and challenges for exploiting drones in agile manufacturing systems	Deja et al., 2020
[15]	Production-intralogistics synchronization of Industry 4.0 flexible assembly lines under graduation intelligent manufacturing system	Li and Huang, 2021
[16]	Smart Manufacturing and Tactile Internet Based on 5G in Industry 4.0: Challenges, Applications and New Trends	Mourtzis, Angelopoulos and Panopoulos, 2021
[17]	The Tactile Internet for Industries: A Review	Aijaz and Sooriyabandara, 2019
[18]	Industry 4.0 from 5G perspective: Use-cases, requirements, challenges, and approaches	Stefanović, 2018

Table 2.15: Results of the SSLR.

Use Case	Occurrence	Source
2) High-definition video broadcasting for AR and VR	7	[1-7]
3) Remote control of mobile robots (AGV and AMR)	9	[1-3,7-13]
4) Remote control of unmanned aerial vehicle and indoor drones	3	[1,12,14]
5) Condition monitoring of machines using IIoT sensors	5	[1-3,7,18]
6) Remote control of crane systems	1	[1]
7) Flexible factory layout monitoring	2	[2,15]
8) Asset indoor tracking	2	[1,3]
9) Robot motion control using tactile internet (haptic feedback)	4	[11,16-18]

The results of the qualitative analysis are eight thematic use case clusters, as shown in Table 2.15. The following section describes each intralogistics use case with its core tasks and critical requirements regarding wireless communication mentioned in the literature.

1) High-definition video broadcasting for augmented reality and virtual reality (AR and VR)

AR and VR applications include the planning and control stage of the intralogistics reference model (see Figure 2.2). Here, AR and VR glasses are used as assistance systems. Regarding intralogistics planning, 3D visualisation of warehouses and factory layouts are described as specific application scenarios. Concerning the control stage, AR and VR are used for pick-by-vision commissioning, virtual warehouse navigation, and 3D visualisation of individual assembly steps. Regarding wireless communication, AR and VR require high data rates for high-definition real-time video broadcasting transmitted with low latencies to synchronise virtual reality with physical reality without time delay.

2) Remote control of mobile robots (AGVs and AMRs)

AGVs are fixed-lane transport systems, while AMRs can perform transport and collaborative tasks such as picking and placing workpiece carriers within a delimited area, autonomously and in a self-coordinated manner (Balogh et al., 2021, p. 2). Regarding wireless communication, several tasks are discussed in the literature. Berndt et al. (2021) and Balogh et al. (2021) identify the fleet management of AGVs or AMRs with a centralised platform as an application scenario for wireless communication. The centralised platform distributes orders to active mobile robots on the shop floor, checks process steps, and shares progress with other users. Oyekanlu et al. (2020) and Gundall et al. (2018) identify the remote control as a scenario for wireless communications. Here, non-safety critical data processing units are outsourced, and on-board processing power is reduced. This increases operational battery lifetime. Safety-relevant units such as obstacle detection remain on the robot. Concerning wireless communication, the remote control of mobile robots requires real-time connectivity, high communication service availability, reliability, and low-latency data transmissions. For navigation, robots' positions must be identified in active mode.

3) Remote control of unmanned aerial vehicles (UAV) and indoor drones

Fellan et al. (2018) and VDE (2017) investigate the automated unmanned vehicle and their requirements regarding communication. Material and inventory tracking and monitoring and surveillance of facilities and processes are described as applications for camera-based UAVs. According to Fellan et al. (2018), camera-based UAVs are particularly suitable in non-accessible areas, such as high-bay warehouses or hazardous areas. Regarding wireless communication, camera-based UAVs need high data rates to transmit high-definition videos and energy-saving technology to increase the battery lifetime and, thus, operational airtime. The 5G positioning service with sufficient accuracy, makes other localisation technologies obsolete. Deja et al. (2020) introduce indoor transport UAVs. The UAVs are equipped with grippers, skids, and part-holding jigs to transport small parts from pickup to delivery areas. They report that the control of UAVs is typically executed on an on-board processing unit, but the trajectory and scheduling data is transmitted to a central unit coordinating drones' operations.

4) Condition monitoring using IIoT sensors (CM using IIoT)

VDE (2017), 5G ACIA (2020) and 3GPP (2020a) specify the use of interlinked wireless sensor networks to monitor the condition of machines. Physical parameters, for example, temperature, moisture, the position of objects and oscillations, can be measured, and preventive steps can be taken in case threshold values are exceeded. With regard to wireless technologies, condition monitoring does not possess stringent latencies, reliability or data rates. However, condition monitoring requires a high connection density of multiple sensors simultaneously within a single network.

5) Remote control of crane systems

VDE (2017) considers the benefits of wireless communication with regard to remotely controlling crane systems and ceiling cranes in warehouses using portable control panels for precise loading and unloading of heavy loads. In terms of wireless connectivity, crane systems operate at walking speed and thus, do not have high requirements regarding the speed but require low latencies, high reliability and safety due to the remote control.

6) Flexible factory layout monitoring (FFLM)

5G ACIA (2020) and Li and Huang (2021) introduce the monitoring of flexible factory layouts using connected sensors to determine the position of modular assembly lines and machines. They introduce wireless connectivity for modular assembly lines and the superordinate synchronisation of processes. A digital shadow is created based on the data, resulting in a holistic process and infrastructure monitoring of the factory layout. The FFLM requires the 5G positioning service and high-end device densities for wireless communication. The data transmission rates and latencies are relatively low, as the FFLM does not directly perform control tasks.

7) Asset indoor tracking

3GPP (2020a) considers the high accuracy of positioning and localisation and the resulting tracking and tracing of assets. The tracking and tracing enable the localisation of moving assets and components and can be used for just-in-time deliveries to subsequent assembly stations.

8) Robot motion control using tactile internet (RMC using TI)

Mourtzis, Angelopoulos and Panopoulos (2021) and Aijaz and Sooriyabandara (2019) describe robot motion control (RMC) using tactile internet (TI) as a use case requiring real-time data transmission. TI acts as the human-machine interface, transmitting haptic feedback from the robot to the controller in real-time. RMC using TI enables high precision control of actuators such as grippers or precise unloading or placing of items in inaccessible or hazardous areas. Based on Mourtzis, Angelopoulos and Panopoulos (2021), potential industries for RMC and TI a, for instance, in chemically hazardous surroundings and eHealth and telemedicine operations in clinically hygienic surroundings. TI possess strict requirements such as ultra-high availability and reliability, real-time data transmission, high security and ultra-low latencies in the sub-millisecond range.

2.4.3 Concepts of real-time communication for industrial use cases

By identifying wireless use cases in intralogistics, it is evident that 5G is seen as an enabler of communication for time-critical applications. As described in Section 2.1.2, the trend in intralogistics is shifting towards CPS. In combination with mobility on the shop floor, use cases such as autonomous mobile robots require high security and real-time (RT) communication (VDI, 2013, p. 7). This is reinforced by the interaction with humans, resulting in additional safety requirements. For this reason, a literature review on RT systems needs to be carried out. This section is intended to analyse RT characteristics, which must be included in the framework. In the remainder of the section, the characteristics of RT systems in an industrial context are summarised.

Trsek (2016) transfers the concept of the automation pyramid to industrial RT (see Figure 2.28).

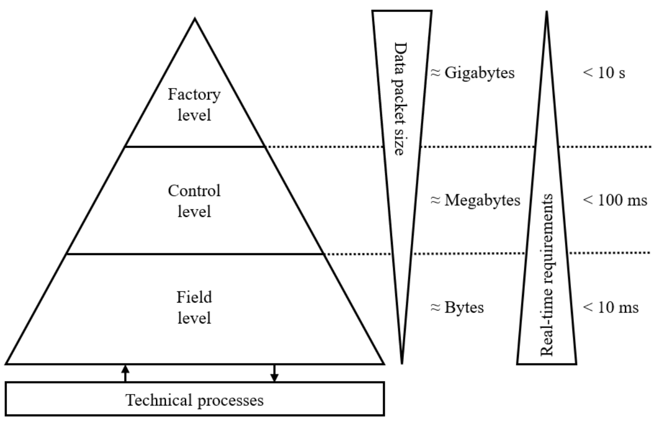


Figure 2.28: Automation pyramid transferred to industrial real-time systems (Trsek, 2016, p. 2)

The three-level automation pyramid is divided into the factory, control, and field levels. The field level represents the interface to the technical process. Trsek's model (2016) illustrates that the data packet sizes increase with each level, from the technical process with a data packet size in the range of bytes to the factory level with a data packet size in the range of gigabytes. Conversely, the closer to the technical process, the lower the RT requirements in terms of data transmission time (latency).

Jasperneite (2009) characterises RT systems by compliance with time barriers and requirements for synchronising processes. In addition, the predictability of compliance with the time barriers is an essential criterion. Jasperneite divides RT applications into two fundamental principles, namely, 1) time-controlled, and 2) event-controlled. Time-controlled RT systems transmit data in defined cycle times. Event-controlled systems are triggered by the occurrence of predefined events, for example, receiving a message or signal interruptions. According to Jasperneite, each industrial system possesses its own RT requirements. Jasperneite identifies the upper limit of the time delay (latency), the latency fluctuation (jitter), and predictability as critical RT criteria. Indicators of predictability are, for example, their availability or reliability (Jasperneite, 2009, pp. 97–100).

Kopetz (2011) defines a RT system as a system in which the output of values of a given system is calculated within predefined time limits, in which the temporal sequence of system's output is significant (Kopetz, 2011, p. 2). In RT systems, the time limits are specified by the system's physical environment since the system's output values relate to changes in the environment. Thus, the time delay between input time and output time in RT systems must have timeliness that is acceptable to the environment. Within the landscape of RT systems, Kopetz (2011) further classifies into *hard* and *soft* RT. In *hard* RT systems, exceeding the time limits leads to significant consequences for the system's environment and poses a danger. In *soft* RT systems, only a reduction in the quality of the system's output is caused by exceeding the time limits. However, according to Kopetz (2011), distinguishing between *hard* and *soft* systems is often complex. Therefore, Kopetz (2011) defines eight system-independent criteria to classify systems into *hard* or *soft* RT. In this context, meeting at least one *hard* RT criterion is sufficient to classify a system as a *hard* RT system. The criteria of their respective subdivisions are shown in Table 2.16.

Table 2.16: Hard real-time versus soft real-time
(Kopetz, 2011, p. 14)

Criteria	Hard real-time	Soft real-time
Response time	Hard-required	Soft-desired
Control of pace	Environment	Computer
Peak-load performance	Predictable	Degraded
Safety	Often critical	Non-critical
Size of data files	Small/ medium	Large
Redundancy type	Active	Checkpoint-recovery
Data integrity	Short-term	Long-term
Error detection	Autonomous	User assisted

In the following, the definition for each *hard* RT characteristic is briefly summarised according to Kopetz (2011). Non-compliance with the following *hard* RT definitions automatically results in the classification as *soft* RT.

Response time. According to Kopetz (2011, p. 14), *hard* RT requirements exclude human intervention in critical situations such as error detection or the detection of objects in the operational area of the application. Therefore, response times in the millisecond range are mandatory. Consequently, failures of a *hard* RT application in meeting the reaction time will immediately lead to a catastrophe endangering humans in the environment or the surrounding area.

C*ontrol of pace*. The application's environment always determines the speed control of a *hard* RT system, for example, by humans collaborating with the application, moving in the same operational area or by successive synchronised process steps (Kopetz, 2011, p. 14).

Peak-load performance. The peak-load performance is strictly defined in *hard* RT systems. The communication technology must guarantee to meet the limits of the peak-load scenario at all times. Consequently, the communication technology must guarantee an ultra-reliable service is always available (Kopetz, 2011, p. 14).

S*afety.* *Hard* RT requires a high level of safety, as safety gaps lead to functional safety errors. In case of an error, the error detection must be identified and eliminated autonomously within defined time limits and without affecting the running operation (Kopetz, 2011, p. 14).

S*ize of data files.* The size of the data packets in *hard* RT systems is small and the database of the system must guarantee data processing within defined time limits (Kopetz, 2011, p. 15).

Redundancy type. The RT system will not reset to a predefined checkpoint in case of errors. This can distort the data, and the time needed to reset to the checkpoint cannot be predicted. *Hard* RT systems stop the running process and shut down the system (Kopetz, 2011, p. 15).

Data integrity. Other systems cannot manipulate the data in *hard* RT systems while the application is actively using the data (Kopetz, 2011, p. 143).

Error detection. According to Kopetz (2011, p. 138), an error is an incorrect state. In *hard* RT systems, detecting errors is autonomous, i.e. the system detects errors and initiates countermeasures within the time limits, such as shutting down the system.

According to Kopetz (2011), not all of the above proposed RT characteristics apply to any given use case, and the classification into *hard* RT based on only one single characteristic is sufficient. Additionally, some of the RT characteristics are from the application's nature, whereas the environment determines others. While a detailed understanding of the system is required to determine the RT characteristics based on the application's nature, the characteristics from the application's environment are relatively simple to decide on.

2.5 Concluding summary of the literature review

The literature review serves as the foundation and theory-building for developing the framework and defining the *practicality* of the approach. Therefore, the literature research encompasses four sections.

The first Section 2.1 covers the fundamentals of intralogistics. Intralogistics includes planning and controlling tasks within a company's site. Due to the increasing complexity of supply chains and the resulting demand for flexible systems, the trend in intralogistics is shifting towards decentralised, self-controlling CPS. In this context, intralogistics systems require reliable, low-latency and high-security wireless communication systems.

Section 2.2 introduces the fundamentals of 5G. This section focuses on the industry-relevant network deployment, namely standalone non-public networks. Standalone non-public networks are based on a pure 5G infrastructure and offer high data security due to their isolation from public networks. In addition, standalone non-public networks are customisable and allow the owner to have full control over them. Moreover, standalone non-public networks combined with further 5G releases guarantee maximum performance and services required by industrial applications. Furthermore, Section 2.2 contains a review of each 5G release and provides tables and lists showing the performance and services that are relevant to the industry. However, only two out of four 5G releases planned are completed in terms of standardisation. This shows that 5G has not yet reached its full capability. In this context, evaluating the *practicality* of 5G for intralogistics use cases must include the mapping of use cases' requirements with the specified performances within the respective 5G releases.

In Section 2.3, factors influencing wireless communications are examined. This section outlines the fundamental physical effects of diffraction, scattering, refraction, reflection, interferences and absorption that can influence wireless communication. In particular, multiple studies reported that the absorption triggered when electromagnetic waves penetrate materials significantly influences signal strength, especially in industrial environments. However, a determination of specific absorption rates for materials depends on various factors such as the frequency, the angle of arrival of the wave on the material and the material properties itself (thickness, material, density). Therefore, the absorption rates measured so far can only serve as estimated benchmarks for an initial assessment.

Finally, Section 2.4 aimed to identify intralogistics use cases requiring wireless communication. The semi-systematic literature review was selected as an appropriate methodology to identify the use cases. The output of the semi-systematic literature review is a collection of eight use cases, namely:

- High-definition video broadcasting for Augmented Reality and Virtual Reality (AR and VR)
- Remote control of mobile robots (AGV and AMR)
- Remote control of UAVs
- Condition Monitoring of machines using IIoT sensors
- Remote control of crane systems
- Flexible factory layout monitoring
- Asset indoor tracking
- Robot motion control using tactile internet (haptic feedback)

Evidentially, the applications identified are often mobile and perform their tasks collaboratively with humans or operate within their environment. This results in high safety requirements characterised by real-time communication. For this reason, the section is followed by a literature review on real-time communication and its requirements. The literature review on real-time systems shows that real-time is divided into *soft* and *hard* real-time. Researchers agree that *hard* real-time is a system that must operate within defined time deadlines. The different approaches presented, demonstrate the difficulties of quantifying real-time generically across several use cases. Thus, real-time requirements for wireless communication need to be derived from the specific use case in each case. In order to classify a system or use case as a real-time use case, various non-quantifiable characteristics and behaviours of systems are presented by several researchers, which can be used to classify systems into *soft* or *hard* real-time. However, the literature review also demonstrates a lack of common consensus among researchers regarding the non-quantifiable characteristics and behaviours of a system resulting in the classification as *hard* or *soft* real-time.

The literature review also serves to define the term *practicality* of this thesis. Concluding on this, *practicality* comprises two fundamental stages.

The first stage represents the use case perspective. From this perspective, the theoretical feasibility is made based on the application requirements and mapping with the performance of individual releases. Thus, conclusions can be drawn as to whether the use case is theoretically feasible and which release is required to implement the use case. Furthermore, in this stage the question must be answered whether 5G makes technically sense as communication.

The second stage represents the use case environment. This perspective includes all influencing factors that can limit 5G communication. In this context, Section 2.3 elaborates that non-line-of-sight scenarios, namely obstacles in the intralogistics shop floor between transmitter and receiver, cause physical effects that can impair the wave transmission over the air interface. In particular, materials such as concrete, aluminium and steel influence up to 90 percent, ultimately affecting the *practicality*. In addition to the intralogistics shop floor, the environmental influencing factors include the 5G network, and the 5G end device. Regarding the 5G network and the 5G end device, it can be concluded from the literature review that they consist of different hardware components. The architecture of the hardware components in the network and the end device can also limit the performance of 5G. In addition, the software implementation of the 5G releases on the hardware by the manufacturer represents another influencing factor.

Therefore, the term *practicality* is composed of the theoretical feasibility from the use case perspective and external influencing factors on the 5G communication from the environmental perspective.

3 Use case classification and analysis

This chapter investigates the use cases identified within the SSLR in Section 2.4 to derive specific characteristics resulting in generic conclusions that serve as a reference for the framework development. For this purpose, the first part of this chapter contains a use case classification to examine the use cases more closely. The second part of this chapter aims to derive critical use cases using morphological analysis. The critical use cases possess the maximum intersection with all other use cases on which specific conclusions can be drawn, serving as generic references for the framework. Thus, the morphological analysis addresses SRQ 4.

3.1 Use case classification

The classification serves to analyse the use cases identified within the SSLR in Section 2.4 in detail. According to Hubka and Eder (1998), classification is the division of objects into groups or classes. Objects are assigned to selected classes within the classification process based on their characteristics serving as a differentiated and closer examination of the classified objects (Hubka and Eder, 1998, 16-17).

3GPP specifies relevant KPIs for industrial use cases (Section 2.2.3.1). The KPIs are quantifiable for each use case and represent the quantifiable classes underlying the classification. A matrix can be constructed using the KPIs and the use cases identified by plotting the use cases on the y-axis and the KPIs on the x-axis. Subsequently, each use case can be mapped to the respective KPI with a quantifiable value. The developed use case requirement matrix is shown in Table 3.1.

Table 3.1: Quantifiable requirements used for the classification

	Quantifiable requirements (KPIs)							
Use cases	Positioning accuracy [cm]	Comm. service availability [%]	Comm. service reliability [%]	End-2-End latency [ms]	Max. device speed [m/s]	Max. date rate [Bit/s]	Device density [devices/m^2]	**Source**
High-definition video broadcasting for AR and VR								
Remote control of mobile robots (AGV and AMR)								
Remote control of UAV for video transmission								
Condition monitoring of machines using IIoT sensors								
Remote control of crane systems								
Flexible factory layout monitoring of assembly lines								
Asset indoor tracking								
Robot motion control using tactile internet (haptic feedback)								

Specific values for each use case must be derived from literature to classify the use cases regarding their quantifiable requirements. In this context, the use case's task from Section 2.4.2.3 is used, as the specific requirements do not depend on the use case itself but rather on the task to be performed by it. The study from VDE (2017, p. 18) and the technical specification for cyber-physical control applications (TS 22.104) from 3GPP (2020a) define parameters for various applications' tasks. With regard to the UAV application, the classification is supplemented with values from the publication by Purucker et al. (2021). Regarding the condition monitoring use case, positioning is not required, as the IIoT sensors are fixed-mounted on the machine. The robot motion control also does not require 5G positioning since this use case possesses strict positioning in the cm-range that 5G cannot deliver and thus, it must be supported by more accurate technologies. Table 3.2 illustrates the use case classification based on their quantifiable requirements with the parameters collected from VDE (2017, p. 18), 3GPP (2020a) and Purucker et al. (2021, p. 1500).

Table 3.2: Use case classification based on the quantifiable requirements (based on VDE, 2017 [1], 3GPP, 2020a [2], Purucker et al., 2021 [3])

	Quantifiable requirements (KPIs)							
Use cases	Positioning accuracy [cm]	Comm. service availability [%]	Comm. service reliability [%]	End-2-End latency [ms]	Max. device speed [m/s]	Max. date rate [Bit/s]	Device density [devices/m^2]	**Source**
High-definition video broadcasting for AR and VR	< 100	> 99.999	99.99	~ 10	< 3	Gbit/s	> 0.02-0.03	[1,2]
Remote control of mobile robots (AGV and AMR)	< 5	> 99.9999	99.999	15-20	< 10	Mbit/s	~ 0.1	[1,2]
Remote control of UAV for video transmission	< 10	> 99.9999	99.999	10-40	< 10	Mbit/s	~ 0.1	[2,3]
Condition monitoring of machines using IIoT sensors	not required	99.99	99.9	100	< 10	kbit/s	10-20	[1,2]
Remote control of crane systems	< 10	> 99.9999	> 99.999	15-20	< 5	Mbit/s	~ 0.1	[1]
Flexible factory layout monitoring of assembly lines	~ 50	99.99	99.9	> 100	< 1	Gbit/s	~ 0.5	[1,2]
Asset indoor tracking	< 50	99.99	99.9	< 200	< 10	kbit/s	10-20	[1,2]
Robot motion control using tactile internet (haptic feedback)	not required	> 99.999999	99.999999	0.25-1	< 10	Mbit/s	< 5	[1,2]

In addition to quantifiable requirements, use cases also possess non-quantifiable requirements and characteristics that can influence the quantifiable requirements and determine whether mobile communication, 5G in particular, is practical or not from a technical perspective. In the following paragraphs, the identified non-quantifiable classes are described in detail.

Traffic class: According to 3GPP (2020a, pp. 12–16), an essential non-quantifiable characteristic is the traffic class describing the type of how data is transmitted and the transmission periodicity, called cycling-time (3GPP, 2020a, p. 44). 3GPP divides the traffic into three different classes:

- *Deterministic-periodic:* The first class is called *deterministic-periodic* traffic, representing use cases that transmit data periodically in a fixed cycling time, and the data must be received at the destination within a specific time threshold (3GPP, 2020a, p. 44).
- *Deterministic-aperiodic*: In this class, use cases do not transmit data periodically but only when a predefined event triggers the data transmission. In the case of data transmission, the information also has to be received at the destination within a stringent time threshold (3GPP, 2020a, p. 44).
- *Non-deterministic:* This class includes use cases that do not have specific time thresholds, and the data transmission time and the periodicity is not critical (3GPP, 2020a, p. 44).

Real-time class: Another non-quantifiable class is represented by real-time and is closely related to the traffic class. Several real-time approaches are presented in the literature review in Section 2.4.3. Kopetz's approach to classifying real-time into *soft* or *hard* is based on explicitly mentioned characteristics of a system (see Table 2.16). According to Kopetz (2011), *soft* or *hard* real-time significantly influence the application as it entails functional safety requirements.

Mobility class and power supply: Mobile communication's name indicates that mobility of use cases is crucial. According to Hofmann (2016, pp. 10–11) and Langmann (2021, p. 159), a use case is considered mobile when movement exists in a two-dimensional area or a three-dimensional room. In this context, an application classified as mobile is supplied with power by a battery (Hofmann, 2016, pp. 10–11; Langmann, 2021, p. 159). The counterpart of mobile use cases are applications considered stationary. In contrast to the quantifiable requirements, the non-quantifiable requirements consist of classes with different characteristics. Here, a use case can only be assigned to one characteristic per class. For instance, a use case can be *hard* or *soft* real-time, but never both. Table 3.3 shows the matrix to classify the use cases regarding their non-quantifiable requirements.

Table 3.3: Non-quantifiable requirements used for the classification

	Non-quantifiable requirements (characteristics)								
	Traffic class			Real-time class		Mobility class		Power supply	
Use Case	Deterministic-periodic	Deterministic-aperiodic	Non-deterministic	Hard	Soft	Mobile	stationary	Battery	Wired
High-definition video broadcasting for AR and VR									
Remote control of mobile robots (AGV and AMR)									
Remote control of UAV for video transmission									
Condition monitoring of machines using IIoT sensors									
Remote control of crane systems									
Flexible factory layout monitoring of assembly lines									
Asset indoor tracking									
Robot motion control using tactile internet (haptic feedback)									

Regarding the traffic class, only the use cases of flexible factory layout monitoring of assembly lines and asset indoor tracking are non-deterministic. This is due to their task of monitoring assembly lines and tracking indoor movements of assets to determine their position. Based on their position, process synchronisations can be made. As can be seen in the quantifiable classification, flexible factory layout monitoring and asset indoor tracking do not have stringent requirements regarding latency. Exceeding the latency thresholds for flexible factory layout monitoring and asset indoor tracking (defined in Table 3.2) does not jeopardise functional safety resulting in non-deterministic traffic. Since exceeding the latency limit endangers functional safety, the remaining use cases are classified as deterministic use cases. The use case condition monitoring of machines using IIoT sensors represents a scenario in which sensors report physical parameters of machines, such as temperature or pressure of valves. This use case represents event-driven traffic, triggered when predefined thresholds are met and thus, classified as deterministic-aperiodic. The use cases classified as deterministic-periodic relate to the control of robots, except for the use case of high-definition video broadcasting of AR and VR. In this case, the use case also possesses stringent latencies for the seamless synchronisation of the physical and virtual worlds.

