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RESEARCH ARTICLE

Toward the Realization of Vertical Slices: Mapping 5G Features to Industrial Requirements

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ABSTRACT 5G network is expected to be highly flexible, enabling its adjustment according to user requirements. To achieve this, 5G leverages network slicing, allowing the division of the network infrastructure into different slices with completely different communication performances. However, this flexibility is not easily achieved, requiring the use of available 5G features, Quality of Service (QoS) parameters, and technologies to adapt the communication performance according to the user requirements. Furthermore, to foster wider adoption of 5G by verticals, it is crucial to simplify the network configuration process by providing common interfaces that accept attributes familiar to vertical users. In this line, having a vertical-oriented network slice manager capable of automating the deployment of slices in 5G networks is crucial. One of the key elements involved in creating such a system is a mapping between common communication attributes and available 5G configuration parameters and features. This mapping facilitates the adjustment of communication performance to meet vertical requirements. With this in mind, the document explores the realisation of such a mapping. First, it analyses the communication attributes defined by well-known organisations (e.g., 5G-ACIA, and 5GDNA); these attributes define the performance requirements of network slices or industrial use cases. Then, it maps these attributes to standardised R17 5G functionalities. The mapping is followed by a validation using the 5GAIner infrastructure (part of the IMAGINE-B5G experimental facilities), a real-world commercial-grade 5G Standalone (SA) network. The results showcase the feasibility of using this mapping to realize vertical slices.

INDEX TERMS 5G, testbed, NPN, QoS, network slicing, R17, I4.0, Industry 4.0, quality of service.

I. INTRODUCTION

5G is the latest generation of commercial radio telecommunications that will revolutionise numerous industrial sectors. However, achieving widespread adoption by verticals requires several enhancements compared to its predecessor, 4G.

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5G's main improvements are flexibility and reliability, enabling the deployment of diverse use cases with distinct requirements over a single network infrastructure while maintaining isolation and security between them. 5G achieves this through network slicing, which divides the network infrastructure into distinct segments or slices. Each slice functions as an independent virtual network, logically isolated from others, and supports unique network characteristics, including performance and accessible services.

The 5G network slices are designed to support three primary communication services: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communication (URLLC), and massive Machine Type Communication (mMTC). Each service has distinct priorities: eMBB emphasizes high throughput and spectral efficiency, URLLC focuses on high reliability and low latency, and mMTC targets low device energy consumption and high connection density.

Despite 5G technologies being available in many countries, expected to cover a third of the world's population by 2025,[1] verticals have shown limited adoption of 5G. One of the key factors to foster adoption is the provision of deterministic services, requiring automated network slice deployment, as detailed in [1].

In 5G, network slice configuration must be performed on demand, driven solely by the use case or network slice attributes. A network slice manager is responsible for deploying and managing slices. It should be able to configure the 5G network according to the required communication attributes, thereby ensuring the network provides the slices with the necessary performance.

However, developing such a network slice manager is more complex than initially anticipated. As a result, there is currently no widely available slice manager capable of configuring the entire network based on industrial requirements. In light of this challenge, the work outlined in this document is part of a broader effort to develop a network slice manager capable of configuring a 5G network to accommodate the network slices requested by users.

In particular, Figure 1 provides an overview of the paper's contribution to the broader 5G ecosystem. The paper focuses on mapping target Key Performance Indicators (KPIs) to available network features and configurations, producing optimal network configurations that meet the performance requirements for industrial use cases.

The target KPIs are derived from Industrial Use Cases and defined standards, while the available network features and configurations are derived from previous works (*) [2] and (**) [3], as highlighted in Figure 1. These features result from the collective development efforts of the 3GPP[2] specifications and market requirements, which define the roadmap for developing new functionalities.

The outcomes of this mapping effort contribute to realizing an optimal network design. This mapping is validated in a commercial-graded 5G network, where the performance of the resulting network configurations is evaluated. Subsequently, the resulting KPIs are compared with the target KPIs, demonstrating the effectiveness of the solution outlined in the document.

The main contribution of this paper is the mapping between communication attributes and 5G features/functionalities. This mapping is the foundation for developing a network slice manager capable of automating the deployment of network slices.

The remaining sections of the document are as follows: Section II provides a brief review of the related work. Section III outlines the attributes identified in 3GPP documents and by industrial organisations such as 5G-ACIA[3] to define a network slice and an industrial communication service. Appendix describes the features used in the mapping process. Section IV provides a potential mapping between communication service attributes and 5G features. To validate this mapping, Section V examines example use cases defined by prominent industrial organisations developing and promoting 5G. It assesses the use case requirements and translates them into 5G network features, explaining the rationale behind the translation. Section VI offers an overview of the network, followed by the results achieved for each use case using the provided configurations. Section VII examines the results, explaining their significance and implications. Section VIII concludes the document by discussing the broader implications of the research effort.

II. RELATED WORK

The 5G network is expected to significantly impact society, offering a wide range of new use cases that enhance overall society. However, before the wide deployment of these use cases, both the use cases and the 5G technology need further development.

Several testbeds were deployed around the world to reduce the access barrier to this emergent technology, such as: [4], [5], and [6]. Additionally, various 5G projects have established their testbeds (e.g. 5G-EVE[4], 5G-VINNI[5], and 5GENESIS[6]), where researchers and industry stakeholders test and validate 5G technology and use cases.

Existing research has already assessed the deployment of use cases with 5G networks. For instance, authors in [7] deployed various use cases across different 5G networks. Similarly, in [8], authors adjusted configurations of 5G networks to support industrial use cases, comparing 5G to 4G performance. Furthermore, [9] deployed multiple use cases in different network slices with resource isolation, while [10] explored several network functionalities to adapt network performance for a specific use case over a 5G network.

However, the full potential of 5G can only be realized by tailoring the network to each use case. Academic publications made significant research on the deployment of slices.

For example, [11] and [12] concentrate on slice control plane and data plane deployment, as well as slice management at the service and functions level. Additionally, [13] and [14] explore the optimization of network resources within slices, while [15] investigates the admission of slices into a network.

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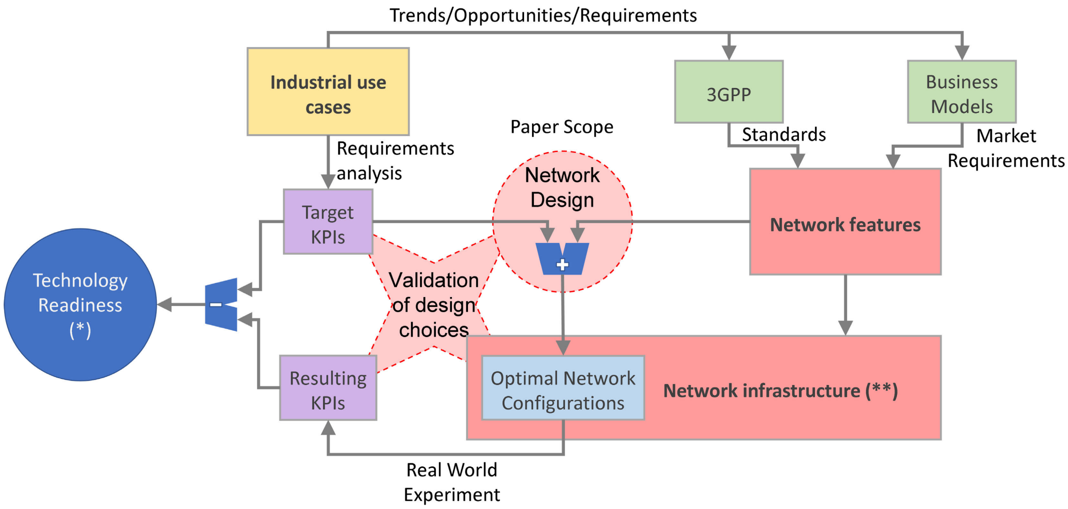

FIGURE 1. **Paper scope within the broader 5G ecosystem.**

Moreover, authors in [16] discuss the isolation and lifecycle management of network slices, and [17] proposes an inter-domain network slicing solution by introducing a Communication Service Management Function (CSMF) capable of communicating with Network Slice Management Function (NSMF) of different network providers. Additionally, [18] analyses 5G network performance when using different frequency bands in the Radio Access Network (RAN).

Furthermore, academic publications are researching specific features and technologies available in 5G, for instance: [19] focuses on Differentiated Services (DiffServ), [20] explores Wake Up Signal (WUS), [21] investigates Multiple Input Multiple Output (MIMO), and [22] examines Coordinated Multi-Point (CoMP).

The academic literature review revealed a notable gap in a comprehensive discussion about the mechanisms available in the 5G network for optimising network resource usage to meet Industrial requirements. Only 5GDNA[7] in [23] provides a limited mapping between 5G technologies and network attributes.

Considering everything, this document comprehensively examines 5G communication attributes and establishes a correlation between communication attributes and available 5G network functionalities. This mapping provides the foundation for configuring network slices in 5G. These 5G mechanisms adapt 5G network communication performance to accommodate the different slice services expected to be available in a 5G network.

III. COMMUNICATION ATTRIBUTES

The network attributes used by the industry and standard bodies to describe use cases were verified to determine the typical communication attributes used. These attributes were gathered from 3GPP, 5GDNA, and 5G-ACIA documentation and are presented in Table 1. Among the attributes, the packet error rate is closely related to reliability, and many settings affect both attributes. Therefore, only reliability is used in the mapping process.

Furthermore, the Transfer interval characterizes the transmission but does not define a KPI. Instead, it aids in the configuration of selected features. Therefore, it is not used in the mapping, but it is considered in the examples provided.

Additionally, all network slice attributes identified in 3GPP documents for release 17 (R17) were examined and outlined in Table 2. Each attribute is accompanied by a brief description, providing a more standardized way to characterize communication.

These two tables provide a wide range of attributes expected from verticals and any 5G user to characterize the performance requirements of 5G communication. However, as this document focuses on network performance manipulation and specific communication functionalities, some attributes presented will not be further discussed, as they serve purposes beyond the scope of this document.

