VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

ÚSTAV TELEKOMUNIKACÍ

DEPARTMENT OF TELECOMMUNICATIONS

IMPLEMENTACE A VYHODNOCENÍ KOMUNIKAČNÍCH PARAMETRŮ TECHNOLOGIE LTE CAT-M V SIMULAČNÍM PROSTŘEDÍ NS-3

SEMESTRÁLNÍ PRÁCE

SEMESTRAL THESIS

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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Semestrální práce

magisterský navazující studijní program **Telekomunikační a informační technika**

Ústav telekomunikací

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NÁZEV TÉMATU:

Implementace a vyhodnocení komunikačních parametrů technologie LTE Cat-M v simulačním prostředí NS-3

POKYNY PRO VYPRACOVÁNÍ:

Cílem diplomové práce bude studium nastupující technologie LTE Cat-M. V teoretické části bude provedeno porovnání LPWA technologií, kdy bude důraz kladen na detailní rozbor technologie LTE Cat-M a to dle 3GPP Rel. 13/14. Následně bude provedena implementace scénářů pro přenos dat v rámci inteligentních sítí. Implementace bude provedena v Network Simulator 3 (NS-3). Praktická část se bude sestávat z vytvoření komunikačního scénáře s využitím modulu LENA / LENA 5G kdy bude pozornost soustředěna na specifický scénář, ve kterém budou koncové zařízení připojeny pouze k jedné základnové stanici. Student navrhne a implementuje úpravy modulu LENA a to tak, aby upravený modul umožňoval komunikaci dle 3GPP Rel.13.

Výstupy SP:
Popis LPWA technologií, zejména pak LTE Cat-M a to dle 3GPP Rel. 13 a 3GPP Rel. 14. Vytvoření scénáře v NS-3 s využitím modulu LENA (5G)/LENA-NB. Prvotní úpravy pro implementaci LTE Cat-M1, ověření funkčnosti v základním scénáři.

DOPORUČENÁ LITERATURA:

[1] Network Simulator 3: Documentation, A Discrete-Event Network Simulator [online], 2019. Dostupné z: https://www.nsnam.org/doxygen/

[2] LIBERG, Olof, Mårten SUNDBERG, Y.-P. Eric WANG, Johan BERGMAN a Joachim SACHS, [2018]. Cellular Internet of things: technologies, standards, and performance. San Diego, CA, United States: Academic Press, an imprint of Elsevier. ISBN 978-012-8124-581.

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Introduction

Communication technologies are constantly evolving for the expanding market and more technologies are being standardized for various use cases. With innovation and automation of processes *Machine to Machine* (M2M) communication is rapidly expanding. *Internet of Things* (IoT) is one of main challenges, modern communication technologies have to address. *Low-Power Wide-Area* (LPWA) networks are one of the solutions for this challenge with promising results. LPWA network supports a large number of devices connected to the Internet. Telecommunication companies respond to the rising trend of IoT applications with development and implementation of new technologies for M2M communication in licensed and license-exempt spectrum.

This thesis briefly describes the legacy communication technologies and the latest fifth generation with the emphasis on deployment options and cellular IoT technologies. With the abilities of the fifth generation, *Massive Machine-Type Communications* (mMTC) are emerging. While the 5G deployment is still in process, current *Long Term Evolution* (LTE) networks are not designed to handle the massive number of devices. New technologies have been developed, such as LTE Cat-M and *Narrow-Band IoT* (NB-IoT) by *The 3rd Generation Partnership Project* (3GPP), that can share the network with mobile users. The 3GPP covers cellular telecommunications technologies, including radio access, core network and service capabilities, which provide a complete system description for mobile telecommunications. The selected technology, LTE Cat-M, is described in chapter three. LTE Cat-M is also compared with other licensed and license-exempt technologies. This thesis is pointing out the unsatisfying behavior of LTE network to a massive device density. Suggesting LTE Cat-M implementation alongside LTE to support mMTC.

1 Next-generation Mobile Systems

1.1 Legacy Communication Technologies

Since the starting point of cellular technology in the 1970s, a lot of individual mobile phone systems have been accustomed, and currently a wide spectrum of phone systems are in use now. Originally there were many countries with their own cellular systems until the possibility of international roaming was first introduced in Europe with *The Global System for Mobile Communications* (GSM), originally called Groupe Speciale Mobile in 1991. GSM as a standard was developed by *European Telecommunications Standards Institute* (ETSI). ETSI is an independent, not-for-profit, standardization organization in the field of information and communications. It is also a founding partner of two major international partnership projects, the 3GPP for 4G and 5G mobile communication and oneM2M that produces standards for IoT communications [1].

3GPP started as an organisation focused on 3G *Universal Mobile Telecommunications Service* (UMTS) techology as the name implies, but later 3GPP has also taken on the GSM standards, 4G LTE, and currently 5G. The collaboration manages a wide range of standards that have been released in form of 3GPP Releases. The standards and specifications enclose all aspects of the cellular communication systems from the *Radio Access Network* (RAN) to the core network, billing authentication and more [2].

Tab. 1.1: Overview of 3GPP Releases [3, 4].

3GPP Release	**Release date**	**Details**
Phase 1	1992	Basic GSM specification
Phase 2	1995	GSM extension including EFR Codec
Release 96	Q1 1997	GSM updates, 14.4 kb/s user data rate
Release 97	Q1 1998	GSM additional features, GPRS
Release 98	Q1 1999	GSM additional features, GPRS for GSM 1900, EDGE, AMR Codec
Release 99	Q1 2000	3G UMTS with WCDMA
Release 4	Q1 2001	UMTS all-IP core network
Release 5	Q1 2002	IMS and HSDPA
Release 6	Q4 2004	HSUPA, MBMS, IMS enhancements, PTT over cellular, WLAN cooperation
Release 7	Q4 2007	Improvements in QoS and latency, VoIP, HSPA+, NFC integration, EDGE evolution
Release 8	Q4 2008	LTE introduced, system architecture evolution, OFDMA, MIMO, dual cell HSDPA
Release 9	Q4 2009	WiMAX/LTE/UMTS interoperability, dual cell HSDPA with MIMO, dual cell HSUPA, LTE Home eNodeB
Release 10	Q1 2011	LTE Advanced, Backward compatibility with Release 8, MC-HSDPA, congestion and overload control
Release 11	Q3 2012	HetNet, CoMP, in-device coexistence, advanced IP interconnection of services, on-line device triggering, PS-only service provisioning
Release 12	Q1 2015	Enhanced small cell operation, extended carrier aggregation, massive MIMO, UE Cat 0, PSM, D2D communication, MBMS enhancements
Release 13	Q1 2016	LTE Unlicensed/License Assisted Access, LTE Cat M1, LTE Cat NB1, elevation beamforming, full dimension MIMO, indoor positioning
Release 14	Q2 2017	LTE support for V2X, in-band carrier aggregation, LTE Cat M2, LTE Cat NB2, mission critical enhancements
Release 15	Q4 2018	5G Phase 1, mMTC, V2X Phase 2, WLAN and unlicensed spectrum use, network slicing, service-based architecture
Release 16	Q3 2020	5G Phase 2, V2X Phase 3, URLLC, unlicensed NR, satellite access in 5G, integrated access and backhaul
Release 17	~2022	Low complexity NR devices, NR 52.6 GHz, edge computing in 5G, MIMO enhancements, 5G Multicast-Broadcast Protocols
Release 18	~2024	5G system with satellite backhaul, Personal IoT and Residential networks, Smart Energy and Infrastructure, Mission Critical Communication enhancements

1.1.1 Second Generation (2G)

It all started with cooperation of European countries to achieve commercial use of cellular network with the possibility of roaming. Second generation is known for mobile approach to digital radio communication system using GSM standards at 900 MHz. The GSM standard is based on a *Multi Carrier* (MC)/*Time Division Multiple Access* (TDMA)/*Frequency Division Duplex* (FDD). It also distinguish between speech and *Circuit Switched* (CS) data, and *Packet Switched* (PS) data. The first steps of this evolution took place in 1997 standards, when *General Packet Radio Services* (GPRS) was introduced to efficiently deliver packet-based services over GSM networks using *Gaussian Minimum Shift Keying* (GMSK) modulation [5].

GPRS provides GSM with a packet data air interface and an *Internet Protocol* (IP)-based core network. The theoretical maximum data rate in the GPRS system is 171 kbps. GSM system was originally designed with an emphasis on voice sessions, the main objective of the GPRS is to offer an access to standard data networks such as *Transmission Control Protocol* (TCP)/IP. With the introduction of 8-*Phase Shift Keying* (PSK) modulation for GSM, *Enhanced Data for Global Evolution* (EDGE) was introduced to provide faster bit rates for data applications, both circuit- and packet-switched. EDGE increased theoretical data rate to 384 kbps and thus considered as a bridge between second and third generation [6, 7, 8].

