NB-IoT: an Operator Perspective

Analysis of Current Usage and Potential Capacity

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by

W.A. Kayser

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Student number:	4360966	
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Thesis committee:	Dr. ir. Fernando Kuipers	TU Delft
	Dr. Remco Litjens MSc	TU Delft, TNO
	Dr.ir. Przemysław Pawełczak	TU Delft
	Ir. Rogier Noldus	TU Delft, Ericsson
	Fred Coerver	VodafoneZiggo

Preface

Before you lies the MSc thesis *NB-IoT: an Operator Perspective*. This document publishes measurements and observations on the current implementation of Narrowband IoT at VodafoneZiggo. The final evaluation provides lessons for academia, operators and for consumers.

This thesis has been written to fulfill the requirements to obtain the degree of Master of Science at the Delft University of Technology and as such marks the end of an exciting journey

Acknowledgments

This thesis has been made possible by VodafoneZiggo, which has given extensive access to data and hardware. I would like to thank Fred Coerver for the many meetings in which tutorials were given on the various tools and brainstorm sessions were held. These sessions have been extraordinarily useful for me. Several others were there to aid in my search such as Roy Crutsen who has helped a great deal when it came to questions on implementation details.

I would also like to thank Dr. Ir. Przemysław Pawełczak and Ir. Jasper de Winkel for their time and effort to guide me trough the process. They challenged me to look further and to be more rigorous. The feedback received was extensive and very valuable.

The ETV has had a large impact on my student career. Not only did I get to know a lot of wonderful people, but it allowed me to develop confidence and skills that are not strictly related to engineering. A special message of thanks goes out to the rest of the board for the amazing year and incredible memories.

This thesis period has been written during the period of COVID-19, which resulted in a much different study environment. My roommates have been an invaluable source of providing support, motivation and the occasional distraction.

Finally, I would like to thank my parents, my brother and friends that have supported me over the years.

W.A. Kayser
Delft, April 14, 2021

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1

Introduction

The Internet of Things (IoT) has been an enormous trend in the past few years and is expected to dominate business strategies the coming decade [32]. IoT allows for the automation of processes, which increases productivity and reduces needed man-hours. Interconnectivity between devices allows for exponential value creation due to Metcalfe's law [81], as more and more solutions are made possible.

There are many techniques for connecting devices to the Internet, each has differing properties and intend to solve different issues. One exciting and growing category is Cellular Internet of Things (CIoT) and is generally managed by a third party. The advantages of such a solution are nationwide coverage, high device capacity and good separation of concern. [96]. These advantages create an environment in which it is easy to deploy numerous devices, with a low investment cost for the consumer.

To implement CIoT, we need to have a network providing coverage over large areas such as countries. The group of technologies that can achieve this is called Low Power Wide Area Network (LPWAN). The four most common examples of these technologies are SIGFOX, LoRa, LTE-Machine (LTE-M) and Narrowband Internet of Things (NB-IoT). The last two of these have been created by the 3rd Generation Partnership Project (3GPP), which is the governing body tasked with the creation of the cellular mobile networks we use today.

For Mobile Network Operators (MNOs) these two are interesting, as they can be used on top of existing LTE installations [46]. Many MNOs still operate a GSM network for IoT applications, which is costly and thus plans are made to decommission these networks. A replacement can be found in these two new technologies as they offer similar experiences to customers [57]. Unfortunately LTE-M will not be discussed in this report due to limitations in measurement methods. The reasoning behind this will be discussed in Chapter 2.

NB-IoT has been created by 3GPP and is released in Release 13. The novel features provided by NB-IoT are a simplified connection set up procedure and a basic data transmission scheme to reduce power consumption. On top of reducing power consumption, the aim of NB-IoT is to reduce the complexity of the User Equipment (UE). Simpler modems reduces the cost of the devices. The 3GPP has set a price target of 5 dollar per device.

NB-IoT provides methods to increase the provided coverage such that devices can stay connected, even in more difficult to reach areas. This collection of measures is called Coverage Enhancement (CE) [20]. Due to all these innovations and sparse transmissions, a battery lifetime of 10 years or more can be expected [36].

Development of NB-IoT and LTE-M systems in Europe was spearheaded by the Vodafone Group. One of the earliest adopters was its subsidiary VodafoneZiggo in the Netherlands [76]. However VodafoneZiggo is not the only provider of LPWAN services. KPN offers LTE-M and LoRa and T-Mobile offers both NB-IoT and LTE-M.

Consumer growth until now has been relatively disappointing due to the large disparity in buzz and adoption [86, 87]. Expectations for the future are high with a projected annual growth of 24.9 % [63]. These expectations are not corroborated by all, as some report that the acceleration will only be noted from 2022 onward [47].

