A Study of Quality of Service (QoS) in Private 5G Networks for Smart Factori 4.0

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Abstract

This paper presents a case study on Quality of Service (QoS) in private 5G networks for Smart Factori 4.0. Specific applications including guaranteed bit rate (GBR) and non-guaranteed bit rate (NGBR) are considered in the simulation configuration for our proposed 5G standalone (5G-SA) network. We observe the performance of the above-mentioned services under single-frequency and double-frequency simulation conditions. The QoS of the proposed 5G-SA network topology will be analyzed in terms of latency, throughput, and signal-to-interference-plus-noise-ratio (SINR), and pathloss. The guaranteed bit rate communication for voice service is considered appropriately suitable for smart factories that require real-time communication and instant alerts with some predefined threshold requirements for the achievable throughput and communication distances. For non-guaranteed bit rate communication which is specifically defined for low latency applications, the system can provide a consistent throughput and low mean delay across different distances. This benefit will enhance data communication for machine-to-machine communication, control systems, and real-time data monitoring applications in today's smart factories.

Keywords: *Quality of Service (QoS), Private 5G Networks, Guaranteed Bit Rate, Non-Guaranteed Bit Rate.*

1 Introduction

Fifth Generation (5G) is a mobile communication system defined by the 3rd Generation Partnership Project (3GPP) which is fully specified in September 2019 [1]. The technology brings significant improvements over the fourth generation (4G) services in three main primary use cases including enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and ultra-Reliable and Low-Latency Communications (uRLLC) as illustrated in Fig. 1 [2]. In 5G network, the download speeds can reach up to 50 Mbps for outdoor and 1Gbps for indoor environment, while these values are halved for the upload speed [3]. For instance, the network demonstrates the ability to deliver a data rate of 1.2 Gbps to airborne flights for a case study on aviation application [4]. It is worth mentioning that the 5G networks is suitable for critical communication application such as autonomous driving, remote diagnosis/surgery, and industrial applications that require extremely high reliability (e.g., 99.9999%), and ultra-low latency (e.g., 1ms) [2], [4]. Additionally, it also introduces specific features and capabilities that enhance network operations which includes network slicing, network exposure capability, scalability, diverse mobility, security enhancements, efficient content delivery, and migration between different network technologies.

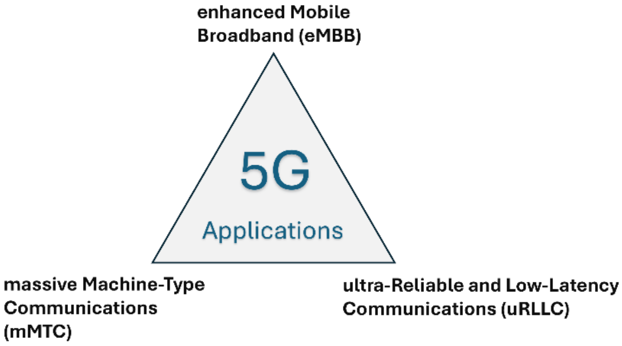

Fig. 1. The three preimary use-cases of 5G networks [2].

Although the above-mentioned aspects contribute to the flexibility and adaptability of the 5G system, its architecture still retains the fundamental elements found in previous generations of mobile communication systems. These elements include the user equipment (UE), the Next Generation-Radio Access Network (NG-RAN), and the 5G Core network (5GC). 5G occupies new radio technology (NR), which frequencies are allocated based on a per-country or per-region basis. The ranges include frequencies up to 1 GHz for rural coverage, 1 to 6 GHz for

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urban/suburban deployment, and higher than 6 GHz for dense urban areas. It also utilizes Multiple-Input and Multiple-Output (MIMO) technology to enhance data transmission and reception efficiency. This technology uses multiple antennas at both the transmitter and receiver to improve spectral efficiency, link reliability, and overall system capacity [5], [6].

