BRNO UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering
and Communication

MASTER'S THESIS

Brno, 2023

Bc. Roman Santa

BRNO UNIVERSITY OF TECHNOLOGY

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF TELECOMMUNICATIONS

ÚSTAV TELEKOMUNIKACÍ

IMPLEMENTATION AND EVALUATION OF THE LTE CAT-M TECHNOLOGY USING THE NETWORK SIMULATOR 3

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

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

AUTHOR
AUTOR PRÁCE

Bc. Roman Santa

SUPERVISOR
VEDOUCÍ PRÁCE

Ing. Pavel Mašek, Ph.D.

BRNO 2023

BRNO UNIVERSITY OF TECHNOLOGY
FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

Master's Thesis

Master's study program **Communications and Informatics**

Department of Telecommunications

Student: Bc. Roman Santa ***ID:*** 187421

Year of study: 2 ***Academic year:*** 2022/23

TITLE OF THESIS:

Implementation and Evaluation of the LTE Cat-M Technology Using the Network Simulator 3

INSTRUCTION:

The diploma thesis aims to study the upcoming LTE Cat-M technology. In the theoretical part, a comparison of LPWA technologies will be detailed, where the emphasis will be given to a thorough analysis of LTE Cat-M technology according to 3GPP Rel. 13/14. Subsequently, scenarios for data transmissions within smart grids will be implemented. The implementation will be done in Network Simulator 3 (NS-3). The practical part will consist of creating a communication scenario using the LENA / LENA 5G module, where focus will be on a specific scenario in which end devices connect to only one base station. The student will design and implement modifications to the selected LENA module so that the modified module enables communication according to 3GPP Rel. 13.

RECOMMENDED LITERATURE:

[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.

Date of project specification: 6.2.2023 ***Deadline for submission:*** 19.5.2023

Supervisor: Ing. Pavel Mašek, Ph.D.

prof. Ing. Jiří Mišurec, CSc.
Chair of study program board

ABSTRACT
This master's thesis contains theoretical introduction to *Long Term Evolution* (LTE) Cat-M technology. Next-generation mobile systems are mentioned in first chapter with an emphasis on 5G cellular *Internet of Things* (IoT) technologies. Second chapter describes *Massive Machine-Type Communications* (mMTC) from *The 3rd Generation Partnership Project* (3GPP) standardization standpoint, IoT communication scenarios, and also includes comparison of *Low-Power Wide-Area* (LPWA) technologies. LTE for Machines is a part of third chapter, with technology overview and physical resources. Simulation environment and used modules are reviewed in the fourth chapter. The simulation results are gathered at the end of fourth chapter. Including testing different number of devices connected and energy consumption with *Power Saving Mode* (PSM) and *Extended Discontinuous Reception* (eDRX).

KEYWORDS
Cellular Internet of Things (IoT), Extended Discontinuous Reception (eDRX), Low-Power Wide-Area (LPWA) Network, LTE for Machines (LTE Cat-M), Network Simulator 3, Power Saving Mode (PSM)

ABSTRAKT
Diplomová práca obsahuje teoretický úvod technológie LTE Cat-M. Prvá kapitola obsahuje opis generácií mobilných sietí s dôrazom na 5G mobilné IoT technológie. V druhej kapitole je popísaný proces štandardizácie Massive Machine-type Communication (mMTC) organizáciou 3GPP. Kapitola taktiež obsahuje aplikované IoT komunikačné scenáre a prehľadné porovnanie Low-Power Wide-Area (LPWA) technológií. LTE Cat-M technológia je stručne popísaná v tretej kapitole. Dôraz je kladený na fyzickú vrstvu a alokáciu zdrojov. Simulačné prostredie a použité moduly sú objasnené na začiatku štvrtej kapitoly. Štvrtá kapitola sa ďalej zaoberá popisom jednotlivých simulačných scenárov a výsledkami simulácií. Simulácie sú rozdelené na dve hlavné kategórie, simulácia počtu koncových staníc a simulácia spotreby energie s využitím režímu úspory energie (PSM).

KĽÚČOVÉ SLOVÁ
Mobilný internet vecí (IoT), Nizkoenergetické siete s ďalekým dosahom, LTE komunikácia pre stroje, Simulácie sietí, Režim úspory energie

Rozšírený abstrakt

Komunikačné technológie podliehajú neustálemu vývoju zvyšujúcim sa požiadavkám spoločnosti. Štandardizačné organizácie ako aj súkromné spoločnosti sa venujú podrobnému výskumu za cieľom stanoviť definitívne pravidlá pre najnovšie štandardy a technológie. Súčasný rastúci trend automatizácie procesov a pripájanie obrovského množstva nových zariadení do siete zvyšuje nároky na vlastnosti sietí. Internet vecí je už veľmi rozšírený pojem v dnešnej spoločnosti, za ktorým sa skrývajú viaceré technológie. Jedným technologickým riešením náročných požiadavie sú nízkoenergetické siete z ďalekým dosahom (LPWAN). Toto zoskupenie technológií preukazuje dobré výsledky pri pripojení veľkého množstva jednoduchých zariadení do internetovej siete. Telekomunikačné spoločnosti preto inovujú svoje technológie a implementujú nové zariadenia ako aj nový softvér do súčasnej infraštruktúry. Tu sa delí trh na dve základné vetvy, technológie v licenčnom pásme a technológie v bezlicenčnom pásme. V tejto diplomovej práci je pozornosť upriamená práve na mobilné technológie v licenčnom pásme.

K pochopeniu konkrétnych mobilných technológií v licenčnom pásme je potrebné najskôr porozumieť mobilným komunikáciám vo všeobecnosti. Na úvod sú preto v prvej kapitole vysvetlené jednotlivé generácie mobilných sietí. Pozornosť je pri tom upriamená najmä na súčasne najviac využívanú 4G a nastupujúcu 5G sieť. Nastupujúce generácie mobilných sietí sa zameriavajú najmä na obrovský počet zariadení a s tým súvisejúce požiadavky. Štandardizácií v tejto oblasti sa venuje hlavne organizácia 3GPP, ktorá pravidelne publikuje nové špecifikácie a odporúčania. V roku 2016 3GPP štandardizovala technológie ako LTE Cat-M a NB-IoT, ktoré by mali poskytovať riešenie pre jednoduchú komunikáciu veľkého množstva zariadení v mobilnej sieti. Jedná sa o softvérové riešenie, ktoré je možné vďaka neustálemu vývoju aplikovať v súčasnej mobilnej sieti. Tieto technológie patria do skupiny masívnej komunikácie strojov (mMTC), ktorej je venovaná druhá kapitola.

Táto diplomová práca ďalej poukazuje na vlastnosti skúmanej technológie LTE Cat-M, kde sa hlavný dôraz kladie na fyzickú vrstvu, ktorá následne ovplyvňuje správanie vyšších vrstiev. K dispozícií je aj prehľad vývoja tejto technológie v jednotlivých verziách.

K simulácii komunikácie v 4G sieti je využívaný voľne dostupný simulačný nástroj Network Simulator 3 (NS-3). Tento nástroj obsahuje moduly pre rôzne sieťové technológie. V rámci tohto simulačného nástroja boli testované viaceré dostupné moduly implementujúce funkcie využívané LTE Cat-M technológiou. Funkcionalita ako aj stav testovaných modulov je obsahom štvrtej kapitoly. Posledná časť tejto kapitoly je venovaná dvom vybraným testom. Prvým je test oficiálneho modulu LENA na zvýšenie počtu koncových zariadení v rámci jednej základovej stanice.

Druhý test je sústredený na spotrebu energie zariadenia využívajúceho režimy úspory batérie (eDRX, PSM). Výsledky simulácií ako aj splnenie cieľov práce samotnej sú diskutované v záverečnej kapitole.

SANTA, Roman. *Implementation and Evaluation of the LTE Cat-M Technology Using the Network Simulator 3*. Brno: Brno University of Technology, Faculty of Electrical Engineering and Communication, Department of Telecommunications, 2023, 68 p. Master's Thesis. Advised by Ing. Pavel Mašek, Ph.D.

Author's Declaration

Author:	Bc. Roman Santa
Author's ID:	187421
Paper type:	Master's Thesis
Academic year:	2022/23
Topic:	Implementation and Evaluation of the LTE Cat-M Technology Using the Network Simulator 3

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the paper and listed in the comprehensive bibliography at the end of the paper.

As the author, I furthermore declare that, with respect to the creation of this paper, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation § 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll. of the Czech Republic, Section 2, Head VI, Part 4.

Brno . . . .

author's signature*

*The author signs only in the printed version.

ACKNOWLEDGEMENT

I would like to thank the advisor of my thesis, Ing. Pavel Mašek, Ph.D. for his guidance and helpful insights throughout the process of assembling this paper. I'd also like to thank my colleague Bc. Le Dinh Thao for the cooperation.

Contents

List of Figures

List of Tables

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 telecommunication 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. Physical layer and resource allocation is also explained within the chapter. LTE Cat-M is also compared with other licensed and license-exempt technologies. Simulating LTE Cat-M technology in *Network Simulator 3* (NS-3) is a challenging task as there are not many projects regarding this simulation tool and Cat-M technology.

Simulations and results are split into two scenarios. The first scenario is trying to address the limitations of the simulation tool in case of the number of devices connected to a single station. The second one is about measurement of energy consumption with power saving features introduced in cellular IoT technologies to extend the battery lifetime. The results in the forth chapter shows the importance of setting up the power saving features with respect to specific parameters. The parameters should be tested and applied for each specific use case to achieve the best results. All of the outputs are discussed in the conclusion at the end of this thesis with suggestions for future development.

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 Enhanced Full Rate 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, Adaptive Multi-Rate 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, push to talk 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, only packet switching 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	Q1 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/*Time Division Multiple Access* (TDMA)/*Frequency Division Duplex* (FDD). It also distinguish between speech and circuit switched data, and packet switched 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].