Regarding the real-time classes from Kopetz (2011), the use cases classified as *hard* real-time have strict latency thresholds. Further, exceeding the thresholds can endanger humans and the environment of the use case. Only condition monitoring, flexible factory layout monitoring and asset indoor tracking are classified as *soft* real-time. The mobility and power supply classification is based on the nature of the use cases. Using the definition of mobility from Hofmann (2016) and Langmann (2021), only condition monitoring of machines using IIoT sensors is classified as stationary as the sensors are mounted in a fixed position on the application. The remaining applications are classified as mobile. Table 3.4 provides the use case classification based on their non-quantifiable requirements.

Table 3.4: Use case classification based on the non-quantifiable requirements

	Non-quantifiable requirements (characteristics)								
	Traffic class			Real-time class		Mobility class		Power supply	
Use Case	Deterministic-periodic	Deterministic-aperiodic	Non-deterministic	Hard	Soft	Mobile	stationary	Battery	Wired
High-definition video broadcasting for AR and VR	×			×		×		×	
Remote control of mobile robots (AGV and AMR)	×			×		×		×	
Remote control of UAV for video transmission	×			×		×		×	
Condition monitoring of machines using IIoT sensors		×			×		×	×	
Remote control of crane systems	×			×		×			×
Flexible factory layout monitoring of assembly lines			×		×	×		×	
Asset indoor tracking			×		×	×		×	
Robot motion control using tactile internet (haptic feedback)	×			×		×			×

3.2 Morphological analysis to select critical use cases

Based on the use case classification, critical use cases must be derived in a morphological analysis to draw generic conclusions serving as the foundation for the proposed framework. These critical use cases serve as reference use cases and ensure the generic design of the framework. In this context, morphological analysis serves as a discipline-independent identification method (Álvarez and Ritchey, 2015, p. 1).

As analysed and described in the use case classification, the applications consist of quantifiable and non-quantifiable requirements, which are essential to evaluate the theoretical feasibility of 5G, and ultimately its *practicality*. Especially for multi-dimensional and non-quantifiable problems, such as identifying critical use cases, morphological analysis is a suitable tool (Álvarez and Ritchey, 2015, p. 1). Therefore, the use case classification matrices from Section 0 are the starting point for the morphological analysis. Figure 3.1 shows the three phases of the morphological analysis. In the remainder of this section, each phase is described in detail.

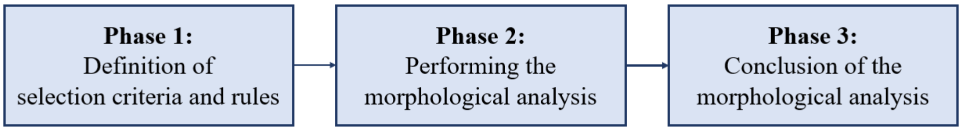


Figure 3.1: Morphological analysis process

3.2.1 Phase 1 – Definition of selection criteria and rules

For conducting the morphological analysis, rules and selection criteria must be defined. The selection criteria and rules underlying the morphological analysis are as follows:

Selection criteria: Search for the most critical values(s) per requirement and highlight the critical values(s) in yellow. The critical non-quantifiable values per requirement are shown in Table 3.5. The critical values per quantifiable requirement are defined in Table 3.6.

Table 3.5: Critical non-quantifiable values per requirement

Non-quantifiable requirements	Critical value
Traffic class	Deterministic (periodic and aperiodic)
Real-time class	Hard
Mobility class	Mobile
Power supply class	Battery

Table 3.6: Critical quantifiable values per requirement

Quantifiable requirements	Critical value
Positioning accuracy	Lowest value
Communication service availability	Highest value
Communication service reliability	Highest value
End-to-End Latency	Lowest value
Max. end device speed	Highest value
Max. data rate	Highest value
End device density	Highest value

Rules for performing the analysis: Run the most critical values through the morphological matrix by using the minimum number of use cases simultaneously. If more than one use case possesses identical values per requirement, and the total minimum number of use cases equals that, the higher occurrence within the SSLR decides the critical use case. The outcome is the ‘critical path’ across all use cases through the matrix (represented in red).

3.2.2 Phase 2 – Performing the morphological analysis

The quantifiable and non-quantifiable matrices from the use case classification are used to perform the morphological analysis. The first step is to mark all critical values per requirement in yellow. The indications from Table 3.5 and Table 3.6 were used to identify the most critical values. Table 3.7 shows the morphological matrix with all critical values per requirement, marked in yellow.

Table 3.7: Morphological matrix with all critical values per requirement

	Morphological analysis															
	Quantifiable requirements (KPIs)							Non-quantifiable requirements (characteristics)								
								Traffic class			Real-time class		Mobility class		Power supply	
Use Cases	Positioning accuracy [cm]	Comm. service availability [%]	Comm. service reliability [%]	End-2-End latency [ms]	Max. device speed [m/s]	Max. data rate [Bit/s]	Device density [devices/m²]	Deterministic-periodic	Deterministic-aperiodic	Non-deterministic	Hard	Soft	Mobile	Stationary	Battery	Wired
High-definition video broadcasting for AR and VR	< 100	> 99.999	99.99	~ 10	< 3	Gbit/s	> 0.02-0.03		×		×		×		×	
Remote control of mobile robots (AGV and AMR)	< 5	> 99.9999	99.999	15-20	< 10	Mbit/s	~ 0.1	×			×		×		×	
Remote control of UAV for video transmission	< 10	> 99.9999	99.999	10-40	< 10	Mbit/s	~ 0.1	×			×		×		×	
Condition monitoring of machines using IIoT sensors	not required	99.99	99.9	100	< 10	kbit/s	10-20		×			×		×	×	
Remote control of crane systems	< 10	> 99.9999	> 99.999	15-20	< 5	Mbit/s	~ 0.1	×			×		×			×
Flexible factory layout monitoring of assembly lines	~ 50	99.99	99.9	> 100	< 1	Gbit/s	~ 0.5			×		×	×		×	
Asset indoor tracking	< 50	99.99	99.9	< 200	< 10	kbit/s	10-20			×		×	×		×	
Robot motion control using tactile internet (haptic feedback)	not required	> 99.999999	99.999999	0.25-1	< 10	Mbit/s	< 5	×			×		×			×

Critical value per requirement

After all critical requirements are identified and marked in yellow, the second step is to perform the analysis. For this purpose, the most critical values are run through the matrix by simultaneously using the minimum number of use cases in total.

Mobile robots require the most precise positioning with an accuracy lower than 5 cm. Regarding the availability, reliability, and end-to-end latency of communication service, the use case robot motion control using tactile internet possesses the highest requirements. Regarding the end device speed, five use cases require communication support of up to 10 m/s. However, to meet the rule of using the fewest possible use cases, robot motion control using tactile internet is again selected as the critical application as it already possesses three other critical values.

Concerning the data rate, two use cases, namely high-definition video broadcasting for AR and VR and flexible factory layout monitoring, require data rates in the Gbit/s-range. In this case, both use cases can be selected as critical. However, high-definition video broadcasting for AR and VR is used more frequently in wireless communication (see Table 2.15). For this reason, this use case is marked as critical. This reasoning is equally applicable to the device density. The use cases condition monitoring using IIoT sensors and asset indoor tracking meet the exact requirements; but condition monitoring using IIoT sensors is selected as critical since it occurred more frequently in the literature.

Table 3.8 shows the identified four critical use cases after the morphological analysis. For the sake of simplicity, all use cases considered non-critical are removed. Furthermore, all non-critical values regarding the remaining critical use cases have been removed from the matrix.

Table 3.8: Morphological matrix with the identified critical use cases

	Morphological analysis															
	Quantifiable requirements (KPIs)							Non-quantifiable requirements (characteristics)								
								Traffic class			Real-time class		Mobility class		Power supply	
Use Cases	Positioning accuracy [cm]	Comm. service availability [%]	Comm. service reliability [%]	End-2-End latency [ms]	Max. device speed [m/s]	Max. data rate [Bit/s]	Device density [devices/m^2]	Deterministic-periodic	Deterministic-aperiodic	Non-deterministic	Hard	Soft	Mobile	Stationary	Battery	Wired
High-definition video broadcasting for AR and VR	< 100	> 99.999	99.99	~ 10	< 3	Gbit/s	> 0.02-0.03		×		×		×		×	
Remote control of mobile robots (AGV and AMR)	< 5	> 99.9999	99.999	15-20	< 10	Mbit/s	~ 0.1	×			×		×		×	
Condition monitoring of machines using IIoT sensors	not required	99.99	99.9	100	< 10	kbit/s	10-20		×			×		×	×	
Robot motion control using tactile internet (haptic feedback)	not required	> 99.999999	99.999999	0.25-1	< 10	Mbit/s	< 5	×			×		×			×

Critical value per requirement

In summary, the following four critical use cases are identified as critical as a result of the morphological analysis, namely, *high-definition video broadcasting for AR and VR, remote control of mobile robots (AGV and AMR)*, *condition monitoring of machines using IIoT sensors* and *robot motion control using tactile internet (haptic feedback)*.

Based on these critical use cases, conclusions are drawn in the third phase to develop the framework. Thereby, the objective is pursued to ensure a generic framework design since the critical use cases possess the maximum intersection with all other use cases.

3.2.3 Phase 3 – Conclusion

In the last phase of the morphological analysis, the identified critical use cases are investigated to derive generic requirements for the framework. Therefore, the subsequent investigation refers to the four identified critical use cases and their non-quantifiable and quantifiable requirements. These critical requirements serve as reference criteria for the framework development, providing the maximum intersection with less critical applications.

Concerning the non-quantifiable requirements, the use case *mobile robot* can serve as a reference since *mobile robots* possess strict requirements regarding real-time (*hard* real-time) and their traffic class but are also classified as mobile and power-supplied by battery. Regarding the quantifiable requirements, the identified four critical use cases and their critical values are mapped to the respective 5G service categories, shown in Figure 3.2.

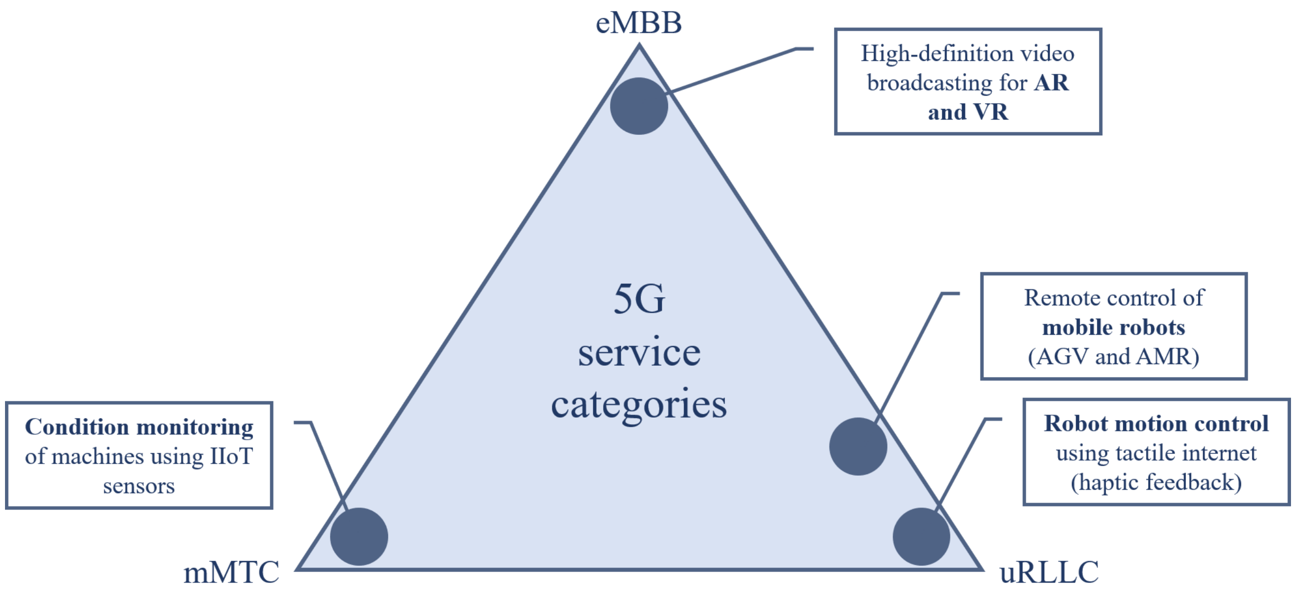


Figure 3.2: Identified critical use cases mapped to the 5G service categories

As shown in Figure 3.2, the critical use cases utilise at least one of 5G's service categories. *High-definition video broadcasting for AR and VR* requires high data rates and is assigned to the eMBB category. In contrast, *mobile robots* for remote control using 5G require low-latency and reliable communication. *Robot motion control* requires strict time delays and is classified into the uRLLC category. *Condition monitoring* speaks to a high device density using 5G-capable IIoT sensors. These sensors can measure, for example, the temperatures and valve pressures. Thus, *condition monitoring using IIoT sensors* represents the mMTC category.

As demonstrated in Figure 3.2, the critical use cases need the full potential of 5G in one of the three service categories. However, it cannot be automatically concluded that no other technology can also deliver the required performance. Therefore, competing wireless technologies must be compared with

5G in the framework development to derive performance thresholds for each of the service categories, which only 5G can perform and thus, be considered theoretically feasible and useful.

3.3 Concluding summary

This chapter aimed to examine the use cases identified within the SSLR in Section 2.3 using the classification method. Based on the classification results, the following conclusion can be drawn. All use cases possess quantifiable and non-quantifiable requirements. The non-quantifiable requirements represent characteristics of the use case having a decisive influence on the quantifiable requirements and the communication technology in consideration. In particular, the mobility and power supply, the real-time class and the traffic class are derived as critical non-quantifiable requirements. However, the real-time class and traffic class are closely connected since they influence each other. Therefore, using the real-time class within the framework might be sufficient.

Furthermore, a morphological analysis was conducted within this chapter to derive the critical use cases that can serve as a reference for the framework development. Summarising the morphological analysis, four use cases, namely, *high-definition video broadcasting for AR and VR, mobile robots, robot motion control* and c*ondition monitoring,* are critical, representing one of the three 5G service categories, called eMBB, uRLLC and mMTC. Therefore, 5G must be compared in the framework with competing wireless technologies regarding the three service categories to derive performance thresholds above which only 5G can perform and thus, be considered practical from the technical perspective.

4 Framework development

The framework to evaluate the *practicality* of 5G for intralogistics use cases in standalone non-public networks is developed in this chapter. By delimitation of this research, the framework adopts an industry-independent design. The proposed design for adapting new technologies by Dietrich (2020) was used as a design backbone to develop the framework. A vertical process flow represents the evaluation process regarding the *practicality* of 5G for intralogistics use cases. The vertical process flow includes two stages representing the two different perspectives within the evaluation process. Stage one is called the *use case specification stage,* in which the theoretical feasibility as the first perspective of the *practicality* is evaluated based on the use case. Stage two is the *environmental analysis stage* covering all parts of the use case's environment. The composition of both stages represents the proposed framework to evaluate the *practicality* of 5G, additionally showing all inter-relationships of individual framework elements.

4.1 Use case specification stage

The first stage of the framework adopts the use case perspective and focuses on the application's specification. Therefore, in the first sub-step, the use case and its tasks must be defined with all critical requirements regarding wireless communication. Sub-step two ensures the suitability of wireless communication. When wireless communication is suitable, the third sub-step analyses whether 5G can meet all specified critical KPIs and is thus, technically feasible with 5G. However, the technical feasibility is insufficient to make decisions about 5G as a useful technology. Therefore, last step aims to identify characteristics of the use case making 5G technically useful. The vertical process flow of the first stage with all considered sub-steps is shown in Figure 4.1. In the remainder of this section, each sub-step is presented in detail.

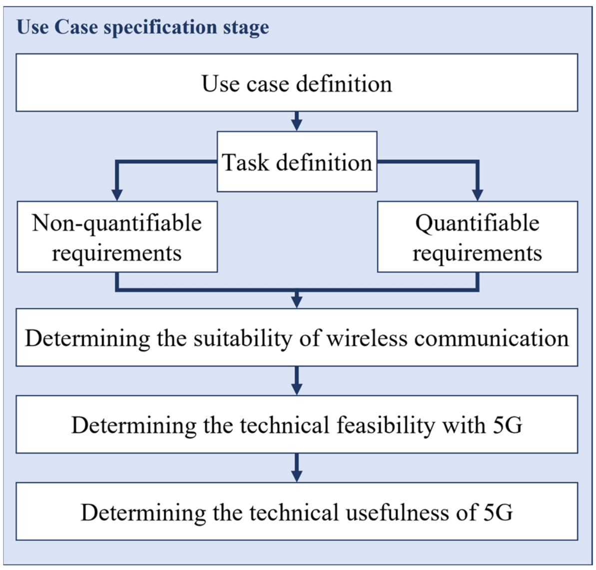


Figure 4.1: Use case specification stage

4.1.1 Use case definition

The first step serves to define the use case. Consequently, the use case definition serves as the input provided by the framework's user and should be carefully carried out since the following sub-steps are based on this definition. In this context, the definition consists of three elements.

First, all tasks 5G performs during the active operation mode of the use case need to be defined. Based on the task definition, the second step creates a requirement profile of the use case regarding wireless communication. The use case classification in Section 3.1 shows that a use case profile must be described by quantifiable and non-quantifiable requirements. Critical wireless communication KPIs describe the quantifiable requirements. These KPIs include the data rate in download and upload, the latency, the end device speed, the availability and reliability of the communication service and the end device density that the wireless communication must cover for the individual use case. Another 5G-specific KPI is described by the positioning service level (a definition per KPI is provided in Section 2.2.3.1). When defining the KPIs, it is important to see that the critical thresholds per requirement are adequate since it is only when the critical thresholds are exceeded that the application's realisation is limited. A requirement profile template for the quantifiable KPIs is developed to assist. The template is shown in Table 4.1.

Table 4.1: Requirement profile template for KPIs

KPIs	Required threshold value
Data rate download [Gbit/s]	
Data rate upload [Gbit/s]	
End-to-end latency [ms]	
End device speed [m/s]	
Communication service availability [%]	
Communication service reliability [%]	
End device density [devices/m²]	
5G positioning service level	

After defining the task and the quantifiable requirements, all required 5G services and characteristics of the application's nature must be specified. Significantly, the characteristics of the application's nature seem trivial. However, for example, the mobility of an application is essential to deciding whether wireless or wired communication is required. As described in Section 2.2.3, the standardisation of 5G also includes enhancements regarding services for industrial purposes. Primarily, three major services are identified, namely, the 5G positioning (see 2.2.3.3), the network slicing (see 2.2.5.5) and the V2X communication for mobile applications (see 2.2.3.3). The required service must be defined to evaluate if 5G is practical for the underlying use case. Therefore, a second template reflects the 5G services and the characteristics of the application's nature. The requirement profile template for 5G services and non-quantifiable requirements is shown in Table 4.2.

Table 4.2: Requirement profile template for 5G services and non-quantifiable requirements

5G services	5G positioning	Yes	
		No	
	Network slicing	Yes	
		No	
	V2X communication	Yes	
		No	
Application's nature	Mobility class	Mobile	
		Stationary	
	Power supply	Battery	
		Wired	

4.1.2 Determining the suitability of wireless communication

After defining the use case, this step determines the type of communication technology. According to Scanzio, Wisniewski and Gaj (2021, p. 4), communication technologies can be divided into wired and wireless systems (see Figure 2.5). 5G belongs to wireless communication, and thus the use case first needs to be checked to determine whether it meets the conditions for wireless communication. As one finding from the use case analysis (Section 3) demonstrated, the application's mobility and power supply can be used for this decision. According to Langmann (2021, p. 159) and Hofmann (2016, pp. 10–11), a use case is mobile when movement exists in a two-dimensional area or a three-dimensional room. If an application can be classified as stationary, a wired connection offers higher reliability and performance due to its physical connection. Therefore, a use case must either be classified as mobile or supplied by battery as the application can potentially change its location and thus, also result in a mobile use case.

When wireless communication is considered suitable, two additional steps need to be carried out in the subsequent process. First, it must be ensured that 5G fully meets the technical requirements of the use case. In this respect, identifying the required release for implementation is also essential. Second, once 5G can theoretically meet the requirements and the use case is technically feasible with 5G, the final step aims to determine whether 5G is considered feasible or whether other wireless technologies are also considered possible for implementation.

4.1.3 Determining the technical feasibility of 5G

This sub-step aims to determine the technical feasibility of 5G for the use case. Subsequently, when 5G meet the use cases' requirements, the required 5G release must be determined. One finding from the literature review is that 5G is standardised in so-called *releases* resulting in different performances that 5G can deliver. Therefore, a spider chart is developed to assist the decision-making about the feasibility and the required 5G release. The spider chart represents all quantifiable KPIs defined by 3GPP for wireless communication (provided in Section 2.2.3) with the specified performances for all 5G releases, namely, Release 15, Release 16, Release 17 and Release 18. Although Release 18 is not yet specified, Release 18 must reflect the target performance of 5G since it represents the last release. The framework user can transfer the requirement profile of the use case into the developed spider chart template and thus identify the release covering all requirements (all positioning service levels are provided in Table 2.4). The spider chart template is shown in Figure 4.2.

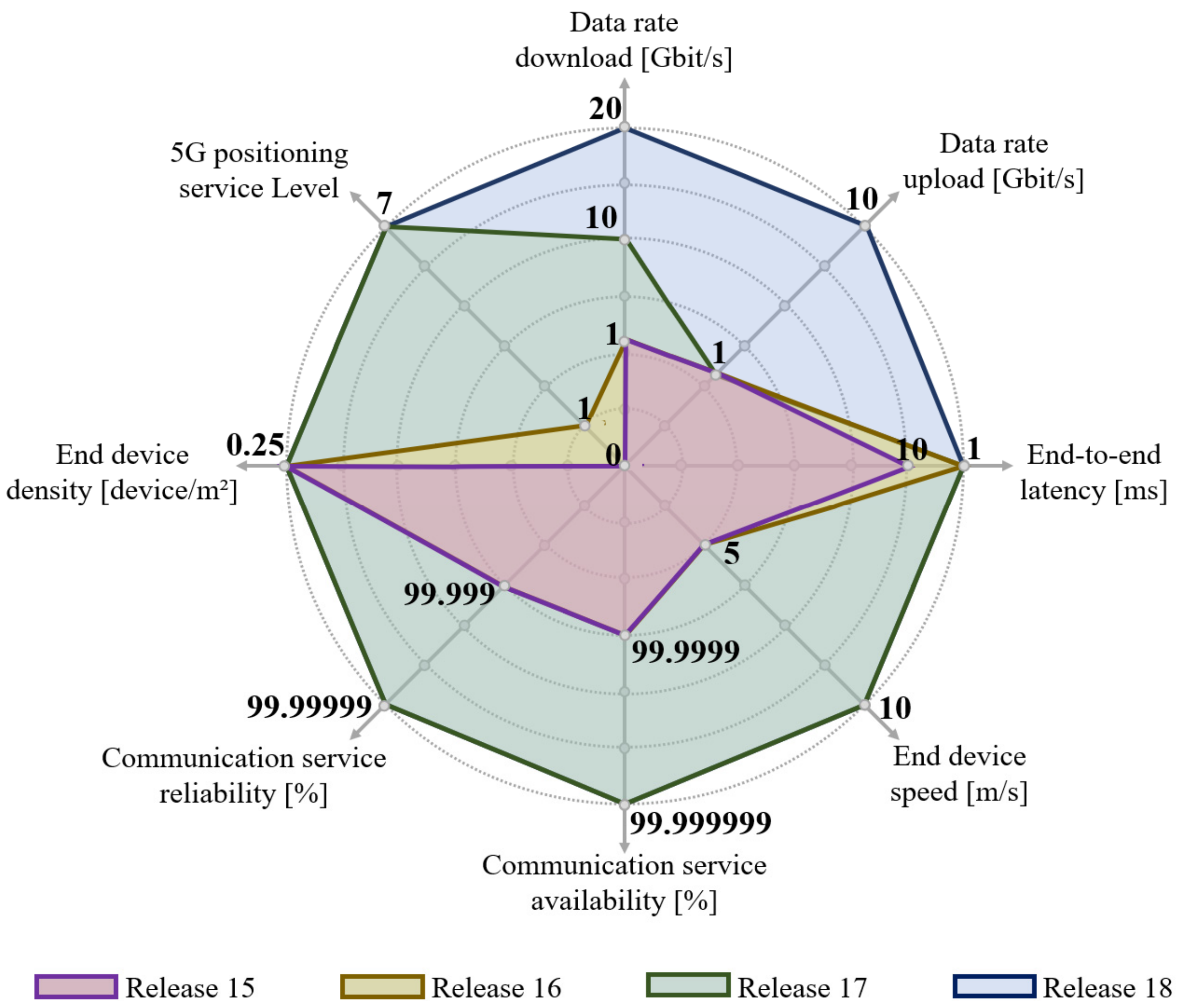


Figure 4.2: Spider chart template to identify the feasibility of 5G and the required 5G release

4.1.4 Determining the technical usefulness of 5G

At this point, the suitability of wireless communication and the feasibility of 5G with the respective 5G release is determined. However, the suitability of wireless communication and the technical feasibility alone do not ensure that 5G makes sense as a wireless technology from a technical perspective. Therefore, 5G's competing wireless technologies and non-quantifiable characteristics of the use case need to be used to identify conditions relating to the unique selling points of 5G. To identify the performance thresholds that only 5G can deliver, a comparison of 5G and Wi-Fi needs to be executed since Wi-Fi is seen as 5G's competing wireless technology. Wi-Fi's latest generation, Wi-Fi 6 Enhanced (IEEE 802.11ax), is the only commercially available wireless technology delivering similar performances to 5G (Oughton et al., 2021, p. 1). To identify the technological advantages and performances that only 5G can offer, the following section compares Wi-Fi 6 Enhanced and 5G.

