TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19
Number 4
December 2025
DOI: 10.12716/1001.19.04.20

Overview of QoS Metrics and Mechanisms Used in Mobile Networks

D. Wawok, W. Bonowicz, P. Zdankowski & J.M. Kelner
Military University of Technology, Warsaw, Poland

ABSTRACT: Mobile networks constitute the primary telecommunications system used in road transport. They also play an important role in maritime transport, particularly in ports and coastal areas. The development of fifth-generation (5G) and beyond technologies — especially non-terrestrial networks (NTNs) and their integration with satellite communication — opens up the potential for mobile connectivity even on the high seas. Quality of service (QoS) in mobile networks is essential for ensuring high performance, reliability, and efficient management of network resources. This paper presents a comprehensive overview of the key QoS metrics and mechanisms employed in mobile networks across different generations, from third (3G) and fourth-generation (4G) to the latest advancements in 5G. It discusses the evolution of cellular networks and strategies for QoS management, with a focus on critical key performance indicators (KPIs) and traffic optimization mechanisms such as bandwidth management, packet prioritization, and service differentiation. The aim is to provide a detailed and systematic review of QoS technologies, highlighting the differences between network generations and their impact on end-users and telecom operators. These topics are particularly relevant in the context of growing demand for high-throughput and low-latency services, making QoS optimization one of the key challenges facing modern mobile networks.

1 INTRODUCTION

Over the past few decades, digital mobile wireless communication systems have evolved from second (2G) to fifth-generation (5G) technologies. With the increasing diversity of provided services and the dynamic development of cellular networks, the importance of quality of service (QoS) has significantly grown. Currently, these metrics provide the basis for the quality assessment of the services provided in mobile networks and the selection of appropriate radio resources to support them. Furthermore, QoS is the foundation for developing key performance indicators (KPIs) for fourth-generation (4G), 5G, and beyond generations of systems [1].

New technologies offer a broader spectrum of services, more energy- and spectrum-efficient utilization of limited radio resources. In 5G, due to the ultra-dense network (UDN) [2] and the need to provide broadband services in a wider range, new frequency ranges (FRs) have been allocated for the needs of developing mobile networks, i.e., the sub-6 GHz band (i.e., FR1, including 700 MHz band and C-band), millimeter-waves (i.e., FR2), and upper mid-band (i.e., FR3) [3]. This enables the delivery of higher-level services (e.g., faster transmission, wider bandwidth, lower latency) compared to older-generation mobile networks. The potential of 5G technology is also visible in terms of military use [4].

On the other hand, regulatory authorities for telecommunications services (such as the Office of Electronic Communications in Poland) are increasingly enforcing improved QoS for end users [5]. Therefore, developing methods and tools for continuously assessing QoS is essential.

In this paper, we demonstrate how QoS metrics and mechanisms are changing in different generations of mobile networks. The remainder of the paper is organized as follows. Section 2 outlines the evolution of digital mobile networks. Sections 3, 4, and 5 provide an overview of QoS metrics and mechanisms in third-generation (3G), 4G, and 5G, respectively. The paper concludes with a summary in Section 6.

2 EVOLUTION OF MOBILE NETWORKS

The first generation (1G) of mobile network, introduced in the 1980s, was revolutionary for its time, enabling analog voice communication. However, its limitations quickly became apparent, such as poor sound quality and a lack of security. A breakthrough occurred in the 1990s with 2G digital networks with Global System for Mobile Communications (GSM) standard revolutionizing communication by introducing short message service (SMS) and improving call quality.

The following decade brought 3G networks, which met the growing user demand for high-speed mobile Internet, allowing for internet-based applications and video calls. The pace of technological development remained high. Long Term Evolution (LTE) standard as 4G networks delivered even faster data transmission and lower latency, enabling high-quality video streaming and broad adoption of cloud services [6].