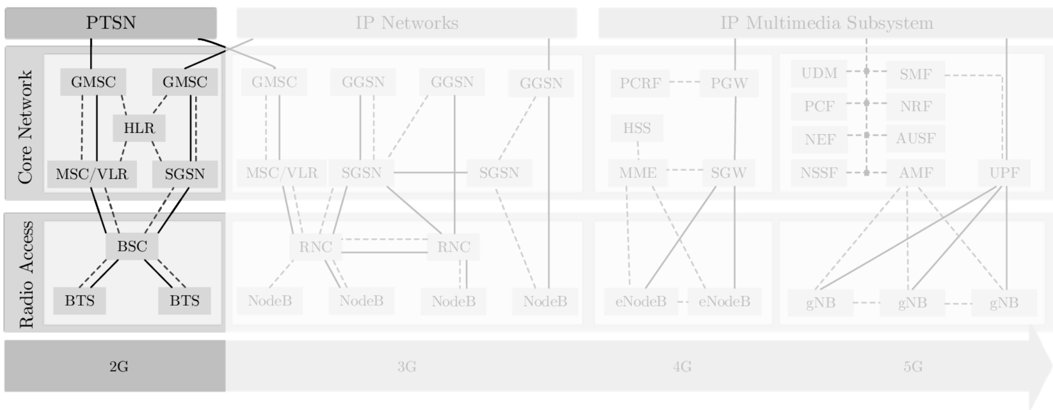


Fig. 1.1: 2G architecture overview [9].

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 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].

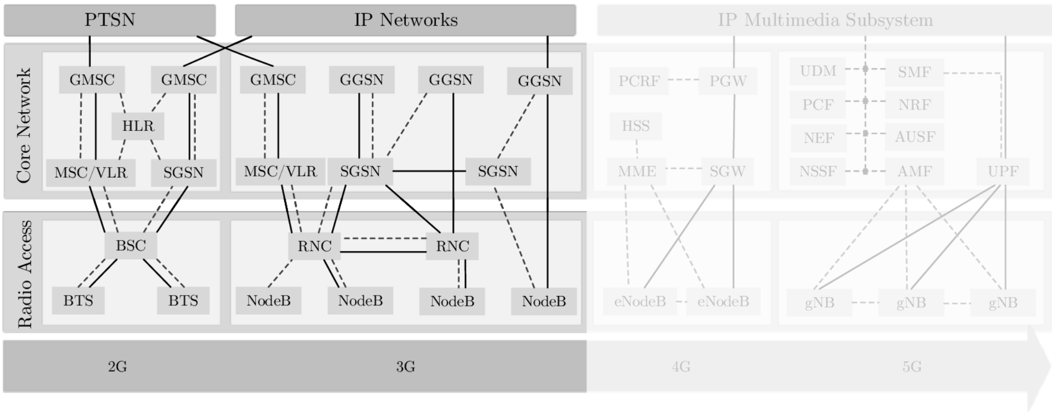


Fig. 1.2: 3G architecture overview [9].

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-Frequency Division Multiple Access* (SC-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. CA allowed data rates to exceed 1 Gbps and with relay nodes 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].

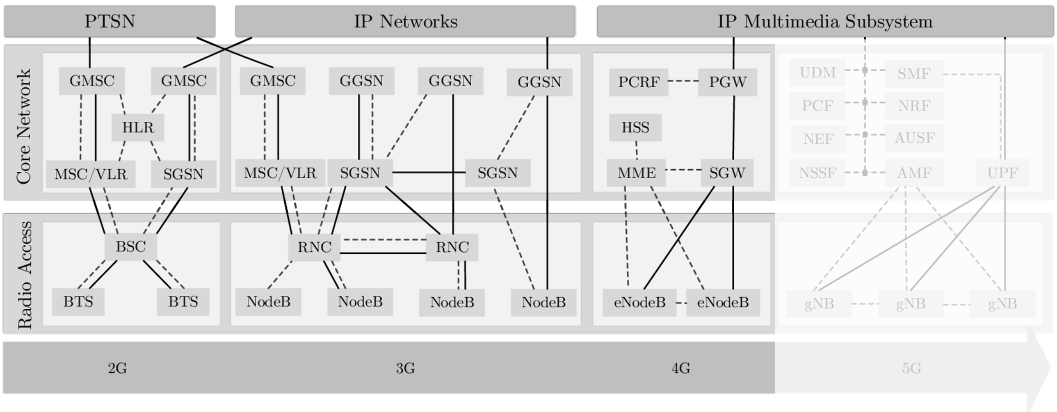


Fig. 1.3: 4G architecture overview [9].

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, 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].

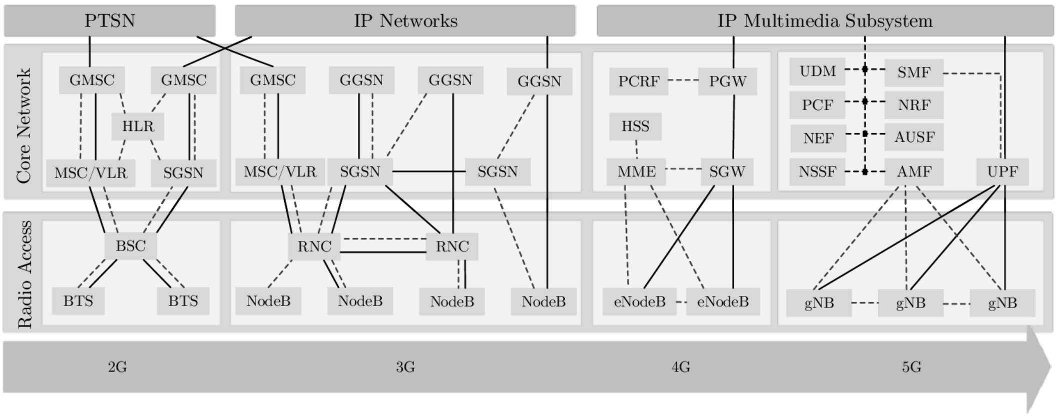


Fig. 1.4: 5G architecture overview [9].

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].

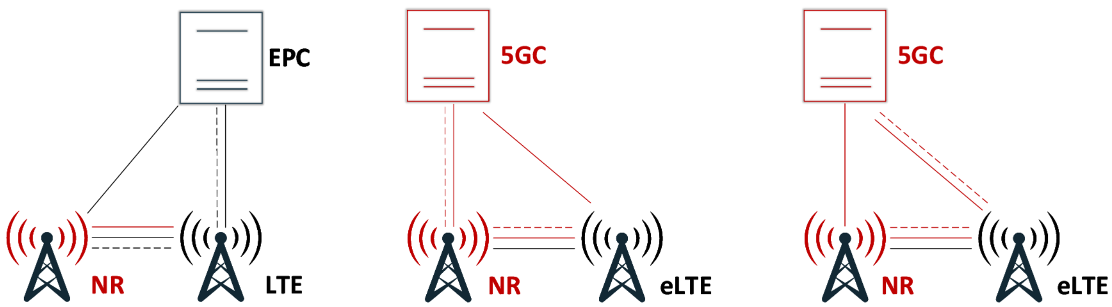
1.2.1 5G NSA

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].

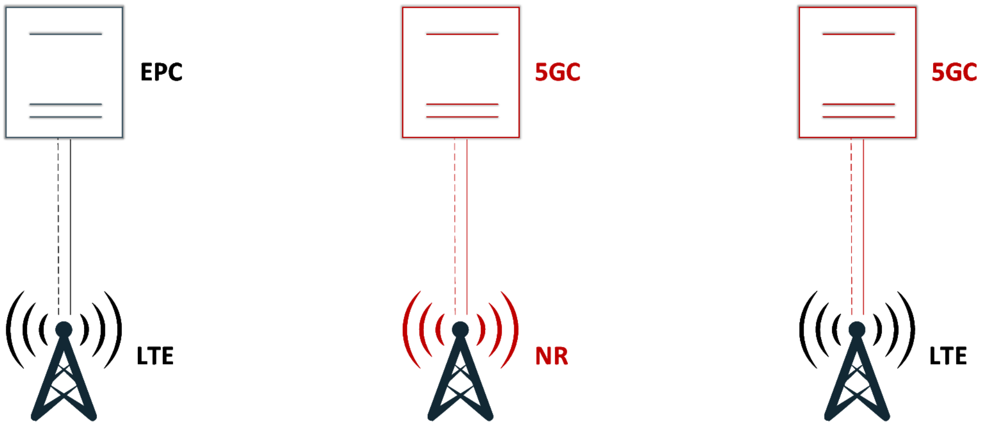
1.2.2 5G SA

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. Physical channels and signals are also described in this section later, both downlink and uplink, to show the simplicity and limited functionality of LTE Cat-M physical layer [19].

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 [19].

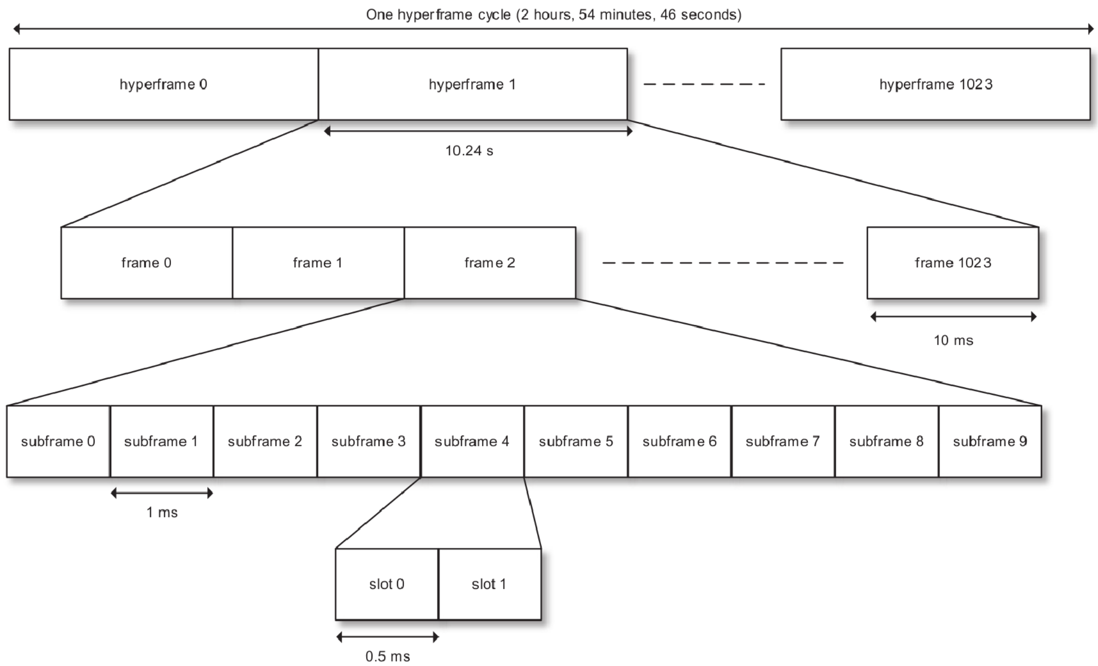


Fig. 3.1: LTE frame structure [19].