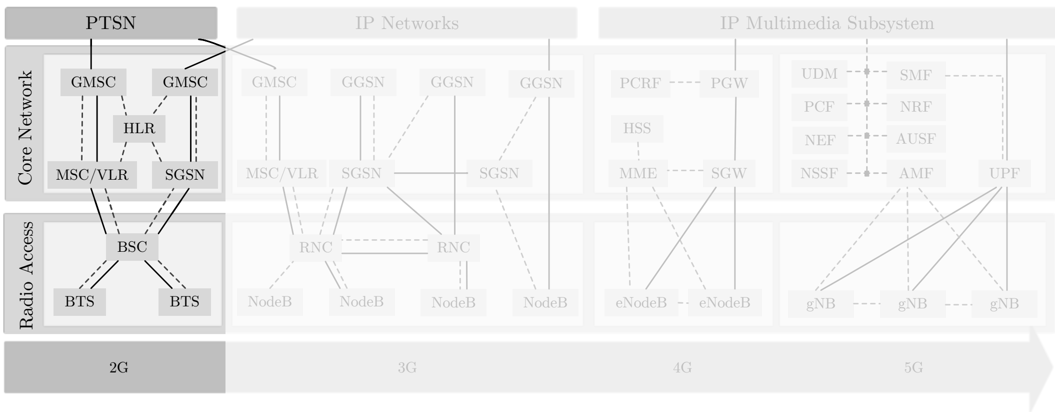


Fig. 1.1: 2G architecture overview [9].

1.1.2 Third Generation (3G)

With higher demand for data rates, multimedia support and network capacity, the third generation evolution was necessary. In 2000, The *ITU Radiocommunication Sector* (ITU-R) approved the global standards for the overall requirements of *Information Management Technology* (IMT) called, IMT-2000. *International Telecommunication Union* (ITU) defined the process of evaluation and the subsequent selection of mobile technologies that fulfill a number of established technical parameters (peak data rate, latency, spectrum efficiency, etc.). Shortly after, the 3GPP developed a new mobile cellular technology UMTS. Alongside UMTS, the *Code Division Multiple Access* (CDMA) version of IMT-2000 (CDMA2000) standard was set for networks based on the competing cdmaOne technology in United States. UMTS uses *Wideband Code Division Multiple Access* (WCDMA) radio access technology to offer greater spectral efficiency and bandwidth to mobile network operators. UMTS is operating in 2 modes. FDD mode where uplink and downlink communications are separated in the frequency domain via different frequency bands. This mode is also called WCDMA. On the other hand, *Time Division Duplex* (TDD) mode where uplink and downlink communications are separated in the frequency domain via different time slots. Both modes use *Direct Sequence* (DS)-CDMA to separate the different users, where each symbol of one user is multiplied by a user specific spreading code. With this CDMA technique multiple users can transmit in the same (larger) band and the decoder, knowing the user's spreading code, can pick up the data of this user. The data of other users appears as noise in this decoding process [1, 7, 10].

The network architecture started to change with *High-Speed Downlink Packet Access* (HSDPA) introducing base station (or *Narrowband* (NB) in 3GPP terminology) based scheduling for the downlink packet-data operation and uses similar methods like GSM evolution such as higher order modulations e.g., 16*Quadrature Amplitude Modulation* (QAM) in WCDMA. This improved the data rate from units of Mbps up to tens of Mbps. Later, a new antenna system that employ multiple antennas at both the transmitter and the receiver was released as *Multiple Input/-Multiple Output* (MIMO) technique. The next release introduced Dual-cell HSDPA operation on adjacent carriers increasing speeds and later *Evolved High Speed Packet Access* (HSPA+) combined with 64QAM with available MIMO provided additional improvements [5, 6, 8].

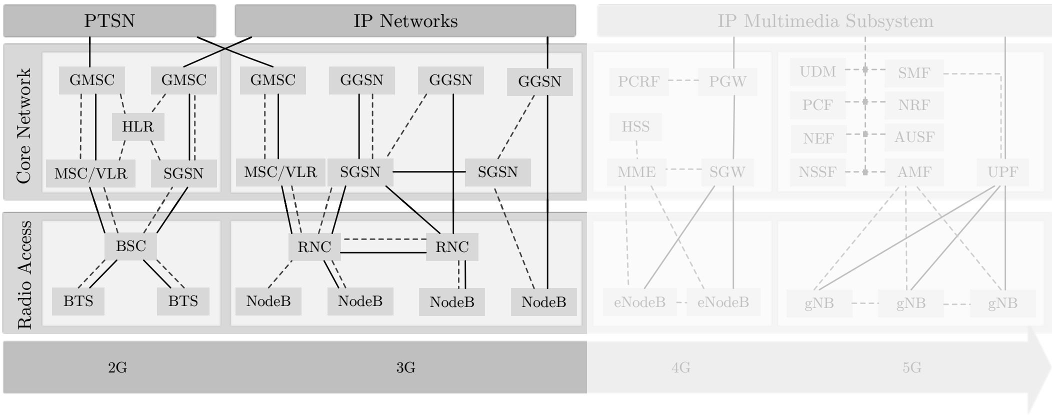


Fig. 1.2: 3G architecture overview [9].

1.1.3 Fourth Generation (4G)

In 2004, the 3GPP started working on LTE/*Evolved Packet Core* (EPC) standardization for IP-based EPC. The 3GPP working groups finished protocol and performance specifications for LTE in December 2008, deploying Release 8. LTE is a step to a new generation of broadband mobile communication standard with high data rate and low latency with only packet-oriented services (IP-based). Radio access network called *Evolved UMTS Terrestrial Radio Access Network* (E-UTRAN) removed *Radio Network Controller* (RNC) moving most of the features into new base station called *E-UTRAN Node B* (eNodeB). While UMTS was using CDMA, LTE is based on *Orthogonal Frequency Division Multiple Access* (OFDMA) in downlink and *Single Carrier* (SC)-*Frequency Division Multiple Access* (FDMA) in uplink. SC-FDMA was preferred because of lower power consumption on *User Equipment* (UE) side then OFDMA. LTE also deals with variations of the radio-link quality through adaptive channel coding and adaptive modulation. Specifically, available modulations are *Quadrature Phase-Shift Keying* (QPSK), 16QAM and 64QAM. The highest theoretical peak data rate is 75 Mbps for uplink, and up to 300 Mbps for downlink (using spatial multiplexing). A year later, Release 9 described the concept of femtocells (home eNodeB) and evolved important features such as *Self-Optimizing Network* (SON), *Evolved Multimedia Broadcast Multicast Services* (eMBMS), positioning support *Location Services* (LCS) and also specified service requirements for *Machine Type Communication* (MTC) [7, 11].

The first release considered 4G, meeting IMT-Advanced radio interface requirements of ITU-R was Release 10 in early 2011. The main new functionalities introduced in LTE-Advanced are *Carrier Aggregation* (CA), enhanced use of MIMO techniques and support for *Relay Nodes* (RN). CA allowed data rates to exceed 1 Gbps and with RN rapidly increased number of simultaneously active subscribers.

Release 10 also encapsulate some network improvements for MTC e.g., protection from potential MTC related overload [3].

LTE-Advanced continues to evolve. New CA configurations are added and there are new features introduced in coming releases of the 3GPP specifications, such as *Coordinated Multipoint Transmission* (CoMP) introduced in Release 11. CoMP improves network performance at cell edges with additional TX/RX antennas providing coverage [9, 6, 12, 13].

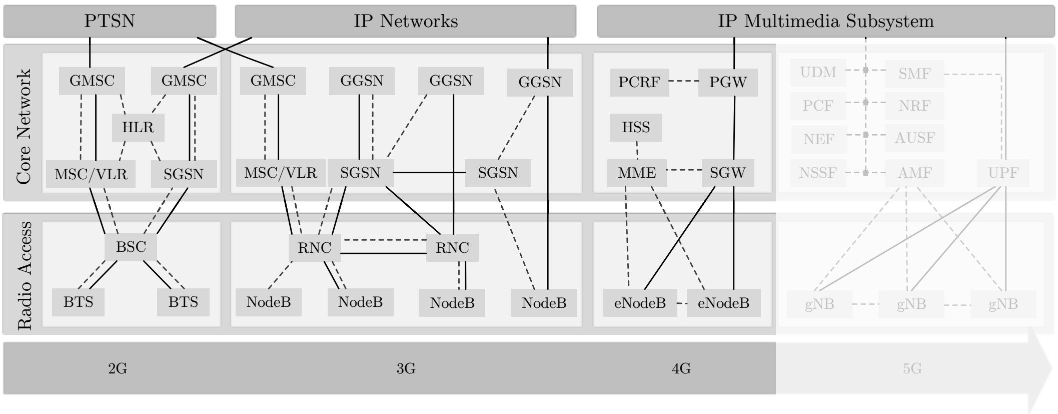


Fig. 1.3: 4G architecture overview [9].

