Narrowband LTE in Machine to Machine Satellite Communication

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ABSTRACT OF THE MASTER'S THESIS

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Recent trends to wireless Machine-to-Machine (M2M) communication and Internet of Things (IoT) have created a new demand for more efficient low-throughput wireless data connections. Beside the traditional wireless standards, focused on high bandwidth data transfer, has emerged a new generation of Low Power Wide Area Networks (LPWAN) which targets for less power demanding low-throughput devices requiring inexpensive data connections.

Recently released NB-IoT (Narrowband IoT) specification extends the existing 4G/LTE standard allowing easily accessible LPWAN cellular connectivity for IoT devices. Narrower bandwidth and lower data rates combined to a simplified air interface make it less resource demanding while still benefiting from the widely spread LTE technology and infrastructure. Applications, such as wide scale sensor or asset tracking networks, can benefit from a global scale network coverage and easily available low-cost user equipment which could be made possible by new narrowband IoT satellite networks.

In this thesis, the NB-IoT specification and its applicability for satellite communication is discussed. Primarily, LTE and NB-IoT standards are designed only for terrestrial use. Their utilization in Earth-to-space communication raises new challenges, such as timing and frequency synchronization requirements when utilizing Orthogonal Frequency Signal Multiplexing (OFDM) techniques. Many of these challenges can be overcome by specification adaptations and other existing techniques making minimal changes to the standard and allowing extension of the terrestrial cellular networks to global satellite access.

Keywords: Machine Type Communication, Internet of Things, Cellular IoT, NB-IoT, LTE, Satellite Communication

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Viimeaikaiset kehitystrendit koneiden välisessä kommunikaatiossa (Machine to Machine Communication, M2M) ja esineiden Internet (Internet of Things, IoT) -sovelluksissa ovat luoneet perinteisteisten nopean tiedonsiirron langattomien standardien ohelle uuden sukupolven LPWAN (Low Power Wide Area Networks) -tekniikoita, jotka ovat tarkoitettu pienitehoisille tiedonsiirtoa tarvitseville sovelluksille.

Viimeaikoina yleistynyt NB-IoT standardi laajentaa 4G/LTE standardia mahdollistaen entistä matalamman virrankulutuksen matkapuhelinyhteydet IoT laitteissa. Kapeampi lähetyskaista ja hitaampi tiedonsiirtonopeus yhdistettynä yksinkertaisempaan ilmarajapintaan mahdollistaa pienemmät resurssivaatimukset saman aikaan hyötyen laajalti levinneistä LTE teknologioista ja olemassa olevasta infrastruktuurista. Useissa sovelluskohteissa, kuten suurissa sensoriverkoissa, voitaisiin hyötyä merkittävästi globaalista kattavuudesta yhdistettynä edullisiin helposti saataviin päätelaitteisiin.

Tässä työssä käsitellään NB-IoT standardia ja sen soveltuvuutta satellittitietoliikenteeseen. LTE ja NB-IoT ovat kehitty maanpääliseen tietoliikenteeseen ja niiden hyödyntäminen avaruuden ja maan välisessä kommunikaatiossa aiheuttaa uusia haasteita esimerkiksi aika- ja taajuussynkronisaatiossa ja OFDM (Orthogonal Frequency Signal Multiplexing) -tekniikan hyödyntämisessä. Nämä haasteet voidaan ratkaista soveltamalla spesifikaatiota sekä muilla jo olemassa olevilla tekniikoilla tehden mahdollisimman vähän muutoksia alkuperäiseen standardiin, ja täten sallien maanpäälisten IoT verkkojen laajenemisen avaruuteen.

Avainsanat: Koneiden välinen kommunikaatio, Esineiden Internet, Cellular IoT, NB-IoT, LTE, Satelliittitietoliikenne

Contents

Abbreviations

3GPP	3^{rd} Generation Partnership Project
4G	4^{th} Generation Mobile Communication Technology
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CIoT	Cellular IoT
CP	Cyclic Prefix
dBm	Power in decibels (dB) referenced to one milliwatt (mW)
DMRS	Demodulation Reference Signal
DL	Downlink
DVB-S2	Digital Video Broadcasting - Satellite - Second Generation
eNB or eNodeB	Evolved Node B, LTE basestation
E-UTRA	Evolved Universal Terrestrial Radio Access
GEO	Geostationary Earth Orbit (35 786 kilometers)
HARQ	Hybrid Automatic Repeat reQuest
ICI	Inter Carrier Interference
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of the Things
ISI	Inter Symbol Interference
ITU-R	The Radiocommunication sector of the International Telecommunication Union
kbps	Kilobits per second
Ku-band	Ku frequency band according to IEEE standard (12 to 18 GHz)
LPWAN	Low-Power Wide-Area Network
LTE	Long Term Evolution
LTE-A	LTE-Advanced
LTE-M	LTE Category-M specification for Machine Type Communication
M2M	Machine to Machine
MAC	Media/Medium Access Control
Mbps	Megabits per second
MTC	Machine-Type Communication
NAS	Non-stratum Access
NB-IoT	Narrowband Internet of Things
NPBCH	Narrowband Physical Broadcast Channel
NPDSCH	Narrowband Physical Downlink Shared Channel
NPRACH	Narrowband Physical Random Access Channel
NPSS	Narrowband Primary Synchronization Signal
NPUSCH	Narrowband Physical Uplink Shared Channel
NSSS	Narrowband Secondary Synchronization Signal
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PAPR	Peak-to-Average Power Ratio
PDU	Protocol Data Unit
PDCP	Packet Data Convergence Protocol

PRB	Physical Resource Block
PSK	Phase Shift Keying
QoS	Quality of Service
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RRC	Radio Resource Control
RLC	Radio Link Control
S-band	S frequency band according to IEEE standard (2 to 4 GHz)
SC-FDMA	Single Carrier Frequency Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UHF	Ultra High Frequency -band (according to IEEE standard 300 - 1000 MHz)
UL	Uplink
UMTS	Universal Mobile Telecommunications System

1 Introduction

This chapter is an introductory chapter for the general topic, the main concepts and the motivation for the work. The second half of the chapter describes the general objective and the structure of the thesis for guidance.

1.1 Motivation

During the last two decades, the worldwide multiplication of connected devices has been driven by the growth of the personal mobile phone market. In urban areas, wireless communication networks have grown larger, offering high throughput connections for data-demanding customers. Recently, this trend has entered a new phase, offering even higher data rate connections to each user and enabling multiple connected devices for various applications. From recent development, it has been estimated that there will be over 50 billion connected devices by 2020 [1].

These so-called smart devices and Internet of Things (IoT) -devices base their functionalities on connectivity to a host device and Internet service infrastructure, instead of relying on classical human-intervention. To achieve connectivity, these devices use ad-hoc or infrastructural networks, built for machine communication. These less human-centric wireless communication protocols, designed for raw data transfer, have led to more packet and data-driven communication, creating new needs for the communication protocols. These IoT applications cover security, tracking, payment, smart grid, and remote maintenance and monitoring services, among others.

Fundamentally, the concept of the Internet of Things refers to the interconnection and exchange of data among new types of physical devices, or devices which traditionally have not been connected to an infrastructure network. The connection to the Internet may be a direct connection utilizing Internet protocols, or an indirect connection via a host device, with only the essential information being exchanged between the IoT device and the host service. In both cases the data from the device is available via Internet service, enhancing device's functionalities. The transferred information can be, for example, sensor or control data from individual devices, and an Internet service can be used to collect and process data streams from multiple devices.

This device-centric communication, also called Machine-to-Machine (M2M), communication in IoT architectures, differs from classical interpersonal communication, where high data rate voice, video and formatted text have been most relevant. The increasing amount of connected devices has pushed existing communication standards ever further; these need to evolve to support higher device densities, and new applications with requirements for high throughput, high availability and low power consumption. These new requirements and applications require new M2M communication standards, moving the focus off previous standards, developed mainly for human-oriented communication.

For infrastructure solutions where connectivity is needed regardless of the device location, the mobile cellular network has been the only widely-spread commercial infrastructure in use. However, recent for development of new Low Power Wide Area

Network (LPWAN) standards aims to create new optimized communication infrastructure for low-powered, intermittently-connected devices with limited capabilities.

The 4th generation mobile communication standard Long-Term Evolution (LTE) technology, launched in the early 2010's, is the current encompassing wireless technology designed for low-latency, high data rate terrestrial use. Competition on new LPWAN standards has also initiated cellular specifications to evolve towards new M2M requirements; cellular networks built for mobile communication are currently used for IoT communication. This trend is referred to as Cellular IoT (CIoT); its advantage is to rely on already existing infrastructure, contrary to other LPWAN technologies. Narrowband-IoT (NB-IoT) is the LTE standard's solution for increasing M2M communication demands and need of LPWAN technologies. [31]

Since the beginning of the satellite industry in 1960s, satellites have been the ultimate medium to achieve global coverage on the remote sensing and telecommunication markets. This global coverage comes at the considerable expense of building a satellite infrastructure. Communication with currently existing satellite infrastructures requires dedicated electronics, making the ground terminals and data transfer over the network expensive. So far, M2M applications over satellite infrastructures have been limited by available capacity and price.

As a result of the growing IoT trend, and the increasing accessibility of space, the concept of space-enabled IoT has emerged, and shows promise for numerous applications (e.g. positioning, communication, etc...). The association of global satellite technology with IoT applications could produce new innovative application possibilities. This work aims to investigate the feasibility of satellite M2M communication, using the existing infrastructural NB-IoT standard.

1.2 Objective of the Thesis

The objective of this work is to investigate the applicability of cellular mobile standards - in particular the Narrowband LTE for IoT (NB-IoT) specification - to Earth-to-space Machine-to-Machine (M2M) communication, and the opportunities for new and existing IoT applications. This thesis analyzes the low-level physical interfaces of the NB-IoT and cellular LTE specifications and reviews the difficulties in adapting these protocols for ground-to-space communication. Finally, the concept of using cellular satellite network in M2M communication and the inherent technical challenges, and the possibility of achieving affordable communication networks using small satellites are discussed.

1.3 Structure of the Thesis

In the second chapter the concepts of Internet of Things, Machine Type Communication and Low-Power Wide Area Networks (LPWAN) are discussed in detail from the perspective of communication networks. Several commonly-used LPWA networks and the design drivers of Machine-to-machine (M2M) communication standards are covered.

The third chapter introduces the general history, basics and challenges of satellite communication and existing types of satellite communication services and their characteristics are described.

In the fourth chapter the LTE standard is covered, with a focus on its main architecture, air interface features, and the fundamentals of its signal modulation techniques.

In the fifth chapter, NB-IoT is introduced as a variant of the LTE specification, with a focus on its air interface features. Most of the LTE features are approached from the perspective of the NB-IoT specification, due to the vast extent of the LTE feature set.

In the sixth chapter, the concept of satellite NB-IoT base station for M2M communication is introduced; possible approaches are analyzed, along with the challenges they present.

Finally, the thesis concludes on the applicability of NB-IoT to satellite communication, and possible future technical solutions and improvements are discussed.

2 Internet of Things

This chapter gives a brief practical background on Internet-of-Things (IoT) application concepts, and their requirements with regards to communication standards. The discussion is then expanded to Machine-Type Communication (MTC) and Machine-to-Machine (M2M) communication, Low-Power Area Networks (LWPAN) and Cellular IoT -concepts. The final section discusses the advantages of various space assets for IoT applications.

2.1 The Internet of Things -trend

Over the past few years, the number of consumer Internet of Things applications has been increasing. It has been estimated that up to 50 billion connected devices will be connected in 2020 [1]. The so-called "IoT trend" can be summed up as a trend to increasingly connect hardware to the Internet, instead of increasing the connectivity between people.

IoT applications are not about making the devices themselves smarter, but rather about connecting devices to the Internet and to cloud services to enhance their feature set. While the connection does not have to be wireless, this approach is generally favoured as it is more convenient for the end user. New innovative IoT applications stretch the capabilities of existing communication techniques, requiring for example ultra low-power, inexpensive communication solutions. These requirements represent challenges for existing cellular and wireless local area networks, which have been designed according to different application requirements. [3]

The possible target IoT applications are numerous; the fields of buildings, energy, consumer & home, healthcare & life-science, industry, transportation, retail, security/public safety, IT & networks could all benefit from IoT-derived services. A range of such possible applications are shown in Figure 1, illustrating the wide diversity of the field. In most applications, the main purpose of IoT applications is remote data collection and remote access - for example, measuring devices monitoring electricity, gas, or water consumption and Industrial Internet applications. In these application the device is commonly considered as a stationary and movement between network nodes or optimized client handover to ensure unbroken connection, are not considered in protocol design. Partial and non-continuous connection can be accepted and short term discontinuities have only little affect on the quality of service. Depending on the application, the base devices may either be very densely concentrated (over 100 000 users per km^2 in urban areas), or sparsely disseminated in a wide-coverage infrastructure, using as few base stations as possible.

The most remarkable technical challenge for IoT applications is probably the increasing number of devices, also known as Massive IoT. Additionally, embedded applications push towards smaller devices, which in many cases cannot be powered from the grid. IoT devices are in many cases powered by batteries, and limited by the amount of available power and other resources. [3]

Due to limited size and power the device must implement many features in data processing communication to extend its lifetime and achieve reasonable operations

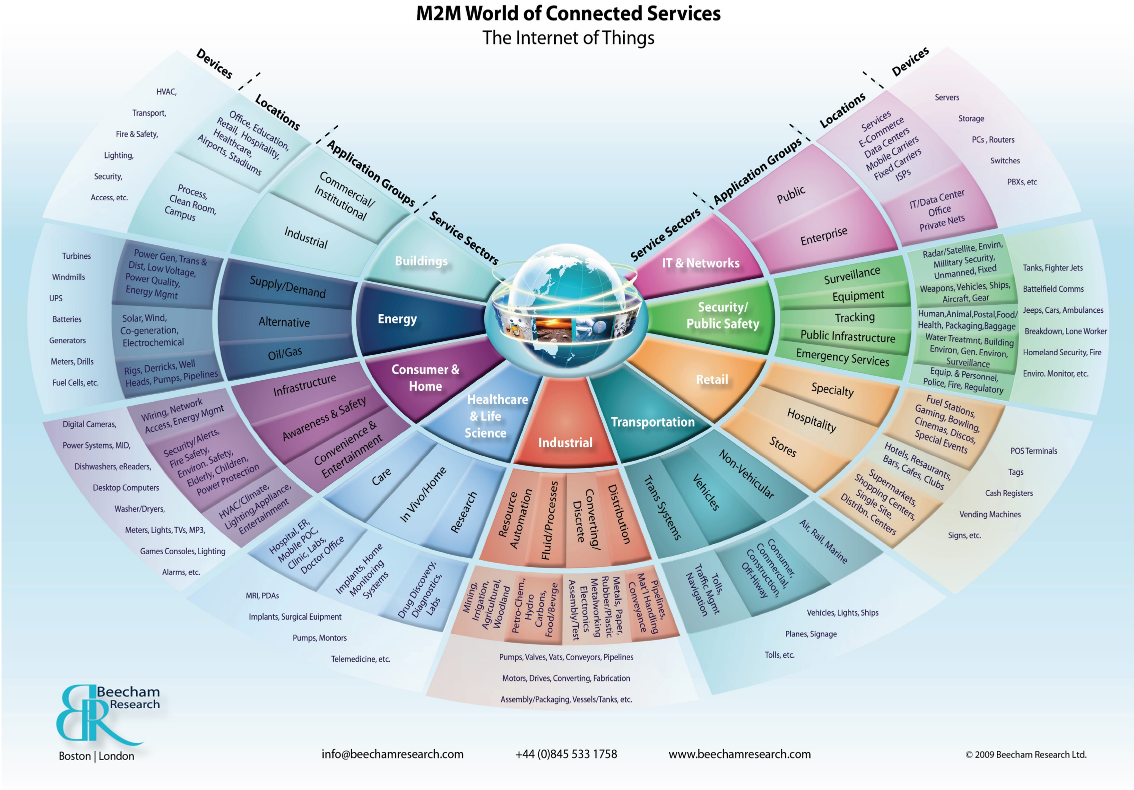

Figure 1: Diverse fields of connected devices which can benefit from M2M communication. [2]

for the application. Wasteful use of resources will require common intervention from trained staff, which would increase maintenance cost. Changing batteries may not even be feasible at all in some application scenarios. [3]

The increasing number of connected devices and device density set new challenges for the communication techniques between the device and its back-end infrastructure. Traditional wireless communication networks, such as WiFi and cellular networks, have been designed to handle tens or hundreds of connected devices per base station before becoming too crowded for reliable communication. The current IoT trend will push these existing architectures to their limits, as a normal household can own several tens of connected devices. For example, NB-IoT specification sets the baseline for device density to 40 devices per household, based on assumptions for London. This corresponds to 52 500 devices per cell tower. Simulations show a NB-IoT cell can handle over 200 000 devices where a traditional 4th Generation LTE base station can only handle up to 750 devices. [30]

2.2 Machine to Machine Communication

Whereas the IoT trend can be mainly considered as a consumer-driven trend, the concepts behind IoT communication are known as Machine to Machine (M2M) communication or Machine Type Communication (MTC).

Machine Type Communication (MTC) is generally separated from traditional communication technologies, even though it might use the same technologies. For example, traditional cellular networks, which have been build for mobile phone usage, have been optimized for high data rate and low latency, and have special channels dedicated only to voice communication. Only few applications IoT applications can benefit these features. MTC takes place between machines without user intervention, thus a different set of requirements can be derived for it. Different compromises can be done in technical level and still achieve feasible Quality of service for the application.

All MTC doesn't require direct Internet connectivity, and sometimes even avoided over complexity or security concerns. In many applications, only a small amount of data is transferred, and this data does not require short transmission delays.

As the main characteristics for MTC are commonly considered:

- Lower needs for low-latency, high-data rate streaming;
- System-critical communication;
- Both dedicated infrastructural and ad-hoc networks;
- Data prioritizing;
- Large differences in device densities between urban and rural areas;
- Wider coverage to reach distant and indoor devices. [30]

Many different wireless standards have been adapted for M2M communication. Unlicensed short-range technologies like ZigBee, Z-Wave or Bluetooth exist, which form independent point-to-point or mesh networks. Most consumer IoT devices connect to the Internet via a local WiFi network, or to mobile phones via Bluetooth due to their common availability within households. Usage of WiFi and Bluetooth can be seen as a compromise due to the lack of an existing large-scale IoT network. Traditional cellular connections would require external SIM (Subscriber Identity Module) -cards for each device, and the required power consumption would not be ideal for battery-powered devices. Some low-power adaptations of wireless technologies targeted at IoT applications, such as Bluetooth Low Energy (BLE), offer significantly lower power consumption.