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 [19].

3.2.2 Downlink physical signals and channels

LTE Cat-M supports limited channels of the legacy LTE physical layer. Reasons for that are mentioned above in 3.1. Also, a new control channel *MTC Physical Downlink Control Channel* (MPDCCH) is used alongside *Physical Downlink Shared Channel* (PDSCH) and *Physical Broadcast Channel* (PBCH). MPDCCH is mapped

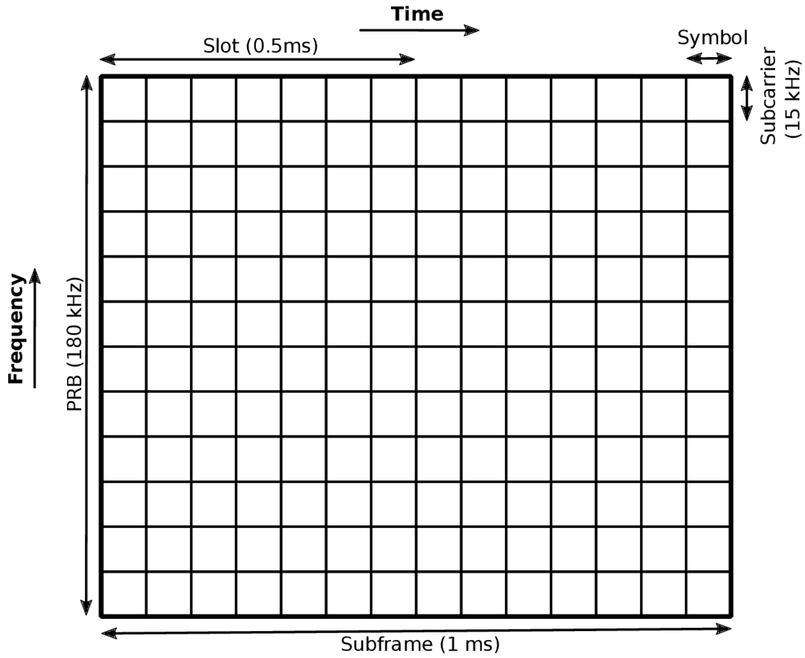


Fig. 3.2: LTE physical resource block (PRB) pair [19].

to the LTE data region to avoid collisions with existing LTE control channels. Physical signals are divided to synchronization and reference signals. *Resynchronization Signal* (RSS) and *MTC Wake-Up Signal* (MWUS) was introduced later in Release 15, so it would be just briefly mentioned in this section [19].

Synchronization signals

- PSS
- SSS
- RSS

Primary Synchronization Signal (PSS) and *Secondary Synchronization Signal* (SSS) are responsible for obtaining cell's carrier frequency, frame timing, duplex mode, CP length and *Physical Cell Identity* (PCID). Both signals transmit periodically to receive the signal over multiple frames. Although, this approach increases the acquisition delay, it avoids additional repetitions. Both signals are transmitted every 5 ms interval. The PSS sequence carries a PCID which correspond to a cell served by a base station. The SSS sequence pattern consists of 2 SSSs within 10 ms. The fisrt SSS sequence carries the PCID and the second SSS the frame timing. LTE supports 168 groups of 3 PCIDs. Devices can use the same PCID as long as they are far apart to avoid overhearing. PSS and SSS are mapped around the LTE carrier into 62 subcarriers.

Release 15 introduced the optional RSS to enhance efficiency in restoring time and frequency synchronization toward a cell. It is optional to transmit for the base station as well as optional for the device to use it. RSS is transmitted less frequently then PSS and SSS, every 160 ms up to 1280 ms intervals [19].

Downlink reference signals

- CRS
- DMRS
- PRS

The three listed downlink reference signals are used by the device for demodulation of physical channels and signal quality measurements.

The *Cell-specific Reference Signal* (CRS) is transmitted from one to four antennas and CRS from all antenna ports is contained in every PRB, mapped to specific RE. The CRS is used demodulaiton of PBCH or PDSCH.

The downlink *Demodulation Reference Signal* (DMRS) is used for PDSCH or MPDCCH demodulation. This reference signal uses the same bandwidth as the associated channel. The DMRS supports up to four antenna ports and also can use beamforming for additional coverage.

The *Positioning Reference Signal* (PRS) is a broadcast reference signal. It is used for positioning, where the device receive the PRS from different time-synchronized base stations and based on *Observed Time Difference of Arrival* (OTDOA) method, the device determines its position. The PRS configuration is delegated through *LTE Positioning Protocol* (LPP) via server called *Evolved Serving Mobile Location Center* (E-SMLC) [19].

PBCH

The PBCH is responsible for *Master Information Block* (MIB) transmission, which contains necessary information for the device to be able to operate in the network.

The PBCH bandwidth consists of 72 subcarries at the center of LTE system bandwidth. The LTE Cat-M specification recognizes PBCH core part, which contains the LTE PBCH, and PBCH repetitions, that are used for coverage improvements. The PBCH repetitions are allowed in all system bandwidths exept the 1.4 MHz. PBCH repetitions in a cell can be enabled by the network. PBCH repetitions are used for isolated cells with challenging signal reception.

The basic *Transmission Time Interval* (TTI) is 40 ms with 24-bit TBS. The transport block is tailed by 16-bit *Cyclic Redundancy Check* (CRC). With the CRC masked by a bit sequence derived from number of CRS antenna ports on the base station, the number of antenna ports is revealed in the process of decoding the PBCH.

There is 40 bits in total that are encoded with the LTE TBCC generating 1920 encoded bits in total. The bits are scrambled using cell-specific sequence to avoid interference from neighbor cells. After scrambling, the 1920 bits are divided into 4 segments, each 480 bits long, and the segments are transmitted one after another in separate frames. One segment is mapped to 240 QPSK symbols spanning across 72 subcarriers. At last, the transmission is diversified with *Space-Frequency Block Coding* (SFBC) using two antenna ports or with SFBC and *Frequency-Switched Transmit Diversity* (FSTD) when four antenna ports are used.

The PBCH is using subframe #0 with four OFDM symbols for the core part transmission and subframe #9 in FDD or subframe #5 in TDD when repetitions are enabled. Each PBCH repetition contains four copies of each OFDM symbol from the PBCH core part. Which means, that PBCH repetitions carry a copy of the CRS too [19].

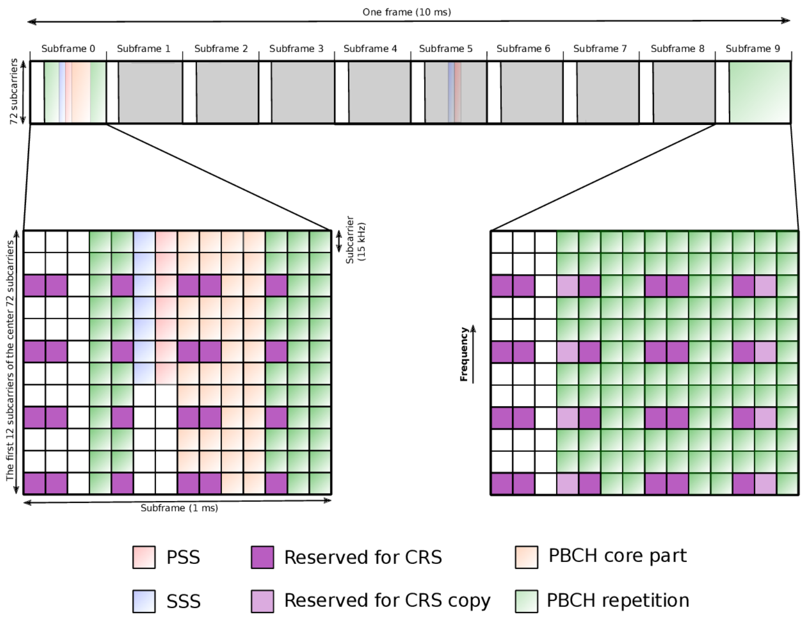


Fig. 3.3: PBCH core part and PBCH repetition in LTE FDD [19].

MWUS

The MWUS can be used for device battery lifetime improvement since Release 15. This signal is used for periodic monitoring of paging occasions during a device idle mode [19].

MPDCCH

The function of MPDCCH is defined as a carrier of *Downlink Control Information* (DCI). The DCI is monitored by LTE Cat-M devices to access the following information.

- Uplink power control command
- Uplink grant information
- Downlink scheduling information
- Indicator of paging or system information update
- Order to initiate a random access procedure
- Notification of changes in multicast control channel (Release 14)
- Explicit positive HARQ-ACK feedback (Release 15) [35]

The MPDCCH was designed following the *Enhanced Physical Downlink Control Channel* (EPDCCH) structure from LTE. There are 16 *Enhanced Resource Element Group* (EREG)s in one PRB pair. Each EREG contains 9 REs. Also, there is *Enhanced Control Channel Elements* (ECCE) which encapsulates 4 EREGs or 36 REs in normal subframes with normal CP length.

