OULUN YLIOPISTO
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DEGREE PROGRMME IN WIRELESS COMMUNICATIONS ENGINEERING

MASTER'S THESIS

A USE CASE OF LOW POWER WIDE AREA NETWORKS IN FUTURE 5G HEALTHCARE APPLICATIONS

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Khalil O. (2018) Matalan tehonkulutuksen ja pitkänkantaman teknologian käyttötapaus tulevaisuuden 5G:tä hyödyntävissä terveydenhoidon sovelluksissa. Oulun yliopisto, sähkötekniikan osasto tai tietoliikennetekniikan osasto, sähkötekniikan koulutusohjelma tai Degree Programme in Wireless Communications Engineering. Diplomityö, 85 s.

TIIVISTELMÄ

Pitemmän aikavälin tarkastelussa matkaviestintäteknologian kehittyminen nykyisin käytössä olevaan Long –Term Evolution (LTE) teknologiaan on tarkoittanut käyttäjille yhä suurempia datanopeuksia. Seuraavassa askeleessa kohti 5. sukupolven matkaviestintäverkkoja (5G) lähestytään kehitystä myös laitteiden tarpeiden lähtökohdista. Toistensa kanssa kommunikoivat koneet, palvelimille dataa lähettävät anturit tai jopa ihmisten kanssa kommunikoivat koneet ovat kaikki eri puolia samasta teknologisesta käsitteestä; esineiden internetistä (IoT). Oleellisin ero koneiden välisessä kommunikoinnissa (M2M) ja IoT:ssä on, että erinäiset laitteet tulevat olemaan yhdistettyinä paitsi toisiinsa myös internettiin. Tätä kytkentäisyyttä varten tarvitaan tarkoitukseen kehitetty matkaviestinverkko.

Sekä lähiverkkoja (LAN) että suuralueverkkoja (WAN) on pidetty mahdollisina IoT mahdollistajina, mutta näiden molempien käsitteiden alle kuuluvissa teknologioissa on rajoitteita IoT:n vaatimusten lähtökohdista, joten uuden teknologian kehittäminen oli tarpeellista. Matalan tehonkulutuksen suuralueverkko (LP-WAN) on käsite, johon luokitellaan eri teknologioita, joita on kehitetty erityisesti IoT:n tarpeista lähtien. LP-WAN voidaan jaotella ainakin itse kehitettyihin ja matkaviestinverkkoihin perustuviin teknologisiin ratkaisuihin. Itse kehitetyt ratkaisut on luotu lukuisten yritysten yhteenliittymissä eli liiansseissa ja nämä ratkaisut keskittyvät lisensoimattomilla taajuuksilla toimiviin langattomiin ratkaisuihin, joista esimerkkinä laajasti käytössä oleva LoRa. Matkaviestinverkkoihin perustuvat lisensoiduilla taajuuksilla toimivat ratkaisut on puolestaan erikseen standardoitu 3GPP-nimisessä yhteenliittymässä, joka nykyisellään vastaa 2G, 3G ja LTE:n standardoiduista päätöksistä. Esimerkki 3GPP:n alaisesta LPWAN –luokkaan kuuluvasta teknologiasta on kapea kaistainen IoT –teknologia, NB-IoT.

Tässä diplomityössä keskitytään terveydenhoidon käyttötapaukseen, missä antureiden mittaamaa tietoa siirretään langattomasti käyttäen sekä LoRa että NB-IoT teknologioita. Työssä kuvataan eri vaiheet ja haasteet, joita liittyi kun rakennetaan erikseen tiettyyn kohteeseen LTE –verkon radiopeitto, jotta LoRa:a ja NB-IoT:a käyttävät anturit saadaan välittämään mitattua dataa halutulle palvelimelle säilytykseen ja myöhempää analysointia varten. LTE-radiopeiton rakensi Oulun yliopiston omistama 5G testiverkko, jonka tarkoitus on tukea sekä tutkimusta että ympäröivää ekosysteemiä tulevaisuuden 5G:n kehityksessä.

Avainsanat: 5G, IoT, LPWAN, mobiiliverkko, LTE, LTE suunnittelu, NB IoT, LoRa, anturit, terveydenhoito.

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ABSTRACT

The trend in all cellular evolution to the Long -Term Evolution (LTE) has always been to offer users continuously increasing data rates. However, the next leap forwards towards the 5th Generation Mobile Networks (5G) will be mainly addressing the needs of devices. Machines communicating with each other, sensors reporting to a server, or even machines communicating with humans, these are all different aspects of the same technology; the Internet of Things (IoT). The key differentiator between Machine-to-Machine (M2M) communications and IoT will be the added -feature of connecting devices and sensors not only to themselves, but also to the internet. The appropriate communications network is the key to allow this connectivity.

Local Area Networks (LANs) and Wide Area Networks (WANs) have been thought of as enablers for IoT, but since they both suffered from limitations in IoT aspects, the need for a new enabling technology was evident. LPWANs are networks dedicated to catering for the needs of IoT such as providing low energy consumption for wireless devices. LPWANs can be categorized into proprietary LPWANs and cellular LPWANs. Proprietary LPWANs are created by an alliance of companies working together on creating a communications standard operating in unlicensed frequency bands. An example of proprietary LPWANs is LoRa. Whereas cellular LPWANs are standardized by the 3rd Partnership Project (3GPP) and they are basically versions of the LTE standard especially designed for machine communications. An example of cellular LPWANs is Narrowband IoT (NB IoT).

This diploma thesis documents the usage of LoRa and NB IoT in a healthcare use case of IoT. It describes the steps and challenges of deploying an LTE network at a target site, which will be used by the LoRa and NB IoT sensors to transmit data through the 5G test network (5GTN) to a desired server location for storing and later analysis.

Key words: 5G, IoT, LPWAN, Cellular, LTE, LTE planning, NB IoT, LoRa, sensors, healthcare.

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FOREWORD

This thesis studies a practical use case in one of the projects of the 5GTN which is part of the CWC at the University of Oulu. I would like to start by thanking the 5GTN project manager Olli Liinamaa for giving me the opportunity to join the 5GTN team, I would ever be grateful for him giving me the first step in my career. I would also like to thank my technical advisor Ville Niemelä for his support and bearing with me through all my questions. Lots of thanks also to my thesis supervisor Ari Pouttu for his continuous guidance. Last but definitely not least, I want to thank Arto Matilainen for his encouragement and his positive spirit.

I will always be grateful for the amazing circle of support I had through this journey, special thanks to Silvia, Mina, Abdellatif and Elbamby for supporting me through hard times and the undivided attention they gave me. Above all, I will always, no matter what I reach, be thankful to my parents, to whom I owe everything.

Lastly, a word to whoever is reading this while going through hard times, just always remember that in life there are ups and downs, but it’s you and only you who decides how far up or how far down you go. So just always believe in yourself, believe that you are not the first person going through a hard time, and as it passed for us it will also pass for you.

Oulu 16.05.2018

Omar Khalil

ABBREVIATIONS AND SYMBOLS

1G	1st Cellular Generation
2G	2nd Cellular Generation
3D	Three-Dimensional
3G	3rd Cellular Generation
3GPP	3rd Generation Partnership Project
5G	5th Cellular Generation
5GTN	5G Test Network
5GTNF	5G Test Network in Finland
ACK	Acknowledge
ADR	Adaptive Data Rate
AE	Application Entity
ALS	Average Length of Stay
AMPS	Advanced Mobile Phone System
APN	Access Point Name
BPSK	Binary Phase Shift Keying
BSC	Base Station Controller
BTS	Base Transceiver Station
CAPEX	Capital Expenditure
CAT	Category
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CP	Cyclic Prefix
CSE	Common Services Entity
CSMA/CA	Carrier-Sensing Multiple Access/Collision Avoidance
CWC	Center for Wireless Communications
DevAddress	Device Address
DL	Downlink
EC-GSM	Enhanced Coverage-Global System for Mobile Communications
EDGE	Enhanced Data Rates for GSM Evolution
e-Health	Electronic Health
eMBMS	Evolved Broadcast Multicast Service
EPC	Evolved Packet Core
EPoSS	European Technology Platform on Smart Systems Integration
ETSI	European telecommunications Standards Institute
EVB	Evaluation Board
FCC	Forward Error Correction
FCnt	Frame Counter
FCtrl	Frame Control
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FHDR	Frame Header
FM	Frequency Modulation

FOtps	Frame Options
FPort	Port Field
FRMPayload	Frame Payload
Gbps	Giga Bit per Second
GDP	Gross Domestic Product
GFSK	Gaussian Frequency Shift Keying
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
H2H	Human to Human
HAL	Hardware Abstraction Layer
HetNet	Heterogeneous Networks
HSPA	High Speed packet Access
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
ISM	Industrial-Scientific-Medical
kbps	Kilo Bit per Second
LAN	Local Area Network
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
LTE-U	Long-Term Evolution for Unlicensed Spectrum
M2M	Machine to Machine
MAC	Medium Access Control
MBB	Mobile Broadband
Mbps	Mega Bit per Second
MEC	Mobile Edge Computing
MHDR	MAC Header
m-Health	Mobile Health
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MMS	Multimedia Messaging Services
mMTC	Massive Machine Type Communications
MTC	Machine-Type-Communications
MTC-D	Machine Type Communications- Domain
MTC-IWF	Machine Type Communications Interworking Function
MTC-S	Machine Type Communications-Server
NB	Narrow Band
NPBCH	Narrowband Physical Broadcast Channel
NPDCCH	Narrowband Physical Downlink Control Channel
NPDSH	Narrowband Physical Downlink Shared Channel
NPRACH	Narrowband Physical Random-Access Channel

NPSS	Narrowband Primary Synchronization Channel
NPUSCH	Narrowband Physical Uplink Shared Channel
NRS	Narrowband Reference Signal
NSE	Network Services Entity
NSSS	Narrowband Secondary Synchronization Channel
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditure
PC	Personal Computers
PCID	Physical Cell Identity
PDN	Packet Data Network
PDP	Packet Data Protocol
PER	Packet Error Rate
PHY	Physical Layer
PSK	Phase Shift Keying
PSM	Power Saving Mode
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAR	Random Access Response
Rb	Bit Rate
RF	Radio Frequency
RFID	Radio Frequency Identification
RNC	Radio Network Controller
RSRP	Reference Signal Received Strength
SGW	Serving Gateway
SMS	Short Messages Service
SNR	Signal-to-Noise Ratio
SPI	Serial Peripheral Interface
SSL	Secure Socket Layer
TCP	Transport Control Protocol
TDD	Time Division Duplexing
TEKES	The Finnish Agency for Innovation
TTI	Transmission Time Interval
UART	Universal Asynchronous Receiver Transmitter
UE	User Equipment
UL	Uplink
uMTC	Ultra-Reliable Machine Type Communications
UMTS	Universal Mobile telecommunications system
UN	United Nations
UNB	Ultra Narrow Band
V2V	Vehicle to vehicle
VoLTE	Voice Over LTE
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WHO	World Health Organization

WiFi	Wireless Fidelity
BW	Bandwidth
CR	Code Rate
CRC	Cyclic Redundancy Check
DE	Data Rate Optimization
H	Header size
max	Maximum
N_S	Network Server
PL	PayLoad
R_b	Bit Rate
SF	Spreading Factor
T_S	Symbol Time

1. INTRODUCTION TO 5G AND IOT

According to "Statista" [1], the total revenue of the telecommunications sector worldwide has increased from 196 billion euros in 2005 to 256 billion in 2011. In Europe alone, revenues are forecasted to increase from 268 billion euros in 2016 to 277 billion in 2019, as shown in Figure 1 [1]. The reason why the telecommunications sector generates such high revenues is because it has reshaped, the way we live our lives, the way we perceive it and the way we interact with it. [1]

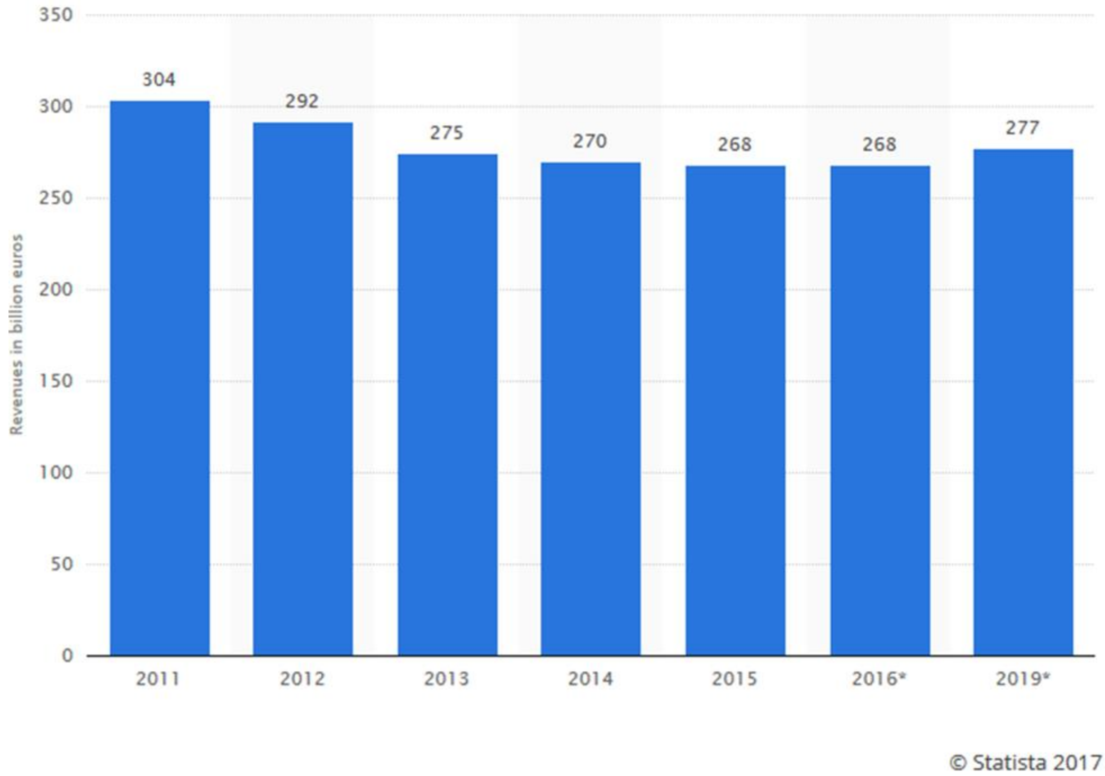

Figure 1. Revenue generated by the telecommunications industry in billions of euros.

Cellular technology´s huge impact on our lives is due to the fact that recent advancements in mobile telecommunications made mobile phones an indispensable part of our lives. The key is in how cellular technology made internet access not a luxury, but some sort of a right to any person. Nowadays, it is much more convenient to access the internet via a mobile terminal than from a fixed internet connection. According to [2], the rate at which fixed-broadband subscriptions increased is negligible compared to the steep boost in the percentage of mobile broadband subscriptions as of 2007.

1.1. Evolution from 1G to 5G

In addition to the constant evolution in the mobile sector, the direction of this evolution also counts. A noticed trend is that the mobile sector´s evolution is in the direction of putting customers in a constant state of connection, “hyper connectivity”. Pushing towards hyper connectivity is not a new idea, in fact it has been the main driver behind all the major cellular generations evolutions.

Since the rollout of the first cellular generation in the early 80s, cellular technology has witnessed massive growth. The first cellular generation, Advanced Mobile Phone System (AMPS), was analog-based and used Frequency Division Multiple Access (FDMA) and Frequency Modulation (FM). It provided the users with a channel capacity of 30kHz and a data rate of around 2.4 kbps (Kilo Bit per Second) [3]. The main drawbacks of this technology were the lack of security measures, the unreliable handover schemes and the relatively complicated hardware which meant large phones sizes and short battery life. [4]

Nearly 10 years later, in December 1991, the Finnish operator “OY Radiolinja AB” started the rollout of the first 2G (Second-Generation cellular technology) commercial cellular network [5]. Standardized by the Global System for Mobile Communications (GSM) group which was created by the ETSI (European Telecommunications Standards Institute) to provide a single unified standard, 2G technology introduced digital modulation which paved the road to all its new applications. Unlike the 1G AMPS system, GSM (Global System for Mobile Communications) provided huge enhancements to cellular communications, such as, increased security, substantially higher capacity, better spectrum efficiency, and relatively better voice quality by offering users a bandwidth of 200 kHz. However, the key feature introduced by GSM was its mobile data capabilities [6]. Although it initially had a relatively very low rate, at a maximum of 14.4 kbps, GSM mobile data introduced users to a whole new world of capabilities. It allowed users novel applications such as Short Messages Service (SMS), which witnessed massive commercial success [7] and also gave them access to basic internet applications such as emails and news delivery. GSM initially used circuit-switching technology for its data transfer. However, GSM evolution did not stop here, the ETSI introduced a new enhancement for GSM called “General Packet Radio Service (GPRS)”. GPRS utilized the concept of packet switching which drastically improved supported data rates. GPRS, or as commonly referred to as 2.5G, allowed GSM services to offer more internet applications such as Multi Media Messaging Service (MMS) and basic internet surfing with data rates of up to 40 kbps. [4]

However, GPRS was not the last evolution of GSM. Few years later, Enhanced Data rates for GSM Evolution (EDGE) was introduced with its cutting-edge 8-PSK (Phase Shift Keying) digital modulation scheme which allowed for 3 bits to be encoded per symbol thus substantially boosting the data transfer capabilities of GSM to reach up to 120 kbps per user. Moreover, another enhancement was introduced to allocate a user more than one time-slot, thus doubling or tripling that user’s throughput, and hence, pushing the data rates to even higher limits. At that point, the direction at which cellular technologies should evolve to was evident [8].

Despite the voice-centric nature of GSM, many GSM operators supported some data transfer but on their voice channels. Thus, the need for more efficient, faster, and dedicated data protocols was evident. GSM service providers shifted their focus to the new era of mobile internet. The market responded very well to internet applications, which in turn, created more demand for higher data rates which then brought new ideas to the market and pushed investors more towards this field, and the cycle kept going.

WCDMA (Wideband Code Division Multiple Access), UMTS (Universal Mobile Telecommunications System) and 3G (Third-Generation cellular technology), are all given names to the technology that was being developed simultaneously as the rollout of 2G networks was still ongoing. To unify all the efforts towards building a standardized technology, the 3rd Generation Partnership Project (3GPP) was established. By the beginning of the 21st century, several rollouts of 3G networks were already taking place [7]. By combining high speed mobile access with Internet Protocol (IP)-based services, 3G took the cellular technology to a whole new level of broadband experience. Looking at the main areas of advancement from 2G to 3G, it is clear that higher data rates was the top priority for 3G technology. 3G main focus was internet access as the demand for multimedia applications grew stronger. Added to that, as handheld phones became more common, users' demand for real broadband experience grew [9]. Accordingly, 3G initially offered 144 kbps for mobile users and around 2Mbps (Mega Bit per Second) for stationary users.

3G allowed for more advanced services, especially for mobile users, such as broadband wireless data and video calls. Additional features were added to 3G networks, with the purpose of further enhancing the user's broadband experience. Such features include High-Speed Packet Access (HSPA), which allowed users data rates of 14.4 Mbps on downlink [7]. Another key issue which 3G facilitated was mobility since 2G technologies had the problem of not being fully interoperable between different countries, thus 3G offered a unified standard to allow universal roaming.

The non-stop increase in user demand for higher data rates, higher capacity, lower latency and high spectral efficiency, triggered the development of Long Term Evolution (LTE). By the time 3G technology was introduced, voice calls' quality was already reasonable. However, 3G suffered from some limitations, such as its CDMA-based air interface, which imposed some limitations to mobile broadband. LTE was introduced to, provide data rates in orders of magnitude higher than that of a single carrier spread spectrum used in 3G, and to reduce latency in a way which the 3G network architecture could not support.

Introduced in 2010, LTE was the first all-IP (Internet Protocol) cellular network. It provided full inter-operability with the previous cellular standards to facilitate inter-standard roaming. The main motive to convert to an all-IP standard is to provide the cellular market a common platform for all legacy technologies to operate efficiently side to side with LTE. The key novel feature which enabled LTE to provide a dramatic increase in data rates while reducing latency is the new topology it introduced. As opposed to 2G and 3G systems, the Radio Network Controller (RNC) and Base Station Controller (BSC) functionalities are performed near the user in the Base Transceiver Station (BTS). This advancement substantially decreased latency and network deployment costs [10]. Figure 2 [11] shows the major trends in the cellular technologies evolution.

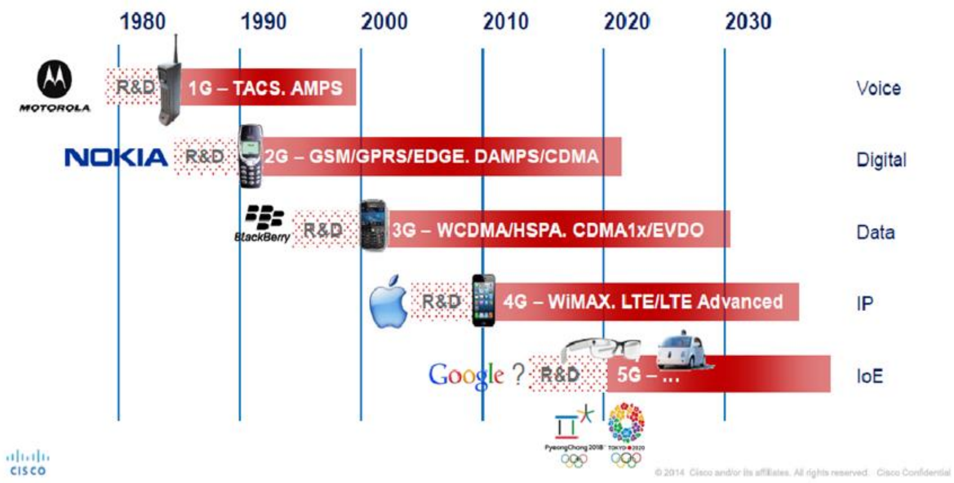

Figure 2. Major trends in cellular evolution.

Since 2010, research and advancements in LTE did not stop. As the demand for better broadband experiences increase, LTE became the most favorable wireless solution as it offered a variety of novel features such as [10]:

- Wider Radio Channels: LTE offers operators flexibility to choose the operating spectrum bands, ranging from 1.4MHz up to 20MHz. Added to that, LTE supports carrier aggregation of up to 5 carriers with a practical limit of 100MHz.

- Easiest MIMO (Multiple Input Multiple Output) Deployment: In legacy cellular systems, adding additional transmitter or receiver antennas was a challenge. LTE allows seamless deployment of MIMO technologies by using new radios and antennas.

- Lowest Latency: Several new features, such as low Transmission Time Interval (TTI) and fewer core network nodes, allows LTE to serve applications with low latency requirements [12].

As of the year 2013 to 2016, the 3GPP defined LTE-Advanced in releases 10 to 12, subsequently, releases 13 to 15 define LTE-Pro. Many regard these recent releases as a step towards 5G (Fifth-Generation cellular technology) as they entail:[12]

- VoLTE: Voice over LTE enables operators to packetize voice transmission over their LTE networks, resulting in higher capacity and higher voice calls quality.

- Integration of LTE with unlicensed bands: In 2016, 3GPP release 13 introduced LTE-U (Long-Term Evolution for Unlicensed Spectrum) which will allow a variety of features such as deploying certain modes of LTE in unlicensed bands as well as LTE/WIFI (Wireless Fidelity) aggregation.

- IoT (Internet of Things) Support: Release 13 introduced two categories which support LPWAN (Low Power Wide Area Network) devices operations in LTE bands. The categories are CAT M1 (Category) and NB1 (Narrowband IoT). Such specifications allow for low-power wide-area communications between IoT devices.

- Full dimensional MIMO: Until the year 2017, base station deployments used 4x4 MIMO. However, release 14 is expected to support configurations of up to 32 antennas in LTE base stations.

- Dual Connectivity: As of release 12, UEs can combine carriers from more than one serving eNodeB. Allowing for higher mobility while maintaining the Quality-of-Service (QoS).

- 256 and 64 QAM (Quadrature Amplitude Modulation): Higher modulation orders allow for more bits to be modulated per symbol which results in higher data rates.

- 1 Gbps (Giga Bit per Second) Capacity: Full dimensional MIMO, carrier aggregation, and high order modulation techniques are shown to provide link capacities of 1Gbps in several lab trials.