2.3 Low Power Wide Area Networks

To fulfill the varying requirements of low power M2M communication new standards and technologies have been developed. These technologies are commonly known as Low Power Wide Area Networks or LPWAN, due to their common design drivers for low-power user applications and long-range connectivity. Building infrastructural network for low-power low-throughput devices raises different problems for the communication system and network designs than for high throughput networks or broadcast services. New well established LPWAN standards for M2M application are for example: Z-Wave, SIGFOX, 6LowPAN, LoRa and Weightless-N.

LWPAN standards as name indicate are non-complex long range infrastructural network making possible to be used in various resource limited application. LPWA communication networks are part of the family of star or infrastructural networks - much like cellular networks - and consist in one or more base station provided by an operator and offers connectivity service for devices in the range of the network. Common LPWAN architecture is represented in Figure 2. LPWAN makes possible wide area less demanding infrastructure and better accessibility in rural environment and does not need to have base station on almost each building like with new cellular technologies. In many standards a good reception with single LPWAN basestation can cover ranges up to 50 kilometres.

Most of LPWA networks operates unlicensed or slightly licensed bands such as ISM (Industrial, Scientific and Medical) band and other sub-gigahertz bands.

Low throughput - from few hundreds of bits per second to hundreds kbits per second - makes the network less demanding for resource limited devices and increases margin for longer.

In LPWAN, a node is not capable to use high transmission power or high datarates for communication and for most of the time might not be in responsive communication mode due to deep sleep modes used to optimize battery use. In traditional cellular networks the connected nodes must be in constant connection to basestation or if turned off reconnection requires multistep handshake procedure to establish connection for data transfer. [3]

The disadvantages of LPWAN standards are their low maturity, meaning that they require the development of a new hardware ecosystem, as well as new network infrastructures. Additionally, multiple existing commercial/proprietary standards compete against each other, adding uncertainty to the development of new devices and applications.

LoRa

LoRa is one of the most widely-adopted LPWAN standards around the world. The name LoRa came from Long-range low-power Radio Network; its specification was originally developed by Cycleo starting from 2009, acquired by SEMTECH in 2012, and placed under control of the LoRa Alliance in 2014. Over 76 operators provide LoRa LPWAN networks in over 40 countries as of April 2018. LoRa aims to establish a low power communication network for IoT and have similar aspects to cellular networks. [6, 7]

The LoRa specification consists in a proprietary physical layer definition (LoRa PHY), and a high-level open-source packeting protocol called LoRaWAN (LoRa Wide Area Network). The LoRa PHY is a physical layer specification which defines the air-interface over between the device node and a basestation which can handle over 60 000 devices in its range. Specification applies an adaptive data rate which gives flexible datarate between 0.3 and 1000 kbit/s in a radius of 22 – 45 kilometers

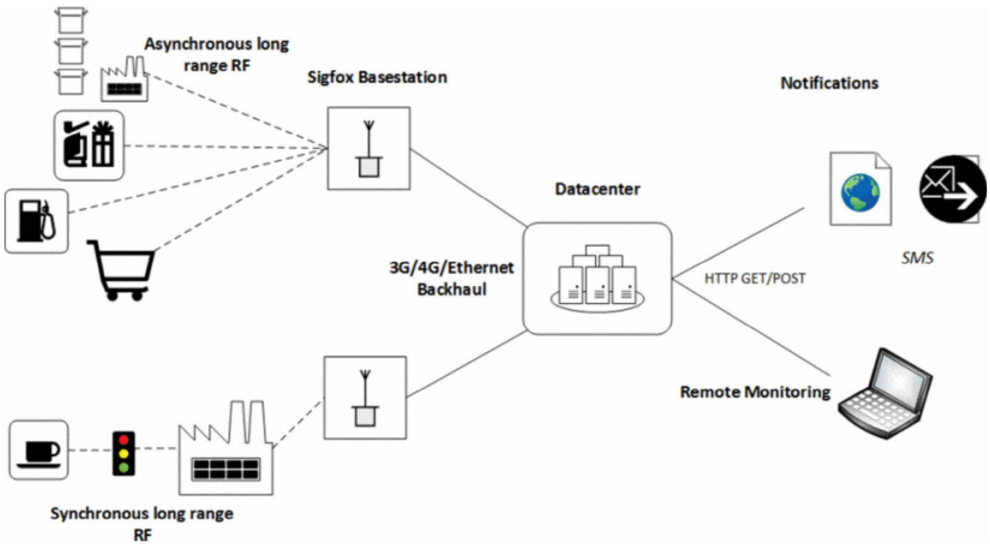

Figure 2: Diagram of SigFox End-to-End (E2E) network architecture. Similar architectural design can be seen many other LPWAN specifications. [4]

around the base station. LoRa's waveform is based on Chirp Spread Spectrum (CSS) modulation technique, and can operate on unlicensed 900 MHz (USA) or 868 MHz (EU) industrial, scientific and medical (ISM) bands. Open source LoRaWAN defines higher level protocols on top or LoRa or another ISM operated protocol. LoRaWAN includes Media Access Control (MAC) protocol for wide area networks, end-to-end security, mobility and localization services and service architecture model, which can be used to transfer data from IoT nodes up to back-end network servers. [6]

Sigfox

Beside the LoRa specification, Sigfox is a second widely spread LPWAN standard, developed by a French SIGFOX company founded in 2009. Sigfox has developed and gained popularity over the world, and particularly in France, in the United Kingdom, and in the Netherlands. Sigfox Networks are established by nation wide Sigfox Network Partners (SNP). For example in Finland the company Connected Finland operates a SIGFOX network, covering 85% of the Finnish population as of 2018. [9, 10]

Like LoRa and other LPWAN specifications the Sigfox's data rate is very low, in the order of 100 to 600 bits/s. The protocol restricts the amount of uplink data (data sent by each end point) to a maximum of 140 messages carrying up to 12 bytes of data per day, and the downlink data is restricted to four messages carrying up to 8 bytes of data. Sigfox uses Ultra Narrow Band (UNB) technology combined with DBPSK and GFSK modulation. The protocol operates on unlicensed ISM bands (868 MHz in Europe, 902 MHz in USA), and the area covered by a single network base station can have a radius over 20 km. The power consumption of devices using Sigfox communication would allow a battery life time in the order of a decade with a single AA battery. Sigfox's detailed low-level specification of the protocol is proprietary, making its detailed analysis difficult. [4, 9, 11]

2.4 Cellular Internet of Things

Cellular IoT, for short CIoT, refers to the concept of using the widely-available cellular network technologies in IoT applications, instead of relying on upcoming technologies. Cellular IoT applications can use 2G, 3G and 4G network technologies.

The use of cellular networks in IoT applications is in many cases non-ideal from an application perspective, and the application itself does not benefit from all the capabilities offered by the cellular network. For example, dedicated voice services are only needed in a few IoT applications. Mobile networks have taken steps towards higher data rate connections, which only benefit a few IoT applications, such as High-Definition security cameras. The bandwidth needs of the majority of IoT applications are much lower. The non-essential features and high data rate capabilities of mobile cellular standards have a negative effect on low-power IoT applications. [31, 66]

To tackle this problem, IoT-specific cellular network specifications have been developed. These adaptations of mobile cellular standards for IoT adopt many LPWAN style features, while still remaining compatible with cellular mobile networks. The main such standards are EC-GSM, LTE-M, NB-IoT, and some parts of the upcoming 5G standards. These can be seen as an evolution of cellular technology towards IoT. The 2nd-generation GSM-based EC-GSM-IoT standard will be covered in the following section, and the LTE-M and NB-IoT standards will be covered in Section 4. [66]

Generally, the differences between LPWAN and Cellular IoT standards for the IoT device itself are small, as cellular IoT is a subset of LPWAN. However, since CIoT standards are based on cellular technologies - and thus not as energy-efficient as LPWAN standards - there is an impact on the device battery life. The core network behind the connection is similar to cellular packet systems.

The most significant benefits in cellular IoT specific standards is the deployment of the network. When a cellular IoT network is deployed, it can use existing base stations and core infrastructures instead of deploying new equipment, and hence use existing band licenses and operational services. When integrated to existing cellular base station networks, the deployment and operational costs of the IoT network are significantly lower. [31, 32]

Extended Coverage GSM for IoT

Extended Coverage GSM for IoT specification, EC-GSM-IoT for short, is a LPWAN technology based on existing 2G cellular which, as suggested by the name, extend its network coverage compared to previous 2G technology and allow new less resource demanding operating modes. EC-GSM-IoT is a direct modification of the GSM protocol, based on the GSM (Global System for Mobile Communications) and GPRS (General Packet Radio Service) technologies, which were developed for the first mass mobile market. The development of EC-GSM-IoT is led by 3GPP like other commercial cellular specification and it was originally published in 2016 on 3GPP's

Release 13 in 2016 beside the LTE-M and NB-IoT specifications. [12, 35]

EC-GSM is an attempt to answer the demand for MTC/IoT communication. This is similar to the philosophy behind LTE-M and NB-IoT, except that EC-GSM uses older GSM technology and infrastructure instead of deploying new hardware, or relying on LTE infrastructures which are still being deployed. A potential downside is the obsolescence of older infrastructure, as older 2G and 3G networks are already being taken down by many operators.

EC-GSM is designed to work inside existing GSM frequency band. This protocol allows for a better indoor reception and a higher number of connected User Equipment(UE). Additionally, it makes possible lower UE power consumption, as by default GSM is less power hungry than LTE. Old GSM base stations (BTS, Base Transceiver Station) are easily upgradeable to support EC-GSM, lowering the network erection costs. EC-GSM-IoT seems particularly suited for rural areas, where GSM networks are already in place, and LTE upgrade are not likely to happen in the near future. [12, 66]

2.5 Space-Enabled Internet of Things

Over the last few years, several concepts have been proposed, which expand IoT networks to orbit and add value to IoT applications with space assets. The concepts of space-enabled IoT have been discussed also by European Space Agency in many of their ARTES (Advanced Research in Telecommunications Systems) projects [18].

Space-enabled IoT can be also viewed form perspective of taking the IoT to the device and making satellite services more connected to the Internet and cloud -services. Traditionally satellite operations work in isolated environment where the data is copied when available or satellite is operated as a transparent data relay for the Internet infrastructure. IoT satellite is more a conceptual design driver than real technology.

IoT applications can gain various functionalities from space assets, such as satellite communication, satellite navigation, and Earth Observation. Some of these assets are more de'facto technologies and nowadays are not even considered as space or satellite services even thought they truly are.

One of the best-known space-based services are Global Navigation Satellite Systems (GNSS), such as the US Global Positioning System (GPS), the European Galileo and the Russian GLONASS-system. GNSS receivers have a low power consumption, tens of milliwatts, and they work anywhere in the world with clear sky, offering at least 10-meter accuracy. GNSS position services can also be used for high-accuracy timing reference, in applications where independent timing and synchronization between nodes is required.

Space-enabled IoT would allow in-situ measurements and near real-time data collection from the end devices, which could benefit researchers, e.g. in for environmental data collection and remote sensing (in form of ocean research with sea buoys, or other distributed measurements in various regions and animal tracking). [18]

Space-enabled IoT networks could deliver data communication services to remote locations where building the terrestrial infrastructure for communication might not be possible or feasible (e.g. mountains, forests, oceans), enabling operational independence of the end device on its location in the world. This would be valuable for applications involving long-range vehicles (e.g. container ships).

Using satellite communication in an IoT context is an emerging topic. In this work, using some technical implementation tools offered by the LTE and NB-IoT standards, are covered.

ICARUS Initiative

One existing example of low-powered IoT application based on space assets is the International Cooperation for Animal Research Using Space (ICARUS) initiative. ICARUS uses tiny 5-gram tracking devices attached to animals to track them from the International Space Station (ISS).

The device uses GPS signals for positioning, and other sensors (temperature, acceleration, magnetic field etc.) to collect data on the animal's movement. It is equipped with a battery and solar cells. The project was initiated in 2002 and started the testing phase in late 2017. [13]

Communication from animal carried sensor node to 400 km high ISS orbit is implemented using a very slow-rate custom CDMA coding of signal and data. Due to vary limited RF transmission power, only 6 mW, the datarate is about 500 bits per second, resulting in 1 784 bits per ISS pass (around one 160 character text message). [13] In this kind of application hundreds of bits per day is feasible amount of data, especially when the ISS orbit can provide near global coverage for the service. [13]

This type of application demonstrates well the use of space assets in IoT world even thought they are still very limited. For example, ICARUS does not have to deal with the problem of indoor connectivity. It can be foreseen that IoT trend is approaching the space assets and shows the potential of the new LPWAN technologies. The number of applications utilizing satellite technology, especially with the communication solutions, will become more accessible in near future.

3 Satellite Communication

In this chapter, a short introduction to satellite communications is given, which covers the history of satellite communication and existing satellite services. The challenges of satellite communication, such as Doppler-shift and latency, and their impact on communication solutions are briefly covered, as they will be relevant in later analysis. The last section of the chapter deals with small satellite concepts, and the possibility to use them in satellite constellations.

3.1 Background

The concept of using artificial satellites orbiting the Earth emerged in the late 19th and early 20th centuries. In 1946, by Arthur C. Clarke proposed the concept of using a geosynchronous satellite as a way to communicate between terrestrial stations - the originality of the concept has been later widely discussed. [15, 16]

The first artificial satellite sent after the second World War in 1950 were designed for the military telecommunication and imaging purposes. Later after the first manned missions the focus to space exploration has move toward Earth remote sensing. The focus of over-the-horizon communication was on the use of short wavelengths reflection off the ionosphere. Passive reflector satellites, such as Echo 1 and 2 and PasComSat, were used to "bounce" the signal from a base station off the body of the satellite, to be picked up by another ground station. [16]

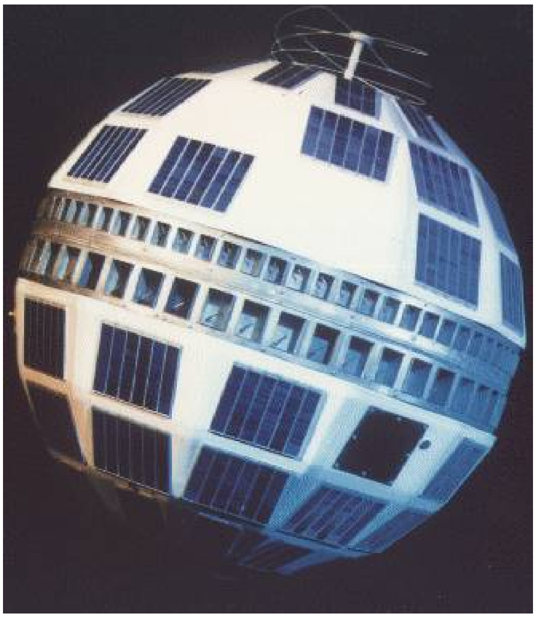

Figure 3: Telstar, first active direct relay communication satellite designed by Bell Labs was launched in 1962. (Source: Wikimedia Commons)

Linear repeaters, which work as a so called "bent-pipe", receive signals transmitted from the ground, and transmit it to another network node. The first such active, direct-relay satellite was Telstar (Figure 3), launched in 1962 by the USA. These satellites use analog repeaters to stream data in real time and transmit it to another ground station. By using such bent-pipe satellites, it is possible to build complex satellite networks, where satellites route the data to each other before forwarding it to the ground segment. Majority of the bent-pipe style repeater satellite were used as commercial broadcast communication but also in inter-satellite and planetary communication. Later satellite repeaters became digital, allowing real-time routing and transcoding of the relayed signal.

Nowadays, the use of satellite communication in consumer application seems imminent. Satellite Internet services are globally available, but are used only in cases where supporting infrastructure doesn't exist and Internet connectivity is necessary. The quality of the service is generally considered poor, and it is usually expensive compared to wired and cellular solutions. Recently, multiple companies, such as Google, Facebook, OneWeb and SpaceX, are investing in satellite constellations to provide worldwide, inexpensive, high-quality Internet connectivity. [16, 69]

The greatest advantage of communication satellites are considered the possibility for beyond-the-horizon communication from perspective of two ground station. The visibility from satellite to ground terminal can be near line-of-sight visibility when the satellite is above the horizon; a satellite can connect ground stations which would not normally see each other due to the Earth's curvature. Thus, even a single satellite can easily build large infrastructural service which covers huge land areas.

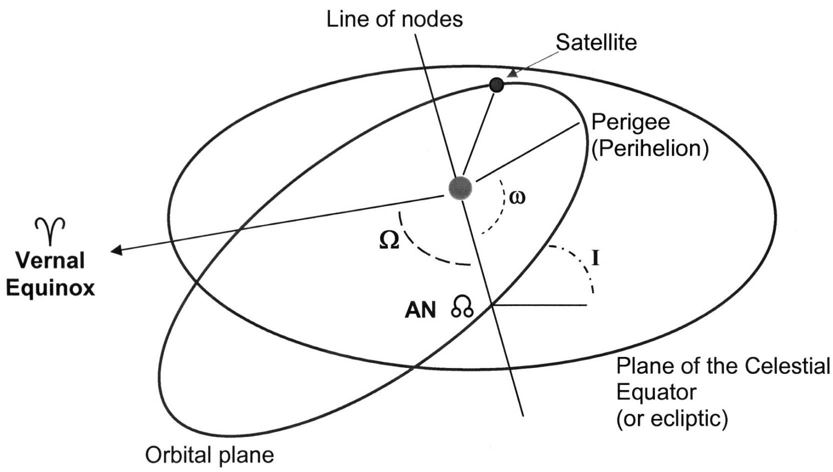

Figure 4: The Orbital mechanics Altitude apogee and perigee. Inclination. These parameters determine the essential parameter, such as ground coverage, visit time, for satellite communication.

Orbital mechanics

Orbits are usually application-specific. For this purpose a set of parameters are used to describe orbital motion. In Figure 4, the essential parameters (perigee, apogee, inclination I, right ascension of the ascending node Ω and Argument of perigee ω) for describing orbital mechanics are illustrated. The perigee - generally periapsis - is the orbit's closest point of approach to Earth, and the apogee - generally apoapsis - is the point on the orbit which is the furthest away from Earth. Perigee and apogee altitudes determine the orbital period and possible synchronization to the Earth's rotation dictating many other secondary parameters in orbit design. The inclination (I) measures the angle between the Earth's equatorial plane and the orbit's plane. The right ascension of the ascending node, Ω, (RAAN) is the angle formed between the axis going through the centre of the Earth and the First Point of Aries, and the axis of intersection between the ecliptic and orbital planes, measured at the point. where the orbit passes from the Southern hemisphere to the Northern hemisphere. The argument of periapsis, ω, is the angle between the line of nodes (going through the ascending node, the centre of the Earth, and the descending node) and the axis going through the centre of the Earth and the orbit's perigee. [15]

Even though number of different orbits are numerous most of the Earth observing or Earth communication satellite are located on two different orbits: on so-called Low Earth Orbits (LEO), between 400 and 2000 km, or on a Geosynchronous Orbit (GEO) at 35 786 km. On Low Earth Orbit satellites Allow relative low and long lifetime orbit around . Satellite can see only small of surface at one time. A constellation of satellites is needed to cover simultaneously the whole globe. The orbit inclination determines the latitudes the satellite can cover by its orbital movement and thus affects and thus can effect significantly to the satellite global coverage and revisit times. Orbit inclinations varies from near equatorial and polar orbits with inclination close to 90 degrees.