Nowadays, we are in the era of 5G networks, which offer data speeds of up to 20 Gbps, ultra-low latency, and support for massive numbers of connected devices (i.e., UDN). 5G technology enables the implementation of advanced projects such as autonomous vehicles, smart cities, and applications in virtual and augmented reality [7].

Each generation not only raised the technological standards but also profoundly impacted our daily lives, reshaping how we work, socialize, and communicate. This paper thoroughly examines each generation, analyzing their development, key technologies, and societal influence.

To effectively ensure and maintain QoS, resource management systems must be designed with QoS requirements in mind. The resource allocation process must consider several critical factors, including resource availability, existing control policies, such as those defined in service-level agreements (SLAs), and the specific quality requirements of applications, expressed through QoS parameters such as delay, jitter, and packet loss [8][9].

Monitoring QoS parameters is essential to verify whether the agreed service levels are being met. If deviations from the expected values occur, the resource management system should reallocate resources appropriately to maintain the desired service quality. Before any resource reservation, the application layer must negotiate QoS parameters through signaling mechanisms. Once the negotiation is successful, the session can begin [9].

In the event of QoS degradation, and if the resource manager cannot compensate, the application should either adapt to the new QoS level or continue service delivery at a reduced level. QoS evaluation is based on analyzing a set of metrics, with the most important being delay, jitter, packet loss, and throughput. Additionally, more detailed indicators may also apply depending on the application type and the used management scheme [8].

In packet-switched networks, the most commonly applied general QoS parameters include [8]:

- delay – the total time for a packet to travel from the sender to the receiver;
- jitter – the variation in arrival time of successive packets;
- packet loss – the percentage of packets lost during transmission;
- throughput – the number of bits successfully transmitted over a given period.

Table 1 provides a more detailed comparison of 1G-5G mobile network standards. All abbreviations appearing in Table 1 are explained in the section before References.

3 QUALITY OF SERVICE IN 3G MOBILE NETWORKS

3.1 *QoS Metrics*

3G cellular networks use Universal Mobile Telecommunications System (UMTS) and High Speed Packet Access (HSPA) standards. In this generation, QoS metrics played a crucial role in delivering consistent performance for services such as voice calls, multimedia messaging service (MMS), video streaming, and mobile Internet access. 3G systems defined four main service classes: conversational, streaming, interactive, and background, each associated with specific QoS requirements.

Key QoS metrics in 3G mobile networks include:

- end-to-end delay – the total time taken for a data packet to travel from sender to receiver; for conversational class, delays below 150 ms were preferred;
- jitter – the variation in delay between successive packets, critical for real-time applications like Voice over Internet Protocol (VoIP);
- throughput – measured as guaranteed bit rate (GBR) and maximum bit rate (MBR), depending on the service class;
- packet loss rate (PLR) – high relevance in video/audio transmission, where loss above 1–2% leads to quality degradation;
- bit error rate (BER) – Indicates the quality of the physical signal transmission by measuring the frequency of bit-level errors.

Table 1. Comparison of 1G-5G mobile networks.

KPI \ Generation	1G	2G	3G	4G	5G
Technology	Analog	Digital	Digital	Digital	Digital
Standard	Different	GSM, GPRS	UMTS / HSPA	LTE / LTE-A / LTE-A Pro	New Radio (NR) / 5G-A
Year introduced	~1980	~1990	~2000	~2010	~2020
Frequency band	~30 MHz	~900 MHz / 1.8 GHz	1.6–2.0 GHz	2–8 GHz	3–6 GHz (FR1), 24–100 GHz (FR2)
Access technology	FDMA	TDMA / FDMA	WCDMA	OFDMA + SC-FDMA	OFDMA + MU-MIMO + beamforming
Data rate	~2 kbps	Up to 64 kbps	144 kbps – 2 Mbps	100 Mbps–1 Gbps (up to 3 Gbps with LTE-A)	>1 Gbps (up to 10–20 Gbps in eMBB)
Latency	~500–1000 ms	~300–500 ms	~100–200 ms	~30–50 ms	<1 ms (URLLC), ~4 ms (typical)
Jitter	Not applicable	High	Moderate	Low	Very low (URLLC)
Packet loss	Not applicable	High	<1–2% (video/audio)	<0.1% for VoIP	<0.001% for URLLC
Network throughput	Very low	Low	Medium	High	Very high
Device density (devices/km^2)	~10	~100	~1,000	~10,000	>1,000,000 (mMTC)
Reliability	Low	Moderate	Good	Very good	Ultra-reliable (>99.999%) for URLLC
QoS	None	Limited	Introduced service classes and QoS metrics	QCI, GBR/MBR, AMBR, PCRF	5QI, network slicing, AI/ML, PCF, reflective QoS
Dominant use cases	Voice only	Voice + SMS	Voice, SMS, MMS, mobile internet, video	VoLTE, streaming, online gaming, cloud services	URLLC, eMBB, mMTC, AR/VR, autonomous systems