1.2 5G Communication Systems

Fifth generation of mobile communication systems is the next expected phase of telecommunications standards after current dominant 4G network that will follow the IMT-2020 requirements of ITU-R. 3GPP aligned the 5G time schedule in Release 15 with IMT-2020 progress but they froze the release in 2018 with the first phase of 5G. They introduced 5G *New Radio* (NR) concept for *Non-Standalone Architecture* (NSA) mode, which means 5G RAN intraworking with 4G RAN and connected to 4G EPC. The second phase of 5G is defined by Release 16 finished 2 years after Release 15, July 2020. Release 16 contains *Multimedia Priority Service* (MPS), *Vehicle to Everything* (V2X) services, 5G satellite access, *Local Area Network* (LAN) support in 5G, terminal positioning and location, security and streaming services, network slicing and the IoT. 3GPP planned on finishing next Release 17 by July 2022 which should contain further 5G NR enhancements [14].

From deployment perspective, there are two main approaches *Standalone Architecture* (SA) and NSA. The difference is in communication between RAN and core network. Standalone architecture stands for technology operating on its own without the need of previous technologies and devices. That is the desired goal to achieve and have the fifth generation New Radio functions independent. NSA on the other hand is cooperation between 4G and 5G either in RAN, where the eNodeBs work with *gNodeB* (gNB)s or by using 4G EPC until operators built the infrastructure to make the switch to SA. There are few options defined for both SA and NSA deployment described in the next sections [15].

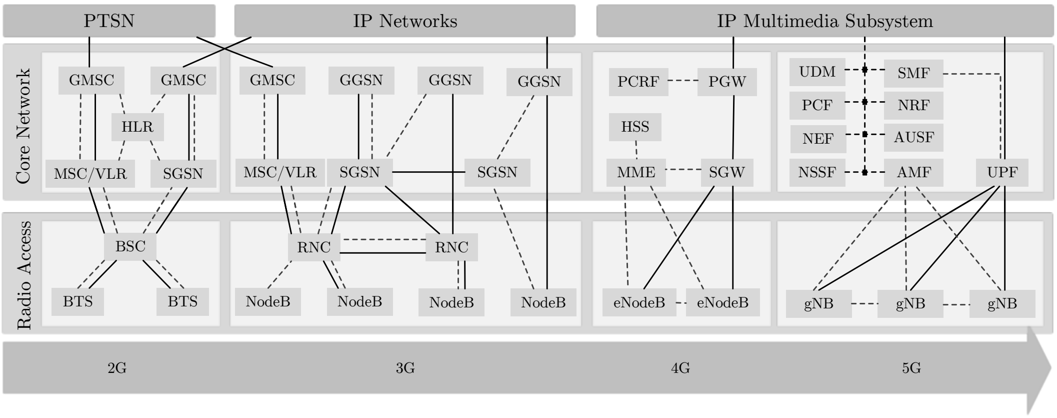


Fig. 1.4: 5G architecture overview [9].

IMT-2020

IMT-2020 is a name for a standard published by the ITU-R in early 2021, which contained a list of requirements for 5G networks, devices and services. Few of the main IMT-2020 requirements are peak data rate evaluated for the *Enhanced Mobile Broadband* (eMMB) use case, for which the minimum downlink peak data rate is 20 Gb/s whereas the value for uplink is 10 Gb/s. Peak spectral efficiency which normalizes the peak data rate of a single mobile station under the same ideal conditions over the utilized channel bandwidth. The peak spectral efficiency for the downlink is set to 30 b/s/Hz, whereas the value for the uplink is 15 b/s/Hz. IMT-2020 brings importance to *User Experience* (UX) data rate also, which is obtained from the fifth percentile of the overall user throughput. Required UX data rate in downlink is 100 Mb/s, whereas it is 50 Mb/s for uplink. For the more dense and populated areas there is area traffic capacity requirement set to 10 Mb/s/m^2. Big change for IMT-2020 compared to IMT-A is latency. For eMMB use case is 4 ms for user plane, whilst it is 1 ms for *Ultra-Reliable Low Latency Communications* (URLLC). The requirement for control plane is 20 ms maximum, but less than 10 ms is preferred. For the mMTC use case there is connection density requirement set to a milion devices per km^2. For moving devices there are four defined mobility classes in 5G: (i) stationary with 0 km/h speed; (ii) pedestrian with 0–10 km/h; (iii)

Vehicular with 10–120 km/h; (iv) high-speed vehicular with speeds of 120–500 km/h [16].

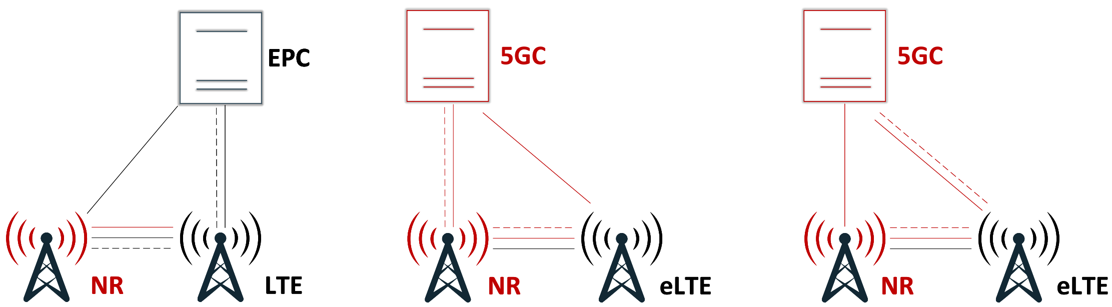
1.2.1 5G NSA

For the smooth transition to a new 5G technology and services, the 3GPP has prepared an optional approach of the 5G deployment. It is important for the operators, that they can select and choose their network strategy development towards full 5G NR network. The NSA scenarios as the intermediate step with the base station element called *New Generation-eNodeB* (ng-eNB). It is a node providing *Evolved UMTS Terrestrial Radio Access* (E-UTRA) user plane and control plane protocol terminations toward the UE. The node is connected via the *New Generation* (NG) interface to the *5G Core* (5GC). Basically a 4G eNodeB communicating with the 5G infrastructure. Options 3, 4 and 7 are representing NSA deployment scenarios.

Option 3/3A represents a scenario where the LTE eNodeB is connected to the 4G EPC with NSA NR. The key is that the NR user plane is connected to the 4G EPC through the LTE eNodeB or directly (Option 3A).

Option 4/4A is the other way around compared with option 3. The 5G NR gNB is connected to the 5G 5GC with NSA E-UTRA. The E-UTRA user plane is connected to the 5GC through gNB or directly (Option 4A).

Option 7/7A is the last NSA option where the NR RAN and 5GC is supporting the LTE NSA RAN [17, 18].



(a) Option 3 (b) Option 4 (c) Option 7

Fig. 1.5: 5G Non-Standalone deployment [18]

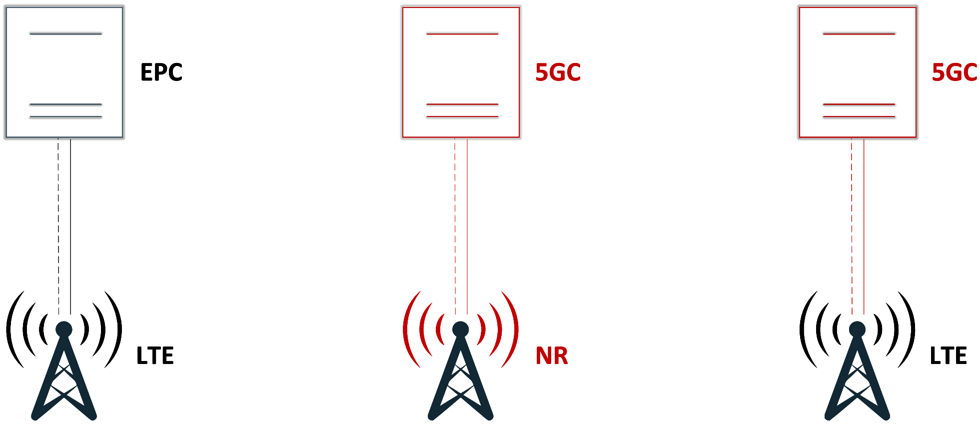
1.2.2 5G SA

The standalone deployment models are as a reference to full 4G and 5G network architectures. There are three options but Option 5 has been deprioritized later in 3GPP specification but it is still explained to cover all possible SA deployment scenarios.