Geostationary or geosynchronous (GEO or GSO) orbits are popular for communication and Earth observation satellites. In both orbits satellite's orbital period is equal to Earth spin rate around its own body. The satellite remains at same longitude all the time. On geosynchronous orbit, depending on the satellite's inclination, the latitude on ground may remain zero. Geostationary orbit is a special case of geosynchronous orbit which the orbital plane is also fixed to Earth equatorial plane and its inclination is zero degrees. This orbit is not stable due to tilt of the Earth's spin axis relative to Earth's orbital plane around the Sun. If not correction maneuvers are executed the orbit will start drifting and the orbit will become just geosynchronous orbit. Geostationary orbit is desired for easier reception with fixed dish antennas but in the end of satellite lifetime the orbit will become geosynchronous before the satellite itself maneuvered to separate graveyard orbit. [16]

3.2 Challenges

Establishing a radio link between ground and space presents different challenges than terrestrial Radio Frequency (RF) -communication. The link between satellite and ground station is usually asymmetric by nature and/or usage. The number of uplinks is limited to a few, but an unlimited number of ground receivers can exist (a good example are GNSS networks). Some point-to-point connections where a satellite and . to relay networks between continents. Broadcast where single ground station streams data up to the satellite which then broadcasts the data to multiple ground terminals.

Satellite communication services are usually asymmetric. Broadcast services which are feasible but on the massive satellite uplink services or user specific are resource consuming. A single satellite orbiting 600 km can see 4.3% of the Earth surface at the time. Thus, the number of ground terminals willing to communicate with the satellite can be massive and out of resources even for a larger satellite. A satellite's area of ground coverage depends heavily on its orbit. While LEO satellites typically see a circular zone with a diametre of about one or two thousand kilometres, a satellite in geostationary orbit can see almost one half of the Earth at the time. [15]

Ground receivers can be simple devices for communication with satellites in LEO and low MEO orbits (e.g. hand-held mobile phones, which are used for GPS reception). However, the transmitter usually needs to be much more complex and powerful to establish a connection to geostationary satellites. Ground terminal need usually to have knowledge of satellite positions to know which satellite can be reached and which direction. For example GPS relies on almanac files which need to be acquired over GPS downstream or from Internet services before location estimate can be calculated, to known which satellite can be heard. [16, 15]

Three main challenges for satellite link designs are signal attenuation due to Free Space Loss, latency due to signal propagation and frequency offsets caused Doppler-shift. Compared to terrestrial link satellite communication suffers less from signal reflection, signal delay-spreading and fast fading, as noise levels against the sky are lower than over the horizon. Where terrestrial links are modeled using Multi-path Rayleigh fading channel models in which multiple echoes of same signals are received, a satellite link is approximated using Additive White Gaussian Noise (AWGN). [16]

First significant factor addition to noise models is the caused by distance between the satellite and the ground terminal. The distance is larger than in most terrestrial cases and it cause the signal to attenuate and delay. The signal attenuation due to distance is called Free Space Path Loss (FPSL) and can be described with the following equation:

$$FSPL(dB) = 10\log_{10}\left[\left(\frac{4\pi df}{c}\right)^2\right], \tag{1}$$

1 where d is the distance between the transmitter and receiver, f is the frequency, and c is the speed of light. The signal disperses in all dimensions in space when the distance increases. The free space path loss equation considers also the power loss of receiving isotropic antenna. The free space loss is the single most significant factor in satellite link budget analysis.

The minimum distance to LEO satellites is a few hundred kilometres when passing overhead, to about 2 000 km when visible over the horizon. 20 dB difference in signal strength between overhead and horizon cases. The distance to geostationary orbit is around 36 000 km at 2 GHz the attenuation is 170 dB. Over a hundred kilowatts of EIRP (Equivalent Isotropically Radiated Power) are needed to reach a ground receiver from GEO with a reasonable Signal-to-Noise Ratio (SNR) and receiver aperture. To overcome the loss of signal without increasing the transmission power, directional high-gain antennas can be used. Small satellite TV dishes pointing to geostationary satellites are a common view around the world.

The atmosphere attenuates electromagnetic signals, especially at higher frequencies (over 3 GHz). The main factor is the absorption of electromagnetic waves by atmospheric water (water vapour, clouds and precipitations). Also other invarities in tropospheric and ionospheric can cause slow fading. These phenomena are generally more important as the line of sight between a base station and a satellite gets closer to the horizon, as the signal has to propagate for a longer distance through the atmosphere. Also closer to the horizon additionally to the larger communication distance the link suffers from other radio and thermal noise from terrestrial sources increasing noise floor. [16]

In additional to the substantial free space loss caused by the distance between nodes, the signal undergoes a propagation delay which is proportional to the path length. The latency from ground to GEO is over 125 ms, while latency to LEO is 2 – 10 ms. The latency changes during a satellite pass, as the distance between ground station and satellite decreases and increases (this does not apply to GEO communications). Millisecond scale delays are significant and need to be considered for example in Medium Access Control to prevent simultaneous transmissions in Time Division Multiple Access (TDMA) system. The propagation delay $t_{propagation}$ is given by:

$$t_{propagation} = \frac{d}{c}, \tag{2}$$

where d is the signal path length, and is c the speed of light in the medium.

Third factor is the frequency shift caused by the orbital velocity. When the source of an electromagnetic signal is moving relative to a receiver, the receiver will observe a shift in the frequency of the signal, which is proportional to the relative speed between the source and receiver. This effect is commonly known as the Doppler effect. In the field of telecommunications, for a terminal receiving a stream from a moving source (e.g. a base station receiving from a satellite, and vice versa), the induced Carrier Frequency Offset (CFO) needs to be compensated for before the demodulation process can take place. This is done by estimating the relative speed from the orbital, or by tracking a pilot signal. The magnitude of the shift depends linearly on the relative velocity between the transmitter and receiver, and on the carrier frequency, as described in the following equation:

$$f_{Doppler} = \frac{v_r f_c}{c}, \tag{3}$$

where v_r is the relative or slant velocity, f_c the carrier frequency and c speed of the light.

In low Earth orbit (LEO), the approach velocity of a satellite relative to ground target can be close to its orbital velocity (>8 km/s), hence Doppler shift plays a significant role. According to the laws of orbital mechanics, it can be generalized that Doppler shifts are less important for satellites at higher altitudes, because their orbital velocity is lower. The effect is usually near zero int the case of communication between a base station and a satellite in GEO orbit (as it only depends on the motion of the base station), which can simplify the receiver design. [15]

The quality of a received satellite signal depends heavily on the environment on the ground. While in rural areas, signal reflections and fast fading relative to the symbol rate are usually not a concern (thanks to an optimal sky visibility), the picture is different in urban environments, because of the presence of tall buildings with flat surfaces. For example, GPS signal reception is typically difficult in a high-rise urban environment, as well as indoors. GNSS services require an unobstructed sky for operation. A possible mitigation strategy against signal reflections is the use of high-gain, directional dish antennas - but this may add a requirement for satellite tracking and not be suitable for every application. [5, 16]

3.3 Satellite Broadcast Services

The most common form of satellite communication service is satellite broadcasting. In satellite broadcasting, a single satellite can transmit a signal to an infinite number of ground users simultaneously. This signal can consist of a radio or a television broadcast, weather information, or other data.

The broadcast is typically done from the geostationary orbit; the signal is received on the ground with a static high-gain antenna, which is required to be fixed for good reception. The satellite transmitter's antenna can be designed to concentrate the signal on specific regions of the Earth, to limit the broadcast to certain countries and increase the signal strength on the ground. Antenna beam forming also allow regional stream.

These architectures allow broadcasting for a large number of users (multicast) the data is not user specific and can be easily streamed. Many broadcast systems allows also transmission of user-specific data, but due to the need for signal targeting, the number of simultaneous users decreases significantly, hence it is not practical. By nature, these architectures are limited to one-way communication, as it would be impossible for a broadcasting satellite to receive signals from millions of ground terminals at once. This limits the possible applications. Multicast services are also constant streams but in slow slow feedback loop for the broadcast transmission are possible and used in some applications but not practical for serving individual users. [16]

Most of the broadcasting communication satellites are located in Geo-synchronous Earth Orbit (GEO), at an altitude of 35 786 km over the Equator. Satellites on the GEO orbit stay almost stationary from the ground segment's point of view, which removes the need for active orbit tracking. The ground station's antenna can be near stationary.

One downside to using geostationary satellites is the long distance from the ground to orbit, which induces a high latency and signal attenuation. It takes roughly 250 ms for signals to go to the orbit and back to the ground, which can cause problems for real-time communication. The high latency and signal attenuation makes it impractical to implement two-directional consumer links via geostationary satellites.

Uplink communication requires a large parabolic dish antennas to close the link budget, hence small mobile terminals are not possible. Frequencies between 6 and 40 GHz to achieve large bandwidth broadcast streams. Also high directivity antennas can be more easily designed and are smaller in physical size due to small wavelength.

One of the most common standards for satellite broadcasting is DVB-S2 (Digital Video Broadcasting - Satellite - Second Generation), which was developed for satellite TV. Its main features are: BPSK, QPSK, 8PSK, 16APSK and 32APSK (Amplitude and Phase Shift Keying) modulation schemes with varying error correction codes; high symbol rate (1 – 31.5 megasymbol per second), operates at high frequency K-bands; pilot signals power of EIRP (Effective/equivalent Isotropic Radiated Power) 51 – 53.7 dBW with highly directional antennas. [17]

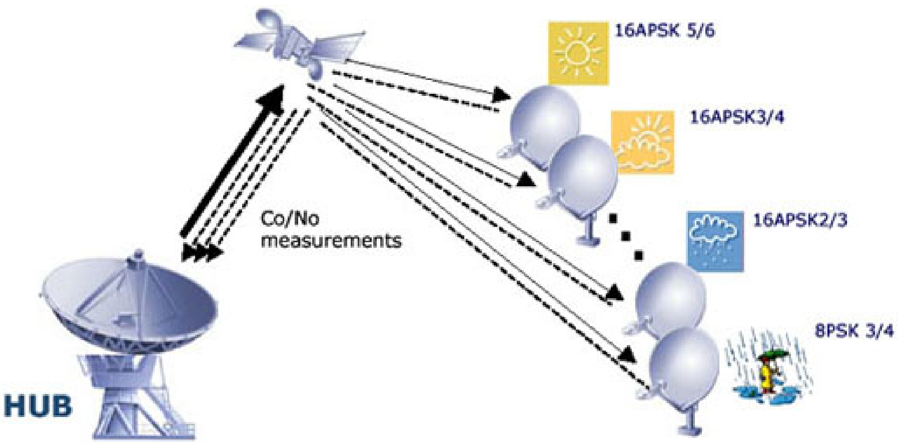

Figure 5: Example of DVB-S2 broadcast streaming over geostationary satellite. DVB-S2 allow regional stream which can utilize.

One special feature of geostationary satellite broadcasting services is the use of Adaptive Coding and Modulation (ACM) methods. In ACM a set of waveforms - modulation and error coding configurations - are defined for use depending on required bandwidth and losses in the signal propagation. In ACM adapts to channel fading according to maximizing throughput and improving signal ground reception. Usage of ACM makes possible to use the best transmission being always as close to Shanon limit as possible. Operation of ACM relies regional return channels which are used to measure channel quality and connects to broadcaster using secondary channels such as Internet. In Figure 5 is illustrated classical satellite television broadcast system where a single ground station upstreams the via satellite to multiple ground users, the satellite simultaneously transcoding the stream.

3.4 Mobile Satellite Services

The second category of satellite communication systems are the mobile satellite systems. In mobile satellite systems, the ground equipment has to be mobile (typically hand-held devices). This includes e.g. satellite phones, satellite message pagers, satellite data services and Global Navigation Satellite Systems (GNSS).

In mobile satellite services, the link budget is mainly limited by ground equipment capabilities, as high-gain antennas, powerful transmitters and pointing capability are not available in handheld applications. These limitations need to be taken into consideration during the mission design. Mobile terminals are best suited to bidirectional communication with satellites in LEO orbit. Mobile systems usually use lower frequencies than broadcasting services, such as the L-Band and S-band between 1 and 4 GHz, which makes the usage of reasonably sized smaller gain antennas possible.

Low-Earth orbits are generally favoured for mobile services compared to MEO and GEO, because the lower altitude generates less free space loss. The lower attitude causes only a slight latency, which is beneficial in many mobile applications. However, this leads to a high relative velocity between the satellite and ground station, which causes a high Doppler shift.

Due to the low orbital altitudes, a satellite's area of ground coverage is much smaller on a LEO orbit than on a GEO orbit. Thus, larger constellations are needed in LEO to achieve constant global coverage. Multiple satellites need to be visible for the ground user at the same time so that when connection to one is lost, the second satellite can be reached without interruption in service.

An example of a LEO communications constellation is the Iridium satellite network, which first satellites were launched in 1997. Iridium is the best-known provider of satellite phone and data services for mobile users. The Iridium constellation consists of 66 satellites, orbiting on 780 km circular orbits around the Earth. The satellites connect to each other, forming a dynamic network in which the data can be routed to the closest ground station. Iridium uses 128 kbit/s L-band (1616 – 1626.5 MHz) links for mobile terminals, with 240 channels (31.5 kHz bandwidth and 41.67 kHz channel spacing) and FDMA/TDMA modulation. Due to its limitations on data rates and number of simultaneous ground terminals the single user data transfer has maintained high cost high which limits wider popularity. An updated series of satellites, called Iridium NEXT, are currently being launched (as of 2018). These satellites are backwards-compatible with existing Iridium systems and extend to support higher data demands. [21]

Another mobile satellite service provider ORBCOMM, an American company, is the largest provider of satellite M2M communication services. It operates a constellation of 31 satellites on 672 – 720 km LEO orbits at a 48° inclination. The ORBCOMM network is best suited for applications which require little data transfer, but require global independence from terrestrial infrastructures. The first-generation satellite network was capable of up to 2400 baud data transfer.[23]

OneWeb, formerly known as WorldVu Satellites, is a company aiming at establishing global broadband Internet access affordable for everybody. Oneweb constellation aims to 648 satellites at an altitude of around 1 200 km operating at the Ku-band (12 – 18 GHz). This allows coverage where at any point there is at least one satellite 55 deg above horizon. Large number of satellites benefits also in distributed load in populated areas. OneWeb's solution requires reasonable large (0.45 – 1 meter diameter) roof mountable ground equipment to establish connection. The production of the first satellites begun in 2018. [69, 70, 71]

3.5 Small satellites

During the last decade the development of small satellite - less than 100 kg mass satellites - has been a growing trend on satellite industry. Smaller satellites allow generally lower development and launch costs thus making development of new satellite services and mission more feasible. The trend relies on general concept that building many small satellites is more affordable than building a large one. The capabilities of smaller satellites are usually more limited than large scale ones due to physical limitation. [20]

For example, CubeSat standard, a small satellite standard developed in 1999 by the California Polytechnic State University and Stanford University, is a mechanical specification which defines a base 10 cm sized cube unit (U), which weights a maximum of 1.33 kg. According to this standard, satellites can be built as multiples of the base unit (1U, 2U, 3U, 6U, 12U and 27U Cubesats are the most commonly encountered). [19] The most significant advantage of the CubeSat standard is its standardized launch pod system which simplifies the satellite's integration to the rocket and thus decrease the cost. Most of the small satellite launches are so called "piggyback" launches where a number of small satellites are launched beside the larger main payload. This way the launch prices can be significantly decreased though the small satellite have very little possibilities to affect to the target orbit. [20]

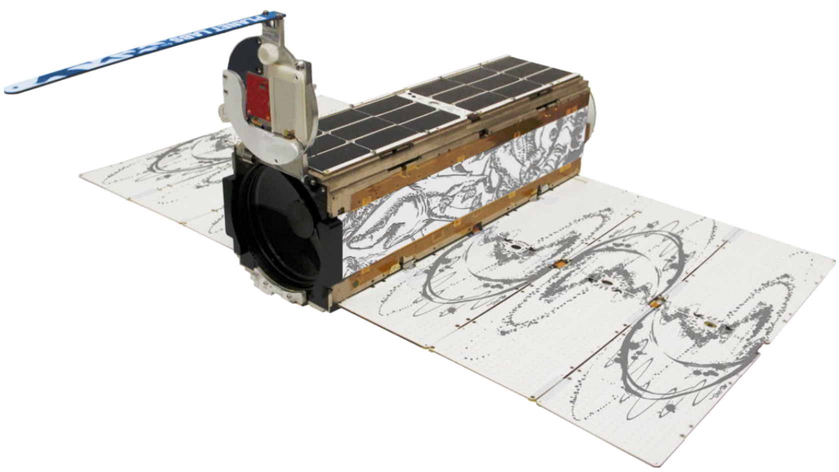

Figure 6: Example of 3 unit sized (10 x 10 x 34 cm) Dove CubeSat by Planet [72]. Canadian Kepler Communications company aims to build M2M satellite communication constellation using same sized satellite. [24]

Small satellite even in Cubesat and nanosatellite scale are starting a significant role in satellite communication. Recently, companies such as the Canadian startup Kepler Communications have, displayed strong interest in developing constellations of CubeSat-class satellites for mobile communication services. They demonstrated successfully Ku-band communication Cubesat in 2018. [24, 25] Other IoT satellite startup-companies are SAT4M2M, Helios, Else and eightyLEO, all founded to tackle IoT space applications. [26]

4 4th Generation Mobile Cellular Network

In this chapter, the general architecture of LTE network is described, with a focus on the LTE air interface and physical layer implementation. Due to the complexity of the specification, all aspects of the LTE air interface cannot be covered in this work.

4.1 LTE specification

Development of the LTE standard was initiated by Nippon Telegraph and Telephone DoCoMo (NTT DoCoMo) of Japan in 2005 as an evolutionary step from GSM and UMTS and it was first time demonstrated in 2007. The LTE was designed to take a larger evolutionary step on used communication technologies compared to 3/3.5G technologies.