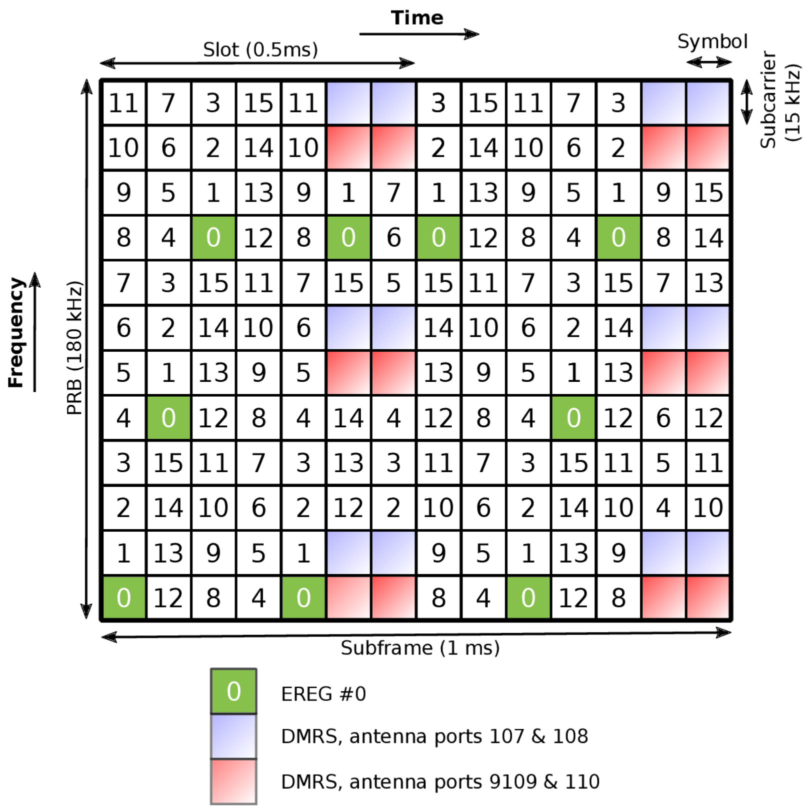


Fig. 3.4: Enhanced resource-element groups (EREGs) for MPDCCH [19].

The bandwidth of MPDCCH spans 2, 4, or 6 PRB pairs. The transmission is either localized or distributed in the ECCE scope. Localized transmission represents EREGs from the same PRB pair are assigned to the same ECCE. On the other hand, distributed transmission allows ECCEs composed of EREGs from different PRB pairs. The advantage of localized transmission is in beam forming or frequency multiplexing MPDCCH with other channels within a narrowband. The distributed transmission excels in frequency diversity.

The MPDCCH supports aggregation of multiple ECCEs to increase coverage. There is 2, 4, 8, 16, or 24 ECCE aggregation for normal subframes and CP length. For example, aggregation level of 24 ECCEs leads to aggregation of all REs in 6 PRB pairs. The decoding order is based on MPDCCH search space, which is described later.

The DCI transmitted through MPDCCH is tailed with 16-bit CRC. The masking sequence of CRC is determined by the *Radio Network Temporary Identifier* (RNTI). The RNTI is a 16-bit number used for addressing one or multiple devices. TBCC coding and rate matching is applied in MPDCCH to match the number of available encoded bits. MPDCCH aggregation level, modulation scheme (QPSK) and unavailable REs have an impact on that number. At last, masking with a scrambling sequence is applied to the MPDCCH transmission and associated DMRS.

Although coverage is enhanced with aggregation, an additional coverage improvement can be achieved with repetitions. Maximum defined number of subframe repetitions is 256 [19].

PDSCH

The primary function of the PDSCH is unicast data transmission. The data from higher layers is segmented into *Tansport Block* (TB)s and transmitted one at a time. Secondary function of the PDSCH is broadcasting system information, paging messages, and random access related messages.

Release 13 introduced modulation and coding schemes with TBS related to CE mode A and B (Tab. 3.2). However, the LTE Cat-M1 devices are restricted to a maximum TBS of 1000 bits. Also, PDSCH is restricted to QPSK only for broadcast and special TBS may apply.

Data in TB is followed by a 24-bit CRC. Standard LTE turbo coding is used with 1/3 code rate, 4 redundancy versions, rate matching, and interleaving. REs before the LTE-M starting symbol and REs occupied by reference signals are not used for PDSCH mapping.

In Release 13, the PDSCH in CE mode A is modulated with QPSK or 16-QAM. The mapping is defined within a narrowband between 1 and 6 PRB pairs. The PDSCH in CE mode B is restricted only to QPSK modulation and mapped to 4 or 6 PRB pairs within a narrowband. The modulation restrictions are supporting the low-cost approach of LTE-M devices and their simple receiver implementations compared to LTE devices supporting at least 64QAM. The maximum number of repetitions is defined by the CE mode A or B. Mode A supports maximum of

Tab. 3.2: PDSCH modulation and coding schemes and transport block sizes in LTE-M (configured with max 1.4 MHz channel bandwidth).

MCS index	**Modulation scheme**	**TBS index**	**Transport block sizes in CE mode A**						**Transport block sizes in CE mode B**	
			# PRB pairs						**# PRB pairs**	
			1	**2**	**3**	**4**	**5**	**6**	**4**	**6**
0	QPSK	0	16	32	56	88	120	152	88	152
1	QPSK	1	24	56	88	144	176	208	144	208
2	QPSK	2	32	72	144	176	208	256	176	256
3	QPSK	3	40	104	176	208	256	328	208	328
4	QPSK	4	56	120	208	256	328	408	256	408
5	QPSK	5	72	144	224	328	424	504	328	504
6	QPSK	6	328	176	256	392	504	600	392	600
7	QPSK	7	104	224	328	472	584	712	472	712
8	QPSK	8	120	256	392	536	680	808	536	808
9	QPSK	9	136	296	456	616	776	936	616	936
10	16QAM	9	136	296	456	616	776	936	Unused	
11	16QAM	10	144	328	504	680	872	1032		
12	16QAM	11	176	376	584	776	1000	1192		
13	16QAM	12	208	440	680	904	1128	1352		
14	16QAM	13	224	488	744	1000	1256	1544		
15	16QAM	14	256	552	840	1128	1416	1736		

32 repetitions and mode B supports up to 2048 repetitions. The CE modes are configurable per cell.

PDSCH in LTE-M inherits some of the original LTE transmission modes.

- TM1: Single-antenna transmission (supported in both CE mode A and B)
- TM2: Transmit diversity (supported in both CE mode A and B)
- TM6: Closed-loop codebook-based precoding (supported in CE mode A only)
- TM9: Non-codebook-based precoding (supported in both CE mode A and B)

LTE-M devices does not support MIMO operation, only a low-cost single receive antenna is expected. Inherited TM2 mode uses SFBC for two antenna ports or a combination of SFBC and FSTD in situation with four antenna ports.

Demodulation of PDSCH uses CRS for TM1, TM2, and TM6 and DMRS for TM9. The scrambling sequence used for PDSCH masking is generated using PCID and RNTI. In case of many repetitions in CE mode B, the same scrambling sequence and redundancy version is used for multiple subframes (4 in FDD and 10 subframes in TDD). Also, using beamforming, the precoding matrix stays the same over multiple subframes specified in the *System Information* (SI) [19].

3.2.3 Uplink physical signals and channels

LTE Cat-M supports limited channels of the legacy LTE physical layer. Reasons for that are mentioned above in 3.1. LTE-M physical layer utilizes *Physical Random Access Channel* (PRACH), *Physical Uplink Shared Channel* (PUSCH), and *Physical Uplink Control Channel* (PUCCH). In case of signals used in uplink, there are reference signals like DMRS and *Sounding Reference Signal* (SRS) to assist with modulation and uplink connection quality [19].

PRACH

The PRACH is responsible for initialization of an uplink connection for the device. It also enables the base station to estimate the time of arrival of uplink transmission. The information is contained within a PRACH preambule.

The configuration of PRACH is defined in LTE as cell-specific, which means the mapping of a signal to a subframe structure has many options defined. The exact mapping configuration is communicated through RRC messages from the base station. In LTE-M, the PRACH has 4 format types depending on the cell requirements. Therefore, the total length of a PRACH preambule varies from 1 ms up to 3 ms.

The CE inherited from LTE-M supports up to 128 repetitions of a PRACH preambule. The exact mapping of the repetitions in the PRACH subframe is defined by the cell-specific configuration. CE mode A supports up to 2 PRACH CE levels and CE mode B up to 4 levels. The network can differentiate each level using different frequencies, different configurations and time intervals, or specific sequences for each preambule group.

Uplink reference signals

- DMRS
- SRS

PUSCH

The PUSCH function is similar to already mentioned PDSCH in 3.2.2 and that is unicast data transmission, but in uplink. Another function of PUSCH is the *Uplink Control Information* (UCI) transmission. The UCI carries scheduling requests, *Channel Quality Indicator* (CQI), or *Hybrid Automatic Repeat Request* (HARQ) information and the transmission is initiated by a request bit in DCI.

Release 13 introduced modulation and coding schemes with TBS related to CE mode A and B. However, the LTE Cat-M1 devices are restricted to a maximum TBS of 1000 bits. Also, PUSCH is restricted to QPSK only for broadcast and special TBS may apply.

Data in TB is followed by a 24-bit CRC. Standard LTE turbo coding is used with 1/3 code rate, 4 redundancy versions, rate matching, and interleaving. PUSCH is mapped to the available SC-FDMA symbols that are not used by DMRS.

In Release 13, the PUSCH in CE mode A is modulated with QPSK or 16-QAM. The mapping is defined within a narrowband between 1 and 6 PRB pairs. The PUSCH in CE mode B is restricted only to QPSK modulation and mapped to 1 or 2 PRB pairs within a narrowband.

The maximum number of repetitions is defined by the CE mode A or B. Mode A supports maximum of 32 repetitions and mode B supports up to 2048 repetitions. The CE modes are configurable per cell.

The scrambling sequence used for PUSCH masking is generated using PCID and RNTI. In case of many repetitions in CE mode B, the same scrambling sequence and redundancy version is used for multiple subframes (4 in FDD and 5 subframes in TDD).

Release 14 and 15 introduced more possibilities and supported features that are not explained but listed below.

- possibility to restrict the PUSCH modulation scheme to QPSK (Release 14)
- support for larger uplink TBS for Cat-M1 (Release 14)
- support for device transmit antenna selection (Release 14)
- PUSCH sub-PRB allocation (Release 15)

PUCCH

The PUCCH is responsible for UCI transmission. The UCI contents are listed below.

- Uplink *Scheduling Request* (SR)
- Downlink HARQ feedback (ACK or NACK)
- Downlink *Channel State Information* (CSI)

The PUCCH transmission is mapped to 1 PRB at the edge of the LTE system bandwidth. PUCCH utilizes inter-subframe frequency hopping between two PRBs with the same distance from the center frequency of the system bandwidth. These PRB pairs are called PUCCH regions and they are configurable. PUSCH is mapped to the available SC-FDMA symbols that are not used by DMRS.

The maximum number of repetitions is defined by the CE mode A or B. Mode A supports maximum of 8 repetitions and mode B supports up to 32 repetitions.