Option 1 is a reference model or a starting point to the 5G deployment. This option represents the 4G architecture with eNodeBs and EPC.

Option 2 refers to gNBs connected directly to the 5GC. This is a reference to the end goal, true 5G network.

Option 5 scenario uses 4G eNodeBs in RAN connected with the NR interface to the 5GC. This scenario is not popular among operator as it does not provide more capacity but only a few new functions in the 5GC [17, 18].



(a) Option 1 (b) Option 2 (c) Option 5

Fig. 1.6: 5G Standalone deployment [18]

1.2.3 Cellular IoT Technologies

The 3GPP have been working on cellular technologies for the past decade to support a wide range of IoT use cases. Cellular legacy (2G, 3G, 4G) communication systems supplied early connectivity for the IoT, but since Release 13 (in 2016), the technologies that support cellular IoT connectivity by default are being developed. The 3GPP is focused on future market needs and new IoT requirements that are transferring to the standardization of cellular networks addressing forthcoming IoT use cases. Those use cases have been defined by three requirements categories in the standardization of the 5G cellular system. Two of them are addressing the IoT communication technologies, respectively MTC requirements [19].

mMTC requirements are defined to address a large number of devices indoors and outdoors. The devices are expected to be simple, yet the system has to provide a level of scalability to withstand a reliable connection for all of them with respect to low latency. The accessibility of the devices may be challenging, therefore a long lasting power supply in form of non-rechargable batteries (lasting 10 years or more) is needed. All of these requirements have to be met within a reasonable price range to allow massive deployment in the field. Possible mMTC use cases are monitoring and metering stations, telemetrics and sensors in the automotive industry, or tracking devices in logistics to name a few. The support of mMTC is provided in 3GPP Release 13 with NB-IoT and *LTE Machine-to-Machine* (LTE-M) technologies [19].

Critical Machine-Type Communications (cMTC) is defined to address high reliability and availability of the devices. In cMTC use cases the latency is crucial parameter and is to be as low as possible to provide fast and reliable communication. Examples of cMTC use cases are remote and autonomous driving and real-time sensor sharing in automotive industry, distribution automation in a smart grid infrastructure, and remotely controlled machines and equipment in smart mining. In the 3GPP standardization, the cMTC requirements are also reffered to as URLLC category defined in Release 15 [19].

NarrowBand IoT

NB-IoT technology was standardized by the 3GPP in 2016 (Release 13). The release included core specifications for the technology using GSM spectrum within an existing LTE network. The 3GPP further improved the system performance and the support of new use cases in Release 14 (2017) and Release 15 (2018). All of the enhancements could be enabled on existing LTE network through software upgrade and therefore improved NB-IoT position among other LPWA technologies. In adition, since Release 15, NB-IoT meets all performance requirements for 5G mMTC use case [19].

The key of success for NB-IoT technology is in simplicity of its devices, that leads to lower power consumption and eventually cost reduction. The most demanding and complex tasks are initial cell selection, demodulation and data decoding. The initial time and frequency synchronization of the device can be achieved with one synchronization sequence found on the network. For modulation, NB-IoT only uses low-order QPSK and does not support MIMO transmissions. With only one antenna, devices work in half-duplex mode with only FDD support (TDD support introduced in Release 15) minimizing the complexity even more. In downlink the *Tansport Block Size* (TBS) is limited for the lowest device category to only 680 bits. NB-IoT does not use computationally demanding LTE turbo code for channel coding, instead it uses *Tail-Biting Convolutional Code* (TBCC) in the downlink channels. For uplink the TBS is slightly larger consisting of maximum 1000 bits [19, 20].

The 3GPP set the maximum transmission power of NB-IoT devices to 20 or 23 dBm in Release 13. Release 14 introduced lower power class that can contribute to lower device cost with a maximum transmit power of 14 dBm. With the limited transmission power and reduced data rate, NB-IoT relies on repetition to ensure reliable communication with the network. Reducing the data rate further enhances coverage of the device with limited power capability. The NB-IoT device operates in two sessions, active data session and idle mode. This is because of the nature of IoT applications that only require infrequent data transmissions. While in the idle mode, the device only monitors paging or only paging occasions periodically. To optimize power consumption, the 3GPP introduced *Extended Discontinuous Reception* (eDRX) and *Power Saving Mode* (PSM). This can reduce average power consumption bellow 3 μA [19, 21].

NB-IoT supports three modes of operation for maximum deployment flexibility. Stand-alone mode uses any available spectrum with bandwidth over 180 kHz. This mode of operation applies for refarming the GSM spectrum, where the NB-IoT carrier with additional guard-band of recommended 100 or 200 kHz bandwidth is used based on the use case [22].

In-band and guard-band modes of operation are designed for the existing LTE networks. In-band mode uses one LTE *Physical Resource Block* (PRB), when guard-band on the other hand utilizes the unused bandwidth of LTE guard-band. This is possible only for 5, 10, 15, or 20 MHz LTE carrier bandwidth [13, 19].

LTE Cat-M

LTE Cat-M technology, also referred to as LTE-M, was first introduced by the 3GPP in Release 12 with LTE device category 0 (Cat-0). This release included initial MTC support for low cost devices. More ambitious was Release 13, which introduced the *Coverage Enhancement* (CE) modes A and B and a new device category M1 (Cat-M1). By definition, all devices with implemented CE support are defined as LTE Cat-M devices. That includes all Cat-M devices since they have mandatory support for CE mode A. More improvements were introduced in Release 14 such as higher data rate support, improved *Voice over LTE* (VoLTE) support, better positioning, multicast support, and a new LTE device category Cat-M2. The 3GPP addressed higher latency and power consumption, lower spectral efficiency and more obstructions and included new use cases in Release 15. After the release, LTE Cat-M technology met all of the performance requirements for the 5G mMTC category [19, 23].

With the introduction of LTE Cat-0 device category in Release 12, the 3GPP addressed a lot of cost reduction techniques identified in previous study. Supporting reduced peak rate of 1 Mbps for user data in downlink and uplink (reduced from at least 10 Mbps and 5 Mbps for higher categories in downlink and uplink respectively). Instead of at least two antennas, Cat-0 devices support a single receive antenna that operates in half-duplex FDD. Cat-0 device power class defined maximum transmit power to 23 dBm [19, 24].

Release 13 standardized LTE Cat-M1 device category that inherited all cost reduction techniques from Cat-0 and introduced more. Bandwidth reduction to 1.4 MHz (instead of 20 MHz), maximum transmit power of 20 dBm within a new power class (14 dBm power class was introduced later in Release 15), power consumption reduction techniques, and CE modes A and B. With CE mode A supporting up to 32 repetitions for data channels and mode B supporting up to 2048 repetitions, Cat-M1 devices exploited less strict IoT application requirements. Power consumption was reduced initially in Release 12 with PSM, but with eDRX from Release 13, the reduced active state of the device and the reduced bandwidth resulted in battery life span of more than 10 years (for standard 5 Wh battery) [19, 25].

2 Massive Machine-type Communication

According to Cisco Annual Internet Report in 2020, there were 2.2 billion active M2M devices and the number will double in 2023. With a massive growth of the IoT market, the 3GPP and other organisations are addressing the market needs with new standards and requirements. The mMTC is one of the 5G technologies addressing this market need. The mMTC requirements cover low complexity of the devices to achieve low prices, extended coverage of +20 dB to satisfy the deployment in deep indoor locations, the density of devices up to 1 million per square km, the latency of 10 seconds or less, and the battery life of the device lasting more than 10 years with 5 Wh battery [26, 27].

Despite the expanding market and uncompromising requirements, the LPWA technologies are capable of satisfying them both. They are currently the most available mMTC technology class on the market and they are growing fast. The LPWA technologies cover both licensed as well as license-exempt spectrum. The 3GPP standardized and regulates LTE Cat-M and NB-IoT technologies for licensed spectrum. Sigfox and LoRaWAN technologies are the most expanded representants of license-exempt spectrum on the market [26, 28].

2.1 3GPP Standardization Activities

Study on facilitating machine to machine communication in 3GPP systems begun already in 2006. First MTC specifications came with Release 9 as service requirements. Studies on UE, system improvements, security aspects, RAN and *GSM EDGE Radio Access Network* (GERAN) improvements for MTC begun with Release 10. All of the mentioned studies has led to the ambitious Release 13, where LTE-M and NB-IoT technologies were standardized. The 3GPP has worked on those LPWA technologies to address the IMT-2020 recommendations by ITU-R. LTE-M and NB-IoT both met the IMT-2020 requirements for the 5G mMTC use case in Release 15 [3, 16].