Fig. 2 shows 5G network infrastructure, which is divided into two types such as the Standalone (SA) and Non-Standalone (NSA) [7]. The 5G-SA networks are fully independent and optimized for 5G use cases that provide better performance and support advanced features. In contrast to its counterpart, the 5G-NSA networks leverage existing 4G infrastructure for an early rollout of 5G services which offers an intermediate solution before a complete migration to SA networks. The advent of 5G networks for both SA and NSA architecture holds immense potential for the realization of smart factory applications. Due to its ultra-low latency, high data rates, and massive connectivity capabilities, 5G is poised to revolutionize industrial manufacturing processes and enable the full realization of the industry 4.0.

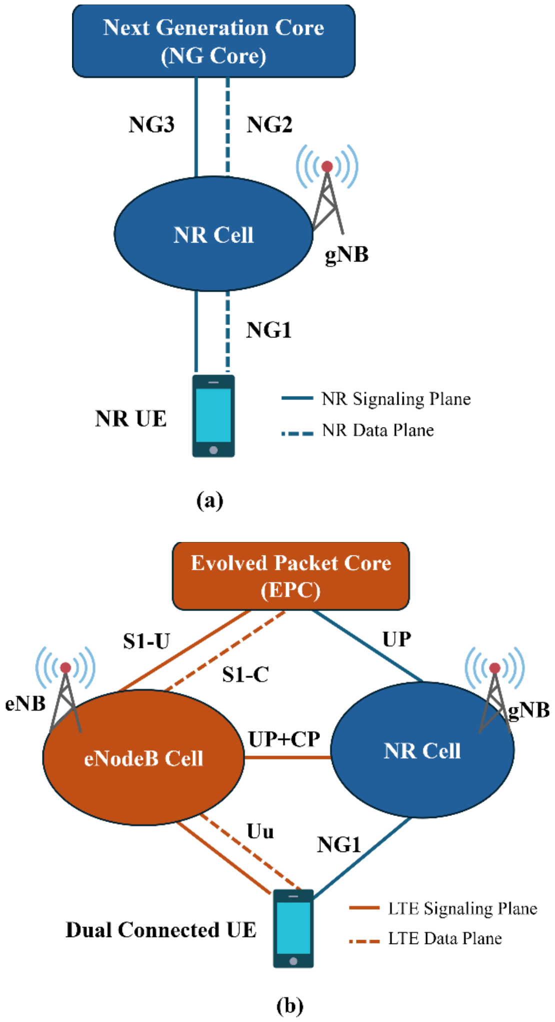

Fig. 2. The two types of 5G network architecture: (a) standalone, (b) non-standalone[7].

Smart Factories 4.0 leverages 5G's capabilities to enable real-time monitoring, control, and optimization of manufacturing operations due to its high-speed and reliable wireless connectivity. Furthermore, its ability to provide ultra-low latency potentially ensures that critical commands are executed in near real-time, enhancing the responsiveness and precision of industrial processes. The vast number of devices that 5G can connect simultaneously enables the deployment of massive-interconnected sensors and actuators, creating a highly efficient and interconnected ecosystem within the factory. However, there are certain qualification criteria to ensure a better quality of service (QoS) on the network. Typically, the QoS mechanism provides an effective assurance on the priority of different types of traffic services and reliability. There are several key performance indicators (KPIs) for monitoring network performance including latency, throughput, reliability, packet loss, jitter, mobility, connection density, energy efficiency, and network coverage.

In this paper, we present an analysis of the QoS for a 5G-SA private networks applied in Smart Factori 4.0. We aim to assess the performance of the two main network services, including the guaranteed bit rate (GRB) and non-guaranteed bit rate (NGBR) communication. The research will observe the performance of the above-mentioned services under single-frequency and double-frequency simulation conditions. The proposed 5G-SA network topology will specifically be analyzed on its QoS in terms of latency, throughput, delay, and jitter requirements that are essential for enabling advanced manufacturing systems in the factories. Experimental setup and methodology employed to evaluate the QoS are comprehensively discussed to effectively evaluate the performance of the network.