IV. 5G FUNCTIONALITIES TO REQUIREMENTS MAPPING

In Appendix, a brief description of all 5G functionalities is provided, while Table 11 presents the meaning of each abbreviation used to help understand the document and the mapping decisions made. This section maps the 5G functionalities presented to the use cases and slice attributes previously discussed.

Figure 2 illustrates the mapping of 5G features to use case and Network slice attributes. The enumeration in the figure corresponds to the one used in the discussion below and helps to understand the connections between attributes and functionalities. While most functionalities impact multiple attributes, the figure may depict some functionalities mapped to only one attribute. This could be due to the functionality having a more pronounced effect on that attribute, or it should

[7] https://www.5gdna.org/?_l=en, (April 2024).

TABLE 1. Use case attributes.

Use case Attributes		3GPP [24]	5GDNA [25] [23]	5G-ACIA [26]
Packet Data Unit (PDU) session Attributes				
Availability		X	X	X
Reliability		X	X	X
Latency		X	X	X
Jitter		X	X	X
User experience Data Rate		X	X	X
Packet Error Rate		X	X	
Communication Direction		X		
Message Size		X		X
Transfer Interval	Lower Bound	X		X
	Target Value	X		
	Upper Bound	X		
User Equipment (UE) Attributes				
Aggregate User experience Data Rate		X		
Battery lifetime		X		
UE Speed / Mobility		X		X
Slice Attributes				
Number of active UEs		X		
Number of UEs		X		
UE Density (UE/m^2)		X	X	
Range (m)		X		
Synchronization	Service Area	X	X	X
	Number of UEs	X		
	Synchronicity budget requirement	X		
Positioning	Availability	X		X
	UE Speed	X		
	Horizontal Accuracy	X		
	Vertical Accuracy	X		
	Heading	X		
	Latency for position estimation of UE	X		
User Plane Transport Protocol				X
Security / Isolation			X	

only be enabled when optimizing the mapped attribute. Enabling these functionalities may affect other attributes, but they are considered secondary requirements for the use case.

Some attributes were excluded because no functionality presented can map to the attribute, or the attribute characterizes communication rather than KPIs. For example, transfer interval defines transmission periodicity, which helps select functionalities to use and values for configuring them, such as Discontinuous Reception (DRX), WUS, configured scheduling, and Time-Sensitive Communication (TSC).

Many use case attributes have a similar mapping compared to network slice attributes, so they will be aggregated whenever possible. When both attributes have the same name, only one name is referenced. When they have different names, the attributes are separated by a "|" symbol, with the use case attribute listed first, followed by the network slice attribute.

The rest of this section focuses on the paper's main contribution, which is the mapping between attributes and functionalities while also explaining how each functionality influences the specified attribute. This mapping is the culmination of extensive theoretical studies and experimental work using a 5G network [2]. It offers the best solutions for interrelating attributes and functionalities and paves the way for realizing fully-fledged network slice manager systems.

1) *Aggregate User Experience Data Rate* can be defined using UE-Aggregate Maximum Bit Rate (UE-AMBR), which limits the maximum throughput each UE can use in all communications employing Non-Guaranteed Bit Rate (Non-GBR) QoS flows.
2) *UL/DL Throughput per UE* can be defined using UL/DL UE-Slice-Maximum Bit Rate (UE-Slice-MBR), which limits the throughput a UE can utilize within the slice.
3) *User Experience Data Rate* is influenced by several functionalities. UL/DL Session-AMBR determines the maximum bit rate of all Non-GBR QoS flows within a PDU session. When UE only uses one connection, this parameter defines the UE's maximum bit rate. Both GBR and delay-critical GBR QoS Flow utilize Guaranteed Flow Bit Rate (GFBR) and Maximum Flow Bit Rate (MFBR) to ensure minimum and maximum throughput. Once a cell accepts a GBR QoS Flow, the GFBR is guaranteed regardless of other users' connections, unless the UE loses resources due to Allocation and Retention Priority (ARP) allocation or the network experiences a critical failure. The Average Window parameter defines the time window used to calculate the UE bit rate, influencing the communication stability of QoS flow guaranteed and maximum bit rates. Lower values provide more stable

TABLE 2. 3GPP network slice attributes.

R17 Network Slice Attributes [27]		**Attribute Description**
Administrative State		State of the Network Slice (NS) instance, if it can be locked, unlocked, or shutting down.
NS Info	NS Instance ID	Specifies the identifier of the NS instance
	NS name	Specifies the name given to the NS instance
	Description	Describes the NS instance
Resource Sharing Level		Specifies if NS resources are shared with other NSs
Coverage Area TA List		List of Tracking Areas where NS can be used
Maximum Number of UEs		Specifies the maximum number of UEs that can simultaneously access the NS instance
UL/DL Latency		Defines the required Uplink (UL)/Downlink (DL) end-to-end Latency (ms), it is also used to evaluate the performance of end-to-end NS
UE Mobility Level		Specifies the mobility level of UE accessing the network slice, which can be stationary, nomadic, restricted mobility, or full mobility.
SST		Specifies the Slice/Service Type (SST) that should be supported.
Availability		Specifies the percentage of time the service should comply with the agreed QoS.
Coverage Area		Specifies the geographic area where NS is accessible
Network Slice Sharing Indicator		Specifies if the NS instance can be shared with several services, or if an exclusive NS instance is necessary for each service
Delay Tolerance		Specifies if the slice supports flexible latency, this is in case it is not necessary for high system performance.
Deterministic Communication	UL/DL	Specifies properties of deterministic communication for periodic user traffic.
	Availability	Specifies if NS supports deterministic communication
	Periodicity List	Specifies a list of periodicities that NS supports
UL/DL Throughput per Slice	Guaranteed Throughput	Defines the UL/DL data rate of the NS in the entire coverage area.
	Maximum Throughput	
UL/DL Throughput per UE	Guaranteed Throughput	Defines the UL/DL data rate supported by NS per UE.
	Maximum Throughput	
UL/DL Maximum Packet Size		Maximum Packet Size supported by the NS.
KPI Monitoring		Specifies a list of Key Quality Indicators (KQIs) and Key Performance Indicators (KPIs) names available for performance monitoring
User Management Open		Specifies if NS customer can manage users, groups, services, and requirements of the NS instance
V2X Communication Models		Defines if Vehicle-to-everything (V2X) communication is supported
Terminal Density		Specifies the user density in the coverage area of the NS.
Activity Factor		Defines the percentage value in the total number of UEs that can be simultaneously active.
UE speed		Maximum speed (km/h) supported by NS, in which QoS can be assured.
Jitter		Specifies the deviation of the time parameters from the desired value.
Survival Time		Specifies the time that the application can run without receiving messages.
Reliability		Specifies the percentage of packets sent through NS that are successfully delivered while complying with the QoS required.
Maximum Number of PDU Sessions		Defines the maximum number of concurrent PDU sessions that NS supports.
Radio Spectrum		Radio Spectrum in which NS is supported.
Maximum UL/DL Data Volume		Maximum UL/DL Data volume transmitted in the NS instance in Mbyte/day.
NB-IoT		Specifies if NS supports Narrowband Internet of Things (NB-IoT) in the RAN.
Synchronicity	Availability	Defines if device synchronicity is supported
	Accuracy	Accuracy of Synchronicity.
Positioning	Availability	Contains the list of positions methods supported by the NS.
	Prediction Frequency	Specifies how often a customer can request position information.
	Accuracy	Specifies the precision of the location information.
Slice Simultaneous Use		Defines if the slice is possible to use with others simultaneously, and which types of slices can be used simultaneously.
Energy Efficiency		Identifies the requirements in terms of energy. This value depends on the SST value: eMBB (UL throughput+Dl throughput)/ energy consumed =(bit/J); URLLC 1/((Latency UL+Latency DL)*energy consumption)=$(0.1\text{ms*J})^{-1}$, exists a variant that takes into account network traffic; and mIoT (registered UE / Energy Consumed) = (user/J) [28]
Network Slice Specific Authentication and Authorization (NSSAA) Suport		Specifies if network slice users need additional authentication and authorization through an Authentication, Authorization and Accounting (AAA) server with additional credentials.
N6Protection		Defines required security functions and rules for NS in N6 interface.
	Security Function ID	Identification of the Security function used.
	Security Function Type	Describes the type of Security Function. E.g. Firewall, Network Address Translation (NAT), antimalware, etc.
	Security Rules	Defines the Security Rules if nothing is defined, the default rules are used.
New Radio (NR) Operating Bands		5G frequency bands that the NS can use.

transmissions for QoS Flows with AMBR, GFBR, or MFBR.

Resource Isolation and Management allocate or prioritize resources for communication, ensuring assured resources or priority in case of network congestion. 256 and 1024 Quadrature Amplitude Modulation (QAM) allows a higher modulation scheme when a UE is in the cell coverage centre, enabling higher data rates with the same spectrum resources. Single User-MIMO (SU-MIMO) enhances UE throughput using the same resources by using spatial multiplexing in communication, thereby multiplying throughput.