2.2 Communication Scenarios for the Cellular IoT

Use cases for cellular IoT has been expanding very quickly, with the main purpose to reduce costs and increase the quality of life. From the top-down perspective, the world is filled with IoT sensors and meters that communicate on cellular network. Smart devices spread throughout countries monitoring utilities and environment in remote locations, e.g. meters, weather stations, flood monitors. Transport and logistics also use IoT technologies for tracking and management with respect to mobility. Smart city is a good example of a complex, high density mMTC use case. On a smaller scale, smart buildings utilize variety of sensors and monitoring devices to increase safety and comfort. At last, there are people using wearables to monitor their activities and health [29].

2.2.1 Smart Cities

The concept of Smart cities represents a comprehensive approach to the functioning of the urban region, which affects various social areas such as culture, infrastructure, environment, energy, social services and others. In each of these areas, it pursues multiple goals that are interconnected and together create a system based on the principles of sustainable development. Public administration, private sector and civil society entities enter the entire system, without which the set goals would not be fulfilled. All this is the reason why there is currently no international legally binding definition for the given concept or a legal framework that would precisely regulate the procedure to achieve the desired state. Individual states follow their own "smart" concepts and methodologies, which are in line with global documents dealing with the above issue [30].

2.2.2 Transport and Logistics

The transport and logistics represent a high level of complexity process related to freight distribution and passenger transportation, that needs an *Information and Communications Technology* (ICT) solutions for providing the high level of logistics services (flexibility, lowest costs and shortest delivery time). They refer to provide effective warehousing, inventory control and shipment of goods before reaching the final destination point. City logistics, city transport and IoT are significant concepts related to sustainability of logistics systems and freight and passenger transportation. City logistics aims to reduce the negative impact of freight movements within cities by improving mobility and decreasing environmental impact in term of congestion without lowering the level of social and economic activities [31].

2.2.3 Smart Meters

A smart meter is an advanced meter that measures the energy consumption of consumers and provides more information to the utility operators to distribute energy accordingly. Voltage, current, frequency, and timestamps are the most important variables transferred with a smart meter. This device has to provide periodical messages as well as urgent messages in case of a malfunction or unauthorized access.

Smart meter supports bidirectional communication, that enables central system to manage firmware upgrades [6].

2.2.4 Wearables

This IoT category represents devices consisting of sensors monitoring health and safety, detecting activities and sports, providing tracking and localization. Monitoring health with sensors, implanted or worn on a body, collecting data and diagnosing symptoms is a common feature of many commercial products. Hearth-rate sensors are used to detect increased physical activity or cardiac arrests. The body temperature is measured to indicate hypothermia, heat stroke and fevers. Respiratory rate is measured with wearables equiped with thermistor sensor counting the number of breaths for patients with asthma and other respiratory diseases. Oximeter sensors measuring the oxygen level in blood had risen in popularity during the COVID19 pandemic [32, 33, 34].

2.3 Comparison of LPWA Technologies

LPWA technologies split into cellular and non-cellular IoT category. LTE Cat-M and NB-IoT technologies represent the 3GPP solution for cellular IoT using licensed spectrum. On the other hand, non-cellular, unlicensed IoT connectivity is represented mainly by Sigfox and LoRaWAN since 2015. The main advantage of technologies in licensed spectrum is, that they use already built cellular infrastructure. The IoT connectivity can therefore be established without installation, management and operation of the IoT solution. Also, 3GPP technologies provide reliable and long-term solutions with large industry support of vendors and service providers. This does not apply to proprietary technologies, which long-term support is at risk, depending on a private sector. But unlicensed IoT technologies do not worry about the cost of licensed spectrum resources; however, they have to deal with the interference in unlicensed spectrum [19].

Tab. 2.1: Comparison of current LPWA technologies [6, 19]

Technology	**Sigfox**	**LoRaWAN**	**LTE Cat NB1**	**LTE Cat NB2**	**LTE Cat M1**	**LTE Cat M2**
Spectrum	ISM	ISM	Licensed	Licensed	Licensed	Licensed
Frequency	868/915 MHz	433/868/915 MHz	700-2100 MHz	700-2100 MHz	700-2600 MHz	700-2600 MHz
Technology	Proprietary	PHY: Proprietary MAC: Open	Open LTE	Open LTE	Open LTE	Open LTE
Bandwidth	100, 600 Hz	125, 250, 500 kHz	200 kHz	200 kHz	1.4 MHz	5 MHz
Link budget	162 dB	157 dB	164 dB	164 dB	155.7 dB	155.7 dB
Max. EIRP	UL 14 dBm[1] DL 27 dBm	14 dBm	23 dBm	23 dBm	23 dBm	23 dBm
Max. payload	UL 12 B DL 8 B	242 B	1600 B	1600 B	8188 B	8188 B
UL data rate	0.1-0.6 kb/s	0.25-11 kb/s[2]	0.3-62.5 kb/s[2]	0.3-159 kb/s	HD: 375[3], 590 kb/s[4] FD: 1[3], 3 Mb/s[4]	HD: 2.625 Mb/s[4] FD: 7 Mb/s[4]
DL data rate	0.6 kb/s	0.25-21.9 kb/s	0.5-27.2 kb/s	0.5-127 kb/s	HD: 300[3], 800 kb/s[4] FD: 0.8[3], 1 Mb/s[4]	HD: 2.35 Mb/s[4] FD: 7 Mb/s[4]
Consumption	Tx: 14 mA Rx: 7 mA PSM: <1 uA	Tx: 44 mA Rx: 12 mA PSM: <1 uA	Tx: 240 mA Rx: 46 mA PSM: 3 uA	Tx: 240 mA Rx: 46 mA PSM: 3 uA	Tx: 360 mA Rx: 70 mA PSM: 8 uA	Tx: 360 mA Rx: 70 mA PSM: 8 uA
Battery life	10+ years	10+ years	10+ years	10+ years	10+ years	10+ years
Module cost	$ 2	$ 6	$ 8	$ 10	$ 10	$ 10
Security	AES-128	AES-128	LTE Security	LTE Security	LTE Security	LTE Security

[1]The value is relevant for EU. [2]50 kb/s for FSK modulation. [3]3GPP Release 13. [4]3GPP Release 14.

3 LTE for Machines (LTE Cat-M)

3.1 Technology Overview

The 3GPP introduced a solution for M2M communications with the LTE Cat-M standardization. The technology was introduced already in Release 12 but a year later, Release 13 came with ambitious features that established a strong foundation for this technology. Coverage improvements with CE modes A and B defining number of repetitions to increase the coverage in challenging, deep-indoor locations. Also, new device category LTE Cat-M1 using 1.4 MHz bandwidth allowing higher data rates (compared to other LPWA technologies 2.1) and VoLTE support. Then, Release 14 introduced support for higher data rates (up to 7 Mb/s) with new device category Cat-M2 utilizing 5 MHz bandwidth. In addition, Release 14 presented VoLTE enhancements, coverage improvements, multicast support and more. In 2018, Release 15 presented support for new use cases with lower device power class and support for higher device velocity. Furthermore, latency was reduced with improved signaling and wake-up signals and early data transmission reduced power consumption. Spectral efficiency was increased too. Standardization process of LTE Cat-M technology followed radio access design principles deliberated in 2013 study [24, 19].

Low device complexity and cost

First pillar of radio access design is low device complexity and cost. This was achieved with reduced peak rate of 1,/Mbps in Release 12 for Cat-0 device category (reduced from initial at least 10 Mbps and 5 Mbps in downlink and uplink), support for a single antenna to reduce power consumption, and half-duplex FDD operation. Later, Cat-M1 device category in Release 13 inherited all cost reduction principles from Cat-0. Additionally, Cat-M1 introduced bandwidth reduction to 1.4 MHz (insead of 20 MHz) and maximum transmit power of 20 dBm within a new power class (14 dBm power class was introduced later in Release 15) [24, 19].

Coverage enhancement

The initial objective was to improve coverage by 20 dB within a LTE network to support deep-indoor metering devices. Based on a fact, that most of the IoT applications do not require very low latency and high data rates, the satisfying coverage can be achieved with a combination of repetition and retransmission techniques. CE modes standardized in Release 13 utilize those techniques. CE mode A allows up to 32 repetitions and CE mode B up to 2048 repetitions [24, 19].