2 Technology Adoption

The enabling technologies for 5G compose of several key components including 5G frequency band, multi-access edge computing, software-defined networking/network functions virtualization, and machine learning. According to 3GPP Releases (R15 and R16), there are two types of frequency spectrum for 5G technology including Frequency Range 1 (FR1) covers low-band (450MHz – 1GHz) and mid-band (1GHz – 6GHz), and Frequency Range 2 (FR2) covers high-band or millimeter wave frequency (24.25GHz – 52.6GHz) [1], [5]. These frequency divisions correspond to three different use-cases such as rural, urban, dense-urban area, respectively. Rural requires larger coverage area than capacity, which is suitable for low-band frequency. Urban requires the balance between coverage area and capacity, which is suitable for mid-band frequency. Dense-Urban requires a larger capacity than low coverage area, which is suitable for high-band frequency.

Unlike the traditional centralized cloud computing networks where data is sent to remote data centers for processing and analysis in models, 5G offers applies a Multi-Access Edge Computing (MEC) capability [8]. The concept refers to the deployment of computing resources and services at the edge of the network, closer to the end-users and devices. MEC offers several benefits in the context of 5G such as low latency, bandwidth optimization, scalability, local data processing [2]. It also reduces the round-trip time for data to travel between devices and remote data centers, resulting in lower latency and improved real-time responsiveness. Additionally, MEC also reduces the amount of data that needs to be transmitted back and forth to centralized data centers which optimize the network bandwidth by offloading processing tasks to the edge. It allows for distributed computing and storage capabilities, enabling seamless scaling of applications and services based on demand. Moreover, it also enables localized data processing, which is particularly useful for applications that require real-time analytics, such as augmented reality (AR), virtual reality (VR), and Internet of Things (IoT) devices [3], [6].

Software-Defined Networking (SDN), and Network Functions Virtualization (NFV) are both keys to transforming the technology of the network industry by bringing flexibility, scalability, and cost-efficiency to network infrastructure [2]. In traditional networking, network devices such as routers and switches have both the control and data plane functionalities tightly integrated. However, SDN decouples these functionalities by centralizing the control plane logic in a software-based controller, which then controls the forwarding behavior of the network devices. Network administrators can dynamically manage and control the network through the centralized controller with SDN, which provides a global view of the network topology. Centralized control allows for programmability, automation, and orchestration of network resources, making it easier to configure, manage, and optimize network operations. Simultaneously, the NFV approach offers a replacement of hardware appliances with software-based virtualized instances running on standard servers. The feature offers several advantages including greater flexibility and agility in scaling network services since the virtual instances can be easily provisioned, moved, or replicated as needed. It also enables cost savings by reducing the reliance on expensive proprietary hardware appliances and promoting the use of commodity off-the-shelf hardware.

Machine learning (ML) is another key role player to enable 5G in various aspects including traffic management, service optimization, resource allocation, and network slicing [6]. The techniques in traffic management analyze network traffic patterns to predict congestion and classify different types of traffic for QoS prioritization. It can also optimize network services by analyzing user behavior and preferences, and dynamically allocates resources based on real-time demand and traffic patterns to optimize resource allocation and ensure efficient operation.

3 Design and Configuration

This study is evaluated through extensive simulations using the NS-3 network simulator, considering realistic channel models, 5G protocol stack, and traffic scenarios. We consider a standalone network architecture of 5G, where the design scenarios focus on guaranteed bit rate (GBR) and non-guaranteed bit rate (NGBR) communication services. GBR refers to the minimum bandwidth that is assured to be available for a specific network service or application. It ensures a certain level of performance and reliability by reserving a dedicated portion of network capacity. This is particularly important for time-sensitive applications, such as real-time video streaming or voice communication, where a consistent and reliable data transfer rate is crucial. On the other hand, NGBR refers to the variable or best-effort bandwidth that is available beyond the guaranteed bit rate. It represents the additional network capacity that can be utilized if it is not already allocated to guaranteed services. It allows for more flexibility in resource allocation, enabling the network to accommodate fluctuating demands and prioritize different types of traffic dynamically. Fig. 3 shows the overall proposed network topology, which the simulation configuration for some critical parameters is defined in Table I for both the single-frequency and double-frequency band scenarios.