The Radiocommunication sector of the International Telecommunication Union (ITU-R) set standards for 4G connectivity in March of 2008, requiring all services described as 4G to adhere to a set of speed and connection standards. While the LTE did not initially fulfill the original requirements for 4G standard, the ITU-R allowed it to be marketed as 4G technology, as long as it provided a substantial improvement over the 3G technology. Later in form of LTE-Advance (LTE-A) standard LTE became a 4G-compliant specification. It was submitted as a candidate 4G system to the ITU-T in late 2009, and was standardized by the 3GPP in *Release 10* in March 2011. [27, 28]

Mobile communication standards defined by ITU-R can be divided into different generations, each which their own distinctive features:

- *1th Generation*: Analog wireless telephone technologies;
- *2th Generation*: Digital encrypted mobile technologies; GSM, EDGE;
- *3th Generation*: Mobile broadband specifications; IMT.2000, UMTS, HSPA/eHSPA, and first LTE specifications;
- *4th Generation*: LTE/LTE-Advance, (WiMAX), packet switched MIMO capable mobile systems; [27]
- *5th Generation*: The next generation of enhancements to 4G standards. The 5G standard will be released in 2020. [66]

Compared to its predecessors, the LTE standard is more data-oriented than the previous 3G standard, and introduces new technologies that provide room for future evolution of the standard - hence its name. Where previous 2G and 3G were designed mainly for human communication, 4G and its successors focus more on Machine to machine communication, where services such as voice communication play a less significant role. LTE standard does not establish dedicated voice communication channels via circuit switching, but instead relies entirely on packet switching. Their focus is on prioritizing low-latency and high-data rate, and redesigning the core network architecture to lower the data overhead. [27, 28]

LTE-Advanced incorporates multiple enhanced features over the LTE standard, which can be grouped into three major categories; Carrier aggregation, to leverage more spectrum and increase data rates; advanced antenna techniques such as MIMO (Multiple Input, Multiple Output) to increase spectral efficiency; PicoCells, to bring most benefit out of small cells and increase capacity per coverage area. LTE also provides a feature called Sidelink, to enable direct device-to-device communication (D2D). [27, 41]

4.2 Network Architecture

LTE is based on a cellular network architecture, as were its preceding mobile standards. In cellular network the radio access network is divided in small "cells" which size varies from hundreds of metres to tens of kilometres, where in a traditional broadcasting network a single radio basestation cover hundreds of kilometers serving all users simultaneously. In cellular architecture, each cell is connected to main core network which manages and makes the whole network works as one large.

In LTE cellular network, a Core Network (CN) connects (typically via terrestrial connections) a series of base stations, each of which creates one or more cells of wireless coverage in its surroundings. Collectively, the base stations and end user devices constitute a radio access network (RAN). In the LTE specification, a base station is called an eNodeB, the RAN is referred to as the Evolved Terrestrial Radio Access Network (E-UTRAN), and the CN is called the Evolved Packet Core (EPC). The structure of LTE network is illustrated in Figure 7.

Cellular networks are suited for mobile applications, because the connection of the end devices to the network is done wirelessly, and the connection can be routed through different base stations as the end device is carried in and out of individual individual cells. Also the cellular architecture distributes the complexity of the radio network over large number of basestation.

An eNodeB is a single base station in the Radio Access Network (RAN) or the Evolved Universal Terrestrial Radio Access Network (E-UTRAN). Each eNodeB is an equipment used to connect wirelessly to the end devices in its area of coverage. From this work's point of view, it is the most relevant radio component in the LTE network. The eNodeB performs signal modulation and demodulation, and Medium Access Control managing the frequency band dedicated for it. Each eNodeB can serve up to 256 logical cells and are connected to other eNodeBs and Core Network.

A Core Network (CN) is an infrastructure connecting base stations together. In the LTE specification, the core network connecting the eNodeB stations is called the Evolved Packet System (EPS). Within the EPS, eNodeBs communicate with each other using an interface protocol called X2. This protocol allows the exchange of user data, as well as traffic load information and commands between different eNodeBs. This is used to handle traffic load effectively, and to handle hand-overs situations, when an end device moves from one cell to another.

MME or the Mobility Management Entity is the protocol responsible for handling all the signaling towards eNodeBs LTE terminals, which includes mobility and session management. MME itself does not deal with user data rather controls the physical

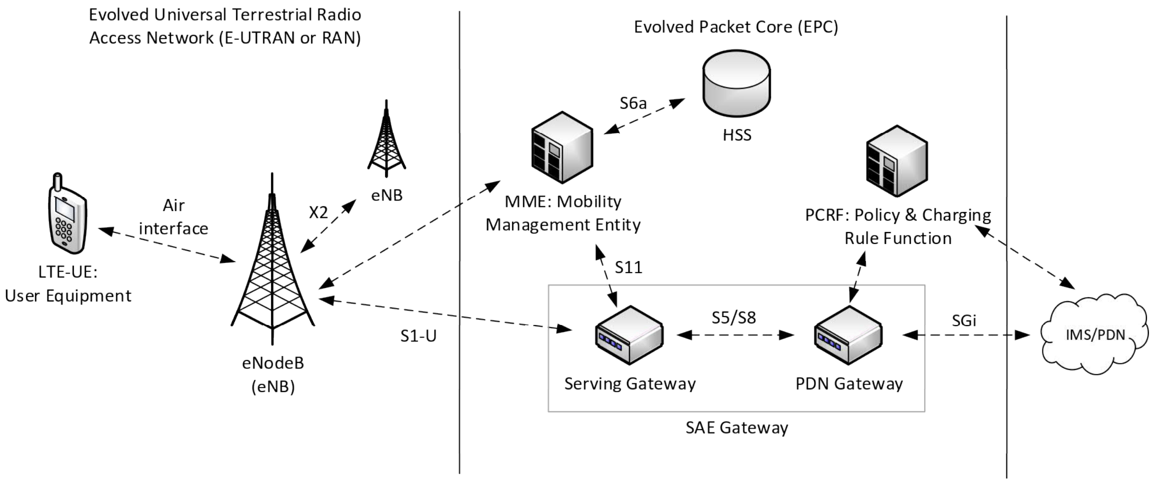

Figure 7: LTE Evolved Packet System (EPS) Network Topology and Architecture [41]

structure of the network. Connected to the MME is Home Subscriber Service (HSS) which is responsible for storing and delivering subscriber information, authentication data and other critical security information.

Serving Gateways (SGW) and Packet Data Network Gateways (PGW) are responsible for routing Control Plane Data and User Plane Data (IP data) through the EPC outside to IP Multimedia (IMS) and Packet Data Network (PDN). PDN Gateway (P-GW) allocates IP addresses and routes packets to Internet and media service providers. [27]

4.3 Protocol stack

LTE covers specifications from the low-level physical interfaces to the high-level network and user management protocol, and can be divided in three levels by the purpose and implementation domain. The LTE protocol stack and its configuration, control and user plane connections are illustrated in Figure 8.

The first level of the stack covers the lowest-level implementation over the Physical on radio domain and the Medium Access Control (MAC) which controls the usage of the physical RF band in the frequency and time domain. It implements transport channels such as Broadcast Channel (BCH), Downlink Shared Channel (DL-SCH), Uplink Shared Channel (UL-SCH) and Random Access Channel (RACH) [41, Section 5.3]. The transport channels' physical waveforms differ from each other, due to their different purpose. The structure of the transport channels and the physical layer (i.e. the air interface) are described in details in the following sections.

The Second level defines the higher level Radio Link Control (RLC) -protocol which is used to forms logical channel and connection between UE end eNodeB. RLC is supports higher level data packet concatenation, segmentation and reassembly, and is fully reliable. Above the RLC protocol is Packet Data Convergence Protocol

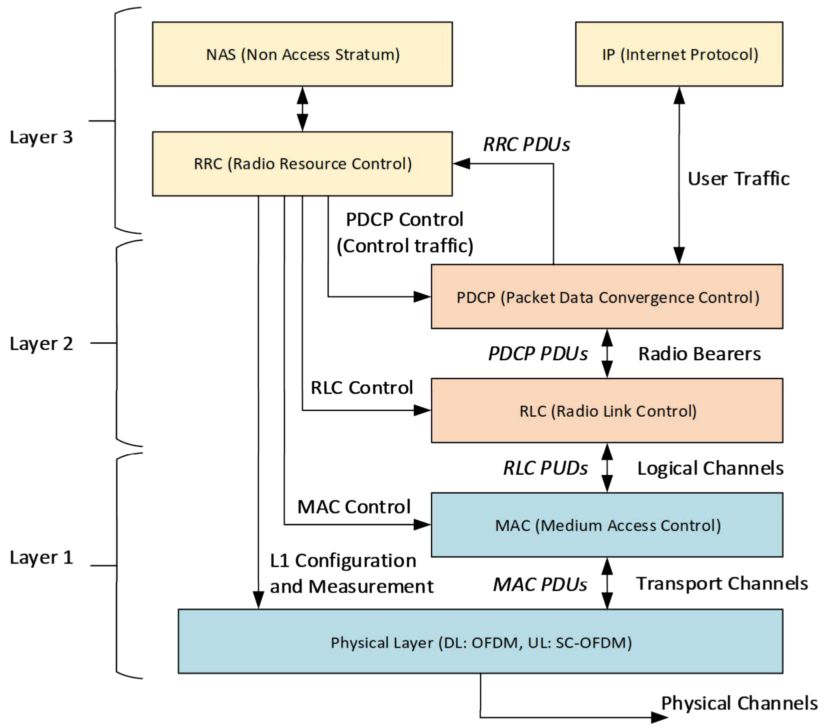

Figure 8: LTE network protocol stack and its control and user plane connections.

(PDCP) which is the main packet protocol used inside the Core network. PDCP implements also user plane security. On top of PDCP are RRC for controlling and other TCP/IP data streams for user data.

The third and highest level protocol, defined in LTE network protocol stack, contains the network level Radio Resource Control (RRC), Non-Access-Stratum (NAS) and general Internet Protocol (IP) data. Radio Resource Control (RRC) define general framework for controlling radio resources between the cells and the eNodeBs. The Non-Access-Stratum (NAS) control-plane protocol is highest level management protocol used between UE and MME at the radio interface to control for example mobility, identity and call control management. [27]

4.4 Air Interface

The LTE Air Interface is defined as the physical layer of the protocol stack and is the most significant change in LTE compared precessing mobile standards. LTE air interface offers a degree of configuration flexibility to allow optimal performance in different environments, especially in urban landscape where wireless signaling suffers from multi-path delay spreading, while allowing high spectral user-bandwidth efficiency.

LTE can operate in Frequency Division Duplex (FDD) or Time Division Duplex (TDD) mode. In FDD the downlink and uplink signals are separated in the frequency domain, with each signal having its own frequency and resource block.

LTE air interface uses Orthogonal Frequency Division Multiplexing (OFDM) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) techniques for its downlink and uplink multiplexing. The basics of the LTE air interface and techniques used in it are covered in the following sections.

4.4.1 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a multiplexing technique based on Multi-Carrier Modulation (MDM) and Frequency Division Multiplexing (FDM). The fundamental idea of OFDM is to pack multiple near-individual subcarriers in a single transmitted carrier side by side, with minimal interference between the carriers. These subcarriers, sometime referred to as tones, are placed so that they are mathematically orthogonal and the subcarriers are place in the minimums of other carriers in the frequency domain. The coded data or channels can then be multiplexed to one or more subcarriers. The orthogonal packing of carriers is illustrated in Figure 9. Each subcarrier can be modulated independently using various modulation schemes such as Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) as long as the orthogonality of the carrier signal is maintained.

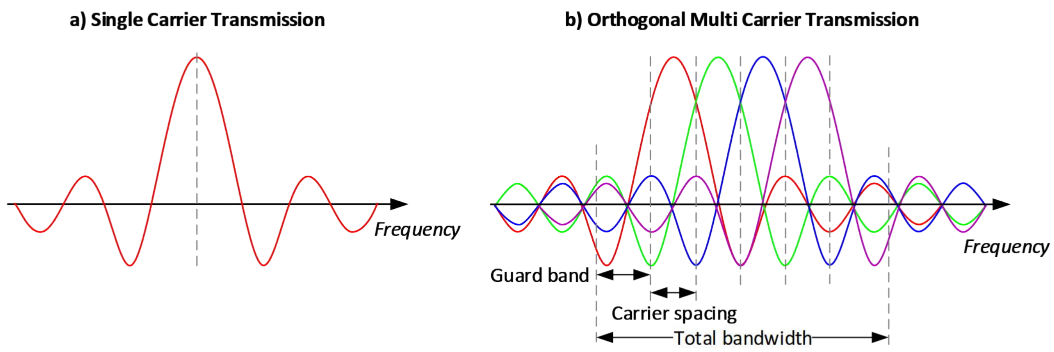

Figure 9: Orthogonal Frequency Division Multiplexing (OFDM) On left a single carrier signal is represented in frequency domain. On right multiple similar carriers are orthogonally packed.

For two signals to be orthogonal, their symbol timing must be synchronized so that the symbol changes occur at the same time. If the subcarriers are not orthogonal, then inter-carrier interference (ICI) will occur.

OFDM is sometimes considered as a modulation technique, but it can also be seen as a transmission technique, where the signal to be transmitted is divided over a large number of lower symbol rate carriers, which span the whole available bandwidth. The role of OFDM is crucial in the LTE downlink physical channel, but it is also used in many other high-bandwidth wireless standards such as WiFi (802.11-specification), WiMAX, and Terrestrial Digital Video Broadcast (DVB-T).

OFDM as a multiplexing scheme can also be used for multiple access in the frequency domain. In this context, the technique is called Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA is similar to Frequency-Domain Multiple Access (FDMA), which is used to divide the frequency space for different users. In OFDMA, the frequency spacing between users can be significantly tighter than with other spectrum sharing techniques, but the frequencies must be orthogonal to each other. To maintain orthogonality between carriers, accurate frequency and symbol timing synchronization are required. Due to its strict frequency synchronization requirement, the OFDMA method is very sensitive to Carrier Frequency Offset (CFO), and thus to Doppler shift. However, in situations where only one transmitter is active and the Doppler shift is the same for each subcarrier, orthogonality is preserved and transmission can occur without problem.

The primary advantage of OFDM is its resistance to the damaging effects of multipath delay spread (fading) in the radio channel, thanks to the longer symbol length. It is well-suited to urban environments, where different carriers can be allocated for different purposes (for example control and pilot signals) and the receiver can selectively demodulate/decode carriers. In the case of OFDMA, multiple transmitters can be fitted into a narrow frequency bandwidth, thereby increasing the spectral efficiency. OFDM is also relatively inexpensive to demodulate when all the carriers are demodulated parallel, using a single Fast Fourier Transform (FFT) operation. This allows the data bandwidth to be scaled up with only a small increase in computational load. The receiver can also selectively demodulate the required subcarriers, and all the received information doesn't have to be processed.

The most significant drawback of OFDM compared to other techniques with high symbol rate and similar spectral efficiency is the high Peak-to-Average Power Ratio (PAPR) of the OFDM signal. PAPR describes how large the peak amplitude of the signal is relatively to its average amplitude. In OFDM, the transmitted signal is close to white noise, and the peak amplitude of the signal can be significant in case of constructive interference between the subcarriers. To transmit a high PAPR OFDM signal without distortion, the power amplifier of the transmitter must to be able to operate linearly over the whole range of signal amplitudes. Since increasing the linearity range of an amplifier reduces its efficiency, more power is required to have a similar average transmission power over radio waves compared to modulations with low PAPR. Hence, OFDM is not considered suitable for applications requiring high transmission power.

Another drawback of the OFDM technique is the orthogonality requirement, especially in the context of OFDMA. When multiple transmitters operate in the same area, they need to establish both frequency and symbol synchronization between each other. The synchronization is commonly maintained using pilot signals, which establish the frequency and timing synchronization onto which the receiver can lock on. This requires accurate timing feedback loops to maintain synchronization in a changing environment, and increases the hardware requirements and power consumption of the receiving device. In many cases, another higher-level synchronization mechanism must also be involved to compensate the delays due to signal propagation.

4.4.2 Single-Carrier Frequency Division Multiple Access

Instead of using purely OFDM or OFDMA methods in the uplink physical layer, LTE also allows using its own variant of OFDM and OFDMA called Single-Carrier Frequency Division Multiple Access (SC-FDMA) for UE to eNodeB transmissions (sometimes, SC-FDMA is also called Linearly Precoded OFDMA). SC-FDMA can be seen as a variant of OFDM/OFDMA, which works both as a multiple-access and multiplexing technique. It relies on the same properties of orthogonal frequencies as OFDM.

The main differences between the two techniques are the structure of the symbols, and how they are spread on different carriers. In OFDMA, over one symbol period, several subcarriers are used to transmit each symbol concurrently; the subcarriers use only a fraction of the available bandwidth.

In SC-FDMA, each subcarrier transmits a symbol using all the available bandwidth, but the symbol period is divided into several sub-periods, each of which is allocated to a different subcarrier. The subcarriers transmit their symbol sequentially, one after another. The different symbol structure when identical symbol sequence is transmitted can be seen illustrated in Figure 10.

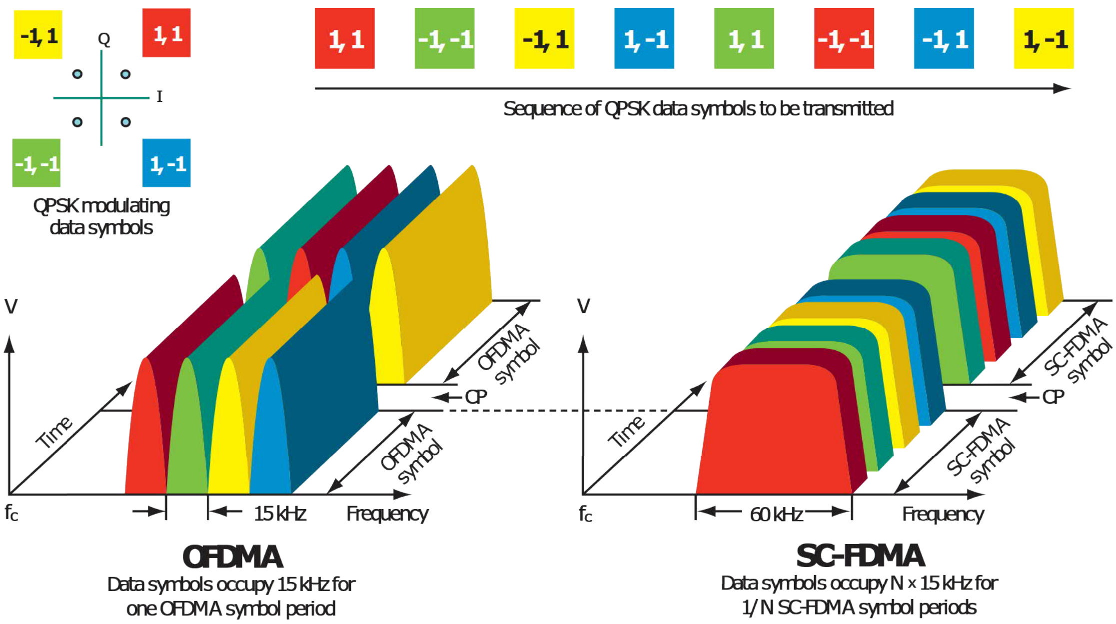

Figure 10: Comparison of OFDMA and SC-FDMA when transmitting a similar sequence of QPSK data symbols [29]

The reason to use SC-FDMA in the LTE uplink is its significantly lower PAPR compared to general OFDM, making it more desirable for battery-powered mobile devices with strict power consumption requirements. SC-FDMA has similar benefits as OFDM/OFDMA regarding the issues of delay-spreading, multi-path and fading, and combines the good PAPR of single-carrier signals with OFDM's spectral efficiency. It is also less sensitive to carrier frequency offset and non-linear distortion, and hence allows the use of less expensive power amplifiers. [27, 29]

The carriers used to transfer SC-FDMA symbols are not required to be clustered together. The LTE specification defines localized and distributed/interleaved SC-FDMA, and single-frequency slots (Physical Resource Block, PRB) can have 2-3 simultaneous active users. Additionally to OFDMA, UEs are multiplexed in the time domain by allocating different resource blocks for different users at different times depending on the traffic load. [29]

In LTE, the SC-FDMA technique is used for multiple access technique (like OFDMA), and the carrier used must comply with orthogonality among carriers/transmitters. Breaking the orthogonality by Carrier Frequency Offset (CFO) or timing offset can cause Inter-Carrier Interference (ICI) and Multiple-Access Interference (MAI) in reception. OFDMA and SC-FDMA are very sensitive to CFO, baseband receiver non-idealities, oscillator frequency shifts, Doppler shift, and timing differences caused by different signal propagation delay. These factors have to be actively corrected. [55]

In LTE, the eNodeB actively monitors the timing and frequency synchronization of the received uplink frames, and commands UEs to apply new timing and frequency corrections. Limits in timing and frequency correction control limits the overall system tolerance: compensation of the signal propagation delay limits the cell size to 100 km, and frequency-offset limits allow relative UE speeds up to 500 km/h due to Doppler-shift. [27, 29]

4.4.3 Cyclic Prefixing

To reduce inter-symbol interference (ISI) caused by multipath, both LTE downlink and uplink use so-called Cyclic Prefix (CP). The idea of the cyclic prefix is to add a copy of the symbol tail in the beginning of each symbol. The protection against delay-spreading provided by cyclic prefixes is illustrated in Figure 11.