- HetNets Support: In cases of spectrum shortage, Heterogeneous Networks (HetNets) enable macro cells and small cells to coexist on the same spectrum.

All this being said, it is also important to observe to where the cellular evolution have gotten us. According to CISCO [11], mobile data traffic has grown 5 times from the years 2011 to 2016, with LTE responsible for 69% of mobile data traffic in 2016. Such penetration was aided by the addition of almost half a billion mobile devices in the year 2016 alone. Moreover, although smartphones accounted only for 45% of total mobile devices, they were alone responsible for 81% of mobile data traffic in 2016. LTE and its advancements took the average download mobile data speeds from 2Mbps in 2015 to 6.8Mbps. On the other hand, and according to CISCO [13], PCs (Personal Computers) will be responsible only for 25% of internet traffic by 2021 whereas smart devices will be responsible for the remaining 75%. The PCs' 25% is a huge decrease from a share of 46% of total IP traffic in 2016. Added to that, it is forecasted that the number of devices connected to the internet will be 3 times more than the total world's population in 2021. Concerning mobile data traffic, CISCO forecasts that mobile data traffic will be multiplied by 7 from 2016 to 2021, which means it will be growing as twice as fast as fixed-IP traffic. To sum up, these statistics reflect the tendency of consumers to be more attracted to mobile, ubiquitous and broadband internet services. [13]

Concerning the future, CISCO predicts that by the year 2021 the monthly global data traffic will be 49 exabytes with mobile devices responsible of one-fifth of this number. Such numbers are not a surprise when knowing that CISCO predicts that by that year the world will have 1.5 mobile devices per capita. These devices will utilize an unprecedented internet speed of around 20Mbps.

Such forecasts show, without any room for doubt, that by the year 2021 there will be a standard, a technology, with pervasive presence, capable of providing a common platform for all legacy communications radio access technologies in addition to providing by its own a radio access technology able to carry the world to a new era, an era where everyone and everything are connected, an era of hyper connectivity. This technology is, 5G.

1.2. What Is 5G?

There is always some sort of vagueness and unclarity regarding what 5G will be. Some argue it will be a 5th generation radio access technology which allows tens of gigabytes of data rates, some argue it will be an enabler for ubiquitous internet applications such as IoT with extreme low latencies, some argue it will be a platform for low-power-low-throughput applications with extremely long battery lives, while some are still confused whether to call it an evolution of cellular technologies or a revolution. But instead of thinking of 5G from the application level, maybe looking at the big picture from the vision level can be more appealing. [12]

5G is expected to create and serve the needs of a fully connected and mobile society, addressing the various aspects of socio-economic transformations. A vision needed to answer for the expected demands of users and businesses of the year 2020 and beyond. Thus, 5G will extend the limits of performance to include, lower latencies, higher data rates, ultra-high reliability, and greater support for mobility. Added to that, 5G is also required to provide the appropriate means to control and manage such a highly heterogeneous environment while ensuring adequate security and privacy. Of course, such parameters will not all be needed for a single application, therefore, 5G network architecture will also encompass modular network functions which can be deployed and scaled according to the application needed. [14]

At the time being, two definitions of 5G exist. The first being that 5G will be a platform where all legacy radio access technologies are consolidated. Such a blend, due to its huge variety of technologies, will enable an almost ubiquitous connectivity, in terms of availability and coverage. The key differentiator in this scheme would be providing massive connectivity to enable Machine-Type-Communications (MTC) such as Machine-to-Machine (M2M) and IoT, achieving somehow hyper-connectivity. The second definition is the classic generational evolution, with the idea of 5G being an evolution to 4G, just as 4G is to 3G. In that sense, 5G will be a radio access network, with certain data rate and latency requirements and whichever technology to provide these requirements will be called 5G. However, this brings us to an issue that many of the 5G requirements can be achieved by already existing LTE networks. Therefore, only applications requiring a true generational shift such as sub 1ms latencies or data rates higher than 1Gbps, will be considered as potential 5G use cases. [15]

1.2.1. 5G Key Requirements

Standardization bodies are not expected to release a standard before the year 2020. However, several research efforts have demonstrated several trail networks to display some of 5G´s expected functionalities. Due to the requirements expected to be fulfilled by 5G, it must meet certain performance criteria. Several industry initiatives have specified the major criteria for 5G to be: [15]

- Practical 1-10 Gbps radio links
- Round-trip latency to be around 1ms
- A hundred-fold increase in maximum number of connected devices
- Reliability reaching 99.999%
- Up to 10 years of battery life
- Nearly 100% coverage

However, since the above-listed requirements are driven from different perspectives, the list does not seem to be coherent. In other words, no technology is expected to deliver all these requirements at the same time. As a matter of fact, even no application is expected to need all these requirements simultaneously.

1.2.2. 5G Key use cases

According to NGMN [14], 5G is required to provide evolution and support for the currently commercial broadband use cases, in addition to giving life to a variety of new applications with varying attributes. Such applications will be supported via various smart devices and will operate in heterogeneous environments. As shown in Figure 3, NGMN classifies 5G use cases into 8 families. Such a classification should act as a reference for setting 5G service requirements and network architecture. This classification is not meant to encompass all possible 5G use cases, but it just acts as an outer envelope to demonstrate the level of flexibility 5G networks should have.[14]

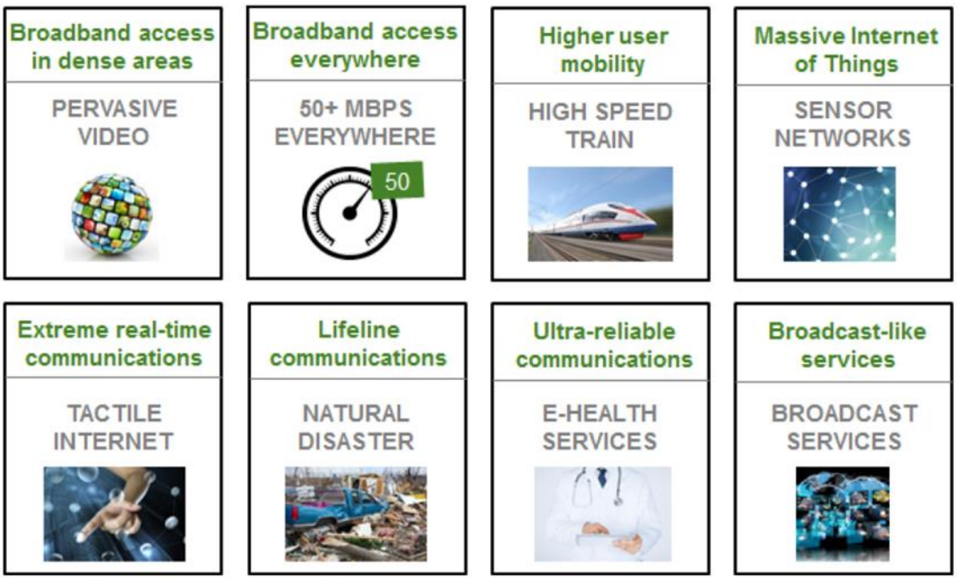

Figure 3. 5G use cases families and related examples.

- Broadband access in dense areas

It is expected that by the year 2020 and beyond, the demand for highly available broadband access will be immense. The challenge with such applications is not much in the broadband aspect as much as it is in the sense of providing this extremely fast broadband experience but in highly populated areas with a dense presence of users. This family of use cases encompass augmented reality applications, multi-user interaction conferences and 3D services. [14]

- Ubiquitous broadband access

This family of use cases is concerned with enabling business opportunities and providing internet access for large percentages of populations living in rural areas. To achieve a truly hyper-connected society, according to NGMN, users must enjoy internet speeds of 50Mbps as an average speed per user even in lightly-populated areas and at cells edges. The key challenge here that 5G must address is the ability to build such networks at ultra-low costs. [14]

- Higher support for higher user mobility

As of 2020 and later, the demand for internet services on highly mobile transportation means is expected to increase. Taking trains as an example, inter-city trains are expected to travel at speeds around 500 km/h. The challenge here is providing passengers with broadband internet access for various applications such as entertainment or office-systems access. Moreover, commercial airliners are planning the same concept for their passengers. Added to that, high mobility support with low end-to-end latency will be crucially important for V2V (Vehicle to vehicle) communications in autonomous driving cars applications. [14]

- IoT

One of the most disruptive novel feature of 5G will be IoT. IoT vision calls for a highly dense presence of small smart devices such as sensors, actuators and cameras, each with its own characteristics and requirements. Some of these devices will be lightweight wearable sensors used to monitor certain physical parameters of a person's body or the environment surrounding her. On the other hand, sensor networks' deployment is expected to bloom with the emergence of IoT. Various industrial and smart city use cases are already present, such applications involve automated metering systems, monitoring systems and surveillance. Sensor types will be classified in a broad sense into two groups, one being sensors requiring low energy and low throughput, and the other requiring broadband connections. The key challenge regarding mass sensors deployment in general is management of huge numbers of devices and their data. [14]

- Real-time communications

One of the most challenging features of 5G will be real-time communications. The difficulty here lies in the fact that this feature may require more than one of the 5G novel features. For instance, self-driving cars would need extremely low-latencies to be able to control it efficiently, as well as support for high mobility and also high throughput. A very interesting application to real-time communications is tactile internet. Tactile internet refers to applications where communication between two points involves not only visual and acoustic senses, but also the sense of touch. This concept would allow humans to sense and control real or virtual objects wirelessly. This allows for countless new applications such as remote surgery, where a surgeon operates on a remote patient by controlling a robot. [14]

- Life-line communications

5G is expected to further enhance emergency communications between authorities and citizens and even between authorities themselves. Applications in this area might involve enhancing the mobile network so that it reaches nearly 100% availability and it can support high traffic surges. These features will come in handy in cases of natural disasters where citizens will need to forward their location or status to the rescue missions. [14]

- Ultra-reliable communications

Reliability here refers to a nearly-constant availability of radio link. Forecasts for the year 2020 and beyond predict a wide deployment for networks utilizing MTC specifically in industry. The e-health (Electronic Health) sector, for example, is expected to witness a revolution with the emergence of 5G. Although mobile health applications will continue growing, remote treatment applications are also expected to appear. Patients will be equipped with sensors monitoring their vitals, and doctors will intervene according to the data relayed by these sensors. Furthermore, remote surgeries will be possible using tactile internet applications to save a patient in an ambulance for example. Thus, such life critical applications require 100% availability and very low latencies. Security authorities might also utilize such technologies to remotely explore hazardous areas or to provide live streams from areas hit by natural disasters. [14]

- Broadcast-like services

As mentioned above, the vision for the year 2020 anticipates a fully-connected society in most technological aspects. One of these aspects is broadcast services. In the future, the legacy Tv and radio systems will not be sufficient for efficient data distribution especially because they lack an uplink channel for interactive services and feedback. Such data distribution is expected to take many forms, it may be local distribution targeting specific users who subscribed to this service. It may also be specific for populations of specific residential areas, or even for a whole population of a country or a continent. [14]

1.3. Introduction to IoT

"The Internet of Things has the potential to change the world, just as the Internet did. Maybe even more so."

Kevin Ashton, 2009

At the time being, more than a couple of billion people use the internet on daily basis. Internet applications are widening every day in a manner which increases the total time people spend online. Internet is being used in a huge variety of our activities; ranging from work emails to accessing multimedia content and even to reach out to friends and family via social media platforms [16]. However, the evolution of the internet is far from over. To fully grasp the idea, we will have to take a look at the early stages of the evolution of the internet, all the way up to the IoT.

Upon the rise of the first Internet network, in the 1960's, the idea was to simply connect remote computers at a university campus via an adequately secure network, mainly for research related purposes. This paradigm was referred to as the "Internet of data". Over the years, the technology became more mature and the number of users increased, thus, the rise of the "Internet of content". As of the 80's the business world was hyped by the idea of communicating via e-mails; sharing documents and data. Various reasons lead to the next big leap in our view of the Internet, to name a few, the fact that we are social creatures who are always looking for ways to facilitate social interactions and cross thousands of miles in mere seconds, the fact that now internet access is not at all a luxury exclusive to a selected few, on the contrary, it became a commodity to a huge percentage of earth's population. These factors contributed and shaped the Internet we know today, an "Internet of people" where social media platforms, such as, Facebook, Twitter and LinkedIN became the hub of the internet. [17][18]

1.3.1. M2M to IoT

Meanwhile, the internet wasn't the only technology evolving. The electronics industry was witnessing an evolution too with the rise of digital sensors, tags, and actuators. Such devices were cheap, abundant and reliable. These properties, aided with the evolution in internet and communications protocols gave the rise to Machine-to-machine communications, also known as machine-type-communications. [19]

M2M communications refer to the exchange of data between two devices. Typical deployments of such networks include asset monitoring, remote sensing, and basically and form of connection that could be automated and integrated into a certain service. A typical M2M system is composed of, devices to be connected, the communication network needed to allow connectivity, and the application itself.

Numerous applications of MTC exist around us, covering a variety of industry sectors and service applications. The segment benefiting the most from the current MTC services is the cars telematics sector, where it is estimated that around 140 million vehicles use MTC to connect to various networks for security, monitoring, road charging and remote vehicle diagnostics. The electricity sector also utilizes automated metering systems for data collection and management of energy consumption.

1.3.2. Evolution to IoT

Until now, the idea was to connect everyone to the internet, but what if we can also connect everything to the internet! It is no secret that IoT is the latest obsession in the world of wireless communications. As a matter of fact, the wireless communications world is not the only body affected with this hype. IoT promises to play a key role in many other fields as well. That is why upon looking for the recent trends in many aspects of technology, one word will keep popping up, IoT.

IoT is expected to change the world as we know it today, if you think this is a bold statement, consider the following. Consider how the internet changed the world we live in today. Some decades ago, no one would have believed that it is possible to video chat with someone thousands of miles far, imagine how this affected our social lives, business meetings, video conferences, how many billions of euros worth of plane tickets have been saved. Moreover, No one would have believed that literally anyone with an internet connection could type any question to a search engine and gain answers in a matter of milliseconds. Imagine how many scientific papers were written with the aid of references from the internet, how many years and years of searching for documents were saved. The list goes on and on. Now imagine the next evolution of the internet, the huge leap it will take into a whole new scheme of sensing, gathering, analyzing data and even acting upon it. How will that impact our lives? Would it only make it easier? Or would it even change it? [18]

According to a report published by the McKinsey global institute in 2015, IoT is forecasted to have an impact of 7.5 trillion U.S dollars in average per a year at the year of 2025, which would make up around 11% of the world's economy at that time.[19]

Although the expression might sound new, the concept itself has been out there since the late 90's. It is believed that the first time the expression "IoT" saw light was in a presentation given by Kevin Ashton about the usage of RFID (Radio Frequency Identification) data and connecting it to the internet [20]. In an article published in 1999 for the RFID Journal, Ashton wrote:

"If we had computers that knew everything there was to know about things—using data they gathered without any help from us -- we would be able to track and count everything, and greatly reduce waste, loss and cost. We would know when things needed replacing, repairing or recalling, and whether they were fresh or past their best. We need to empower computers with their own means of gathering information, so they can see, hear and smell the world for themselves, in all its random glory. RFID and sensor technology enables computers to observe, identify and understand the world—without the limitations of human-entered data."

Since that time, new ideas have been evolving about what exactly would the IoT be, but the vision was not clear until the year 2005, when the first IoT report was released. Since that time, new ideas have been evolving, broadening the concept and incorporating many potential applications in it, ranging from medical care, industry, transportation, sensors networks, to smart cities. [22]

One of the key contributors to the rising of such a concept as IoT is the ubiquitous presence of devices "things" around us, which if supplied with the appropriate communications protocols, could be able to interact cooperatively with each other and even with their environment, thus eliminating the need for human intervention in numerous fields [23]. The exact meaning of the term "things" may have changed during the years, but the main concept remains the same, which is, to create computers with the ability to perceive certain aspects within its environment and react to it independently. [24]

IoT is simply a network of devices with processing units, storage units and communications interfaces which are interconnected together. Such a network would allow for integrating virtually anything to it, as long as it has internet capabilities [25]. Connection and integration to the IoT is not exclusive to smart phones, sensors and such devices, as a matter of fact, mature ideas are already calling for a mass integration which encompasses home-appliances, clothes, cars and even to human bodies. According to "The cluster of European research projects on the Internet of things", it is expected the by the year 2020, 50-100 billion devices will be connected to the internet. Some organizations, such as CISCO, even went as far as defining the IoT as the point when there would be more devices connected to the internet than people. [22]

- Challenges to the IoT

Through deep understanding of the vision of the IoT, we can easily conclude that the Internet infrastructure we know today will definitely be insufficient for the full realization of the IoT. It is no more a matter of interconnected computers, IoT encompasses vast networks of sensors, microcontrollers, and internet protocols. Evolution of the current internet seems inevitable.

Among the highest priority issues that need to be addressed is the issue of capacity. Since IoT promises connection to billions if devices, appropriate addressing schemes need to be developed. On the bright side, numerous research institutions are working and collaborating to rollout IPv6 (Internet Protocol Version 6) which promises 128 bits of address space. In addition, many experts tie the development of the IoT to the maturity of the communications protocols between machines in M2M communications.

- Applications to the IoT

No one disagrees about the benefits IoT research will return to its investors and perhaps the whole society. Again, also no disagrees that IoT's applications are countless. But here rises an important question: Which of the IoT applications are expected to be the most beneficial to investors?

In a report organized by the "RFID Working Group of the European Technology Platform on Smart Systems Integration (EpoSS), experts expressed their first vision about IoT applications and divided them to 3 categories. [26]

One type of application would address "things on the move". RFID tags are already heavily used in industry, goods tracking, theft protection, storage management and more. IoT with the aid of nanotechnology would enable further deployment of even smaller and smarter sensors and interconnect them all together in a manner which enhances intelligent logistic management.

The second type of applications would be around "ubiquitous intelligent services". With IoT, devices will not only be able to perceive their surrounding environment but will also be able to communicate in-between themselves. This exchange of information will be guided by pre-installed algorithms to reach common goals.

Lastly, an important field of applications is the "ambient and assisted living", which is also in the interest of this thesis. Such applications are steered towards enhancing the quality of life of the elderly, the disabled or in general people in need of special assistance. This field has a huge range of applications as sensors on a patient's body sending vitals to a centralized computer, to movement sensors which would tell nurses if a patient falls. These networks when interconnected and operable with the ability to analyse input data independently can save much time, much human resources, and even many lives.

1.4 Thesis Objectives

This thesis work aims to serve as a survey and a practical guide. The topics surveyed are, recent trends in cellular evolution, M2M (Machine-to-machine) communications and IoT (Internet-of-Things). Moreover, different aspects of M2M communications are discussed in addition to means to enable M2M; LPWANs. (Low Power Wide Area Networks). Different types of LPWANs are considered and their differences and applications spectrum is also surveyed. As for the practicalities, this thesis work aims to present the challenges of implementing an LTE network to be used as an enabler for IoT. Challenges include the RF (Radio Frequency) planning part as well as the main idea of using LPWANs as an enabler for IoT future-5G healthcare use case applications

2. LPWANS: NEW ENABLERS FOR THE INTERNET OF THINGS

Since the emergence of the first cellular technology, till LTE, the growth in cellular networks has been human-driven. However, this does not seem to be the case for IoT. Being the anticipated upcoming huge leap towards a fully connected society, IoT is mainly devices-driven. As shown in Figure 4 according to a forecast by "Machina Research" [27], 7 billion of the 30 billion devices expected to be connected by the year 2025 will be devices utilizing cellular IoT and LPWAN protocols for communications, generating a total revenue reaching 4.3 trillion U.S dollars by the year 2024.

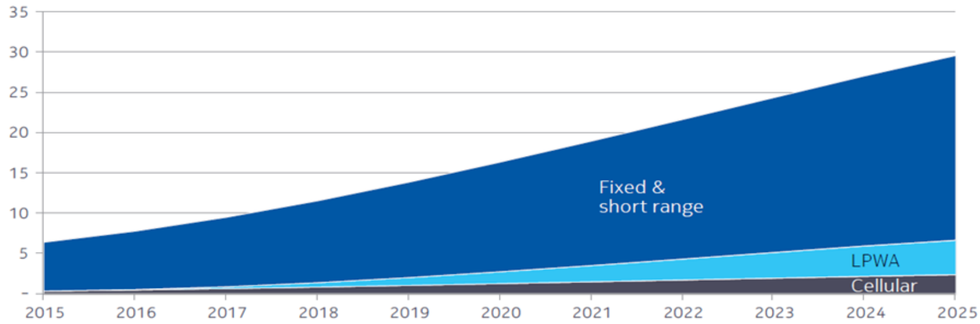

Figure 4. The estimated impact of IoT in U.S dollars on various industry aspects.

Moreover, according to CISCO, 50 billion devices will be deployed and connected by the year 2020 [27]. Lastly, as forecasted by Ericsson [29], the number of connected devices utilizing M2M communications will surpass the number of human-operated devices such as tablets and smartphones. Such indications pave the way for the transformation of MTC to IoT.

The reason IoT is expected to witness such massive deployment and generate such huge revenues is that it promises to revolutionize how we live our lives, how we work, and how we interact with our surrounding environment. Furthermore, IoT is forecasted to offer solutions to chronic global challenges such as energy sources scarcity, population explosions and pollution 0. However, to reach this vision, devices must have the ability to independently sense their environment and process this data in a manner that allows smart decision making. The wide variety of services IoT promise has a serious downside which is the need for a communications paradigm to serve such broad applications. Such a variety in applications also means a variety in characteristics, where devices could have data rates ranging from a few bps to Mbps or communications ranges of a few meters to tens of kilometres. Moreover, devices may operate either in licensed band or unlicensed bands.

Originally, M2M and IoT services were enabled by two different means, either by Local Area Networks (LANs) or by Wide Area Networks (WANs). Each with its own technology specification and communications protocols. Short-range wireless-sensor technologies such as Zigbee and Z-Wave were the main players in the LAN (Local Area Network) model, whereas the WAN model was realized by legacy cellular systems such as GSM. Each model had its own drawbacks which inhibited wide-deployment. The LAN model was heavily criticised by its low coverage, lack of scalability and high network management costs since the LAN paradigm dictates that most of the network components are owned and managed by the owners. On the other hand, the WAN model was not optimal due to the fact that cellular standards were not built to handle the traffic of MTC or devices. This is highlighted in high power consumption, very high increase in data rates on the expense of frame error rates or latency, while for some MTC high data rates are not as critical as low latency or high reliability. Thus, the emergence of LPWANs. [30]

2.1. LPWANs

MTC and IoT are terms that cover a wide variety of applications and use cases, basically any two devices communicating independently can be called MTC devices and any object connected to the internet can be called an IoT device. In such a paradigm, communications differ substantially from human-to-human communications. To name a few, MTC tend to, have most of its payload on the uplink direction, consist mainly of short but frequent bursts of data, serve a huge number of devices and most importantly, runs on devices which have an expected very long battery life time. [31]

Two approaches are available to handle the IoT and MTC requirements. First solution would be to design novel protocols and systems dedicated to serve the needs of low-power-wide-area networks (LPWANs). Examples of these LPWAN approaches are LoRAWAN [32] and Sigfox [32]. Another option would be to adapt existing cellular technologies to the demands of LPWAN, such as 3GPP’s release 13: NB-IoT and LTE CAT M1. [34]

Low-power-wide-area-networks (LPWANs) are designed to specifically address IoT needs and replace non-cellular wireless systems used in the past for MTC applications such as ZigBee, Bluetooth, Z-Wave, etc. The features that make LPWANs favourable are their wide range and their support for low-data-rate low-power devices. The above-mentioned legacy systems had a range of only a few hundred meters, which leaves no other option for extended coverage other than densifying the deployment and adding more gateways. This results in dense multi-hop mesh networks which immediately cancels any hope for the most prominent features of IoT which are cheap deployments and low latencies [30]. On the other hand, cellular systems like GSM or LTE offer high scalability and wide area coverages. Though, their very high-power consumption presents a serious challenge for utilization in IoT scenarios. Added to that, decommissioning of some GSM networks has already started [34]. Thus, the need for novel wireless solutions to serve M2M and IoT demands. [36]

LPWANs allow massive deployment of mobile devices with low battery consumption. But such features are at the expense of low data rates, in the range of tens of kb/s and relatively higher latencies in ranges of many milliseconds to few seconds. Thus, it’s clear that LPWANs do not cover all shades of IoT applications, to be more specific, LPWANs are more suitable for scenarios which are delay-tolerant, need low power consumption, wide coverage, and low data rates. Such applications are referred to as massive IoT, as opposed to critical IoT which need ultra-low latencies and ultra-high reliability; an area better realized with cellular IoT. Which actually is intuitive as it isn’t expected for low-cost solutions as LPWANs to adhere to stringent network latency or availability requirements. Though, LPWANs are still valid for a broad spectrum of applications. As depicted by Figure 5 LPWANS are still very suitable for applications such as home -automations, smart cities, wearable devices and a lot more of IoT applications which utilize small bursts of data on low-data rates. [30]

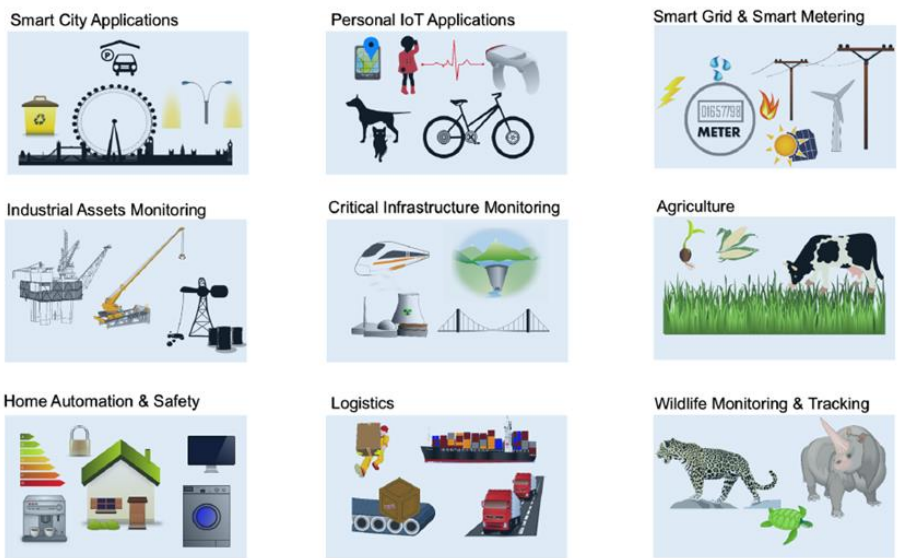

Figure 5. Applications of LPWANs across various sectors.