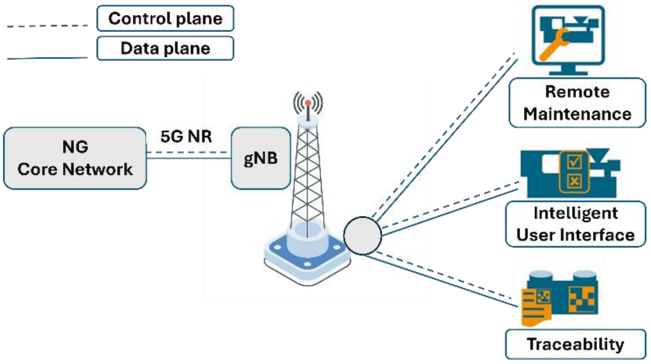

Fig. 3. Private 5G network topology for smart factori 4.0.

TABLE I. SIMULATION CONFIGURATION FOR SIGNLE AND DOUBLE FREQUENCY BAND FOR A DIRECT FROM UE TO gNB.

Parameter	**Single Frequency Band**		**Double Frequency Band**	
	Guaranteed Bit Rate (GBR)	**Non-guaranteed Bit Rate (NGBR)**	**Guaranteed Bit Rate (GBR)**	**Non-guaranteed Bit Rate (NGBR)**
IMSI UE(ID)	2	1	2	1
Central Frequency	28 GHz	28 GHz	28 GHz	28 GHz
Bandwidth	100 MHz	100 MHz	100MHz	100 MHz
Transmit Power (TxPower)	48 dBm	48 dBm	48dBm	48 dBm
Number of packets per second	10000	10000	10000	10000
Number of bytes per packet	1252	100	1000	100
Numerology (sub-carrier)	2	4	2	4
MIMO Antenna elements for UE	2x2	2x2	2x2	2x2
MIMO Antenna elements for gNB	8x8	8x8	8x8	8x8
Beamforming Method	Directpath	Directpath	Directpath	Directpath
Antenna height for gNB	4 m	4 m	4 m	4 m
Antenna height for UE	1.5 m	1.5 m	1.5 m	1.5 m
Environment	Umi_Streetcanyon	Umi_Streetcanyon	Umi_Streetcanyon	Umi_Streetcanyon
Antenna radiation pattern	Isotropic	Isotropic	Isotropic	Isotropic

3.1 Path Loss and SINR

QoS parameters are key identifier metrics used to assess the performance and effectiveness of a network including path loss, delay, throughput, signal-to-interference-plus-noise ratio (SINR). Path loss refers to the reduction in signal strength that occurs as a wireless signal propagates through a medium or travels over a distance. It is a natural phenomenon caused by factors such as distance, obstacles, and environmental conditions. As the signal travels, it spreads out and loses power, resulting in a decrease in signal strength at the receiver compared to the transmitted power. Path loss is a critical consideration in wireless communication systems, as it affects the coverage area, signal quality, and overall performance. Various mathematical models and empirical formulas, such as the Friis transmission equation and the Okumura-Hata model, are used to estimate and predict path loss based on factors like frequency, distance, antenna height, and the surrounding environment.

$$Path\,Loss = 20\log_{10}(d) + 20\log_{10}(f) + k \qquad (1)$$

Where, *d* is the distance between the transmitter and receiver in meters (m), *f* is the frequency of the signal in hertz (Hz), and *k* is a constant that accounts for system-specific factors such as antenna gains, propagation environment, and other losses.