From the figure can be seen the affect of summation delay-spread signals. The cyclic prefix prevents the previous symbol's information to interfere with next symbol. At the same time the original frequency and phase components remain recoverable. All though cyclic prefix is often used in OFDM systems, it is also applicable to single-carrier schemes. In SC-FDMA, cyclic prefix can also correct timing errors between transmitted subcarriers.

All though cyclic prefixing places an overhead on the signal, it can be essential for information recovery. LTE specifies two different CP lengths, to be used depending on the environment around the cell and desired cell radius. In normal CP length is 4.7 microseconds - which represents 7% of the total symbol length - and extended length (16.67 microsecond), which causes 25% overhead. The optimal length usually depends on the desired cell size, and should be at least as long as the longest possible echo inside the cell. In the worst case, the length of the CP must be equal to the round-trip time (RTT), which depends on the cell size. Extended CP can be used in scenarios with particularly high delay spreading.

Cyclic prefixing is also essential for OFDMA system; it adds a guard period between the symbols. During this guard period, the carriers transmitted by different transmitters chance the symbol and can cause interference due to small timing

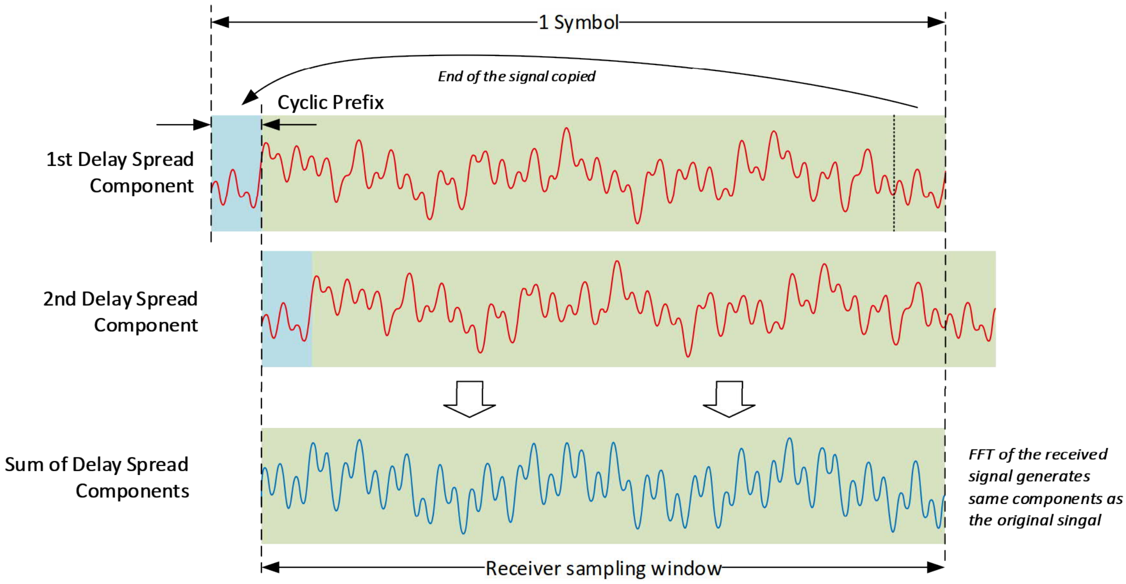

Figure 11: Example of summation of delay-spread signals with Cyclic Prefixing. The frequency components and phases of original signal are still recoverable after delayed spreading.

errors. Without the cyclic prefix the signal orthogonality would not remain resulting Inter-carrier Interference (ICI). [27]

4.4.4 Frame and Protocol Structure

The LTE is a completely packet-switched protocol. The data transmission is organised into radio frames, subframes and slots, which each have their own structure and purpose. The duration of a LTE radio frame is 10 ms long, and it consists of 20 slots of 0.5 ms. A subframe is defined as two consecutive slots. This frame structure is illustrated in Figure 12.

In the frequency domain, the LTE channel is divided in Physical Resource Blocks (PRB), which each cover 180 kHz bandwidth and have 12 OFDM subcarriers. A single LTE channel covers at least 6 PRBs having 1.4 MHz channel bandwidth. Practically a single cell covers 20 MHz bandwidth. In Frequency Division Duplex (FDD) mode, the uplink and downlink have their own, separate allocated resource blocks. At the logical level, the channel forms a two-dimensional symbol-subcarrier grid, where one axis represents time (position of the symbol within the frame and slot) and the other represents frequency (OFDM subcarrier frequency band within the channel and PRB). An example of this resource grid system and its usage is illustrated in Figure 13.

Each subframe/cell can be seen as single transmitted packet, and certain positions inside a frame are dedicated to certain functions. For example, the first subframes in the LTE frame are dedicated for Broadcast Channel (BCH) which carries Master

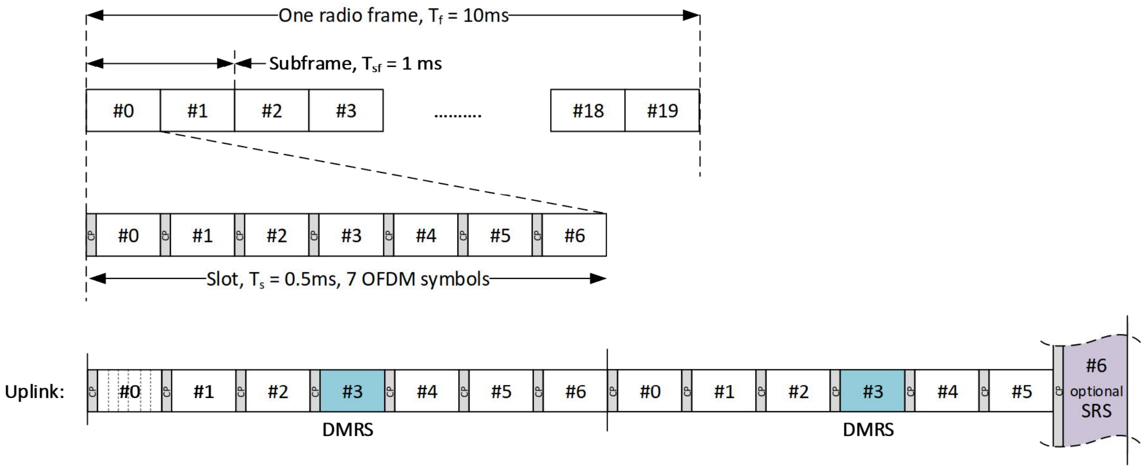

Figure 12: LTE framing divided to radio frames in which consists two slots and up to 14 symbols. [27, 42]

Information Block for cell identification. In uplink, symbol #3 accommodates the Demodulation Reference Signal (DMRS) used in uplink demodulation at the eNodeB, to estimate the frequency and timing offset of the subframe. Additionally, the last symbol of the slot can be dedicated for an optional, wider bandwidth Sounding Reference Signal (SRS), which is used to estimate the channel quality. SRS is transmitted by the UE on the eNodeB's request, and covers multiple physical resource blocks (PRBs). When using the TDD-mode the resource grid dedicates some of the subframe-PRB sections for UE uplink transmissions. Medium Access Control layer controls the usage of the uplink resource cells. [27]

4.4.5 Random Access

To initiate an upper-level RRC connection with the eNodeB and transmit data to it, the user equipment need to establish frequency and timing synchronization. This initial synchronization is done using a Random Access procedure, which is one of the most important steps when UE tries to connect to eNB. The random access procedure is managed at the MAC level; the eNodeBs identify UEs, and schedule channel allocations for them. This procedure is known as RACH (Random Access Channel).

Before RACH, the UE must synchronize with the eNodeB's downlink stream using synchronization frames (PSS and SSS). By receiving the downlink synchronization, the UE can receive the Master Information Block of the cell, which is needed for the initial network configuration. According to the information in the network configuration, the UE can initiate the procedure. When the RACH is initiated the UE does not have accurate symbol uplink synchronization with eNodeB. Thus, the RACH signal has the first easily detectable part, which can be used to determine the uplink synchronization, and a second identification part which identifies the

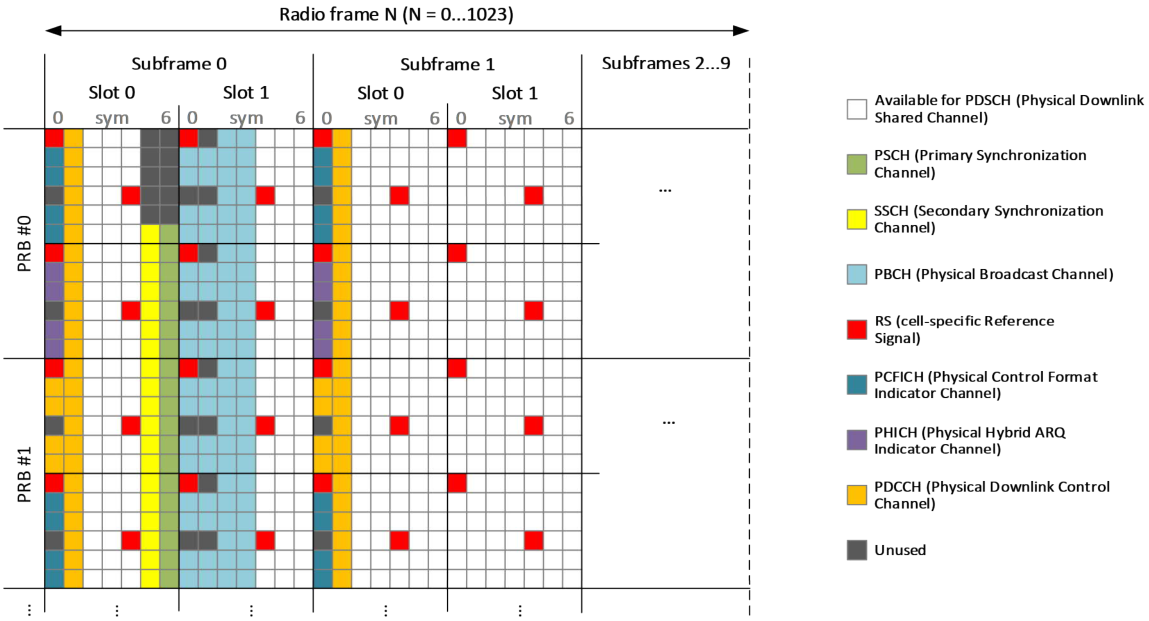

Figure 13: Example of FDD LTE downlink channel as a symbol-subcarrier resource grid in which various cells are reserved for transmission types depending on channel configuration. In FDD-LTE most of the cells are received for user downlink data channel (PDSCH). [27]

contacting device. After receiving the eNB responses with the Random Access Response (RAR), the eNodeB assigns a temporary ID for the UE, and the UE is alloted uplink time and channel regularly.

The physical structure of RACH is designed so that it can be heard over eventual third-party traffic, and doesn't interfere with another transmission. For this reason, the timing of the RACH procedure is not totally random, but aimed at specific subframes depending on RACH configuration, as indicated by the cell's Master Information Block. The physical structure and purpose of the random access procedure in NB-IoT is described in more details in Section 5.4.

To achieve timing synchronization between multiple, in LTE uplink the utilize Timing Advance -method where eNodeB tells each UE how much earlier it should transmit its packet so that the signal is received on the eNodeB inside the correct time slot. Timing advance is relatively to downlink frame synchronization and is different for each UE depending on the distance between. Initially, an UE's timing advance is calculated by the eNB from the timing of the RACH signal, and the timing correction is sent back in the RAR data packet. After the initial synchronization, the eNodeB can use the uplink reference signals - such as the Demodulation Reference Signal (DMRS), transmitted in the middle of each slot - to adjust the UE's timing advance. The maximum initial timing advance defined in the specification is 667 µs, which corresponds to a cell radius of 100 km. After initialization, the timing advance can be adjusted for greater cell sizes. [27][44, page 78]

4.5 LTE in Machine to Machine communication

Due to the increasing need for M2M communication protocols in various IoT application, the 3GPP started in its *Release 12* in March 2015 by specifying key physical layer changes and RF enablers to enhance LTE's suitability for the IoT market As previously defined, in MTC there is less demand for high data rates, no need for voice communication, less mobility requirements, and more infrequent communication. In Table 1, different LTE specifications for MTC are compared by their main capabilities.

The density of machine-type UEs can be significantly higher than the typical mobile phone density. At the same time, MTC UE are generally less mobile and have different Quality of Service requirements. The normal cellular LTE network can handle up to 1000 UEs per cell, and serve simultaneously 50 users per PRB. In massive MTC scenarios, this figure can be as high as 10,000 UEs per cell, if a single long-range eNodeB is used to serve low-throughput IoT devices. [27]

The LTE-M specification, also known as LTE Cat-M1, Cat-M and eMTC (Evolved MTC), was published by 3GPP in *Release 13* to cover for Machine-to-machine (M2M) communication. Due to the loose definition of MTC, the 3GPP technical specification uses the term "Bandwidth-reduced Low-complexity, Coverage Enhancement" (BL/CE) - for the LTE-M1 implementation.

LTE-M's most significant difference with normal LTE is its narrower bandwidth requirement (the channel spans 1.4 MHz (6 PRBs) instead of 20 MHz) while still remaining backward-compatible. The LTE-M link is half-duplex from the UE perspective, and supports full mobility between cells. The network can be deployed in-band utilizing existing networks, making its deployment as a new specification much simpler. [32]

A second LTE specification adaptation for M2M communication is NB-IoT, originally known as LTE Cat-M2. NB-IoT reduces the complexity of the air interface even more compared to LTE-M, allowing the deployment of long-life, battery-operated equipments. The NB-IoT specification is covered in detail in the next section.

	LTE Rel-8 Cat-1	LTE Rel-12 Cat-0	LTE Rel-13 Cat-M1	NB-IoT Rel-13	EC-GSM-IoT Rel-13
DL peak rate	10 Mbps	1 Mbps	1 Mbps	0.2 Mbps	0.5 Mbps
UL peak rate	5 Mbps	1 Mbps	1 Mbps	0.2 Mbps	0.5 Mbps
Duplex mode	Full	Half or Full	Half or Full	Half	Half
UE bandwidth	20 MHz	20 MHz	1.4 MHz	0.18 MHz	0.2 MHz
Maximum transmit power	23 dBm	23 dBm	20 or 23 dBm	23 dBm	23 or 33 dBm
Relative modem complexity	100%	50%	20-25%	10%	Not evaluated

Table 1: Comparison of LTE Cellular IoT specification [32]

5 Narrowband Internet of Things

In this section, the concept of Narrowband Internet of Things (NB-IoT) is introduced, and the relevant extensions to the LTE specification are described. The discussion concentrates on the physical-level downlink and uplink definitions, and on Medium Access Control.

5.1 Background

The first NB-IoT specification was released in August 2016 as a part of 3GPP's *Release 13* specification, and later extended in *Release 14*. The work for specification development was originally initiated in the GSMA NB-IoT Forum guided by 3GPP and industry contributors, such as Nokia, Alcatel-Lucent, and Ericsson. The NB-IoT specification was originally referred to as LTE Cat-M2, or a second-type LTE specification for Cellular IoT Machine Type Communication, which was derived from the LTE Cat-M1 specification, to define an even lower-power variant of the specification. LTE-MTC (LTE Cat-M1) was originally defined in the previous *Release 12*. [36]

The idea behind NB-IoT is to adapt the LTE protocol to use less power than needed on a mobile cellular network, while retaining the use of similar technologies for easier integration with existing mobile infrastructure; a NB-IoT network can co-exist with the LTE network, and possibly use parts of the infrastructure, including the eNodeB hardware and the Core Network. NB-IoT uses a similar access scheme and core network architecture than LTE, and can be considered a lightweight air interface built on top of an optimized LTE network architecture. [35, 36] While LTE-MTC was a simplified but backward-compatible variation of the LTE specification, in NB-IoT the backward comparability was broken to simplify the design of the radio modem. Most of the LTE-Advanced features are not supported in NB-IoT, such as carrier aggregation, dual connectivity, and device-to-device services.

Most of the technical changes implemented in NB-IoT from the standard LTE specifications can be derived from the need for lower power consumption and simpler hardware requirements. Each base station will be capable of serving up to around 55000 devices in its cell (thus providing for about 40 devices per household, in an area with about 1400 households per square kilometer). NB-IoT will efficiently support devices with low data rates (i.e. a few hundred kilobits per second maximum throughput) in exchange for simplicity and low cost ($5 or less) and significantly increased radio sensitivity (deep indoor coverage). The NB-IoT basestations are called eNodeB, as in the case of LTE. The network can be deployed as a stand-alone network, or using parts of the existing LTE eNodeB infrastructure.