2.1.1. Design goals and techniques

Despite the wide variety of LPWAN applications, LPWANS’ designs are usually governed by the following characteristics:

- Low power: deployment of a huge number of devices in a wide are can make the task of changing devices’ batteries very challenging and costly. Thus, ultra-low-power operation must be supported in any proposed IoT solution.

- Cheap hardware: building on the idea above, a wide deployment of remote devices indicates that the RF interfaces if these devices must be simple, which translates to cheap.

- Adequate RF protocols: to aid with the low power consumption, the duty cycles of the devices must support schemes where devices switch to sleep mode when there is no need to send or receive data.

- Network infrastructure: network deployment should be efficient and with the option of upgrading existing networks without the need to build new ones from scratch.

- Data security: although IoT applications may vary, data security remains a very important challenge in most of the applications as the data between a device and a gateway may contain private details about people or work plans.

- Appropriate data link: although devices may be stationary, deployment scenarios may cause a device to be next to high ways which will cause significant fading. [37]

Currently, several LPWAN technologies are competing to prove the best solution for IoT and MTC use cases. Each of them utilizes a few novel communications techniques to try and reach the above-mentioned characteristics:

- Long range

One of the main goals of LPWANs is to provide wide-area coverage with the ability to penetrate to deep indoor environments such as basements. To allow for communication ranges exceeding cellular technologies, an extra 20 dB is needed in the link budget. This can be achieved by a number of ways. Firstly, the choice of bandwidth. LPWANs being open technologies, they operate in in the unlicensed frequency spectrum. In this case they can operate either in the 2.4 GHz band or the sub-1 GHz band. For less signal attenuation and better penetration, most LPWANs operate in the sub-1 GHz band. Secondly, the choice of modulation techniques. Since LPWANs need to offer link budgets of around 150 dBs, to enable communications ranges of several kilometers, this must be on the expense of high data rates. Instead of utilizing high order modulation techniques which send several bits per symbol, thus increasing overall data throughput with the drawback that the total energy is divided among several bits. LPWANs physical layers (PHY) choose to decrease the order of modulation and send les bits per symbol which reduces the data rate but increases the energy per symbol thus allowing for symbol detection at very low receiver sensitivities reaching -130 dBm. Modulation techniques which allow such comprises are narrowband and spread spectrum techniques.

Narrowband modulation encodes data in very low bandwidths, thus increasing spectral efficiency and minimizing the noise experienced in each band. Thus, receivers don’t have to rely on the processing gain from frequency dispreading as symbols already arrive at the receiver with relatively less noise. Which leads to simple and inexpensive chips’ designs. Another option would be to further decrease the band on which the data is sent, reaching in some cases only a 100 Hz. This is called ultra-narrowband modulation. Obviously, this will further decrease the noise and increases spectral efficiency which translates to higher number of supported devices. But on the other hand, it dramatically decreases the data rate to the point that devices need to be active for extended periods of time to send and receive data which eventually decreases their battery life. Examples of standards which use this are SIGFOX, WEIGHTLESS and TELENSA. [38]

- Ultra-low Power Consumption

Low power consumption is a must for IoT and M2M applications. Many applications specify that around 10 years of battery life-time is needed. This can be achieved by a number of methods such as, the right choice of, network topology, Medium Access Control (MAC) protocols and utilizing duty cycling.

As discussed earlier, the commonly used mesh-topologies are unsuitable for low-power applications since forwarding data over multiple hops is costly and also causes congestion at major nodes. Added to that, relying on multiple hops dictates that devices waste their precious battery power being on and listening in case another device wants to send or receive through them. Thus, many LPWAN standards use the star topology where devices are directly connected to the gateways.

Implementing complicated and advanced MAC (Medium Access Control) protocols for cellular networks is manageable as DL (Downlink) power consumption is not an issue and mobile phone users don’t mind charging their devices every day. But when it comes to LPWANs, the huge overhead control signalling required by heavyweight MAC protocols is unjustifiable. For short range WANs, Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) is heavily used. However, the effectiveness of CSMA/CA relies on the number of devices served by a base station [39]. Thus, rendering it ineffective for LPWANs. On the other hand, the ALOHA scheme proves a good solution for LPWANs as it doesn’t rely on carrier sensing thus reducing transceiver’s complexity and power consumption.

The main idea behind duty cycling is that devices turn-off their radio transceivers during periods of inactivity, thus decreasing battery consumption. This is realized according to the application type, traffic type and device type. For example, LoRaWAN specifications allow for 3 classes of devices for the purpose of duty cycling. Where devise of class A are usually of for a pre-agreed time, which is right after an UL (Uplink) transmission, when the device turns on its receiver and listens in case of an incoming DL transmission. Such an on/off scheme substantially enhances battery life time. Moreover, duty cycling is anyways one of the conditions of operating in unlicensed frequency bands. [30]

- Low Cost

To allow LPWAN technologies to compete in a wide variety of use-cases, even where legacy short-range solutions and cellular technologies are already prominent, the key factor is low Capital Expenditure (CAPEX) and low Operating Expenditure (OPEX). Low hardware expenses of around 5$ and low subscription per unit costs of around 1$ offer a huge incentive for end-users and solution providers to shift towards LPWANs. [40]

To achieve such low operating costs, LPWANs implement a number of techniques to serve the needs of massive deployments at affordable prices.

A key factor in devices' costs is their hardware complexity. The main reason why legacy cellular technologies aren't the optimum enabler for Massive MTC and IoT deployments is the high complexity of their transceivers as they need to perform complex signal processing at high data rates. Thus, Low device complexity plays an important role in reducing devices' costs. Especially given that IoT devices will mostly process low data rates and short bursts of data. Added to that, the choice of the appropriate network topology aided with the adequate random-access schemes allows for a huge number of devices to be served by a single gateway, again, reducing overall costs.

One of the biggest expenses network operators have to withstand is the cost of buying new spectrum. That's why many LPWANs operate in unlicensed frequency bands such LPWANS include LoRa or Sigfox. However, even in the case of cellular IoT, in-band deployments allow for implementing the cellular IoT technology such as NB (Narrow Band) IoT or LTE CAT M1 in the network's already owned spectrum. Thus, eliminating the need of buying new spectrum.

- Quality of service

As already discussed, LPWANs are expected to cater for a broad spectrum of IoT applications, each with its own specific requirements. Latency for example, one specific use case such as electricity metering might be delay tolerant whereas another use case such as fire alarm systems needs minimum latency, Therefore, LPWANs must allow for a variety of Qos options in the same LPWAN.

- Scalability

One of the key features of LPWANs is the support to a huge number of devices. The challenge is it accommodate the ever-increasing number of connected devices while maintaining the required network service. Such efficient scalability can be achieved by a number of means, such as exploiting diversity techniques and adaptive channel selection and data rate. Complex nodes such as gateways or backend systems should have the capability to exploit all possible diversity techniques, such as channel, time, space, and hardware diversity. This use of parallel transmissions allows for higher number of connected devices.

After optimizing the number of transmission streams, still further optimization could be done on the data stream itself. Allowing for a dynamic and adaptive choice of, channels, modulation schemes and transmission power control can deeply enhance transmission links and make them more reliable and efficient. This agility depends strongly on the LPWAN technology. For instance, in cases where the base station is unable to feedback devices about their UL packets' quality, devices may resort to measures such as sending the same packet on multiple UL paths with the assumption that one of them might succeed and reach the base station. Of course, this comes at the expense of power consumption and increased interference. [30]

2.1.2. Different types of LPWANs

Due to the extensive research in the area of LPWANs and IoT, a wide variety of proprietary technologies appeared. Each with its own advantages and drawbacks.

Table 1 highlights the main features of some of the key players in the proprietary LPWAN domain then some light will be shed on each of these technologies. Afterwards, in the following section we will discuss one of these technologies in more details.

Table 1. [30] Technical specifications of various LPWA technologies

	SIGFOX	LORAWAN	INGENU	TELENSA
Modulation	UNB DBPSK(UL), GFSK(DL)	CSS	RPMA-DSSS(UL), CDMA(DL)	UNB 2-FSK
Band	SUB-GHZ ISM:EU (868MHz), US(902MHz)	SUB-GHZ ISM:EU (433MHz 868MHz), US (915MHz), Asia (430MHz)	ISM 2.4GHz	SUB-GHZ bands including ISM:EU (868MHz), US (915MHz), Asia (430MHz)
Data rate	100 bps(UL), 600 bps(DL)	0.3-37.5 kbps (LoRa), 50 kbps (FSK)	78kbps (UL), 19.5 kbps(DL) [39]	62.5 bps(UL), 500 bps(DL)
Range	10 km (URBAN), 50 km (RURAL)	5 km(URBAN), 15 km (RURAL)	15 km (URBAN)	1 km (URBAN)
Num. of channels / orthogonal signals	360 channels	10 in EU, 64+8(UL) and 8(DL) in US plus multiple SFs	40 1MHz channels, up to 1200 signals per channel	multiple channels
Link symmetry	×	✓	×	×
Forward error correction	×	✓	✓	✓
MAC	unslotted ALOHA	unslotted ALOHA	CDMA-like	?
Topology	star	star of stars	star, tree	star
Adaptive Data Rate	×	✓	✓	×
Payload length	12B(UL), 8B(DL)	up to 250B (depends on SF & region)	10KB	?
Handover	end devices do not join a single base station	end devices do not join a single base station	✓	?
Authentication & encryption	encryption not supported	AES 128b	16B hash, AES 256b	?
Over the air updates	×	✓	✓	✓
SLA support	×	×	×	×
Localization	×	✓	×	×

A. SIGFOX

Already present in 45 countries, SIGFOX is one of the main providers for LPWANs. Since 2010 till present, SIGFOX's customer base had been expanding to reach 60 countries in 2018 [41]. Based on their patented technologies, SIGFOX and the partners are offering a turnkey solution for a LPWAN. The main architecture of the network provided by SIGFOX is the base station equipment which supports software-defines networking functionalities and allows to be connected to the backhaul network by IP connectivity.

The air interface between the base station and the connected devices is Binary Phase Shift Keying (BPSK) and modulated in an ultra-narrow band of only a 100Hz. The solution operates in the sub 1GHz part of the ISM (Industrial-Scientific-Medical) band. As discussed earlier, LPWANs providers benefit from trade-off between data rate and bandwidth in a different way than cellular operators. For instance, SIGFOX operates in a 100Hz bandwidth, which dramatically reduces data rates to around a 100bps. But on the other hand, this results in a very appealing set of characteristics for LPWANs, such as, very high receiver sensitivity due to the reduced noise, very low power consumption as well as simple antenna designs. Although the above-mentioned data rate might seem very low, it's worth mentioning that in 2017 SIGFOX expanded their partners to jump from serving 32 countries to 60 countries in just one year. Such statistics reflect the fact that for IoT applications, data rates come last in the list of priorities, as opposed to power consumption or long range, especially that SIGFOX supports ranges as long as 50kms in rural areas.

In SIGFOX's initial solution, there was no need for DL transmissions, but as the technology became more mature, UL communications was introduced. As part of the efforts to reduce battery consumption by reducing the amount of time the device stays on, DL transmissions occur only in a pre-agreed window right after UL transmissions. To adhere to duty cycle regulations, UL messages must be kept under 140 messages per day, each comprising of 12-bytes maximum [41]. Due to obvious asymmetry in the radio link access, DL messages are modulated by Gaussian Frequency Shift Keying (GFSK) to support higher data rates of up to 600bps.

On the other hand, DL transmissions are kept at a very low amount of maximum 8 bytes per day. This obviously means that SIGFOX networks don't support UL messages acknowledgments. However, SIGFOX overcomes this drawback by allowing end devices a variety of frequency and time diversity techniques, as well as the ability for redundant transmissions. Thus, devices send their UL packets more than once and on any frequency channel. For instance, in Europe, SIGFOX divided the 868.180-868.220 band to 400 channels, 100Hz each. Which allows for high frequency diversity for the devices to send at, since anyways base stations can scan all the channels. [42]

B. INGENU RPMA

Previously known as "On-Ramp Wireless", INGENU is a leader wireless solutions provider, with its products mainly focused around machine connectivity. Random Phase Multiple Access (RPMA) is a random-access scheme, and one of 32 different patented technologies developed by INGENU.

Two main features distinguish INGENU from other proprietary LPWAN technologies. The first being that INGENU operates in the 2.4 GHz ISM band, thus avoiding the stringent spectrum regulations imposed on utilizing the sub 1GHz license-free band. For instance, mitigating the duty-cycle regulations on the sub 1GHz band allows INGENU devices to leverage from higher data rates and higher capacities. [44]

Secondly, INGENU's RPMA, which is a multiple access scheme used in INGENU's UL transmissions. The main idea behind it is that it expands the duration of a time slot then allows multiple devices to share access to this single time slot, each with a different random offset delay [45]. To mitigate interference, RPMA doesn't allow access to different transmitters at the beginning of the time slot, thus increasing signal-to-noise ratio. At the base station level, multiple demodulators are used to receive signals at different times within the same time slot. Moreover, for DL transmissions, base stations utilize CDMA to spread the signal before transmissions. RPMA allows receiver sensitivities of about -142dBm and a link budget of 168dB with dynamic power control algorithms for devices to insure reliable transmission with minimal interference. [44]

C. TELENSA

Being the lead provider for smart-cities solutions, Telensa provides a smart end-to-end solution and a central management system for smart cities IoT applications. Using their developed Ultra Narrow Band (UNB) modulation scheme [38], Telensa offers connectivity between their end-devices and the wireless gateways. Telensa operates in the unlicensed sub 1GHz band offering high communications ranges and low data rates. Telensa PLANet, which is the central management system solution provided by Telensa, is deployed in over 50 cities in 8 different countries. Its UNB radio system offers a variety of preferred features for IoT applications, resulting in 8 million devices adopting Telensa's UNB radio system. [46]

2.2. LoRa

Amongst all the novel LPWAN solutions, one of the most successful models is LoRa. The huge adoption and wide deployment LoRa witnessed is due to its performance which is tailored to provide an infrastructure for IoT. To be more specific, LoRa is tailored for applications which need very low power consumption and low device-maintenance costs. [47]

The LoRa solution comprises of two main parts. Firstly, the LoRa modulation technology. LoRa or LoRa PHY, is the proprietary spread spectrum modulation scheme created by Semtech under the LoRa Alliance and based on chirp spectrum modulation. It spreads messages over a wide band creating a signal which is similar to noise, thus making it resilient to jamming or unauthorized detection. At the receiver, processing gains renders the signals immune to noise and interference. Secondly, the medium access protocol LoRaWAN defined by the LoRa specification [47]. One of the most important features of LoRa is it´s agility. The LoRa physical layer defines communications in various bands, depending on the region of operation it operates in the 433, 868 or the 915 MHz unlicensed bands. LoRa data messages are also very flexible in size, ranging from 2 to 255 octets with data rates of up to 50kbps. Moreover, LoRa allows for 3 classes of end devices to allow for more flexible deployment. In addition, LoRa supports a range of spreading factors which trade data rate for increased coverage. Despite the fact that LoRa´s PHY is proprietary to Semtech, the LoRaWAN developed by the LoRa Alliance is open for developers to contribute to it. [48]

2.2.1. LoRa Network Architecture

Lora networks typically consist of 3 main nodes, gateways, end-devices, and a network server. End-devices communicate with gateways over the air-interface via single-hop communications. This communication is bidirectional to allow for software upgrades, multi-casting and over-the-air activation. Gateways are connected to the network server via a regular IP connection. As shown in Figure 6 [49],

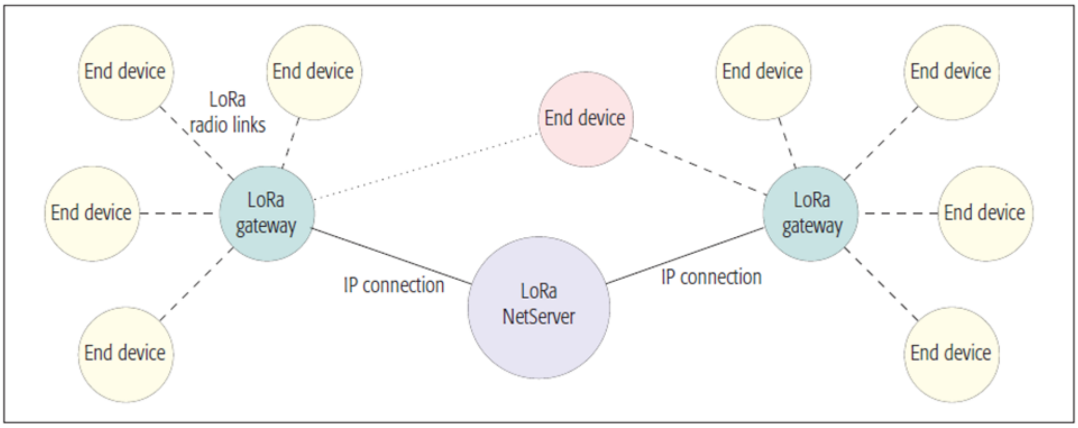

Figure 6. Lora network architecture.

Lora networks are laid out in a star-of-stars topology where each end device is allowed to connect to one or more gateways. Subsequently, duplicated messages are filtered out in the network server. Moreover, servers also choose which gateway to reply to a transmitting end-device. In such a topology, the server is responsible for most of the network management functionalities, thus making gateways just a relay between end-device and servers, virtually transparent to the end-devices.

Star-of-stars topologies provide a good compromise between radio coverage, battery consumption and network complexity. To mitigate interference, end-devices can communicate with gateways using a variety of different data rates and channels. Where communications via different data rates to not interfere with each other.

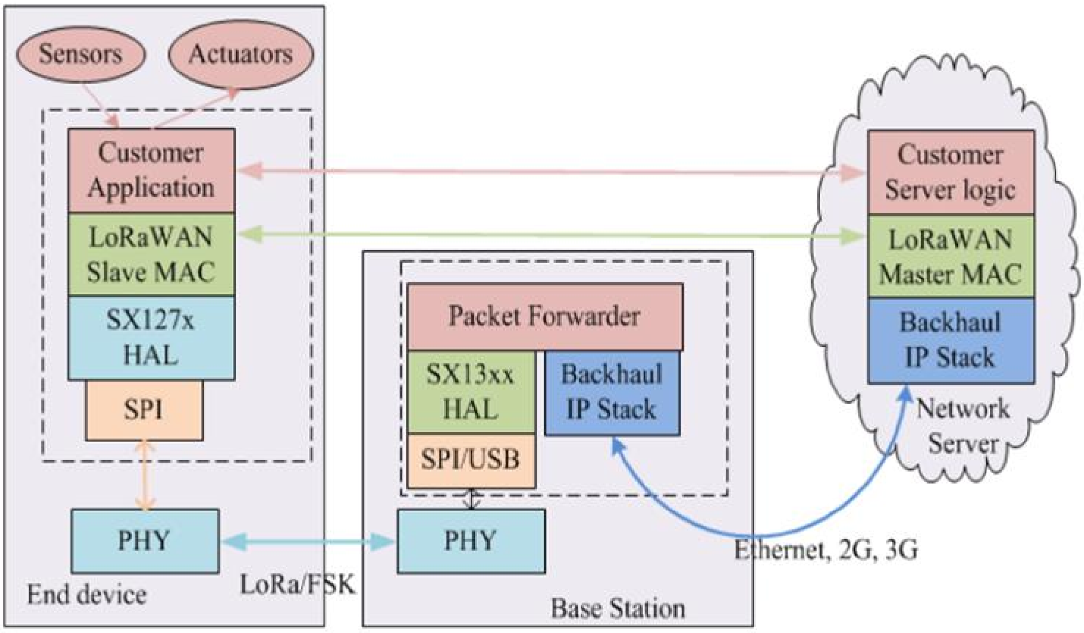

Figure 7. LoRa protocols architecture.

As depicted in Figure 7 [50], LoRa network components are equipped with various protocol stacks to allow for more options for the developers. For the end-device stack, the LoRaWAN defines the physical layer (PHY), Serial Peripheral Interface (SPI), and SX127x Hardware Abstraction Layer (HAL). Various end-device parameters such as the modulation technique used and configurations registers can be accessed via the SPI (Serial Peripheral Interface) interface. The LoRaWAN slave is responsible for communicating with the master MAC in the server. The gateways are equipped with IP stack to facilitate backhauling via IP either over cellular air interface or wired IP connections.

2.2.2. LoRa physical layer

The modulation technique used to encode LoRa data messages is a chirp spread spectrum scheme which encodes information by using linear variations in frequency over time of the frequency chirps. At the decoder side, frequency variations between the transmitter and receiver are in the form of timing offsets, thus they are easily eliminated. This results in non-complex decoding and mitigates Doppler effects [51]. Moreover, decoders do not need to be complicated as the frequency offset between the transmitter and receiver can reach up to 20% without QoS degradation.

As for channel coding, LoRa uses FCC (Forward Error Correction) by adding redundancy bits to messages. This aids in combating the interference caused by using frequency hopping spread spectrum systems. The reason for choosing chirp spread spectrum modulation is that it provides better results against co-channel and adjacent channel interference. [52]

In LoRa modulation, several factors are used to describe the system performance as they affect the bitrate, decoding complexity and the resilience to interference. Such factors include the BandWidth (BW), Spreading Factor (SF), and the Code Rate (CR). The bandwidth has the most impact as it determines the band of frequencies over which the chirps will span.

Communications between LoRa end-devices and their gateways are spread over a number of spreading factors and also over various frequency channels. Basically, the choice of a specific spreading factor trades-off data rate for more coverage, especially that communications over different spreading factors do not interfere with each other. LoRa networks can support data rates ranging from 0.3 kbps up to around 40kbps, depending on the spreading factor used. In order to suit more applications, LoRa supports the use of Adaptive Data Rate scheme (ADR) which allows allocation of different spreading factors to end-devices, depending upon the target battery-life and the network capacity needed.

A LoRa symbol consists of 2^{SF} chirps, meaning it can encode a total number of SF information bits. Chirps span the entire allocated frequency band. As shown in Figure 8 [53], the symbol starts with a series of upwards chirps and when it reaches the end of the band it restarts from the minimum frequency again. Data is encoded in the varying position of the frequency discontinuity.