These metrics were monitored primarily at the radio network controller (RNC) and used to inform radio resource management (RRM) decisions. Metrics like BER were also utilized to adapt physical layer (PHY) parameters dynamically [10].

3.2 *QoS Mechanisms*

In UMTS networks, QoS mechanisms were designed to differentiate services and prioritize traffic based on the application's sensitivity to latency, packet loss, and bandwidth requirements. The architecture introduced multiple service classes and integrated control mechanisms at both radio and core network layers.

Key QoS mechanisms in 3G include:

- traffic classes – four QoS traffic classes (conversational, streaming, interactive, background) defined the nature and sensitivity of services; conversational class, for instance, was prioritized for low-latency voice calls;
- bearer services – dedicated bearers were created with specific QoS attributes; these bearers determined how user data was handled across the UMTS core;
- radio access bearers (RABs) – these defined end-to-end QoS between the user equipment and core network;
- RRM – a critical component responsible for admission control, load balancing, power control, and handover decisions based on QoS demands;
- admission control and scheduling – evaluated whether new QoS flows could be admitted based on available radio capacity;
- QoS negotiation via non-access stratum (NAS) signaling – user terminals initiated session requests with QoS parameters, which the network evaluated before accepting and reserving resources.

These mechanisms ensured that high-priority services received preferential treatment, although their effectiveness was often constrained by network congestion and radio environment variability [9].

3.3 *Radio Signal Quality Parameters in 3G*

In 3G mobile systems (UMTS/HSPA), radio signal quality is primarily assessed using a set of physical-layer parameters that guide resource allocation, power control, and mobility management. These metrics are crucial for ensuring call stability, minimizing dropped connections, and maintaining throughput.

In 3G, the following radio signal quality parameters are defined [11]:

- received signal code power (RSCP) measures the received power on the common pilot channel (CPICH); it reflects the strength of the useful signal without considering interference; RSCP values typically range from –120 dBm (very weak) to –60 dBm (very strong); a signal stronger than –85 dBm is generally considered sufficient for stable voice and low-rate data services;
- energy per chip to noise power density ratio (Ec/No) expresses signal quality by comparing the pilot signal to the overall noise and interference level; values vary from –24 dB (poor quality) to 0 dB (excellent quality), with values above –10 dB preferred for good user experience;
- BER provides insight into the physical link reliability by indicating the proportion of received bits that are corrupted; acceptable service typically requires BER below 10^{-3}; although not directly visible to the user, BER is monitored internally to trigger error correction or retransmission processes.

Together, these parameters are periodically reported by the user equipment (UE) to the RNC and are critical inputs to RRM decisions such as handovers or code allocation.

4 QUALITY OF SERVICE IN 4G MOBILE NETWORKS

4.1 *QoS Metrics*

The introduction of LTE brought a more refined and comprehensive QoS assessment system, supported by the Evolved Packet Core (EPC). Later, LTE Advanced (LTE-A) and LTE-A Pro were introduced as evolutions of the LTE standard for 4G networks. Unlike 3G, LTE uses a fully Internet Protocol (IP)-based architecture and applies a unified QoS model across the network.