The uplink data rate capacity of an NB-IoT connection depends on number of used subcarriers/tones. In multi-tone mode, the usable data rate can be up to ~50 kbps, and in single-tone mode up to ~20 kbps. The number of tones depends on the UE's capabilities. The downlink data rate ranges from 20 to 200 kbps using a single physical resource block (PBR). [35, 36, 31]

NB-IoT requires ultra low power consumption, enabling a battery life of up to 10 years with a battery capacity of 5 Wh for devices that only transmit a few bytes a day. For the user equipment (UE), the NB-IoT connection is treated as half-duplex, simplifying the design of its RF front-end. From the eNodeB's perspective, though, the communication is full-duplex to achieve better utilization of the spectrum. [36, 31] The maximum User Equipment transmit power is 23 dBm (200 mW). NB-IoT also brings improved indoor coverage, low delay sensitivity (allowing slower command processing), and lower hardware requirements. This helps bring down the UE cost, with radio equipment in devices costing $5 or less. NB-IoT standard is thus suitable for applications with stringent size or power requirements. The cell coverage radius can extend up to 100 km, with a Maximum Coupling Loss (MCL) of 164 dB. [35, 36]

To simplify protocol, the NB-IoT specification doesn't allow mobility between the UEs like LTE-MTC and mobility is allowed only in RCC idle mode. This means that if the UE moves away from the eNodeB, the network cannot perform a hand-over to another eNodeB as in LTE. Instead, the connection times out, and the UE must search and reconnect to a new eNodeB. Generally in M2M and IoT communication, constant connection from a moving vehicle is not prioritized as much as in mobile cellular network and in many application the device is stationary by its nature. [35, 36]

5.2 Deployment

One of the main benefits of cellular IoT networks is their close integration to existing mobile networks, and the possibility to coexist with operating mobile networks with minimal interference. The NB-IoT specification has been designed to operate in three different modes, depending on the ambient mobile network. These modes or deployment methods are in-band, guard band, and standalone. They are illustrated in Figure 14 relatively to a co-existing LTE carrier.

Under the in-band and guard-band configurations, the IoT network operates in a licensed GSM or LTE band besides an existing network. It can also use the same eNodeB hardware as the coexisting cell. NB-IoT network cell can co-exist with LTE, UMTS and GSM cells in the same frequency band. When deployed in in-band configuration One or more physical resource blocks between LTE carriers are dedicated for the IoT network. The resource assignment between the LTE and NB-IoT is not fixed. However, not all resource blocks within the LTE carrier can be used, due to conflicts with LTE synchronization signals. With the guard-band configuration, the IoT network is place on the which is normally reserved for . In both configurations, the NB-IoT carrier must be orthogonal with the coexisting LTE PRBs. [36, 35]

In-band and guard-band deployment methods try to minimize frequency use, and utilize existing bandwidth allocations. This way, they are easy and cheap to implement for operators with an existing LTE network. GSM frequencies (700 MHz, 800 MHz, 900 MHz etc.) or higher-frequency LTE bands around 1-2 GHz may be used. Bands can be chosen, for example, from existing GSM frequency pairs, where the two frequencies are 45MHz away from each other.

In the standalone configuration, the NB-IoT network can work independently

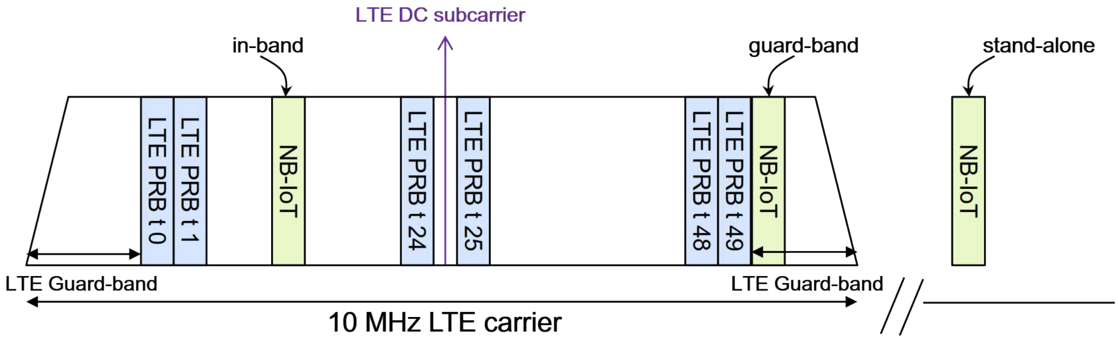

Figure 14: Three NB-IoT network's deployment options (In-band, Guard-band and stand-alone) relatively to existing LTE carrier. [35]

from other networks (which was not permitted by LTE-MTC). This enables an LPWAN-like deployment, where only the local IoT network is created. The standalone configuration's the minimum bandwidth requirement is 180 kHz + 2x 10 kHz guard band at each edge. In Frequency Division Duplex (FDD) configuration, uplink and downlink use separate frequencies, and the UE either receives or transmits (half-duplex). [36]

Even though the NB-IoT specifies to use only one single PRB covering 180 kHz bandwidth for communication, in Multi-Carrier Configuration, the eNodeB can use multiple PRBs if allocated. Each UE still operates on a single PRB at a time. The eNodeB uses an additional carrier channel for the anchor carrier, and can command UEs to operate on another less-occupied frequency if needed. After this reassignment, the UE still operates using a single downlink and uplink frequency carrier. [36] [41, Section 5.5a]

5.3 Downlink

Similarly to LTE, NB-IoT uses the OFDM scheme to divide the frequency band into multiple subcarriers which can be operated nearly independently. Each OFDM symbol is transmitted with a cyclic prefix, to protect against multipathing and symbol timing offset. Cyclic Prefixing is used with the same configurations as in LTE [35]. (TS-36.300: Section 5.1.1a: Basic transmission scheme based on OFDM for NB-IoT)

NB-IoT is specified as a half-duplex FDD link on the User Equipment side, meaning that there is no requirement for the UE to be capable to simultaneously transmit and receive. Yet, the eNodeB must be capable of full-duplex communication to be able to serve other UEs on adjacent subcarriers. Duplexing between downlink and uplink is done under eNodeB's control, so that no UE downlink transmission is carried out during an uplink time slot. Between every switch from UL to DL (or vice versa), there is at least one guard subframe (SF) for the UE to be able to do the necessary processing and switching. [36]

NB-IoT offers two numerology options. Nominal 15 kHz sub-carrier spacing (with normal or extended CP) and narrower 3.75 kHz sub-carrier spacing are available.

With the 15 kHz sub-carrier spacing, the channel parameters are similar to those in the LTE PHY. In the 3.75 kHz mode, the symbol rate is lowered to achieve narrower bandwidth. With 15 kHz sub-carrier spacing, the 180 kHz bandwidth is divided for 12 subcarriers. For carrier modulation, NB-IoT may only use lower-order BPSK and QPSK modulation techniques. Tail-Biting Convolutional Coding (TBCC) which Code rate can be varied by puncturing rate. Turbo code error coding is not supported as in LTE, due to its complexity, which would be incompatible with low-power devices. [36]

The NB-IoT up/downlink channels are divided into five downlink and two uplink physical channels, which have different physical appearance, structure and timing in the air. These NB-IoT physical channels are:

- NPBCH: Narrowband Physical Broadcast Channel
- NPDSCH: Narrowband Physical Downlink Shared Channel
- NPDCCH: Narrowband Physical Downlink Control Channel
- NPSS: Narrowband Primary Synchronization Signal
- NSSS: Narrowband Secondary Synchronization Signal
- NPUSCH: Narrowband Physical Uplink Shared Channel
- NPRACH: Narrowband Physical Random Access Channel

In LTE, there are three extra downlink and one extra uplink physical channels, which were removed in NB-IoT for simplicity. [41]

Narrowband Physical Broadcast Channel

Narrowband Physical Broadcast Channel, NPBCH for short, is the main downlink broadcast channel used to send cell-wide information to all the user equipment. NPBCH is used, for example, to carry the network Master Information Block (MIB or MIB-NB) which describes the current network configuration. The MIB is needed to establish an active connection with the node. [36, 43]

Narrowband Physical Downlink Shared Channel

Narrowband Physical Downlink Shared Channel, or NPDSCH for short, is the main downlink traffic channel which is used to transfer user plane data to the UE. NPDSCH carries the downlink Shared DL-SCH and Paging Channel (PCH) for NB-IoT UEs. The maximum Transport Block Size (TBS) of NPDSCH is 680 bits. In comparison, without spatial multiplexing, LTE supports TBS greater than 70,000 bits. [35, 36, 43]

Narrowband Physical Downlink Control Channel

Narrowband Physical Downlink Control Channel, or NPDCCH for short, is used to inform the NB-IoT UE about the resource allocation of Downlink Channel (DL-SCH) and Paging Channel (PCH). Additionally, NPDCCH carries a Downlink Control Indicator (DCI) field, similarly to LTE. This DCI carries both downlink and uplink resource allocation information (e.g. whether the uplink resource is persistent or non-persistent), as well as descriptions of the downlink data transmitted to the UE. [35, 36, 43]

Narrowband Synchronization Signals

To establish time and frequency synchronization, NB-IoT uses three signals; the Narrowband Primary Synchronization Signal (NPSS), Narrowband Secondary Synchronization Signal (NSSS) and Narrowband Reference Signal (NRS). These signals are regularly transmitted by the eNodeB. The UE uses these synchronization signals to achieve radio frame, subframe, slot and symbol synchronization in the time domain. NPSS is used to discover the cell during the cell search, by identifying the center of the channel bandwidth in the frequency domain. [35]

The Primary Synchronization Signal (NPSS) is transmitted in subframe #5 in every 10 ms frame. The NPSS is used to identify the cell, and is used in cell search and initial connection. NPSS detection is one of the most computationally-demanding operations from a UE perspective. Synchronization signals use length-11 Zadoff-Chu sequences to ensure reliable reception. Also by using different synchronization signaling schema than LTE network, the NB-IoT network avoids possible signal miss-reception in in-band configuration. The secondary synchronization signal (NSSS) is transmitted by the eNodeB periodically every 20 ms. The NSSS is used to acquire the Cell ID and frame timing, and contains the necessary information to decode the downlink broadcast channel (NPBCH). [35, 36] A third type of synchronization reference signal (Cell Reference Signal, CRS), called the Narrowband Reference Signal (NRS), can be used to measure channel metrics such as the Reference Signal Received Power (RSRP) and the signal-to-interference and noise ratio of the reference signal (RS-SNR). In Figure 15, the positions of the synchronization signal in the time-subcarrier resource grid are illustrated. [27, 36]

5.4 Uplink

The NB-IoT uplink transmission can support multi-tone and single-tone transmission schemes, depending on the desired uplink data rate and UE capabilities. Multi-tone transmission is based on SC-FDMA, similarly to LTE, with the same 15 kHz subcarrier spacing, 0.5 ms slot, and 1 ms subframe as LTE. This modulation scheme is known as Class-1 modulation. Additionally to the LTE specification, in the simplified single-tone mode, the UE can only transmit using single-subcarrier signal. The single-tone transmission mode supports two numerologies: 15 kHz and 3.75 kHz subcarrier spacing using BPSK. Depending on the number of used tones, the uplink data rate can be up to ~50 kbps for multi-tone, and ~20 kbps for single-tone. In both

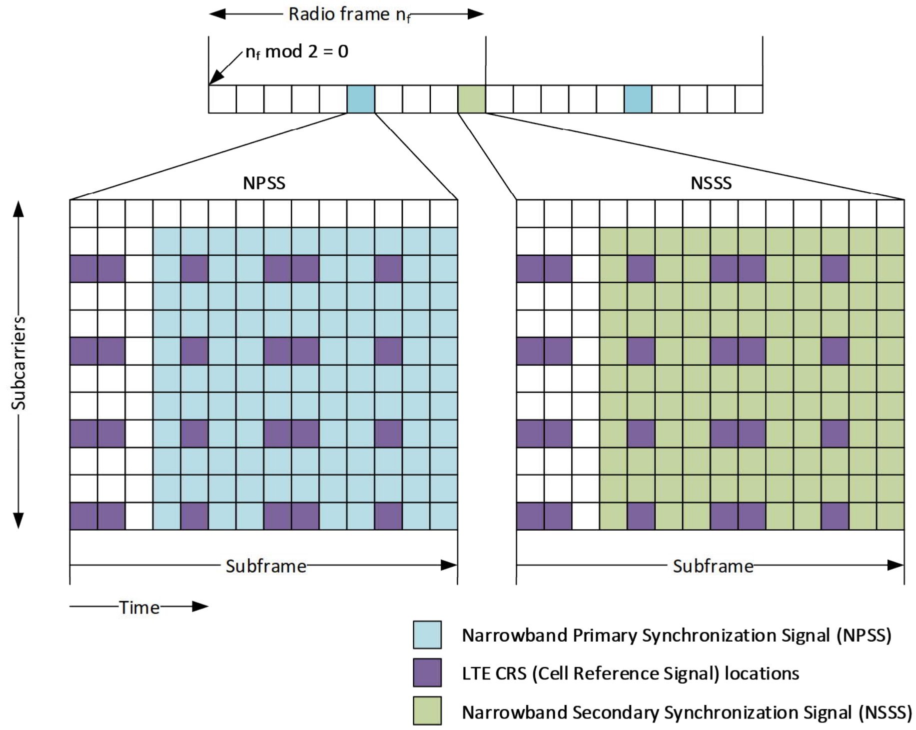

Figure 15: NB-IoT downlink synchronization frames (NSSS and CRS signals) and their positioning in subcarrier-time resource grid [36].

schemes, NB-IoT uses only lower-degree Phase Shift Keying (PSK) modulations; $\pi/2$-BPSK, $\pi/4$-QPSK and $\pi/8$-8PSK (Class-2 modulation), compared to LTE's uplink which uses high-degree Quadrature Amplitude Modulation (QAM) techniques up to 64-QAM. [36] [41, Section 5.2]

Similarly to the LTE air interface, the uplink signal synchronization is delivered inside each slot (Figure 12). To achieve timing and frequency synchronization, NB-IoT uplink uses two reference signals: the Demodulation Reference Signal (DMRS) and the Sounding Reference Signal (SRS). DMRS is a synchronization signal present in each slot, which can be used to receive individual transmission. DMRS is transmitted on 4th or 5th block of the slot, depending on subcarrier spacing. A similar mid-slot reference signal is used in the LTE air interface (Figure 12). The DMRS signal uses a so-called Zadoff-Chu sequence for secure reception. Characteristics of the Zadoff-Chu sequence are described later in the section. [41, Section 5.2.4] The second type of reference signal is the Sounding Reference Signal (SRS). SRS can be transmitted by any UE at the eNodeB's request, and covers the whole physical resource block. The purpose of the SRC is to sound the signal environment between the UE and eNodeB. Based on the sounding result, the eNodeB can switch the UE to operate on different subcarriers for better reception. The SRS is always transmitted as the last symbol of a slot (symbol #7). [36]

To operate, the NB-IoT uplink has three synchronization requirements: symbol timing acquisition, by which the correct symbol start time is determined; carrier frequency synchronization, which mitigates the effect of frequency errors resulting from Doppler shift and errors from electronics; and sampling clock synchronization.

Narrowband Physical Uplink Shared Channel

The physical NB-IoT uplink consists two channel types, the Narrowband Physical Uplink Shared Channel (NPUSCH) and the Narrowband Physical Random Access Channel (NPRACH), which differ in physical representation and usage. From these frames types the NPUSCH is main frame type which is used to deliver both user and control data between UE and eNodeB, and vastly simplifies the LTE uplink channel formatting. [35]

NPUSCH is used to carry the upper-level Uplink Shared Channel (UL-SCH) information, as well as Hybrid Automatic Repeated Request (HARQ) acknowledgement and non-acknowledgement (ACK/NACK), in response to downlink transmission for the NB-IoT UE. The maximum Transfer Block Size (TBS) of an NPUSCH packet is 1000 bits.

At a higher level, NPUSCH packets can be divided into two types: Format 1 and Format 2. The Format 1 is used for general data uplink, and can utilize multi-tone transmission allocating 12, 6 or 3 subcarriers. The Format 2 NPUSCH packets is used for HARQ and MAC-level control channel which carries packet acknowledgements and other control information. The Format 2 can use only single-tone transmission and supports repetition codes for increased reliability. [35, 36] [41, Section 5.2.3a]

Narrowband Random Access Channel

To establish a connection to the eNodeB, the User Equipment uses a random access channel procedure called Narrowband Physical Random Access Channel (NPRACH). User Equipment transmit the NPRACH signal after establishing synchronization of the cell broadcast synchronization signal, and receiving the cell configuration information. The random access procedure has been designed to cause minimal interference to other users due to lack of uplink timing and frequency synchronization. [35] [41, Section 5.2.5a]

The NB-IoT NBRACH procedure differs significantly from LTE's Physical Random Access Channel (PRACH), which is designed to cover six resource blocks of uplink subframes which corresponds 1.08 MHz bandwidth. Due to the 180 kHz total bandwidth for NB-IoT systems, using LTE PRACH is not possible. [54, 44]

Due to lack of timing and timing synchronization, NBRACH uses so-called Zadoff-Chu (ZC) sequences. These signals have a Constant Amplitude Zero Autocorrelation (CAZAC), and have a very low PAPR, which makes it possible to use higher transmission power for the handshake, and thus extends the cell coverage. ZC sequences present very good autocorrelation and cross-correlation properties that make them perfect candidates for the PRACH procedure. NPRACH is based on a legacy LTE procedure (PRACH), but instead of transmitting one really wide burst, NPARCH uses single-subcarrier wide frequency hopping transmission. The hopping pattern consist of two layers: inner fixed size, and outer pseudo-random -hopping sequence.

Each transmitted ZC sequence is orthogonal to adjacent carriers. An example of the hopping pattern is illustrated in Figure 16. [35, 54, 44]

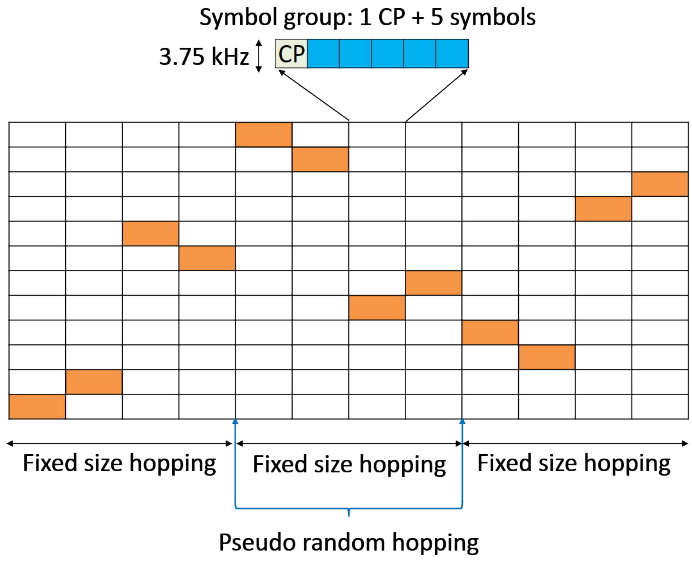

Figure 16: NB-IoT uplink uses a random access frequency hopping patterns for reliable low bandwidth "handshake" to connect to the eNodeB station [54].