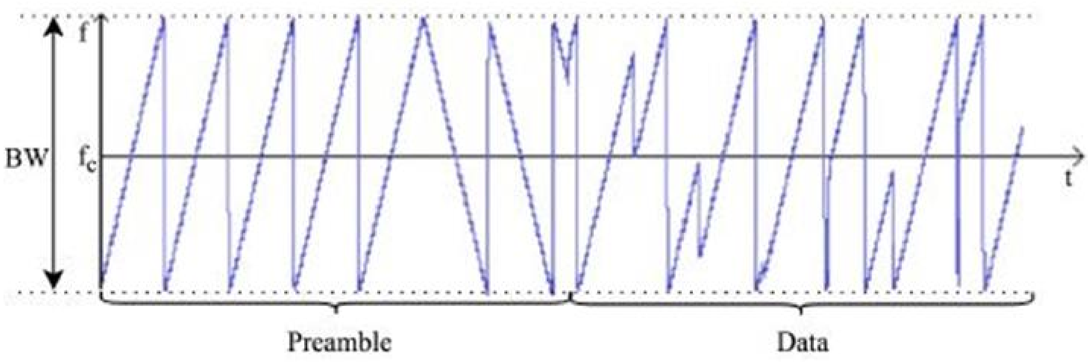

Figure 8. LoRa protocols architecture.

In LoRa, chirp rate depends solely on the bandwidth, in other words, they are equal, thus, there is one chirp per second per hertz. This implies that an increase of one in the spreading factor will halve the frequency range over which the chirp spans, as well as double the symbol time. On the other hand, it will not have the bitrate since an extra bit will be transmitted per symbol in the same time.

As depicted by equation (1) [55], bandwidth also plays an important role in determining the bitrate. It can also be seen that for a constant spreading factor, increasing the bandwidth will decrease the symbol time which translates to an increase in symbol and bit rate. Symbol time is defined as:

$$T_s = \frac{2^{SF}}{BW} \quad (1)$$

As for LoRa´s forward-error-correction codes, equation (2) [55], describes the relationship between Code Rate (CR) and the effective bitrate. Bit rate is defined as:

$$R_b = \mathrm{SF} \times \frac{BW}{2^{SF}} \times \mathrm{CR} \quad (2)$$

Equation (2) can also be used to forecast the effect of varying the bandwidth or the code rate on the error rates and the receiver´s sensitivity. In classic communications theory, increasing the bandwidth decreases the receiver´s sensitivity. While in LoRa, receiver's sensitivity might be increased by increasing the spreading factor. Moreover, a decrease in the code rate, while decreases the bitrate, helps reducing the Packet-Error-Rate (PER) if the interference is in short bursts. In other words, a 4/5 code rate does not decrease packet errors as much as code of 4/8.

2.2.3. LoRa physical frame format

Before ending the discussion about the bandwidth and spreading factors, it´s important to discuss the LoRa physical frame format. As shown by Figure 9 [49], the LoRa frame starts with a preamble, which is consecutive upwards chirps spanning the whole frequency spectrum. Towards the end of the preamble is the sync word, which is basically the last two upwards chirps. The sync word is a one-byte identifier for the LoRa network; meaning that a LoRa end-device will not decode a frame if while decoding the preamble it figures out that the sync word is referring to a different LoRa network. Lastly, after the sync word comes 2.25 downchirps equivalent to 2.225 symbols. LoRa allows for a flexible configuration of the preamble size, where it can be set to a range of values from 10.25 to 65,538.

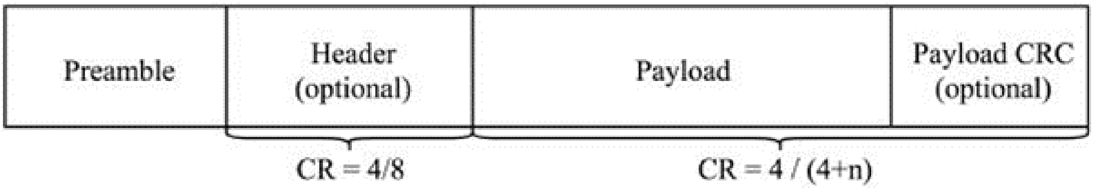

Figure 9. LoRa physical frame format.

Optionally, the preamble can be followed by a frame header. The header is always coded with a coding rate of 4/8 and it indicates a number of parameters, such as; the actual size of the payload in bytes, the code rate of the end of the frame, and the presence of absence of a *CRC*. The payload size stored in the header is one-byte thus limiting the size of the payload to 255 bytes. Obviously, when such parameters are already known, the presence of a header becomes insignificant. Moreover, the header contains a *CRC* of its own to differentiate valid headers from the invalid ones.

According to Semtech´s datasheet [53]. Equation (3) shown below is used to determine the size of a payload n_s given all the previously discussed parameters.

$$n_s = 8 + max\left(\left\lceil\frac{8PL - 4SF + 8\,CRC + H}{4 \times (SF - DE)}\right\rceil \times \frac{4}{CR}, 0\right) \tag{3}$$

n_s is then added to the preamble´s number of symbols to give the size of the whole frame. In equation (3), *PL* refers to the payload size in bits, *CRC* is 16 by default if defines and zero otherwise, *H* refers to the header size and is 20 when defined and zero otherwise, and *DE* is the data rate optimization which is 2 when defines and zero otherwise. Given the minimal settings, the number of symbols needed to transmit the LoRa payload is 8.

2.2.4. LoRaWAN protocol

As previously specified, LoRaWAN is the MAC protocol utilized by the LoRa devices to communicate through the LoRa PHY. LoRaWAN specifies 3 types of end-devices:

- Class A: this class of LoRa end-devices enjoys the basic feature of sending an uplink transmission at any time it chooses. On the other hand, for downlink transmissions, this class of devices only listens for a short period of time right after an uplink transmission. Clearly, class A devices provide the best battery consumption, since it activates its receivers only for a short period of time.

Though, this feature comes at the cost of added latency and decreased flexibility as it limits the devices′ applications to areas where uplink data can be constrained.

- Class B: devices belonging to category B are basically the same as class A except for the added option of scheduled receive slots. In addition to listening in time slots following an uplink transmission, class B devices also listen in pre-scheduled time slots determined by a synchronized beacon from the gateway. Such devices obviously allow for more flexibility in deployment.
- Class C: lastly, class C devices have nearly constantly activated receivers, thus allowing for minimal latency but on the expense of high power consumption. Such devices are very crucial in time-critical applications.

2.2.5. LoRa messages and MAC commands format

As discussed in section 3.2.3, LoRa messages start with a preamble then a frame header which are followed by the actual physical payload of the message. Figure 10 [55], describes the structure of various levels of LoRa messages, starting with the radio physical layer message till the structure of the frame header.

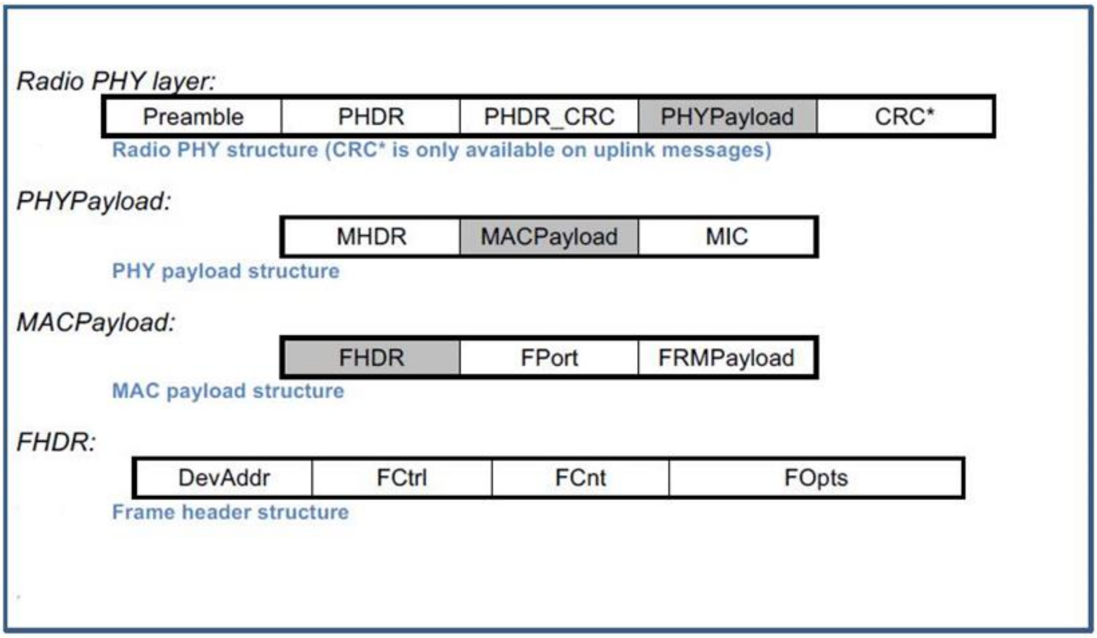

Figure 10. LoRa frame elements.

PHY payload:

The PHY payload starts with a 1-byte MAC header (MHDR). This header specifies the LoRa message type. LoRa messages can have various types, it can be a join-request, join accept, or a data message. The MHDR is followed by a varying-size MAC payload. The PHY payload frame ends with a 4-byte message integrity code (MIC). The MAC layer (PHY payload) frame structure is shown in Figure 11 [55]

Size (bytes)	1	1..*M*	4
PHYPayload	MHDR	MACPayload	MIC

Figure 11. MAC Layer (PHY payload) frame structure.

MAC Payload:

As shown in Figure 12, the MAC payload of LoRa data messages consist of a frame header (FHDR), then an optional port field (FPort) and ends with an optional payload field (FRMPayload).

Size (bytes)	4	1	2	0..15
FHDR	DevAddr	FCtrl	FCnt	FOpts

Figure 12. Structure of FHDR.

Figure 13 [55], shows the structure of the frame header of the MAC payload. The header starts with a 4-byte device address (DevAddress) followed by a single-octet frame control (FCtrl) then a 2-byte frame counter (FCnt) and ends with an up-to-15-bytes frame options (FOpts) block. FCtrl blocks usually carry information about the ADR control in addition to message Acknowledge (ACK) data. FCtrl also carries information about whether the FOpts exists or not and its size. The FCnt blocks carry information about the number of frames sent and received by either the end-device or the gateway. Finally, the FOpts block, when present, carries MAC commands which are piggybacked on the data frames.

The second and third block of a MAC payload, the port field and frame payload respectively are inter-connected. If the FPort field is present, it means the FRMPayload is not empty. When FPort is present, a value of 0 means that the FRMPayload carries only MAC commands. The remaining of FPort values are application specific.

2.3. Cellular IoT

According to [56], it is expected that most M2M communications will be served by cellular 3GPP networks while less than a third of MTC devices will be served by proprietary LPWANs. This difference is due to the fact that cellular networks in general are already ubiquitously present, better managed, and have already established infrastructures.

Cellular IoT has numerous applications, a trial to create a single platform that would support all or most of the cellular IoT application would be exhaustive.

Cellular M2M communications may be used for a simple sensor device which runs on minimal energy and transmits very little traffic, and also it may be used for video surveillance, which would need far more energy consumption and sophisticated communications links.

2.3.1. Cellular IoT applications classifications

Due to the large array of potential applications of cellular IoT, several classifications exist as an attempt to have a unified overview of the possible use cases. Application can be classified according to. [56]

Reliability and number of connected devices:

In this category, two types of MTC applications exist, massive MTC and ultra-reliable MTC. Massive MTC (mMTC) is the array of applications where deployment scenarios constitute a very large number of remotely-connected devices such as sensors or actuators. As a result, data rates degrade proportional to the increase in the devices´ numbers. The main focus in this category is to provide massive connectivity with minimal energy consumption on the device side. The second category of applications are concerned with deployment scenarios which need Ultra-Reliable Machine Type Communications (uMTC). Such applications include vehicle-to-vehicle communications where the cost of missing a packet would be very high. The main focus in this category is on providing a service which is almost always available even if with some graceful degradation in QoS at sometimes, which comes on the expense of fewer number of connected devices with less data rates. [56]

Mobility and dispersion levels:

According to whether or not the connected devices are mobile, and to how dispersed they are, applications can be classified to 4 different categories. Namely, fixed and either concentrated or dispersed, and mobile while being fixed or dispersed. A smart grid application for instance is a typical example of fixed and disperse applications. On the other hand, a fleet-tracking sensors system is a good example of a mobile and disperse system. Contrarily, a smart-home use case represents the category of fixed and concentrated deployments. [56]

Level of delay tolerance:

According to their level of delay tolerance, M2M application could be classified into 4 categories, elastic applications, hard real-time applications, delay-adaptive applications, and lastly rate-adaptive applications. A typical example of a class 1 application would be a remotely-deployed MTC device downloading data from the MTC server, here some delay could be tolerated. A class 2 example would be a tracking system, were less delays can be tolerated than class 1. As for class 3, it concerns applications which have customized tolerance levels. The last class of applications refers to scenarios where communicating nodes can adjust their transmission rates in accordance to the available communications resources to control the delays. [58]

Data reporting mode:

According to the mode by which a device decides to report to its controlling server, applications could be classified into five categories, time-driven, query-driven, event-driven, continuous-based and lastly hybrid-based. Simply put, time-driven devices send data to their servers in specific pre-determined time windows. Event-driven devices transmit data reports in case of a certain pre-determined event happening. Query-driven devices report data when it receives certain instruction from its server. Probably the most energy-consuming type would be the continuous-based category where devices open a never-ending communications channel with the server. Lastly, hybrid scenarios are when devices adopt more than one strategy for their uplink messages. [60]

2.3.2. MTC communications over conventional cellular networks

In the past, GSM networks were thought of as the wireless technology which will give rise to M2M communications. This belief was based on the -back then- understanding of the requirements of M2M communications and that GSM networks were the most suitable to meet these requirements. In more details, GSM´s low data rate, energy efficiency and low device complexity were the main attractions towards the adoption of GSM for MTC. There were even applications already being developed at that time such as using SMS services of GSM and GPRS technologies to enable communications between machines.

However, as of the year 2010, this belief changed due to various reasons. Firstly, as the technology became more mature and more use cases started to appear, it was obvious that GSM will not be able to cater for the increasing demands of MTC. For example, it was obvious that GSM cannot handle the massive number of devices envisioned by MTC, nor can it handle the high data rates required in some applications. Moreover, by that time, many operators were already preparing their spectrum re-farming strategies and some even announced the full shut down of their 2G GSM networks [60].

The research community started then briefly turning their heads to the 3G networks family, such as UMTS and HSPA. However, these thoughts did not remain for much time due to the very high-power consumption of 3G devices and their high complexity. [61] [61]

2.3.3. Standardization of reference MTC architecture

Along with the advancements of M2M communications, the network complexity increases. Firstly, M2M encompasses a very wide array of applications, corresponding to an equivalently wide array of wireless access techniques used. Furthermore, M2M differ from H2H (Human to Human) communications in a sense that the same protocols that worked efficiently for H2H communication may prove inefficient for M2M communications. Thus, several efforts by various standardization bodies such as the European Telecommunications Standards Institute and the 3GPP are focusing on developing a unified efficient architecture for cellular IoT. [62]

Reference M2M network architecture by ETSI:

As depicted in Figure 13 [63], the proposed architecture by ETSI consists of two domains, namely, the devices/gateways domain and the network domain. Devices and gateways connect to the network domain either directly or indirectly. In the indirect mode, a gateway acts as a relay between the devices and the network. The network domain provides the connectivity between M2M devices and the application layer.

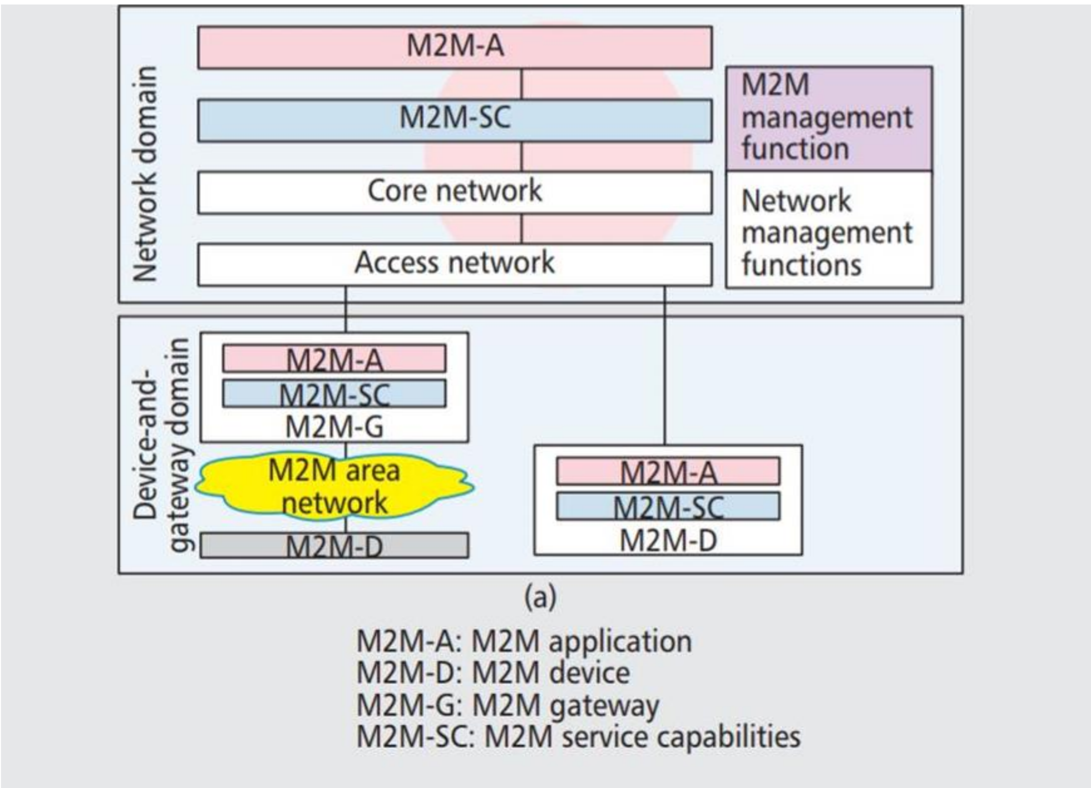

Figure 13. ETSI M2M network architecture.

Table 2 [63] details the functions of each node.

Table 2. Functions of nodes in the ETSI proposed M2M architecture

Element	Functionality
M2M-D	Device which runs M2M application
M2M-G	Gateway which provides connectivity to devices
M2M Area Network	The wireless access technology used between devices and gateways
M2M-A	Applications which run the service
M2M-SC	Service capabilities layer, provides common functions to various applications
M2M management function	Functions which manage the M2M-SC in the network domain
M2M core network	Central node which provides various services to M2M-A
M2M access network	Connects devices and gateways to the M2M core network

Reference M2M network architecture by 3GPP:

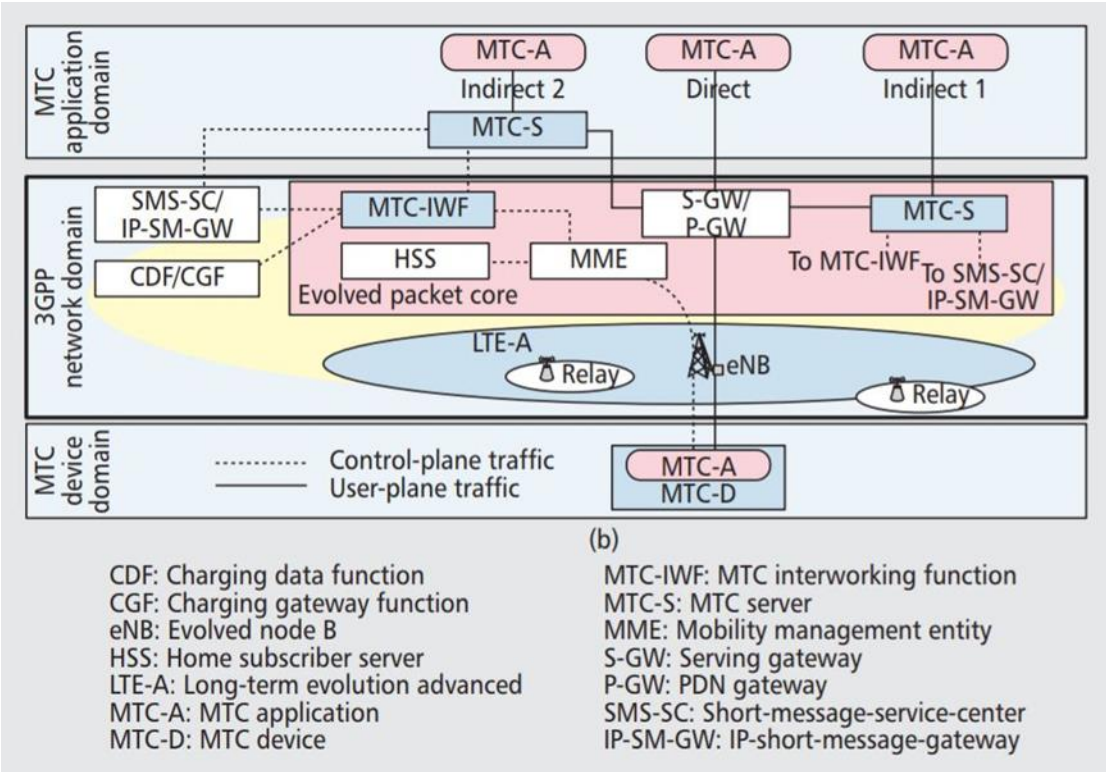

Figure 14. M2M architecture by 3GPP.

As shown in figure 14 [65], M2M is referred to as MTC in the 3GPP terminology. The 3GPP reference architecture consists of the MTC Device domain (MTC-D), the MTC Application domain (MTC-A) and the conventional 3GPP network domain.

The latter, as in conventional LTE systems, provide IP connectivity to the MTC-D and MTC Servers (MTC-S). However, the major difference in the 3GP architecture is the addition of a new network element called the MTC InterWorking Function (MTC-IWF). In addition, an important difference between this architecture and the one proposed by ETSI is that in the 3GPP network the main focus is on the wireless access and core network improvements. Table 3 [63] provides the functionalities of different nodes in the architecture. For the sake of simplicity, legacy nodes from the conventional LTE-A Evolved Packet Core (EPC) will not be mentioned as it is out of the scope of this chapter.

Table 3. Functions of nodes in the proposed MTC architecture by 3GPP

Element	Functionality
MTC-D	MTC device, similar to handheld smart phones but optimized for MTC
MTC-S	Server, it connects to several MTC-D and routes data to the MTC network
MTC-A	Application, it resides in the top layers in the devices
MTC-IWF	Interworking function, a logical node which hides the internal 3GPP network topology from the MTC-S and routes signalling messages between MTC-S and the 3GPP network

Reference M2M architecture by IEEE:

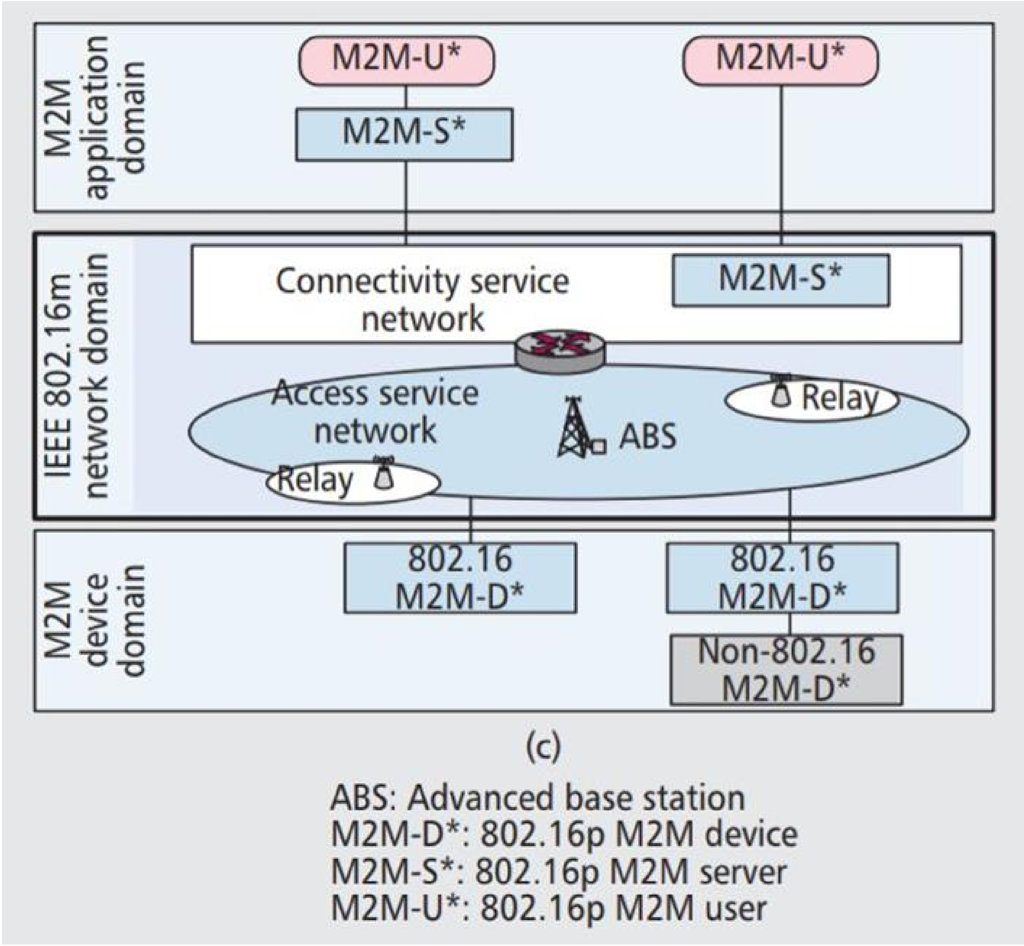

Figure 15. M2M reference architecture by the IEEE.