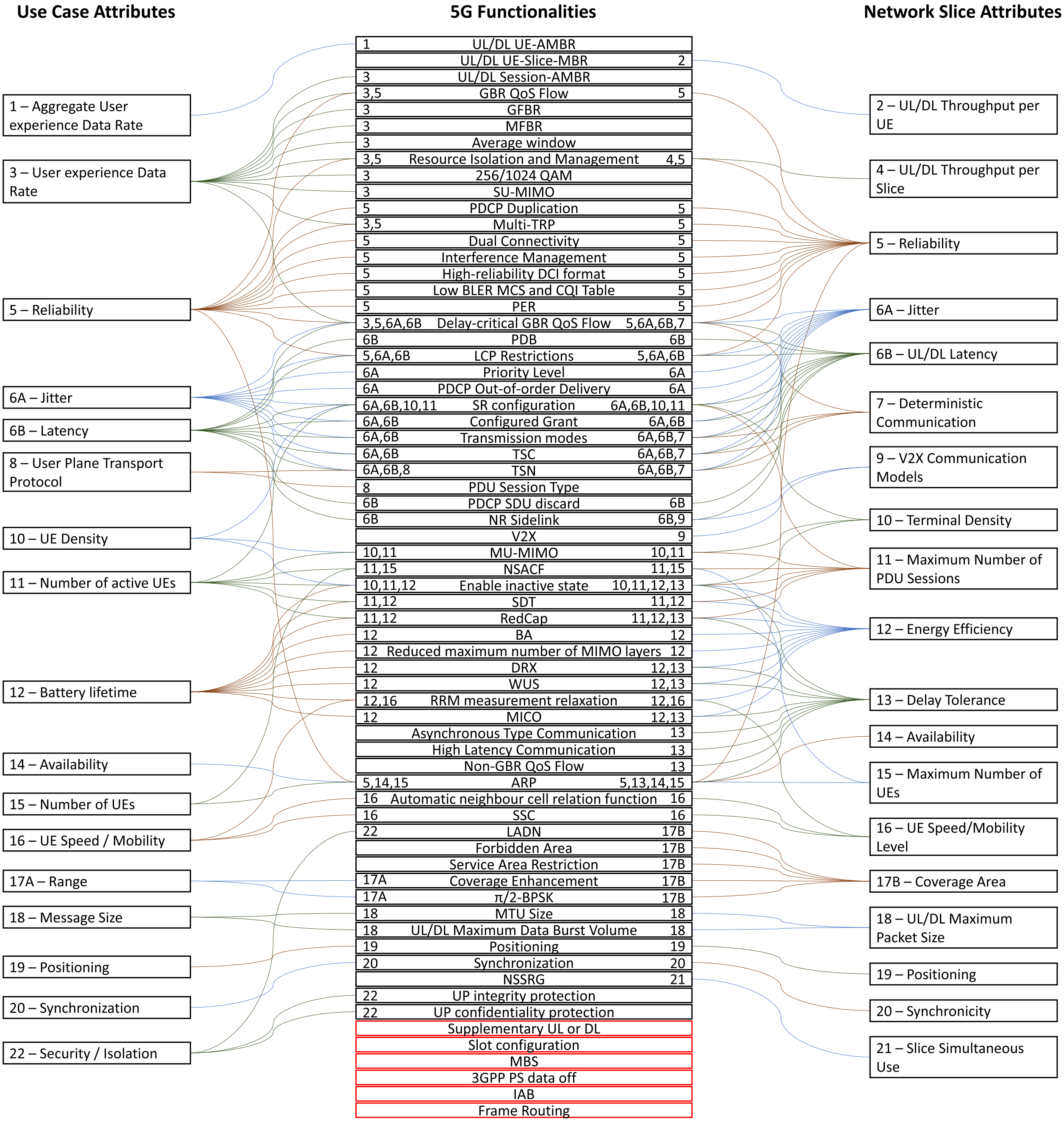

FIGURE 2. Use case and network slice attributes mapping to network functionalities.

SU-MIMO is a specific application of multi-Transmission and Reception Point (multi-TRP), where the UE connects with several TRPs in the same cell. Multi-TRP can also be employed with neighbour intra-frequency cells. In this scenario, communication performance can be enhanced when the UE is out of the cell coverage centre, improving the communication signal by communicating with multiple antennas.

4) *UL/DL Throughput per Slice* can be controlled using Resource Isolation and Management, which defines specific resource pools available to each slice. This provides guaranteed throughput to slices by allocating specific resources to each slice and limiting the maximum throughput, ensuring that each slice can use only a certain amount of resources. As a result, each slice may have a reserved resource pool and access to a shared resource pool.

5) *Reliability* can be controlled through the following functionalities. Resource Isolation and Management allocate resources or prioritise access to resources,

increasing the probability of communication by ensuring the availability of necessary transmission resources. Packet Data Convergence Protocol (PDCP) duplication decreases the packet loss probability during transmission by sending packets two times in the same TRP with different transmission resources. Multi-TRP transmits the same packet to all TRPs, increasing the likelihood of successful transmission. Dual connectivity can be employed when extreme reliability is required, sending the same packet through two different networks with different levels of disjoint paths depending on requirements, thus reducing the probability of losing both packets due to the same problem.

Interference Management can adjust radiation parameters in intra-frequency cells to reduce noise generated between them. High-reliability Downlink Control Information (DCI) format modifies the transmission parameters of control channels to enhance reliability, by reducing the coding scheme or increasing transmission power compared to less demanding transmissions. Low Block Error Rate (BLER) Modulation and Coding Scheme (MCS) and Channel Quality Indicator (CQI) tables prioritize low block error probability in transmission over throughput by selecting a lower modulation scheme. GBR and Delay-critical GBR QoS Flows utilize the Packet Error Rate (PER) to define the maximum packet error rate acceptable for guaranteed throughput. Logical Channel Prioritization (LCP) restrictions ensure better performance by allocating the best resources, in terms of latency or reliability, to the logical channel used. ARP impacts reliability by determining whether resources can be allocated from one UE to another, ARP pre-emption vulnerability must be disabled to avoid the reallocation of resources to higher-priority transmissions.

6) *Jitter (A) and Latency (B)* were not extensively mapped to the functionalities covered by reliability. However, any functionality enhancing reliability also impacts jitter by reducing packet retransmissions. Additionally, as jitter and latency are closely related, and most functionalities affect both attributes, they are presented together. Delay-critical GBR QoS Flow with Packet Delay Budget (PDB) can define the maximum transmission delay of PER percentage of packets in the GFBR throughput transmission, thus defining transmission latency and limiting jitter. LCP restriction can be used to allocate resources with lower latency and less noise to reduce jitter.

   Priority level differentiates between flows when requesting resources, ensuring that high-priority flows have faster access to communication resources than other flows. PDCP out-of-order delivery allows packet forwarding without waiting for all previous packets to arrive. Scheduling request (SR) configurations define the periodicity at which UEs can make scheduling requests; lower periodicity reduces latency and jitter. Configured grant allocates resources with a certain periodicity without requiring scheduling requests from UEs, reducing time wasted in scheduling transmission resources.

   There are two transmission modes: Acknowledged Mode (AM), where the receiver informs the sender of successful transmission or not, and Unacknowledged Mode (UM), where the receiver does not inform the sender of packet arrival. In cases of extreme latency requirements, unacknowledged mode is advised, as the acknowledgement time may exceed or be too close to the latency requirement. However, in flows with less demanding latency restrictions, acknowledged mode reduces packets lost.

   TSC and Time Sensitive Networking (TSN) employ different mechanisms to minimize jitter while ensuring low latency. TSC is a technology used in 5G networks to guarantee performance, while TSN is a protocol used in other types of networks. Therefore, using both functionalities can ensure optimal performance when communication traverses different technologies.

   PDCP service data unit (SDU) discard ensures that the RAN discards packets not transmitted within the designated timeframe, reducing resource wastage caused by packets transmitted after latency requirements have passed.

   NR Sidelink reduces latency in Device-to-Device (D2D) communication when devices are closed by enabling direct communication between devices. This bypasses the User Plane Function (UPF) and only passes through the RAN once, thus reducing latency.

7) *Deterministic Communication* requires the use of Delay-critical GBR QoS Flow, ensuring that PER percentage of packets are transmitted with a latency below the PDB. TSN and TSC, with resource reservation and time synchronization of network equipment, can provide deterministic communication.
8) *User Plane Transport Protocol* can be defined using PDU session type, enabling the selection of Ethernet, Internet Protocol (IP) version 6 (IPv6), IP version 4 (IPv4), and Unstructured, supporting other protocols. TSN can be a protocol required since it defines the protocol used at both ends of the 5G network.
9) *V2X Communication Models* are enabled by activating V2X functionality in a 5G network. Since Vehicle-to-Vehicle (V2V) communication is often necessary in V2X scenarios, NR sidelink can provide D2D communication, reducing latency. Additionally, Multicast–Broadcast Services (MBS) with one-to-many communication is a functionality commonly used in V2X communications.
10) *UE Density* | *Terminal Density* represents the number of UEs within a determined physical area. These attributes are affected by the same functionalities as the following attributes. Therefore, the next paragraph explains all of them together.