SINR is a metric used in wireless communication systems to measure the quality of a received signal. It represents the ratio of the desired signal power to the combined interference and noise power in each channel or frequency band. The desired signal power refers to the power of the intended signal that is being received, while interference refers to unwanted signals from other sources that can degrade the signal quality. Noise represents random fluctuations in the received signal that are unrelated to the desired signal or interference. A higher SINR value indicates a stronger and cleaner desired signal relative to the interference and noise, resulting in better signal quality and improved communication performance. SINR is an important parameter used in various aspects of wireless system design, such as link budget calculations, capacity estimation, and determining the achievable data rates in a given communication scenario.

$$SINR = (Signa\,Power)/(Interference\,Power + Noise\,Power) \qquad (2)$$

Where, *Interference Power* is the power of the interfering signal and *Noise Power* is the power of the background noise measured in decibels (dB).

3.2 Throughput and Delay

Throughput refers to the rate at which data can be transmitted or processed over a network or system. It is a measure of the amount of data that can be successfully transferred within a given period. Throughput is typically expressed in terms of bits per second (bps), and it represents the effective data transfer rate, considering factors such as network congestion, latency, and protocol overhead. Higher throughput indicates a faster and more efficient data transfer, allowing for the transmission of larger volumes of data in a shorter amount of time. Throughput is a crucial performance metric in networking and communication systems, as it directly impacts the responsiveness, efficiency, and overall capacity of the network. *Channel Bandwidth* is the allocated bandwidth for the communication channel in hertz (Hz).

$$Throughput = Channel\,Bandwidth \times \log_2(1 + SINR) \qquad (3)$$

In telecommunication, delay measure in millisecond (s) refers to the time it takes for data or a signal to travel from a source to its destination. It encompasses various components, including transmission delay, propagation delay, processing delay, and queuing delay. Transmission delay refers to the time required to push all the bits of a packet onto the network link and depends on the packet size and the link's data rate. Propagation delay is the time taken for a signal to travel from the source to the destination which depends on the distance between the two points and the propagation speed of the medium. Processing delay is the time required to process the packet at the network devices, such as routers or switches. It includes tasks like packet inspection, routing table lookup, and error checking. Lastly, Queuing delay is the time spent by a packet in a queue at a network device, waiting to be processed or transmitted which depends on the congestion level of the network and the priority of the packet.

$$Delay = Processing\ Delay + Transmission\ Delay + Propagation\ Delay + Queuing\ Delay \qquad (4)$$

4 Results

4.1 GBR_Voice and NGBR_Low_Lat

The simulation demonstrates promising performance for the GBR_CONV_VOICE application shown in Table II. With a high packet reception percentage of 99.9988255%, it indicates that most voice packets transmitted from the user equipment (UE) were successfully received at the destination. The SINR value of 31.4672dB indicates a strong signal quality, suggesting that the desired signal is significantly higher than the interference and noise levels. This is crucial for voice applications, as it ensures clear and reliable voice communication. The pathloss of -

82.7852dB represents the attenuation of the signal as it propagates over the distance of 10m. A lower pathloss value indicates better signal strength at the receiver, which is favorable for maintaining a high-quality voice connection.

TABLE II. RESULT OF THE SIMULATION AT A DISTANCE OF 10 m.

Parameter	**GBR_CONV_VOICE**	**NGBR_LOW_LAT**
Tx Packets	596000	596000
Tx Bytes	612688000	76288000
TxOffered	82.24	10.24
Rx Bytes	612680804	76287744
Throughput	82.239118	10.239968
Mean delay	0.832141 ms	0.271427 ms
Mean jitter	0.12 ms	0.03 ms
Rx Packets	595993	595998
Packet Received Percentage	99.9988255%	99.99966443%
SINR	43.7372 dB	43.7702 dB

The simulation indicates that the NGBR_LOW_LAT application performs very well under the given conditions. With a high packet reception percentage of 99.99966443%, it demonstrates that the majority of the transmitted packets were successfully received at the destination. The SINR (Signal-to-Interference-plus-Noise Ratio) value of 30.4392 dB indicates a strong signal quality, suggesting that the desired signal is significantly higher than the interference and noise levels. This is crucial for low latency applications, as it ensures reliable and responsive communication. The pathloss of -82.2188 dB represents the attenuation of the signal as it travels over the distance of 10m. A lower pathloss value indicates better signal strength at the receiver, which is advantageous for low latency applications that require quick and efficient data transmission.