Figure 15 shows the reference architecture for M2M networks as depicted by [66], which comprises of the device, network and application domains. Similar to the operation of the reference architecture proposed by the 3GPP, the network domain provides the devices and the servers with the IP connectivity necessary for communications. Table 4 [63] enlists the functions of various nodes of the architecture.

Table 4. Functions of nodes in the proposed MTC architecture by IEEE

Element	Functionality
M2M-D	802.16p-M2M device,
M2M-S	802.16p-M2M server, communicates with one or more device
M2M-U	M2M subscriber

Project OneM2M reference architecture:

In 2012, the OneM2M project was established in cooperation between various standardizations bodies from all around the world such as ETSI from Europe, CCSA from China, TTA from Korea, and TIA and ATIS from North America, to handle and unify the development efforts in the M2M cellular networks field. By the beginning of 2015, the OneM2M project released their proposed M2M network architecture [64].

As depicted in Figure 16 [56] the architecture consists of three main nodes, the Application Entity (AE), the Common Services Entity (CSE) and the Network Services Entity (NSE). Similar to the M2M-A in the ETSI architecture, the application entity implements an M2M application service logic. The CSE acts as central functions node which handles subscriptions and devices management tasks. The NSE´s main task is to provide services to the CSE.

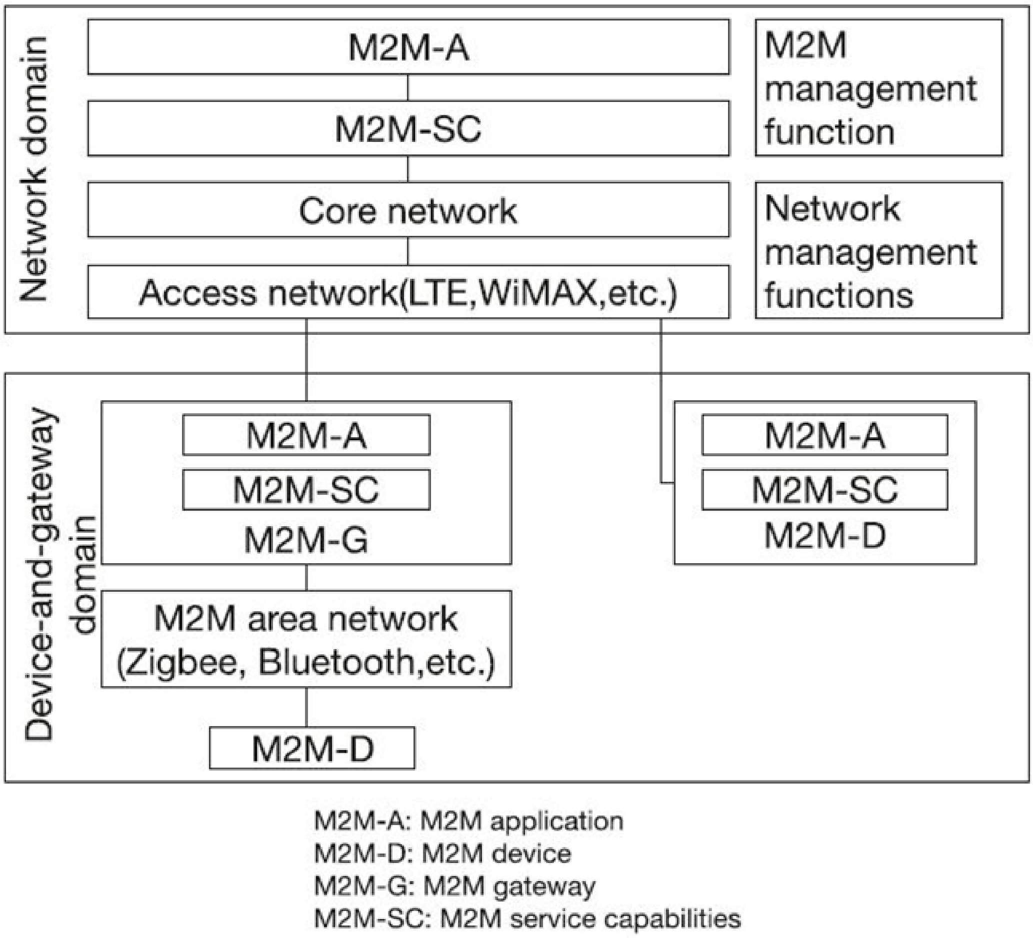

Figure 16. M2M network Architecture proposed by OneM2M project.

2.3.4. LTE-Based solutions for cellular IoT

As discussed earlier, cellular IoT is expected to dominate a huge part of the IoT and M2M market in the upcoming years. To realize this vision, cellular technologies must be able to compete in the LPWAN market and to offer services to M2M and IoT applications. In addition, cellular technologies must prove their ability to enable IoT applications. The key requirements which cellular IoT must provide are:

- Support for massive deployments of devices
- Wide-service spectrum

- Low-cost devise
- Long battery lives
- Extended coverage

Realizing this vision is accomplished via a number of enhancements to conventional networks´ air interface, core network and subscriptions database. On one hand, the air interface must entail support for narrower bandwidths, low complexity transmission protocols and energy efficient communications. One the other hand, coverage needs to be enhanced to reach deep indoor deployment scenarios.

Nokia [67] estimate that most of the cellular IoT applications will be centred around automotive services and utility meters. In addition, Nokia predicts that although 2G and 3G modules dominate a big share in the cellular IoT market, LTE is expected to start competing in the IoT market due to its ongoing new enhancements.

LTE systems operate on both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) schemes. Both with a subframe of size 1millisecond. Such small subframe times is considered an advantage when trying to reduce latency. However, 3GPP since release 12 have been introducing novel features in LTE to enhance its performance for IoT demands.

Enhancements in 3GPP Rel.12:

In release 12, new protocols have been standardized which will operate on devices with only 40%-50% of the cost of regular LTE modules. Such lower costs will come at the expense of reduced capabilities such as the relying on one receiving antenna instead of the two used for diversity. Moreover, the peak data rates for such M2M category devices will be limited at 1 Mbps in contrast to the 5 Mbps which was enabled by the lowest category of non M2M devices. In addition, new half-duplex devices will be introduced with the aim of reducing device complexity, cost and energy consumption by removing duplexers and switches. [67]

As part as their efforts to reduce modules´ power consumption, the 3GPP introduced a new Power Saving Mode (PSM) option. Devices operating in PSM set a times with their home network which starts when they end a connection and turn idle. Upon reaching zero on the times, the devices switches to PSM and remains in it till the device itself needs to transmit a packet. Furthermore, battery life can be prolonged by altering the device´s activity scheme when idle. Which means, a device should only active when sending data, and not being obliged to be active by paging cycles. Figure 17 [67] shows the relation between paging cycle, transaction cycle and battery life in months for LTE M2M device (category M2M/ Cat.M) operating with two AA batteries. Using the above-mentioned methods, as of Rel.12, battery life of devices could be enhanced to reach up to 11 years.

Paging cycle / Transaction cycle	2.56s Rel. 8	10.24s	1 min	10 min Rel. 12	1 h	2 h	1 day
15 min	3,7	4,5	4,9	4,9	4,9	4,9	4,9
1 hour	8,1	13,8	17,0	17,8	17,9	17,9	17,9
1 day	13,2	39,1	84,9	108,0	110,8	111,1	111,3
1 week	13,5	42,0	99,4	132,1	136,2	136,6	137,0
1 month	13,6	42,3	101,6	135,9	140,2	140,7	141,1
1 year	13,6	42,5	102,3	137,1	141,4	141,9	142,3

Figure 17. Trade-off between paging cycle, transaction cycle and battery life in months for Cat.M devices.

Rel.12 has specified many ways to achieve M2M service requirements by reducing devices complexity and KPIs but still complying with LTE standards. Though, to ensure LTE´s competitive performance, further reductions in complexity are addressed in Rel.13 and beyond. Figure 18 [67] depicts reductions in KPIs in releases 8 till 13.

	Rel-8 Cat-4	Rel- 8 Cat-1	Rel-12 Cat-0	Rel-13
Downlink peak rate	150 Mbps	10 Mbps	1 Mbps	~200 kbps
Uplink peak rate	50 Mbps	5 Mbps	1 Mbps	~200 kbps
Max number of downlink spatial layers	2	1	1	1
Number of UE RF receiver chains	2	2	1	1
Duplex mode	Full duplex	Full duplex	Half duplex (opt)	Half duplex (opt)
UE receive bandwidth	20 MHz	20 MHz	20 MHz	1.4 MHz
Maximum UE transmit power	23 dBm	23 dBm	23 dBm	~~20 dBm
Modem complexity relative to Cat-1	125%	100%	50%	25%

Figure 18. 3GPP Releases and their respective KPIs to meet M2M requirements.

Release 12 witnessed the specification of category zero (Cat.0) devices, with the aim of reducing device´s complexity, cost and power consumption. The most important of these reductions were:

- Introduction of half-duplex FDD scheme.
- Reducing the receive bandwidth of device to reach 1.4MHz. Such small bandwidth allows for simple devices which can still operate in all LTE networks.
- The elimination of the receive diversity and its extra antennas
- Reducing data rates which reduces devices´ hardware complexity.

Enhancements beyond 3GPP Rel.12 [67][68]:

3GPP kept further reducing the devices´ complexity via a number of ways:

- Further elimination of transmission diversity. Devices not supporting MIMO
- Introduction of narrowband communications. Bandwidths even below 1.4MHz
- For some devices, such as sensors, very low data rates will be applicable, even below 200 kbps.

2.3.5. NB IoT

With the aim of further enhancing cellular networks to be more appealing for IoT use cases, 3GPP in its Rel.13 offered a wide array of new features to draw more IoT applications to the cellular networks platform. Such features include Enhanced Coverage-GSM-IoT (EC-GSM) [69] and LTE category M (LTE-M) [70], both aiming to introduce new modifications to existing GSM and LTE networks, such as extended coverage or more power efficiency, to fit MTC traffic. However, a third option was also offered, Narrowband IoT (NB IoT) which offered even more capabilities and flexibility to operate with already existing LTE networks on ultra-low-end applications.

NB IoT is expected to target a very specific category of IoT applications. It has been customized for applications which do not need huge amounts of UL data nor applications involving tracking which requires lots of handover. Specifically, NB IoT serves applications which aim to utilize a massive number of connected devices but at a low data rate with considerable delay. Such applications include metering devices and remotely-deployed sensors. This category of applications at first seems realizable using conventional LTE networks, however, the massive number of devices would create a huge signaling overload on the network. In other words, the signaling overload caused by human traffic is worthy because the actual packets sent by human-type-communications is huge. On the other hand, the actual packets sent by sensors or meters is very small, so it is considered not worthy of the signaling load it creates. Thus, the need to create a new radio access technology customized for small packets with minimal overhead signaling.

However, the main goals of NB IoT did not stop at minimizing overhead signaling. Mostly, metering devices are deployed in non-easily-accessible area, thus making the lifetime of the metering device basically the life time of the battery. Consequently, devices have a very long battery lifetime. Moreover, deployment scenarios may also dictate that devices are deployed at areas with poor radio coverage. Thus, NB IoT devices must also leverage from an improved link budget. Lastly, as mentioned earlier, NB IoT is targeting massive deployments of devices, which dictates that a device´s price should be kept a minimum to encourage business use cases, typically around 5 US$.

The way NB IoT is able to provide such requirements, is simply by omitting other non-essential (in the MTC context) requirements which are supported by conventional LTE. For instance, NB IoT does not offer support for active-mode handover; only idle-state cell-reselection is possible. Added to that, NB IoT does not support carrier-aggregation, dual connectivity, nor device-to-device communications.

Lastly, since NB IoT does not support delay-sensitive or data rate-sensitive services, it lacks the concept of QoS as a whole.

Core Network:

As a step to bring the cellular EPS architecture one step closer to efficiently supporting MTC, two modifications were applied to the conventional EPS. The user-plane cellular-IoT EPS optimization and the control-plane cellular-IoT EPS optimization.

A couple of modifications to the cellular core-networks were deemed necessary in order to fully support MTC, the cellular-IoT EPS optimization.

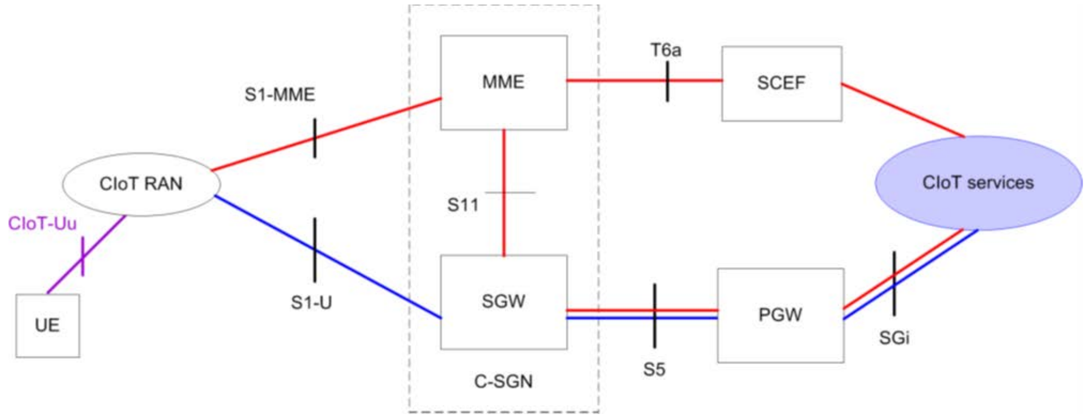

Figure 19. In red, Control plane CIoT optimisation and in blue user-plane CIoT optimisation to the EPS.

Figure 19 [69] shows the user-plane and control-plane modifications applied to the EPS. Shown by red, the control-plane optimization allows UL data, sent from the eNB to the MME, to take one of two paths, either to the Packet Data Network (PDN) via the Serving Gateway (SGW), or to the Service Capability Exposure Function (SCEF). From either two nodes, data is finally routed to the cellular IoT applications server. Consequently, DL data follows the same path. The reason this modification is suitable for MTC is that it allows for sending the data over the signalling radio bearer, thus eliminating the need for setting up a dedicated data radio bearer. Embedded in the modification is the introduction of a new node, the SCEF, which is responsible for the transmission of non-IP packets over the control-plane.

On the other hand, modifications to the user-plane, shown in blue, are limited as data still follows the same path as in conventional LTE, from SGW and PGW to the server via radio bearers.

Operation Modes:

One of the main advantages of NB IoT is its ease of deployment. NB IoT operates on an 180kHz band [71] which gives it great flexibility of deployment. The design choice of 180kHz was to fit NB IoT transmissions into a single resource block, thus allowing easy mapping to LTE transmission. This flexibility offers three deployment scenarios depicted in Figure 20: [69]

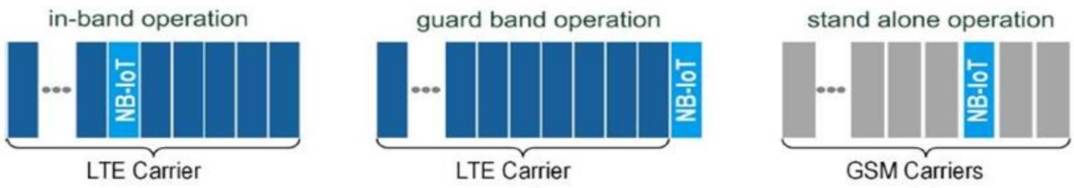

Figure 20. Different NB IoT deployment scenarios.

- In-band operation, which means NB IoT data will be sent via LTE resource blocks within the band of conventional LTE
- Stand-alone operation, which means NB IoT packets will be sent over re-farmed GSM spectrum
- Guard band operation, which implies the utilization of resource blocks of the LTE frequency guard bands

Frame and slot structure:

As shown by Figure 21 [69], NB IoT utilizes OFDM (Orthogonal Frequency Division Multiplexing) in a way similar to conventional LTE. With a 15kHz subcarrier spacing between12 subcarriers producing a 180kHz resource block which is also one 0.5ms time slot. One square in the figure refers to one resource element which is equivalent to one subcarrier in a symbol.

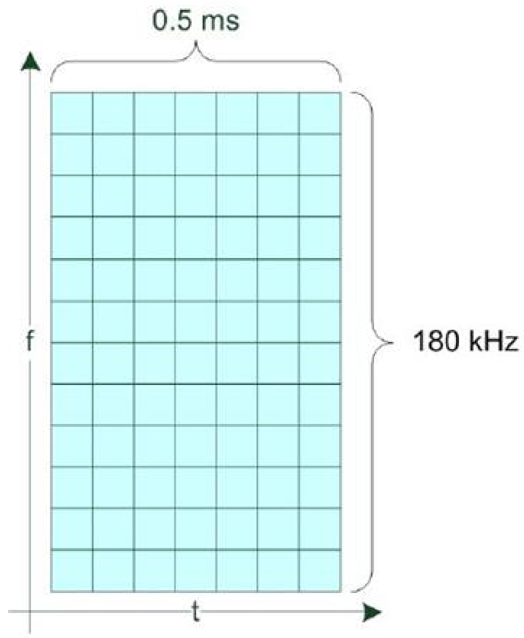

Figure 21. Resource grid for NB IoT.

Figure 22 [69] shows how slots are mapped to subframes then to frames. Seven resource elements correspond to one 0.5ms slot. Two slots form a 1ms subframe. Ten subframes form a 10ms radio frame. 1024 radio frames form a system frame. Utilization of the same terminology and numerology as LTE ensures safe coexistence between NB IoT and LTE.

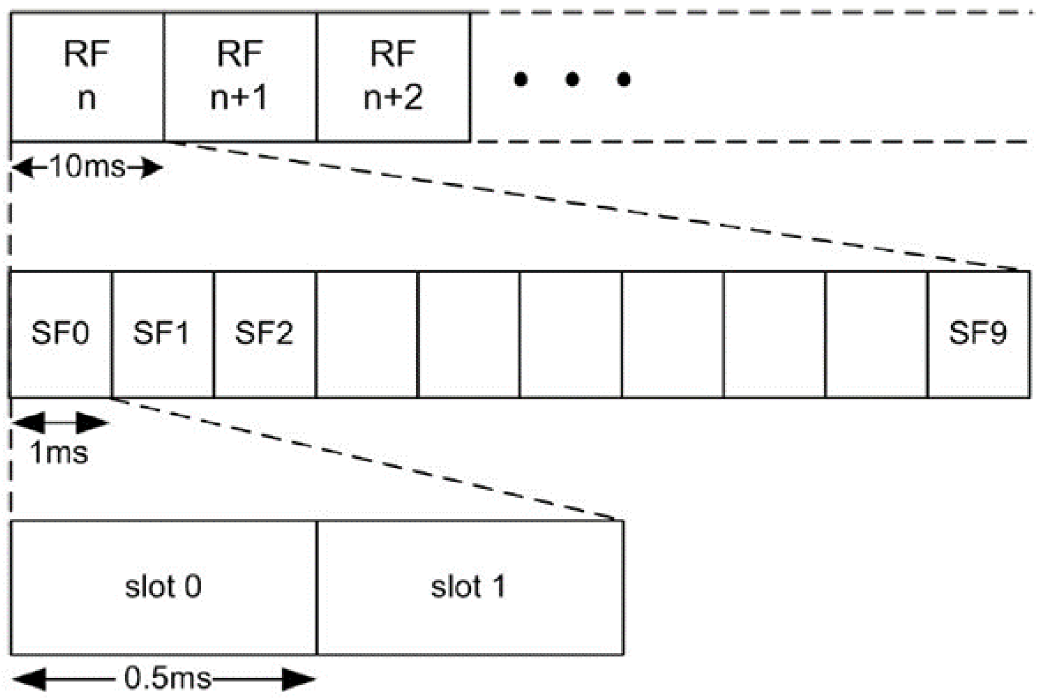

Figure 22. Frame structure.

Downlink Channels:

NB IoT utilizes physical channels similar to LTE, with a difference that NB IoT channles are multiplexed in time. For DL messages, three physical channels and two physical signals are defined:

- Narrowband Physical Broadcast Channel (NPBCH)
- Narrowband Physical Downlink Control Channel (NPDCCH)
- Narrowband Physical Downlink Shared Channel (NPDSCH)
- Narrowband Reference Signal (NRS)
- Primary and Secondary Synchronization Signals (NPSS and NSSS)

NPSS and NSSS are used for synchronization purposes such as frequency synchronization and cell ID search. NPSS is transmitted in the fifth subframe of each frame in the last 11 OFDM symbols. On the other hand, the NSSS is transmitted in subframe number 9 with a 20ms periodicity, again, using the last 11 OFDM symbols of the subframe.

The NPBCH, being a broadcast channel, carries the Master Information Block (MIB). It's transmitted in the first subframe. It remains unchanged all over the 640ms duration of the TTI. On the other hand, the NPDCCH has many functions. It carries scheduling information, HARQ acknowledgments, Random Access Responses (RAR) as well as paging indications.

Uplink Channels:

NB IoT has two channels defines for UL:

- Narrowband Physical Random-Access Channel (NPRACH)
- Narrowband Physical UL Shared Channel (NPUSCH)

Since the RACH channel of the conventional LTE is 1.08MHz in bandwidth, a random-access channel for NB IoT had to be specifically designed. The NPRACH preamble consists of 4 symbol groups, within each group exists 5 symbols and one Cyclic Prefix (CP). For Format 0 (cell radius of 10Km) the CP length is 66.67 µs whereas for Format 1 (cell radius of 40Km) the length is 266.7 µs. Each symbol is modulated using a 3.75 kHz tone. The NPRACH can be repeated up to 128 times to support wide coverage areas. [73]

The NPUSCH varies in size, depending on its function. NPUSCH of format 1 is utilized for UL transmissions and is of size 1000 bits. While format 2 NPUSCH is used for sending HARQ acknowledgments of the NPDSCH. Format 1 uses the LTE turbo code for error correction while format 2 uses a repetition code. While Format 1 NPUSCHs are formed based on the conventional LTE slot structure with 7 OFDM symbols per slot with the median symbol reserved for the Demodulation Reference Symbol (DMRS), the format 2 NPUSCH reserves the 3 median symbols for DMRS.

Resource Mapping:

In case of in-band deployment, the maximum coexistence efficiency must be ensured to avoid degrading the quality of the LTE nor the NB IoT system. Orthogonality between the signals of the two systems is maintained primarily by avoiding mapping of NB IoT signals over resource blocks already taken by LTE. Figure 23 [73] shows an example of the 12 subcarriers in a resource block, where in the top chart the stand alone/guard-band deployment is depicted. In this case, the NPDCCH, NPDSCH or NRS are free to be mapped to any resource element, depicted as a block, since there is no threat of over-mapping over LTE resource elements. Whereas, in the lower chart, blue and red resource elements are taken by LTE CRS and PDCCH thereby NB IoT is not using symbols 0 to 3. In NB IoT, a device learns its deployment mode through the cell acquisition procedure, only then could it figure out which resource elements to ignore as they are utilized by LTE. But since NPSS, NSSS and NPBCH are used to transmit master system information and initial synchronization signals, which are needed to know the deployment mode, the UE (User Equipment) ignores the first 3 symbols at all times.