11) *Number of active UE | Maximum Number of PDU Sessions* define the number of active UEs concurrently connected. In high UE density scenarios, typically involving Reduced Capabilities (RedCap) devices, certain functionalities take into account UEs with low throughput or sparse transmissions.
For instance, SR configuration determines the SR transmission periodicity and impacts the number of connected UEs to the same cell. A lower SR periodicity limits the number of active UEs due to congestion in control plane resources. Multi User-MIMO (MU-MIMO) enhances terminal density enabling antennas to communicate simultaneously with multiple UEs, optimizing time and spectrum resources.
The inactive state allows UEs to conserve energy and network resources while maintaining a PDU session, increasing the number of UEs in a limited space. Combining the inactive state with Small Data Transmission (SDT) allows UEs to transmit small data packets without transitioning to the active state, further reducing network resource consumption and increasing connection density. The Network Slice Admission Control Function (NSACF) controls the number of UEs connected to the network through a slice, specifying the maximum number of active UEs.
12) *Battery lifetime | energy efficiency* is affected by the following functionalities. The inactive state allows UEs to minimize control communication while retaining a PDU session during inactivity periods, reducing the energy wasted on maintaining a network connection. SDT enables periodic transmission of small packets while UEs are in the inactive state. Transitioning to the idle state can decrease energy consumption even more, but UE loses PDU session, requiring a more energy-intensive and time-consuming reconnection process compared to the process from the inactive state. The choice between these states depends on the use case's latency requirements and transmission periodicity, as each state offers advantages over the other in certain scenarios, balancing energy efficiency with the need for maintaining connectivity.
RedCap enables UEs with limited capabilities to use a 5G network, using hardware and software optimizations to minimize power consumption. Meanwhile, BA allows UEs with low throughput requirements to use a portion of the spectrum available in the cell. For instance, by using a narrower bandwidth, such as 20 MHz instead of a wider bandwidth like 100 MHz, UEs can reduce energy consumption. Additionally, BA involves reducing the maximum number of MIMO layers, enabling UEs to operate with fewer MIMO layers. This deactivates unused antennas, further decreasing energy consumption.
DRX organizes time into cycles, each comprising online and offline duration. During the offline period, UEs can deactivate antennas, only activating them during the online phase to monitor the Physical Downlink Control Channel (PDCCH) for new messages. This reduces the energy spent on monitoring PDCCH. With WUS, power savings are further enhanced as UEs only monitor the wake-up signal, which is much shorter than the DRX online duration. Upon receiving the WUS signal, UEs perform a normal DRX cycle to receive control channel information from the network.
Radio Resource Management (RRM) measurement relaxation enables UEs to skip monitoring signals from neighbour cells when stationary or at the centre of cell coverage, conserving energy expended on such monitoring.
Mobile Initiated Connection Only (MICO) allows UEs in the idle state to not monitor network control channels, reducing UE energy consumption when transmitting sparse messages, such as one message per day. However, all downlink communications must tolerate delays since the UE will not receive downlink messages between transmissions.
13) *Delay Tolerance* refers to scenarios where transmission timing is not critical, allowing UEs to transmit when sufficient network resources are available or prioritize energy savings over latency. In such cases, UEs can disable communication or disconnect from the network without impacting the use case.
Technologies like DRX, WUS, Non-GBR QoS Flow, RedCap, inactive state, and idle state, are suitable functionalities for delay-tolerant communications.
MICO ensures UEs transmit only when necessary, prioritizing energy saving over latency. However, for MICO to be effective, asynchronous type communication support and high-latency communication are required, allowing the network to store downlink control and user plane packets while UE is inaccessible.
Low-priority ARP with pre-emption vulnerability allocates resources based on priority, ensuring high-priority communications receive resources when necessary. Conversely, delay-tolerant use cases transmit during off-peak hours, using unused resources in the 5G network.
14) *Availability* is impacted by ARP, which determines the access priority to network resources. ARP can prioritize critical end devices with pre-emption capability and high priority, ensuring they have communication when necessary. In contrast, non-critical devices are assigned pre-emption vulnerability and lower priority, giving them access to the network when it is not congested. When pre-emption vulnerability and capability are disabled, ARP decides the resource allocation among multiple UEs simultaneously requesting resources. In such cases, high-priority UEs are prioritized but cannot preempt allocated resources.
15) *Number of UEs | Maximum Number of UEs* indicates the number of UEs attached to the network. UEs in the Radio Resource Control_Connected

(RRC_CONNECTED) and RRC_INACTIVE states maintain active PDU sessions, while those in the RRC_IDLE state are attached to the network without an active communication session. However, being attached facilitates the establishment of PDU sessions. NSACF directly impacts this attribute by specifying the maximum number of UEs associated with a network slice. Additionally, ARP allows UEs with sporadic periodic communications to preempt resources from UEs that are delay-tolerant but have more frequent communication. Consequently, UEs with sparse communication temporarily preempt resources for their transmission, releasing them immediately after transmission.

16) *UE Speed/Mobility Level* encompasses both quantitative (speed) and qualitative (mobility) aspects of velocity. When UE mobility level ranges from stationary to limited within a cell's range, RRM measurement relaxation can be used. In such scenarios, UEs do not need to perform handovers, thus eliminating the need to track neighbour cells. However, for UE mobility levels varying from nomadic to restricted or full mobility, the Automatic neighbour cell relation function plays a crucial role in facilitating the handover process, thereby mitigating any adverse impact on communication performance. Additionally, defining the Session and Service Continuity (SSC) value is essential, but the value depends on specific use case requirements. SSC offers three configurations: In Mode 1, the UE maintains the PDU session with the same UPF regardless of the access network used; in Mode 2, the network releases the PDU session while instructing the UE to establish a new connection immediately; and in Mode 3, the network and the UE collaboratively establish a new PDU session before releasing the old PDU session.
17) *Range (A) | Coverage Area (B)* is context-dependent and can be configured using several functionalities. These include: Local Area Data Network (LADN), which specifies the area of slice operation, Forbidden Area, which identifies regions where UEs cannot access the network via any technology, and service area restriction, which determines areas where UEs cannot use the NR network but can use other technologies.
When specifying the maximum distance between UE and gNodeB Coverage enhancement can be used. Coverage Enhancement involves configuring gNodeB to extend network coverage, which is useful in locations where antenna deployment is challenging or impossible. Additionally, Lower Modulation Schemes can enhance the signal-to-noise ratio, improving reliability or coverage, but reducing throughput. For example, Pi/2-BPSK (Binary Phase Shift Keying) is the lowest modulation scheme that maximizes gNodeB coverage.
18) *Message Size | UL/DL Maximum Packet Size* is directly shaped by the MTU (Maximum Transmission Unit) size, which defines the maximum packet size in the communication between UE and PDU session anchor UPF (PSA-UPF). Packets larger than the MTU size are segmented during transmission. Additionally, for Delay-critical GBR QoS Flows, the Maximum Data Burst Volume defines how much data the access network must support while maintaining performance requirements during a PDB period, indirectly establishing the maximum message size the UE can transmit while maintaining required transmission KPIs.
19) *Positioning* is provided by the 5G Network Positioning functionality. This feature offers various configurations including position precision, frequency of position measurements, and whether it uses relative or absolute precision.
20) *Synchronization | Synchronicity* in 5G is provided by synchronization mechanisms, which encompass time synchronization, aligning all clocks with a universal timing standard, and frequency synchronization, ensuring uniform time intervals across devices, but absolute time may vary between devices. Synchronization configurations also specify the protocol utilized and the precision level provided.
21) *Slice Simultaneous Use* is managed through the Network Slice Simultaneous Usage Group (NSSRG). The NSSRG maintains a list of slices that can be used simultaneously. If the list within NSSRG is empty, UEs cannot connect to multiple slices simultaneously.
22) *Security and Isolation* can be enforced through UP integrity and confidentiality protection, ensuring the security of user plane communication within the network. While these configurations only affect internal 5G network traffic, mechanisms like LADN can provide additional isolation by restricting network operations to defined areas, creating local networks. LADN in conjunction with Multi-access Edge Computing (MEC) or similar technologies, allows verticals to confine network traffic within their premises, isolating their user plane from external networks, even when the 5G control plane is provided by the operator's infrastructure.
23) *Functionalities without attribute (highlighted in red in Figure 2)* have no association because their impact may be difficult to characterize by a single attribute, or because the attributes available are too generic to capture their effects. For instance, the user experience data rate is indirectly influenced by most functionalities.
The Supplementary UL/DL and Slot configuration adjust antenna uplink and downlink resource allocation according to the network's requirements. Supplementary UL/DL requires a sub-3GHz spectrum band to expand the available bandwidth. Slot configuration defines the percentage of spectrum resources allocated for uplink and downlink within a Time Division Duplexing (TDD) antenna.

MBS and NR sidelink can be associated with V2X Communication Models due to requiring D2D and one-to-many communication in V2X scenarios. However, these functionalities are not exclusive to V2X use cases; they are applicable in various scenarios that necessitate D2D and one-to-many communication.

The 3GPP PS data off feature restricts available services on devices by defining a list of accessible services for UEs while active. By configuring critical services, this feature reduces bandwidth consumption during peak hours by disabling non-essential and delay-tolerant services, thereby freeing up communication resources.

Integrated Access and Backhaul (IAB) enables 5G UEs to operate as mobile NR cells. With IAB technology, a UE can connect to the network via 5G radio while simultaneously providing network coverage in its vicinity. This facilitates the deployment of mobile cells that do not require Cable connections (such as Ethernet or Fiber) for backhaul, as they establish their backhaul connection through the 5G radio.

Frame Routing, depending on its implementation, can contribute to deploying energy-efficient end devices. This feature enables the deployment of a 5G gateway that seamlessly connects various equipment using another access network, which can be wired or wireless. With Frame Routing, end devices establish direct 5G PDU sessions with UPF, enabling direct communication with the network. Additionally, the IP address is provided by the 5G network, eliminating the need for port NAT (Network Address Translation) or similar protocols that introduce additional processing overhead. This streamlined communication process can lead to simpler and more energy-efficient data transmissions.

V. USE CASE EXAMPLE

Three use cases were selected to provide a realistic validation of the proposed mapping. The selections were from those defined by reputable industry organizations and standard bodies, such as 5G-ACIA and 3GPP documentation. The selection criteria also considered the performance requirements of each use case, ensuring that they align with one of the three primary 5G services.

From the 5G-ACIA documentation [26], the Mobile robots use case with mMTC-like performance and the Motion Control use case with URLLC-like performance were selected. Additionally, from the 3GPP documentation [24], the Robotic Aided Surgery use case with eMBB-like performance was chosen. The significant discrepancy between the performance requirements of these use cases highlights the versatility achieved with the proposed mapping.

The next subsections discuss the functionalities that can be enabled, considering the attributes of each use case. However, some functionalities have a configuration granularity that extends beyond a single slice, impacting multiple use cases simultaneously. The functionalities operate at different levels of granularity, such as QoS Flow, PDU Session, UE, slice, cell, multi-cell, and UPF. Each level of granularity delineates the scope of the impact of the functionality being activated. For example, configuring at the QoS Flow level only affects a specific Flow, while configuring at the UE level impacts all communications involving the affected UE. Notably, configurations at the cell, multi-cell, and UPF levels affect more than one single slice. Therefore, before enabling or disabling them, it is necessary to consider broader network or multi-use case requirements.

TABLE 3. Mobile robots attributes.

Communication Service Availability	99.9999%
Communication Service Reliability	1 year
End-to-End Latency	100 ms
Transfer Interval	100 ms
Survival Time	500 ms
Message Size	500 bytes
Mobility	4km/hour
Positioning Service	yes, accuracy: 1m
User Plane Protocol	IP

A. MOBILE ROBOTS

This use case is extracted from Table 5 in the [26] document and features the attributes outlined in Table 3. It provides communication for the fault-tolerance mechanisms of the AGVs (Automated Guided Vehicles) application layer. The AGV sends a status packet every 100 ms to the control system. If the AGV receives no response within 500 ms, it sends a disconnection alarm and transitions to an idle state. While idle, the AGV sends a status packet every second. If no response is received within 5 seconds, the AGV considers the connection lost. In such a scenario, the AGV shuts down, halting its tasks, which impacts the production line and restricts other AGVs from passing through the location of the disconnected AGV.