The main QoS metrics in 4G include:

- QoS class identifier (QCI) – a standardized value assigned to each bearer, defining priority, delay budget, and packet loss tolerance;
- priority level – Specifies the handling priority of resource allocation requests during network congestion;
- packet delay budget (PDB) – defines the maximum allowable delay for packet delivery (e.g., 100 ms for QCI 1 used in Voice over LTE (VoLTE));
- packet error loss rate (PELR) – the acceptable PLR, specific to each QCI class;
- GBR and MBR – applied to services requiring fixed bandwidth (e.g., real-time streaming);
- aggregate MBR (AMBR) – a shared limit for all non-GBR services per user.

PHY indicators such as channel quality indicator (CQI) further enable adaptive modulation and coding (AMC) to enhance QoS provisioning dynamically [12].

4.2 *QoS Mechanisms*

LTE networks revolutionized QoS by shifting to a flat IP-based architecture and incorporating enhanced control mechanisms through the EPC. The separation between control and user planes enabled more flexible and scalable QoS handling.

Notable QoS mechanisms in 4G networks include:

- EPS bearers – defined QoS flow attributes for each user session. Bearers could be GBR or non-GBR;
- QCI – each bearer was associated with a QCI value, which determined scheduling priority, PDBs, and error loss rates;
- policy and charging rules function (PCRF) – a core network entity responsible for dynamic QoS policy enforcement based on user profiles and service type;
- access point name (APN)-based QoS – enabled different QoS policies for various data services linked to distinct APNs;
- evolved node base station (eNodeB) scheduling algorithms – performed real-time traffic scheduling and resource allocation based on QCI values;
- bearer establishment and modification procedures – allowed dynamic creation, modification, or removal of bearers in response to changing service conditions.

These mechanisms allowed LTE networks to deliver differentiated services such as VoLTE, video streaming, and web browsing with distinct quality guarantees [13].

4.3 *Radio Signal Quality Parameters in 4G*

LTE networks introduced standardized and efficient methods of assessing signal quality by using dedicated reference signals. These metrics not only help the network adapt to changing radio conditions but also support critical features such as adaptive modulation and handover decisions.

The 4G standard defines the following radio signal quality metrics [14]:

- reference signal received power (RSRP) measures the average received power of LTE downlink cell-specific reference signals (CRSs); it is used to determine signal strength and typically ranges from –140 dBm to –80 dBm; an RSRP above –100 dBm is generally adequate for stable connections;
- reference signal received quality (RSRQ) is derived from RSRP and received signal strength indicator (RSSI), i.e., the total received power; it combines signal strength with interference levels; values range from –19.5 dB to –3 dB, with values above –10 dB indicating good quality;
- signal-to-interference-plus-noise ratio (SINR) is a key metric for evaluating data transmission conditions; it represents the quality of the received signal relative to interference and noise, ranging from –10 dB to +30 dB; high SINR (above 10 dB) is necessary for high-throughput services such as video streaming;
- CQI is a UE-reported value that reflects the modulation and coding scheme (MCS) suitable under current radio conditions; it is derived from SINR and is used by eNodeB to schedule user data efficiently.

These metrics are essential in LTE for maintaining service reliability and ensuring efficient radio resource utilization, especially in environments with varying interference and load conditions.

Examples of QoS and signal quality metrics measurements for UMTS and LTE networks, and video live-streaming YouTube services are presented in [15].

5 QUALITY OF SERVICE IN 5G MOBILE NETWORKS

5.1 *QoS Metrics*

5G New Radio (NR) networks introduced sophisticated QoS monitoring mechanisms to accommodate a diverse array of services, ranging from ultra-reliable low-latency communications (URLLC) to massive machine-type communications (mMTC). QoS in 5G is defined using the 5G QoS identifier (5QI) and associated parameters, along with growing emphasis on quality of experience (QoE) from the user's perspective.