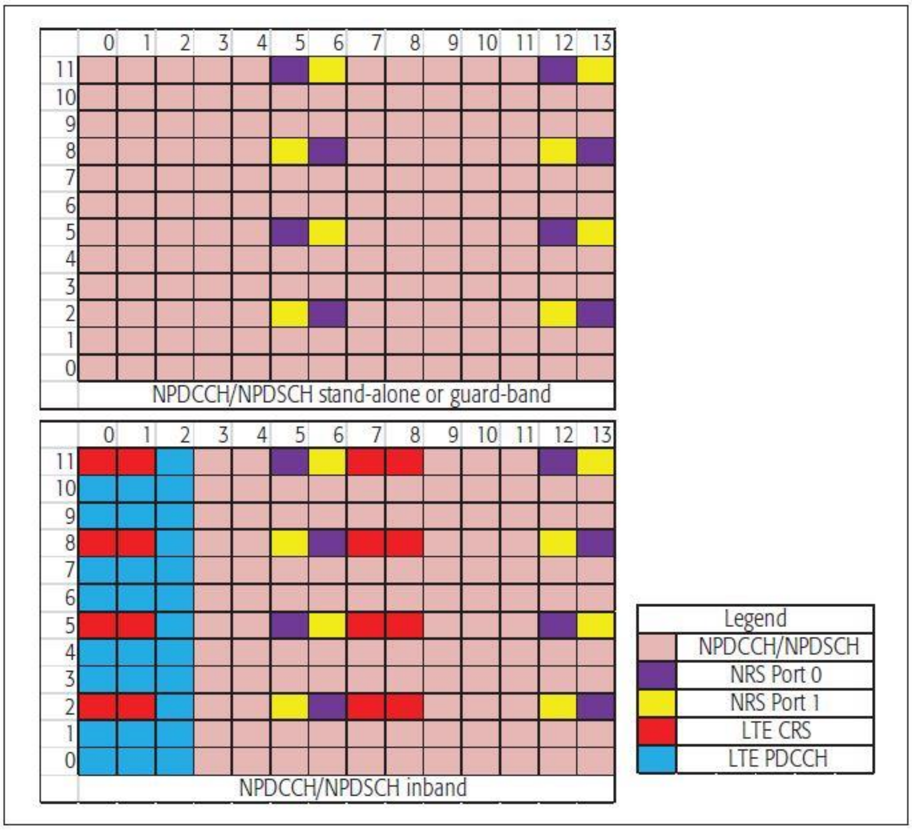

Fig 23. Resource mapping of NB IoT

Cell Search and Initial Acquisition Procedures:

Cell search and initial acquisition are pillar stone procedures for connection establishment between a UE and its serving cell as soon as the UE is switched on. These procedures refer to the steps where the UE connects to a suitable cell and acquires its important parameters such as frame timing, subframe timing and symbol timing. It also involves the UE synchronizing its receiver to the carrier frequency of its serving cell. Due to some inaccuracies that might be caused by the local oscillator of the UE´s receiver, frequency offsets might exist too. Moreover, synchronization also involves the UE acquiring the absolute frame and subframe number reference and determining the symbol timing alignment with DL frames.

Since NB IoT is intended to cater for the needs of MTC, this entails deployment of low-cost low-complexity devices. Consequently, low-cost oscillators might cause an initial Carrier Frequency Offset (CFO). In addition, in-band and guard-band deployments might introduce additional raster offset which increases the overall CFO. Synchronization steps of NB IoT must mitigate these difficulties and still provide service at low SNR (Signal-to-Noise Ratio) levels.

NPSS and NSSS are the main signals used in synchronization. The former being used to obtain the CFO and symbol timing while the latter provides the Physical Cell ID (PCID) and the timing within an 80ms block. After initial synchronization, the UE starts obtaining the MIB via the NPBCH.

Random Access Procedure:

The random-access procedure for NB IoT communications is to some extent similar to that of conventional LTE, but with some slight modifications. As discussed earlier, NB IoT supports 3 coverage-enhancement levels to be able to serve remotely-deployed devices. The main idea of the coverage enhancement is that a UE repeats its random-access request multiple times to mitigate path loss effects.

Random access procedures are built upon 4 steps:

- The device sends to its serving cell a random-access request
- The cell responds by providing the device with the parameters needed in further steps such as the timing advance and UL resources scheduling
- The device uses these values to identify itself to the network
- The network responds by resolving any contention-based issues caused by multiple simultaneous UL transmissions.

The modification done to fit the coverage enhancement levels idea is that a UE first measures its DL received signal level to estimate in which coverage level it is then uses this value to know how many times it should repeat its random-access request in addition to its transmit power.

3. 5G IN HEALTHCARE

3.1. 5G in healthcare

According to the World Health Organization (WHO), m-health (Mobile Health) refers to the use of smart mobile devices to aid in medical practices. While e-health refers to the transfer of medical-assistance resources from human means to electronic means. [73]

A variety of applications already exist for m-health such as monitoring, positioning, measuring vital signs, electronic reminders for medications, personal guidance systems and many more. A major boost in m-health applications was given by the wide spread of 3G and 4G networks, in addition to smart phones. Such m-health applications facilitate the process of collecting data about patients which could significantly improve the healthcare experience. This could allow for better personalized treatment plans, easier access to healthcare information by patients, in addition to providing healthcare in remote areas. [74]

However, 5G promises even more breakthrough in healthcare. 5G is expected to bring around the needed technology to facilitate a number of novel practices in medicine such as the tactile internet.

3.1.1. The need for 5G in healthcare

The reasons why e-health and m-health sectors are gaining an ever-increasing amount of attention lately is that it will facilitate the transition of healthcare from hospital-based to distributed patient-centered care model. This is due to the huge load healthcare is putting on Europe´s Gross Domestic Product (GDP) [75] where Europe currently spends one tenth of its GDP on healthcare. Moreover, the increase in the costs of healthcare as a percentage of the GDP surpasses the average increase in economic growth. This is also indicated by a number of factors such as the Average Length of Stay (ALS) in hospitals, the number of beds in hospitals, in addition to the costs of following up and maintaining hospital assets. All these indications point to the immediate need for less centralized and more distrusted healthcare models.

Having a less centralized healthcare system does not necessarily mean the total elimination of actual hospitals and care centers. It simply refers to off-loading central nodes and relying more on state-of-the-art well-equipped rural nodes. Treatments could be delivered to patients in nursing homes, clinics, or even through the internet at their homes. Added to that, more attention can be given to preventing sickness by monitoring susceptible patients´ lifestyles habits by collecting data through m-health and e-health and analyzing them.

As part of the United Nations (UN) new Sustainable Development Goals (SDG), providing universal healthcare is at the Centre of attention of its next 15 years plan.

Moreover, according to the Economists´ Declaration [77] investments in pro-poor universal healthcare pays off multiple of times.

According to [77] the current healthcare system suffers the following deficiencies:

- As discussed earlier, current healthcare schemes rely on moving the patient to the central healthcare facility, thus creating a non/patient/centric system. This causes issues to immobile patients and also to their guardians as they have to move the patient which might result on postponing the visit till the guardian has free time.

- Due to the lack of "Big Data" analytics, treatment plans are not personalized to every patient. Instead, they rely on general averages which might not be suitable for a specific patient.

- Some healthcare facilities are not easily accessible by all patients due to socio-economic or geographical reasons. Which might cause inconvenience to some patients.

- The margin for human errors is huge. According to a report by the "Institute of Medicine", a department of the "National Academy of Sciences" [79], human errors in hospitals are to be blamed for over 90,000 deaths annually, and over 20 billion dollars.

3.1.2. The role of 5G in disrupting the current healthcare system

Several healthcare advances with IoT:

IoT brings connect-able things together with means of radio access networks and also brings the connected devices to connection to a common cloud. These devices, in the context of healthcare, could be sensors which measure, monitor and report important data about patients to a central cloud where healthcare personnel are. The idea of IoT will possibly revolutionize current healthcare systems and upgrade them to be patient-specific. It can give rise to cutting-edge applications in areas of patient-monitoring, elderly-care, remote treatments, drug-intake monitoring and much more. IoT-based healthcare services can help reducing costs, increasing resources efficiency, decrease doctors´ response-times and above-all increase the quality of life of people in need of healthcare. Figure 24 [79] shows some of the recent trends in IoT healthcare applications.

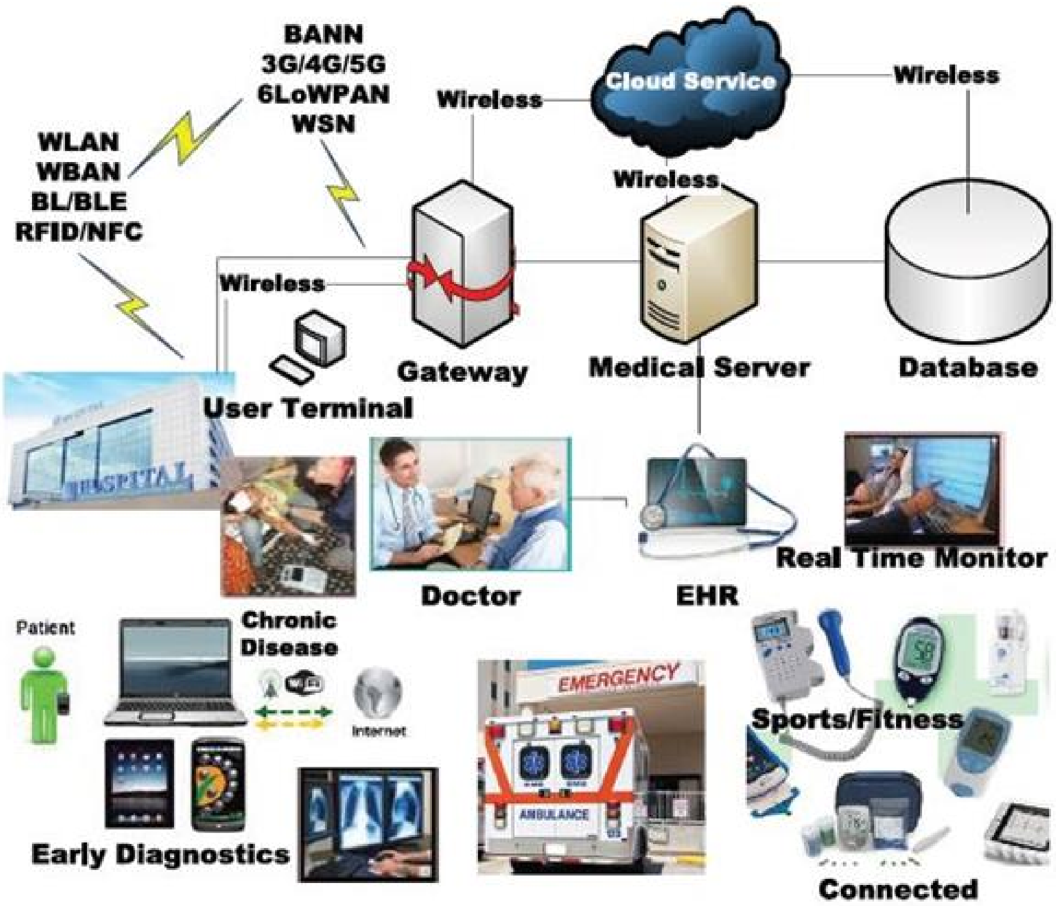

Figure 23. Different applications to 5G in healthcare.

Cheaper and cost-effective secure interactions are becoming possible through wireless connectivity between patients and healthcare providers. Novel radio access networks specially designed for IoT can help in real-time patient-monitoring, early prevention of diseases and medical emergencies. Application servers and databases will also help delivering on-demand services to patients in need. [80]

Big Data in healthcare:

Building upon the idea illustrated above about patient-centric healthcare systems, big data analytics plays an important role in realizing this vision. Since we are living in a merely digital world, ubiquitously deployed sensing devices deployed around us can gather huge amounts of data about us, big data. When the same concept is applied in healthcare systems, it can lead to major advances and opens door to major development efforts. Continuous monitoring of a patient´s heart rate, blood glucose levels, blood cells ‘oxygen-saturation, eating habits, body temperature and even emotions could provide deep insight into the patient´s behaviour and needs. Thus, appropriate analysis of this huge amount of data can lead to creating a personalized treatment plan that perfectly fits this patient´s case. [81]

However, not all patients are willing to share such private details about their personal lives with strangers as they worry this information might be used in an un ethical manner, thus, this issue should be treated delicately by creating tailored rules and regulations to give patients control over the use of such sensitive data. An example of such a scheme is illustrated in Figure 25. [82]

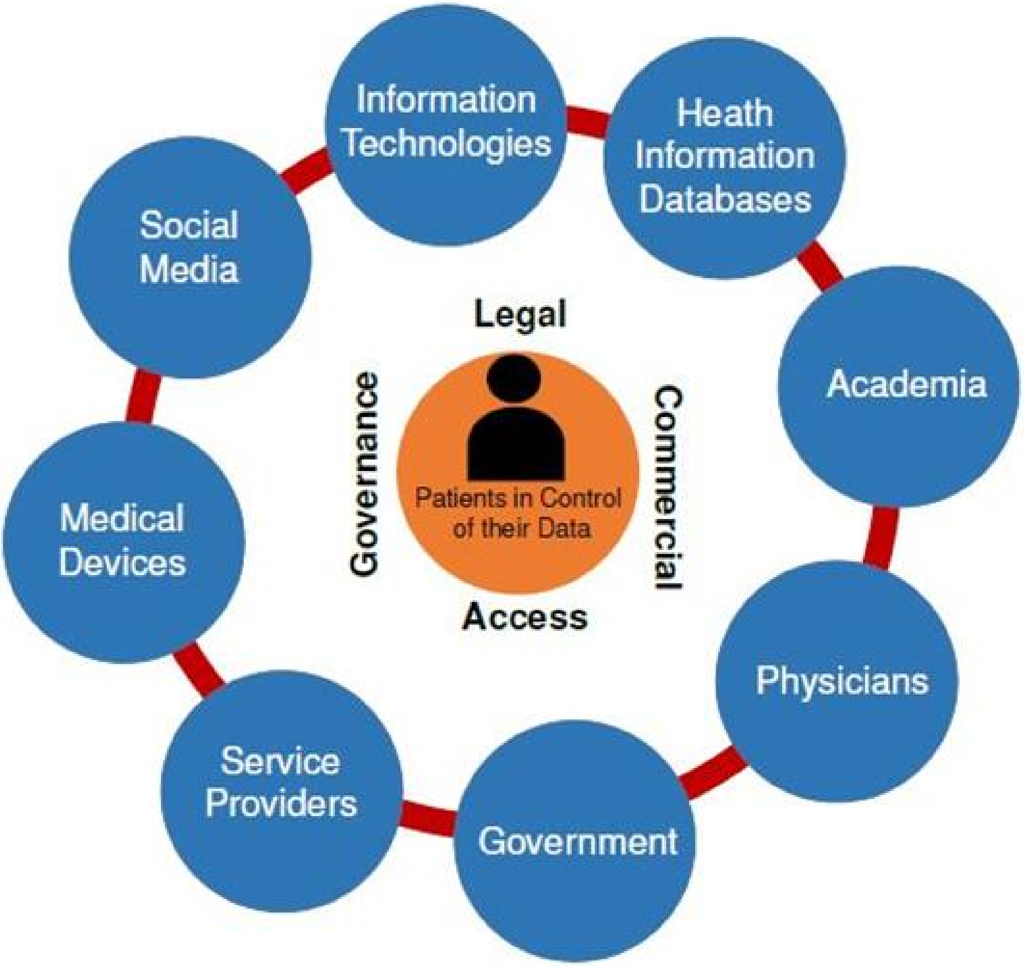

Figure 24. An example of a patient-centric big data ecosystem.

Wireless Connectivity:

Due to the ever-lasting research around wireless radio access technologies and their never-ending advancements, they provide a very persuasive infrastructure to bring connectivity to the healthcare sector. Added to that, the expected 5G extreme-Mobile-BroadBand (eMBB) will allow for novel features in the healthcare sector that were unimaginable before. A novel feature expected to be enabled by eMBB is telemedicine. Telemedicine refers to providing medical assistance remotely. Examples of telemedicine involve electronic sharing of reports, x-rays, texts and voice through wireless links between a patient and his healthcare provider. [83]

Moreover, it is also expected that new advancements in ultra-reliable low-latency communications will pave the way to the realization of remote surgery applications. Obviously, ultra-reliability and extremely low latencies are a corner-stone to allow for haptic feedback and tactile internet applications. As shown in Figure 26 [77] telemedicine will provide huge advantages for immobile patients thus drastically increasing the healthcare quality.

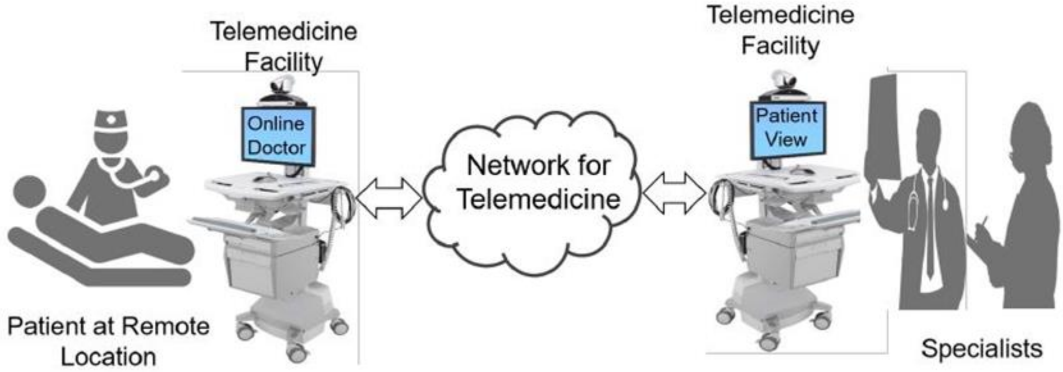

Figure 25. General example of telemedicine architecture.

Added to that, reliable communications links with high support for mobility could also give rise to a new type of healthcare, healthcare-on-the-go. For example, the time a patient spends in an ambulance can be put into use by starting his treatment in the ambulance. These applications require reliable and fast communication links connecting the hospital with the ambulance with the ability to share live video and vast vital readings.

3.2. 5G Test Networks

Parallel to theoretical advancements in 5G technology, real testing environments are vital to thoroughly test and observe how new applications function in real-life circumstances. Although simulations software is now abundant, they still can't replace a real-life environment. Since 5G is the new hot topic in the wireless world nowadays, networks vendors and research centers are investing more in network testbeds which function as a real-life experimentation system to allow applications developers to test their ideas before entering commercial markets. Such testbeds are very helpful to test the potential of new applications throughout all stages, from simply an idea to actual product testing.

Several efforts have emerged recently to address this demand, with each facility addressing a specific area of the 5G technology. Most famous of them are in Finland, Germany, Spain and the UK, covering aspects from air interface, hardware implementation, all the way to cloud networking and virtualization [83]. 5GTNF (5G Test Network in Finland) aims to unify and coordinate all the research efforts of test networks in Finland working under TEKES (The Finnish Funding agency for innovation) to build one integrated testbed. The aim is to provide, national and international researchers, with a coherent heterogeneous testing platform where they can trial new ideas, validate standards and prove concepts in a real-life environment. Via the 5GTNF, Finland is targeting to be the world's most attractive site for 5G testing. In this project, works the Finnish government along with 15 partners involving industry leaders such as Nokia and a number of leaders in the research area such as Oulu University's Centre for Wireless Communications (CWC). [85]

3.2.1. 5GTN in Oulu University

The 5GTN project at the CWC is a unique testing environment, designed to, not only facilitate developing and testing new applications, but also to aid the process of creating the new business models which would benefit from these new advancements. In addition to the new features promised by 5G such as the extremely low latencies or very high speed mobile broadband, 5G also will bring around new technologies such as small cell access points, network function virtualization, software-defined networks, cloud computing and IoT. These technologies allow for plenty scenarios and novel services, in addition to challenges in terms of business models and novel traffic models. Thus, the 5GTN is constantly incorporating the latest infrastructure for 5G to enable service-innovations and offer a testing environment for network vendors and chipset manufacturers. [86]

Apart from the ultra-high reliability, extremely low latencies and very fast broadband connections, one of the novel revolutionary features expected to be introduced by 5G is a spectrum sharing scheme called "Co-primary Spectrum Sharing". The basic idea behind Co-primary spectrum sharing is to allow operators to use a predefined spectrum allocated specifically for sharing between operators in the small cells domain. Such a scheme, despite its obvious benefits for operators in terms on infrastructure investments and lower latency services, is still yet not very welcomed by operators due to it being a new paradigm very different than the legacy 100%-operator-owned networks. What operators need at this moment is to be shown clearly, and in a well-studied manner, the promising incentives to why they should shift to that scheme, and that is main aim of the small-cell-based 5GTN in Oulu. [87]

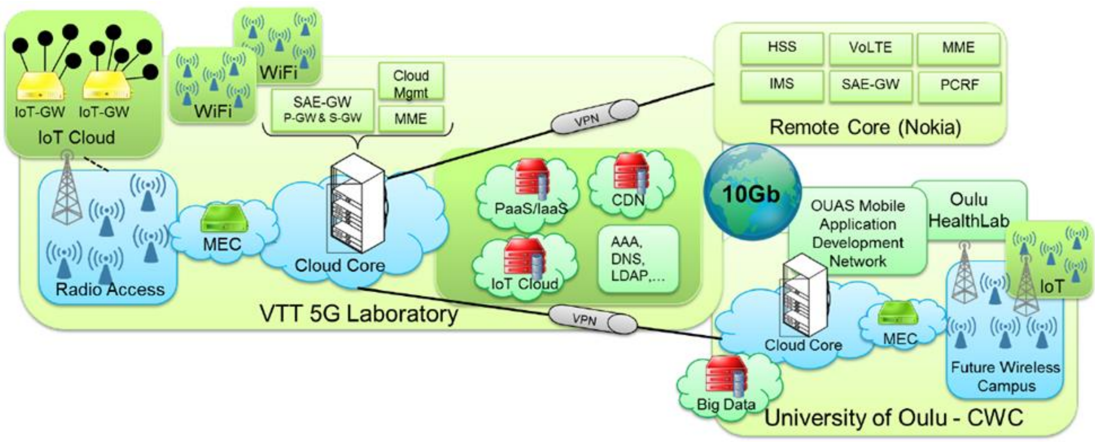

Figure 26. 5GTN architecture.

The 5GTN architecture is shown in Figure 27 [84] is composed of 2 main networks, a restricted-access network in the VTT 5G research lab, and an open-access network in the CWC at the University of Oulu. Although the two environments are interconnected, they serve different purposes. The restricted-access network in the VTT premises serves as a private environment for confidential research and development of new services. On the other hand, CWC's open-access network acts as a carrier-grade platform targeting public users with the ability to accommodate trials and experimenting new applications, ideas and devices. 5GTN in the CWC is specifically targeting mobile operators giving them a state-of-the-art platform to develop new business models focused around the usage of small cells and spectrum sharing. The CWC 5GTN consists of one macro base station and an ever-increasing number of small cells to accommodate a wide variety of service tests.

In the initial deployment phase of the 5GTN, it was based on LTE standards, i.e, LTE small cells and the LTE evolved packet core running on an OpenStack cloud-based infrastructure. Though, further advancements introduced a wide variety of low-power-wide-area networks such as LoRa. Advancements are not restricted only to technologies, but it extends also to the number of test networks, thus, further extensions to the 5GTN are always undergoing to different parts of the city of Oulu. Extensions are not always in the aspect of new test networks, the 5GTN networks at the CWC and at VTT premises are also connected, creating a heterogeneous environment for testing of new applications in the areas of software defined networks, network-management sharing and network functions virtualization. Cloud services are also being installed to allow for testing and verification of various IoT applications and M2M type communications models.