Analysing the use case attributes, the availability aligns with the maximum value defined in the 5G-ACIA document. While the reliability requires one year without failure, the survival time allows three packet retransmissions before approaching a service failure. The latency and throughput requirements are not stringent for a 5G network, with packets sent every 100 ms resulting in 40 Kbps. Mobility is nomadic with low speed, and the positioning attributes require low accuracy. Additionally, the user plane protocol required is the default 5G protocol. Considering these attributes, the use case is well-suited for employing an mMTC service, reducing end-device power consumption.

The use case requires Positioning, the Automatic neighbour cell relation function, and SSC mode 2 or 3 depending on the flexibility needed. Considering the latency and throughput requirements, energy-efficient functionalities such as reducing the maximum number of MIMO layers, DRX, WUS, and BA can be enabled. Additionally, a RedCap device can be utilized. The SR configuration or configured grant must allow UEs to communicate at least once every 100 ms.

TABLE 4. Mobile robots functionalities.

mMTC Service	
Required Functionalities	
Positioning	1 meter precision
Automatic Neighbour Cell Relation Function	
SSC	mode 2 or 3
ARP	Medium-High priority with pre-emption capability
GBR QoS Flow	Minimum of 20 Kbps guaranteed bit rate
Average Window	0.5 to 1 s
PDB	100 ms
SR Configuration or Configured Grant	allowing a transmission each 100 ms
Transmission Mode	Acknowledged Mode (AM)
Optional Functionalities	
DRX	Cycle of 100 ms or below
WUS	
Bandwidth Adaptation (BA)	
Reduced Maximum Number of MIMO Layers	
RedCap	
MU-MIMO	

TABLE 5. Motion control attributes.

Communication Service Availability	99.9999%
Communication Service Reliability	10 year
End-to-End Latency	1 ms
Transfer Interval	1 ms
Survival Time	0 ms
Message Size	64 bytes
Positioning Service	No
User Plane Protocol	TSN
Time Synchronization Precision	900 ns

The attributes such as the number of UEs are not defined. However, MU-MIMO and AM transmission modes can be used. To ensure high availability and reliability, a high ARP priority value with pre-emption capability can be assigned, ensuring UEs always maintain a network connection. Pre-emption vulnerability should be disabled to prevent resource loss to another use case. Moreover, a GBR QoS flow of at least 20 Kbps can be used. The average window should be set to at least 0.5 seconds and a maximum of 1 second if GBR falls below the necessary throughput. The PDB should be 100 ms or below.

All the functionalities that should and can be enabled for this use case are presented in Table 4.

B. MOTION CONTROL

This use case is from Table 6 on [26] and has the attributes presented in Table 5. The use case provides connectivity for a motion control system, responsible for controlling moving or rotating parts of a machine. Examples are printing presses, machine tools, and packaging machines. The failure of these use cases usually means a complete shutdown of the production line, thereby imposing demanding requirements in communication such as very low latency, high reliability, and deterministic communication.

Considering the attributes, availability needs to be maximized, while reliability is set at 10 years without survival time, indicating zero tolerance for packet loss. Latency is specified at 1 ms with the TSN protocol, and a 64-byte packet is transmitted each millisecond, resulting in a throughput attribute of 512 Kbps per second. Additionally, clock synchronization with a precision of 900 ns is required. Given these attributes, the use case demands a URLLC service, so the enabled functionalities should be tailored accordingly.

Several key functionalities must be enabled to meet the stringent reliability and low latency requirements. First, 5G Synchronization with a precision of 900 ns is necessary to ensure precise timing across the network. Additionally, maximum ARP priority with pre-emption capability must be employed.

A Delay-critical GBR QoS Flow should be implemented with specific parameters such as a minimum PER, a PDB of 1 ms, and a guaranteed rate of at least 512 Kbps to ensure reliable and timely data transmission. Resource Isolation and Management, coupled with LCP Restrictions, can reserve resources with minimal noise and latency for all devices involved in the use case.

Furthermore, enabling PDCP Duplication, multi-TRP, Dual Connectivity, Interference management, High-reliability DCI format, and Low BLER MCS and CQI table can reduce packet loss in control and user plane transmissions. Leveraging the maximum priority level, PDCP Out-of-order delivery, configured Grant, TSC, and TSN can minimize latency.

Considering the latency threshold of 1 ms, employing UM transmission mode disables acknowledgements, which would arrive after the required timeframe. Implementing PDCP SDU discard with a threshold of 1 ms or lower can prevent resource wastage by discarding packets that exceed latency restrictions.

Additionally, MU-MIMO should be disabled to avoid interference, while SU-MIMO can be enabled or disabled based on network performance and requirements.

The functionalities are summarized in Table 4.

C. ROBOTIC AIDED SURGERY

This use case, sourced from Table 5.2-1 in [24], is outlined in Table 7. It provides communication in invasive surgical procedures where precision and delicacy are crucial. The system facilitates intricate tissue manipulation and access to challenging anatomical locations. It translates the surgeon's hand movements into smaller, more precise actions, enabling the manipulation of tiny instruments with greater flexibility than the human hand. Additionally, it filters out hand tremors and other inconsistencies to ensure consistent surgical outcomes.

The attributes of this use case emphasize high availability and reliability, with a survival time of 1 ms. Given the static nature of the UE, mobility-related features can be disabled. These attributes position the use case between an eMBB and a URLLC service. A high-priority ARP with pre-emption capability is necessary to meet the high availability requirement. Similarly, configurations to minimize packet loss are crucial

TABLE 6. Motion control functionalities.

URLLC Service	
Required functionalities	
Synchronization	900 ns precision
ARP	Maximum priority with pre-emption capability
Delay-Critical GBR QoS Flow	512 Kbps of guaranteed bit rate
PER	Minimum value
PDB	1 ms
Resource Isolation and Management	With enough resources for all use case transmissions
LCP Restrictions	selecting resources with the lowest noise and latency
PDCP Duplication	
Multi-TRP	
Dual Connectivity	
PDCP Duplication	
Interference Management	
High-Reliability DCI Format	
Low BLER MCS and CQI Table	
Priority level	Maximum
PDCP Out-of-Order Delivery	
TSC and TSN	
Configured Grant	1 ms duration
Transmission Mode	Unacknowledged Mode (UM)
PDCP SDU Discard	<1 ms
MU-MIMO Disabled	
Depends on network performance	
SU-MIMO	

TABLE 7. Robotic aided surgery attributes.

Communication Service Availability	99.9999%
Communication Service Reliability	>1 year
End-to-End Latency	<20 ms
Transfer Interval	1 ms
Survival Time	1 ms
Message Size	250 to 2000 bytes
User Experienced Data Rate	2 to 16 Mbit/s
UE Speed	stationary
Number of UEs	2 per 1000 km^2 = <1 per antenna

to ensure high reliability. The user experience data rate ranges from 2 to 16 Mbps, necessitating reasonable throughput and prompting the need for configurations to enhance throughput and reduce network resource consumption.

The use case requires a delay-critical GBR QoS Flow with a GFBR close to or equal to UE throughput. Resource Isolation and Management should reserve the majority of resources necessary for communication. PER should be configured with a low value, and PDB should be equal to or below 20 ms. Depending on cell performance, functionalities such as PDCP duplication, multi-TRP, interference management, High-reliability DCI format, and Low BLER MCS and CQI table may be necessary. Configured grant with a 1 ms frequency or an SR configuration allowing UEs to request every 10 ms must be configured. Additionally, a high priority level, PDCP Out-of-order delivery, PDCP SDU discard close to 20 ms, and AM transmission mode should be enabled. Depending on the network and UE placement relative to antennas, 256/1024 QAM and inter-cell multi-TRP focused on throughput can be enabled. SU-MIMO should also be enabled. The 20 ms latency also permits the use of DRX with a cycle lower than 20 ms.

The functionalities to use are summarized in Table 8.

TABLE 8. Motion control functionalities.

Between eMBB and URLLC Service	
Required functionalities	
ARP	High priority with pre-emption capability
Delay-critical GBR QoS Flow	from 2 to 16 Mbps of guaranteed bit rate
PER	Low value
PDB	$\leq$ 20 ms
Resource Isolation and Management	$\leq$ resources required for transmission
Priority Level	High value
SU-MIMO	
PDCP Out-of-Order Delivery	
PDCP SDU Discard	20 ms
Transmission Mode	AM
Optional functionalities	
Configured Grant	1 ms
SR Configuration	with SR periodicity of 10 ms or below
PDCP Duplication	
Multi-TRP	
Interference Management	
High-Reliability DCI Format	
Low BLER MCS and CQI Table	
256/1024 QAM	
Inter-Cell Multi-TRP focused on throughput	
DRX	20 ms Cycle or below

VI. USE CASE DEMONSTRATION

This section demonstrates how the mapped functionalities adjust 5G network communication performance based on the use case attributes. It begins by introducing the 5Gainer network [3] used in the evaluation, followed by an overview of the testing methodology. Finally, it presents the results obtained from each use case evaluation.

A. 5GAIner

5GAIner (part of the IMAGINE-B5G[8] experimental facilities) is a real-world 5G commercial-graded infrastructure with Release 15 (R15) software. It comprises multiple locations, including the Instituto de Telecomunicações (IT) of Aveiro and the University of Aveiro. This infrastructure primarily serves research purposes, allowing IT and its partners to develop, test, and validate various 5G technologies.

Figure 3 presents a schematic of the 5GAIner infrastructure. The network core comprises a Standalone (SA) 5G core, 4 switches, and 2 routers. It also includes four RAN sites: two indoor RAN sites, a MEC site with RAN, and an external site. 5GAIner contains the following control network functions: Session Management Function (SMF), Access and Mobility Management Function (AMF), Authentication Server Function (AUSF), Network Repository Function (NRF), Network Slice Selection Function (NSSF), and Unified Data Management (UDM).

While the infrastructure lacks the full spectrum of control functions, it can still support the planned use cases. Despite performance and configurability limitations inherent in R15,

[8]https://imagineb5g.eu/, (April 2024).