One of the purposes of the random access procedure is to establish the UE-specific timing advance for timing synchronization. Without timing synchronization, the orthogonality of the uplink cannot be ensured. The initial timing advance correction set in the RACH procedure (defined in MAC RAR frame) can be up to 667.7 µs, and the maximum correction per update frame is up to 16.7 µs. These flight times corresponds 200 km and 5 km distances limiting the maximum cell size to 100 km. [44, page 78] [36, 27]

5.5 Scheduling and Medium Access Control

The purpose of the Medium Access Control (MAC) is to control the usage of the common transfer medium so that each device can access a common medium in a controlled manner - for example, ensuring that each device is alloted some time to use the medium, so that transmissions don't collide with each other. In NB-IoT and LTE, each cell has a frequency-time domain resource grid for uplink and downlink, of which the "cells" can be reserved for various needs (as illustrated in Figure 13). In LTE uplink, each eNodeB has one or more physical resource blocks which are dedicated for its use. By using the Narrowband Physical Downlink Control Channel, the eNodeB can indicate which subcarriers/slots are reserved for the UE for possible uplink transmissions. [16, 27, 36]

NB-IoT uses asynchronous adaptive Hybrid Automatic Repeated Request (HARQ) for both downlink and uplink. HARQ has two main methods: ARQ (Automatic Repeated Request) and FEC (Forward Error Correction) using Tail-Biting Convolution

Coding (TBCC). This allows more reliable higher latency communication, with a longer decoding time allowed for the UE, tolerating report latencies of 10 seconds at the logical level. [36]

5.6 User Equipment

As mentioned previously, the User Equipment (UE) design is at the center of the NB-IoT specification. The eNodeB does not expect the UE to receive data when it is scheduled to transmit, or less than one subframe after the transmission is expected to end (half-duplex operation). The maximum UE transmission power is limited to 100 mW (20 dBm). By having lower bandwidth requirement for the UE, the NB-IoT allows to UE hardware to run on lower sampling rate reducing need signal processing. A single antenna port (i.e., user equipment) is capable of tracking only one reference signal and a single HARQ process compared to full LTE specification. [35, 36]

To achieve 10-year battery life NB-IoT implements many Power Save Modes (PSM). can be reached, if the UE transmits only 200 bytes of data per day. The specification implements enhanced Discontinuous Reception (eDRX) cycles, during which the user equipment can enter deep sleep mode by turning its radio off for up to 40 minutes. During the eDRX cycle the eNodeB excepts the UE to stay inside the cell and queue the its messages. After the cycle UE returns to listening mode for limited duration to receive possible paging messages from eNodeB. After this the UE will start a new eDRX cycle. The full LTT specification limits the the eDRX cycle up to 2.56 seconds. [35, 36, 66]

6 Cellular Machine to Machine Satellite Network

In this chapter, a concept for a M2M satellite communication system and usage of an NB-IoT air interface for space-to-ground communication are evaluated. This chapter analyses the general suitability of the NB-IoT infrastructure and the challenges of using the NB-IoT air interface on satellite downlink and uplink scenarios.

6.1 Concept

Due to a demand for more advanced M2M communication and limitations of currently existing mobile satellite networks, the idea of extending the existing terrestrial network to space has become more appealing. Combination of LPWAN and satellite network has become interesting concept both in technical and business perspective and telecommunication companies around the world has started to investigate the possibilities of adaptation of mobile standards to satellite communication.

Many commercial satellite data providers, such as Iridium and Orbcomm, offer communication solutions for M2M communication. However relies on a proprietary protocols limiting the general competition on the device market. Usage of widely adapted communication standards for satellite communication, like with digital television broadcast networks, could benefit the evolution on both technical and business side. Also the current generations of the Iridium and Orbcomm networks can be seen to be limited by the possible number of ground terminals. Both Iridium and Orbcomm have increased network data throughput and user capacities in their recent satellite upgrades but exact numbers of the network's capabilities and scalability are not known. [21, 23]

One possibility to develop the future satellite M2M networks is to adapt existing and upcoming mobile communication standards for satellite use. Recently released Cellular M2M and IoT specification offers interesting application for satellite communication. The possibility of usage of NB-IoT is investigated in this chapter.

LTE network protocol and infrastructure have been designed for terrestrial use and thus the specification includes designed choices which are not favorable for ground to space communication. More commonly, satellite links are used to connect the LTE eNodeB's network to the backbone infrastructure, instead of using it to connect the user equipments to a satellite basestation. These two conceptual ideas are illustrated in Figure 17. At the time of writing, only few mentions about using LTE systems for satellite communication were found.

On the LTE research field, Papaleo et al. describe the problems caused to the LTE's HARQ functionalities by the long propagation delay for a geostationary satellite scenario, and proposed possible fixes [47]. Also, Francesco Bastia et al. propose a series of advanced solutions for signal PAPR reduction techniques, improvements to the Random Access procedure, and methods to maximize the system capacity in large round-trip time situations. [48] Otherwise, the LTE air interface's suitability has not been discussed much. Applying the complete LTE air interface to satellite communication is problematic, and rises new technical challenges. NB-IoT specification offers similar but simplified air interface compared to complete LTE specification.

IoT Satellite Service Architectures

Classical communication satellites are either broadcasting or Internet relaying satellites which have been mainly designed to provide direct real-time connectivity between different ground locations. Direct relay connection require simultaneous connection to both ends of the chain; otherwise, the link can be relayed via other satellites using inter-satellite communication.

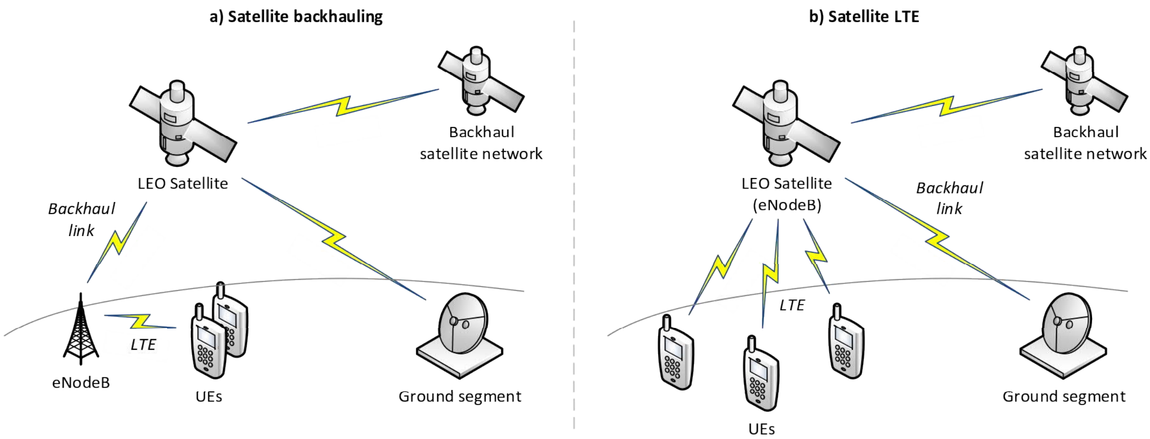

Figure 17: a) Satellite backhauling for terrestrial LTE network and b) LTE used for space-to-ground link

M2M satellite networks can be used for example maritime, smart agriculture, defense, mining applications in which require low throughput and direct connectivity to ground segment is rarely needed. Due less restrictive requirement, M2M satellite connectivity can be used to deliver different service than just direct Internet connectivity.

For example, satellite services exist, which provide regular, non-realtime data transfer to the ground. During a overpass a IoT node can push telemetry information to the satellite's storage which is then later downlink to the ground segment when ground segment connectivity is available. A concept of remote IoT terminal data collection service is illustrated in Figure 19. This "carrier pigeon" concept can be operational even at lower altitudes and with low satellite network coverage. In Figure 18 is simulated a sparse 27 satellite M2M constellation which can give 2 hour revisit time for every ground location. Even more sparse constellations with longer revisit time could give benefits for many IoT applications. Even with a single satellite polar orbiting satellite, a global ones per day coverage can be achieved.

Another M2M data delivery concept is a global firmware broadcasting networks, originally proposed in the ESA Advanced Research in Telecommunications Systems (ARTES) programme [63]. In this concept the satellite network would be utilized as a broadcasting network for essential firmware and configuration data. The ground terminals could receive management information during the satellite overpass without active requesting.

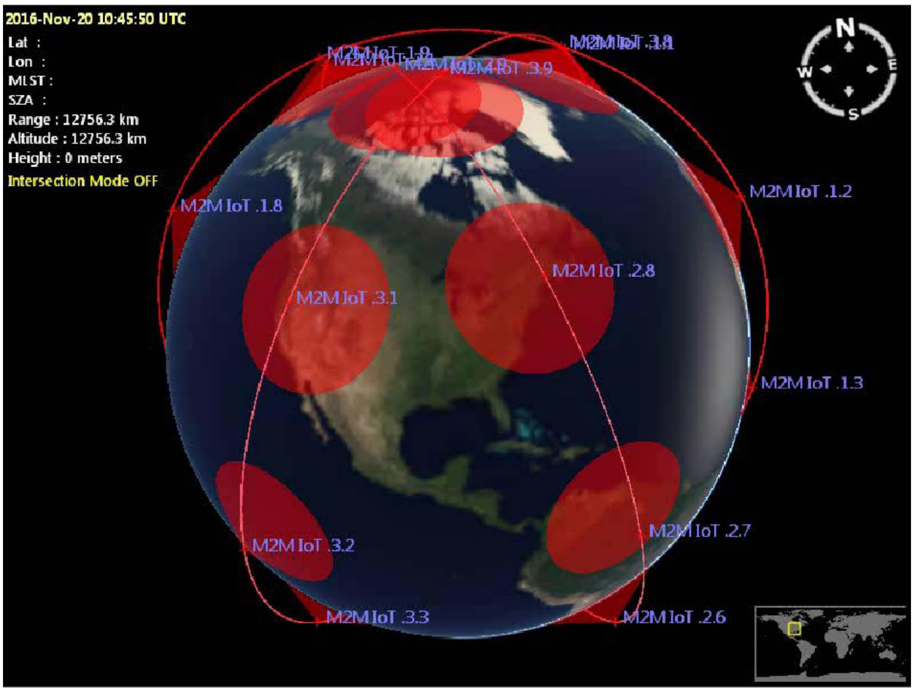

Figure 18: Example of simulated sparse 27 satellite M2M IoT constellation which gives two hour revisit time for every ground location [64]. Many IoT applications could benefit even more sparse communication constellations.

6.2 Challenges

Space-to-earth communication faces multiple challenges from the LTE air interface's perspective. It requires wide mobility support from the eNodeB, as in this situation, the eNodeB is moving instead of UE. However, the NB-IoT specification dropped many mobility features when compared to the parent LTE specification.

One of the most significant obstacles is the carrier frequency offset caused by the orbital movement and the Doppler shift. Each ground terminal experience satellite's carrier frequency in different due relative velocity and thus the shift cannot be corrected by the satellite. Additionally, it is hard to separate the effects of Doppler CFO and clock non-idealities on measured frequency offsets. Clock non-idealities remain nearly constant over longer time periods, while the offset caused by Doppler shift continuously varies depending on the phase of the overpass. The LTE air interface has been designed to operate normally with device velocities up to 120 km/h, and can be functional in speeds of 250 – 350 km/h or 500 km/h depending on frequency band selection, before the worst-case Doppler shift breaks modulation orthogonality. [27, 56] At a carrier frequency of 2 GHz, this speed represents a maximum Doppler shift of f_{dmax} = 45365 kHz to LEO (at range velocity 6.8 km/s), which is significantly larger than a LTE's 15 kHz subcarrier spacing. A normal user on a terrestrial LTE network can only experience such speeds inside airplanes, and high-speed Maglev trains, which travel at up to 430 km/h.

The second apparent challenge in ground-to-space communication is the significantly greater distance between the eNodeB and the UE; for example, the distance between a ground terminal and a satellite in a circular 600 km LEO orbit varies from 600 to 2500 km. (Figure 20) In the NB-IoT specification, the Maximum Coupling Loss (MCL) can be 164 dB. The Free Space Loss caused by a 2500 km propagation distance (distance to LEO at 0 degree elevation) is 166 dB, resulting in the link margin theoretically being near closing in a line of sight connection, and no other losses are experienced. The increase in free space loss can generally be compensated by increasing the directivity of the antennas and transmission power.

In addition to the increased free space loss, the distance affects the signaling delay. For a similar 600 km LEO scenario, the latency caused by signal propagation is between 4 – 8 ms. An increase in signal propagation delay affects timing in the link level Medium Access Control. In case of a direct overpass, the distance can diminish from 2500 km to 600 km in less than 6 minutes (at 5 km/s), which causes a continuous drift in timing synchronization. Due to change of signal propagation delay and synchronization signal needs to be corrected constantly. Thus, the drift rate in LEO communication scenario can be estimated to be up to 23 ppm. This drift rate remain nearly linear in short time scale during the pass and can be estimated using mathematical estimation algorithms and active measurements.

The network scalability creates a clear third challenge for the satellite network. From the low Earth orbit a single satellite can easily provide coverage for the whole Earth but it must be also capable to serve as many client. Thus, satellite's large coverage sets a number of new technical challenges for the link. Increasing the number of simultaneous satellite on highly dense areas is not possible. Increase of the number of satellites in the constellation increases mainly the revisit time of the network instead of balancing the spatial demand for the network.

Deployment

NB-IoT and other cellular IoT are designed to coexist by sharing partly the same frequency allocation. In this In-band deployment the spectrum packing can be done by utilizing the orthogonal nature of different carrier signals and similarities on the radio front-end. NB-IoT can be also deployed independently in standalone-configuration with any other network or frequency allocation. This is crucial for the space deployed network. In-band or guard band deployment methods and co-existence with LTE or GSM network are not possible due to significant frequency error caused by Doppler effect and synchronization issues. Each cell must have at least 200 kHz bandwidth including guard band at the edges. Different satellites in the constellation may share same frequency allocation if the ground footprint of the satellites does not overlap.

Wireless communication link capabilities depends on the selected frequency band and available bandwidth on many way. Generally due to better availability of wider bandwidths, high frequency band from 2 to 7 Ghz such as S, C, Ku, Ka -bands, are favored in ground to space communication. Though, usage of these bands require highly directional antennas due to increase in free space loss as seen in Equation 1. Large high directional antennas can be problematic for many mobile applications. The IoT applications are size limited and not capable to have antenna pointing.

Due to these fact, lower frequency bands (<2 GHz) are more favourable on mobile satellite systems. For example GPS and Iridium network operate at L-band (around 1.6 GHz). (Usage of this frequency range is assumed later in the work.) These frequencies are also widely reserved for terrestrial mobile networks. High demand for the frequency bands and global coverage of the satellite service can make the frequency licensing difficult. Frequency band significantly affects also to experienced Doppler shift as previously noted in Equation 3. Smaller the experienced Doppler shift between different users, tighter it's possible pack in frequency domain to and thus also favors usage of lower frequencies.

6.3 Cellular Satellite Network

The fundamental idea of cellular architecture is to decentralize the wireless Radio Access Network (RAN) between user equipment while still keeping the necessary core network centralized (Illustrated in Figure 7). This way the network can be operated as a single larger network at thought the cellular access network is distributed. The similar concept can be partly modified for satellite basestation architecture. Satellite ground footprint forms the cell in which near-static ground terminals move when the satellite passes over the ground location. This footprint is possible to divide into smaller cells for practical reasons and lower number of simultaneous users per cell.

The Core network is an essential part of the cellular network and the RAN is now able to operate without connection to the cellular operator's core network. Each basestation (eNodeB) must be connected to a number of services (described in Section 4.2) to be operational. In terrestrial network connection to Core Network is implemented by static wired connections which are built as a part of the infrastructure. This backhaul connection can be implemented using other wireless or microwave links, over Internet, or even using relay satellites. [27] For a satellite basestation to be operational, a connection to the core network parts must be ensured using secondary link, "backhauling", or by distributing the core functionalities to the individual satellites and managing the distributed core with another techniques.

Backhauling connection can give constant connection to core network but requires the secondary channel which is used connect to the ground segment. This can be achieved by having dense enough ground station network near operational areas or by backhauling using direct connection inter-satellite links. For example, in Iridium network the satellites use each other to route data to other ground terminals and stations [21]. For inter-satellite link, eNodeB's backhaul could be also done using geostationary satellites which can provide near-constant connection to the core network. However, usage of GEO satellite relays introduces larger delays to link.

Another way to solve connectivity to core network, is to embed most essential core network, such as subscriber and network management, functionalities to the same satellite the eNodeB is operating and distribute core network. This way the

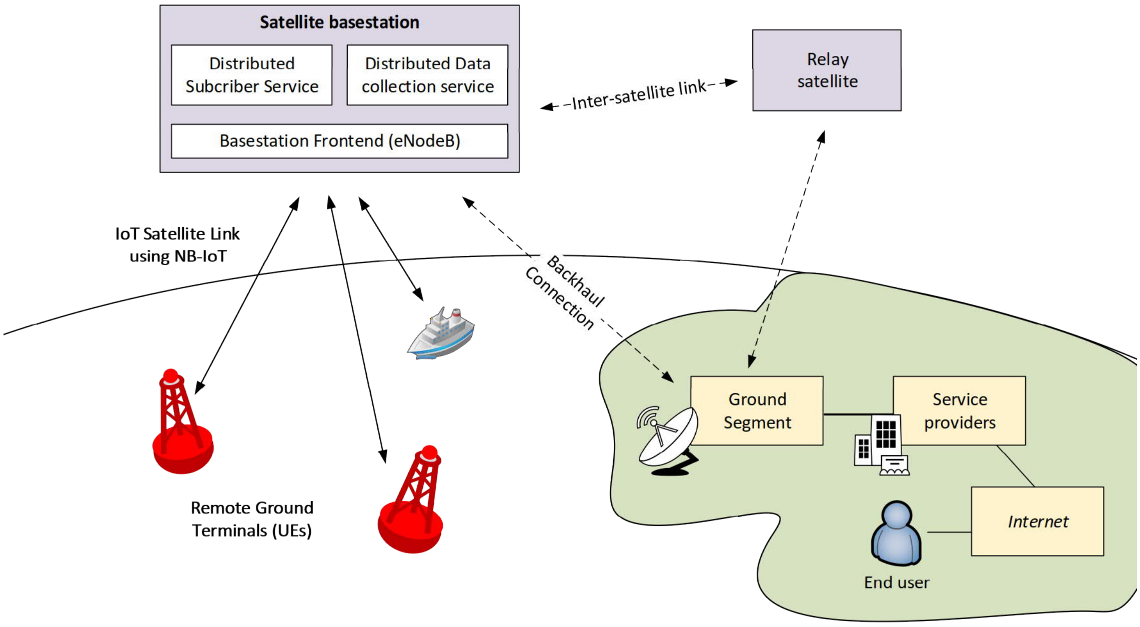

Figure 19: Example of architecture for a satellite NB-IoT network concept.

requirement for constant backhaul connectivity can be eased and the satellite network can be operational for ground terminals under the limitations. In the distributed operation mode, the satellite can offer service, like data storage and configuration management, ground terminals as previous discussed. NB-IoT specification implement services deliver non-IP data (Non-IP Data Delivery, NIDD) and service architecture to provide services without using "power hungry" IP protocol [36].