New and extended 5G QoS metrics include:

- 5QI – the enhanced equivalent of QCI, encapsulating defined parameters like PDB and PELR for each service type;
- reflective QoS – allows uplink flows to inherit downlink QoS characteristics automatically;
- delay tolerance level – the maximum tolerable delay for specific applications;

– reliability – probability that a packet will be successfully delivered within a defined time frame (e.g., >99.999% for URLLC);
– availability – the duration the network can maintain a connection with guaranteed QoS;
– latency (one-way and round-trip) – time taken for a packet to travel one direction or round-trip; critical for applications like remote surgery and virtual reality;
– effective data rate – real throughput considering retransmissions and network congestion;
– user experience metrics (i.e., QoE) – perceived service quality indicators such as video buffering, loading times, and resolution stability.

Additionally, 5G networks use artificial intelligence (AI)/machine learning (ML)-based mechanisms to predict and adapt QoS parameters in real-time. Network slicing allows each virtual slice to have tailored QoS profiles, optimized dynamically based on user demand and application context [7][16][17].

5.2 *QoS Mechanisms*

5G introduces a more advanced, software-driven approach to QoS, leveraging network slicing and service-based architecture (SBA) to deliver application-specific quality guarantees. Unlike previous generations, 5G allows for flexible, real-time service-level management.

Primary QoS mechanisms in 5G include:
– 5QI – analogous to QCI in LTE but more granular, defining default delay, reliability, and priority for each traffic flow;
– session and service continuity (SSC) modes – govern how QoS is maintained across mobility events and session transitions;
– policy control function (PCF) – replaces PCRF, providing enhanced policy management and QoS enforcement across network slices;
– network slicing – supports multiple logical networks over shared infrastructure, each with its own QoS profile tailored for services like URLLC, enhanced mobile broadband (eMBB), or mMTC;
– reflective QoS – enables dynamic mirroring of downlink QoS settings in the uplink, reducing signaling overhead;
– unified data management (UDM) – centralizes user subscription and QoS profile management across the network;
– application function (AF) – communicates with PCF to request QoS changes based on application demands;
– AI/ML-driven QoS optimization – predictive algorithms manage resource distribution and QoS adaptation based on real-time analytics.

These mechanisms support diverse 5G use cases with unprecedented granularity, flexibility, and efficiency [18][19][20].

5.3 *Radio Signal Quality Parameters*

5G NR networks build upon LTE's framework for radio quality evaluation but adapt it to new technical features such as massive MIMO, beamforming, and millimeter-wave operation. Signal metrics are based on synchronization signal blocks (SSBs), which are broadcast periodically for measurement purposes.

In 5G, additional parameters for radio signal quality assessment are used [21]:
– synchronization signal RSRP (SS-RSRP) measures the power of synchronization signals, used in initial access and mobility decisions; the expected range is similar to LTE: –140 dBm to –80 dBm;
– synchronization signal RSRQ (SS-RSRQ) reflects the quality of the synchronization signals relative to interference and total received power; acceptable values lie between –19.5 dB and –3 dB, with values above –10 dB preferable for stable connectivity;
– synchronization signal SINR (SS-SINR) measures the SINR on the SSB; it is crucial for beam management and high-throughput data sessions; values range from –10 dB (poor quality) to +30 dB (excellent quality);
– beam-based CQI and per-beam RSRP metrics allow for fine-grained optimization of signal quality and mobility; in 5G, CQI may be reported per beam, enabling the next generation node base station (gNodeB) to select and dynamically adjust the best transmission beam.

5G also leverages AI/ML-driven analytics to predict signal quality trends and proactively adjust radio parameters. In millimeter-wave bands (FR2), where signal propagation is more sensitive to blockage, continuous monitoring of these metrics is vital for maintaining service continuity and quality.