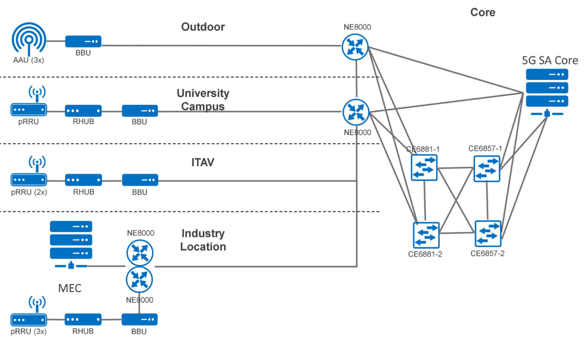

FIGURE 3. 5GAIner infrastructure.

such as supporting only eMBB slices and lacking features available in later releases, 5GAIner effectively emulates a commercial 5G infrastructure. Continuous improvements are anticipated, adding new functionalities, network functions, and releases over time.

The infrastructure uses a reserved band owned by Altice, a Portuguese operator. Table 9 outlines the antenna configurations during evaluations, offering insight into the network's performance. A more comprehensive overview of the 5GAIner network can be found in [3], along with an initial performance analysis.

TABLE 9. gNodeB technical specifications.

Specification	Values
Maximum bandwidth	20 MHz with 30kHz subcarrier spacing
Frequency band	Center frequency of 3790.02 MHz (n78 band)
Output power per port	24 dBm
Demultiplexing	TDD
DL Modulation	BPSK; QPSK; 16/64/256QAM
UL Modulation	BPSK; QPSK; 16/64QAM
MIMO	4T4R
Network Slicing	eMBB Slices
Slot assignment	4 Downlink: 1 Uplink (Slot structure 2)

Since 5GAIner is an R15 5G network, it only supports some previously discussed functionalities. So the evaluation will concentrate on those.

B. EVALUATION

The evaluation assesses the achievable throughput, latency, packet loss, and UE power consumption in the 5GAIner network with the available configurations. Due to the current absence of the synchronization feature, latency and energy consumption evaluations need to be conducted separately.

The latency and packet loss evaluation used the configuration outlined in Figure 4. In the downlink scenario, packets are transmitted from the server through the 5G network to the UE (Huawei CPE2 [Customer Premises Equipment] pro connected to a single-board computer). The UE then forwards the packets via an Ethernet cable connected to the 5G network's outer router, which subsequently routes them back to the server. For the uplink evaluation, packets travel in the opposite direction. The server records the time upon transmission and reception, calculating the difference between these times to determine latency. This evaluation is conducted separately for uplink and downlink over the course of a full day, with packets sent at each transfer interval according to the respective use case requirements.

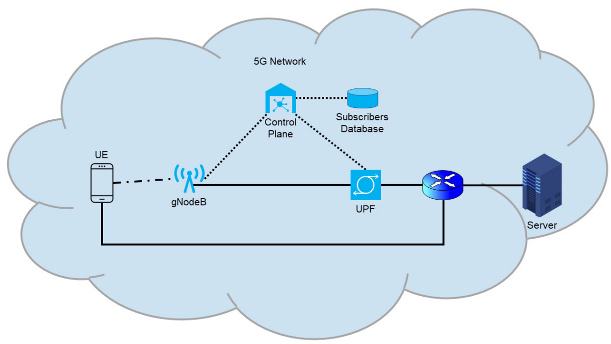

FIGURE 4. Network deployment for latency evaluation.

Energy consumption and throughput evaluation were performed with the configuration shown in Figure 5. This setup uses a Huawei P40 Pro as a UE, sending packets to the server, which then sends them back to the UE. A USB Digital tester records the power consumption of the UE, while 5G metrics record communication throughput. This evaluation was conducted over four hours, with packets sent according to the communication requirements of the use case. Subsequently, the mean energy consumption for each hour was calculated and presented in the results.

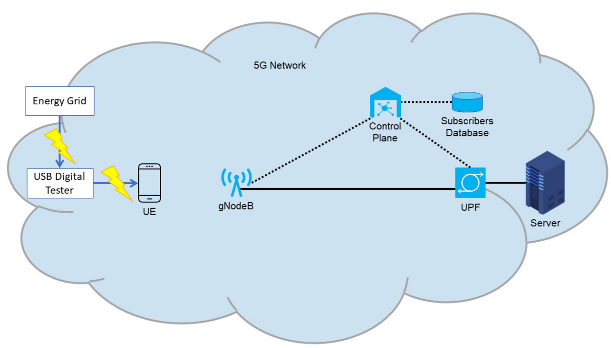

FIGURE 5. Network deployment for energy evaluation.

The USB Digital tester measures the energy required to power a Huawei P40 Pro with a fully charged battery, minimal screen brightness, ultra energy-saving mode, and the Termux application running the necessary commands throughout the entire test. The presented values exclude the end device energy consumption under the same configurations but when not connected to the network.

The use case incorporates various functionalities. To help in understanding the configuration decisions, Table 10 outlines the default network configuration values. These values serve as a baseline for configuring each parameter.

The uplink preallocation functions as a deployment version of the configured grant, allocating resources every few

TABLE 10. Default configuration values.

3GPP	5GAIner configuration	Default Value
Priority Level	Priority Level	90 (low values higher priority)
	Scheduling priority Weight Factor	700
GFBR	GFBR	0 bps
PDB	PDB	300 ms
Average Window	Average Window	2000 ms
SR configuration	SR Period	40 slots (20 ms)
Low BLER MCS and CQI table	IBLER	10
DRX	DRX	disabled
MIMO	MIMO	SU-MIMO enabled
Configured grant	uplink preallocation	smart uplink preallocation enabled with 250 ms duration

milliseconds regardless of their usage, instead of gathering to a defined periodicity. In this release, UEs are required to send dummy packets in unused allocated resources, wasting energy. Initial BLER (IBLER) serves to simulate the Low BLER MCS and CQI table; by enforcing a lower IBLER value, the cell is compelled to use lower MCS schemes, reducing BLER. Disabling SU-MIMO can mimic the intra-cell multi-TRP when used to enhance reliability. Priority level simulation involves two different parameters: priority level, determining the priority among UEs' QoS Flows, and the Scheduling Priority Weight Factor, specifying the priority among QoS Flows when requesting resources. For SR configuration, the SR period can be configured, determining the periodicity at which UEs can initiate an SR.

All configurations are set up on the RAN, and only non-GBR QoS Flow can be used due to network restrictions. Despite these limitations, it is possible to simulate a GBR QoS Flow using GFBR in RAN and core configurations.

C. MOBILE ROBOTS

To evaluate the Mobile Robots use case, the following configurations were applied: GFBR was configured to 20 kbps, PDB to 100 ms, Average Window to 500 ms, SR period to 160 slots (corresponds to 80 ms in a cell with 30 Khz of subcarrier spacing), DRX with 80 ms cycle and 10 ms on duration, and MIMO was disabled. In this simulation, the UE or the server sends a 500-byte packet every 100 ms.

Figure 6 presents the latency results, indicating the probability of packets arriving within 100 ms. The recorded packet loss was below 0.001%. To meet strict latency requirements, it may be necessary to decrease the SR period. With the current configuration, there were instances of five consecutive uplink packets exceeding the 100 ms latency threshold per day. However, the configured values generally suffice to support the use case, as at least one packet is successfully transmitted during this survival time.

The approximate communication energy consumption was 0.74 mW, with uplink and downlink Radio Link Control (RLC) layer throughput recorded at 42 Kbps. Total UE throughput, which includes control layer throughput, can be measured at the Medium Access Control (MAC) layer. At the

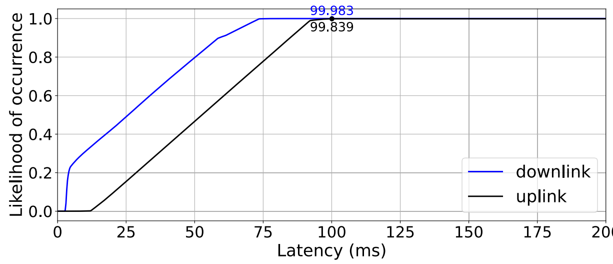

FIGURE 6. Downlink and uplink latency performance achieved for mobile robots use case.

MAC layer, downlink throughput reached 110 Kbps, while uplink throughput was 62 Kbps.

D. MOTION CONTROL

The configurations for this use case are as follows: 512 Kbps GFBR, 1 ms PDB, IBLER set to 1, MIMO disabled, Priority level set to 1, Scheduling Priority Weight Factor set to 1000, and Uplink preallocation enabled with a duration above 1 ms. This use case is simulated by having the UE or server send a packet with 64 bytes every millisecond.

Latency results are presented in Figure 7 with the probability of a packet arriving before 1 ms latency. The registered packet loss was below 0.0005%. As expected and demonstrated in the results, this use case is impossible to deploy in an R15 5G network, since the required URLLC performance is only available from Release 16 onwards.

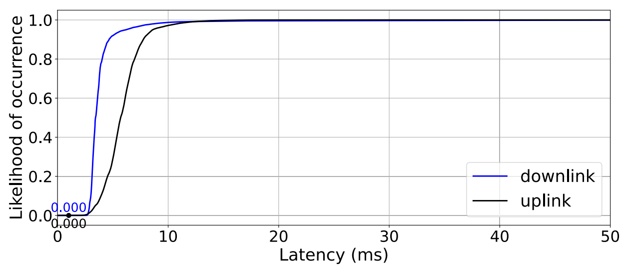

FIGURE 7. Downlink and uplink latency performance achieved for motion control use case.

The approximate communication energy consumption was 1.73 mW, with RLC layer throughput of 530 Kbps downlink and 530 Kbps uplink. The MAC layer throughput, which includes control plane throughput, was 820 Kbps downlink and 605 Kbps uplink.