3.2.2. 5GTN Vertical Use Cases

Growth and expansion of the 5GTN is always pointing to where possible use cases are. This process is guided by the 5GTN partners and projects. As an example, the 5GTN stared adopting new cellular IoT technologies such as NB IoT and LTE-M as parts of its efforts to keep its unfractured up-to-date. Moreover, 5GTN also supports new prototypes for 5G radio links. In addition, several novel technologies are also supported such as Mobile-Edge Computing (MEC) and Evolved Broadcast Multicast Service (eMBMS). [87]

Media Use Case:

The idea behind the media use case is to test the effect 5G can have on the media industry. The scenario entails transmitting high-resolution, real-time, high bit-rate video and audio content via 5G links. Then, this content should be distributed to a massive number of users reliably. [85]

A current limitation to media content applications is the unsuitable LTE link. Therefore, the 5GTN uses a Nokia-made 5G proof of concept radio link media content production testbed which operates at 3.95 GHz with a 200MHz bandwidth. The testbed is able to support a 4K video camera.

Other limiting factors halting the wide-spread of 5G-based media content distribution systems are, asymmetrical quality at user-side, already occupied cellular cells and poor spectrum efficiency. To overcome these issues, the 5GTN uses the eMBMS which is able to support up to 4 times the number of users. The aim of this use case is to study the feasibility of using the eMBMS for the service providers in a real-life environment. The study includes the acquiring the high-end content, the UL to the core network via the 5G proof of concept link, in addition to distribution of this content to mobile users via the eMBMS.

Sports Use Case:

The main idea behind this use case is connecting several wearable sensors to sports clothing and collecting several vital readings from these sensor devices during exercise such as distance covered, heart-rate, and more. Such information paves the way for a whole new set of applications concerning wellbeing, either for people practicing sports or official bodies such as coaches and training institutes.

As shown in Figure 28, Cellular IoT is used as means of connectivity between the sensor devices and the application server. In this project, works the 5GTN, VTT and several other bodies. The reason for utilizing cellular IoT technologies is their long-range, already-abundant, and secure radio links.

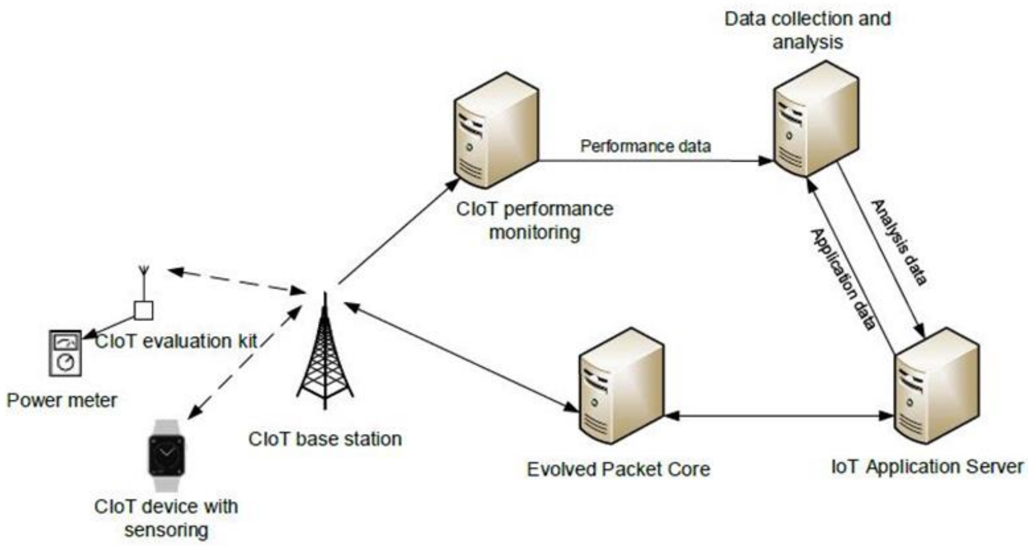

Figure 27. Architecture for Sports Use Case.

4. PRACTICAL IMPLEMENTATION

For the 5GTN, the healthcare vertical is one of the most promising application fields. It involves a large number of partners, a huge amount of new technologies tested, and a real-life environment to bring IoT ideas and applications to test and evaluate their feasibility and performance.

The main idea in this case is to utilize 5G and IoT applications to enhance the life quality and quality of received service for a group of elderly citizens in an elderly-care home. The aim is to create customized assistance plans for the elderly to suite their personal daily routines. In other words, to help the care-providers in giving assistance tailored in its type and timing to suite each citizen in person. The way to realize this is basically by monitoring sensor reading from the elderly rooms and by analyzing these readings the care-providers can know when a certain person wakes up, when are the best time to visit their room, when to serve them meals etc.

The initial plan is to utilize reading from water and electricity consumption meters. These readings are then analyzed by suitable algorithms and the results can provide solid basis in understanding the daily routine of people. A whole overview of the use case architecture is presented in Figure 29.

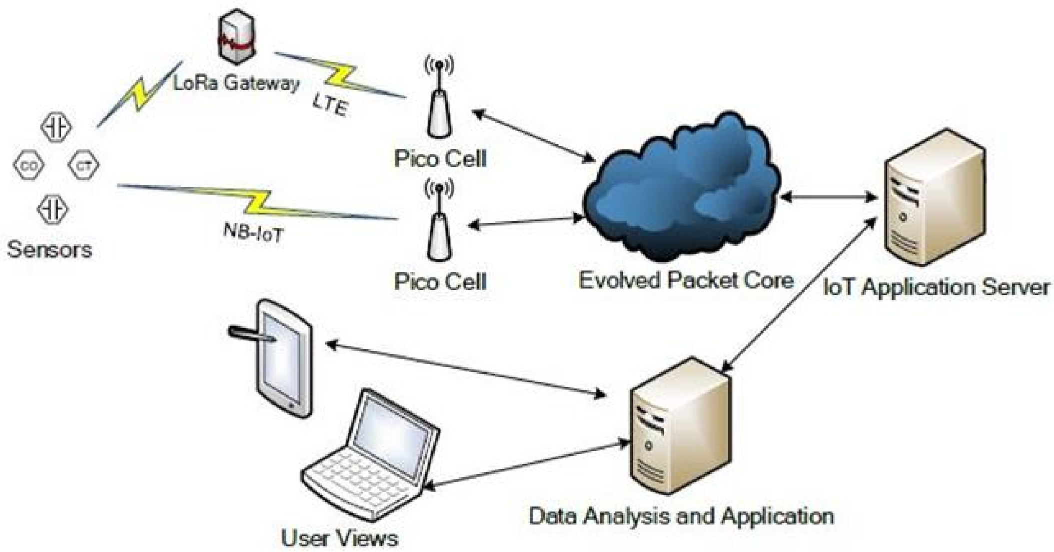

Figure 28. Caritas case architecture.

As shown in the figure, this use case will be used to verify the practical aspects of connecting IoT devices via various radio links. A LoRa network is deployed as an interface between LoRa supporting sensors and the LoRa gateway. The LoRa gateway is then connected via LTE to the 5GTN pico-cells. On the other hand, NB IoT supporting sensors will also be deployed. Obviously, they will be connected to the LTE pico-cells via the NB IoT radio access. Lastly, the LTE pico-cells are backhauled to the 5GTN core network via IP connectivity. The 5GTN plan for this use case is to implement and verify several healthcare applications via several radio access networks, several sensor vendors, and integrating the data to the 5GTN IoT platform.

4.1. LTE Network Planning

The LTE network is considered a corner-stone for the 5GTN healthcare use case. Building a stable fully functional LTE network in the building was a top-priority for the use case. The network had to provide good LTE coverage at all corners of the building, to allow for the vast number of application awaiting to be built on top of the LTE layer. Simultaneously, the network had to be cost-efficient to provide a good and persuasive business model for applications developers. [88].

4.1.1. LTE Planning Challenges: A Macro or Micro Cell?

One of the earliest challenges we encountered in the deployment phase is whether a macro base station would better serve our use case or is deploying several micro cells better? When considering the case of a macro site deployment, we had two options. Firstly, we can deploy the macro site in a neighboring building to our target building. On The other hand, the macro site could be deployed on the roof of our target building. Generally, coverage from a macro site would reach indoor users by means of reflection and diffraction [89]. Thus, many duplicates of the signal will reach the receiver, each with its own delay component, creating multipath propagation fading. Added to that, as shown by Figure 30, upon surveying the site to create the drafts, it was noticed that there are no high buildings next to our target building to deploy on top of it the macro.

Figure 29. Google view of the target building.

The lack of neighboring high building creates an issue on deep indoor coverage [89]. Thus, it was agreed that the best course of action is deploying indoor micro or pico-cells.

4.1.2. LTE Planning Challenges: Outdoor Leakage

A common problem with indoor radio planning is outdoor leakage. This basically refers to strong interference from other outdoor macro sites to inside the building, and also to RF power leakage from inside the building to outside. In commercial networks this is an issue due to the dense deployments of RF sites and also due to the severe QoS degradation caused by interference in 3G and 4G systems. However, for the 5GTN case, even though we are not a commercial operator, otherwise a micro-operator, still we have some considerations to tackle.

The challenge is that our RF license is limited to a specific area and no RF power should leak to outside these boundaries. Another scenario is that probably in the future, as the 5GTN expands and grows, we will have a nearby macro site in the area and this case it will be operating on the same radio frequency, thus outdoor leakage must be avoided. However, this challenge, by coincidence, was made easier for us as this deployment takes place in Finland where nearly all glass windows are double tilted. Of course, this is primarily to keep indoor temperatures warm as the mercury plummets in the winter. However, it worked for our favour as tilted windows typically provide a 20-40dB attenuation to RF signals [89].

A good solution to the isolation problem is the corner-placement of the pico-cells. To create RF dominance inside the building. Accordingly, this will be the methodology behind the placement of one of our pico-cells. More about this in the next chapter.

4.1.3. LTE Planning Challenges: Number and Position of Antennas

Another challenge we faced in the deployment phase was how to provide coverage in the entire building in the most cost-effective way. To do so, a number of tricks where put to use in order to provide optimum coverage with least costs and least interference.

- The “Corridor Effect”:

As shown in Figure 31, our target building is characterized by long corridors, with several apartments alongside of the corridor. Consequently, deploying the pico-cells in one of the apartments was not an option as this might cause health concerns to the person living in the apartment. Thus, due to the nature of the building in our use case, the effect of deploying pico-cells in corridors was studied. The “Corridor Effect” [89] refers to the unique distribution of RF power radiating from a cell placed in a corridor.

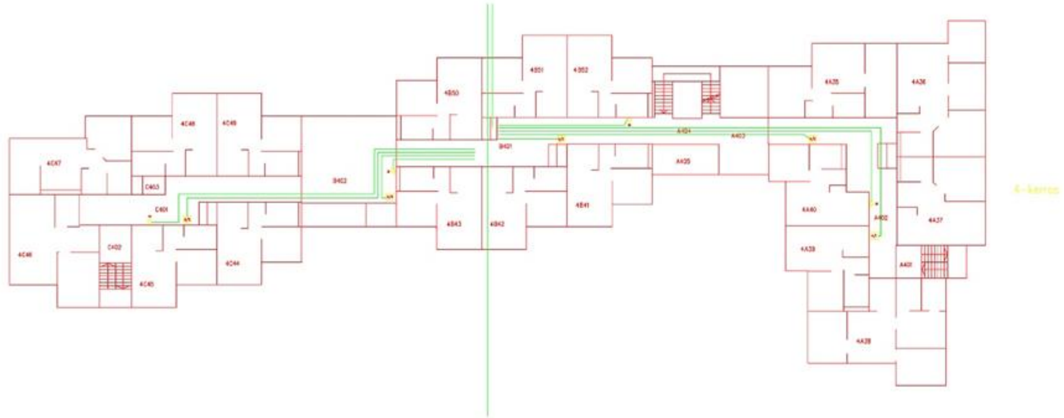

Figure 30. Floor plan of the 4th floor as a sample of the target building.

Typically, installing pico-cells in corridors has a number of upsides such as the easy access to electrical and ethernet infrastructure, avoidance of placing emitting antennas in apartments where residents live, and also the usage of the "corridor effect" to our advantage as a facilitator to the propagation of the RF signals along the corridors.

- The "Corner Office" Problem:

In designing indoor systems, a typical problem is the temptation of installing only one pico-cell in the center of a floor. The temptation lies in the cost-reduction achieved by just placing one cell in the center and thus covering both sides of a floor [89]. On the other hand, the issue here lies in the lack of RF dominance in the corners of the floor. However, this is for commercial operators who need certain levels and quality of RF signals for human-type traffic. In our case, the issue was not with the lack of dominance, our issue was more about the coverage profile caused by placing one cell in the middle of the floor and thus having two weak-coverage areas at the two ends of the floor against placing one cell at one side of the floor and thus having only one weak-coverage area at the other end of the floor.

- The Inter-Floor Interleaving:

A very important aspect of indoor RF planning that was used to our benefit is the inter-floor interleaving. Occasionally, in some buildings, the building structure allows for RF signals to penetrate the ceilings of the building and thus one cell in, for example, the 3rd floor may provide coverage to both the 4th and 2nd floor as well. [89]

4.1.4. Deployment Decisions

Thus, it was decided to use two pico-cells in total to provide coverage for the entire five floors building. To utilize the inter-floor penetration of signals, one cell (PCI 38) was placed in the ground floor. The second cell (PCI 42) was placed in the 4th floor. Moreover, to study and utilize the "corridor effect", Cell 42 in the 4th floor was placed in the center of the floor while cell 38 was placed in one end of the ground floor. Figures 32 and 33 show the floor plan of the 1st and 4th floors respectively with the position of the cell illustrated by the black dot.

Figure 31. Floor plan of 1st floor with cell position pointed to by the black dot.

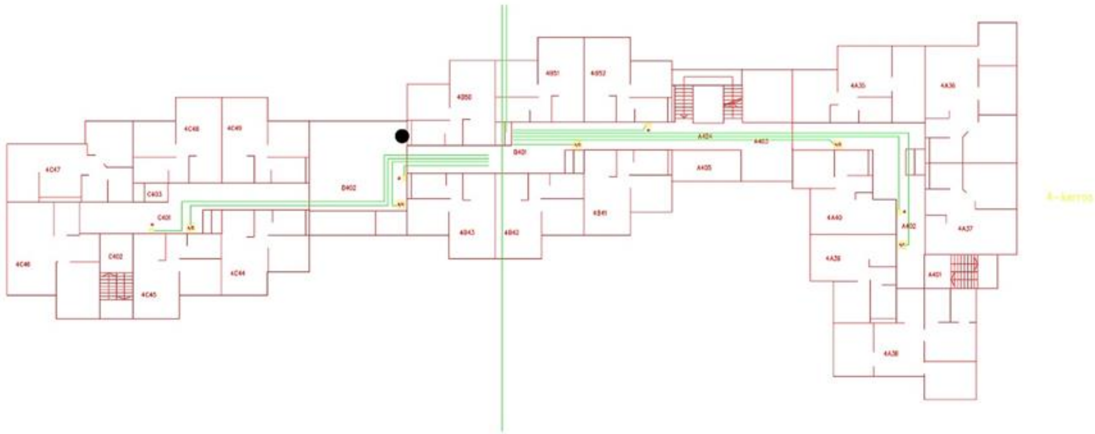

Figure 32. Floor plan of the 4th floor with cell position pointed to by the black dot.

4.2. LoRa Network Deployment

Since the 5GTN runs on the EPC architecture specified by the 3GPP, it lacks support for LoRa protocols and interfaces. Thus, integrating a LoRa network to the 5GTN is not straightforward. However, with the help of SDN and NFV, virtual instances can be created over the EPC which might remove the need for dedicated hardware. The LTE core network running by the 5GTN allows for other external IoT applications. However, different levels of integration are possible, according to [89] an integration scenario possible is by routing LoRa packets through an LTE modem to the LTE core network. This LTE modem would have the support for Subscriber Identity Module (SIM) cards to use the LTE radio access to route the LoRa packets to the core network. The LoRa-LTE module supports both LTE and LoRaWAN protocols and interfaces. The module acts as an LTE UE and establishes a connection to the pico-cells deployed in the case study building via standard S1 connections. According to this setup shown in Figure 34. [91]

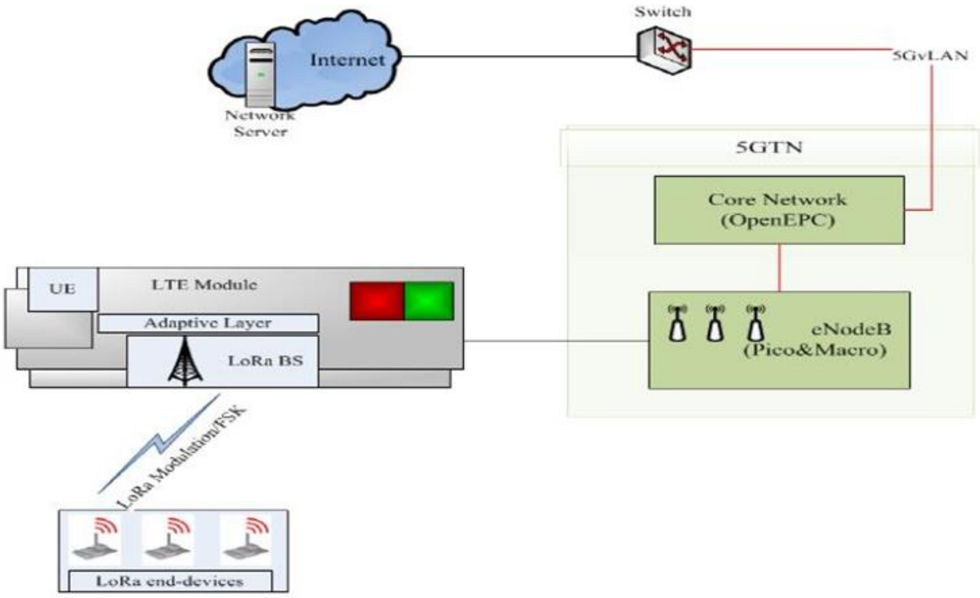

Figure 33. LoRa deployment in case study building.

LoRa gateway uses its own front-haul to collect data from the sensor devices, and then uses the LTE connectivity as a backhaul to route data through the LTE pico-cells to the 5GTN core network. LoRa transmits packets to the IoT cloud platform via cellular network using MQTT protocol. This is enabled by the LoRa-LTE modem used, which in our case is the MultiConnect Conduit [92] gateway. It provides support for LoRa and LTE interfaces in addition to application tools for different integration scenarios. The Conduit platform supports integration by allowing configurable integration options that can be made to suit different applications. The Conduit gateway supports both a base station and network server functionalities. The backhaul side is done either via LTE (when installing a SIM card) or by ethernet. [91]

As for the application layer, according to [93] the LoRa network server functionalities can be virtualized on the cloud platform. Using the Openstack cloud, the network functions of a LoRa server could be set up and operated on the Openstack APIs. [94]

4.3. NB IoT Device Integration with the 5GTN

Due to time limitations regarding the practical implementation of NB IoT access network in the case-study building and finishing this diploma thesis work, the option of integrating the NB IoT devices to the LTE network in the case-study building was not valid yet. Hence, integration was done at the Oulu University campus 5GTN LTE network as a prototype which will be replicated when the network at the case-study building is ready.

The kit used in this case study is the Quectel BG96 kit. It includes:

- An evaluation board
- BG96 RF module which supports LTE Cat M1 and Cat NB1
- Several RF cables, power cables, UART cables and connectors

4.3.1. The Evaluation board

To illustrate integration steps, an Evaluation Board (EVB) is used as a platform. Evaluation boards are used to test the functionality of RF modules. The evaluation board used is the “Quectel UMTS/HSPA/LTE EVB” [95]. The evaluation board provides application developers an easy-to-use interface to explore in depth the options granted by the kit. Figure 35 shows the evaluation board before connecting any accessories to it.

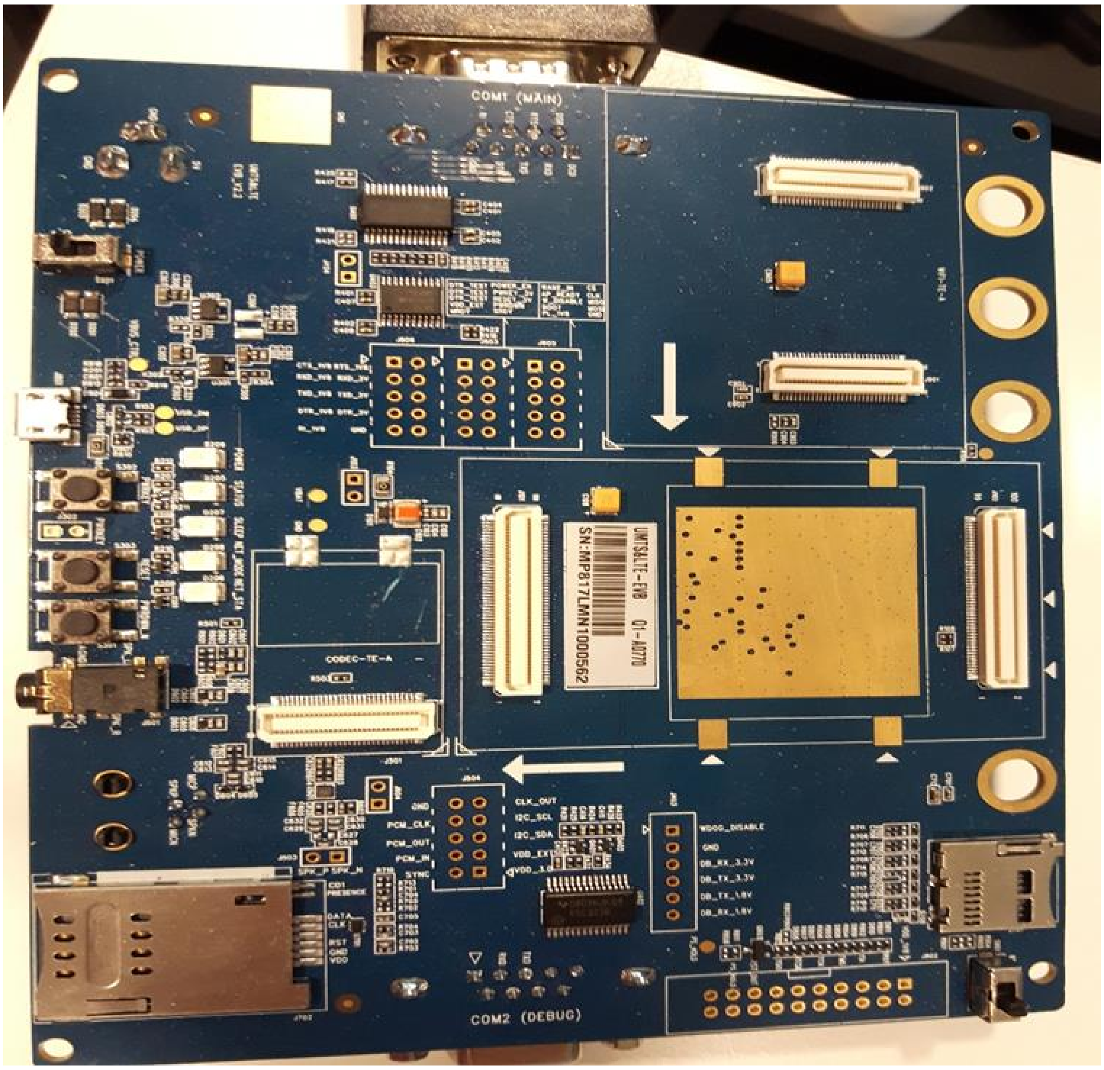

Figure 34. EVB used.

The importance of the EVB is that it is where all the other accessories of the kit are connected. As shown in the above figure, it allows for connecting an RF modue, a Wi-Fi module, a codec module, in addition to 2 slots for UART connectors and a power cable. Moreover, this model of the EVB has a slot for connecting the SIM card and an earphones 3.55 standard jack. After connecting the needed RF and codec modules, the UART (Universal Asynchronous Receiver Transmitter) cable is used to connect the EVB to a computer running the appropriate software and the EVB is turned on by the on/off switch. The EVB also has a slot for connecting a GPS (Global Positioning System) module.