One major area of growth for NB-IoT is China. China currently makes up for 90 % of all NB-IoT connections in the world. These devices are split over two providers, China Unicom and China Telecom [30, 55]. There is an enormous push for smart cities with smoke detectors [55], smart parking [104] and lighting [28].

This growth in usage is not found in all countries. As some operators start to doubt the economic feasibility of an NB-IoT network. One example of this is the Japanese operator NTT-DOCOMO which stopped its NB-IoT service [24] in 2020. One of the reasons for the slow growth could be the move to more decentralized solutions such as Amazons Sidewalk network [14, 52] or the trust in systems that have been in place longer.

A better description of NB-IoT might be formed via the use cases. NB-IoT is mostly used for applications that require intermittent uploads of data. Examples of these applications are medical sensing, environmental sensing, asset tracking or metering usage of resources [19, 55, 66, 75, 90, 95, 105]. Applications need to be developed to not require low latencies or high bandwidth, as the latency can grow up to 10 seconds and the throughput per cell is limited at 250 kbps. NB-IoT devices are often idle and thus are not well-suited for data reception at varying time intervals. With this knowledge it is not advisable to use this technology for devices which have stringent time requirements, but is generally well suited for measurements and periodic reporting. It can also be possible to use energy harvesting to prolong the lifetime [48].

1.1 Research Questions

Given NB-IoT is already present in the Netherlands for some time, it is time to investigate whether NB-IoT indeed behaves as it was projected to behave. Therefore, this thesis will answer the following research question. *How is a NB-IoT network used and will the capacity match the expectations?* To answer these questions several subquestions need to be answered first.

Research question and subquestions

How is a NB-IoT network used and will the capacity match the expectations?

1. What type of traffic is generated by NB-IoT and how is it different from LTE?
2. Does CE provide additional coverage, and what techniques are used?
3. Can NB-IoT usage be characterized and grouped based on traffic patterns?
4. What impact does the new RA design have on the performance of the NB-IoT network?
5. How many devices will be able to make use of the NB-IoT network?

These questions need some more elaboration on how they will be used to answer the main question. Recent works will also be discussed to find the current state of academic research on NB-IoT. Both of these tasks will be done below.

A lot of research has been done on the traffic patterns for conventional mobile networks [12, 54, 67, 117]. For NB-IoT this research has been lacking, thus the first question needs to be answered before continuing. Some research has been done to investigate the behavior of IoT traffic when using Long Term Evolution (LTE) [40, 41, 74]. However, traffic patterns have not yet been measured for NB-IoT. Multiple papers have been written on potential applications and their traffic patterns either on test networks [18] or live networks [27, 75, 90, 98, 104] from various operators. The downside of these papers is that they do not capture all the different applications on the network. A good understanding of the traffic patterns will lead to better estimates of the capacity [45].

The second question has been formulated to investigate the successfulness of the different measures that are taken to improve the coverage. The effects of CE have been noted during a measurement campaign using a moving UE [61, 64]. Theoretical analysis has also been done on the effects of CE [11, 13]. No measurements are known that are based on nation-wide operator data, as many rely on small data sets or simulations. The utilization of CE needs to be known to determine the generated load on the network.

The third question sets out to improve current models that are used to simulate NB-IoT traffic. Earlier research showed that traffic patterns of cell towers could be used to determine the type of neighborhood [43, 117]. This is possible due to the fact that population density and usage is mostly correlated [38]. NB-IoT devices are not dictated by the location of homes, but the placement is dictated by projects of large companies. By answering the third question, we aim to get a better understanding of the varying nature between projects and if multiple cells are dominated by similar behavior. This will allow for better peak load and average load modeling to find the limits of the network.

NB-IoT has a slightly different Random Access (RA) design than conventional LTE, however larger changes have been made to accommodate CE. Theoretical analysis has been done on these changes [39, 50, 51, 72, 80]. The previous works did not include CE, however some papers do include the effects of CE [13, 71]. Improvements based on timing offsets have been proposed [125] as well as machine learning based solutions [26]. Real world effects have not been publicized before, as this analysis requires cooperation from a MNO. However, the performance of the RA is key to understand the usage of radio resources and the maximum capacity of cells. This information is also needed to optimize the planning of the RA.

Question five was chosen as the capacity of the network is important for the operator, but also for the consumer who wants to plan their deployment of devices. A target number of Fifth Generation (5G) was established by 3GPP of one million devices per square kilometer was defined [21]. Theoretical analysis on the number of devices that can be connected has been done, where the data of actual cells was used with fictional devices[39, 64]. However real world capacity measurements have not been made public yet.