The available PUCCH resource for SR can be used for uplink grant request. If the SR resource is not available, random access procedure is used. Allocation of HARQ feedback resource is done when PDSCH has scheduled a transmission. PUCCH periodically allocates CSI resources based on the RRC configuration.

PUCCH and PUSCH are not able to transmit at the same time. If such transmission is scheduled, then the outcome depends whether repetition is set. No repetition means, that the UCI is multiplexed into PUSCH based on the LTE definition. In PUCCH or PUSCH transmission with repetitions, the PUSCH transmission is dropped in current subframe. In case of PUCCH transmission with repetition and the UCI contains more of the same content type, only the UCI with the highest priority is selected, otherwise the process is driven by the LTE standards.

4 Thesis Results

4.1 Network Simulator 3

This chapter is dedicated to basic overview of simulation tool NS-3 and modules considered for LTE Cat-M1 implementation. These modules are an extension of original LENA module, which provides support of LTE network in NS-3.

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. [36].

4.1.2 LENA module

LENA module is an open-source LTE/EPC simulator developed by *Centre Tecnologic 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 [37].

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 [37].

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 [37].

4.1.3 5G-LENA

A pluggable module developed for NS-3 in early 2019 as a successor of the LENA module. As the old module handled LTE/EPC simulations, the 5G-LENA is focused on NR features. The new module is also developed by a mobile networks group within a public research institute of CCTC [38].

The main focus of 5G-LENA module was an integration of already drafted mmWave module with newly implemented PHY and MAC layer. This means that plenty of new classes are added to this module but the rest of the architecture is inherited from the original LENA module (e.g. RLC, PDCP, RRC). The functionality of the module therefore extends the LENA module with some features from Release 15 [39].

The module does not support any additional features regarding the LTE Cat-M1 technology. Therefore, this module is not more suitable for a new implementation than the previous LENA module. 5G-LENA module contains new NR classes for lower layers but the important new RLC layer implementation is still missing, which is crucial for saving power and extending the battery duration of an UE using LTE Cat-M1 technology.

5G-LENA module is overall a reasonable project following new releases and extending the simulation options to up to 100 GHz channel frequencies. The new features focus on utilizing higher frequencies with wider sub-carrier spacing and corresponding frame structure. The main use case for this module is in testing the behavior of NR or 5G communication between UE and gNB through mm waves [38].

4.1.4 LENA-NB

The LENA-NB module is a project of Communication Networks Institute, TU Dortmund. This module was developed to enable NB-IoT simulations in NS-3. The current state of this module is presented bellow with a comment about usability at the end. The module is still in development and the authors are actively working on further improvements [40].

This module is built on NS-3 version 3.32 and it extends the original LENA module. As mentioned before, this module contains implementation of NB-IoT technology within LENA module. LENA-NB implements new control information structures such as MIB and *System Information Block* (SIB) following the Release 13 regarding NB-IoT. As NB-IoT technology defines new channels, different to the LTE channels, NPRACH channel was implemented to satisfy the random access procedure of NB-IoT [40].

With the mandatory support for repetitions, the original LENA resource scheduler, which handles scheduling resources over a subframe is not suitable for cellular IoT technologies. As NB-IoT needs to keep track of the whole spectrum over multiple subframes to handle repetitions. This was implemented alongside the existing scheduler to ensure the backward compatibility [40].

As the main component of NB-IoT is a connection resume procedure, which is not supported in LENA module, the resume procedure was implemented close to the already implemented setup procedure. Implementation of connection release by LENA is not finished, therefore this module adds to the existing functionality and implements connection release with UE suspended state, as well as connection resume procedure on the eNodeB side [40].

With the implemented suspend state, power saving features could be added as well. The eDRX and PSM is implemented with all the appropriate timers. After an observation of the module, the implementation does not follow the standard defining the message flow between UE and eNodeB. This approach suggests that this feature is not the main focus of the authors and comments with suggested improvements were found throughout the code [40].

This module contains more features related to NB-IoT technology and later 3GPP releases. One of them is an implementation of IoT optimization, which enables the user data to be transmitted over the NB-IoT control plane. Another feature implemented, which was introduced in Release 15 is early data transmission. This feature is used to speed up infrequent small data transmissions with newly implemented mechanism during random access procedure [40].

This contribution to the NS-3 framework is very good for NB-IoT simulation purposes. The scalability of the code is obvious as the contributors add more and more to the existing LENA structure. A closer look at the implementation shows a lot of unfinished methods, which could mean, that the development is still in progress. On the other hand, there have not been many updates since the module was published, so the future of this module remains uncertain.

For the purpose of this thesis, LENA-NB module was closely inspected and reviewed for a possibility of LTE Cat-M1 adaptation. The expectations of usability were suppressed with some experiment modifications, which led to a chain of errors. With the lack of documentation available for this module, there is not much space left for modification.

4.1.5 IDLab NB-IoT

This module is a product of IDLab a joint research initiative between the University of Antwerp and Ghent University. The module was published in 2019. It consists of power saving features (eDRX, PSM) and energy evaluating module. The module was built on NS-3 version 3.29.

PSM and eDRX

The power saving features were briefly introduced in Section 3.1. To understand the implementation of the module, the features need to be explained more in detail.

Both eDRX and PSM are UE features, that working together, are able to save a significant amount of battery. The UE in case of LENA module spends all of the time in RRC connected state, which drains a lot of energy. The use case of IoT enables UEs to disconnect from eNodeB and remain the most of the time in so called sleep state. In this state, the device antenna is inactive, which is the main power consumer.

The eDRX feature is used after the connected state of the UE which allows the device to wake up again in case of any transmission detected. The eDRX state consists of paging occasions in defined intervals called eDRX cycles. For example, eDRX cycle of 25 s will occur 2 times in a 1 minute eDRX state. The important values defining eDRX behavior are the eDRX timer or T3324, the eDRX cycle timer and a *Paging Time Window* (PTW). The standard defines the PTW as increments of 1.28 s (from 1.28 s up to 20.48 s) and it corresponds to a time window in which the UE connects to the paging channel and listens for any incoming transmission. The eDRX cycle is also defined by the standard as minimum 5.12 s and up to 2621 s (44 min.). On the other hand, the T3324 timer has no defined value. The value should be tested and modified for specific use case. Lower value saves more energy as the UE goes to a PSM state faster but higher value allows a communication with the UE (acknowledgements, etc.) for the price of more energy consumed [19, 25].

After the T3324 timer expires, the UE switches to the PSM state. This state represents a sleep state and consumes minimal amount of energy. The UE is unreachable in this state but it can wake up for the uplink transmission, in which case all the timers (eDRX and PSM) reset. The most important parameter of PSM is the T3412 timer. This timer represents the duration of the RRC idle state of the UE. The PSM duration can be calculated as T3412 subtracted by T3324. The standard defines the T3412 between 0 s and 413 days. Different values should be tested for a specific use case and the most suitable value should be chosen [19, 25].

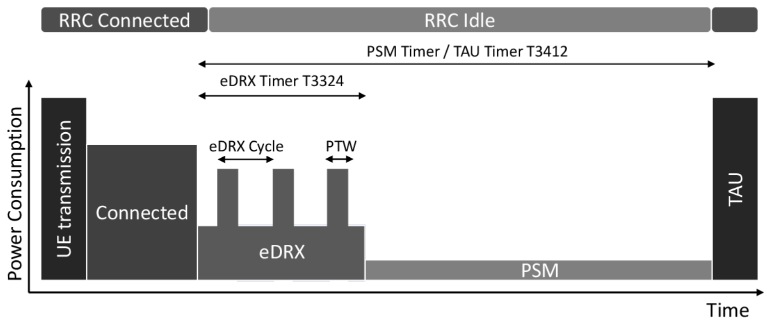


Fig. 4.1: Overview of connection states and energy consumption with PSM and eDRX[19].

After module inspection, changes were made according to LTE Cat-M1 technology. As this module was built on the original LENA module, there were only a few changes identified as NB-IoT related changes. On the figure 4.2, there is an architecture of the LTE protocol stack with modified layers highlighted (orange).

At first the control messages were implemented according to LTE Cat-M1 specification in Release 13. The MIB and SIB message structures were simplified and considered sufficient for the energy evaluation. The authors of this module introduced 4 new states in the RRC layer (IDLE_SUSPEND, IDLE_PAGING, SUSPEND_PAGING, IDLE_PSM), which are used in PSM and eDRX modes. As identified later during simulations, there were one state missing for more accurate energy evaluation. Therefore, CONNECTED_TAU state representing a *Tracking*

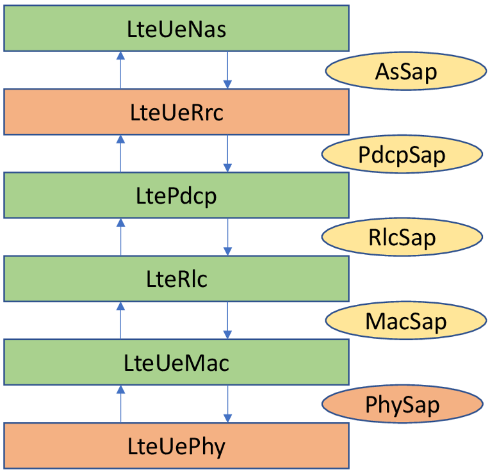


Fig. 4.2: LTE protocol stack (UE)[36].

Area Update (TAU) procedure was added. The RRC layer also defines a behavior of each state with corresponding timers. All these changes are implemented on the UE side. The eNodeB is extended only with CONNECTION_SUSPEND and CONNECTION_PSM states which are assigned to each UE accordingly [41].

The UE physical layer introduces 2 more queues to the original LENA module. Both queues are implemented to store data (user and control), while the device is suspended. Also, the reception of the control messages is modified on this layer to support the new MIB and SIB messages. The module was further modified to support TBS according to LTE Cat-M1 standard [41].

4.2 Simulations

In this section, the simulation scenarios are listed and described. The first simulation was focused on the original LENA module limitations for the number of UEs. After experimenting with other modules described earlier in this chapter, the focus shifted to energy evaluation of PSM and eDRX states. The simulations were running on modified IDLab NB-IoT module.

4.2.1 Increased number of devices

Simulation scenario of an LTE network is implemented using original LENA module, 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 as the goal is to only observe the peak data rate over a short time period with delay and eventually packet loss.