Exemplary measurements of signal quality and QoS metrics for the iPerf and Hypertext Transfer Protocol (HTTP)-browsing scenarios in 5G are described in [22] and [23], respectively.

6 CONCLUSIONS

The rapid evolution of mobile networks from 3G through 4G to 5G has been accompanied by significant advancements in QoS mechanisms and metrics. Each generation introduced increasingly sophisticated tools to ensure service reliability, minimize latency, and optimize bandwidth usage, adapting to the growing complexity and diversity of user demands. In 3G networks, QoS mechanisms focused on basic traffic classification and radio resource control. LTE (4G) further enhanced QoS management through standardized bearer architectures and a unified IP-based framework. The advent of 5G marked a paradigm shift by introducing network slicing, AI-driven optimization, and real-time policy enforcement tailored to diverse application needs such as URLLC, eMBB, and mMTC.

These developments underline the critical importance of dynamic and intelligent QoS solutions in the face of modern connectivity challenges. As the demand for high-throughput, low-latency, and highly reliable communication continues to grow, particularly in transport, smart cities, and industrial automation, maintaining and improving QoS remains a central task for network operators and researchers alike. Continued innovation in QoS frameworks will be essential to support the next wave of mobile technologies and ensure seamless user experiences across all service domains.

ABBREVIATIONS

1G – first-generation
2G – second-generation
3G – third-generation
4G – fourth-generation
5G – fifth-generation
5G-A – 5G Advanced
5QI – 5G quality of service identifier (5G QoS identifier)
AF – application function
AI – artificial intelligence
AMBR – aggregate maximum bit rate
AMC – adaptive modulation and coding
APN – access point name
AR – augmented reality
BER – bit error rate
CPICH – common pilot channel
CQI – channel quality indicator
CRS – cell-specific reference signal
eMBB – enhanced mobile broadband
eNodeB – evolved node base station (evolved node B)
Ec/No – energy per chip to noise power density ratio
EPC – Evolved Packet Core
FDMA – frequency division multiple access
FR – frequency range
GBR – guaranteed bit rate
gNodeB – next generation node base station (next generation node B / 5G New Radio node B)
GPRS – General Packet Radio Service
GSM – Global System for Mobile Communications
HSPA – High Speed Packet Access
HTTP – Hypertext Transfer Protocol
IP – Internet Protocol
KPI – key performance indicator
LTE – Long Term Evolution
LTE-A – Long Term Evolution Advanced
MBR – maximum bit rate
MCS – modulation and coding scheme
MIMO – multiple-input-multiple-output
ML – machine learning
MMS – multimedia messaging service
mMTC – massive machine-type communications
MU-MIMO – multi-user multiple-input-multiple-output
NAS – non-access stratum
NR – New Radio
NTN – non-terrestrial networks
OFDMA – orthogonal frequency division multiple access
PCF – policy control function
PCRF – policy and charging rules function
PDB – packet delay budget
PELR – packet error loss rate
PHY – physical layer
PLR – packet loss rate
QCI – quality of service class identifier (QoS class identifier)
QoE – quality of experience
QoS – quality of service
RAB – radio access bearer
RNC – radio network controller
RRM – radio resource management
RSCP – received signal code power
RSRP – reference signal received power
RSRQ – reference signal received quality
RSSI – received signal strength indicator
SBA – service-based architecture
SC-FDMA – single carrier frequency division multiple access
SINR – signal-to-interference-plus-noise ratio
SLA – service-level agreement
SMS – short message service
SS – synchronization signal
SS-RSRP – synchronization signal reference signal received power
SS-RSRQ – synchronization signal reference signal received quality
SS-SINR – synchronization signal signal-to-interference-plus-noise ratio
SSB – synchronization signal block
SSC – session and service continuity
TDMA – time division multiple access
UDM – unified data management
UDN – ultra-dense network
UE – user equipment
UMTS – Universal Mobile Telecommunications System
URLLC – ultra-reliable and low-latency communications
VoIP – Voice over Internet Protocol (Voice over IP)
VoLTE – Voice over Long-Term Evolution (Voice over LTE)
VR – virtual reality
WCDMA – wideband code division multiple access