Comparison of 5G and Wi-Fi 6 Enhanced

Wi-Fi 6 Enhanced represents the latest generation of Wi-Fi (Oughton et al., 2021, p. 1). In the context of wireless technologies, the generations of Wi-Fi and mobile communication compete against each other (Oughton et al., 2021, p. 1; ZTE, 2020, p. 31). For this reason, the spectrum characteristics and technical performances of both wireless technologies must be compared. Table 4.3 compares Wi-Fi 6 Enhanced with 5G standalone non-public networks regarding their spectrum.

Table 4.3: Spectrum comparison of 5G and Wi-Fi 6 Enhanced
(based on Maldonado et al., 2021, p. 9; Oughton et al., 2021, p. 9; ZTE, 2020, p. 32)

Characteristics	Wi-Fi 6 Enhanced	5G standalone non-public networks
Frequencies	2.4 GHz/ 5 GHz	– Germany: 3.7-3.8 GHz – South Africa: 700 MHz-3.5 GHz
Interoperability	global	country-specific
Frequencies	public	licensed
Access	public	private
Security	low	high
Air-interface competition	uncontrollable	controllable

Table 4.3 shows that 5G offers private access due to the licensed frequencies concerning the spectrum. Consequently, 5G provides a high level of data security and is protected from access by unauthorised subscribers. For this reason, the air interface competition of 5G is controllable, as no third-party subscriber can occupy the air interface with its radio waves. In contrast, Wi-Fi 6 Enhanced is based on globally allocated and public frequencies in the 2.4 GHz and 5 GHz ranges. In this case, any subscribers' end device with the technical capabilities can use these frequencies. Thus, data security

cannot be guaranteed with Wi-Fi 6 Enhanced. In addition, the simultaneous transmission of radio waves from multiple end devices can stress and finally overload Wi-Fi's public frequencies. Therefore, Wi-Fi's air-interface competition is uncontrollable. In terms of frequencies, one technical disadvantage of 5G is the country-specific regulation of frequency bands and the resultant lack of interoperability across countries. However, as shown in Table 4.3, Germany and South Africa operate in similar frequency bands, ensuring interoperability, especially concerning end devices. In conclusion, 5G offers its spectrum potential for applications that require a high level of data security due to licensed frequencies.

After comparing the spectrum of Wi-Fi 6 Enhanced and 5G, the technical parameters of both technologies must be compared to define thresholds above which only 5G can deliver the performance. Table 4.4 provides a comparison of the technical performances.

Table 4.4: Technical comparison of 5G and Wi-Fi 6 Enhanced
(based on Maldonado et al., 2021, p. 9; Oughton et al., 2021, p. 9; ZTE, 2020, p. 32)

Characteristics	**Wi-Fi 6 Enhanced**	**5G standalone non-public networks**
Downwards compatibility	yes	no
Max. data rate (Download)	9.6 Gbit/s	10 Gbit/s – 20 Gbit/s
Max. data rate (Upload)	5 Gbit/s	1 Gbit/s – 10 Gbit/s
Min. latencies	~ 100 ms	1 ms
Handover strategy	hard/ not seamless	soft/ seamless
Handover latencies	~ 100 ms	1 ms
Max. MU-MIMO	8x8	128x128
Network slicing	no	yes
Positioning service	no	yes
V2X communication	no	yes

5G does not offer backward compatibility with previous generations regarding the technical parameters. Therefore, 5G standalone-capable end devices are mandatory for communication in 5G standalone non-public networks. Regarding the maximum data rate, 5G can provide up to 20 Gbit/s in download and 10 Gbit/s in upload depending on the 5G release, whereas Wi-Fi 6 Enhanced is limited to 9.6 Gbit/s in download and 5 Gbit/s in upload. A further advantage of 5G is the low latency communication of 1 ms. Even when changing radio cells, 5G promises to enable latencies of 1 ms due to the so-called soft handover. In contrast, Wi-Fi guarantees latencies of around 100 ms and does not ensure soft handovers between two radio cells. Regarding the number of end devices, the Multi-MU-MIMO (see Section 2.2.5.4) ensures the communication of eight end devices in download and upload at the same time without performance losses in the case of Wi-Fi 6 Enhanced. 5G can handle up to 128 end devices simultaneously without performance losses. However, the MU-MIMO capability in general also depends on the hardware capability. 5G is currently the only wireless communication offering network slicing (see Section 2.2.5.5). Network slicing provides advantages in guaranteeing customised resources for critical use cases. Furthermore, 5G also offers its own 5G positioning service with different levels of accuracy, while Wi-Fi 6 Enhanced cannot localise end devices. Comparing the technical characteristics of 5G and Wi-Fi 6 Enhanced, thresholds can be defined for each of the peaks of 5G's main service categories. When the application requirements exceed at least one of Wi-Fi's thresholds, only 5G can deliver the required performance regarding the respective service. The 5G service categories (introduced in 1.1) mapped with the Wi-Fi 6 Enhanced thresholds for each category are shown in Figure 4.3.

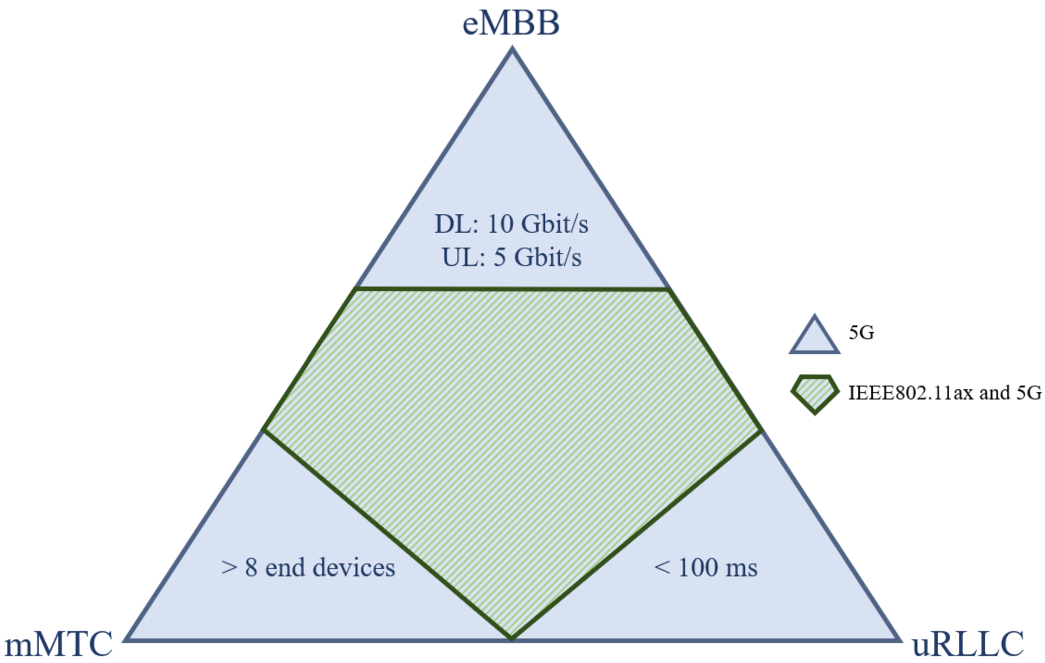


Figure 4.3: 5G service categories mapped with Wi-Fi 6 Enhanced thresholds

As shown in Figure 4.3, the green pentagon marks the performance range that both Wi-Fi 6 Enhanced and 5G can cover. However, when the data rate thresholds (eMBB) of 10 Gbit/s in download and 5 Gbit/s in upload, latencies below 100 ms (uRLLC) and more than eight end devices without performance loss are required (mMTC), only 5G can offer the performance. For this reason, the first part of the decision flowchart to determine the technical usefulness of 5G checks these values. The first part of the flowchart is shown in Figure 4.4.

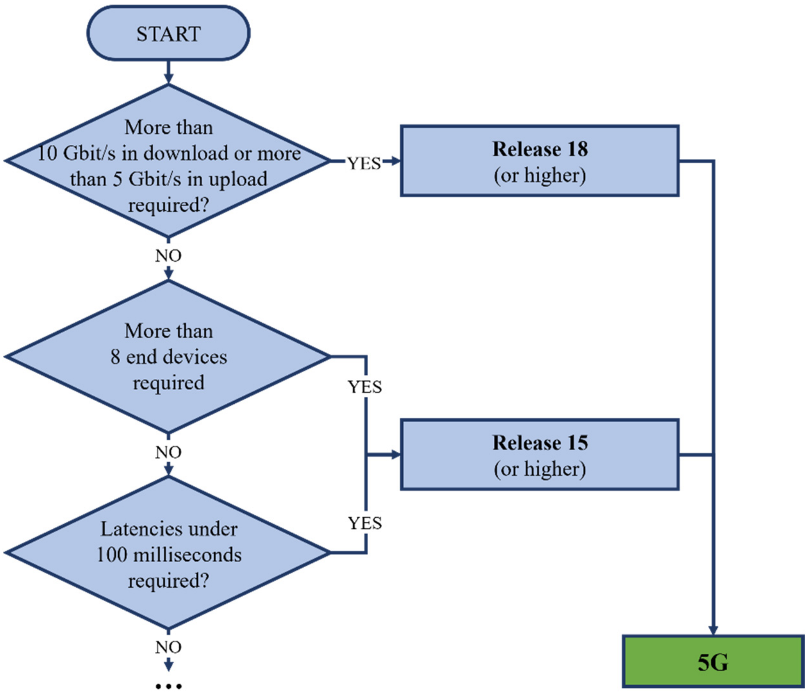


Figure 4.4: Part 1 of the flowchart to determine the usefulness of 5G

Furthermore, as shown in Table 4.4, three 5G services, namely the 5G positioning service, network slicing and V2X communication, are provided exclusively by 5G. Therefore, the second part of the flowchart aims to identify whether these services are required. The second part of the flowchart is shown in Figure 4.5.

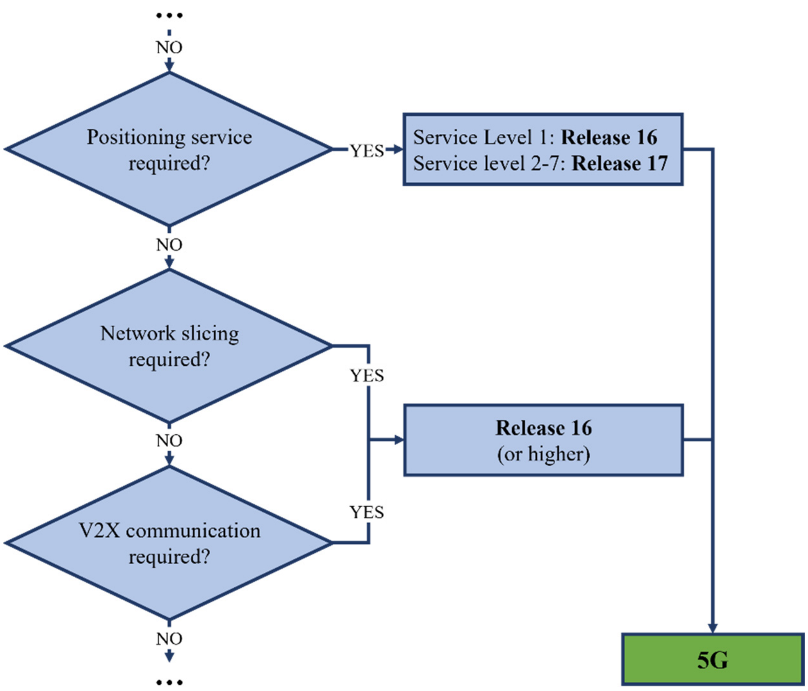


Figure 4.5: Part 2 of the flowchart to determine the usefulness of 5G

After the performance parameters in Part 1 of the flowchart and the required services in Part 2 of the flowchart are identified that cannot be provided by any other wireless technology, in particular Wi-Fi 6 Enhanced, the last step is to determine the applications' type of real-time. Here, 5G is the only wireless technology considered for real-time applications due to its ultra-reliable communication with latencies in the millisecond range and its high data security due to licensed frequencies. Against the background that 5G was not considered useful in Part 1 and Part 2 of the flowchart, the last step is to consider whether *hard* real-time is required based on the characteristics of the use case and its environment since 5G is the only wireless communication that can guarantee *hard* real-time. The findings from the literature review on real-time (provided in Section 2.4.3) serve as the foundation for developing Part 3 of the flowchart, aiming to classify the application as *hard* or *soft* real-time. Following Kopetz (2011), various characteristics can be used to classify *hard* and *soft* real-time. This framework proposes to use the *response time* of systems, defined by Kopetz (2011), since it can always be applied, independent of the application and without needing detailed knowledge about the system itself. Therefore, the response time is summarised below:

- **Response time.** The response time of an application in *hard* real-time systems is defined by the time limits in which data must be sent or processed to trigger reactions in critical situations and avoid catastrophes. Conversely, Kopetz (2011) classifies an application as *hard* real-time when exceeding the defined time limits can endanger people or cause environmental catastrophes. The user must define the catastrophe scenario. A catastrophe such as a production stop can be environmentally and economically harmful.

Using the *hard* real-time characteristics proposed by Kopetz (2011) leads to the third part of the flowchart. In this context, 5G is only considered a useful technology from the use cases' perspective when *hard* real-time is required since 5G represents the only wireless communication guaranteeing *hard* real-time using latencies in the millisecond range, the high reliability and quality of service. In the case of *soft* real-time, and when all previous decisions are answered with *NO*, alternative wireless technologies can be used to realise the use case.

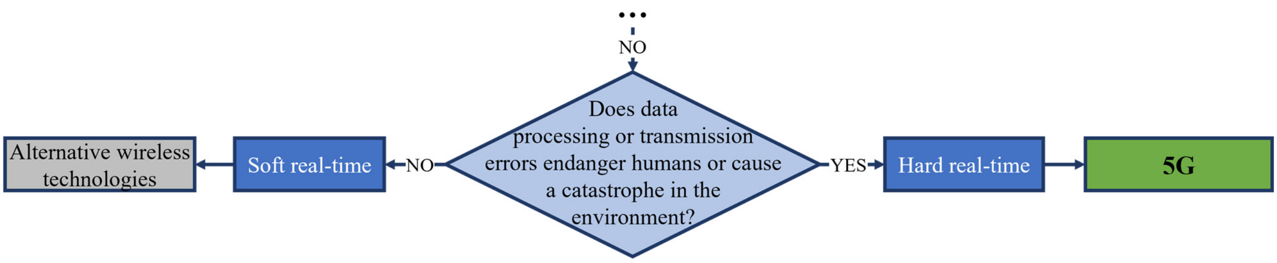


Figure 4.6: Part 3 of the flowchart to determine the usefulness of 5G

The proposed complete flowchart to determine the *practicality* of 5G from the use case perspective is represented by the amalgamation of all three parts of the decision flowchart (the complete flowchart is attached in Appendix A).

4.2 Environmental analysis stage

Stage two, the *environmental analysis stage* represents the environment in which the use case operates. The background literature review on factors influencing wireless communication led to the finding that certain environmental circumstances can influence the 5G communication and these need to be considered when evaluating the *practicality*. In contrast to the first stage, this stage is not quantifiable since environmental factors are always situation-specific. Thus, the user is advised of all steps to be considered that can impact 5G. However, the degree of impact cannot be explicitly quantified.

The *environmental stage* is divided into three sub-stages covering all parts of the environment of use cases, namely the intralogistics shop floor, the 5G network, and the 5G end device. In this context, the sub-stages are arranged logically, based on their impact on subsequent stages. For example, the intralogistics shop floor impacts the air interface of 5G and the design and settings of the 5G network and thus, must be analysed first. Figure 4.7 shows the *environmental analysis stage*.

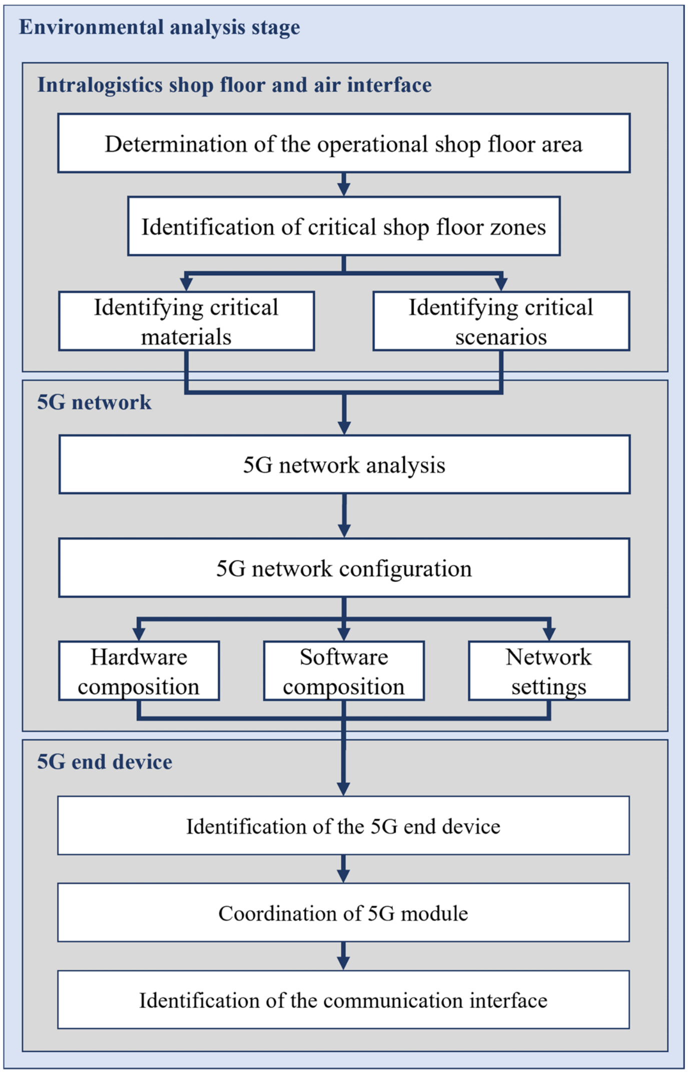


Figure 4.7: Environmental analysis stage

Figure 4.7 shows that the framework covers all parts of the use case environment, namely the intralogistics shop floor, the 5G network and the 5G end device. A further illustration from the 5G network perspective clarifies that all parts having an impact on the *practicality* of 5G for applications are covered by the framework. The intralogistics shop floor and its layout influences the air interface of 5G. Conversely, the 5G network and the 5G end device can directly influence the *practicality* of 5G for intralogistics applications. Therefore, the *environmental analysis stage* can also be transferred to the fundamental structure of 5G networks, consisting of a radio access network (RAN) and a core network (CN), shown in Figure 4.8. As illustrated in Figure 4.8, the following sub-stages investigate the influences of a complete 5G standalone non-public network from end-to-end (end device-to-core network) in three stages. This holistic investigation ensures that all parts of the 5G communication are covered by the *environmental analysis stage* that can impact the *practicality* of 5G.

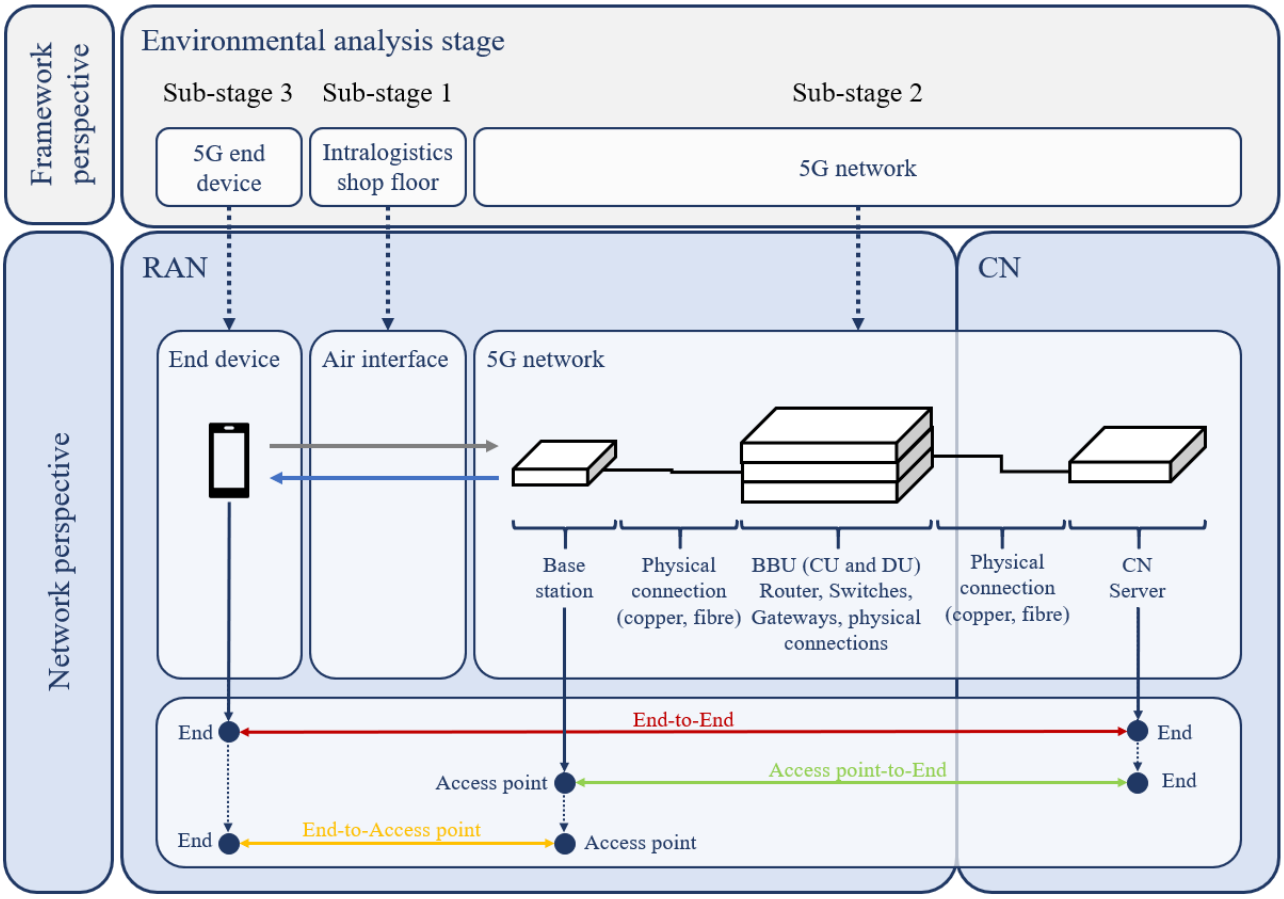


Figure 4.8: Fundamental structure of 5G networks from end-to-end

4.2.1 Intralogistics shop floor and air interface

The intralogistics shop floor represents the first part of the *environmental analysis stage* and aims to identify critical materials and scenarios within the use cases' defined operational area. From the literature review, it is evident that the design of the shop floor area in which the use case operates plays a decisive role in evaluating the *practicality* of 5G, since the design of the shop floor can impact the air interface and the design of the 5G network. Therefore, critical materials absorbing the electromagnetic waves in non-line-of-sight (NLOS), described in Sections 2.3.1 and 2.3.3, and critical scenarios such as cell changes of mobile applications, referred to as handover (described in Section 2.2.5.3), must be identified. Figure 4.9 shows the considered steps of the intralogistics shop floor.