This has not halted development in improving capacity. The most common solution is increasing the spectral density. A compressed version of Orthogonal Frequency Division Multiplexing (OFDM) called Fast-OFDM has been suggested [70, 120] to increase the capacity of the channels. An alternative for this problem based on symbol repetitions has also been investigated [60] or better turbo codes [123]. However these papers miss data on the actual capacity of the NB-IoT network. Thus, the capacity of the network needs to be investigated in this thesis.

1.2 Structure

The rest of the thesis is organized as follows. An introduction will be given on the technology behind NB-IoT and the method of measurement will be explained in Chapter 2. Chapter 3 will discuss the current usage of the NB-IoT network. Then, in Chapter 4 a closer look will be taken at the benefit of CE and the effects of path loss. Next, in Chapter 5 the possibility of modeling and categorizing projects will be investigated. Chapter 6 will take a deep dive into the current situation of RA with NB-IoT. The results of the previously mentioned chapters will be combined in Chapter 7, where the capacity of the network will be analyzed under the current situation and with various improvements found in the chapters before. Finally in Chapter 8, this thesis concludes with an analysis of the benefits provided and the lessons learned that are applicable for academia, the users of the network and the operators. In the appendices an overview of the acronyms used in this report can be consulted, along with an analysis of all acronyms used by the 3GPP and a short introduction to AT commands.

2

Network Structure and Measurement Process

Current cellular architectures consists of many Network Elements (NEs), protocols, architectures, interfaces and software. This chapter will give an insight in the architecture of a NB-IoT network and on specifics for VodafoneZiggo. Subsequently, a small primer will be given on the protocols used for the radio connection between an IoT device and the cell tower. Next, different data collection and analysis methods of modern cellular networks will be discussed. Finally, details are given on the hardware employed, along with the reasoning behind the omission of LTE-M in this report.

2.1 NB-IoT Architecture

This section will give a short introduction on the technology behind NB-IoT and unfortunately has to skip details in exchange for brevity and clarity. More information can be found in the very long 3GPP specifications for which [1] is the introduction, but many more documents are needed to capture all aspects. The website Sharetechnote is one of the few places that documents specifics on NB-IoT [101] in a clear and concise manner. The book Cellular Internet of things 2nd edition provides a deep analysis of the physical layer [68] along with the parameters that can be tuned.

This thesis describes the workings of NB-IoT as of Release 13, which is the version closest to what the software from Ericsson provides. In later releases more enhancements are added and the technology is uplifted to 5G [84]. Unfortunately those changes can not be investigated in this thesis.

The architecture of NB-IoT borrows many concepts from LTE. This is also needed to simplify the deployment of the network. Readers may already be familiar with LTE networks or other cellular networks and may find a lot of similarities. For others some design decisions may sound odd, however this is mostly due to fact that with LTE and other cellular networks sessions need to be managed and connections need to be reliable over a long time.

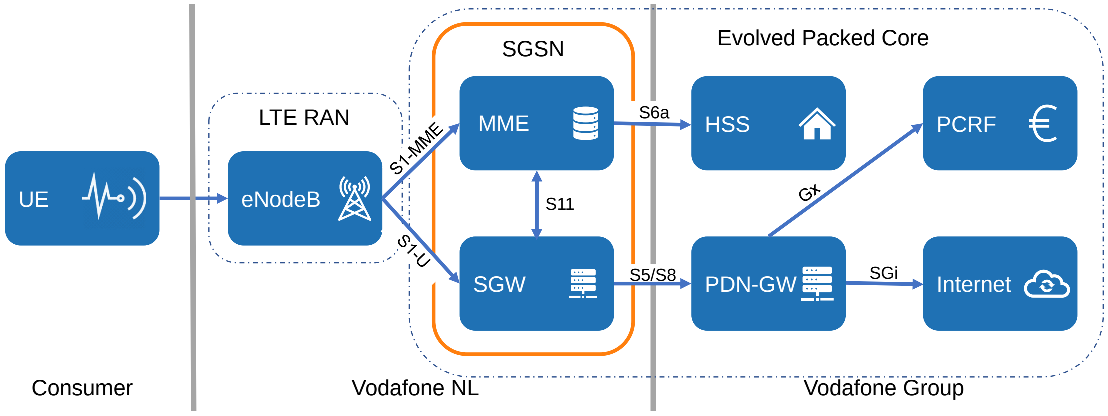


Figure 2.1: Schematic overview of the VodafoneZiggo NB-IoT network [1]. The dashed lines denote NE that are often grouped together based on function. The two NEs grouped by the orange continuous line is the Serving GPRS Support Node (SGSN), which is an alternative name for an element that does both functions. The vertical wide gray lines denote the separation of concerns over multiple parties. The following abbreviations are used: User Equipment (UE), Radio Access Network (RAN) Evolved Node B (eNodeB), Mobile Management Entity (MME), Serving GateWay (SGW), Packet Data Network GateWay (PDN-GW), Home Subscriber Server (HSS) and Policy and Charging Rule Function (PCRF).