REFERENCES

[1] P. Rost et al., “Mobile network architecture evolution toward 5G,” IEEE Communications Magazine, vol. 54, no. 5, pp. 84–91, May 2016, doi: 10.1109/MCOM.2016.7470940.
[2] S. M. A. Zaidi, M. Manalastas, H. Farooq, and A. Imran, “Mobility management in emerging ultra-dense cellular networks: A survey, outlook, and future research directions,” IEEE Access, vol. 8, pp. 183505–183533, 2020, doi: 10.1109/ACCESS.2020.3027258.
[3] D. Shakya et al., “Comprehensive FR1(C) and FR3 lower and upper mid-band propagation and material penetration loss measurements and channel models in indoor environment for 5G and 6G,” IEEE Open Journal of the Communications Society, vol. 5, pp. 5192–5218, 2024, doi: 10.1109/OJCOMS.2024.3431686.
[4] D. Zmysłowski, P. Skokowski, K. Malon, K. Maślanka, and J. M. Kelner, “Naval use cases of 5G technology,” TransNav, International Journal on Marine Navigation and Safety od Sea Transportation, vol. 17, no. 3, pp. 595–603, Sep. 2023, doi: 10.12716/1001.17.03.11.
[5] J. Mongay Batalla, S. Sujecki, J. M. Kelner, P. Śliwka, and D. Zmysłowski, “On studying active radio measurements estimating the mobile network quality of service for the Regulatory Authority’s purposes,” Computer Networks, vol. 235, p. 109980, Nov. 2023, doi: 10.1016/j.comnet.2023.109980.
[6] M. Sauter, From GSM to LTE-Advanced Pro and 5G: An introduction to mobile networks and mobile broadband, 3rd ed. Hoboken, NJ, USA: Wiley, 2017.
[7] H. Zhang, N. Liu, X. Chu, K. Long, A.-H. Aghvami, and V. C. M. Leung, “Network slicing based 5G and future mobile networks: Mobility, resource management, and challenges,” IEEE Communications Magazine, vol. 55, no. 8, pp. 138–145, Aug. 2017, doi: 10.1109/MCOM.2017.1600940.
[8] “ITU-T Recommendation Y.1541: Network performance objectives for IP-based services,” International Telecommunication Union (ITU), Geneva, Switzerland, Y.1541 (12/2011), Dec. 2011. Accessed: Jun. 01, 2024. [Online]. Available: https://www.itu.int/rec/T-REC-Y.1541-201112-I/en
[9] 3GPP, “TS 123 107 - V18.0.0 - Digital cellular telecommunications system (Phase 2+) (GSM); Universal Mobile Telecommunications System (UMTS); LTE; Quality of Service (QoS) concept and architecture (3GPP TS 23.107 version 18.0.0 Release 18),” 3GPP/ETSI, ETSI TS 123 107-V18.0.0, Apr. 2024. [Online]. Available: https://www.etsi.org/deliver/etsi_TS/123100_123199/123107/18.00.00_60/ts_123107v180000p.pdf
[10] H. Holma and A. Toskala, Eds., WCDMA for UMTS: Radio access for third generation mobile communications, 3rd ed. Chichester, England; Hoboken, NJ, USA: Wiley, 2004.
[11] 3GPP, “TS 125 215 - V11.0.0 - Universal Mobile Telecommunications System (UMTS); Physical layer; Measurements (FDD) (3GPP TS 25.215 version 11.0.0 Release 11),” 3GPP/ETSI, ETSI TS 125 215-V11.0.0, Nov. 2012. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/125200_125299/125215/11.00.00_60/ts_125215v110000p.pdf