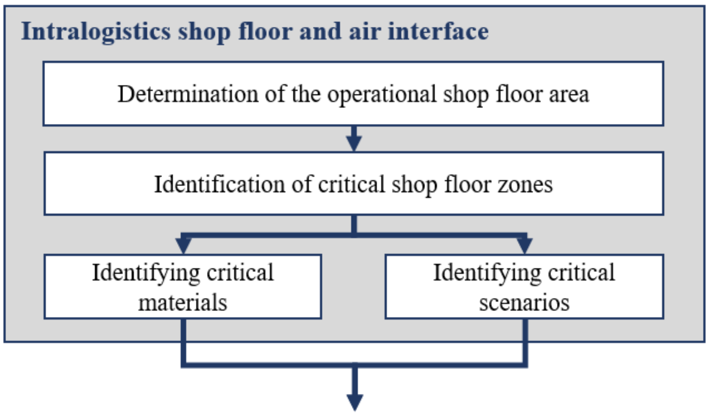


Figure 4.9: Sub-stage 1 – Intralogistics shop floor and air interface

4.2.1.1 Determination of the operational shop floor area

The determination of the operational shop floor forms the foundation to evaluate the *practicality* of 5G from an environmental perspective since all critical environmental scenarios in which the use case can be situated must be identified in this step. In addition, this phase also involves making strategic decisions that influence subsequent environmental stages, such as the design of the network.

First, it is necessary to determine the shop floor area on which the mobile application operates. This involves defining the area and identifying the number of square metres that must be covered by 5G. The appropriate number of indoor base stations can be determined based on the identified size and in coordination with the antennas' maximum transmission power. Importantly, defining the area represents merely an initial step. After defining the two-dimensional area, the three-dimensional room delimited by the area needs to be considered in all subsequent steps. As shown in Figure 4.9, after the operational shop floor is defined, this stage proposes to identify critical zones that include the identification of critical materials in NLOS connections and of critical scenarios.

4.2.1.2 Identification of critical shop floor zones

The second step addresses the identification of all critical shop floor zones within the defined operational area. The critical zones are comprised of two subsequent steps. First, all possible NLOS areas must be identified in which the line-of-sight (LOS) between transmitter and receiver is disrupted by surrounding materials (description on NLOS is provided in Section 2.3.1). The literature review on influencing factors of wireless communication leads to the finding that various physical effects occur that interfere with 5G in intralogistics environments. Transferring this finding to the 5G network perspective, the air interface of the 5G network in particular is affected by the intralogistics shop floor. To illustrate this, Figure 4.10 shows all parts of the 5G network and highlights the air interface (green) as the part affected by the intralogistics shop floor.

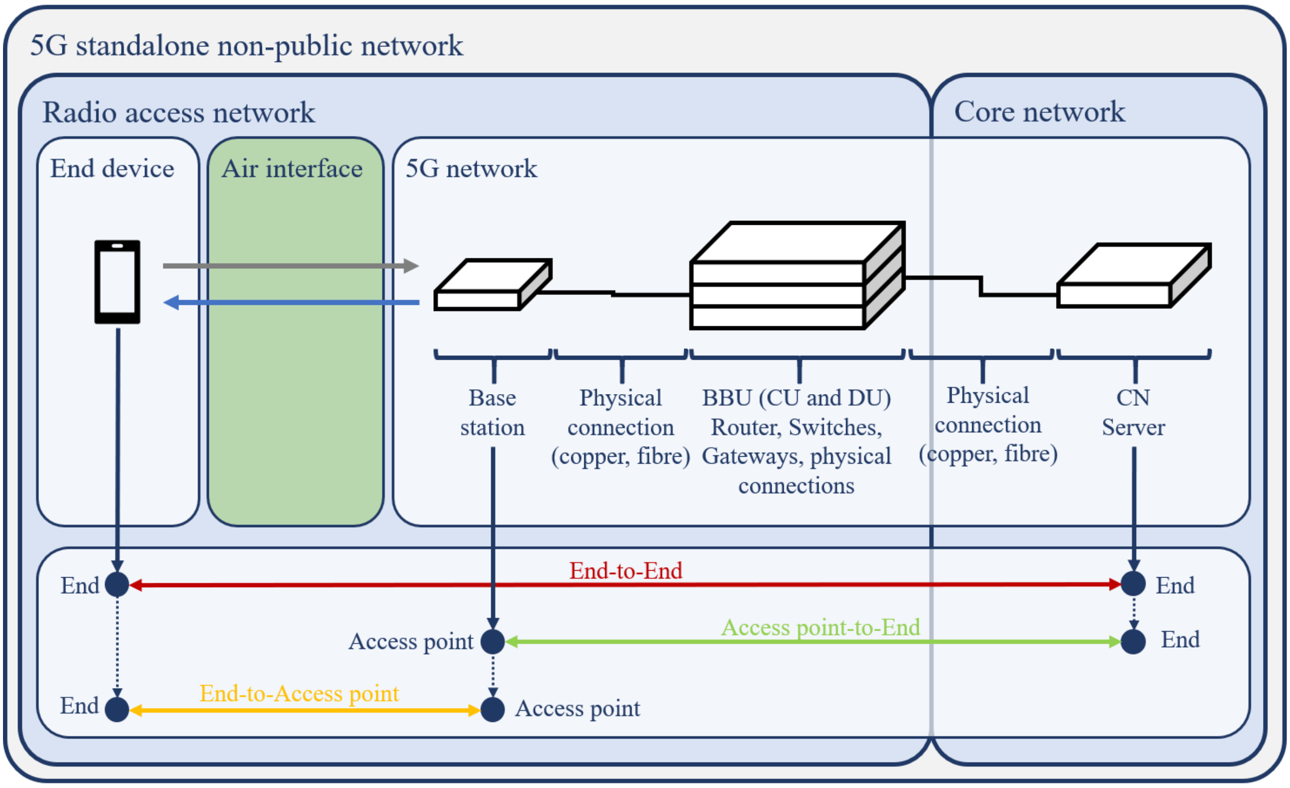


Figure 4.10: Air interface analysis between end (end device) and access point (5G network)

In particular, the absorption of materials in NLOS scenarios is found to be critical and can significantly impact the air interface. Foremost among these materials are reinforced concrete and metallic materials such as metal and aluminium, which can influence 5G by absorbing up to 90 percent of the signal (see Table 2.10). However, absorption is influenced by material properties. Furthermore, 5G offers two possible frequency ranges for 5G (see Section 2.2.5.6). Frequency range one transmits waves in the sub-6 GHz band, whereby the wavelengths are in the centimetre range. In contrast to this, frequency range two transmits waves in the millimetre range. Thus, the higher the frequency, the shorter the wavelength, resulting in poor materials penetration. Fundamentally, the following general rule can be derived:

The higher the frequency of 5G and the thicker and denser the material, the higher the absorption of the signal and the greater the impact on the practicality of 5G for intralogistics use cases.

When critical zones are identified in which materials such as autonomous mobile robots move between metallic high-bay warehouses or robots in metallic cells interfere with the transmission, preventive actions can be considered. For example, the systematic installation of additional base stations in detected locations can guarantee coverage with 5G signals in critical zones. In this case, NLOS connections are replaced by LOS connections. Otherwise, a redesign of the shop floor should be considered.

After identifying critical materials in NLOS, possible critical scenarios must be analysed. In this respect, critical scenarios are all situations in which 5G must ensure failure-free communications to avoid endangering the environment. For example, 5G enables a so-called soft (seamless) handover between mobile 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 beforehand and must be taken into account for the configuration of the 5G network and the shop floor design.

4.2.2 5G network

The 5G standalone non-public network represents the second stage of the *environmental analysis*. Since the framework aims to evaluate the *practicality* of 5G, the network must be analysed and configured to ensure the performance, services and resources required for the respective use case. The configuration of the network is influenced by the intralogistics shop floor, and by characteristics of the use case in terms of safety and stringent transmission times.

The 5G network stage is divided into the network analysis and the network configuration, consisting of the hardware and software composition and all required network settings. Figure 4.11 shows the 5G network stage as part of the *environmental analysis*.

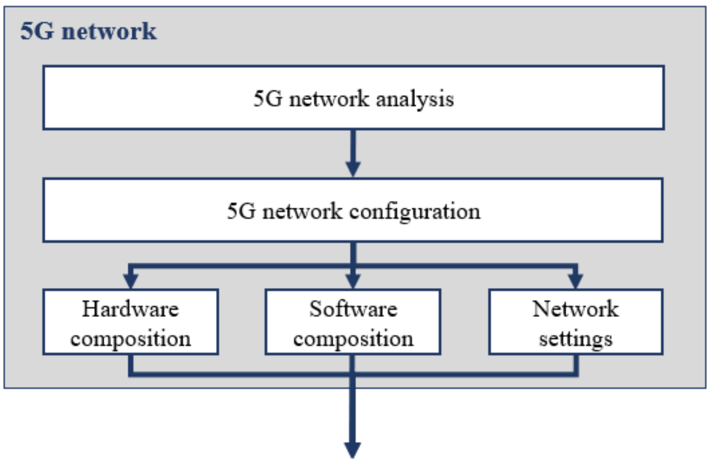


Figure 4.11: Sub-stage 2 – 5G network

4.2.2.1 5G network analysis

The network analysis must be carried out in this stage to identify possible 5G network-internal bottlenecks that can impact the *practicality*. Bottlenecks can be of a physical nature due to the hardware infrastructure and different cabling types employed, that limit the transmission throughput, but also of a virtual nature such as software bottlenecks. As described in the literature review (Section 2.2.5), the 5G network fundamentally consists of the radio access network and the core network. However, when adopting the architectural perspective of 5G networks, different components and network setups can be established depending on the specific deployment. In addition to mandatory components for 5G networks, such as the base station and the base band unit (BBU), the infrastructure can also be equipped with various routers, switches, gateways and edge-clouds resulting in a broad spectrum of deployment-specific 5G networks. Additionally, the 5G core network is designed as a service-based architecture (described in Section 2.2.5.2) allowing for the first time in mobile communication a customised multi-service infrastructure with virtualised networks and network functions. Therefore, bottlenecks can occur on the physical level including all components that limit the performance of 5G as well as on the virtual level regarding software and services. Therefore, analysis of the 5G network must be considered in terms of physical and virtual bottlenecks. As shown in Figure 4.12, this stage proposes to analyse the 5G network (green) from the access point (base station) to the network's end (core network).

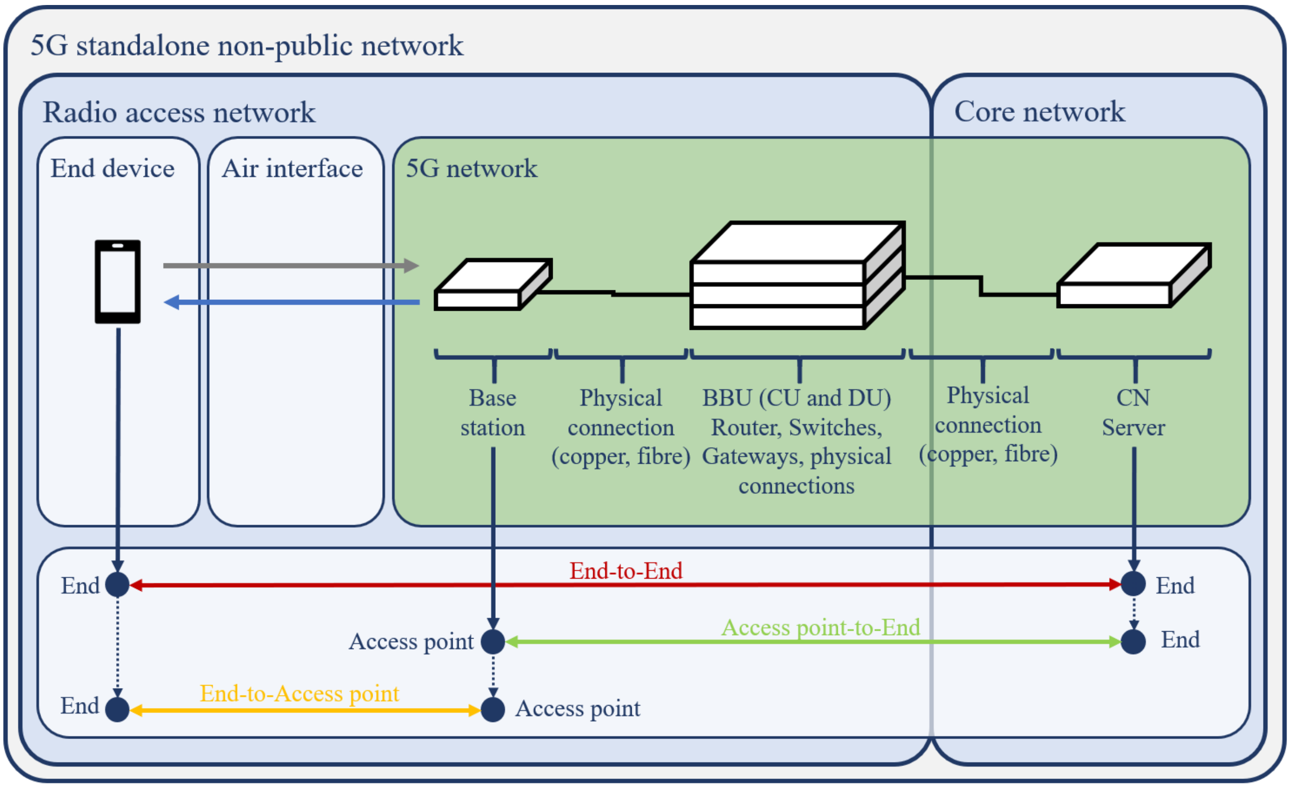


Figure 4.12: 5G network-internal analysis from access point-to-end

Analysing a network is a challenging task as bottlenecks can occur at different levels and may trigger further bottlenecks as they have mutual influences on each other (Patounas et al., 2020, p. 5). Therefore, this framework proposes a systematic network analysis in three steps.

The first step concerns the analysis at the infrastructure level and examines physical bottlenecks. The second step involves the analysis of virtual bottlenecks on the service layer. Finally, when physical and virtual bottlenecks are identified, the third step includes stress tests of the network in terms of measurements from end (end device) to end (core network). This order is chosen since virtual bottlenecks can be considered infrastructure-independent. However, a network without virtual bottlenecks that lack physical infrastructure limits the entire 5G communication.

Based on Patounas et al. (2020, p. 4), mobile network bottlenecks can be divided into five categories:

1) Interference
2) Packet loss
3) Congestion
4) Computational resources
5) Delay

While interferences in the air interface are already considered within the intralogistics shop floor stage, the 5G network analysis must examine bottlenecks 2) to 4) more closely. Packet loss, congestion, computational resources and delay can be further subdivided into *causes* and *effects*. In this context, data congestion and computational resources represent *causes*, triggering packet losses and time delays in network-internal data processing as resulting *effects*. For this reason, considering the data congestion and computational resources is sufficient when investigating physical bottlenecks.

Data congestion is caused by traffic overloads (Pham and Betts, 1994, p. 513). A traffic overload occurs when the throughput capacity of the traffic supply by the infrastructure is lower than the current traffic throughput demand. This results in so-called congestion queues, in which data packets are processed sequentially (Pham and Betts, 1994, pp. 512–513). As a result, time delays and packet losses occur, leading to an impairment of the current time-critical task of the use case. Data congestion bottlenecks can be traced back to two main causes on the physical infrastructure layer.

First, the network components are limited by their internal hardware architecture to a certain performance of data throughput and computational resources, and second, the physical connections between individual network components are limited to a certain throughput. With regard to the physical connections, several variables must be considered that impact the data throughput capacity such as the material, cable diameter and length, wavelength, network type, and cable type. Typically, copper and fibreglass cables are used for the physical connection of networks. Therefore, it is essential to investigate components' performance in terms of computational resources and throughput capacity but also to consider the physical connections between components. This is to ensure that the infrastructure is aligned with the need of the use case on the infrastructure layer when evaluating the *practicality*.

When physical bottlenecks are identified, virtual bottlenecks must be analysed. The virtual bottlenecks are located on the network function and service layer of the network. One finding from the background literature review regarding network functions on the 5G core network is that the availability of the network functions is linked to the 5G releases. Furthermore, a specific composition of various network function instances in the 5G core network enables 5G services. Thus, the 5G core network that provides the network functions needs to be aligned with the required 5G release identified within the *use case specification stage* to ensure that the network can provide the required network function stacks.

After checking for physical and virtual bottlenecks, the final step consists of network measurements to ensure performance under critical conditions in the intralogistics environment. However, the measurements should only be carried out when the network can provide the required performance capacity with all identified bottlenecks. If limiting bottlenecks are identified, making implementing the use case impractical, the next proposed step of the 5G network stage, called 5G network configuration, must be performed first.

Regarding stress tests, various tools exist to emulate defined worst case scenarios for the respective use case. In this regard, the worst case scenarios are given by the thresholds defined in the *use case specification stage.* Simulated data packets are sent over the 5G network to subject the network to the stress test. Example tools that can be used for 5G network simulations are *iPerf3* (iPerf3) and the Linux-based *netem* (wiki.linuxfoundation.org/netem). Different KPIs are proposed in the literature to ensure the performance. However, a robust measurement that might indicate any bottleneck include the round-trip time (RTT), throughput and packet loss (Patounas et al., 2020, p. 7). The RTT is the time a data packet takes to travel from one end-point (end device) of the network to the other end-point (core network) and back to the end-point (end device). Therefore, the RTT is also referred to as end-to-end-to-end latency. In this context, the required maximum RTT of a use case is the doubled end-to-end latency. Packet loss is measured by a defined number of packets, which are counted as arrived packets at the second measuring point. Throughput, in contrast, can be measured with individual packages by changing the packet size.

4.2.2.2 5G network configuration

After network bottlenecks are identified, this sub-step aligns and configures the network in accordance with the use case requirements. This stage is composed of three main parts, namely, the hardware composition, software composition, and network settings.

The investigation of the intralogistics shop floor identified critical NLOS scenarios that apply in this sub-stage when additional base stations are required at the hardware level to turn NLOS into LOS scenarios. Furthermore, the 5G network analysis influences the network configuration in terms of its hardware. All identified hardware bottlenecks must be eliminated in this step by the composition and adaption of suitable components to ensure that the network can provide the required performance. When hardware bottlenecks are eliminated, the network components must be flashed with the required software and 5G Release.

Regarding network settings, the technical parameters of the radio access network must be configured. For example, the transmission power of the base stations must be aligned and set up to cover the entire operational shop floor. In particular, handover scenarios between several base stations must be considered when setting up the transmission power of the base stations. Furthermore, in the case of critical applications, required computational resources can be reserved as 'slices' exclusively for their application on each component of the radio access network and core network to guarantee their availability.

4.2.3 5G end device

The 5G end device is part of the 5G radio access network and represents the interface between the 5G standalone non-public network and the application. The end device must meet the requirements of both the use case and the 5G network to ensure compatibility. In the context of the network analysis in the previous sub-stage in Section 4.2.2.1, the end device is currently reported as the most significant bottleneck having a decisive influence on performance in terms of 5G standalone non-public networks (Marek, 2022). Therefore, this stage is not part of the 5G network stage but is considered the final critical stage regarding the *practicality* evaluation. As shown in Figure 4.13, the proposed first step is the identification of the end device type. After determining the required type, the end device must be coordinated with the network in terms of its compatibility and performance. Finally, the integration of the end device on the application's site needs to be investigated. For this purpose, the communication interface between the end device and the application needs to be identified.

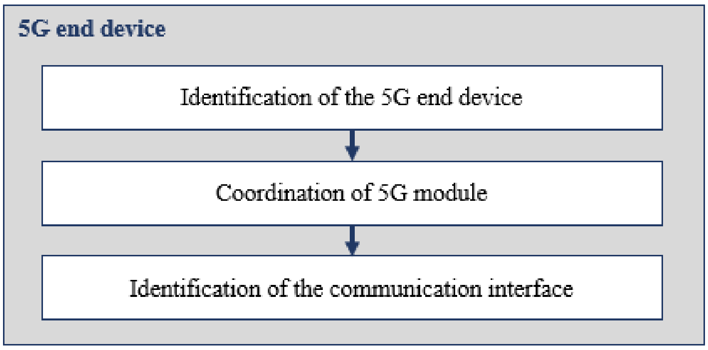


Figure 4.13: Sub-stage 3 – 5G end device

4.2.3.1 Identification of the 5G end device type

First, the type of 5G end device must be identified. As described in the background literature review, various types of 5G end devices exist. The selection of a suitable end device depends on the application and the tasks that the 5G module undertakes. Furthermore, with different protocols existing between the 5G network and the 5G module, the end device must be expanded with a compatible interface, such as a 5G gateway. To select a suitable end device, it has to be clarified whether the end device handles only the 5G communication tasks or whether it takes over control of tasks directly involving actuators or sensors. In the case of pure positioning tasks, mobile 5G trackers can be considered sufficient. An overview of different types of terminals is provided in Section 2.2.5.3, that can serve as a first reference guide.

4.2.3.2 Coordination of 5G modules

The different types of industrial end devices and their composition of hardware and software components can influence the *practicality* of the end device acting as the interface between the application and the 5G network, as shown in Figure 4.14.

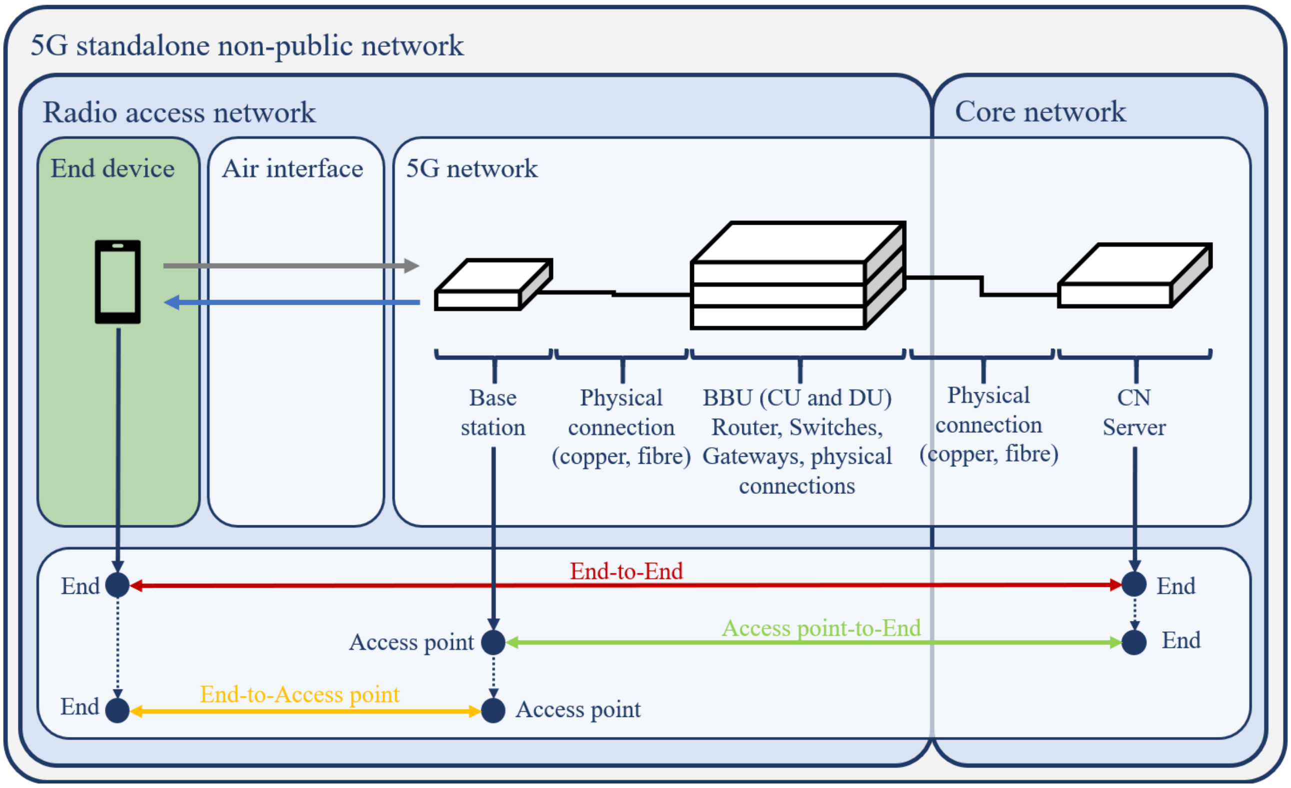


Figure 4.14: End device coordination with the 5G network from end-to-access point

Each end device contains a 5G module (the logical architecture of a 5G terminal is provided in Section 2.2.5.3) that must be checked in terms of hardware and software to meet the use case requirements and ensure compatibility with the network. The first step is to ensure compatibility with the network regarding the hardware. As shown in the background literature review, two types of 5G networks exist; non-standalone (NSA), and standalone (SA). The SA architecture uses its own 5G core network, protocols and own frequencies when establishing the SA architecture as a NPN. As a result, backwards compatibility with previous generations of mobile networks cannot be established. Consequently, the 5G module must support the SA architecture which is important to consider when selecting a 5G module. Another aspect influencing the hardware and software aspects of the 5G module are the country-specific regulations for frequency distribution (described in Section 2.2.5.6). The different, country-specific frequency bands for 5G result in the 5G module having to be checked regarding the support of the individual frequency band. The specific business model of the network in terms of using licensed or sub-leased frequencies does not influence this respect. Finally, a review on the software side should be carried out regarding the 5G release. 3GPP provides specifications purely for 5G end devices. Based on the required 5G release identified within the *use case specification stage*, the end device must be equipped with the required release in terms of software. Concerning the performance, the measurement study of end devices from Lackner et al. (2022) shows that 5G modules with identical 5G chipsets achieve different performances. This demonstrates that software represents a significant bottleneck in 5G communication between the module and the network and can also impact the *practicality*. For this reason, the 5G module must be coordinated with the use case's requirements and the 5G network in terms of software and hardware and, thus, represents the last stage of the *environmental analysis*.

