Paper

Comparative Analysis of QoS Management and Technical Requirements in 3GPP Standards for Cellular IoT Technologies

Valery Tikhvinskiy[1,2], Grigory Bochechka[1,2], Andrey Gryazev[3], and Altay Aitmagambetov[4]

[1] *LLC Icominvest, Moscow, Russian Federation*
[2] *Moscow Technical University of Communications and Informatics, Moscow, Russian Federation*
[3] *Federal State Unitary Enterprise Central Science Research Telecommunication Institute, Moscow, Russian Federation*
[4] *International IT University, Almaty, Kazakhstan*

https://doi.org/10.26636/jtit.2018.122717

Abstract—Optimization of 3GPP standards that apply to cellular technologies and their adaptation to LPWAN has not led to positive results only enabling to compete on the market with the growing number non-cellular greenfield LPWAN technologies – LoRa, Sigfox and others. The need to take into consideration, during the 3GPP standard optimization phase, the low-cost segment of narrow-band IoT devices relying on such new technologies as LTE-M, NB-IoT and EC-GSM, has also led to a loss of a number of technical characteristics and functions that offered low latency and guaranteed the quality of service. The aim of this article is therefore to review some of the most technical limitations and restrictions of the new 3GPP IoT technologies, as well as to indicate the direction for development of future standards applicable to cellular IoT technologies.

Keywords—3GPP, EC-GSM, LTE, NB-IoT, QoS, standardization, RAT.

1. Introduction

The global economy is rapidly becoming digital. The creation of a digital single market is currently one of European Union's key priorities [1]. With the technological aspect of digital economy considered, one comes to the conclusion that ICT technologies have become a basis of the modern digital economy, as they connect nearly everything in the world. The Internet of Things (IoT) is the most prominent one. Applications for vertical markets require development of new wireless access technologies based on modern 3GPP cellular solutions, optimized for low-power wide area (LPWA) technology requirements. LPWA applications are characterized by the sending of small payloads of data at infrequent intervals (perhaps just a few times an hour).

The attractiveness of the concept of creating and standardizing the low-power wide area technology based on 3GPP has been proved by the infrastructure that is already operational and by the explosive growth in demand for IoT services with CAGR, expected to reach over 33–50% by 2022 [2], [3].

However, in addition to positive results, such as reduction of the cost of devices and meeting the requirements for LPWA, the transition to narrowband technologies has also brought about significantly limited opportunities, such as Quality of Service (QoS), mobility and a number of others. Narrowband IoT is a machine type communication (MTC) technology that is specifically optimized for IoT.

This article is devoted to a comparative analysis of the impact that 3GPP standards applicable to new narrowband IoT access technologies exert on QoS in IoT access networks, as well as to the impact of these technologies on the IoT business model.

2. Analysis of 3GPP Cellular IoT Standardization of LPWA Requirements

In November 2015, 3GPP provided for specifications for Narrowband IoT (NB-IoT). New radio access technologies (RAT) for cellular IoT, based, to a great extent, on the non-backward-compatible variant of E-UTRA/GERAN, address improved indoor coverage, support a massive number of low throughput devices, as well as offer low delay sensitivity, ultra-low device cost, low device power consumption and optimized network architecture.

LPWANs are low-power wireless wide area networks technologies that specialize in interconnecting devices with IoT/M2M applications that have low data rates, require long battery lives and operate unattended over prolonged periods time, often at remote locations.

Table 1
Cellular IoT technology parameters

Parameters	LTE-M (1.4 MHz)	NB-IoT (180 kHz)	EC-GSM (200 kHz)
Improved coverage including indoor	156 dB MCL (+15 dB improvement)	164 dB MCL (+20 dB improvement)	164 dB MCL (+20 dB improvement)
Range (outdoor)	< 11 km	< 15 km	< 15 km
Massive IoT capacity	> 52 kdev./cell/180 kHz	> 52 kdev./cell/180 kHz	> 52 kdev./cell/180 kHz
Data rate	< 1 Mbps	< 200 kbps	< 70 kbps
Battery life	> 10 years	> 10 years	> 10 years
Latency	< 10 s	< 10 s	< 10 s
Low cost IoT module	5 USD (2016)/ 3.3 USD (2020)	4 USD (2016)/ 2–3 USD (2020)	5.5 USD (2016)/ 2.9 USD (2020)
Spectrum deployment scenario	In-band	In-band, stand alone, guard-band	Stand-alone
Network upgrade	To be determined	Yes (HW/SW?)	Yes (HW/SW?)