4.3.2. The BG96 RF module

BG96 is a series of LTE Cat M1/Cat NB1 modules which support novel 3GPP cellular IoT access technologies [95]. It provides a data rate of 300kbps in downlink and 375kbps in uplink. Its main characteristics are low-power consumption and compatibility with other Quectel RF modules. In addition, the BG96 module supports a wide variety of internet protocols such as TCP (Transport Control Protocol)/IP, UDP and HTTPS in addition to a variety of industry-standard interface such as USB and UART. Figure 36 shows the BG96 RF module used in this study case

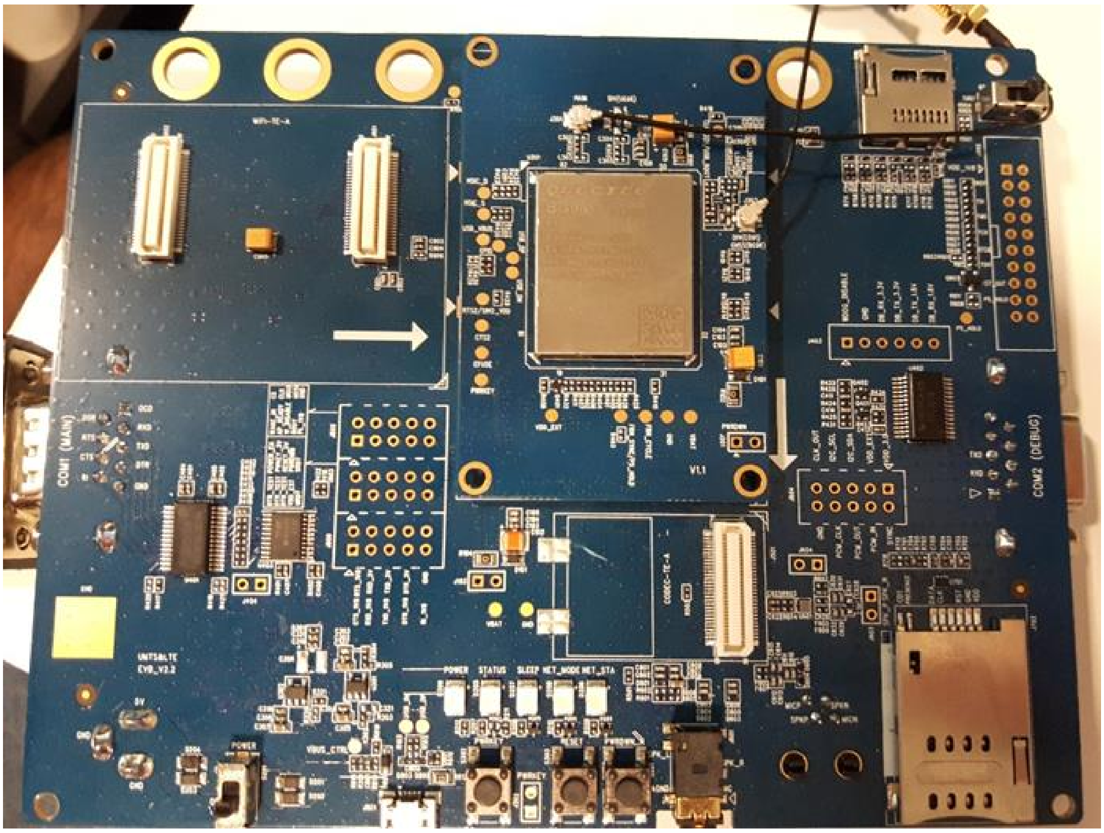

Figure 35. BG96 module connected to the EVB.

4.3.3. The User Interface and AT Commands

As its common with communications modems, configuration and setting up of the parameters needed for establishing a connection is done via AT commands. AT stands for ATtention and every command line starts with the letters AT. In our case, a software called “QCOM” is used to communicate with our modem [95]. Figure 37 shows the Graphical User Interface (GUI) of the software.

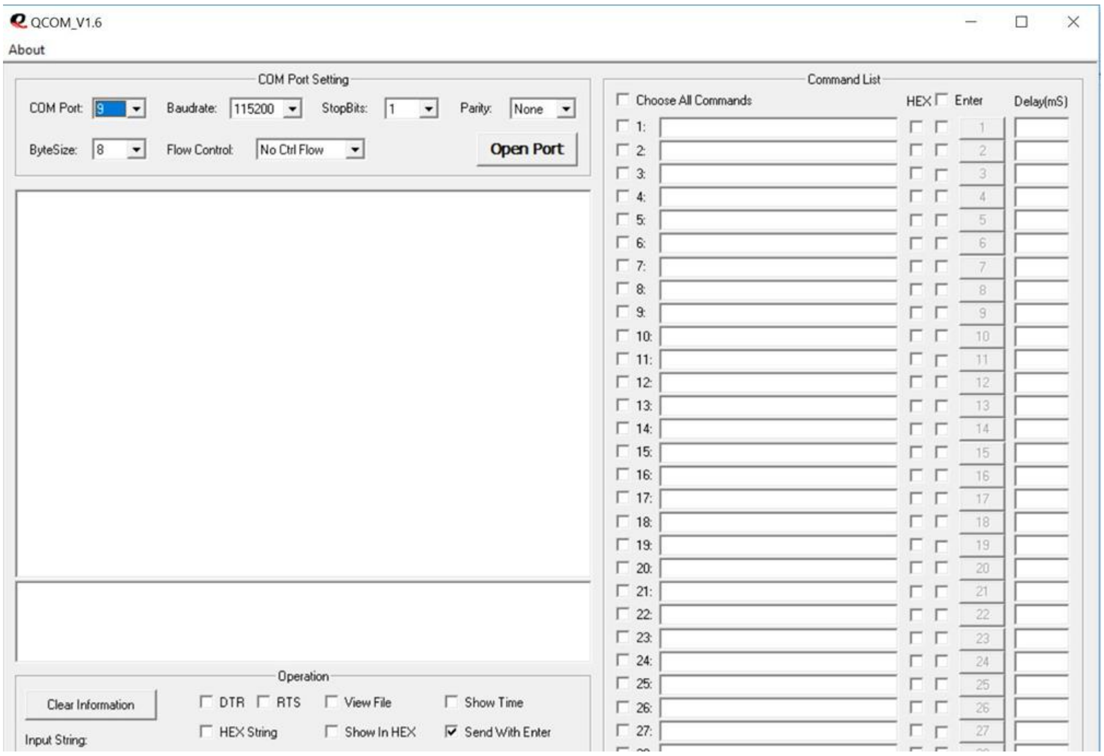

Figure 36. QCOM software interface.

4.3.4. Integration to 5GTN

In order to send data from the kit to the 5GTN IoT platform, several steps are required. First of all, a Packet Data Protocol (PDP) context must be activated [97]. The PDP context allows the exchange of IP packets between the UE and the network. The PDP context uses the 5GTN Access Point Name (APN) to establish this connection. During the connection-establishment procedure, many parameters are used to define the TCP/IP context such as the IP address of the server running our IoT platform, the IP version used, the APN, and the context ID. PDP contexts connect UEs to the PDN. The AT command used for setting up the PDP parameters is “AT+QICSGP”. Afterwards, the command “AT+QIACT” is used to activate the context.

To be used in the “handshake” procedure, the Secure Sockets Layer (SSL) parameters must be correctly configured and the SSL context must be activated [98]. The SSL context defines a group of parameters such as the protocol version, ciphers, and trusted certificates [99]. The BG96 modules supports up to 6 SSL contexts, each one with its appropriate parameters. The AT command to define the SSL context is “AT+QSSLCFG”. During the SSL context definition procedure, parameters configured are the SSL version, cipher suites, ignore time, CA certificate path, client certificate path, client key path, security level and the negotiate time [98].

Different SSL versions exist such as SSL 3.0, TLS 1.0 to TLS 1.2. TLS stands for Transport Layer Security and it is just a new name of the SSL protocols since he SSL version 3. In our case, we used the setting 4 which means support for all SSL versions. [98]

Afterwards, the Hypertext Transfer Protocol over SSL (HTTPS) parameters should be set. [98].

The AT command used is “AT+QHTTPCFG” which requires defining the context ID with the same ID defined for the PDP context and also requires the SSL ID. Lastly, to send messages to our IoT platform server, the command “AT+QHTTPURL” is used. This AT command sets the URL of the server intended for communications. After defining the receiver URL, the AT command for sending a “post message” AT+QHTTPPOST is used to post a message on the IoT server.

5. TEST RESULTS

To test how much the theoretical RF planning guidelines brought us to achieving the coverage intended for our use case, we carried out radio measurements all over the building. Figure 38 shows a sample result of the radio measurements using a mobile application running on a Samsung S7 mobile terminal to measure the Reference Signal Received Power (RSRP).

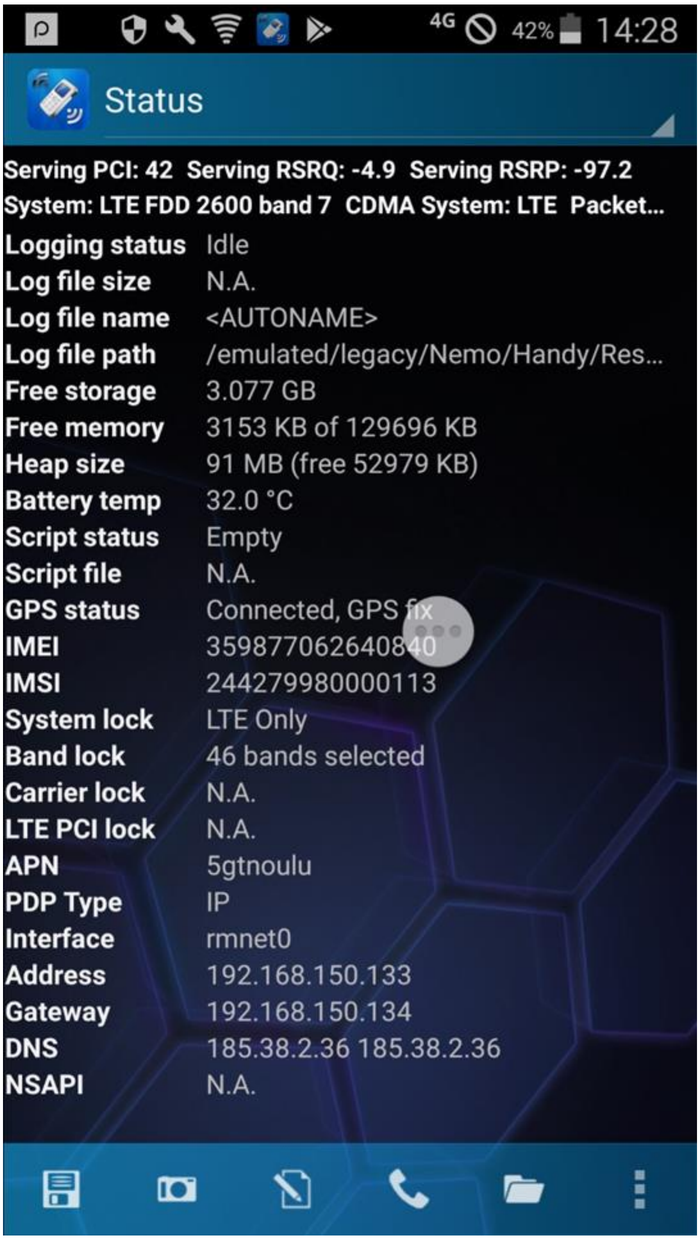

Figure 37. Sample radio measurement result.

5.1. RSRP measurements

In LTE networks, UE measures two aspects of a received signal, RSRP and RSRQ (Reference Signal Received Quality). The RSRP refers to the average power of LTE resource elements which are carrying cell-specific reference signals. While the RSRQ measurement incorporates also the quality of the signal in terms of relative power to the noise and interference [99].

However, since in our case there is no outer interference to account for, we will only consider the RSRP as an indicator to the coverage level.

5.2. Measurements results

The results of mapping the RF measurements to the floor plans of the 1st to 5th floor are shown in Figures 39 to 43 respectively.

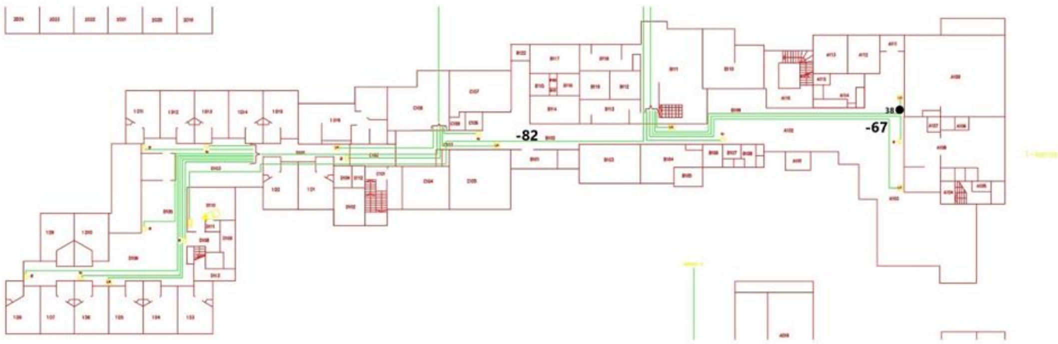

Figure 38. RF measurements in dBm for the 1st floor.

The black dot to the right of the above figure indicates the location of the pico-cell on the 1st floor. This pico-cell has the Physical Cell Identity (PCI) 38. As shown, the first floor has no coverage issue.

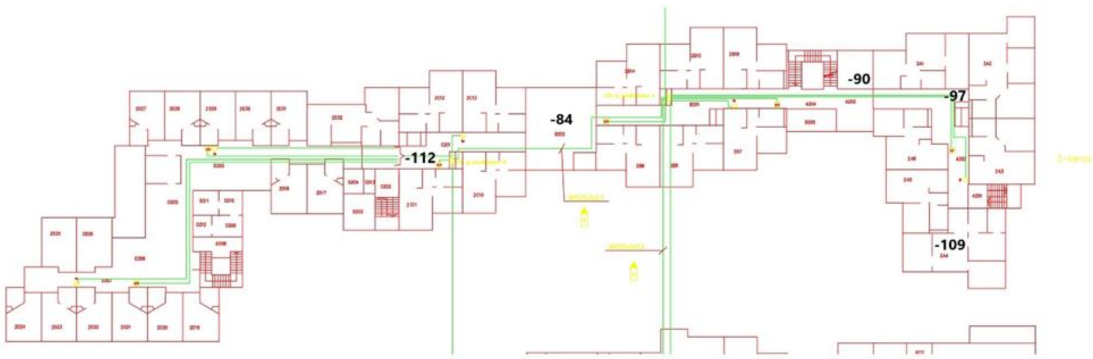

Figure 39. RF measurements in dBm for the 2nd floor.

Figure 41 demonstrates the effects of inter-floor signal penetration. It is noticed that that the area right above the position of cell 38 does not have the best coverage level because despite of its proximity, the ceiling between the 1st and the 2nd floor still attenuates the signal. However, the best coverage level is the (-84) spot as it is a hall with no ceiling between the floor thus.

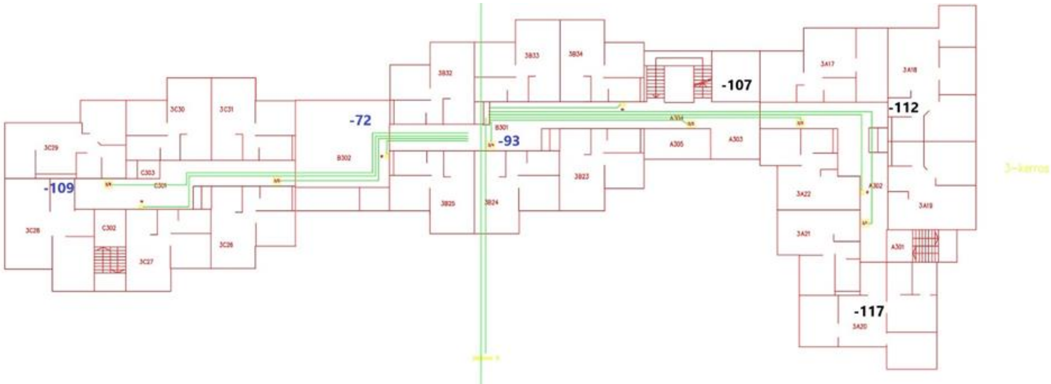

Figure 40. RF measurements in dBm for the 3rd floor.

The RSRP values in blue refer to the RF signal of cell 42. As shown in Figure 42, left wing of the floor is dominated by cell 42 while the right wing is dominated by cell 38. This is due to the position of cell 42 which is the 4th floor on the left part. Thus, due to the signal penetrating the 3rd floor ceiling, the RF coverage if this 3rd floor is split between the 2 cells.

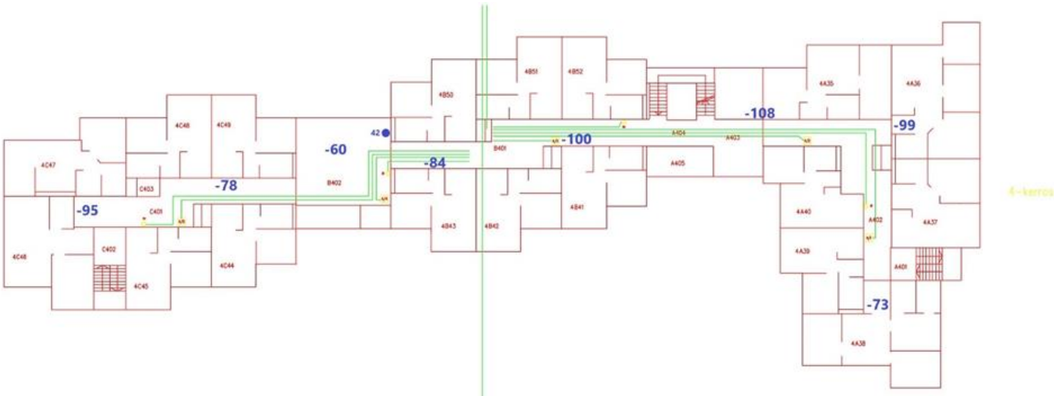

Figure 41. RF measurements in dBm for the 4th floor.

Figure 43 shows the coverage levels of the 4th floor as well as the position of the pico-cell 42 shown by the blue dot.

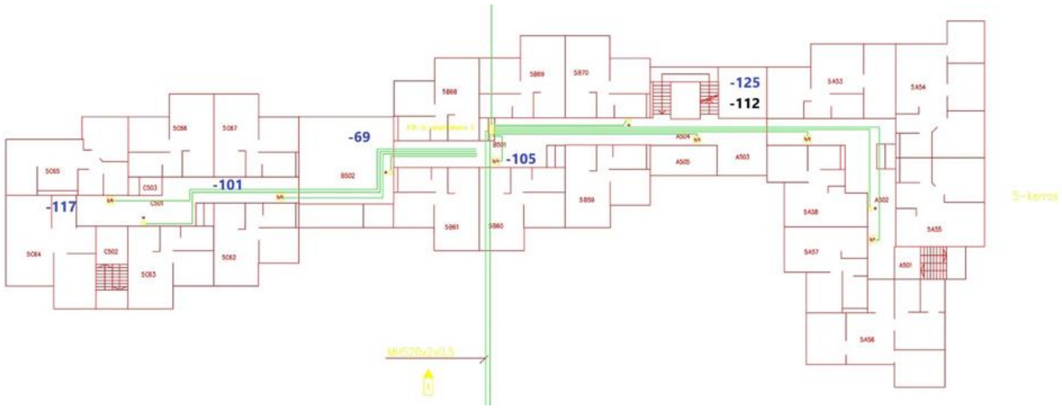

Figure 42. RF measurements in dBm for the 5th floor.

Figure 44 shows interesting findings in the coverage levels of the 5th floor. While on the left wing the measurements tend to be intuitive, it can be noticed how the RF power of cell 38 (4 floors away) dominate the power of cell 42 due to the difference in positioning. The area on the left with the two reading shows that cell 38 covers it better as it is a hollow area of the stairs thus it is better covered by the cell vertically closer to it as opposed to cell 42 which is horizontally closer.

5.3. Conclusions

As shown by the results, the pico-cell placement used did achieve the desired coverage. RF coverage from the first floor was sufficient to cover also floors 2 and 3. While Floor 5 was covered using the pico-cell installed at the 4th floor. The corridor effect was utilized to achieve coverage through all the length of the floors. Moreover, the pico-cell placement was optimum as cell 38 was to the end of the 1st floor while cell 42 was in the middle of the 4th floor, thus each cell had a different coverage profile which resulted in interleaved-coverage where the two cells cover each other dead spots.

6. DISCUSSION

The aim of this thesis is threefold. At the beginning, the reader is presented with a survey about LPWANs, including their different types, aims, techniques, and applications. In addition, the survey also explains how LPWANs are the new enablers for IoT implementations. Secondly, this thesis also explains some of the practical aspects and challenges faced in real-life implementations of IoT networks. Lastly, the practical aspects of planning an LTE network is discussed and different implementation scenarios (regarding the positions of the pico-cells) are discussed.

The reason the research community disregarded LANs and WANs as potential enablers for IoT applications is that such legacy network architectures impose certain restrictions on connected devices which does not suite the requirements of IoT. Some of the restrictions are the high energy consumption of 3GPP cellular WANs in addition to the high network management costs and high latencies of LAN networks. These were the main drivers for the research community to steer away from conventional network architectures and focus more on LPWANs.

LPWANs are mainly categorized into two main types, proprietary and cellular. Proprietary LPWANs refer to network protocols and devices created usually by an alliance of companies in cooperation. This type of networks offers very low power consumption and wide ranges, which attracts many IoT applications. Moreover, they operate in unlicensed bands which elevates many restrictions on testing and development. On the other hand, cellular LPWANs are specified by the 3GPP in its releases, either 12 or 13. They are mainly added options to a regular LTE network which offers the advantage of not having to implement new networks, a simple software updates makes the network up and running. In this type of LPWANs, the advantage is in the ease of management which cellular networks are characterized with.

On the practical side, deploying an indoors LTE network which provides coverage for 5 floors at a target building has its own challenges in terms of coverage-to-cost ratio. The challenge was to place the pico-cells at the optimum positions to provide coverage for 5 floors using only 2 pico-cells. There were 2 scenarios to be studied, first we had to identify on which floors should each pico-cell be placed and secondly at which part of the floor should the pico-cell be positioned. As the results show, the placement plan was found to be according to an interleaving scheme. One pico-cell was placed at the first floor to the end of the floor, while the second pico-cell was placed in the 4th floor towards the middle of the floor. The aim of this plan was to utilize the phenomenon where RF signals can travel in between floors; penetrating the ceilings. As shown in the RSRP test results, the entire 5 floors of the building were covered.

Future work can be carried out building on this thesis, with the introduction of NB IoT coverage in the building. The future work could be studying the differences between LoRa and NB IoT in terms of coverage, network management and interoperability between the 2 LPWANs.

7. SUMMARY

The applications to IoT are numerous, and so are the techniques and methods to be exploited. As future enablers for IoT applications, LPWANs offer a wide variety of options to serve the needs of IoT applications. Either proprietary or cellular 3GPP-based LPWANs, they provide the needed requirements for IoT such as low battery-consumption and wide coverage areas. The healthcare sector is expected to witness a massive transformation with the realization if IoT in healthcare applications. The study case used in this thesis includes LoRa and NB IoT networks. However, the LPWANs need appropriate LTE coverage to connect the sensor reading to the 5GTN IoT platform.

The main aim of the measurements results was to validate a number of issues. Firstly, to study the "corridor effect" on the RF propagation and prove that signal reflection in corridors can enhance coverage even to the area behind the pico-cell. Secondly, to study the extent to which inter-floor propagation could be utilized to avoid placing a pico-cell in each floor. Third, to study the difference in coverage occurring when a pico-cell is placed to the end of a floor and when it is placed in the middle of the floor.

Points one and two were validated and the measurements supported the theory mentioned in section *4.3.1*. However, point 3 was not theory-based, it was rather a practical experiment and the results can be viewed in a number of ways. It can be viewed from a perspective showing that placing the cell at one end of the floor results in only one low-coverage area at the other end, thus it is better than placing it in the middle which would yield two low-coverage areas at either ends of a floor. This opinion was proven wrong as the "corridor effect" compensated for the long distance between the cell and the end of the floor.

Another perspective would be that the setting we used is the optimum setting for our use case as placing the two cells in two non-vertical positions allowed for the maximum utilization of the inter-floor propagation phenomenon and the corridor effect which provided coverage all over the building

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