4.2.3.3 Identification of the communication interface

Finally, the communication interface (protocol) of the end device has to be identified. Importantly, the 5G end device and the application must provide and support the interface. External interfaces are provided by both the use case ('use case' is understood to mean the machine/ application or asset to be equipped with the 5G module) and the 5G device manufacturer. Therefore, the external interfaces provided by the use case have to be interoperable with the interfaces of the 5G module. Typically, USB and Ethernet interfaces are supported by industrial 5G devices. However, when selecting a compatible 5G module, it also must be ensured that the interfaces themselves are able to physically deliver the required data throughput. For example, Ethernet (Cat6) can provide data rates of up to 10 Gbit/s (Soorty et al., 2010, p. 1525) and USB3.0 up to 5 Gbit/s (Ingle and Dharkar, 2013, p. 13). For this reason, identifying the appropriate interface between the 5G module and the application is essential to guarantee the required performances. After identifying the appropriate interface, the functionality of the communication with the application must also be ensured. The application-internal server requires the driver software for the 5G module. To allow communication between the driver software on the applications server and the 5G module, the firewall of the application-internal server needs to be reconfigured with regard to the assigned LAN ports and IP addresses.

4.3 Proposed framework

The developed vertical process flow consists of logically connected steps linking the use case specification in Stage one with its environment in Stage two to enable a holistic evaluation of the *practicality* of 5G as communication. However, individual elements of both stages can impact subsequent steps. These interrelationships can also impact the *practicality* evaluation, and thus, the proposed conceptual framework links the vertical process flow with the interrelationships of individual elements.

During the *use case specification stage*, the framework proposes to define the use case and evaluate the feasibility of 5G before identifying 5G as technically practical. In the proposed vertical process, the use case is first defined by the framework user and subsequently evaluated. As shown in Figure 4.15, during the determination of the technical feasibility, the required 5G release is identified as output. Additionally, within the determination of 5G's usefulness for the respective use case, all required 5G services are identified.

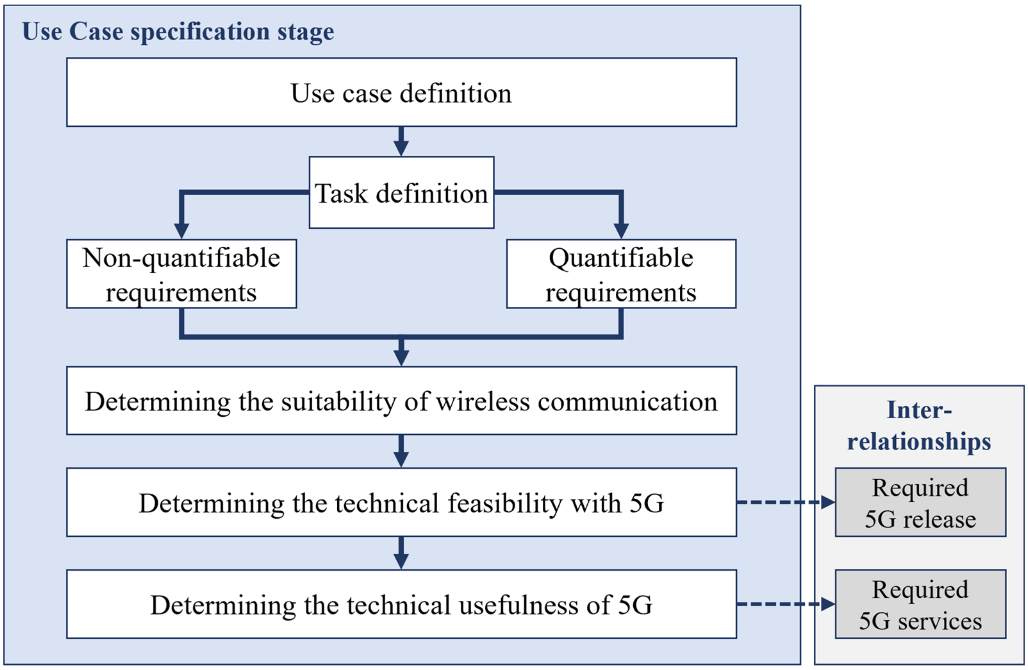


Figure 4.15: Interrelationships resulting from the use case specification stage

Both the required 5G release and the 5G services are outputs of the *use case specification stage* and influence the following evaluation steps in the vertical process flow. In this context, the 5G release and the 5G services influence the core network configuration, the radio access network, and the type of end device. Therefore, all components must support the release using software and must be compatible. Moreover, the required release also influences the hardware. For example, all components may support Release 16 and thus provide services such as network slicing on the software side. However, parts of the radio access network, such as the base band unit or the base stations, cannot provide the network slicing from the hardware side. This demonstrates the importance of coordinating all components in terms of software and hardware.

In the *environmental analysis stage*, the intralogistics shop floor is a critical influencing element for subsequent steps in the proposed framework in terms of interrelationships (see Figure 4.16). The number of identified critical zones, materials and scenarios influence the required number of base stations and their location and must be derived for each shop floor. In addition, the intralogistics shop floor influences network settings, especially in the radio access network, such as the transmission power of base stations. Furthermore, in highly critical cases, the intralogistics shop floor may negatively influence 5G to the extent that 5G is not practical for the application.

The network analysis aims to identify bottlenecks within the network that can affect the *practicality* (described in Section 4.2.2). Bottlenecks, such as low-performance switches or limited data throughput or limited transmission times due to the cabling, can significantly impact *practicality*. Therefore, the identified bottlenecks result in a specific network design after the network is laid out in the network configuration step.

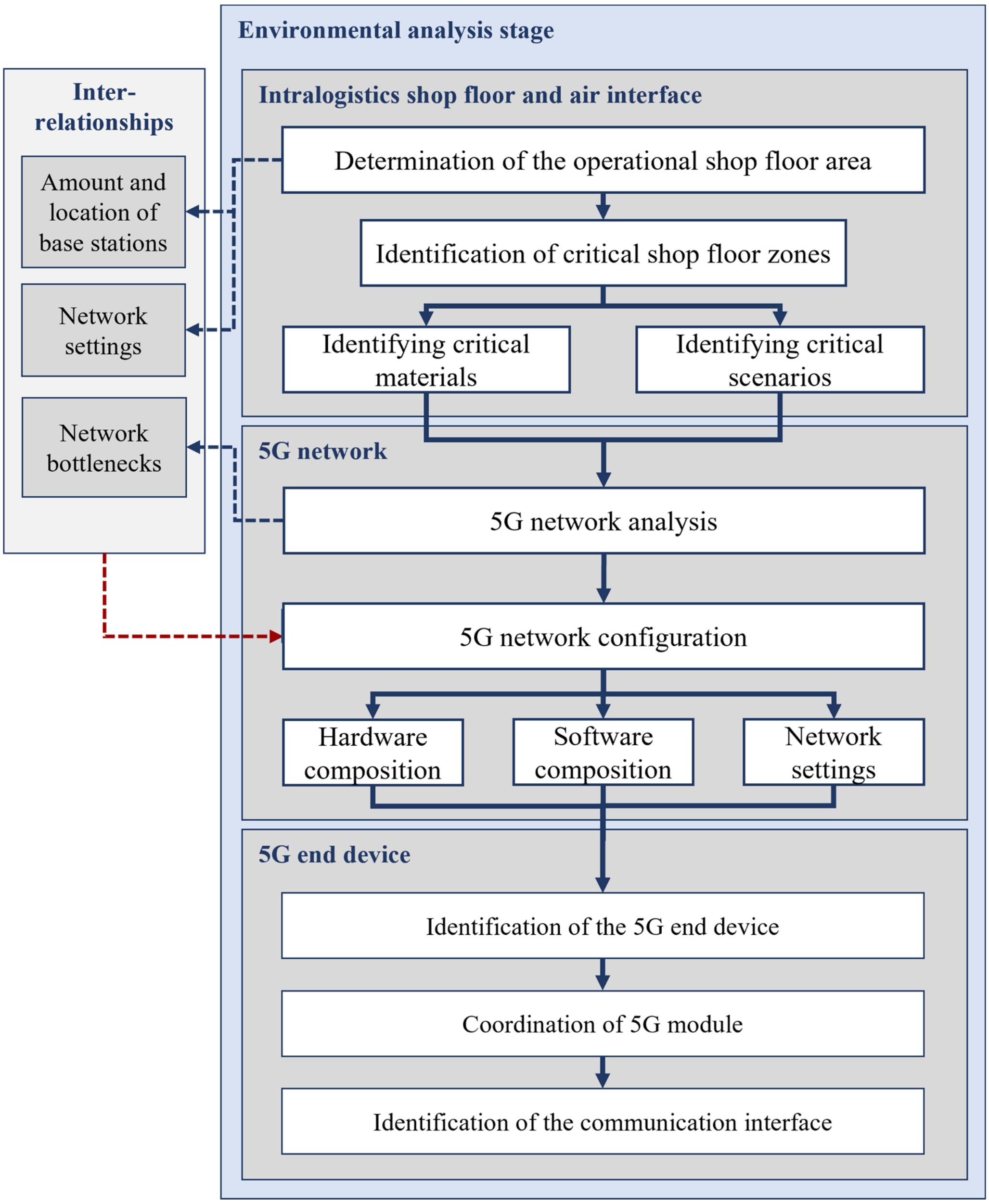


Figure 4.16: Interrelationships resulting from the environmental analysis stage

Figure 4.17 shows the complete conceptual framework to evaluate the *practicality* of 5G for intralogistics use cases in standalone non-public networks. The proposed framework links the vertical process flow of the *use case specification stage* and the *environmental analysis stage* with the interrelationships of individual framework elements.

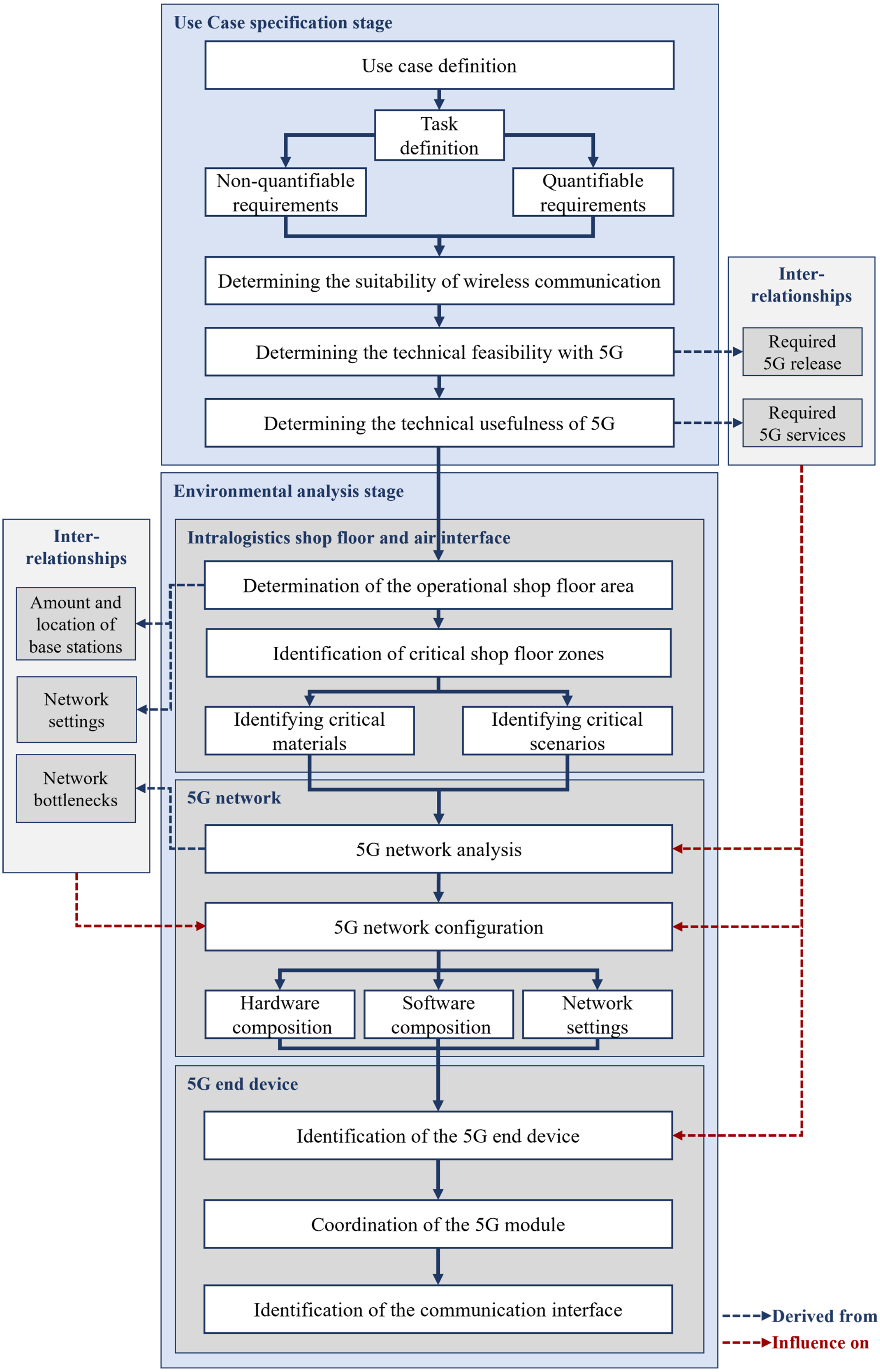


Figure 4.17: Framework to evaluate the practicality of 5G for intralogistics use cases in standalone non-public networks

4.4 Concluding summary

In this chapter, the framework to evaluate the *practicality* of 5G for intralogistics use cases is developed. The framework is an industry-independent and generic framework for indoor intralogistics use cases. The *practicality* evaluation of 5G comprises two different perspectives, which are reflected as stages in the framework. The first stage evaluates the *practicality* of 5G from the use case perspective and is therefore called the *use case specification stage*. Here, characteristics and performance parameters are identified, leading to whether 5G is considered technically practical from a use case perspective.

The second stage adapts the perspective of the environment of the use case. The *environmental analysis stage* investigates the environment in which the use case is to be integrated. For this purpose, all environment parts are considered, namely the intralogistics shop floor, the 5G network and finally, the 5G end device, acting as the interface between the network and the use case. The resulting proposed conceptual framework combines the two perspectives in terms of the developed vertical process flow. Additionally, the proposed framework links the vertical process flow with the inter-relationships between individual framework elements that need to be considered when evaluating the *practicality* of 5G as a communication technology for intralogistics use cases.

5 Validation of the framework

This chapter covers the validation and verification of the developed framework. First, the validation strategy, underlying conditions and the validation environment are outlined. Second, the framework's validation is carried out through an autonomous mobile robot case study in the learning factory *Werk150* at Reutlingen University.

5.1 Validation strategy, conditions and environment

According to Ryan and Wheatcraft (2017), validation is defined as a "set of activities ensuring and gaining confidence that a system can accomplish its intended use, goals, and objectives in the intended operational environment" (Ryan and Wheatcraft, 2017, p. 1280). Following Jabareen's (2009, p. 54) methodology for validating a conceptual framework to ensure that it "makes sense" to outsiders and its usability, the framework is validated using a case study.

This case study is conducted in the learning factory *Werk150* at Reutlingen University. *Werk150* provides a realistic production and intralogistics environment with an area of 800 square metres (m^2) for research and development activities and project collaborations with small and medium-sized enterprises. For this reason, *Werk150* is equipped with state-of-the-art technology such as flexible assembly lines, storage and warehouse systems, collaborative robots and machines, automated guided vehicles and an autonomous mobile robot (AMR). In addition, *Werk150* is equipped with various wireless communication systems such as Wi-Fi, Bluetooth, localisation technologies and a dedicated 5G standalone non-public network.

The 5G standalone non-public network operates on licensed frequencies between 3.7-3.8 GHz and is based on the indoor AirScale system from Nokia. The radio access network has two pico radio heads (base stations) with 4x4 MIMO, maximum transmission power of 250 mW and a base band unit. The 5G core network runs on a local edge cloud (NDAC Edge HP EL1000) in the learning factory *Werk150.* The base band unit is connected to a GPS antenna installed outside the *Werk150* building to synchronise the time on all network components. The 5G standalone non-public network coverage is limited to the indoor shop floor area of the *Werk150* building and provides access only to authorised subscribers. Therefore, the 5G network in *Werk150* provides a realistic environment as it would occur in industry to conduct the case study.

The case study is carried out using an AMR use case (see Figure 5.1) in collaboration with the AMR's manufacturer. The AMR has an integrated roller conveyor and can transport payloads of up to 100 kilograms. In addition, the AGV is equipped with front and side laser scanners for obstacle detection guaranteeing unrestricted mobility of the AMR in *Werk150*.

The main tasks of the AMR are the transport of small load carriers, the automatic loading of shelves and conveyor belts and the transportation of smaller assembly groups.

Figure 5.1: Autonomous mobile robot at the learning factory *Werk150*

5.2 Case study on evaluating 5G for autonomous mobile robots

The AMR use case is specified in cooperation with the AMR manufacturer and serves as input for the framework. Subsequently, this input is used, and all individual steps of the framework are carried out to validate the framework. Both stages and all considered sub-steps of the proposed framework are carried out in the following sections for the AMR use case.

5.2.1 Use case specification stage for the AMR

The first stage of the proposed framework aims to identify if 5G can be considered technically feasible for the AMR. To this end, the proposed steps of the use case specification stage are carried out and described in the following sections.

Use case definition

The AMR use case is defined in cooperation with the manufacturer. The case study primarily aims to integrate the AMR into the 5G standalone non-public network and explore whether 5G is a practical communication platform for AMRs. Therefore, the following tasks for the AMR prototype to be performed by 5G are defined within the scope of the case study:

- Communication between AMR and central fleet management server (FMS) for the following:
  - Sending laser scanner data from the AMR to the FMS
  - Sending AMR’s position from the AMR to the FMS
  - Receiving start/ stop signals from the FMS
  - Receiving waypoints from the FMS

Based on these tasks, a requirement profile for the AMR is established. The KPIs proposed in the framework are used and defined with measurable threshold values. Regarding the data rate for download and upload, the upper thresholds are defined as 1 Gbit/s since the data packets of the scanner are small in the range of kbit/s and require considerably less than 1 Gbit/s. The lower threshold of 10 ms defines the latency between the AMR and FMS for sending and receiving data packets. In this case study, the tasks to be performed by 5G are not time-critical since the AMR is equipped with on-board laser scanners and can recognise obstacles without the need for 5G. Concerning the end device density, the value of 0.00125 devices per square metre is calculated using the equation *(1)*. The *Werk150* area is 800 m² in size.

$$End\ device\ density = \frac{End\ devices}{Werk150} = \frac{1\ AMR}{800\ m^2} = 0.00125 \qquad (1)$$

Table 5.1 shows the specified AMR requirement profile underlying this case study.

Table 5.1: AMR requirement profile for KPIs

KPIs	Required threshold value
Data rate download [Gbit/s]	> 0.1 Gbit/s (~ kbit/s)
Data rate upload [Gbit/s]	> 0.1 Gbit/s (~ kbit/s)
End-to-end latency [ms]	< 100
End device speed [m/s]	≤ 5
Communication service availability [%]	> 99.99
Communication service reliability [%]	> 99.9
End device density [devices/m²]	0.00125
5G positioning service level	not required

Additionally, the framework proposes a requirement profile for 5G services and non-quantifiable requirements to define the use case. The requirements profile applied to the AMR use case shows that a 5G-specific service is not required to perform the specified tasks.

In addition, the AMR is a mobile use case powered by battery. Table 5.2 summarises the defined non-quantifiable requirements of the AMR for this case study.

Table 5.2: Requirement profile for 5G services and non-quantifiable requirements for the AMR

5G services	5G positioning	Yes	
		No	×
	Network slicing	Yes	
		No	×
	V2X communication	Yes	
		No	×
Applications' nature	Mobility class	Mobile	×
		Stationary	
	Power supply	Battery	×
		Wired	

Determining the suitability of wireless communication

After the definition of the AMR use case, the suitability of wireless communication is identified for the AMR as proposed in the framework. In this case, both mobility and the battery-powered operation are given as shown in Table 5.2. Therefore, wireless communication is required as a technology for the AMR.

Determining the technical feasibility with 5G

In this step, the given requirement profile of the AMR for KPIs (see Table 5.1) is used and translated into the proposed spider chart to identify the technical feasibility of 5G. In this context, all given performance requirements must be met by 5G. Additionally, the spider chart identifies the release needed to implement the use case. As can be seen from the spider chart in Figure 5.2, the AMR requirement profile (red) can be covered by the 5G release 15 (purple). Since the 5G network at the learning factory *Werk150* has only release 15 implemented so far, a higher release, for example, release 16, would have resulted in the termination of the case study at this point. Figure 5.2 illustrates the spider chart applied to the AMR requirement profile. For simplicity, all releases that are not required have been greyed out.

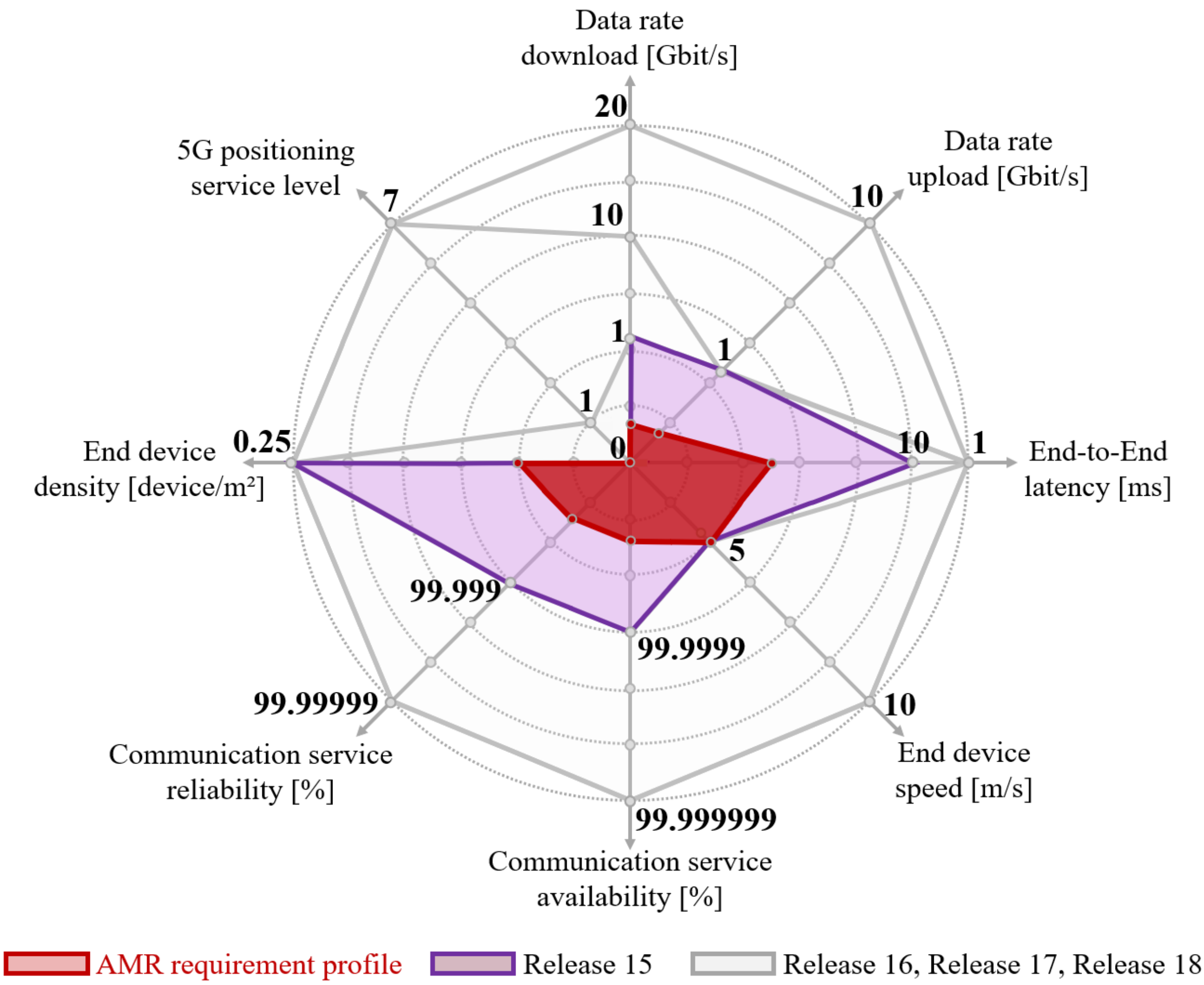


Figure 5.2: Identifying the technical feasibility of the AMR use case with 5G Release 15

Determining the technical usefulness of 5G

During the previous step, all tasks of the AMR were identified as being technically feasible based on the specified KPIs using the 5G Release 15. This step requires evaluating Wi-Fi's capacity to cover the performance and whether non-quantifiable characteristics of the AMR support the adoption of 5G. For this purpose, the proposed decision flowchart from the framework is used. Figure 5.3 presents the decisions considered for the AMR. In addition, the decision path is highlighted in red. The decision flowchart reveals that 5G is feasible since only 5G can guarantee the required latency of under 100 ms. As a result of the decision path, the 5G Release 15 is again identified as the minimum required 5G release for this AMR case study based in the defined tasks.