Long device battery lifetime

LTE Cat-M devices were designed to operate in challenging conditions. They are expected to run for more than 10 years. First, Release 12 introduced PSM. PSM allows devices to sleep between transmission and reception periods without disconnecting from the LTE network. This feature is used by many 3GPP radio access technologies. Then, eDRX was introduced in Release 13. With eDRX, the device can listen for pending data indications without establishing a full network connection. The duration of the low-power sleep of LTE Cat-M devices can be as low as 320 ms and up to 43 minutes. Additionally, the power consumption of LTE Cat-M devices is reduced with minimized transmit and receive bandwidths [24, 19].

Support of massive number of devices

A lot of IoT scenarios expect a large device density and the 3GPP standardized techniques like *Access Class Barring* (ACB) and overload control already in Release 10 and 11 to address this issue. More recently, suspend/resume mechanism of the *Radio Resource Control* (RRC) layer was introduced to reduce the required signaling after a period of inactivity and resuming the RRC connection as long as the device is still in the same cell [19].

Deployment flexibility

LTE Cat-M technology supports paired bands for FDD and also unpaired bands for TDD operation and new bands have been added in every release. Although, LTE Cat-M devices works with reduced bandwidth, the technology supports the same bandwidths as LTE network itself (1.4, 3, 5, 10, 15, and 20 MHz) [19].

Coexistence with LTE

LTE Cat-M design builds on already available LTE physical layer, therefore using OFDMA in downlink and SC-FDMA in the uplink. Same numerology is applied (frame structure, resource grid, *Cyclic Prefix* (CP) lengths, subcarrier spacing, channel raster, etc.), that means ordinary LTE users with smartphones and mobile modems can coexist with LTE Cat-M devices in the same LTE cell and on the same LTE carrier with dynamically shared resources. LTE Cat-M traffic can be also scheduled at night or in time periods, when the ordinary active LTE users are inactive and the LTE Cat-M can utilize all the resources available (allocated LTE spectrum and available bandwidth) [19].

3.1.1 Comparison Based on the 3GPP Releases

The table bellow shows the most significant features introduced in Release 13, 14, and 15. Newer releases (Release 16 and 17) has had significantly smaller impact on LTE Cat-M technology and therefore, they will not be mentioned.

Tab. 3.1: New LTE-M features introduced in 3GPP releases [3, 19]

Release 13 (2016)	Release 14 (2017)	Release 15 (2018)
Cost reduction • New device category M1 **Coverage improvements** • CE modes A and B **Reduced power consumption** • 20 dBm power class • PSM • eDRX **Bandwidth reduction** • 1.4 MHz (instead of 20 MHz) • Maximum of 6 PRBs • Maximum 1000 bits/TBS **Peak rates** • Uplink 1 Mbps • Downlink 800 kbps **FH for unicast transmission** **E-CID and OTDOA support**	**Support for higher data rates** • New device category M2 • Higher uplink peak rate for Cat-M1 • Wider bandwidth in CE mode • More downlink HARQ processes in FDD • ACK/NACK bundling in HD-FDD • Faster frequency retuning **VoLTE enhancements** • New PUSCH repetition factors • Modulation scheme restriction • Dynamic ACK/NACK delays **Coverage improvements** • SRS coverage enhancement • Larger PUCCH repetition factors • Uplink transmit antenna selection **Multicast support** **Improved positioning** **Mobility enhancements**	**Support for new use cases** • Support for higher device velocity • Lower device power class **Reduced latency** • Resynchronization signal • Improved MIB/SIB performance • System info update indication **Reduced power consumption** • Wake-up signals • Early data transmission • ACK/NACK feedback for uplink data • Relaxed monitoring for cell reselection **Increased spectral efficiency** • Downlink 64QAM support • CQI table with large range • Uplink sub-PRB allocation • Flexible starting PRB • CRS muting **Improved access control**

3.2 Physical Layer

This section is dedicated to LTE Cat-M physical layer with emphasis on physical resources, which demonstrate the integration of this technology with existing LTE standards.

3.2.1 Physical Resources

Frame structure

LTE Cat-M utilizes LTE frame structure consisting of 3 frame layers. From the top, there is a hyperframe cycle consisting of 1024 hyperframes. Each hyperframe spans 10.24 s. Hyperframe encapsulates 1024 frames with length of 10 ms. Frames then consist of 10 subframes (with 1 ms length), each divided into 2 (0.5 ms) slots. Each slot contains 7 *Orthogonal Frequency Division Multiplexing* (OFDM) symbols when normal CP is used or 6 OFDM symbols with extended CP length. Each frame has its own unique position in the structure and can be identified with a frame number.

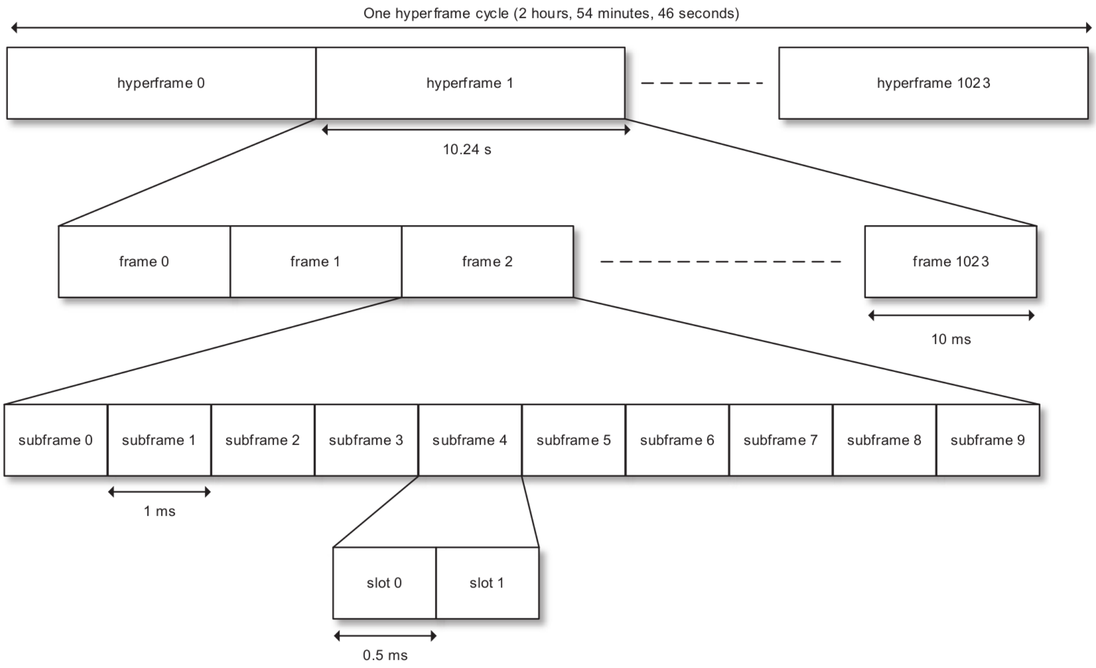


Fig. 3.1: LTE frame structure [19]

3.2.2 Resource grid

LTE resource grid represents one frame with detail to OFDM symbols in PRBs and their usage. PRB is the smallest unit of resources that can be allocated for transmission. The PRB spans 180 kHz in frequency and 1 slot in time. In frequency, 1 PRB consists (for most channels and signals) of 12 subcarriers with 15 kHz spacing. A subcarrier per symbol represent the smallest discrete part of a frame called *Resource Element* (RE), that carries the data.

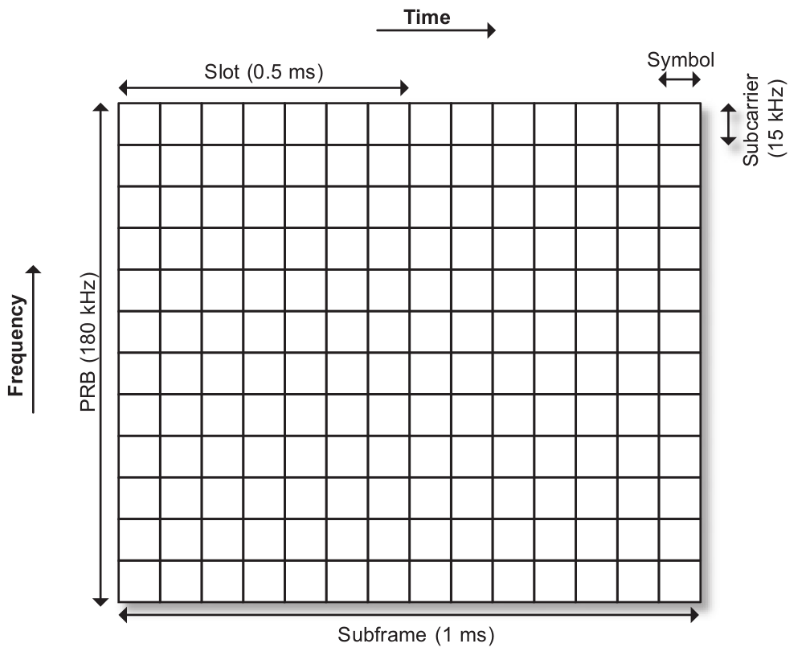


Fig. 3.2: LTE physical resource block (PRB) pair [19]

4 Thesis Results

4.1 Network Simulator 3

This chapter is dedicated to basic overview of simulation tool *Network Simulator 3* (NS-3) and module LENA, which extends NS-3 with LTE network functionality.