3GPP Requirements include some important market and technological parameters [4]:

- low-cost devices should be less than 5 USD,
- long battery life in order of 10 years,
- extreme low data rate network support,
- extended coverage similar to GPRS, with the maximum coupling loss (MCL) of approx. 164 dB,
- support of a massive number of devices, requiring high cell capacity (40 devices per household, 55,000 devices per cell),
- low data and low latency support (a few kbps and below 10 s),
- low deployment and operation cost, and very high network availability,
- consistent and meaningful user experience – QoS.

Three different cellular IoT technologies (Table 1) are standardized in 3GPP, with two of them based on E-UTRAN and one – on GERAN [5]:

- the first solution was LTE-M, released in 2014, under Release 12, as an evolution of LTE Advanced, optimized for IoT in the 3GPP RAN working group. Further optimization was continued in Release 13, with specifications completed in 2016;
- NB-IoT is the narrowband evolution of E-UTRAN for IoT, developed in the 3GPP RAN working group. It was included in Release 13, with technical specifications completed in 2016;
- EC-GSM-IoT is an evolution of GERAN, optimized for IoT in the 3GPP GERAN working group, included in Release 13, with specifications completed in 2016.

The first solution, i.e. LTE-M or eMTC, differs from the LPWA solutions in that it uses a standard LTE air interface and a broadband radio channel with the bandwidth of 1.4 MHz in relation to other technologies. LTE-M offers a new power-saving functionality, suitable for serving a IoT applications. In LTE-M, the power saving mode and eDRX [6] extend battery life for LTE-M to 10 years or more. LTE-M has a reduced peak rate. This can be achieved by limiting the maximum block size to less than 1000 bits, or the number of physical resource blocks (PRBs) allocated each time to 6 or less, or by reducing the modulation order, i.e. QPSK only.

LTE-M traffic is multiplexed over the full LTE carrier, and it is therefore able to tap into the full capacity of LTE. New functionalities for substantially reduced device cost and extended coverage for LTE-M are also specified within 3GPP.

NB-IoT is a 3GPP RAT that forms a part of the cellular IoT network. It provides access to network services via E-UTRA, with the channel bandwidth limited to 180 kHz, corresponding to one physical resource block (PRB). NB-IoT is a subset of E-UTRAN. The NB-IoT technology provides lean setup procedures, while capacity evaluation indicates that each 180 kHz NB-IoT carrier can support more than 200,000 subscribers. The solution can be easily scaled up by adding multiple NB-IoT carriers. NB-IoT also comes with an extended coverage of up to 20 dB, and battery saving features.

Table 2
Bandwidth of NB-IoT channel in compared to LTE channels

Channel bandwidth NB-IoT [MHz]	0.18	1.4	3	5	10	15	20
LTE [MHz]	1	6	15	25	50	75	100

The bandwidth of one NB-IoT channel is equal to that of one resource block (RB), and 6-100 times smaller than that of an LTE legal channel (Table 2) [7].
NB-IoT shall support 3 different operating spectrum scenarios (Fig. 1):

- stand-alone operation utilizing, for example, the spectrum currently being used by GERAN systems, as a replacement for one or more GSM carriers (Fig. 1a),
- guard band operation utilizing the unused resource blocks within the LTE carrier's guard-band (Fig. 1b),
- in-band operation utilizing resource blocks within a normal LTE carrier (Fig. 1c).