First simulation is focused on increasing the number of UEs to a maximum possible number that LENA module and NS-3 can handle. For this purpose, two scenarios are created to demonstrate the difference and compare the results.

In the fist scenario, 10 UEs are connected to a single eNodeB. The aim of this simulation is to gather reference data of the LTE network handling small number of devices. Data rate, delay, and packet loss are monitored after the initiation occurs with the focus on high traffic generation from UEs to eNodeB.

The second scenario is extended for a communication of 300 UEs with a single eNodeB. As more than 300 UEs reach the limit of LENA module. The simulation for more than 300 devices show inconsistent initiation often leading to errors in simulation. The LENA module is limited by the eNodeB implementation which cannot handle the enormous traffic of more than 300 UEs. The topology of both simulation scenarios is shown in the image bellow.

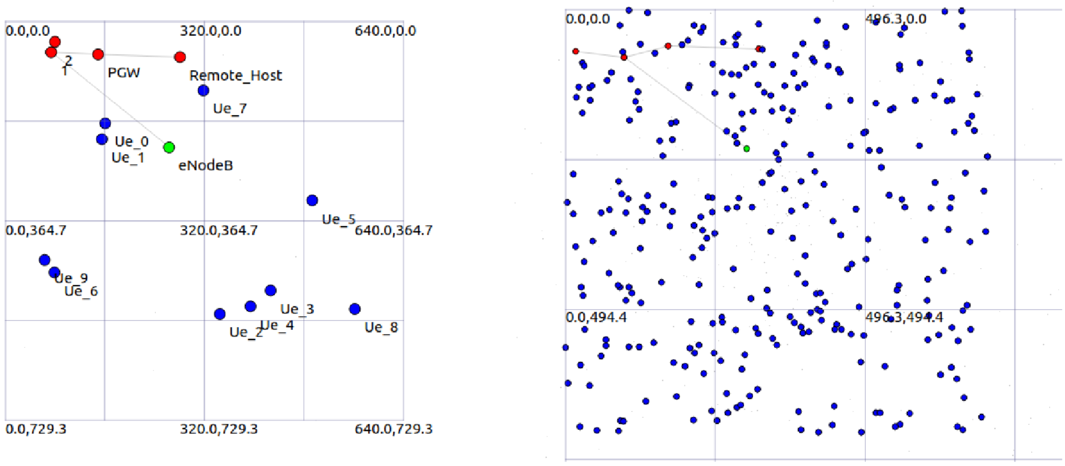
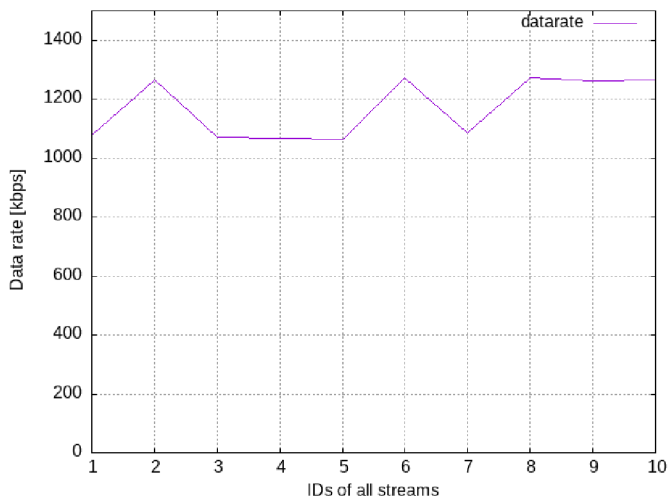
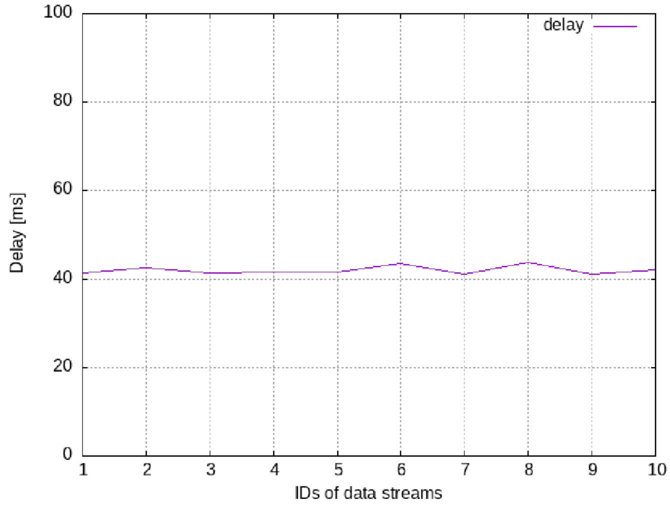


Fig. 4.3: Topology of the initial (left) and extended (right) scenarios

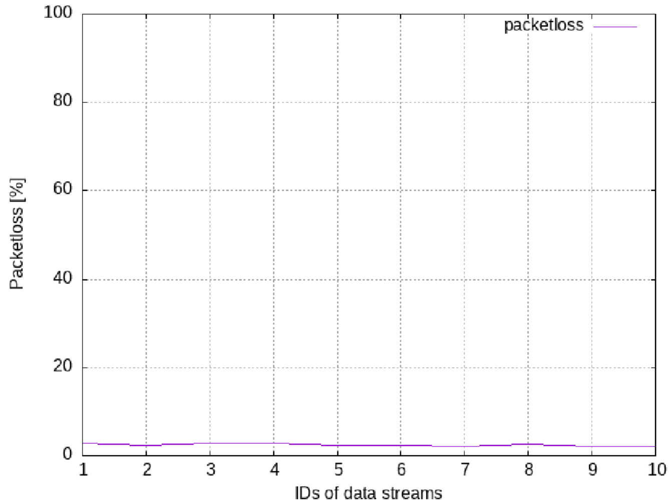
In the topology above, there are visible entities of EPC but the traffic there is not monitored as the focus is on RAN. The results on the next page represent a state of an LTE network after established connection of the UEs.



(a) Data rate

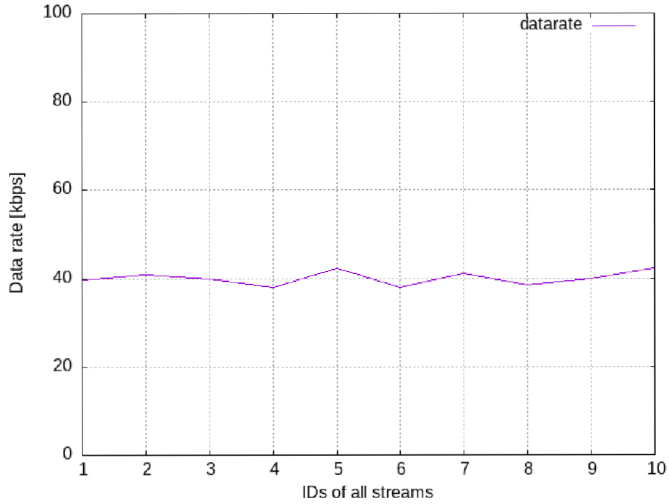


(b) Delay

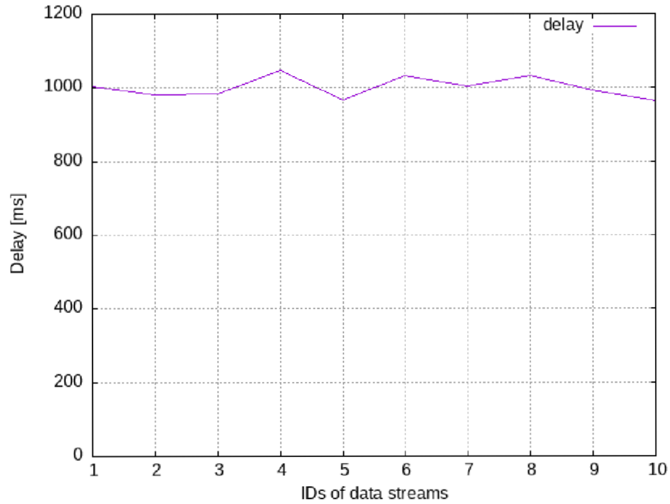


(c) Packet loss

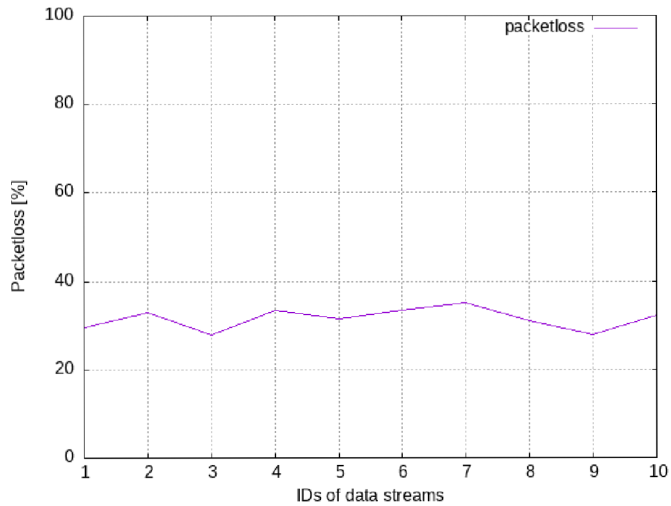
Fig. 4.4: Results from the initial scenario simulation



(a) Data rate



(b) Delay



(c) Packet loss

Fig. 4.5: Results from the extended scenario simulation

4.2.2 Energy evaluation

This simulation scenario is implemented on IDLab NB-IoT module with modifications for LTE Cat-M1 technology. The simulation defines several timers for PSM and eDRX. First, T3324 timer representing the duration of the eDRX state. Second, eDRX cycle duration, which defines how many paging occasions will occur during the eDRX state. Third, T3412 timer defined as a duration of both eDRX and PSM states. As a custom energy module is defined over the UE states, monitoring of the energy consumption is possible for any scenario.

First simulation is about how often does a UE wake up for transmission and how a different PSM (T3412) timer values change the energy consumption. The simulations ran for 24 hours with a constant values of other (T3324 and eDRX cycle) timers. The results are shown in the table and represented in a figure bellow.