E. ROBOTIC AIDED SURGERY

Since the previous use case employs Uplink pre-allocation, this scenario demonstrates the performance with a different configuration. Here, the SR Period is used, and uplink preallocation is disabled. Furthermore, a low SR Period is acceptable due to the low number of UEs per antenna required, demanding less than one device per antenna. The configurations made are as follows: 8.8 Mbps of GFBR, 20 ms of PDB, 5 for IBLER, SU-MIMO enabled, 10 of Priority Level, 900 Scheduling Priority Weight Factor, 20 slots (10 ms) for SR Period, and a DRX cycle of 20 ms with an on duration of 10 ms. This use case is simulated by making UE or server send a packet with 750 bytes each millisecond.

Latency results are presented in Figure 8, showing the probability of a packet arriving before 20 ms latency. The registered packet loss was below 0.001%. However, with the current configurations, the use case cannot be deployed, as two consecutive packets may experience latency higher than 20 ms seven times per minute. To address this issue, reducing the SR period to 10 slots or implementing uplink preallocation would help reduce uplink latency. Downlink latency can be reduced by disabling DRX or reducing its cycle. Nonetheless, achieving extreme levels of reliability while ensuring the required latency may be challenging without features like TSC, or delay-critical GBR QoS Flow.

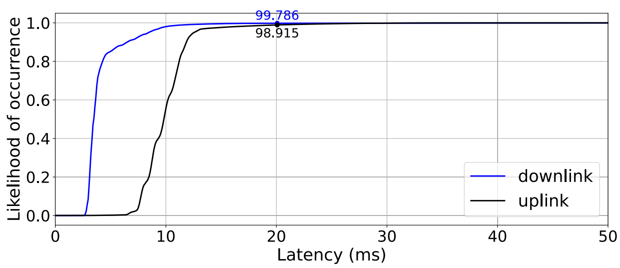

FIGURE 8. Downlink and uplink latency performance achieved for robotic aided surgery use case.

The approximate communication energy consumption was 1.74 mW, with an RLC layer throughput of 6.3 Mbps downlink and 6.3 Mbps uplink. The MAC layer throughput, which includes control plane throughput, was 8 Mbps downlink and 6.4 Mbps uplink.

VII. DISCUSSION

This document explores industrial use case attributes used by industrial organizations and the network slice attributes specified by 3GPP. Leveraging the QoS configurations, technologies and mechanisms available in a 5G network, briefly outlined in Appendix, to establish a mapping between the attributes and the functionalities. This provides general guidance for selecting appropriate functionalities to meet the communication requirements imposed on the 5G network.

As discussed in Section IV, each functionality impacts multiple attributes, and depending on the required communication attributes, different functionalities must be enabled to achieve the desired performance, often at the expense of other KPIs. For example, to reduce latency, configured grant and SR configurations can be used. Configured grant reduces latency but may result in increased energy consumption and/or resource utilization. SR configurations reduce latency at the cost of reducing the number of UEs connected to the network simultaneously, by allowing each UE to consume more control plane resources.

The presented mapping is then evaluated using three documented use cases to check the performance obtained when adapting the network configurations for each use case. The assessment is made using an R15 5G network and as demonstrated the Mobile Robots use case is possible to deploy with the current release. If the latency requirements are strict, the SR period and DRX cycle must be reduced, increasing packets that arrive before the required latency. Therefore, an R15 network can deploy this use case.

The Motion Control use case implementation is not feasible without a URLLC slice, due to the stringent latency requirements of 1 ms, which is available from R16 onwards. To meet the use case demands, functionalities such as delay-critical GBR QoS Flow, TSC, and TSN are essential to ensure the required performance.

The Robotic Aided Surgery use case requires additional mechanisms to reduce jitter. Even though latency performance can be minimized with a 10-slot SR period, the minimum supported by the network used, and decreasing the PDB value, this change would further limit the number of UEs connected to the network. Additionally, Non-GBR QoS Flows are limited in latency performance, since they can only guarantee 98% of packets are below the PDB value in non-congested networks. So this use case requires a Delay-critical GBR QoS Flow with a low PER. Even though this evaluation shows a 5G network can support the use case and with the discussed adjustments to reduce latency further, requirements could be met when no alternative mechanisms are available to ensure the required performance.

Mobile Robots have approximately 60% less energy consumption compared to other use cases. However, the throughput difference is much higher, showing that even though mMTC slices are supported, the network is not optimized for them. This is evident from the discrepancy between the throughput in the MAC and RLC layers of Mobile Robots and the other use cases, which have much less difference. This discrepancy arises because mMTC is supported in later releases and UEs are not optimized for mMTC slices. Implementing a redcap UE with additional features should further optimize resource consumption in terms of throughput and energy consumption.

The energy consumption and throughput results in Robotic Aided surgery demonstrate an R15 network optimized for eMBB use cases. This optimization is evident in the minimal

TABLE 11. Glossary.

AAA	Authentication, Authorization and Accounting	NEF	Network Exposure Function
AGV	Automated Guided Vehicles	Non-GBR	Non-Guaranteed Bit Rate
AM	Acknowledged Mode	NR	New Radio
AMBR	Aggregate Maximum Bit Rate	NRF	Network Repository Function
AMF	Access and Mobility Management Function	NS	Network Slice
ARP	Allocation and Retention Priority	NSACF	Network Slice Admission Control Function
AUSF	Authentication Server Function	NSMF	Network Slice Management Function
BA	Bandwidth Adaptation	NSSAA	Network Slice Specific Authentication and Authorization
BLER	Block Error Rate	NSSF	Network Slice Selection Function
BPSK	Binary Phase Shift Keying	NSSRG	Network Slice Simultaneous Usage Group
BWP	Bandwidth Part	PDB	Packet Delay Budget
CoMP	Coordinated Multi-Point	PDCCH	Physical Downlink Control Channel
CPE	Customer Premises Equipment	PDCP	Packet Data Convergence Protocol
CQI	Channel Quality Indicator	PDU	Packet Data Unit
CSMF	Communication Service Management Function	PER	Packet Error Rate
D2D	Device to Device	QAM	Quadrature Amplitude Modulation
DCI	Downlink Control Information	QoS	Quality of Service
DiffServ	Differentiated Services	R15	Release 15
DL	Downlink	R16	Release 16
DRX	Discontinuous Reception	R17	Release 17
eMBB	enhanced Mobile Broadband	RAN	Radio Access Network
GBR	Guaranteed Bit Rate	RedCap	Reduced Capabilities
GFBR	Guaranteed Flow Bit Rate	RLC	Radio Link Control
IAB	Integrated Access and Backhaul	RRC	Radio Resource Control
IBLER	Initial BLER	RRM	Radio Resource Management
IP	Internet Protocol	SA	Standalone
IPv4	IP version 4	SDT	Small Data Transmission
IPv6	IP version 6	SDU	Service Data Unit
KPI	Key Performance Indicator	SMF	Session Management Function
KPIs	Key Performance Indicators	SR	Scheduling request
KQIs	Key Quality Indicators	SSC	Session and Service Continuity
LADN	Local Area Data Network	SST	Slice/Service Type
LCP	Logical Channel Prioritization	SU-MIMO	Single User-MIMO
MAC	Medium Access Control	TDD	Time Division Duplexing
MBR	Maximum Bit Rate	TRP	Transmission and Reception Point
MBS	Multicast–Broadcast Services	TSC	Time-Sensitive Communication
MCS	Modulation and Coding Scheme	TSN	Time Sensitive Networking
MEC	Multi-access Edge Computing	UDM	Unified Data Management
MFBR	Maximum Flow Bit Rate	UE	User Equipment
MICO	Mobile Initiated Connection Only	UE-AMBR	UE-Aggregate Maximum Bit Rate
MIMO	Multiple Input Multiple Output	UL	Uplink
mMTC	massive Machine Type Communication	UM	Unacknowledged Mode
MTU	Maximum Transmission Unit	UPF	User Plane Function
multi-TRP	multi-Transmission and Reception Point	URLLC	Ultra-Reliable Low Latency Communication
MU-MIMO	Multi User-MIMO	V2V	Vehicle-to-Vehicle
NAT	Network Address Translation	V2X	Vehicle-to-everything
NB-IoT	Narrowband Internet of Things	WUS	Wake Up Signal

difference between the throughput of the RLC and MAC layers. Motion control has a higher discrepancy in the throughput due to the uplink preallocation, which prompts UEs to transmit a dummy packet in allocated slots that are not used. Consequently, this leads to higher throughput in the uplink MAC layer, increasing energy usage during communication, which results in energy consumption similar to Robotic Aided Surgery despite having much lower throughput. Moreover, the energy consumption of Robotic aided surgery is notably reduced due to DRX, which temporarily deactivates end device antennas during the offline part of the cycle.

VIII. CONCLUSION

The work presented in this document constitutes a cornerstone within a broader endeavour focused on automating network slice deployment in 5G networks. This undertaking began with a comprehensive understanding of various 5G functionalities and an assessment of their impact on communication [2]. This paper complements previous work by addressing the crucial step of mapping these functionalities to communication parameters, serving as the foundation for the final objective of developing a network slice manager capable of automating network slice deployment. Considering the comprehensive nature of the work, encompassing the entire endeavour in a single document would substantially increase its size compared to the current one. Moreover, the contributions provided contain significant information for other researchers and technology developers to pursue their ideas in developing a vertical-oriented network slice manager.

APPENDIX
5G FUNCTIONALITIES BRIEF DESCRIPTION

The terms functionality and feature are used in this document to encompass various configurable aspects of 5G, including QoS parameters, RAN and core configurations, and other related technologies. This terminology is employed to simplify the comprehension of the document and to refer collectively to any technology, QoS parameter of 5G configuration presented below.

The 5G functionalities described below are based on R17 specifications outlined in various 3GPP documents, including [29], [30], [31], [32], [33], and [34].

Please note that some functionalities may be dependent on the values of others, such as PER and PDB, which depend on the QoS Flow type. However, for brevity, these differences are not described here. The descriptions provided offer a concise overview of each functionality.