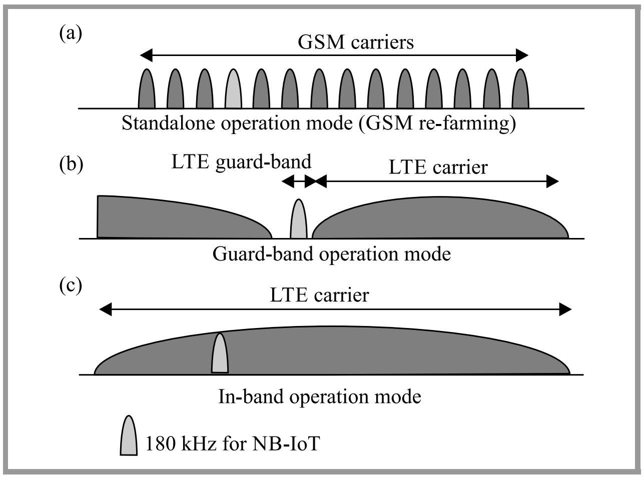

Fig. 1. Spectrum scenarios for operation of NB-IoT.

NB-IoT will support the following features:

- 180 kHz user equipment (UE) RF bandwidth for both downlink and uplink,
- each resource element of NB-IoT can accommodate 1 modulation symbol, e.g. 2 bits for QPSK,
- the modulation symbol rate per resource block is 144 ksps or 168 ksps,
- single synchronization signal design for the different modes of operation, including techniques to handle overlap with legacy LTE signals.

The EC-GSM functionality enables coverage improvements of up to 20 dB with respect to GPRS on the 900 MHz band. EC-GSM defines new control and data channels mapped over legacy GSM. The EC-GSM operation spectrum scenario assumes stand-alone operation only. EC-GSM provides a combined capacity of up to 50,000 devices per cell on a single transceiver.
The introduction of LPWAN requirements to 3GPP standards has led not only to positive results, but has also significantly limited the use of cellular IoT devices in critical cases for such applications. Therefore, it is advisable to further analyze the consequences of optimization of 3GPP technologies to LPWAN, and to assess their impact on the IoT application market.

3. Results of 3GPP RAT Standards' Optimization to LPWAN

Analysis of the optimization of 3GPP technical specifications to LPWAN reveals some limitations and restrictions for technical features of narrow-band technologies optimized for IoT (i.e., 3GPP TS 36.300, 3GPP TS 23.401, 3GPP TS 23.203 [7]-[9]).

3.1. NB-IoT

NB-IoT is the first of such technologies, and it provides access to network services via E-UTRA with channel bandwidth limited to 180 kHz (Table 2). The downlink transmission scheme for NB-IoT in the frequency domain uses one resource block per NB-IoT carrier, with the OFDM sub-carrier spacing of $\Delta f = 15$ kHz, at all times, and with half-duplex operation being the only one supported.
For NB-IoT uplink transmission, both single-tone transmission and multi-tone transmission are possible. For single-tone transmission, there are two numerologies defined: 3.75 kHz and 15 kHz subcarrier spacing, based on single-carrier FDMA. Multi-tone transmission is based on a single-carrier FDMA. There are 12 consecutive uplink sub-carriers with the uplink sub-carrier spacing of $\Delta f = 15$ kHz.
A number of functions including inter-RAT mobility, handover, measurement reports, public warning functions, guaranteed bit rate (GBR), closed subscriber group (CSG) mode, support of Home eNode B (HeNB), relaying, carrier aggregation, dual connectivity, multimedia broadcast multicast services, real-time services, interference avoidance for in-device coexistence, RAN assisted WLAN interworking, sidelink communication/discovery, emergency call, VoLTE, self-configuration/self-optimization, congestion control for data communication - are not supported in NB-IoT. A number of E-UTRA protocol functions supported by all Rel-8 devices are not used in the NB-IoT technology and need not be supported by eNBs and IoT-devices only using NB-IoT. Restrictions of the NB-IoT technology in the LTE user plane include:

- the user plane is not used when transferring data over a non-access stratum,
- multiplexing of the common control channel and the dedicated traffic channel in the transition from the radio resource control (RRC) idle mode to the RRC connected mode is not supported,
- a non-anchor carrier can be configured when an RRC connection is re-established, resumed or reconfigured additionally when an RRC connection is established.