One essential feature in cellular architecture are the managed user hand-overs between cells when mobile user moves from one cell to another without interrupting the connection. In NB-IoT specification hand-overs considered to be outside of the IoT requirements due to static nature IoT devices and no need for continuous long lasting connections such as phone calls. In cellular satellite network case, regardless of the mobility of the ground user the orbital movement of the satellite limits the time UE is inside the cell thus the connection cannot be carried longer than the overfly duration without handover to another satellite. Handover to another satellite requires large enough satellite constellation to ensure next satellite is reachable before one pass is over. The duration of the pass can widely vary for LEO satellite from few minutes to over ten minutes.

6.4 Downlink

From signal propagation perspective, the LTE air interface can operate over satellite downlink channel. Like in terrestrial scenarios, to be able to receive the satellite downlink signal the ground terminal must in have acquire timing and frequency synchronization with the eNodeB. In satellite communication the synchronization to

Doppler shifted signal can be done by estimating the shift based on locking the local reference clock to known pilot signals. In NB-IoT the cell specific pilot signals are transmitted every 640 ms keeping the frequency shift.

From timing and frequency synchronization perspective, single transmitter OFDM carrier can work without any problem. Because there is only single transmitter each subcarrier gets shifted, due to Doppler shift, equal amount and the subcarriers remain orthogonal. UE as the mobile station must track and compensate this Doppler shift which can be significant compared to total signal bandwidth.

In Figure 20 is plotted a simulated overpass of 600 km low Earth orbit satellite. From simulations, we can approximate the worst case Doppler shift from LEO to ground on 1.6 GHz to be ±34 kHz which is half of the total downlink bandwidth. Max frequency drift 841 Hz/s at zenith and on average 175 Hz/s.

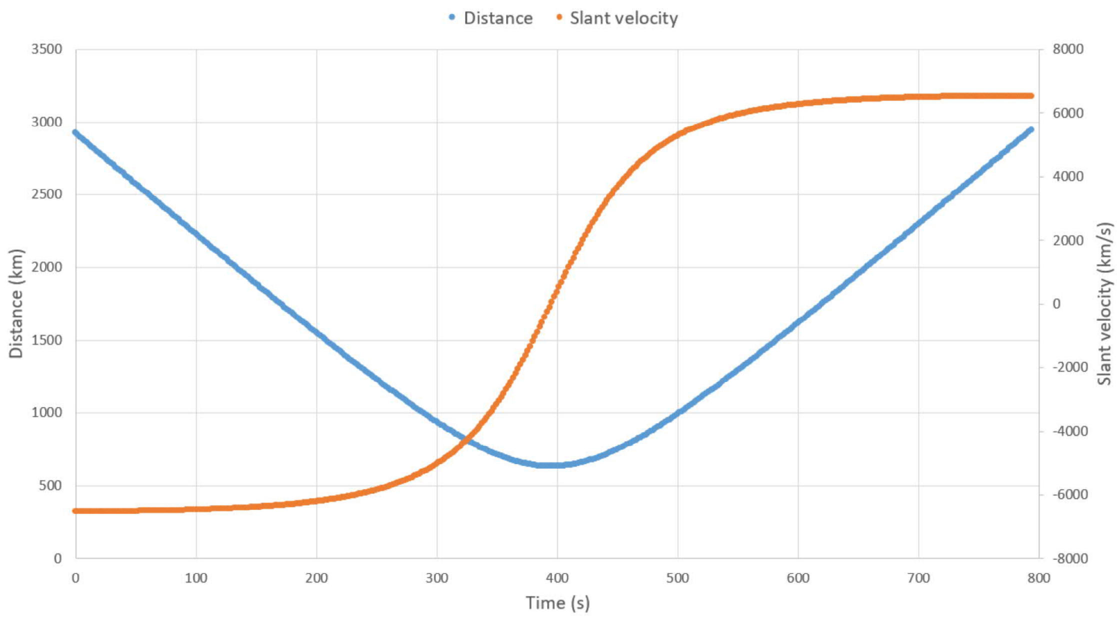

Figure 20: Example of simulated 600 km communication satellite near direct overpass. The experienced Doppler shift due to orbital motion is relative to the slant velocity according to Equation 3.

Due to orbital motion, from UE perspective the eNodeB's symbol timing drifts slowly when the distance between satellite and ground decreases. This timing drift can be corrected from downlink synchronization signals (NPSS and NSSS). eNodeB transmits its primary synchronization signal (PSS) as the fist slot corresponding 10 ms interval. Frequency drift due to Doppler between two synchronization signal can be 8.4 Hz and timing drift 0.2 µs. Cyclic prefixing used in the air interface, offers guard periods to protect against small timing offset. Using normal CP length the timing error can be 4.7 µs before causing inter-symbol interference. When assuming maximum approach velocity of 6 km/s, synchronization must be corrected every 230 ms. Thus, it's possible to maintain the synchronization with the downlink stream by resynchronizing on every PSS without Doppler shift estimation. Previous synchronization error and knowledge of the orbital motion can be also used to estimate small frequency and timing errors.

Peak-to-Average Power Ratio efficiency

Multi-carrier OFDM signal is well-known for its high Peak-to-Average Power Ratio (PARP) due to its Gaussian noise like signal nature when number of subcarrier increases. Due to the high PAPR, the transmitter's power amplifier must operate wide dynamic range to be able to transmit the signal without distortion. This results in low efficiency because the high power amplifier is not operated in its optimal region and power losses are significant when using high power transmission. Thus, OFDM is rarely used in space applications where the transmission power must be high and the same time the available power on the satellite is limited. Especially, in GEO satellite broadcast services the transmission power must be hundreds of watts even when using high gain antennas. By placing the satellite in lower LEO, the EIRP and transmission power requirement decreases.

The development on high efficiency power amplifiers for 4th and 5th generation mobile basestation has improved the high power amplifiers efficiency and linear range on which the amplifier can operate linearly. Also various digital signal processing techniques have been designed to lower the OFDM signal PAPR and to compensate distortion caused by amplifier non-linearity at the amplitude peaks. E. Al-Dalakta discusses PAPR and ICI reduction techniques for OFDM based satellite communication systems in his dissertation. [61] Using these methods make the high PAPR modulation techniques less problematic and it has been estimated by the European Telecommunications Standards Institute (ETSI) that usage of wideband OFDM signaling will be used in space-to-earth links [45]. [59, 49, 61]

6.5 Uplink

In LTE/NB-IoT, the uplink multiple access scheme is based on OFDMA/SC-FDMA systems where users are divided in subcarrier and time domain. As previously discussed, the disadvantages of these methods are the very accurate symbol timing between transmissions and need to frequency synchronization. Frequency offset, due to Doppler shift, can ruin the signal orthogonality resulting inter carrier interference when the subcarriers overlap in frequency domain. Traditionally the issue is solved by allocating wide enough guard bands around the uplink transmission and receiving each uplink stream as an individual stream. This lowers the spectral efficiency of the network and decreasing the throughput. Also reception of many unsynchronized transmissions, compared to OFDM reception, can be considered to be computationally more demanding for the satellite lowering the maximum number of uplink streams.

If the downlink Doppler shift can be estimated from the downlink synchronization signal and because the uplink shift is equal but opposite in sign. NB-IoT allows single tone transmission which lowers bandwidth utilization but is sensitive to frequency offsets and timing errors. The worst case scenario where the experienced Doppler-shifts between are $-f_{Doppler}$ and $f_{Doppler}$ are relatively rare.

One method for uplink carrier offset compensation is to correct the transmission frequency according to the received downlink synchronization frames and pilot tones. Even if the frequency offset caused by orbital motion gets compensated, frequency offset caused by clock inaccuracies can remain and must compensated in a other way. Different frequency offsets can also combined together to form a more accurate offset estimate, for example by using Kalman filter or other optimal estimation method.

If the downlink Doppler shift can be estimated from the downlink synchronization signal and because the uplink shift is equal but opposite sign. Still not possible to correct the frequency error so well that the uplink transmissions could be orthogonal with each other. Unused guard subcarriers need to be left between transmissions to avoid inter carrier interference.

On the uplink demodulation on the eNodeB is based on orthogonally packet and time synchronized. This way the eNodeB can demodulate the multiple users efficient and minimal. If the timing synchronization is broken the demodulator must detect decreasing the performance and less simultaneous transmission can be received. In uplink, the cyclic prefixing can be used to correct part of the inter-symbol interference caused by to similar to downlink.

Due to the fact that LTE/NB-IoT air interface is based on OFDM. Time scale of the timing advance could be corrected. But requires modifications the LTE Terrestrial LTE networks corrects the timing synchronization caused by propagation delay by having timing advance as large as the maximum cell size. By doing this UEs have timing synchronization on frame/slot level and symbol level. For success full uplink reception symbol level synchronization is needed. Frame/slot level synchronization makes uplink decoding simpler and is required TDD mode. Symbol timing correction can be also possible to base on GNSS a timing reference. This would provide accurate reference which timing error could be compared, but at requires additional hardware for every ground terminal.

In LTE medium access control scheme, the eNodeB allocates the uplink resources to UEs by telling which uplink subcarriers are in use for the UE and in which time slot. Thus, it's possible for the eNodeB to accurately coordinate which subcarrier are being used and also estimate real UEs reception. This can be used to avoid

The second approach for fixing the demodulation problem is to ignore synchronization and accept the decrease in uplink throughput due to additional time-frequency guard areas. Try to receive each UE's uplink signal individually without caring it's accurate synchronization to other transmissions. This is increases significantly the required computational power per uplink stream and lower the throughput. One of the advantages of OFDMA technique is the computationally lightweight demodulation process for multiple parallel transmissions which cannot be utilized anymore.

In uplink in middle of each slot is transmitted Demodulation Reference Signal (DMRS) can be used to symbol synchronization required for the demodulation. In case of NB-IoT the number of simultaneous transmissions is already limited by frequency bandwidth of single PRB to 12 or 48 simultaneous non-synchronized. Also multiple UEs can be multiplexed in time domain when high throughput is not required in the IoT use-case. [62]

One solution to manage multiple users with varying Doppler shifts is to use antenna diversity as part of multiple access scheme. By having multiple directional antenna each antenna-receiver pair can be dedicated for smaller ground terminal group and avoid inter carrier interference in uplink. Antenna diversity makes also possible to use multiple radio frond-ends lowering overall requirements for single transceiver.

In Figure 21 is illustrated the antenna beam pattern used by OneWeb communication satellite. Users inside each beam experiences roughly equal Doppler shift allowing lowering inter-user interference. Also due to directivity, same frequency bands can be used between antennas.

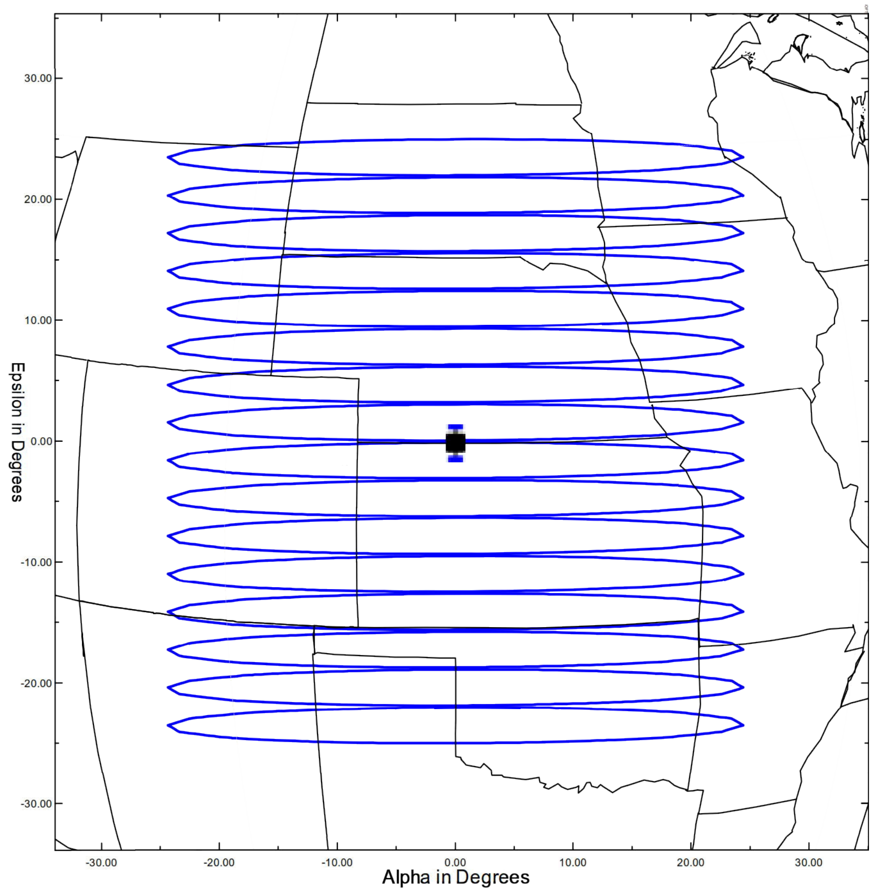

Figure 21: Example of antenna pattern array used for optimize spectrum usage on OneWeb satellite satellite constellation. Each user inside a beam experiences roughly same Doppler shift lowering inter-user interference. [70]

For the Random Access scheme specified in the NB-IoT should not work also for space communication. NB-IoT's NBRACH has designed to tolerate carrier frequency and timing offset in the random access procedure up to certain limit. But a possible concern raises from the possible number of UEs trying to connect to the satellite. If a number of UEs are geographically (in a city e.g.) grouped to together all devices detect the downlink transmission over short time causing a rush of random access overwhelming the eNodeB. This can result the eNodeB's inability to handle all simultaneous random access attempts.

6.6 Ground User Equipment

To achieve an operational satellite IoT network, the ground user equipment require to take special considerations. As noted before the ground user equipment have an own role when establishing connection to the satellite network. For example, the ground terminal must implement features for satellite listening and waiting and have a general concept of the network which not not 100% available. IoT UE can idle/sleep until it receives satellites synchronization signal. Lock on the signal and establish bidirectional connection with the satellite.

Still, to be feasible it should utilize the same hardware components as in terrestrial use and be based on commercial NB-IoT modem and hardware and other existing technologies. Exact modification required to the are difficult to evaluate due to proprietary modem designs. NB-IoT chipsets on UEs also designed to have only limited amount of signal processing power. Due to this fact, the UE might not have the required processing capabilities to do complex distortion and carrier frequency compensation.

NB-IoT specification sets the maximum transmission power of UE to 100 mW which need to be increased due to increased Free Space Loss. Part the of increased losses in the link can be compensated by using more directional antennas which need to be static and omni-directional. No active pointing toward the satellite or knowledge of orbits is required.

7 Conclusion

The ongoing IoT revolution is happening around us and various IoT devices are starting to make a great impact to our life even though we might not realize it. Rise of new application field has accelerated development of M2M communication standards, leading to development of many new LWPAN technologies, such as LoRa, SIGFOX and Z-wave, to fulfill this demand. This trend can be also seen in, for example, many MTC/IoT variants of LTE specification and in plans of upcoming 5G specifications.

Satellite networks for wireless communication has existed since the beginning of the space-age even though a boom for satellite communication has not yet been seen. Nowadays, accessing satellite network, compared to terrestrial networks, is expensive and is generally utilized only when absolutely no other solutions are available. Rising need by IoT satellite communication increases demand for more flexible and versatile satellite communication networks. These new satellite networks could be utilized for example in M2M communications applications, such as cargo and asset tracking systems and environmental data collection and remote sensing research.

Utilization of the LTE specification in satellite communication is less investigated topic due to high complexity of the specification and the problematic nature of the technologies used in LTE.

NB-IoT specification published by 3GPP in 2016 brings a new standardized communication protocol for IoT application. NB-IoT offers a lightweight version of the LTE for M2M communication still having the many benefits of LTE such as existing built infrastructure and core services. The most significant change in NB-IoT compared to LTE-Advance specification is its simplified air interface allowing less resource demanding modem designs. Due to its simplified design and roots in mobile communication standards, its applicability for satellite communication has raised interest [64].

LTE air interfaces most remarkable challenges for satellite use are in usage of Orthogonal Frequency-Division methods (OFDMA) for multiple access, spectrum management and in space communication low latency design. OFDM methods are rarely seen due its high sensitivity for Carrier Frequency Offset (CFO) and timing which can cause significant inter carrier interference and distortions to the signal. In satellite communication frequency offsets caused by orbital motion and long delays caused by signal propagation are natural parts of the link and need to considered in low level protocol design but can be overcome with smart design choices. OFDM techniques suffer also from high Peak-to-Average Power Ratio (PAPR) which decreases the efficiency of the transmission system and can cause significant power losses when high transmission power is required. Due to these facts the OFDM systems have not reach popularity in space applications. New Techniques to compensate distortions caused by amplifier non-linearities have been developed and more OFDM based satellite systems will be seen in the future [45].

LTE network, like its precessing mobile standards, is based on cellular network architecture which relies on small terrestrial radio cells connected core network. Adaptation of cellular architecture, where distributed cell works as a one large using varying backhaul methods, to satellite network can break the network if direct connectivity to ground segment cannot be ensured. Smaller satellite networks might have only rarely connectivity to the ground network making service less operational. By using distributed core network architecture, the satellite network can offer more coherent satellite access even without ground connectivity and develop new kind satellite communication services for machine type communication, for example carrier pigeon -style data storage, paging services, localized configuration firmware broadcast service.

When final extensions of 4G standards are still being under deployment, the upcoming 5th generation of mobile communication standards (5G New Radio) is planned to introduce a completely new air interface and applications. 5G standard tries to bring closer the fusion of mobile communication and M2M/IoT communication so that there could be one wireless application independent infrastructure to which connect in effective manner. In recent announcement by European Space Association, ESA, have been announced its plans to develop and demonstrate the added value that satellite brings in the context of 5G. [73]. Some of the topics covered in this works can be applied also for 5G technologies. [66, 51, 34]

In the future, satellite communication will play more significant role in wireless communication and more everyday IoT and machine to machine application can benefit from new space-assets. New research work around fusion of satellite communication and mobile standards has increased but the applicability of current LTE and NB-IoT specifications for satellite communication is still considered problematic requiring many modifications. This work can be seen as paving the road for next generation mobile and satellite communication standards.

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