4.1.1 NS-3

NS-3 is a discrete-event network simulator used primarily in research and education. It is free, open-source software, licensed under GNU *General Public License version 2* (GPLv2).

Software is implemented in C++ programming language. Simulation core of NS-3 is connected with libraries and modules (statically or dynamically), that together define the simulated topology. NS-3 library is also available in Python language, which enable users to program in this language as well [35].

4.1.2 LENA module

LENA module is an open-source LTE/EPC simulator developed by *Centre Tecnològic de Telecomunicacions de Catalunya* (CCTC). Module was created to enable implementation and testing of control algorithms for LTE networks, load balancing, heterogeneous networking, *Multi–Radio Access Technologies* (Multi-RAT), cognitive LTE systems, etc. LENA module is based on NS-3 software [36].

Module consists of 2 main components:

1. **LTE model** — contains protocol stack for LTE radio interface: *Radio Link Control* (RLC), *Medium Access Layer* (MAC), RRC, *Packet Data Convergence Control* (PDCP), *Physical Layer* (PHY).
2. **EPC model** — contains interfaces, protocols and enitites of core network. They are located in *Serving Gateway* (SGW), *Packet data network Gateway* (PGW), *Mobility Management Entity* (MME) and partially eNodeB nodes.

LTE model

Requirements of LTE model are set for support and evaluation of:

- radio resource control
- packet scheduling with *Quality of Service* (QoS)
- inter-cell interference coordination
- *Dynamic Spectrum Access* (DSA)

Network simulation can be configured for each cell to use different frequencies and bandwidths. DSA supports band overlapping of different cells.

To achieve the most realistic representation of LTE standard, LENA module implements MAC Scheduler. This extension allows testing of real system algorithms in simulation environment. Higher layers use model based on IP packets. Therefore, it is important to mention, that LTE scheduler and *Radio Resource Management* (RRM) do not use IP packets, but they work with RLC frames on link layer and thus correct functionality of this layer is very important [36].

EPC model

This model is designed to allocate resources for end-to-end IP connection for LTE model. Therefore, it supports connection of a lot of UEs to the Internet through RAN with more eNodeB stations. Stations are connected to associated SGW and PGW nodes. There is no need to implement additional interfaces as 3GPP standard recommends, due to single unified SGW/PGW node. EPC model supports only internet protocol IPv4. Also, this model can be used with any NS-3 application that uses either TCP or *User Datagram Protocol* (UDP) transport protocol. UEs can use applications with different QoS profiles. That includes classification of TCP/UDP transfer through IP protocol, which is sent from UE in uplink and from PGW in downlink [36].

4.2 Simulations

Simulation scenario of LTE network is fully implemented, consisting of RAN and EPC, to monitor behavior of a LTE network to increased number of UEs. All UEs are randomly positioned in the area of eNodeB. The transmission is packet-based and controlled by the TCP. The simulation time is set to 10 seconds.

4.2.1 Initial Scenario

In the fist scenario, 10 UEs are connected to single eNodeB. The aim of this simulation is to gather reference data of fully functional LTE network. Data rate, delay, and packet loss are monitored. The topology of the simulation is shown in the image bellow.

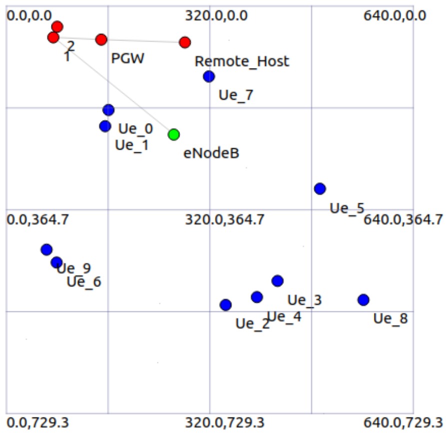
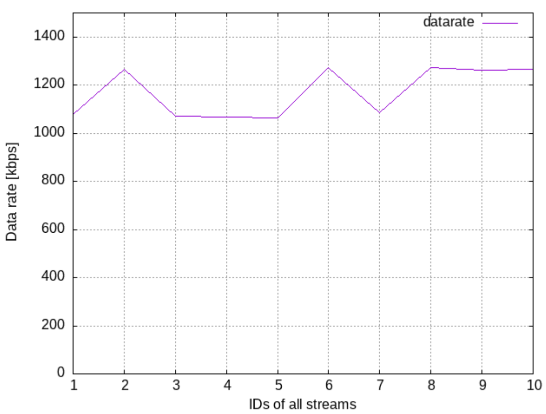
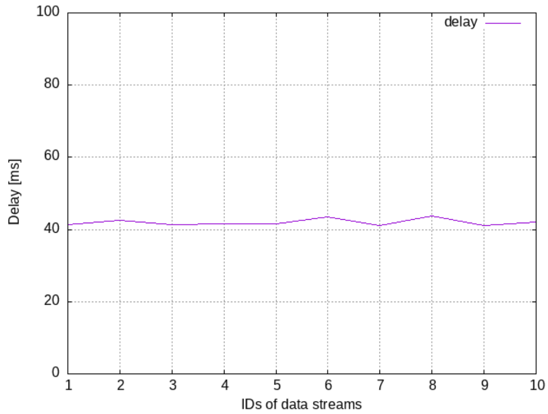


Fig. 4.1: Topology of the initial scenario

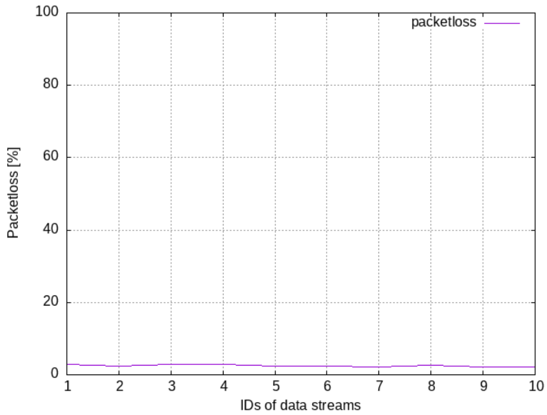
Results



(a) Data rate



(b) Delay



(c) Packet loss

Fig. 4.2: Results from initial scenario simulation

4.2.2 Extended Scenario

The second scenario is extended for a communication of 300 UEs with a single eNodeB. Monitoring the same data as in previous simulation for comparison. Scenarios with more than 300 devices caused an error within the LTE module. The topology of the second simulation is shown in the image bellow.