Restrictions of the NB-IoT technology in LTE control plane include:

- NB-IoT devices don't make reporting and control measurements for RRC,
- data radio bearer (DRB) is not used,
- access stratum (AS) security is not used,
- there is no differentiation between the different data types (i.e. IP, non-IP or SMS) in the access stratum,
- RRC connection reconfiguration and RRC connection re-establishment are not supported.

Handover, measurement reports and inter-RAT mobility are not supported in NB-IoT.
LTE optimization towards NB-IoT has led to a situation in which GBR bearers are not supported by NB-IoT. The PDN gateway (P-GW) uses the RAT type to ensure that GBR bearers are not active when the cellular IoT device is using the NB-IoT technology [8].
The mobility of UE is handled by the handover procedure, except for when the NB-IoT is being used, in which case there are no handover procedures.
Inter-RAT mobility to and from NB-IoT is not supported. In Release 13, NB-IoT does not support TDD operation.

3.2. EC-GSM

Extended coverage GSM (EC-GSM) technology is an evolution of EGPRS providing a streamlined protocol implementation and reducing IoT device complexity, while simultaneously supporting energy efficient operation with extended coverage compared to GPRS/EGPRS. IoT access network with EC-GSM could use as little as 600 kHz of the spectrum.
EC-GSM also mandates the use of an improved security framework by both the network and the IoT-device. In EC-GSM, the IoT device is able to operate in an extended coverage mode, in both uplink and downlink, which is means an improved IoT device and BTS sensitivity and interference performance. The feature has been designed to improve coverage by 20 dB and also the interference level by 20 dB compared to GPRS/EGPRS.
IoT devices supporting EC-GSM may support extended discontinuous reception (eDRX) and/or the power saving mode (PSM), and shall support the use of relaxed mobility related requirements. The EC-GSM technology is functional only when all three network nodes: SGSN, IoT devices and base station system (BSS), are compliant with the feature requirements of EC-GSM.
EC-GSM realizes extended coverage (EC) through coverage classes. A coverage class determines the total number of blind repetitions to be used when transmitting/receiving radio blocks. An uplink/downlink coverage class applicable at any point in time can differ between different logical channels. EC-GPRS devices operate in four different coverage classes, where each class is approximated with a level of extended coverage compared to GPRS/EGPRS operation denoted as CC1, CC2, CC3 and CC4 respectively [10]–[12].
Limitations and restrictions of the EC-GSM technology include:

- EC-GSM does not support dynamic absolute radio-frequency channel number (ARFCN) mapping,
- in networks where EC-GSM is supported, the frequency re-use cluster size is expected to be smaller than in networks not supporting EC-GSM,
- dual transfer mode is not supported in EC-GSM operation,
- no simultaneous uplink and downlink packet transfer is supported in EC-GSM,
- EC-GSM makes use of fixed uplink allocation for allocating uplink resources for EC packet data traffic channels and hence does not support the uplink status flag (USF) base uplink allocation.

GSM standards define the GPRS QoS classes that can be requested by GPRS devices, including EC-GSM IoT devices. GPRS QoS profiles are considered a single parameter that defines the following data transfer class attributes, according to the GSM/GPRS standard [11]:

- precedence class,
- delay class,
- reliability class,
- peak throughput class,
- mean throughput class.

This means that the EC-GSM technology, used as GSM/GPRS, has to employ the "best effort" principle for QoS management, which is not sufficient to offer real time IoT services. Therefore, in spite of the limitations and restrictions related to the optimization of 3GPP RAT standards, the solutions obtained make it possible to cover all IoT applications existing on the market, with the LTE-M technology used for critical (real time) IoT applications and NB-IoT/EC-GSM technologies used for other, non-critical IoT applications.

4. Impact of 3GPP Standard Optimization on QoS Management

Each 3GPP technology – 2G (GSM), 3G (UMTS) and 4G (LTE) is characterized by QoS classes, and the evolution from 2G to 4G has resulted in a two-fold increase of QoS class numbers, to 9 [6]. QoS priority queuing and QoS bandwidth management, the fundamental mechanisms of a QoS configuration, are configured within the QoS class definition. QoS priority queuing and bandwidth management determine the order of traffic and how traffic is handled upon entering or leaving a network.