Tab. 4.1: Results of energy consumption [J] for different UL intervals and PSM timers

PSM timer / ***UL interval***	**1**	**3**	**6**	**12**	**24**
1	20.251	20.251	20.251	20.251	20.251
2	11.546	11.250	11.250	11.250	11.250
6	5.743	5.348	5.250	5.250	5.250
12	4.292	3.897	3.799	3.749	3.749
24	3.567	3.172	3.073	3.024	2.996

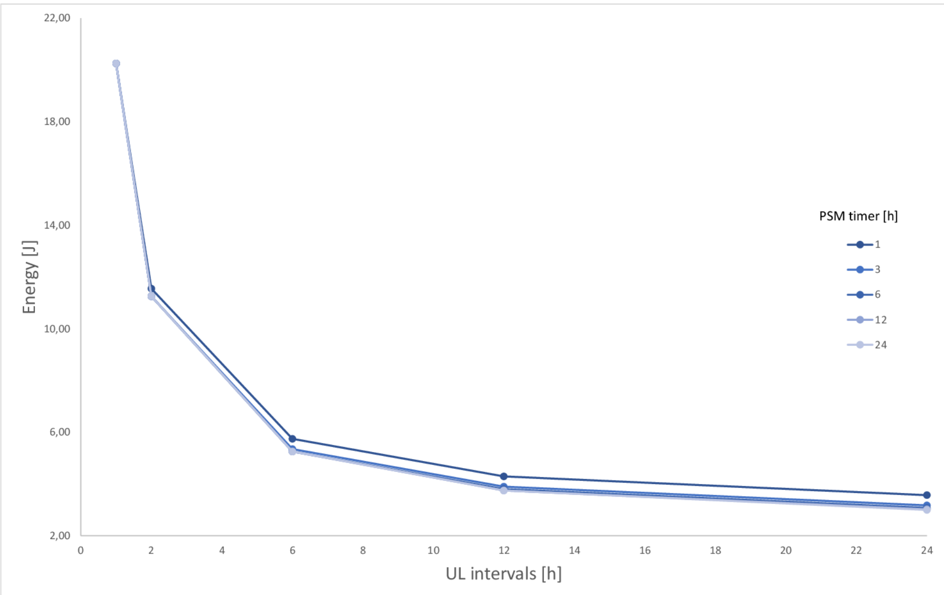


Fig. 4.6: Energy consumption based on different UL intervals and PSM timers

The goal of the second simulation is to show the importance of choosing the right combination of parameters (T3324, T3412). The results are shown in the table and displayed in a figure bellow. The results were further extrapolated to acquire the estimate battery lifetime of a 18000 J standard battery. The simulation time is 24 hours with a constant eDRX cycle of 25 s.

Tab. 4.2: Results of energy consumption [J] for different PSM and eDRX timers

eDRX timer [min] **PSM timer [h]**	**0.5**	**1**	**2**	**4**	**6**
1	3.376	3.567	3.949	4.859	5.770
2	3.176	3.271	3.462	3.918	4.373
3	3.109	3.173	3.300	3.603	3.907
4	3.075	3.123	3.219	3.446	3.674
5	3.052	3.090	3.167	3.341	3.515
6	3.041	3.073	3.137	3.289	3.441
8	3.025	3.049	3.097	3.211	3.325
10	3.015	3.031	3.069	3.161	3.244
12	3.008	3.024	3.056	3.132	3.208
18	3.008	3.024	3.056	3.132	3.208
24	2.991	2.999	3.015	3.053	3.091

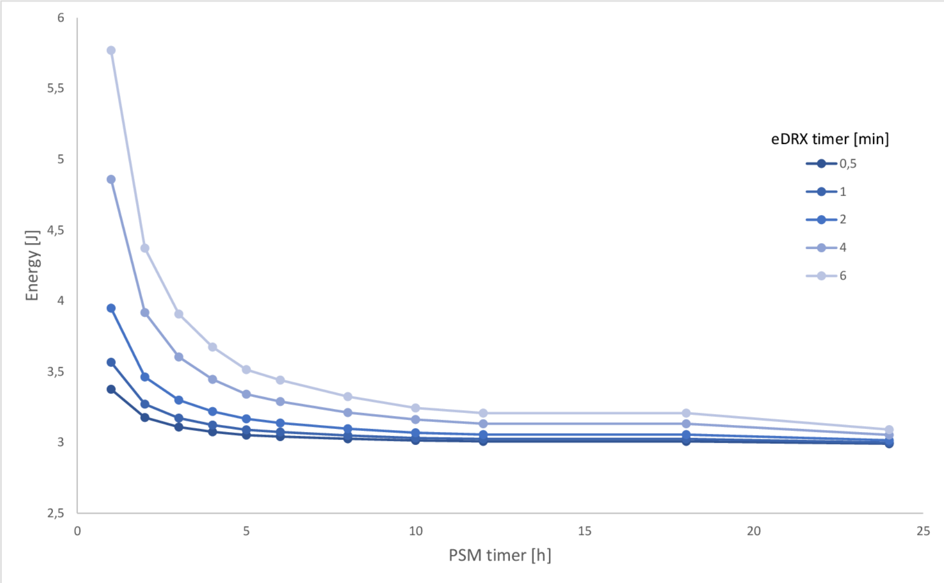


Fig. 4.7: Energy consumption based on different PSM and eDRX timers

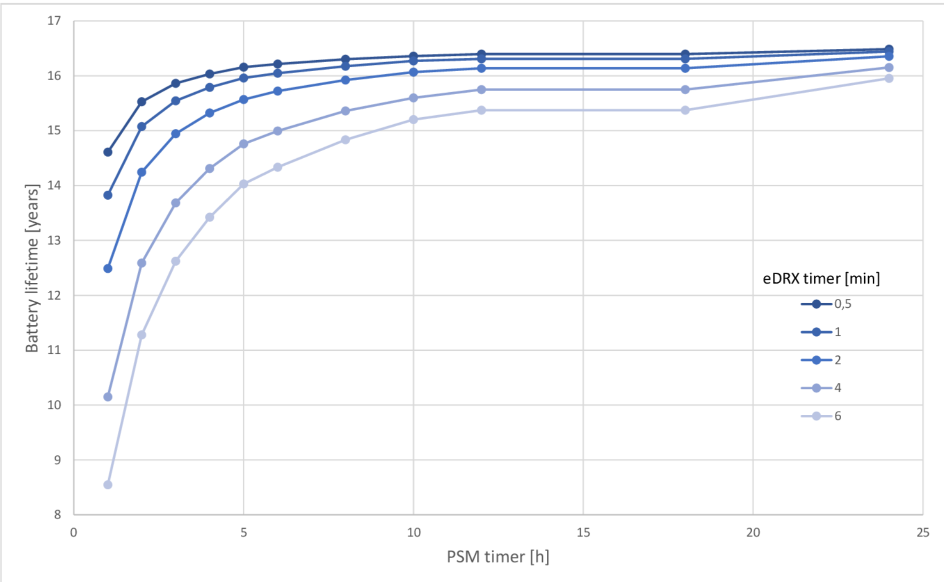


Fig. 4.8: Estimated lifetime of a battery based on defined timer values

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 *Internet of Things* (IoT) market, there has been adaptations of implemented technologies to support the still rising *Machine to Machine* (M2M) communication. The new generations of broadband cellular networks provide more support for M2M communication and even support the *Massive Machine-Type Communications* (mMTC) use case. One of the solutions to the mMTC are *Low-Power Wide-Area* (LPWA) technologies. They provide a significantly extended communication range in a reasonable price range. Each LPWA technology excel in slightly different field, e.g. *NarrowBand IoT* (NB-IoT) is good for small infrequent data transmissions in deep indoors or LTE Cat-M supports *Voice over LTE* (VoLTE) and higher data rates. They both use licensed frequency spectrum for transmission.

Nowadays, the deployment of the fifth generation is currently being implemented in the *Non-Standalone Architecture* (NSA) mode, i.e., options 3 and 3x. The *Standalone Architecture* (SA) is planned to be the major implementation in the upcoming years, therefore the focus is on previous generation, *Long Term Evolution* (LTE). The limits of the LTE network design are simulated using *Network Simulator 3* (NS-3). The tests performed according to the *The 3rd Generation Partnership Project* (3GPP) Release 8-10 with 10 connected devices to a single *E-UTRAN Node B* (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 *Transmission Control Protocol* (TCP) connection. On the other hand, the extended scenario with 300 *User Equipment* (UE)s 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 at the beginning of execution.

The second simulation scenario was focused on testing different timer values and UL intervals and their energy consumption. The first test unit demonstrates the insignificant effect of power saving features, when the UE transmits data frequently. The actual values of the *Extended Discontinuous Reception* (eDRX) and *Power Saving Mode* (PSM) timers are less important as the UE wakes up before the timers expire. The effect is displayed in Tab. 4.1, as the values of specific UL interval do not change rapidly for different PSM timer values. Maximal energy consumption difference of 16 % is achieved for the longest UL interval (24 h.). The conclusion from the testing is that PSM and eDRX is most efficient in use cases with infrequent data transmission. The second testing unit was performed to understand the relation between energy consumption and different timers. The results in Fig. 4.7 show daily energy consumption of a UE. Longer eDRX duration significantly decreases battery lifetime. Also, it is recommended to set up the eDRX timer lower than 10 % of PSM timer. Following the recommendation, the energy consumption falls bellow 3.5 J per day. Extrapolating the daily consumption in Fig. 4.8, the simulation also confirms the expected battery lifetime of LTE Cat-M devices exceeds 10 years with properly set up power saving features.

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. The power saving features (PSM and eDRX) are important for cellular IoT technologies and their implementation is not yet officially implemented in NS-3. Only a few research projects have been working on implementation of these features and the cellular technology itself. Projects or modules included in this thesis are a promising start for proper simulation of LTE Cat-M or NB-IoT.

Bibliography

[1] GSMA. About Us. https://www.gsma.com/aboutus/. [Online].

[2] 3GPP. The 3rd Generation Partnership Project. https://www.3gpp.org/. [Online].

[3] 3GPP. Releases. https://www.3gpp.org/specifications/67-releases. [Online].

[4] 3GPP. Work Plan. https://www.3gpp.org/specifications/work-plan. [Online].

[5] G. Sébire M. Saily and E. Riddington. *GSM/Edge : Evolution and Performance*. Wiley, 2010.