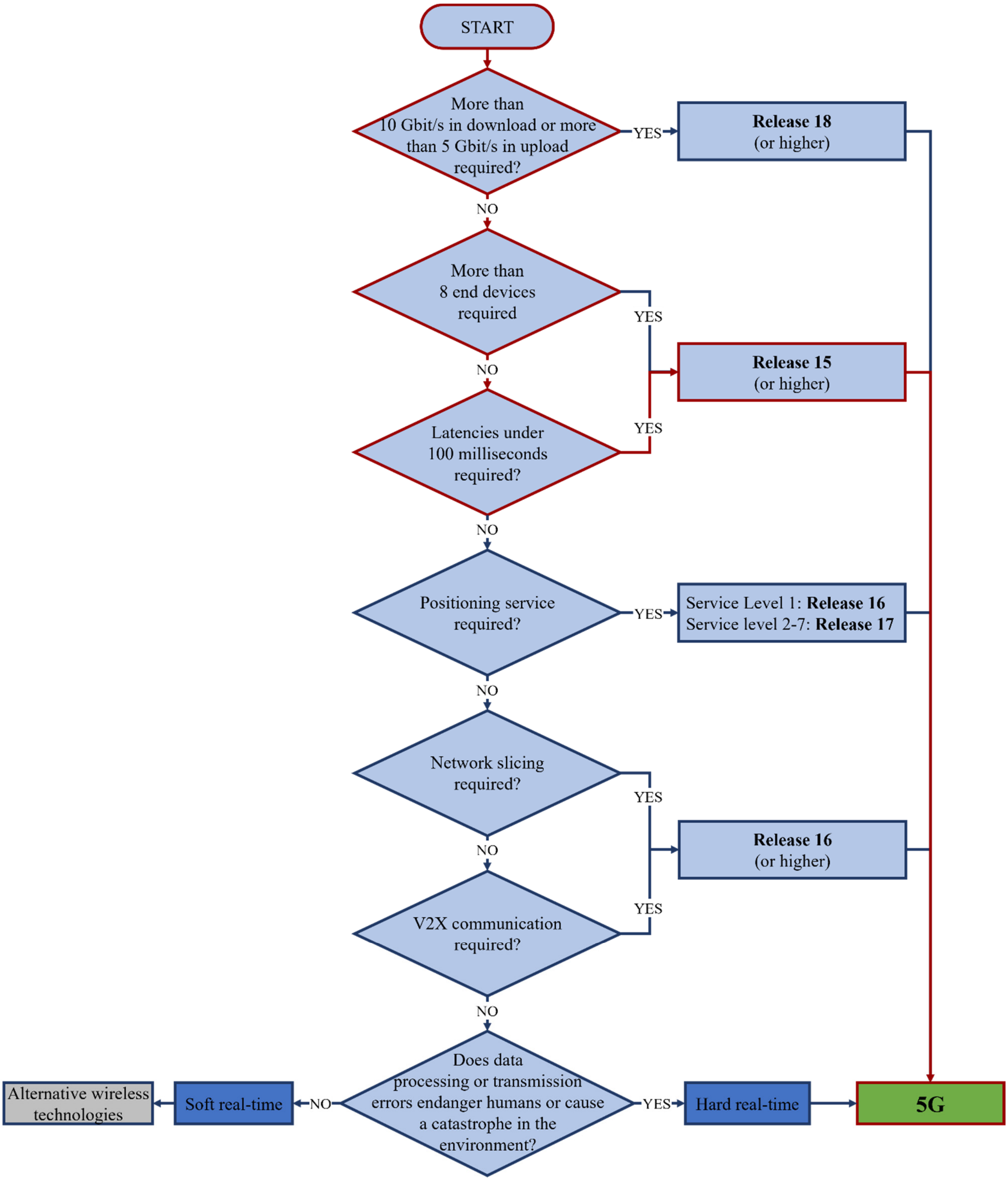


Figure 5.3: Considered decisions to determine the technical usefulness of 5G for the AMR

5.2.2 Environmental analysis stage for the AMR

The learning factory *Werk150* represents the environment of the AMR and is, therefore, examined in detail to identify influencing factors that can interfere with 5G between the network and the AMR. In the following section, all proposed environmental sub-stages are carried out.

Intralogistics shop floor and air interface

The intralogistics shop floor and potential influencing factors on the air interface between the end device and base station need to be identified in this phase for the AMR use case in *Werk150*. In the first step, an area of 340 m² is defined as AMR's operational shop floor. Figure 5.4 marks this area at the learning factory *Werk150* in green.

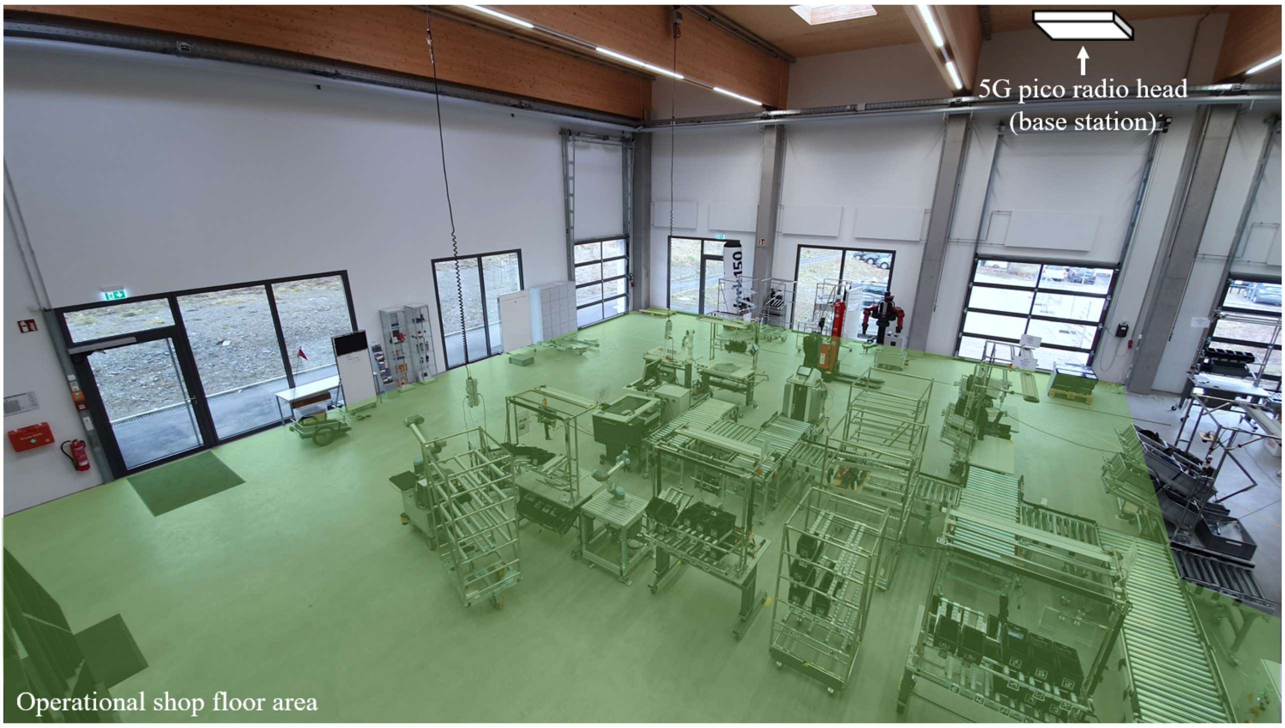


Figure 5.4: Operational shop floor area of the AMR at the learning factory *Werk150*

As shown in Figure 5.4, the operational shop floor includes metallic assembly stations, Kanban systems, and robots. Therefore, metallic materials and concrete walls and floors encircle the AMR and can thus absorb 5G signals and cause interferences. However, Figure 5.4 also shows that the LOS connection between the pico radio head (base station) and the end device exists in all cases in the marked green area.

One influencing factor that needs to be analysed within the *5G network* sub-stage is the influence of other wireless technologies, specifically Wi-Fi, Bluetooth and various localisation technologies, which also transmit in *Werk150* and, therefore, use the air interface to some extent in similar frequency ranges to 5G. The frequencies of 5G are between 3.7–3.8 GHz and are therefore in the sub-6 GHz band, similar to Wi-Fi (2.4 GHz and 5 GHz).

5G network

The 5G standalone non-public network at Reutlingen University exclusively covers the indoor area of *Werk150*. The framework proposes the analysis of the 5G network regarding possible network-internal bottlenecks in a three-step process. The first step aims to investigate physical bottlenecks while the second step analyses virtual bottlenecks. The aforementioned steps are not required for this case study, as the 5G network is sufficiently designed by experts for a data throughput capacity of 10 Gbit/s at the infrastructure level. Therefore, data congestions for AMR are theoretically not expected. With regard to the time delay (latency), the measurements performed during stress tests can reveal bottlenecks. Virtual bottlenecks are not expected, as the AMR does not require specific 5G services in the core network, such as the 5G positioning or V2X communication.

The final step of the network analysis is carried out through empirical measurements for the AMR case study as proposed by the framework. The measurements are conducted using the proposed KPIs from the framework, namely round-trip time (RTT), download throughput, upload throughput, and packet loss. Figure 5.5 shows the KPIs used for the 5G network analysis measurements.

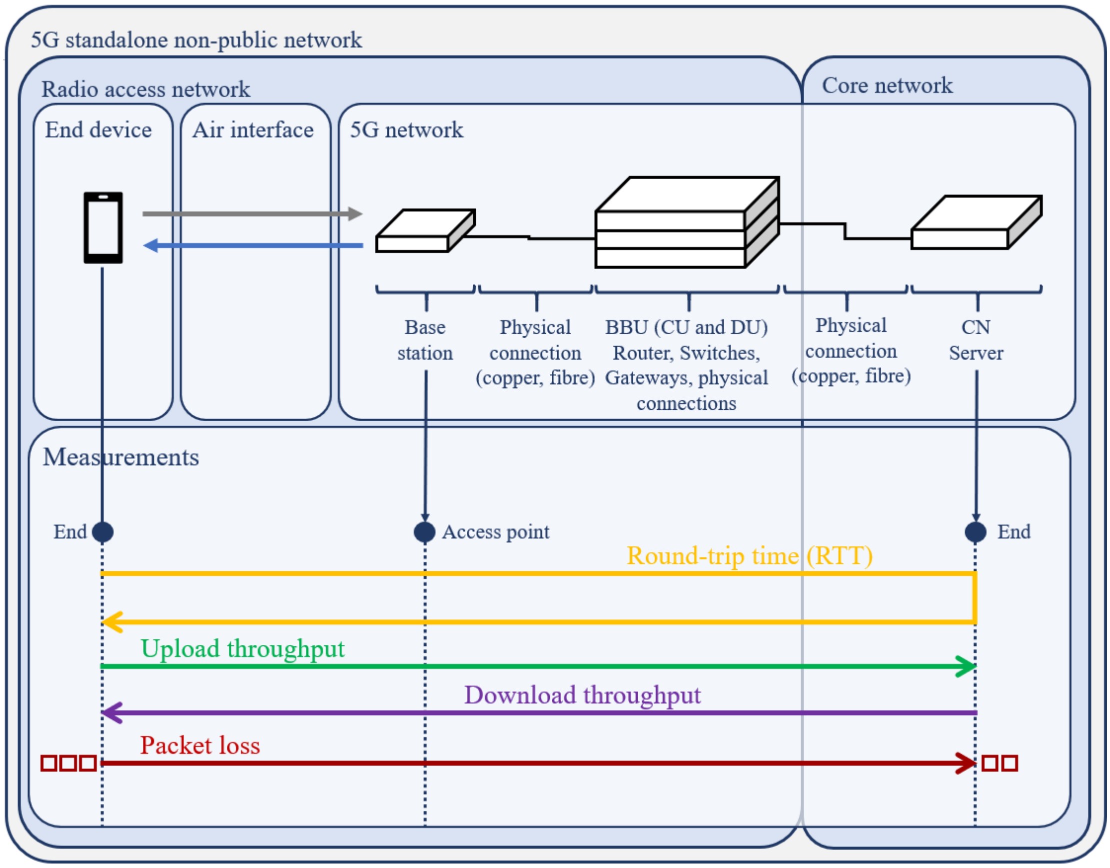
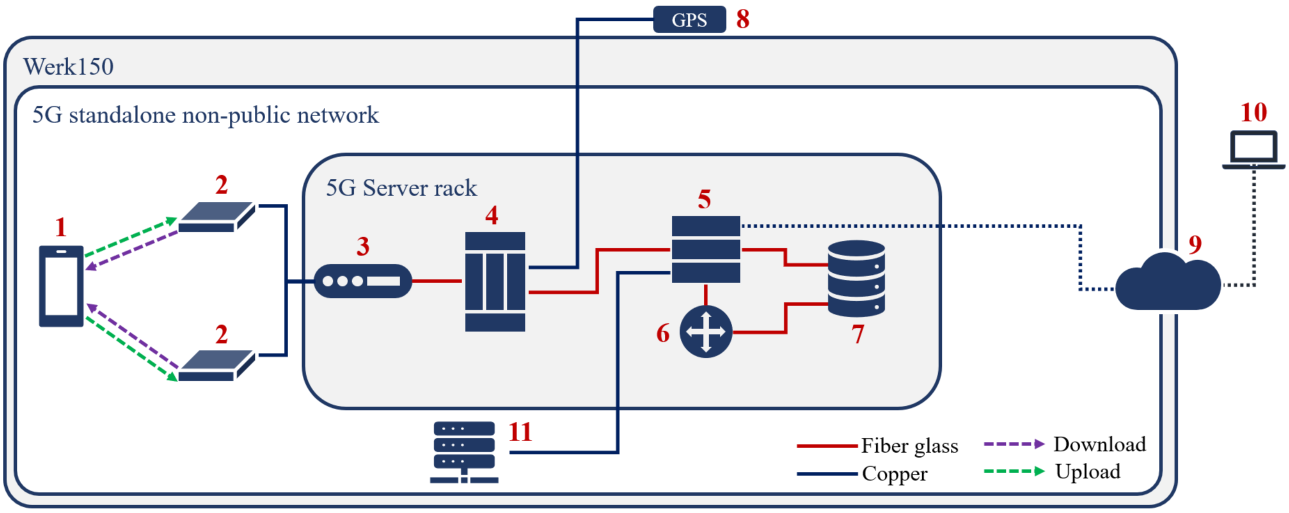


Figure 5.5: Visualisation of the KPIs used to conduct the 5G network analysis for the AMR

Additionally, the measurements are carried out using different end devices for the following two reasons. First, various end devices possess different 5G chipsets, revealing further insights about end devices' performance and potential bottlenecks. Second, using different end devices can support the selection of an appropriate end device for the AMR in the *end device* sub-stage.

The measurement setup ensures a complete end-to-end analysis of 5G for the AMR in the defined operational shop floor area; thus, network bottlenecks can be identified. Consequently, conclusions can be drawn regarding the *practicality*. As network analysis of 5G standalone non-public networks is a largely unresearched area, the results of this network analysis were published at the 55th CIRP Conference on Manufacturing Systems 2022. In the following paragraphs, the measurement setup, including the 5G network architecture, the measurement tools, the end devices, the measurement procedure, and the results, are presented in detail.

Regarding the 5G network architecture, the 5G standalone non-public network in *Werk150* serves as the testbed for the measurements. The network architecture is shown in Figure 5.6.



1) End device
2) Base station (Nokia ASiR AWHQB AirScale)
3) Range extender (Nokia ASiR Hub)
4) Baseband unit (Nokia AirScale indoor BBU)
5) Router
6) Gateway (SRX300)
7) Local edge (NDAC HP EL1000)
8) Outdoor GPS antenna
9) Cloud (Nokia NDAC)
10) Central management (Service provider interface)
11) Measurement server/ virtual machine

Figure 5.6: 5G standalone non-public network architecture and measurement setup at *Werk150* (adopted from Lackner et al., 2022, p. 1133)

The RAN is based on Nokia's indoor AirScale system module and operates on licensed frequencies between 3.7–3.8 GHz. The RAN is equipped with two ASiR-pRRH (AWHQB) AirScale base stations (2) with 4x4 MIMO, operating on the n78-band with a maximum transmission power of 250 mW. The base band unit is based on ASIK and ABIL components from Nokia (4). The 5G core network runs on the local NDAC edge cloud HP EL1000 (7). For clock master synchronisation, a GPS antenna

(8) is installed outside the building connected to the BBU. The radio uses the time division duplex method with a download-to-upload ratio of 70% to 30%. To run the measurement software tools, a Linux-based virtual machine (11) on a locally hosted edge server is used, equipped with an Intel (R) Xeon (R) Silver 4116 CPU at 2.1 GHz. The virtual machine has eight virtual CPUs and 8-gigabyte random access memory. All network configurations for the measurements are shown in Table 5.3.

Table 5.3: Network configurations used for the measurements
(adopted from Lackner et al., 2022, p. 1133)

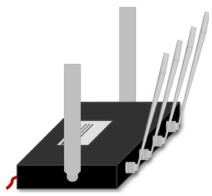
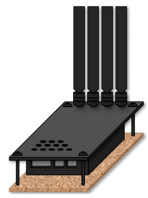
Characteristics	**Network configurations**
Radio Access Technology	5G New Radio (2 base stations in total)
5G Network deployment	Standalone
Frequency spectrum	3.7-3.8 GHz
Bandwidth	100 MHz
Band	n78
5G Core network version	6.2021.35.2974
gNB/ BBU version	5G20A
Software release	Release 15
Transmission power	50 mW (17 dBm)
Transmission mode	Time Division Duplex
Download-to-Upload ratio	70% to 30%
Subcarrier spacing	30 kHz

Three software tools are used to validate the measurements. The tool *iPerf3* serves as the reference tool, which is identified using the network measurement tool comparison study from Yildirim et al. (2008). *iPerf3* covers all required KPIs for the measurements. In addition, *iPerf3* is an open source tool and is frequently used in the telecommunications industry. For validation, the tools *LibreSpeed* and *OpenSpeedTest* are used. All tools solely use the transmission control protocol (TCP) for communication. In addition, the maximum transmission unit (MTU) for all tools is set to 1500 bytes to generate comparable measurements. The tools are implemented and executed locally only on a network-internal server without connection to public networks.

As can be seen in Figure 5.5, the data packets are sent from the end device (End) via the air interface to the base station (Access point), subsequently to the 5G core network (End), and in the case of the RTT, back to the end device (End). Network bottlenecks limiting the *practicality* of the AMR can be identified with this setup when the measurements do not meet the requirements of the AMR.

Five different standalone-capable end devices are selected for the network analysis measurements. Table 5.4 provides an overview of the end devices and their specifications for the network analysis.

Table 5.4: Overview and specification of the end devices used for the measurements (adopted from Lackner et al., 2022, p. 1134)

	Nokia SRS621	**Huawei P40 Pro+**	**Quectel Modem**	**M2M SIMCom**	**Waveshare 5G HAT**
					
Type	Router	Smartphone	Modem	Router	Module
5G module	FM150-AE (M2)	Kirin 990 5G	RM500Q-GL (M2)	SIM8200EA (M2)	SIM8200EA (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	0.9 Gbit/s	1.25 Gbit/s	0.9 Gbit/s	0.5 Gbit/s	0.5 Gbit/s
Ext. interface	Ethernet (CAT6)	USB-C 3.1	USB 3.0	Ethernet (CAT6)	USB 2.0
Software	SQM06 V1.1.5	11.0.0.193 C432E3R5 P3	RM500QGL ABR11A03 M4G	SIM8200 M44A-M2 V1.4.4	SIM8200 M44A-M2 V1.20

The end devices include two routers, a smartphone, a modem and a module. Four of the five end devices use Qualcomm's Snapdragon SDX55 5G chipset with a theoretical transmission rate of up to 7.5 Gbit/s (Qualcomm, 2022). The Huawei P40 Pro+ utilises their in-house Balong5000 chipset with a peak data transmission rate of 4.6 Gbit/s (Hisilicon, 2022). Although four of the five end devices use the identical SDX55 chipset, different data rates for download and upload are specified by the end device manufacturers. For example, the M2M router from SIMCom achieves a theoretical peak value of 4 Gbit/s in the download. In the upload, the Huawei P40 Pro+ ranks first with a theoretical 1.25 Gbit/s. The differences in performance are related to the different architectures of the 5G modules and the hardware components used, such as internal 5G antennas. As shown in Table 5.4, the end devices use different software versions, which can also influence the theoretical performance capacity. Another limiting factor are the external interfaces. For example, USB 2.0 achieves a data throughput of 480 Mbit/s (Semiconductor, 2009, p. 1). In contrast, USB 3.0 can transmit data with a speed of up to 5 Gbit/s (Dharkar et al., 2013, p. 13) and USB 3.1 and Ethernet Cat6 up to 10 Gbit/s (EL Sabbagh, 2015, p. 105).

Regarding the measurement procedure, the RTT, the download and upload throughput and the packet losses are always measured in the same LOS connection between end device and the base station by collecting 50 data points per tool and end device in a 10-second interval. In sub-experiments, 50 data points proved suitable, as the median showed almost no change from this point on.

After the measurements are carried out, the subsequent section presents and discusses the results of the 5G network analysis in the context of this case study. The throughput in download and upload as well as the RTT are illustrated as boxplot charts. In this context, the coloured boxes contain 50% of the measured data. Regarding the download throughput, the Nokia SRS621 router, the Huawei P40 Pro+ smartphone and the Quectel modem can achieve average values between 600 Mbit/s and 830 Mbit/s. Considerably lower values are achieved by the M2M SIMCom router and the Waveshare module. Here, the SIMCom router achieves average values between 118 and 140 Mbit/s, whereas the Waveshare oscillates between 50 Mbit/s and 267 Mbit/s. Figure 5.7 shows the results of the download throughput per end device and tool in a boxplot chart.

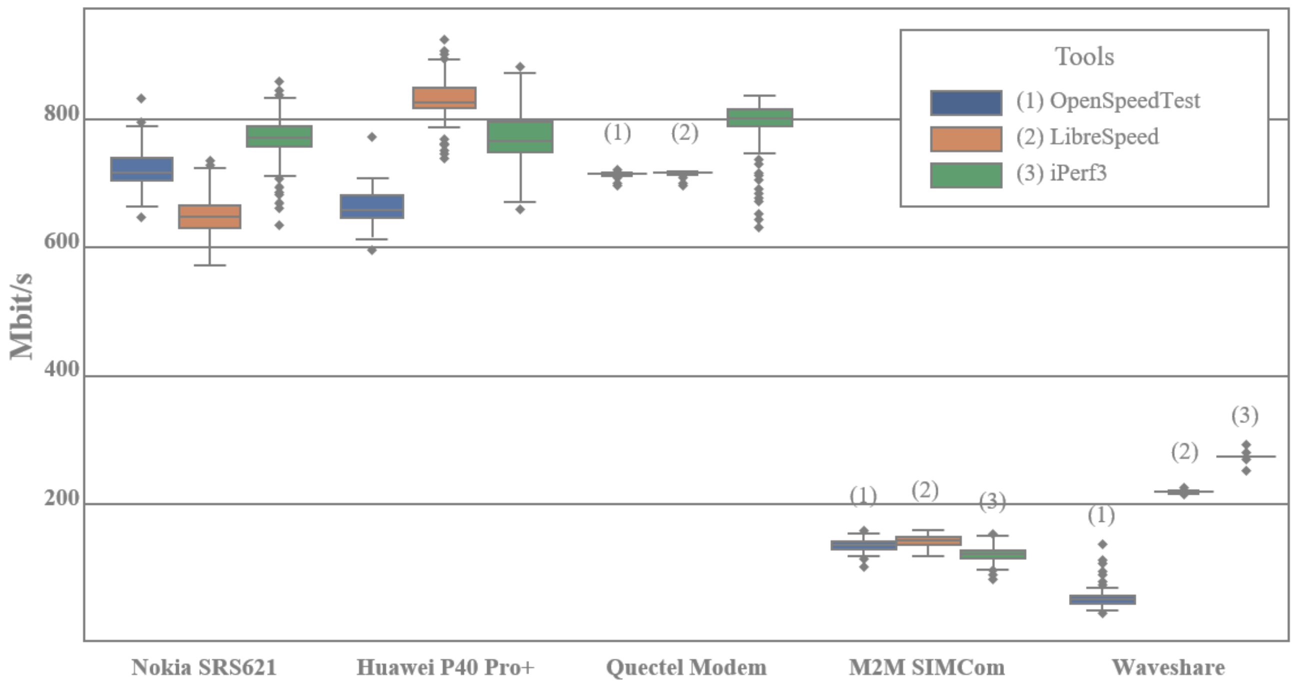


Figure 5.7: Boxplot chart of the download throughput of the 5G network per end device and tool (adopted from Lackner et al., 2022, p. 1135)

It is evident from Figure 5.7 that the performance of the end devices differs. In addition to the influence of the end device-specific parameters (see Table 5.4), the network configuration also influences the measurement results. The available resources of the RAN are divided and reserved accordingly using the download-to-upload ratio of 70%-to-30%. The specified capacity within the release determines the available resources. In this case study, 5G can provide a maximum of 1 Gbit/s as specified by the software Release 15. This results in a performance limitation according to the configuration, which can represent a bottleneck. In this case study, the download-to-upload ratio of 70%-to-30% does not represent a bottleneck, as lower data rates are required for the AMR. Concerning the download throughput results, the specified limits of at least 100 Mbit/s (see Table 5.1) are achieved by all end devices within the 5G standalone non-public network except for the Waveshare measurement using the OpenSpeedTest tool. Because the iPerf3 and LibreSpeed tools provide significantly higher values and are close to each other, this low data rate can likely be attributed to a mismeasurement using OpenSpeedTest. Excluding this mismeasurement, no bottlenecks are identified in terms of the download throughput.