QoS classes distinguish the ability of 3GPP networks to provide services without quality assurance (best effort or non-GBR) and with guaranteed bit rate (GBR). QoS in 3GPP networks is the ability of the network to enforce different priorities for different application types, subscribers or data sessions, while guaranteeing a certain level of performance of a data session.

A steady increase in the number of mobile applications that control QoS based on the service quality requirements requires implementation of QoS management principles at the network level, and calls for the bearer services to offer the necessary, high-level data exchange.

LTE and UMTS networks propose two major types of bearers:

- guaranteed bit rate (GBR) used for dedicated bearers,
- non-guaranteed bit rate (Non-GBR) used for default or dedicated bearers.

QoS classes allow both 3GPP RAT-compliant subscribers and services to be differentiated. Premium subscribers can be prioritized over basic ones. Real time services can be prioritized over non-real time services.

GBR offers QoS support for the following:

- for real-time services,
- minimum amount of reserved bandwidth,
- always consumes resources in a eNB, regardless of whether it is used or not,
- GBR bearers will be defined with the lower latency and jitter tolerances which are typically required by real-time services.

Each bearer is associated with a predetermined GBR QoS parameter value. If the traffic carried by the GBR bearer conforms to the value associated with the GBR bearer, then there is no chance of congestion-related packet loss in the service utilizing the GBR bearer. A GBR bearer usually is established on an "on-demand basis", because it blocks all transmission resources by reserving them while performing the admission control function.

Non-GBR offers limited support of QoS-related issues:

- no specific network bandwidth allocation,
- for best-effort services (file downloads, email, and Internet browsing),
- packet loss experienced in the case of congestion,
- the maximum bit rate for non-GBR bearers is not specified on a per-bearer basis. However, an aggregate maximum bit rate (AMBR) will be specified on a per-subscriber basis for all non-GBR bearers.

This bearer is mainly used for such applications as web browsing and FTP transfer. Services utilizing non-GBR bearers are prone experience to congestion-related packet losses. No specific transmission resources are blocked. A non-GBR bearer is established in the default or dedicated bearer, and remains established for a longer period of time.

LTE networks include the following: LTE evolved packet system (EPS) bearer, external bearer, E-RAB, S1 interface bearer, S5 interface bearer, S8 interface bearer, LTE radio bearer, etc. [6], which are basically a virtual concept and are a set of network configurations to provide special treatment to traffic. The bearer is a kind of a pipe or tunnel in which message transfers between network entities occurs, and the pipe is identified through a unique ID.

An LTE EPS bearer provides user plane connectivity between the UE and the PDN gateway. This EPS bearer is known as a default EPS bearer, and it is used to provide "always-on" connectivity.

Other EPS bearers can be established to connect to other PDN gateways or to provide different LTE QoS to the same PDN gateway. These EPS bearers are known as dedicated EPS bearers. All user plane data transferred using the same EPS bearer has the same QoS.

The bearers have two or four QoS ID parameters depending on whether they are providing real time or best effort services (Table 3):

- QoS class indicator (QCI),
- allocation and retention priority (ARP),
- GBR – real-time services only,
- maximum bit rate (MBR) – real-time services only.

Table 3
LTE QoS parameters

LTE QoS parameters	GBR	Non-GBR
QoS class identifier	Supported	Supported
Allocation and retention priority	Supported	Supported
Guaranteed bit rate	Supported	
Maximum bit rate	Supported	
APN aggregate maximum bit rate		Supported
UE aggregate maximum bit rate		Supported

The analysis of 3GPP RAT optimization shown above indicates that the limitations and restrictions created during optimization of the LTE standard to NB-IoT for LPWAN networks lead to a loss of the ability to use 1-4 classes of QoS supporting real-time services (Fig. 2). In the table of QoS classes shown in Release 13, Note 13 appeared which indicates that the packet delay budget is not applicable to the NB-IoT technology or does not apply when EC is used for WB-E-UTRAN (see TS 36.300 [8] and TS 23.302 [9]). This indicates that no packet delay budget is guaranteed and, consequently, GBR is not guaranteed as well.