The result of simulation using standalone infrastructure applications NGBR_LOW_LAT_EMBB, indicates a specific type of low latency enhanced mobile broadband traffic. The measurements were taken at 10 m, indicating a close proximity between the transmitter and receiver. During the measurement, 596,000 packets and 76,288,000 bytes were transmitted. The offered load or traffic intensity, represented by TxOffered, was 10.24. The achieved throughput was 10.239968, indicating a relatively low data transfer rate. The communication exhibited low delay, with a mean delay of 0.271427ms, and low jitter, with a mean jitter of 0.03ms, suggesting stable and consistent transmission. The packet received percentage was very high at 99.99966443%, as 595,998 out of the transmitted packets were successfully received. The Signal-to-Interference-plus-Noise Ratio (SINR) value of 43.7702 dB indicates a strong and clear signal. However, the pathloss value of -83.9147 dB suggests a considerable loss of signal strength along the transmission path. In conclusion, the results indicate a reliable and efficient communication link for low latency enhanced mobile broadband traffic at a close distance, with high packet reception and a strong SINR. The low delay and jitter values further support the stability of the transmission.

4.2 Comparison of Throughput and Delay

The result of simulation using standalone infrastructure applications GBR_CONV_VOICE, indicates a type of voice traffic. The measurements were taken at 10 m, suggesting a close proximity between the transmitter and receiver. The data transmission was significant, with 596,000 packets and 612,688,000 bytes transmitted. The TxOffered was 82.24. The throughput achieved during the measurement was 82.239118, indicating a relatively high data transfer rate. The communication exhibited low delay, with a mean delay of 0.832141 ms, and low jitter, with a mean jitter of 0.12 ms, indicating stable and consistent transmission. A high packet received percentage of 99.9988255% demonstrates reliable packet reception, as 595,993 out of the transmitted packets were successfully received. The obtained SINR of 43.7372 dB indicates a strong and clear signal. However, the pathloss value of -83.9147 dB suggests a considerable loss of signal strength along the transmission path.

Overall, the results indicate a reliable and efficient communication link for voice traffic at a close distance, with high throughput, minimal delay, and stable transmission. The high packet reception rate and strong SINR further reinforce the quality of communication. The application experiences a significant decrease in throughput as the distance increases as illustrated in Fig. 4. At 10 m, the throughput is 102.3988, which drops to 1.176054 at 50 m, and finally reaches 0 at 100 m. This indicates that the application's ability to transmit data decreases with distance, leading to a complete loss of throughput at longer distances. The mean delay for the GBR_CONV_VOICE application shows a substantial increase as the distance increases. At 10m, the mean delay is 0.832171, which dramatically rises to 5450.12281 at 50 m. This indicates a significant latency increase. However, at 100m, the mean delay returns to 0, either indicating no successful transmission or an issue with the simulation setup.

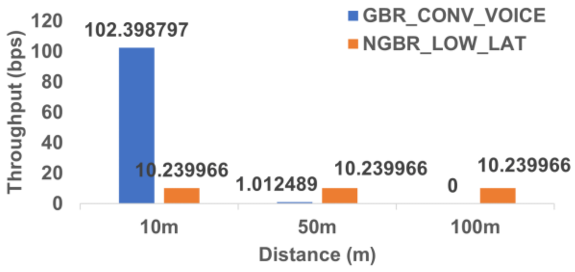

Fig. 4. A comparison of simulation results of throughput.