The boxplot diagram for the upload data rates in Mbit/s per end device is shown in Figure 5.8. The upload per end-device ranges 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 boxplot diagram for the upload throughput per end device and measurement tool is shown in Figure 5.8. Similar to the download, it can be seen that the Nokia router, the Huawei smartphone and the Quectel modem are in a similarly high upload range. The uploads for these three devices are over 100 Mbit/s, in most cases over 150 Mbit/s with an average of about 170 Mbit/s, depending on the measurement tool. However, the values vary significantly between OpenSpeedTest, LibreSpeed and iPerf3 for the Huawei P40 Pro+ and the Quectel modem. Additionally, the boxplot chart for the upload throughput shows outliers, especially in the case of iPerf3. iPerf3 automatically adjusts the size of data packets at the beginning of each measurement series. This phenomenon is called up-fading. However, the required upload by the AMR is achieved by four out of five end devices. The Waveshare shows slightly lower performance.

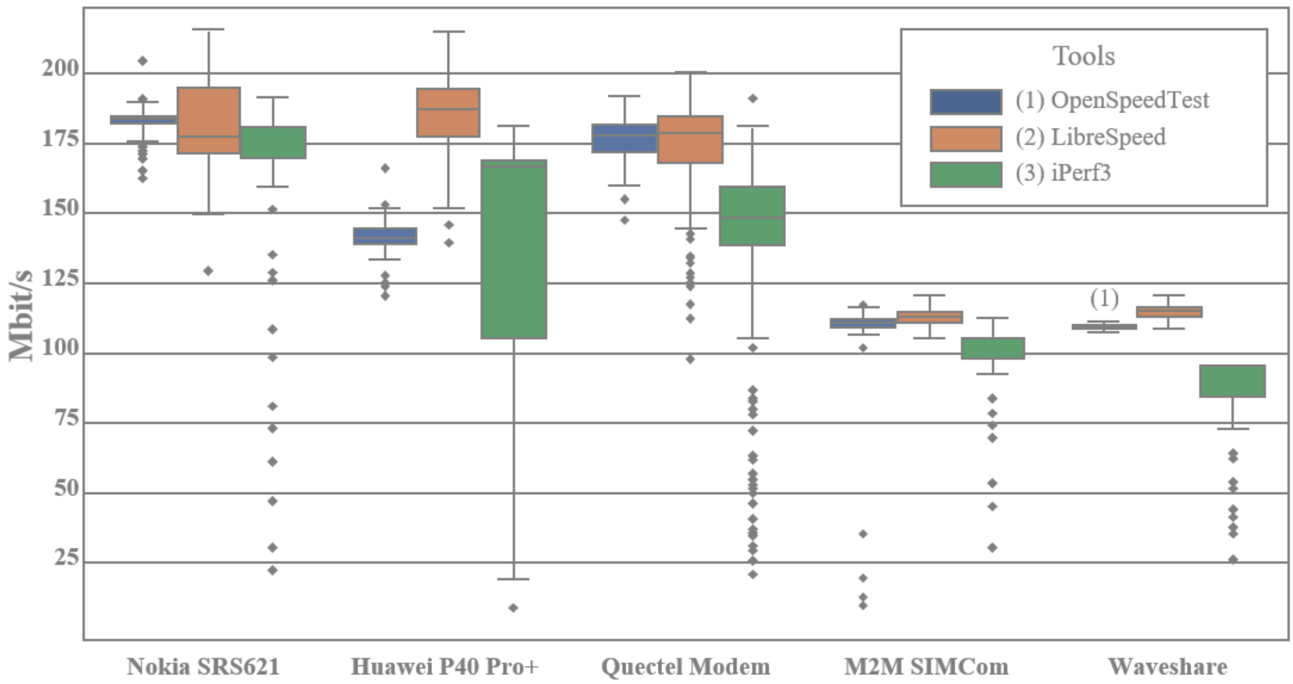


Figure 5.8: Boxplot chart of the upload throughput of the 5G network per end device and tool (adopted from Lackner et al., 2022, p. 1135)

Regarding the RTT, upward outliers are observed in the measurements with LibreSpeed and Ping. In fact, this is the opposite of up-fading (also called down-fading), in which the data packet size of the RTT adjusts slightly over the time of the measurements. By removing the outliers appearing at the beginning of the measurement, it can first be observed that the RTT is generally within an acceptable time range with maximum values of 30 milliseconds (ms) that a data packet requires from the end device to the core network and back to the end device. With 5G Release 15, end-to-end latencies of > 10 ms are specified. Since the RTT represents twice the end-to-end latency, the measured average values are already close to the targeted 20 ms RTT. However, it is also generally noticeable that the RTT fluctuates significantly for the SDX55 chipset, installed in all devices except Huawei's smartphone. The results of the RTT are presented in Figure 5.9.

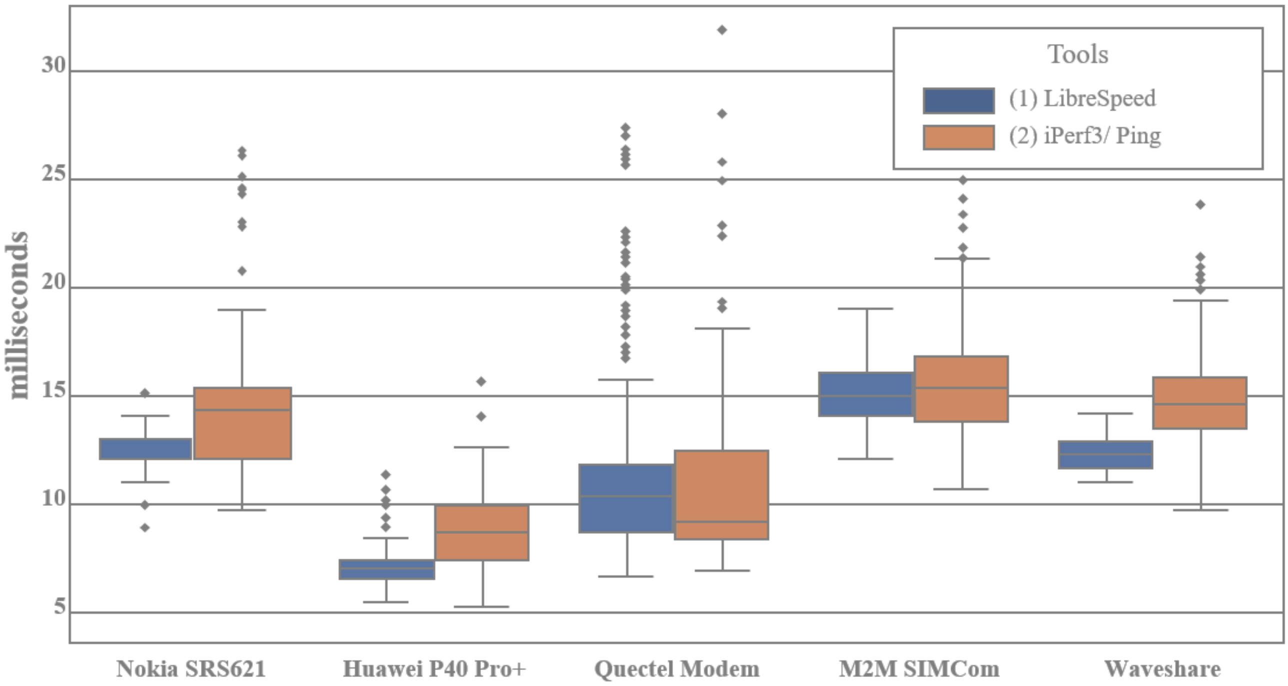


Figure 5.9: Boxplot chart of the round-trip time of the 5G network per end device and tool (adopted from Lackner et al., 2022, p. 1135)

In the AMR case study, the RTT is not considered a bottleneck since none of the end devices exceed the threshold of 100 ms. In addition, the interpretation of the RTT measurements' standard deviations indicate that each end device's measurement series only deviates slightly, except for the Quectel modem. In particular, the Huawei P40 Pro+, the M2M SIMCom router and the Waveshare end device show stable RTTs. This indicates the high reliability of these end devices in the 5G network. The maximum RTT combined with a low standard deviation is particularly relevant for realising 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 packets (0.33%). A summary of all measurement results in terms of throughput, RTT and packet losses is presented in Table 5.5.

Table 5.5: Summary of the 5G network measurement results
(adopted from Lackner et al., 2022, p. 1136)

		Throughput		**Round-trip time**			**Packet loss**
		Average download Mbit/s	Average upload Mbit/s	Average RTT ms	Maximum RTT ms	Standard deviation ms	Percentage (lost packets) %
iPerf3	Nokia SRS621	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 Modem	791.9	141.6	10.5	32.6	5.6	0
	M2M SIMCom	118.2	101.4	15.6	30.7	2.6	0
	Waveshare	267.7	83.1	14.8	28.8	2.4	0
LibreSpeed	Nokia SRS621	646.4	179.0	12.6	15.0	1.4	-
	Huawei P40 Pro+	830.4	181.2	7.2	11.4	1.1	-
	Quectel Modem	751.2	171.6	10.5	27.5	3.5	-
	M2M SIMCom	139.2	112.1	15.2	19.0	1.5	-
	Waveshare	215.9	113.2	12.5	14.1	0.9	-
OpenSpeedTest	Nokia SRS621	720.4	180.6	-	-	-	-
	Huawei P40 Pro+	657.1	140.3	-	-	-	-
	Quectel Modem	748.4	173.9	-	-	-	-
	M2M SIMCom	132.8	106.6	-	-	-	-
	Waveshare	50.9	108.4	-	-	-	-

The study results show that different performance levels exist between end devices. Unexpectedly, identical chipsets (SDX55) perform differently. The architecture of the 5G module on which the chipset is implemented can influence the implementation of protocols between internal interfaces and thus the performance of the end device. In addition, these observations can also be an indication of software issues (Lackner et al., 2022, p. 1136).

Concluding the network measurements for this case study, all end devices can meet the required performance of the AMR specified in the *use case specification stage* (see Table 5.1). Therefore, the 5G network, including the available end devices, does not represent a bottleneck for the AMR case study in the *Werk150* environment.

However, the measurements reveal insights regarding end devices' performance. Here, however, the measurements also show that identical chipsets perform differently. Consequently, when implementing time-critical use cases, the end device and the use case requirements must be thoroughly coordinated. Thus, the end devices must be analysed, tested and coordinated with the use case before implementation.

Furthermore, the metallic and concrete environment described in the *intralogistics shop floor and air interface* sub-stage can lead to interferences in the air interface and absorption by materials within *Werk150*. Therefore, a second measurement series is conducted, analysing material influences on 5G in NLOS connections. As the measurements do not demonstrate significant absorption, this section only presents the results of the measurement (A description of the material absorption measurements can be found in Appendix C). The measurements are carried out using a reference signal strength measured without material, then with concrete (50 mm), stainless steel (1.5 mm) and finally with aluminium (1.0 mm). The materials are selected because they encircle the AMR in *Werk150* and are reported as critical materials regarding signal absorption (see Table 2.10). For each measurement, the end devices are encased in an airtight box made of the respective material. Subsequently, 50 data points of the received signal strength are measured at the end device site. As a result of the data evaluation, a conclusion can be drawn. The signal strength remained in a very good to normal range even with the critical materials of the thickness in which they occur in NLOS scenarios in *Werk150*. As a result, the materials that surround the AMR do not have a critical influence on 5G in the defined shop floor area.

5G end device

Finally, the framework needs to select an appropriate 5G end device as proposed. The 5G network analysis measurements showed that the 5G end device currently represents a bottleneck regarding their performance even when identical chipsets are installed. However, all end devices met the required performance for the AMR case study.

As a first step, the framework considers identifying a suitable end device type. From the background literature review, routers are typically end devices for mobile robot connectivity since routers combine reliability and low-latency communication with an accurate time synchronisation for safety-critical protocols. Therefore, a 5G router was selected as the appropriate end device type for the AMR. Additionally, the framework proposes coordinating the end device with the use case and ensuring that the end device can achieve the required performance. In this case study, the measurements of the different end devices discussed in the previous section are used for this step. Here, the Nokia SRS621 router and the SIMCom 5G router meet the required performance of the AMR. Concerning the external interface, the Nokia router and the M2M SIMCom router provide an Ethernet (CAT6) interface compatible with the AMR server. Thus, the Nokia router and the SIMCom router comply with all requirements of the AMR and do not limit the *practicality* of the AMR using 5G. For reasons of accessibility of router-internal data and configuration options, the SIMCom M2M 5G router (see Table 5.4) is finally selected to integrate the AMR into the 5G network.

5.2.3 Integration of the AMR into the 5G standalone non-public network

Through the steps conducted from the perspective of the use case and the environment proposed by the framework, 5G is considered to be a practical communication solution for the AMR in the learning factory *Werk150*. Therefore, the final step of the case study covers the integration of the AMR into the 5G ecosystem. To integrate the AMR into the 5G standalone non-public network, the AMR is equipped with the selected 5G M2M SIMCom router. The M2M SIMCom router's driver software is flashed on the AMR-internal server. Furthermore, the interfaces are reconfigured in terms of IP-addresses. Figure 5.10 shows the AMR equipped with the SIMCom M2M 5G router.

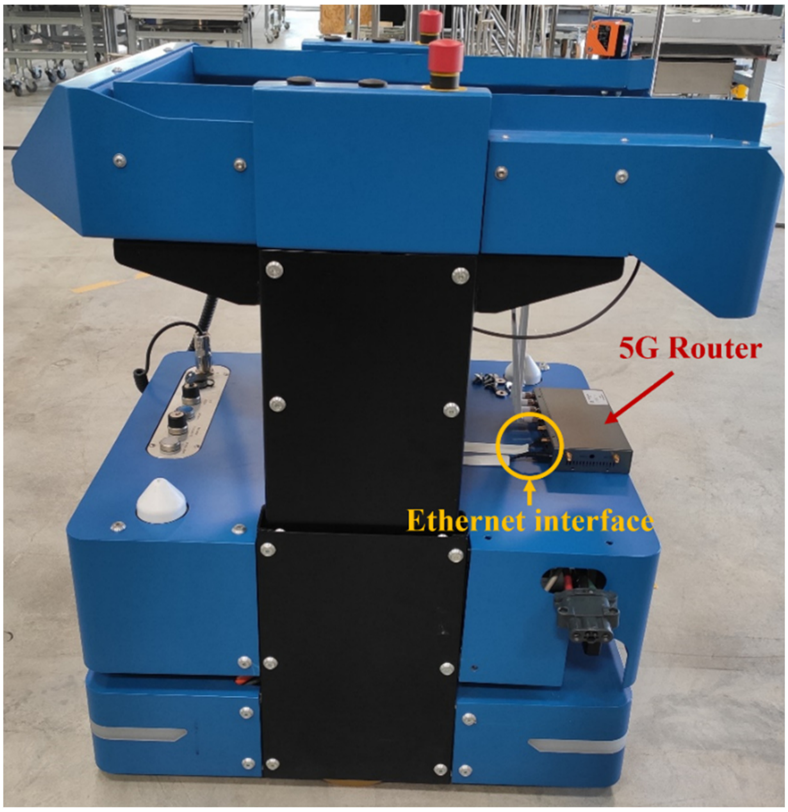


Figure 5.10: AMR equipped with the SIMCom M2M 5G router

After the AMR was equipped with the 5G router and the Ethernet interfaces were configured, the defined tasks from the *use case specification stage* for this case study were executed. For this purpose, the FMS provides a graphical user interface, which includes a map of *Werk150*. The graphical user interface allows the selection of waypoints and the triggering of start and stop signals. In addition, the scanner data and AMR's position are stored on the FMS and are available via the user interface. Repeatedly performing various driving commands demonstrates that the AMR is able to execute all defined tasks within the defined performance thresholds using 5G (Release 15). Thus, the framework's output, that 5G represents a practical technology for the AMR in the learning factory *Werk150,* is validated by this case study.

5.3 Concluding summary

In this chapter the framework is validated. For this purpose, an autonomous mobile robot case study was conducted in the learning factory *Werk150* at Reutlingen University. From the use case perspective, 5G can be identified as a practicable communication technology for the AMR using the proposed framework. For the environmental analysis, the learning factory is first analysed and subsequently a thorough network analysis is performed with various end devices to test whether the requirements of the AMR can be covered by 5G. The measurement results show that the 5G network can cover the requirements of the AMR. Finally, the AMR was equipped with a 5G router and integrated into the 5G standalone non-public network. Thus, this AMR case study demonstrates the validation and practical applicability of the framework.

6 Conclusion and recommendations

This chapter starts with a summary of the thesis. The second part reviews the contributions of this research and provides the researcher's conclusion. Finally, this chapter closes with limitations and recommendations for future research, including a new research gap revealed by this thesis.

6.1 Summary of the research

The research aims to develop a framework for evaluating the *practicality* of 5G for intralogistics use cases in standalone non-public networks. For this purpose, the thesis is divided into six chapters: (1) introduction of the research; (2) literature review; (3) use case analysis; (4) framework development; (5) validation of the framework; (5) conclusion and recommendations. In the following paragraphs, each chapter is briefly summarised.

Chapter 1 introduces and defines the research and presents the reader with initial background to the research of 5G. Furthermore, this chapter states the research problem underlying the research, the resulting research questions and objectives, and the research contribution. The research design and methodology are presented, providing the researcher with the required tools to conduct the research. Finally, the chapter closes with delimitations and limitations and a thesis outline.

Chapter 2 contains the literature review and is part of the data collection process of this project. Therefore, Chapter 2 provides the fundamentals and definitions of intralogistics, 5G standalone non-public networks and its 5G release process. Subsequently, all external factors influencing 5G in standalone non-public networks are presented. In the last part of this chapter, a semi-systematic literature review identifies eight intralogistics use cases requiring wireless communication, forming the foundation for the framework development.

Chapter 3 presents the classification and analysis of the identified use cases within the semi-systematic literature review from Chapter 2. First, the use cases are classified based on their critical requirements and non-quantifiable characteristics. Second, after classifying the use cases, a morphological analysis is conducted based on the use case classification to derive critical use cases which serve as reference use cases for the framework.

Chapter 4 covers the framework development. The conceptual framework is represented by a vertical process flow consisting of two stages, namely, the *use case specification stage* and the *environmental analysis stage*. The proposed vertical process flow of both stages includes several sub-steps to evaluate the *practicality* of 5G for intralogistics use cases. Finally, the proposed framework combines the vertical process flow with the interrelationships of individual elements of the framework which have a mutual influence on each other.

Chapter 5 represents the validation of the framework. The validation is carried out as part of an autonomous mobile robot case study. Thereby, 5G can be shown to be a technically practicable communication technology for the AMR use case. Within the environmental network analysis stage, several empirical measurements are carried out to perform initial end-to-end tests to analyse the network and to ensure that 5G can meet the required performance of the AMR. Finally, the AMR is integrated into the 5G standalone non-public network and tested against all defined tasks. This AMR case study demonstrates the practical applicability of the framework.

Chapter 6 summarises and concludes the research. Furthermore, limitations of the framework are highlighted, and finally, recommendations for future research are presented, including a new research gap revealed by this thesis.

6.2 Key findings and research contribution

This section summarises the key findings for each research question, defined in Chapter 1. First, the SRQ are summarised, followed by the PRQ. Based on the summary, the research contribution can be drawn.

SRQ 1 *What performances and services in 5G standalone non-public networks are required to evaluate the practicality, and in what 5G releases are these performances and services available?*

5G is specified by 3GPP and comprises four releases, namely Release 15, Release 16, Release 17 and Release 18. As of today, Release 15 and Release 16 are specified. Release 17 is currently in the development stage and Release 18 is only briefly outlined. However, Release 18 can be expected to meet the predefined targets, as it represents the last 5G release. The individual releases include KPIs for standalone non-public networks specifically for industrial applications. 3GPP has defined these quantifiable KPIs as critical parameters to evaluate 5G in the industrial context. Table 6.1 summarises the critical KPIs with the respective specified parameters per 5G release.

Table 6.1: Performance KPIs required to evaluate the practicality of 5G

KPIs	**Release 15**	**Release 16**	**Release 17**	**Release 18**
User experienced data rate download (Gbit/s)	1	1	10	< 20
User experienced data rate upload (Gbit/s)	0.5	0.5	1	< 10
End-to-end latency (ms)	> 10	> 1	< 1	< 1
End device speed (m/s)	< 5	< 5	< 10	< 10
Communication service availability up to (%)	99.9999	99.9999	99.999999	99.999999
Communication service reliability up to (%)	99.999	99.999	99.99999	99.99999
End device density (end device/m²)	0.25	0.25	0.25	0.25
Positioning service level (SL)	-	SL 1	SL 1-7	SL 1-7

To elaborate the performance parameters for each 5G release for standalone non-public networks shown in Table 6.1, a total of more than one hundred studies and specification documents have been studied in the course of this research and consolidated in tables.

Furthermore, 5G provides exclusive 5G services due to its service-based architecture. The evaluation of the *practicality* of 5G regarding these services depends on the requirements of the respective use case. However, three main services that are particularly interesting for industrial applications are identified, namely, network slicing (provided in Section 2.2.5.5), 5G positioning (provided in Section 2.2.3.3, 2.2.3.4 and 2.2.3.5) and vehicle-to-everything communication (provided in Section 2.2.3.3). Of course, 5G offers considerably more than the three aforementioned services that are in the spotlight of this thesis. However, the scope of the research is defined in terms of services that are relevant for 5G standalone non-public networks in the industrial context. Services of interest for public networks, such as high-speed support of railways, have not been included.

SRQ 2 *What influencing factors occur in the intralogistics that can impact the practicality of wireless communication?*

Fundamentally, interferences mainly occur when obstacles between the base station and the end device prevent a direct line of sight communication path. In this context, the influences can be described through six different physical effects; namely, interference, diffraction, scattering, reflection, refraction and absorption. From this, various interferences can emerge.

First, a propagation delay shift can occur due to the so-called multipath fading error, in which a signal is received multiple times by the base station at different times due to refraction, thereby blocking resources for other signals. Another disturbance, described as the most critical effect in the literature, is signal attenuation due to the absorption of electromagnetic waves during the penetration of materials. In this case, several variables need to be considered that affect the absorption behaviour, such as the wave frequency, the angle of entry of the wave onto the material and the material properties. The material properties consist of density, surface properties and thickness. Experimental damping measurements report damping behaviour of 30 to 90 percent, especially for reinforced concrete, metallic materials and aluminium. However, an accurate prediction of the absorption is difficult due to the variables involved.

Therefore, measurements of the influence of three critical materials, namely concrete, stainless steel and aluminium were carried out in this thesis. The results showed that the materials as they occur in *Werk150* do not limit applications on the shop floor. However, the measured results are only applicable for *Werk150*. In any other environment, the signal attenuation may vary due to different material properties.

SRQ 3 *What wireless indoor use cases and their critical requirements regarding wireless communications occur in the intralogistics?*

To answer the SRQ2, a semi-systematic literature review was conducted in Section 2.4 resulting in eight intralogistics use cases that require wireless communication, as listed below:

- High-definition video broadcasting for Augmented Reality and Virtual Reality (AR and VR)
- Remote control of mobile robots (AGV and AMR)
- Remote control of UAVs
- Condition Monitoring of machines using IIoT sensors
- Remote control of crane systems
- Flexible factory layout monitoring
- Asset indoor tracking
- Robot motion control using tactile internet (haptic feedback)

Based on the background literature review, these eight use case groups are identified. To analyse the critical requirements of the use cases, an analysis of the use cases was conducted in Chapter 3. To this end, the critical parameters for each use case group were identified based on existing background literature.