The QoS mechanism working with GBR services will be essential for the development and implementation of many IoT applications. Cellular RAT technologies have a mature QoS functionality, and this allows to use cellular RAT in spite of wide frequency channels for critical IoT applications.

QCI	Resource type	Priority	Packet delay budget	Packet error loss rate	Example services
1	Guaranteed bit rate (GBR)	2	[illegible]	[illegible]	Conversational voice
2		4	[illegible]	[illegible]	Conversational video (live streaming)
3		5	[illegible]	[illegible]	Non-conversational video (buffered streaming)
4		3	[illegible]	[illegible]	Real time gaming
5	Non-GBR	1	100 ms	10^{-6}	IMS signalling
6		7	100 ms	10^{-3}	Voice, video (live streaming), interactive gaming
7		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g. www, e-mail, chat, FTP, P2P file sharing, progressive video, etc.)
8		8			
9		9			

Fig. 2. Loss of LTE QoS classes for NB-IoT .

Critical IoT applications will have very high demand for reliability, availability and low latency. The biggest barrier to using IoT for driverless cars is the absence of GBR services. Vehicle-to-vehicle communication is a typical delay-sensitive service with a millisecond-level latency constraint. It also requires extreme reliability, e.g. a nearly 100% success rate for decoding when the combined speed of vehicles passing each other is about 300 kph.

Extremely low latency, in combination with high availability, reliability and security, will be required by Tactile Internet [13]. Tactile Internet will set demanding requirements for cellular IoT networks. The outlined use cases will require round-trip latencies of as little as 1 ms. From the physical layer perspective, each packet must not exceed a duration of 33 μs to enable a one-way physical layer transmission of 100 μs [14]. However, the modulation used in LTE networks is not capable of achieving this requirement, as each OFDM symbol is approximately 70 μs long. The current 1 ms transmission time interval (TTI) of LTE produces, in practice, a 10–20 ms round trip time, while a future LTE Advanced Pro solution should provide even less than 2 ms round trip time and a less than 1 ms one-way delay. However, shorter TTI requires higher available bandwidth.

The abovementioned limitations and restrictions concerned with the use of cellular IoT technologies force the standardization bodies (3GPP, ETSI) to work on improving them.

The STQ mobile working group, ETSI, has opened a new working item with reference number DTR/STQ-0062 – focusing on TR speech and multimedia transmission quality (STQ); Quality of Service for IoT, Discussion on QoS aspects of services related to the IoT ecosystem, and has started the work on QoS aspects of cellular IoT technologies.

The SA WG2 3GPP working group plans to provide additional input to the evaluation and intends to conclude solution 15 for key issue 6 – "Inter-UE QoS for NB- IoT control plane optimization". This solution will be based on a mechanism where eNB fetches QoS information from MME after reception of the UE's indicator S-TMSI in the RRC connection request message. Additional input is provided clarifying the magnitude of the impact from the additional eNB – CN round-trip-time.

5. Conclusions

The 3rd Generation Partnership Project successfully completed standardization of two RATs: NB-IoT (Narrowband-IoT) and EC-GSM in June 2016, with the new 3GPP RAT-based narrowband technologies optimized for IoT. These technologies are competitors of non-cellular IoT – access technologies from the LPWAN family (LoRa, Sig-fox, etc.).

NB-IoT and EC-GSM RAT offer enhancements in both LTE/GERAN air interfaces and networks that will provide new levels of efficiency for low-throughput, delay-tolerant communications common in many IoT applications. Optimization of 3GPP RAT and its adaptation to narrow band cellular IoT RATs has led to some limitations and restrictions, which prevent it from being used in most real-time IoT applications in consumer-based and industrial IoT. Two of out of three 3GPP IoT RATs support only Non-GBR (best effort) classes of QoS, due to their inability to transmit control traffic in the narrow 180–200 kHz channel band of NB-IoT and EC-GSM.

Further optimization of cellular IoT RATs, offer under Releases 14 and 15, will place higher priority on critical IoT communication and QoS.