[6] M. Štůsek. *Research on Reliable Low-Power Wide-Area Communications Utilizing Multi-RAT LPWAN Technologies for IoT Applications*. PhD thesis, Brno University Of Technology, 2021.

[7] ETSI. Mobile Technologies. https://www.etsi.org/technologies/mobile. [Online].

[8] J. Romero T. Halonen and J. Melero. *GSM, GPRS and EDGE Performance: Evolution Towards 3G/UMTS*. Wiley, 2004.

[9] M. Condoluci and T. Mahmoodi. Softwarization and Virtualization in 5G Mobile Networks: Benefits, Trends and Challenges. *Computer Networks*, vol. 146:pp. 65–84, 2018.

[10] ITU-R. FAQ on International Telecommunications (IMT). https://www.itu.int/en/ITU-R/Documents/ITU-R-FAQ-IMT.pdf. [Online].

[11] 3GPP. Bands Applicability in RSRP, RSRQ FDD-FDD Inter Frequency Tests for 5MHz Bandwidth. Technical report, 3GPP, November 2013.

[12] A. Toskala H. Holma and J. Reunanen. *LTE Small Cell Optimization: 3GPP Evolution to Release 13*. John Wiley & Sons, 2016.

[13] S. Parkvall E. Dahlman and J. Skold. *4G: LTE/LTE-Advanced for Mobile Broadband*. Elsevier Science, 2011.

[14] J. Penttinen. *5G Explained: Security and Deployment of Advanced Mobile Communications*. Elsevier Science, 2011.

[15] X. Lin and N. Lee. *5G and Beyond: Fundamentals and Standards*. Springer International Publishing, 2021.

[16] ITU-R. IMT Vision - Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond. Technical Report M.2083, ITU-R, September 2015.

[17] GSMA. Road to 5G: Introduction and Migration. Technical report, GSMA, April 2018.

[18] GSMA. Operator Requirements for 5G Core Connectivity Options. Technical report, GSMA, May 2019.

[19] O. Liberg, M. Sundberg, E. Wang, J. Bergman, J. Sachs, and G. Wikström. *Cellular Internet of Things: From Massive Deployments to Critical 5G Applications*. Mara Conner, 2 edition, 2020.

[20] 3GPP. LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding. Technical Report TS 36.212, 3GPP, October 2018.

[21] J. L. Aufranc. A Look at LoRaWAN and NB-IoT Power Consumption. `https://www.cnx-software.com/2018/03/29/a-look-at-lorawan-and-nb-iot-power-consumption`. [Online].

[22] 3GPP. Cellular System Support for Ultra-Low Complexity and Low Throughput Internet of Things. Technical Report TR 45.820, 3GPP, August 2016.

[23] 3GPP. Study on Self Evaluation Towards IMT-2020 Submission. Technical Report TR 37.910, 3GPP, March 2018.

[24] 3GPP. Study on Provision of Low-Cost Machine-Type Communications (MTC) User Equipments (UEs) Based on LTE. Technical Report TR 36.888, 3GPP, Jun 2013.

[25] Ericsson, Sierra Wireless. IMT-2020 Self-Evaluation: mMTC Coverage, Data Rate, Latency and Battery Life. Technical Report R1-1903119, Ericsson, Sierra Wireless, March 2019.

[26] Cisco. Cisco Annual Internet Report (2018–2023). Technical Report C11-741490-01, Cisco, March 2020.

[27] ETSI. Study on Scenarios and Requirements for Next Generation Access Technologies (3GPP TR 38.913 Release 15). Technical Report TR 138 913 V15.0.0, ETSI, September 2018.

[28] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer. A Comparative Study of LPWAN Technologies for Large-Scale IoT Deployment. *ICT Express*, vol. 5, 2019.

[29] Ch. Kuhlins, B. Rathonyi, A. Zaidi, and M. Hogan. Cellular Networks for Massive IoT. Technical Report Uen 284 23-3278, Ericsson, January 2020.

[30] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi. Internet of Things for Smart Cities. *IEEE Internet of Things Journal*, vol. 1(no. 1):pp. 22–32, 2014.

[31] S. Chung. Applications of Smart Technologies in Logistics and Transport: A Review. *Transportation Research Part E: Logistics and Transportation Review*, vol. 153, 2021.

[32] A. Majumder, Y. ElSaadany, R. Young, D. Ucci, and M. Rebaudengo. An Energy Efficient Wearable Smart IoT System to Predict Cardiac Arrest. *Advances in Human-Computer Interaction*, 2019:pp. 1–21, 2019.

[33] F. Khan, M. Jan, and M. Alam. *Applications of Intelligent Technologies in Healthcare*. Springer, 2019.

[34] F. Dian, R. Vahidnia, and A. Rahmati. Wearables and the Internet of Things (IoT), Applications, Opportunities, and Challenges: A Survey. *IEEE Access*, vol. 8:69200–69211, 2020.

[35] 3GPP. Evolved Universal Terrestrial Radio Access (E-UTRA), Multiplexing and Channel Coding. Technical Report TS 36.212, 3GPP, 2019.

[36] Nsnam. NS-3 Documentation. `https://www.nsnam.org/documentation/`. [Online].

[37] R. Drápela. Implementation of Communication Technology LTE Cat-M1 Utilizing the Network Simulator 3. Master's thesis, Brno University of Technology, 2018.

[38] N. Patriciello, S. Lagen, B. Bojovic, L. Giupponi. NR-U and IEEE 802.11 Technologies Coexistence in Unlicensed mmWave Spectrum: Models and Evaluation. *IEEE Access*, 8:71254–71271, 2020.

[39] M. Mezzavilla, M. Zhang, M. Polese, R. Ford, S. Dutta, S. Rangan, and M. Zorzi. End-to-End Simulation of 5G mmWave Networks. *IEEE Communication Surveys and Tutorials*, 20(3):2237–2263, 2018.

[40] J. Pascal, T. Gebauer, and C. Wietfeld. From LENA to LENA-NB: Implementation and Performance Evaluation of NB-IoT and Early Data Transmission in Ns-3. In *Proceedings of the 2022 Workshop on Ns-3*, WNS3 '22, page 73–80, New York, NY, USA, 2022. Association for Computing Machinery.

[41] A. Sultania, C. Delgado, and J. Famaey. Implementation of NB-IoT Power Saving Schemes in ns-3. In *Workshop on Next-Generation Wireless with ns-3*, 2019.

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
GPRS	General Packet Radio Services
EDGE	Enhanced Data for Global Evolution
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
WLAN	Wireless Local Area Network
QoS	Quality of Service
VoIP	Voice over IP
HSPA+	Evolved High Speed Packet Access
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
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
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
QAM	Quadrature Amplitude Modulation
EPC	Evolved Packet Core
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
RNC	Radio Network Controller
MTC	Machine Type Communication
M2M	Machine to Machine
IoT	Internet of Things

TDD	Time Division Duplex
FDMA	Frequency Division Multiple Access
SC-FDMA	Single Carrier-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
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
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
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 Tecnologic 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
MPDCCH	MTC Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PBCH	Physical Broadcast Channel
DCI	Downlink Control Information
MWUS	MTC Wake-Up Signal
PSS	Primary Synchronization Signal
SSS	Secondary Synchronization Signal
RSS	Resynchronization Signal
CRS	Cell-specific Reference Signal
DMRS	Demodulation Reference Signal
PRS	Positioning Reference Signal
PCID	Physical Cell Identity
MIB	Master Information Block
TTI	Transmission Time Interval
CRC	Cyclic Redundancy Check

TBCC	Tail-Biting Convolutional Code
SFBC	Space-Frequency Block Coding
FSTD	Frequency-Switched Transmit Diversity
EPDCCH	Enhanced Physical Downlink Control Channel
EREG	Enhanced Resource Element Group
ECCE	Enhanced Control Channel Elements
RNTI	Radio Network Temporary Identifier
SI	System Information
TB	Tansport Block
OTDOA	Observed Time Difference of Arrival
LPP	LTE Positioning Protocol
E-SMLC	Evolved Serving Mobile Location Center
PRACH	Physical Random Access Channel
PUSCH	Physical Uplink Shared Channel
PUCCH	Physical Uplink Control Channel
UCI	Uplink Control Information
SR	Scheduling Request
CSI	Channel State Information
CQI	Channel Quality Indicator
TAU	Tracking Area Update
PTW	Paging Time Window

List of appendices

A Content of the electronic attachment

The electronic attachment contains all files needed for simulations discussed in this thesis with raw and exported results for preview. The attachment is an archive of NS-3 program (version 3.29) available from the official NS-3 website. The program contains too many files to list them in this section therefore, only folders and files related to this project are included in the list bellow.

NS-3 uses *waf* tool for easy compiling and execution of simulation scenarios. Execution and simulation was handled within Linux default terminal. The process consists of configuration, compilation and execution and the example commands are shown bellow.

```
./waf configure --disable-python
./waf build
./waf --run scratch/<<scenario-filename>>
```

```
/ ........................................ root of the attached archive
├── bake ................................. compilation tool
├── netanim-3.108 ........................ simulation traffic/topology generator
├── ns-3.29 .............................. simulation environment
│   ├── build ............................ built and executable files
│   ├── scratch .......................... simulation scenario folder
│   │   ├── lte-full.cc .................. device numbers simulations
│   │   └── third-psm.cc ................. energy consumption simulations
│   ├── scripts
│   │   └── sim_script.sh ................ example script for longer simulations
│   ├── results
│   │   ├── simulation_outputs ........... raw output files
│   │   └── outputs ...................... visual output representation
│   ├── src .............................. source codes of all modules
│   │   └── lte .......................... modified LENA module
│   │       ├── lte-ue-rrc.cc ............ UE RRC layer
│   │       ├── lte-enb-rrc.cc ........... eNodeB RRC layer
│   │       ├── lte-control-messages.cc .. control message definitions
│   │       ├── M1-lte-rrc-sap.h ......... LTE Cat-M1 message definitions
│   │       ├── lte-spectrum-phy.cc ...... UE physical layer handling transmission
│   │       ├── lte-ue-phy.cc ............ UE physical layer handling data processing
│   │       └── lte-enb-phy.cc ........... eNodeB physical layer handling data processing
│   └── changes.txt ...................... overview of the main implementation
└── pybindgen-0.21.0 ..................... python support package
```