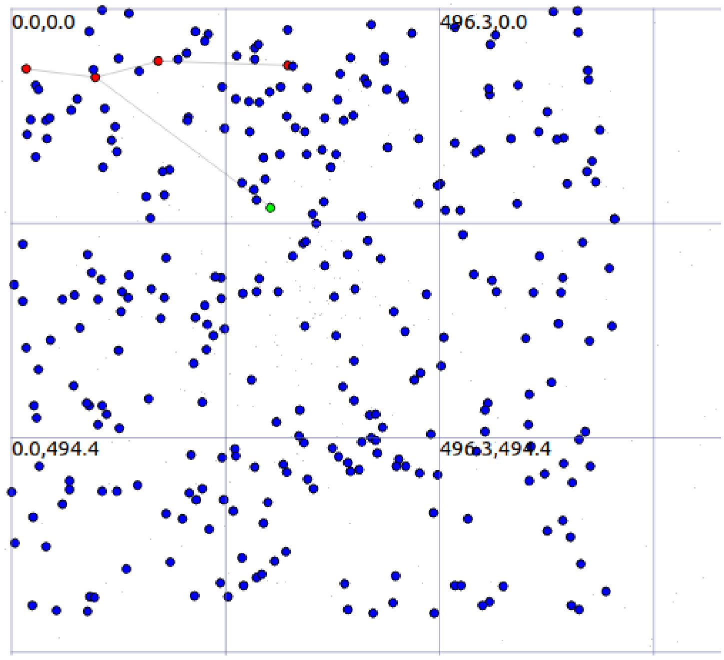
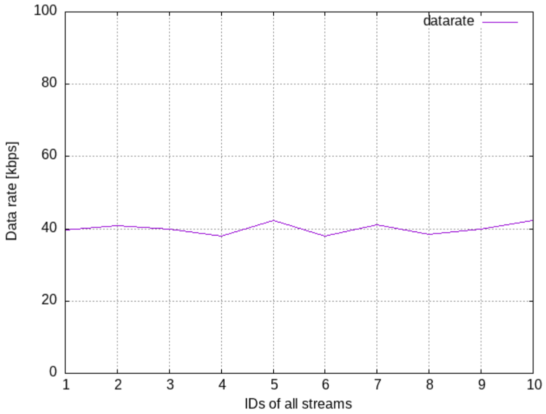
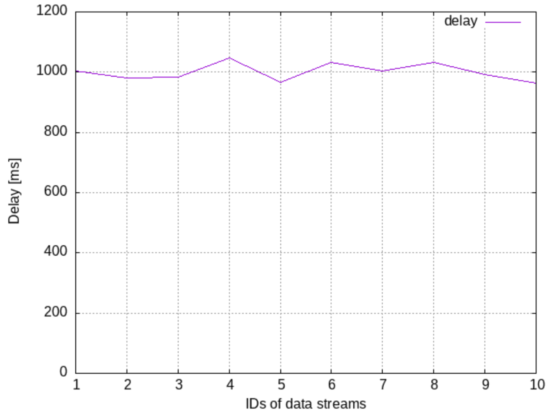


Fig. 4.3: Topology of the extended scenario

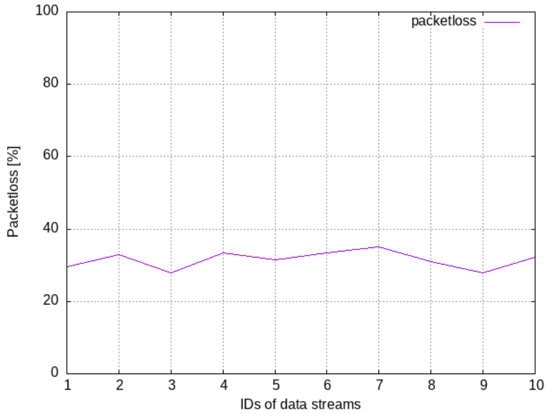
Results



(a) Data rate



(b) Delay



(c) Packet loss

Fig. 4.4: Results from extended scenario simulation

Conclusion

As a reaction to a massive number of devices online, communication technologies have been rapidly evolving. Cellular networks are most commonly the native connectivity method deployed for most of mobile devices. With the expanding IoT market, there has been adaptations of implemented technologies to support the still rising M2M communication. The new generations of broadband cellular networks provide more support for M2M communication and even support the mMTC use case. One of the solutions to the mMTC are LPWA technologies. They provide a huge coverage in a reasonable price range. Each LPWA technology excel in slightly different field, e.g. NB-IoT is good for small infrequent data transmissions in deep indoors or LTE Cat-M supports VoLTE and higher data rates. They both use licensed spectrum for transmission.

Nowadays, the deployment of the fifth generation is not yet finished, therefore the focus is on previous generation, LTE. The limits of the LTE network design are simulated using NS-3. The tests with 10 connected devices to a single eNodeB shown an average data rate of 1.2 Mbit/s. The latency was recorded bellow 50 ms, averaging 41 ms with only 2 % packet loss using TCP connection. On the other hand, the extended scenario with 300 UEs transmitting to a single eNodeB performed different, showing much worse results. Only 40 kbit/s average data rate and an average delay of 1 s was recorded with packet loss up to 40%. Simulations with even more devices led to an error during execution.

With LTE Cat-M technology available as a software upgrade of existing LTE network, future simulations should withstand hundreds of devices. For example, smart networks are a promising use case. The module for LTE Cat-M is not yet implemented in NS-3; therefore, there is a potential for future work.

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Symbols and abbreviations

GSM The Global System for Mobile Communications

ETSI European Telecommunications Standards Institute

3GPP The 3rd Generation Partnership Project

IoT Internet of Things

UMTS Universal Mobile Telecommunications Service

LTE Long Term Evolution

RAN Radio Access Network

EFR Enhanced Full Rate

GPRS General Packet Radio Services

EDGE Enhanced Data for Global Evolution

AMR Adaptive Multi-Rate

WCDMA Wideband Code Division Multiple Access

IP Internet Protocol

IMS IP Multimedia Subsystem

HSDPA High-Speed Downlink Packet Access

HSUPA High-Speed Uplink Packet Access

MBMS Multimedia Broadcast Multicast Services

PTT Push to Talk

WLAN Wireless Local Area Network

QoS Quality of Service

VoIP Voice over IP

HSPA+ Evolved High Speed Packet Access

NFC Near Field Communication

OFDMA Orthogonal Frequency Division Multiple Access

MIMO	Multiple Input/Multiple Output
WiMAX	Worldwide Interoperability for Microwave Access
LTE-A	Long Term Evolution-Advanced
HetNet	Heterogeneous Networks
CoMP	Coordinated Multipoint Transmission
PS	Packet Switched
CA	Carrier Aggregation
UE	User Equipment
PSM	Power Saving Mode
D2D	Device-to-Device
V2X	Vehicle to Everything
mMTC	Massive Machine-Type Communications
URLLC	Ultra Reliable Low Latency Communications
NR	New Radio
MC	Multi Carrier
TDMA	Time Division Multiple Access
FDD	Frequency Division Duplex
GMSK	Gaussian Minimum Shift Keying
PSK	Phase Shift Keying
TCP	Transmission Control Protocol
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
IMT	Information Management Technology
CDMA	Code Division Multiple Access
DS	Direct Sequence

QAM	Quadrature Amplitude Modulation
DC	Dual Cell
EPC	Evolved Packet Core
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
RNC	Radio Network Controller
eMBMS	Evolved Multimedia Broadcast Multicast Services
LCS	Location Services
MTC	Machine Type Communication
RN	Relay Nodes
M2M	Machine to Machine
IoT	Internet of Things
CS	Circuit Switched
TDD	Time Division Duplex
SC	Single Carrier
FDMA	Frequency Division Multiple Access
QPSK	Quadrature Phase-Shift Keying
SON	Self-Optimizing Network
eNodeB	E-UTRAN Node B
NB	Narrowband
NSA	Non-Standalone Architecture
SA	Standalone Architecture
MPS	Multimedia Priority Service
LAN	Local Area Network
gNB	gNodeB
eMMB	Enhanced Mobile Broadband

UX	User Experience
ng-eNB	New Generation-eNodeB
E-UTRA	Evolved UMTS Terrestrial Radio Access
NG	New Generation
5GC	5G Core
NB-IoT	NarrowBand IoT
LTE-M	LTE Machine-to-Machine
cMTC	Critical Machine-Type Communications
URLLC	Ultra-Reliable Low Latency Communications
TBS	Tansport Block Size
TBCC	Tail-Biting Convolutional Code
eDRX	Extended Discontinuous Reception
LPWA	Low-Power Wide-Area
PRB	Physical Resource Block
VoLTE	Voice over LTE
CE	Coverage Enhancement
CP	Cyclic Prefix
GERAN	GSM EDGE Radio Access Network
ICT	Information and Communications Technology
E-CID	Enhanced Cell Identity
TBS	Transport Block Size
FH	Frequency Hopping
OTDOA	Observed Time Difference of Arrival
HARQ	Hybrid Automatic Repeat Request
HD	Half Duplex

SRS	Sounding Reference Signal
PUCCH	Packet Uplink Control CHannel
PUSCH	Packet Uplink Shared CHannel
MIB	Master Information Block
SIB	System Information Block
CQI	Channel Quality Information
CRS	Cell-specific Reference Signal
ACB	Access Class Barring
RRC	Radio Resource Control
OFDM	Orthogonal Frequency Division Multiplexing
RE	Resource Element
NS-3	Network Simulator 3
GPLv2	General Public License version 2
CCTC	Centre Tecnològic de Telecomunicacions de Catalunya
Multi-RAT	Multi–Radio Access Technologies
RLC	Radio Link Control
MAC	Medium Access Layer
PDCP	Packet Data Convergence Control
PHY	Physical Layer
SGW	Serving Gateway
PGW	Packet data network Gateway
MME	Mobility Management Entity
DSA	Dynamic Spectrum Access
RRM	Radio Resource Management
UDP	User Datagram Protocol