Essentially, the observation is made that applications generally can be described by two types of requirements. The first type is represented by quantifiable parameters defined with measurable values. The second type of requirement is described by non-quantifiable characteristics. In particular, the real-time classification into *hard* or *soft* real-time, the mobility, the power supply and the traffic class, which describes the type of data transmission, are identified in terms of non-quantifiable use case characteristics.

SRQ 4 *What intralogistics use cases can be used as reference use cases for the framework development to ensure a generic design?*

Considering the limitation of the framework to follow a generic approach for intralogistic indoor use cases, the reference use cases have to cover all potential scenarios. Therefore, critical use cases must be used, that have the maximum intersection with all use cases. For this elaboration, the morphological analysis method is consulted to systematically derive the critical use cases.

As a result, four critical use cases are identified that can be classified into one of the three 5G service categories. *High-definition video broadcasting for Augmented Reality and Virtual Reality* represents the eMBB service category. *Remote control of mobile robots* and *Robot motion control using tactile internet* represent uRLLC and *Condition monitoring of machines using IIoT sensors* the mMTC category. These four applications have the highest requirements in their respective 5G service categories. For this reason, these four critical use cases serve as a reference for the framework development to ensure a generic framework design.

PRQ	*How can a framework assist the decision-making process of companies in evaluating the practicality when adopting 5G for intralogistics use cases in standalone non-public networks?*

A generic framework is developed for evaluating the *practicality* of 5G for intralogistics use cases. The framework is divided into two stages.

The first stage is called *use case specification* and evaluates the feasibility and usefulness of 5G based on technical requirements and characteristics of the use case. First, the framework proposes the definition of the use case and subsequently the fundamental check of the suitability of the use case for wireless technologies. Two characteristics from the nature of the application serve this purpose, namely mobility and battery power supply. These have been identified as prerequisites to a fundamental suitability of wireless communication. Third, it is suggested to compare the performance requirements of the use case with the performance of the 5G releases to identify the general feasibility with 5G and the required 5G release. Finally, after ensuring the feasibility of the intralogistics use case with 5G, the last step of the first stage proposes to ensure that 5G offers a technical added value compared to the emerging competing wireless technology; namely, Wi-Fi 6 Enhanced.

The second stage is called the *environment analysis stage* and is divided into three sub-stages, namely the intralogistics shop floor and air interface, the 5G network, and finally the 5G end device. The order is logically derived from the consequences of the stages for the following stages. In the *intralogistics shop floor stage*, all influencing factors that can lead to interference with the air interface in the environment of the application are examined. The first step is to delimit the area of application operation. In the next step, the framework suggests defining critical zones within the site of operation. The critical zones consist of critical materials encircling the application and critical scenarios, such as areas where the application may be in close proximity to people. These critical areas, where materials and critical scenarios potentially occur, need to be carefully assessed for 5G coverage to ensure 5G availability. This may also lead to the need to integrate additional base stations into the network to provide coverage for the critical zones. The second sub-stage is the *5G network*. In the first step the framework proposes a network analysis to identify possible network-internal bottlenecks that may limit 5G's capacity and, consequently, the *practicality* of 5G for the use case. The physical and virtual bottlenecks must be identified and finally the network should be stress tested. After the network analysis, the network must then be adapted depending on the identified critical zones from the *intralogistic shop floor stage* and the identified network-internal bottlenecks. This configuration consists of hardware and software composition and network settings. The last sub-stage is called the *5G end device*. Here, the end device type must be identified. Finally, the required performance of the use case must be coordinated with the end device's performance to ensure that the end device can meet the requirements and thus, do not limit 5G.

The research contribution of this thesis is divided into theoretical and practical parts.

Regarding the theoretical part, the main contribution is the conceptual framework to evaluate the *practicality* of 5G for intralogistics use cases. To identify this contribution, publications in Section 2.4.1 in related works regarding the *practicality* of 5G in intralogistics were examined. The investigated literature shows that current research approaches only the evaluation of 5G for use cases based on its target performance. The evaluation of the feasibility of 5G for applications can thus be derived from existing approaches but not regarding the actual performance of 5G in an industrial environment. For this reason, the term *practicality* combines the theoretical feasibility and environmental influencing factors within the evaluation process to enable a holistic evaluation of 5G.

Through the theoretical research contribution, an underlying practical problem is addressed. The framework enables decision-makers to reduce the technical uncertainties associated with introducing 5G. Thus, the framework can support companies' decision-making on whether 5G is a technically feasible technology and what environmental factors need to be considered in the evaluation process. In this way, the framework can contribute to the successful introduction of 5G in companies and minimise time consumption, technical uncertainties and, ultimately, financial risks. To the best of the author's knowledge, a similar *practicality* evaluation approach does not yet exist.

6.3 Limitations and recommendations for future research

Based on the limitations of this thesis, recommendations for future research, including a new research gap, are presented in this section.

5G is currently at the beginning of its life cycle and cannot yet achieve the full performance spectrum aimed for. This research shows that the high industrial expectations for 5G are justified but cannot be fulfilled so far. This is primarily due to the lack of transparency in the 5G release process and the lack of consideration of the time gap between the theoretically specified 5G releases and the implementation of 5G in the network infrastructure. This gap currently leads to a limited use of private 5G networks, especially in the industry. To close this gap between theoretical approaches and practical applications, further development towards 5G's promised target state is required. Moreover, further research on 5G in the industrial environment is needed to decrease the technical uncertainties resulting in decision-makers' reluctance to adopt 5G. Once the target performance is reached, 5G will be able to provide its full potential to the industry. In this context, the validation of the proposed framework is based on a prototypical AMR case study in cooperation with the manufacturer of the AMR. The main focus of this case study was to integrate the AMR into the 5G ecosystem. Highly critical tasks of the AMR were not part of this case study. For this reason, the proposed framework should undergo further validation cycles in complex industrial environments including critical tasks. However, as a precondition, 5G must provide improved performances, which can be expected with upcoming 5G releases.

Another limitation of this thesis is the technical consideration of the use case and the environment in the context of the *practicality* evaluation. An economical view of 5G standalone non-public networks is not considered. However, since the deployment of 5G standalone non-public networks requires dedicated infrastructure, an economic analysis of 5G might be a further decision-making criterion for adopting 5G. Thus, the economic perspective, including country-specific regulations, represents a recommended course of action resulting from this thesis.

The proposed framework for evaluating the *practicality* is composed of two stages, namely the *use case specification* and *environment analysis*, guiding the intralogistics decision-makers through the evaluation process in chronological order. In this process, the framework assists in the *practicality* evaluation of a single use case. While a use case might consist of multiple end devices, the requirements for 5G remain the same. However, in case an organisation intends to operate various use cases with different requirements over one shared 5G network infrastructure, the complexity of the evaluation process increases drastically. As a first theoretical solution approach to safely operate multiple use cases, 5G promises the integration of the so-called network slicing for the first time in the history of wireless communication. Network slicing is intended to overcome the previous issue of a one-size-fits-all solution by establishing multiple virtual networks over one physical infrastructure. This is supposed to provide customised services and performance for different applications. However, network slicing is currently only a theoretically defined and generic concept. Further research on customised communication solutions and network slicing-as-a-service can thus be of considerable benefit to industries and socially valuable.

Regarding industrial benefits, network slicing is seen as an enabler concept for the parallel operation of several applications. Tailored services can be provided to multiple applications to ensure reliable, safe, and tailored communication. Furthermore, network slicing can be seen as a technology-independent concept. In this context, research of industrial network slicing-as-a-service concepts can be transferred to other communications technologies, such as Wi-Fi.

Regarding the social benefit, the trend towards human-machine collaboration in intralogistics increases the challenge of the secure operation of mobile machines and the safe transmission of sensitive data. In this context, network slicing enables the prioritisation of critical applications, which are allocated their own network resources to ensure secure data transmission. This, in turn, increases the security for humans in applications' environment.

However, with the current state of research, a technology-independent network slicing-as-a-service and the investigation of conditions under which applications require tailored networks are largely unexplored in the industrial context which represents a new research gap revealed by this thesis.

6.4 Concluding summary

This chapter provides an overview of the research carried out in this thesis. First, a summary of all chapters is provided. Second, the key findings to the research questions are highlighted and subsequently, the theoretical and practical research contribution is presented. Finally, the limitations of this thesis are outlined and the resulting recommendations for future research are given, including a new research gap revealed by this thesis.

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Appendix A – Flowchart to determine the technical usefulness of 5G

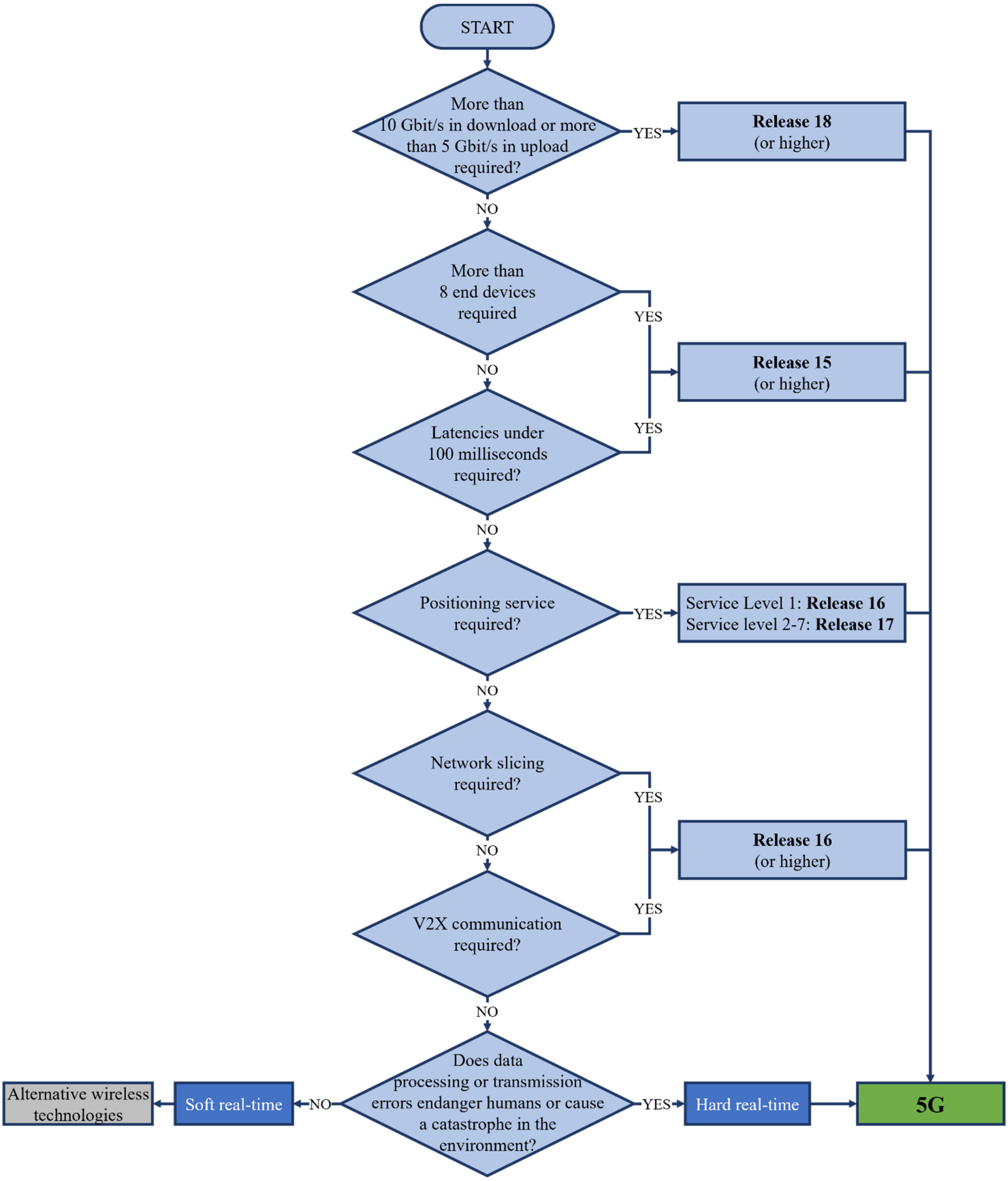

Figure A.1: Flowchart to determine the technical usefulness of 5G

Appendix B – Measurement source codes

This appendix contains source codes used for the measurements. The following python source codes enabled to access and skim end device-internal data about the signal strength. These source codes are listed below for each end device (IP addresses, usernames and passwords are removed).

B.1: Nokia SRS621 Industrial Router

```
import requests
import ast

ip = ''
username = ''
password = ''
payload = {'username': username, 'password': password}

with requests.Session() as s:
    p = s.post('http://{}/action/login'.format(ip), data=payload) #login to router
    resp =
s.get('http://{}/data.html?method=obj_get&param=["systemOnlineTime","systemRunningT
ime","lteMainStatusGet","lteOperatorGet","lteModeGet","lteCellidGet","lteRsrp0","lt
eRsrp1","lteRsrq","lteSinr","lteCellidGet_5g","lteRsrp0_5g","lteRsrp1_5g","lteRsrq_
5g","lteSinr_5g","networkWanSettingsIp","networkWanSettingsMask","networkIpv6WanSet
tingsIp","networkIpv6WanSettingsMask","systemGpsLongitude","systemGpsLatitude","sys
temGpsAltitude","networkWanSettingsDns","networkIpv6WanSettingsDns1","networkIpv6Wa
nSettingsDns2"]'.format(ip)) #convert answer from string to dict
    resp = ast.literal_eval(resp.text #print(resp)
    rsrp0 = resp['lteRsrp0_5g']
    rsrp1 = resp['lteRsrp1_5g']
    print(rsrp0) #!/bin/bash
```

B.2: Huawei P40 Pro+

```
import os
import time
from datetime import datetime
import argparse

parser = argparse.ArgumentParser(description='Read signal of quectel')
parser.add_argument('-n','--num', help='Description for foo argument',
required=False)
parser.add_argument('-d','--delay', help='Description for bar argument',
required=False)
args = vars(parser.parse_args())

n = int(args['num']) or 1
d = int(args['delay']) or 1

print("Timestamp; RSRP; RSRQ; SINR")

for i in range(0,n):
    stream = os.popen('adb shell dumpsys telephony.registry | grep -i
signalstrength')
    output = stream.read() #print(output)
    ct = datetime.now()
    ssrsrp = output[output.find('ssRsrp = ')+9:output.find('ssRsrp = ')+12]
    ssrsrq = output[output.find('ssRsrq = ')+9:output.find('ssRsrq = ')+12]
    ssSinr = output[output.find('ssSinr = ')+9:output.find('ssSinr = ')+12]
    print("{};{};{};{}".format(ct,ssrsrp,ssrsrq,ssSinr))
    if i < n-1:
        time.sleep(d)
```

B.3: M2M SIMcom 5G Module

```
import requests
from datetime import datetime
import time
import argparse

parser = argparse.ArgumentParser(description='read parameters from m2m router')
parser.add_argument('-u','--user', help='username', required=False)
parser.add_argument('-p','--pass', help='password', required=False)
parser.add_argument('-n','--num',  help='number of measurements', required=False)
parser.add_argument('-d','--delay',help='delay between measurements in seconds',
required=False)
args = vars(parser.parse_args())

user = args[''] or ""
password = args[''] or ""
n = int(args['num']) or 10
d = int(args['delay']) or 10

URL = "http://192.168.1.1/cgi-
bin/luci/admin/modem/get_csq?luci_username={}&luci_password={}".format(user,passwor
d) #print(URL)

print("Timestamp; rssi; csq; rsrq; rscp; percent")

for i in range(0,n):
    r = requests.get(url = URL, params = None)
    data = r.json()
    dateTimeObj = datetime.now()
    print("{};{};{};{};{};{}".format(dateTimeObj,
data['n5grssi'],data['n5gcsq'],data['n5gecio'],data['n5grscp'],data['n5gper']))
    if i < n-1:
        time.sleep(d)
```

B.4: Quectel USB Modem

```
import os
import time
from datetime import datetime
import argparse

try:
    parser = argparse.ArgumentParser(description='Read signal of quectel')
    parser.add_argument('-n','--num', help='Description for foo argument',
required=False)
    parser.add_argument('-d','--delay', help='Description for bar argument',
required=False)
    args = vars(parser.parse_args())

    n = int(args['num']) or 10
    d = int(args['delay']) or 10

    stream = os.popen('sudo systemctl stop ModemManager')
    time.sleep(5)

    print("Timestamp; RSRP; SNR; RSRQ")

    for i in range(0,n):
        stream = os.popen('sudo qmicli -d /dev/cdc-wdm0 --nas-get-signal-info')
        output = stream.read()
        ct = datetime.now()
        rsrp =""
        snr = ""
        rsrq= ""
        for line in output.split('\n'):
            if line.find('RSRP') > -1:
                start = line.find("'")+1
                rsrp = line[start : line.find("'",start+1)]
            if line.find('SNR') > -1:
                start = line.find("'")+1
                snr = line[start : line.find("'",start+1)]
            if line.find('RSRQ') > -1:
                start = line.find("'")+1
                rsrq = line[start : line.find("'",start+1)]

        print("{};{};{};{}".format(ct,rsrp,snr,rsrq))
        if i < n-1:
            time.sleep(d)
finally:
    stream = os.popen('sudo systemctl start ModemManager')
    print('finish')
```

Appendix C – Material absorption measurements

For the material absorption measurements in non-line-of-sight scenarios, four end devices were measured, each with different critical materials. For this purpose, signal strength parameters were collected using the source codes from Appendix B. The following appendices provide an overview of the measurement series and results.

C1: Overview of the measurement series

The material absorption measurements were performed without material (reference measurement), with 50 mm concrete, 1.5 mm stainless steel and 1.0 mm aluminium using four different end devices (see Figure C.1). 50 measurement points were collected per measurement and per parameter. Since not all parameters were available for all end devices, the RSRP (Reference Signal Received Power) value was used, as the RSRP-value was either available or at least calculable from other collected parameters.

collected data

measurement series	Nokia SRS Route	Huawei P40 Pro	Quectel USB Modem	M2M Simcom
without material	x	x	x	x
concrete 50mm	x	x	x	x
stainless steel 1.5mm	x	x	x	x
aluminium 1.0mm	x	x	x	x

signal strength parameter matrix

Device	RSRP	SNR	RSRQ	RSSI	CSQ	RSCP
Nokia SRS Router	x	x	x	x	x	x
Huawei P40 Pro	x	x	x	x	x	x
Quectel USB Modem	x	x	x	x	x	x
M2M Simcom	x	x	x	x	x	x

x Measurement/ existing value
x Calculation/ from existing values
x Value that cannot be collected/ cannot be measured or calculated

All values of a parameter can be tapped or calculated on all devices
At least 3 out of 4 devices have the searched value or the value is calculable
Only 2 or fewer devices provide the value

RSRQ [Watt] = N * RSRP [Watt] / RSSI [Watt]
N = Number of resource blocks
100 MHz bandwidth

Figure C.1: Overview of the material absorption measurements

C2: Measurement testbeds

Three absorption boxes made of concrete, steel and aluminium were constructed for the measurement setup. To simulate the critical NLOS scenarios, the end devices were placed in the material absorption box for the measurements (see Figure C.2).

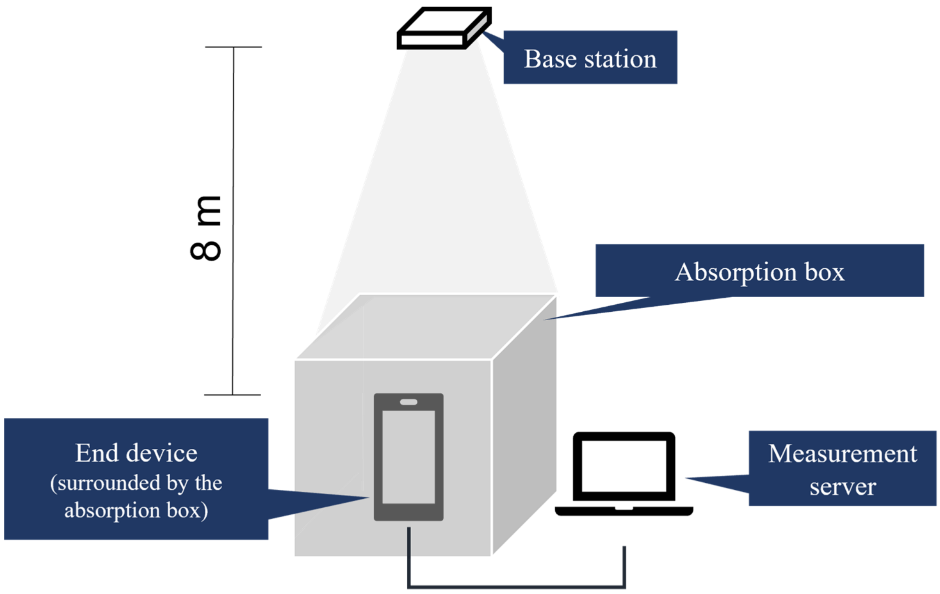

Figure C.2: Exemplary measurement setup with an end device encased by the absorption box

The RSRP-value is used to evaluate the material absorption on the signal strength of 5G. For this purpose, a reference table that classifies the RSRP-value from very bad to very good was used to analyse the results of the material absorption. Figure C.3 shows the reference classification of the RSRP-value.

RSRP range [dBm]	Classification
< -80	Very good
- 90 to -80	Good
-100 to -90	Normal
-120 to -100	Bad
> -120	Very bad

Figure C.3: Reference classification of the RSRP-value
(adopted from Widyasmoro et al., 2019, p. 34)

C3: Results

The RSRP value is used to evaluate the material absorption on the signal strength of 5G. The measured RSRP values for the terminals and the different materials are shown as a boxplot diagram in Figure C.4. The boxplot is also coloured to match the reference table in Figure C.3. It is evident from Figure C.4 that all RSRP-values can be classified from very good to normal. For this reason, the incoming signal strengths are adequately given for the materials used, ensuring that there is no limitation of 5G on the shop floor in the *Werk150*.

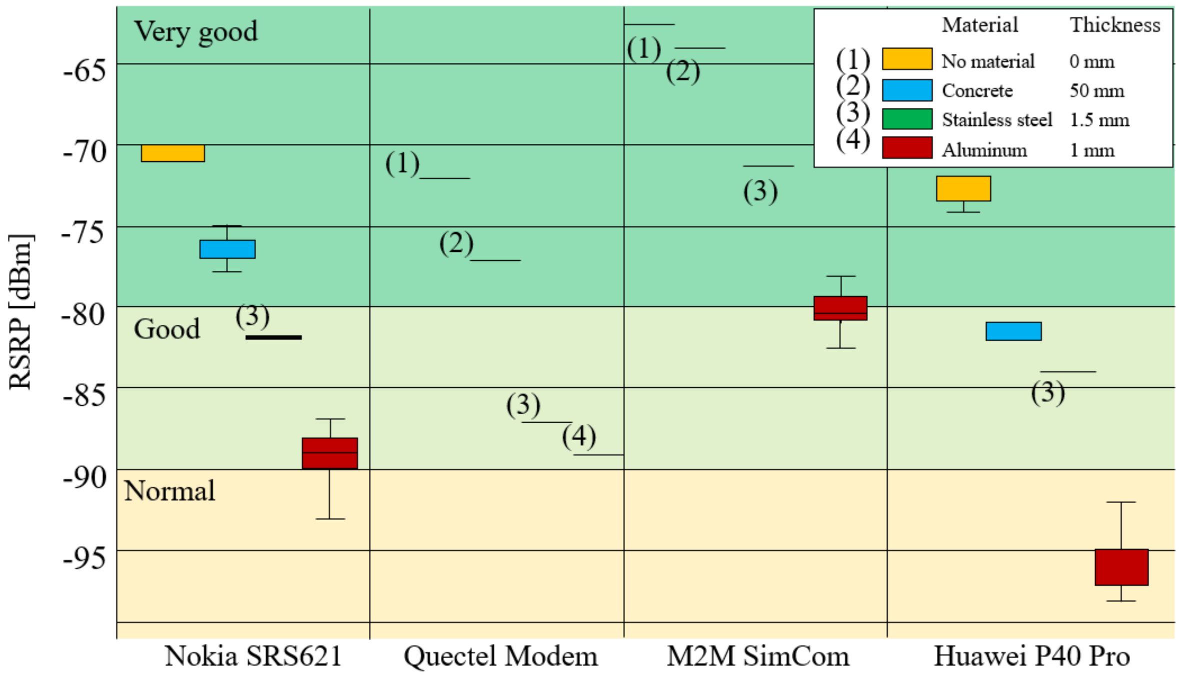

Figure C.4: Boxplot chart of the RSRP-value per end device and material