1) *QoS Flow type* Each 5G communication must be associated with one of three types of QoS Flow. These QoS flows can be categorized as follows: (i) **Non-GBR**, normal communication without throughput guarantees; (ii) **GBR**, the network ensures a predefined throughput for communication; and (iii) **Delay-critical GBR**, in addition to throughput guarantees, this type also ensures a predefined latency for communication.
2) *UL/DL UE-AMBR (Aggregate Maximum Bit Rate)* This parameter defines the maximum bit rate for all Non-GBR QoS Flows of a UE.
3) *UL/DL UE-Slice-MBR (UE per Slice-Maximum Bit Rate)* This parameter defines the bit rate limit for all PDU Sessions of a UE within a slice.
4) *UL/DL Session-AMBR* This parameter defines the maximum bit rate for all Non-GBR QoS Flows associated with a single PDU Session of a UE.
5) *Guaranteed Flow Bit Rate (GFBR)* This parameter defines the assured bit rate that the network reserves for a QoS Flow.
6) *Maximum Flow Bit Rate (MFBR)* defines the maximum bit rate that a QoS flow can use.
7) *Average window* This parameter defines the time window used by the RAN to enforce MFBR, GFBR, and AMBR.
8) *Resources Isolation and Management* This functionality enables the allocation of resources to a specific slice. These resources are exclusively available for use by the slice, allowing for specialized customization, or they can belong to a shared pool, with the slice having prioritized access.
9) *256/1024QAM* This functionality represents the highest modulation schemes supported in the network, enabling the transmission of more bits per slot. While it increases throughput, it sacrifices transmission robustness.
10) *SU-MIMO* This functionality increases spatial multiplexing of transmission by using multiple antennas at both ends of the transmission. These additional antennas can improve signal demodulation, reducing packet loss, or they can be used for spatial multiplexing, thereby multiplying the transmission throughput.
11) *Multiple Transmission/Reception Point (multi-TRP)* This functionality enables a UE to transmit and receive the same information through different TRPs. These TRPs can be from the same cell or from two adjacent intra-frequency cells.
12) *Dual connectivity* This functionality enables UEs to connect to two different RANs with disjoint paths, allowing the transmission of the same information through two different networks.
13) *Interference Management* This functionality enables mechanisms to reduce or avoid interference caused by cells or UEs using the same spectrum.
14) *High-reliability DCI format* This functionality uses configurations with higher reliability in the control channel for uplink and downlink scheduling.
15) *Low BLER MCS and CQI Table* These tables are designed to achieve a BLER error of 10^{-5} by employing 64QAM MCS tables with reduced spectral efficiency.
16) *Packet Error Rate (PER)* This parameter sets the maximum allowable rate of packet lost in transmission for a GBR QoS Flow. For delay-critical GBR, it represents the upper limit of the total number of lost packets, including those that are not received and those that arrive after the PDB.
17) *Packet Delay Budget (PDB)* This parameter specifies the maximum latency allowed for communication between the UE and the last UPF in a QoS Flow.
18) *PDCP Duplication* This functionality involves sending the same packet two times simultaneously to increase the likelihood of successful transmission, thereby reducing packet loss.
19) *LCP (Logical Channel Prioritization) restrictions* This feature limits logical channels to use specific resources. It enables the allocation of resources that are less affected by noise or have lower transmission latency to critical services or those with more demanding requirements in terms of latency or packet loss.
20) *Priority Level* This parameter defines the priority in scheduling resources among different QoS Flows.
21) *PDCP Out-of-order Delivery* This functionality permits the RAN's PDCP layer to forward unordered packets, reducing the latency of subsequent packets when a packet is lost in transmission.
22) *SR (Scheduling request) configuration* This functionality defines how UEs request resources for user plane transmission, including the periodicity and priority of these requests.
23) *Configured grant* This functionality enables the periodic reservation of transmission slots that a UE can utilize for transmission. Consequently, UEs do not need

to send an SR to transmit in the reserved slots allocated by configured grants.

24) *Transmission modes* This functionality specifies whether transmission in the RLC and PDCP layer uses Acknowledged (AM) or Unacknowledged mode (UM), indicating whether the RAN needs to acknowledge successful packet transmission.
25) *Time Sensitive Communication (TSC)* This functionality uses configured grants, semi-persistent scheduling, or dynamic grants, along with delay-critical QoS Flows, to provide a more efficient schedule for periodic traffic.
26) *Time Sensitive Networking (TSN)* This functionality utilizes slot reservation, time synchronization, and other technologies to ensure a transmission slot is available along the entire path when UE needs to transmit.
27) *PDU session type* This defines the type of PDU session used in the connection, which can be IP, Ethernet, or Unstructured.
28) *PDCP SDU discard* This feature sets a timer in which the RAN attempts to transmit each packet. If the packet is not successfully transmitted during this timer, it is discarded.
29) *NR Sidelink* This functionality enables direct communication between UEs, reducing latency in D2D (device-to-device) communication.
30) *V2X* This functionality uses multiple network features to optimize the network for vehicular communications.
31) *MU-MIMO* This functionality increases spatial multiplexing of transmission by using multiple antennas at the gNodeB side, allowing it to communicate with multiple UEs simultaneously using the same time and frequency resources.
32) *Network Slice Admission Control Function (NSACF)* This functionality monitors and controls the number of UEs and/or the number of PDU sessions per network slice.
33) *Enable inactive state* This functionality allows UEs to maintain a dormant state while remaining connected to the network. This intermediate state facilitates reduced energy consumption when the UE is not transmitting, while still enabling a quick resumption of connection when a new transmission is necessary.
34) *Small Data Transmission (SDT)* This feature facilitates the transmission of small packets when UEs are in the RRC_INACTIVE state.
35) *Reduce Capabilities (RedCap)* utilizes several of the mentioned features to enable RedCap UEs to connect to the network. These reduced capability UEs sacrifice performances in several network parameters to minimize energy consumption.
36) *Bandwidth Adaptation (BA)* enables UEs that require small bandwidth to only use a portion of the available Bandwidth Part (BWP) of the antenna for communication, rather than utilizing the entire bandwidth.
37) *Reduced maximum number of MIMO layers* lowers the number of MIMO layers, requiring fewer active antennas for UE communication and reducing UE energy consumption.
38) *DRX (Discontinuous Reception)* defines cycles during which UE only monitor control channels for part of the cycle, deactivating antennas for the remainder of the cycle.
39) *WUS (Wake-Up Signal)* further reduces the time UE antennas remain active compared to DRX. In this mode, UE only monitors the WUS signal during each cycle. Upon receiving the WUS signal, it initiates a normal DRX cycle in the subsequent cycle.
40) *Radio Resource Management (RRM) measurement relaxation* allows UEs to stop measuring neighbour cells' signals when they are stationary and/or outside the cell edge.
41) *Mobile Initiated Connection Only (MICO)* ensures that UEs do not listen to control channels while in idle states, allowing only UEs to initiate communication by requesting a change to the connected state. The network sends control or user plane messages only when the UE is in the connected state.
42) *Asynchronous Type Communication* permits the AMF to update the session context while the UE is idle, transmitting the changes to the UE when it re-enters the connected state.
43) *High Latency communication* utilizes buffering downlink data in the UPF, SMF, or Network Exposure Function (NEF) when communication is not feasible, such as when the UE is unreachable due to enabled power-saving mechanism.
44) *Allocation and Retention Priority (ARP)* determines the importance of each QoS Flow when a UE attempts to access the network. It also specifies whether a connection has pre-emption capability or vulnerability. Communications with higher priority and pre-emption capability can preempt resources from less critical communication with pre-emption vulnerability.
45) *Automatic neighbour cell relation function* simplifies the task of configuring neighbour cells. This function enables the gNodeB to automatically add and remove neighbour cells from a table used to facilitate handover processes, thereby enhancing its efficiency.
46) *SSC (Sessions and Service Continuity)* determines the behaviour of the PDU session during handovers and whether the session can be maintained. If the session cannot be maintained, a new PDU session must be established for the UE to keep access to the network.
47) *LADN (Local Area Data Network)* can be used to confine a specific data network to a defined area, ensuring that the network is not accessible outside of it.
48) *Forbidden Area* completely restricts access to any type of access network for the UE in the defined area.

49) *Service Area Restriction* can be used to define the areas where a UE can or cannot connect to the network. In the non-allowed areas, the UE can still access the network through a non-3GPP access network.
50) *Coverage Enhancement* increases the coverage area a cell can provide for 5G services by adjusting functionalities such as increasing PUSCH repetitions and the number of slots used to transmit a single block of data.
51) *Pi/2-BPSK* is the lowest modulation scheme that can be used when it is necessary to maximize the transmission distance between the UE and the cell.
52) *MTU (Maximum Transfer Unit) size* defines the maximum size of a packet transmitted between UPF and UE.
53) *UL/DL Maximum Data Burst Volume* defines the maximum data burst of a Delay-critical QoS Flow during a PDB duration.
54) *Positioning* provides the location of a UE. This position can be absolute or relative to the antenna's location.
55) *Synchronization* ensures that the difference in clock time or clock frequency of network equipment remains in an acceptable error range.
56) *Network Slice Simultaneous Registration Group (NSSRG)* contains the information of which slices the UE can simultaneously access.
57) *Supplementary UL or DL* increases 5G network spectrum by using sub-3GHz spectrum, to increase the UL or DL bandwidth.
58) *Slot configuration* defines resource allocation between UL and DL in a TDD cell.
59) *UP (user plane) integrity protection* defines if integrity protection is applied over the RAN.
60) *UP confidentiality protection* defines if confidentiality protection is applied over the RAN.
61) *Multicast and Broadcast Services (MBS)* permits the transmission of a single packet to multiple devices, using the same network resources, reducing resources spent in one-to-many communications. This communication can be to everyone in the network (broadcast) or to a specific group of UEs (multicast).
62) *3GPP PS data off* can be used to restrict the number of services a UE can use. When this is enabled, UEs are only allowed to access the list of services defined in the 3GPP Data Off Exemption Services.
63) *Integrated Access and Backhaul (IAB)* permits capable UEs to become an IAB-UE functioning as an extended gNodeB providing network coverage around it. This IAB-UE can increase the network coverage where there is no cable connection or in case of coverage failure due to gNodeB in the area being down. The IAB-UE instead uses a 5G wireless connection to connect to the core, instead of a wired connection as usual gNodeBs.
64) *Frame Routing* permits a 5G end-device to work as a gateway, while the devices connected through this gateway, receive a full 5G network connection without having 5G radio capabilities.

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