[12] S. Sesia, I. Toufik, and M. Baker, Eds., LTE. The UMTS Long Term Evolution: From theory to practice. Chichester, U.K: Wiley, 2009.
[13] 3GPP, "TS 123 203 - V18.0.0 - Digital cellular telecommunications system (Phase 2+) (GSM); Universal Mobile Telecommunications System (UMTS); LTE; Policy and charging control architecture (3GPP TS 23.203 version 18.0.0 Release 18)," 3GPP/ETSI, ETSI TS 123 203-V18.0.0, Apr. 2024. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/123200_123299/123203/18.00.00_60/ts_123203v180000p.pdf
[14] 3GPP, "TS 136 214 - V14.2.0 - LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements (3GPP TS 36.214 version 14.2.0 Release 14)," 3GPP/ETSI, ETSI TS 136 214-V14.2.0, Apr. 2017. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/136200_136299/136214/14.02.00_60/ts_136214v140200p.pdf
[15] D. Zmysłowski and J. M. Kelner, "Drive test-based correlation assessment of QoS parameters for exemplary measurements scenario in suburban environment," in 2022 18th International Conference on Web Information Systems and Technologies (WEBIST), Valletta, Malta: SciTech Publishing, Oct. 2022, pp. 497–504. doi: 10.5220/0011575800003318.
[16] "ITU-T Recommendation G.1011: Reference guide to quality of experience assessment methodologies," International Telecommunication Union (ITU), Geneva, Switzerland, G.1011 (07/2016), Jul. 2016. Accessed: Jun. 01, 2024. [Online]. Available: https://www.itu.int/rec/T-REC-G.1011/en
[17] "ITU-T Recommendation Y.3147: Quality of service requirements and framework of deterministic communications for remote device control services over IMT-2020 and beyond," International Telecommunication Union (ITU), Geneva, Switzerland, Y.3147 (04/2025), Apr. 2025. Accessed: Jun. 01, 2024. [Online]. Available: https://www.itu.int/epublications/es/publication/itu-t-y-3147-2025-04-quality-of-service-requirements-and-framework-of-deterministic-communications-for-remote-device-control-services-over-imt-2020-an/en
[18] "ITU-T Recommendation Y.3113: Requirements and framework for latency guarantee in large-scale networks including the IMT-2020 network," International Telecommunication Union (ITU), Geneva, Switzerland, Y.3113 (02/2021), Feb. 2021. Accessed: Jun. 01, 2024. [Online]. Available: https://www.itu.int/itu-t/recommendations/rec.aspx?rec=14595
[19] "ITU-T Recommendation Y.3170: Requirements for machine learning-based quality of service assurance for the IMT-2020 network," International Telecommunication Union (ITU), Geneva, Switzerland, Y.3170 (04/2020), Apr. 2020. Accessed: Jun. 01, 2024. [Online]. Available: https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=13691
[20] X. Foukas, G. Patounas, A. Elmokashfi, and M. K. Marina, "Network slicing in 5G: Survey and challenges," IEEE Communications Magazine, vol. 55, no. 5, pp. 94–100, May 2017, doi: 10.1109/MCOM.2017.1600951.
[21] 3GPP, "TS 138 215 - V16.2.0 - 5G; NR; Physical layer measurements (3GPP TS 38.215 version 16.2.0 Release 16)," 3GPP/ETSI, ETSI TS 138 215-V16.2.0, Jul. 2020. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138200_138299/138215/16.02.00_60/ts_138215v160200p.pdf
[22] D. Zmysłowski and J. M. Kelner, "Mobile network operators' assessment based on drive-test campaign in urban area for iPerf scenario," Applied Sciences, vol. 14, no. 3, Art. no. 3, Jan. 2024, doi: 10.3390/app14031268.
[23] D. Zmysłowski and J. M. Kelner, "Correlational analysis in QoS parameter assessment for 5G emerging networks in Poland," in 2023 Signal Processing Symposium (SPSympo), Karpacz, Poland, Sep. 2023, pp. 226–229. doi: 10.23919/SPSympo57300.2023.10302684.