References

[1] GSMA Report. The Mobile Economy, 2017 [Online]. Available: www.gsma.com/mobileeconomy/

[2] "Digital Single Market Strategy for Europe", European Commission, Brussels, Belgium, 2015.

[3] Global Narrowband – IoT Market Research Report – Forecast to 2022, MRFR, Market Research Future, Maharashtra, India, 2017.

[4] 3GPP TR 36.888 "Study on provision of low-cost Machine-Type Communications (MTC) User Equipments (UEs) based on LTE".

[5] "LTE evolution for IoT connectivity", Nokia, White Paper, 2016.

[6] V. O. Tikhvinskiy, S. V. Terentiev, V. P. Visochin, *LTE/LTE Advanced Mobile Communication Networks: 4G Technologies, Applications and Architecture*. Moscow: Media Publisher, 2014.

[7] TS 36.300 3GPP Project; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 13).

[8] TS 23.401 3GPP Project; Technical Specification Group Services and System Aspects; General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (Release 13).

[9] TS 23.302 3GPP Project; Technical Specification Group Services and System Aspects; Policy and charging control architecture (Release 13).

[10] TS 36.331 3GPP Project; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (Release 13).

[11] TS 45.002 3GPP Project; Technical Specification Group Radio Access Network; GSM/EDGE Multiplexing and multiple access on the radio path (Release 13).

[12] TS 44.060 3GPP Project; General Packet Radio Service (GPRS); Mobile Station (MS) – Base Station System (BSS) interface; Radio Link Control/Medium Access Control (RLC/MAC) protocol.

[13] "The Tactile Internet", ITU-T Technology Watch Report, Geneva, Switzerland, August 2014.

[14] A. Aijaz, M. Simsek, M. Dohler, and G. Fettweis, "5G radio access for the Tactile Internet", in "5G Mobile Communications", W. Xiang, K. Zheng, X. Shen (Sherman), Eds. Springer, 2016.

Valery O. Tikhvinskiy is a Deputy General Director of Icominvest LLC, a finance investment company operating in the telecommunications sector, He is the chairman of the Information and Telecommunications Technologies branch of the Russian Academy of Natural Sciences, and a Doctor of Economic Sciences (2003). He received a Ph.D. in Radio Engineering (1988), is a Government Prize laureate (2002), a Member of the State Duma Committee Expert Council (since 2002). He is an Editorial Board Member of the Mobile Telecommunications (since 2002) and T-Com Journals (since 2007). He works as a Professor at the Moscow Technical University of Communications and Informatics (MTUCI, since 2001) and is a Visiting Professor at the Tunisian Telecommunications Institute (IsetCom) (since 2005).
E-mail: v.tikhvinskiy@icominvest.ru
LLC Icominvest
Ostozhenka 28
119034 Moscow, Russia

Moscow Technical University of Communications
and Informatics
Aviamotornaya 8a
111024 Moscow, Russian Federation

Grigory Bochechka is a Head of the Innovation Center Department of Icominvest LLC and Chairman of the WG14 Innovation Management Committee at the information and telecommunications branch of the Russian Academy of Natural Sciences. He received his Ph.D. degree in Specialty Systems, Networks and Telecommunication Devices.
E-mail: g.bochechka@icominvest.ru
LLC Icominvest
Ostozhenka 28
119034 Moscow, Russia

Moscow Technical University of Communications
and Informatics
Aviamotornaya 8a
111024 Moscow, Russian Federation

Andrey Gryazev received his Ph.D. degree in Management and Communication Systems in 2015. He is now acting General Director of the Russian Federal State Unitary Enterprise – the Central Telecommunication Scientific and Research Institute. His scientific research interests are in the fields of modern telecommunication technologies, economy and regulation in the field of radio communications, quality of service for fixed and mobile communications.
E-mail: agryazev@zniis.ru
Federal State Unitary Enterprise Central Science
Research Telecommunication Institute
First Passage of Perovo Pole 8
111141 Moscow, Russia

Altay Aitmagambetov is a Professor at the International University of Information Technology, a candidate of technical sciences, and a member of the International Telecommunications Academy.

E-mail: altayzf@mail.ru
International IT University
Almaty, Kazakhstan