The NGBR_LOW_LAT application maintains a consistent throughput of 10.23997 across several distances of 10 m, 50 m, and 100 m as shown in Fig. 5. This suggests that the application can sustain a stable data transmission rate regardless of the distance between the source and destination. The mean delay for the NGBR_LOW_LAT application remains consistently low across all distances. At 10 m and 50 m, the mean delay is 0.271428, indicating low latency. At 100 m, the mean delay slightly increases to 0.275892, suggesting a slight elevation in latency but still maintaining an acceptable level of delay.

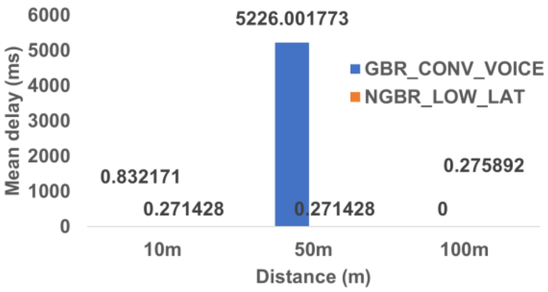

Fig. 5. A comparison of simulation results of mean delay.

5 Conclusion

We have successfully analyzed the performance of our proposed stand-alone 5G network infrastructure for smart factories, particularly for two application domains including guarantee and non-guarantee bit rate communications. The guaranteed bit rate communication for voice service is considered appropriately suitable for smart factories that require real-time communication and instant alerts with some predefined threshold requirements for the achievable throughput and communication distances. For non-guaranteed bit rate communication which is specifically defined for low latency applications, the system can provide a consistent throughput and low mean delay across different distances. This benefit will enhance data communication for machine-to-machine communication, control systems, and real-time data monitoring applications in today’s smart factories. Therefore, it is always significant to carefully consider the application requirements and prioritize communication services when deploying the 5G networks for any smart specific factories. It is also necessary to assess the availability of network resources, evaluate the tradeoffs when both the voice and low-latency data communication are required to meet the specific criteria defined for the factori 4.0 environment.

6 Declarations

6.1 Competing Interests

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

6.2 Publisher's Note

How to Cite

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References

[1] A. Ghosh, A. Maeder, M. Baker, and D. Chandramouli, "5G evolution: A view on 5G cellular technology beyond 3GPP release 15," *IEEE Access*, vol. 7, pp. 127639-127651, 2019.

[2] S.-Y. Lien, S.-C. Hung, D.-J. Deng, and Y. J. Wang, "Efficient ultra-reliable and low latency communications and massive machine-type communications in 5G new radio," in *GLOBECOM 2017-2017 IEEE Global Communications Conference*, 2017, pp. 1-7.

[3] P. Varga, J. Peto, A. Franko, D. Balla, D. Haja, F. Janky, G. Soos, D. Ficzere, M. Maliosz, and L. Toka, "5G support for industrial IoT applications—challenges, solutions, and research gaps," *Sensors*, vol. 20, no. 3, p. 828, 2020.

[4] A. Baltaci, E. Dinc, M. Ozger, A. Alabbasi, C. Cavdar, and D. Schupke, "A survey of wireless networks for future aerial communications (FACOM)," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 4, pp. 2833-2884, 2021.

[5] J. Zhang, E. Björnson, M. Matthaiou, D. W. K. Ng, H. Yang, and D. J. Love, "Prospective multiple antenna technologies for beyond 5G," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 8, pp. 1637-1660, Aug. 2020.

[6] A. Aijaz, "Private 5G: The future of industrial wireless," *IEEE Industrial Electronics Magazine*, vol. 14, no. 4, pp. 23-29, Dec. 2020.

[7] S. Dubey, and M. Jasraj, "Improvement of Throughput using Dual Connectivity in Non-Standalone 5G NR Networks." In *2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT)*, IEEE, pp. 6-12, 2020.

[8] P. Madduru, "Artificial intelligence as a service in distributed multi access edge computing on 5G extracting data using IoT and including AR/VR for real-time reporting," *Information Technology in Industry*, vol. 9, no. 1, pp. 912-931, 2021.