The architecture of NB-IoT is schematically presented in fig. 2.1. Every blue rounded and filled box corresponds to a Network Element. One special grouping of the NE is the pair of the Mobile Management Entity (MME) and the Serving GateWay (SGW), as this can also be combined into a single entity called the Serving GPRS Support Node (SGSN). Furthermore the network can be split into two sections. The first being the RAN, which is the set of all eNodeB. The second is the Enhanced Packet Core (EPC) and consists of all entities needed to manage the RAN and the subscribers.

The NB-IoT network is jointly managed by Vodafone NL and Vodafone Group. Vodafone NL manages the eNodeBs, MMEs and SGWs. Vodafone Group takes care of the other NE, and this is shared with other networks in Europe. The separation created by the gray lines denote who is responsible for which section.

Each interface between NEs has their own protocol stack, with differing network layers similar to the OSI model. Luckily it is not needed for this thesis to learn each protocol. The first two layers are predominantly Ethernet and the third layer is based on Internet Protocol (IP). For the layer four protocol either User Datagram Protocol (UDP) or Stream Control Transmission Protocol (SCTP) is used depending on the interface. Each interface has a unique fifth layer protocol associated and they will be detailed below if necessary for this thesis.

2.1.1 Cells

A device wanting to get connectivity can have multiple forms, for simplicity the 3GPP calls them User Equipment (UE). The UE will try to connect to a cell which is hosted by the eNodeB. The eNodeB is an integrated unit that creates the waveforms and directly communicates with different eNodeBs, the MME and SGW. This is a departure from the system used in Global System for Mobile communication (GSM) and Universal Mobile Telecommunication System (UMTS) as these generations needed a separate controller for the radio. eNodeBs are connected to the core network via cable or via microwave back haul. Multiple eNodeBs are placed at the same site to create sectors and to make use of different frequency bands.

There are three methods to create NB-IoT cells [20].

1. Stand alone without a corresponding LTE cell.
2. Within the band of an existing LTE deployment.
3. At the guard-band of an existing LTE deployment.

The first method can be used to create a cell out of any carrier with a bandwidth of 200 kHz, replacing a single GSM carrier. The second method occupies a section of the bandwidth of an existing LTE carrier. The third method operates on the guard-band of an LTE carrier, which was originally designed as a buffer to allow for roll off signal power to reduce interference between channels. This coexistence has been analyzed in [35].

The first option for the deployment type was not suited to the current situation as it would not allow for reuse of eNodeB hardware. The second option has more interference [99], more Physical Resource Blocks (PRBs) are taken from the LTE cell and some NB-IoT PRBs need to be used for LTE signaling. Thus, the choice was made to deploy NB-IoT in the guard-band in the case of VodafoneZiggo.

2.1.2 Location of Cells

VodafoneZiggo has deployed NB-IoT cells at all of the LTE 800 MHz cells since the start of 2020. During the years 2018 and 2019 a stepwise roll-out of cells was used to spread out the investment and to monitor the effects of the roll-out.

Due to the utilization of the guard-band and the current bandwidth allocations in the Netherlands, the downlink is transmitted at 801 MHz and the Uplink at 842 MHz for the Vodafone network. These are both the lower value at which the carriers for the 800 MHz stop. The uplink has a higher carrier frequency to reduce the effects of interference. Later on this might be transferred to the 700 MHz bands to improve coverage even further.

Cells are placed to match the expected capacity and coverage. The location of NB-IoT cells can be found in fig. 2.2, which shows a higher density of cells in urban areas. Currently, there are 13400 NB-IoT cells in the Netherlands. From the location data exported from the Structured Query Language (SQL) database, the distribution of distances between cells can be found. During this, care has been taken to factor in the directions of the sectors. This distribution of Inter Site Distance (ISD) can be seen in fig. 2.3. The most common value is 800 meters and the average distance is 1660 meter.

2.1.3 Authentication

The authentication process is not unique to NB-IoT, as the method is shared with LTE. Understanding authentication is vital for understanding control flow over the radio and the function of various NEs.

When a Subscriber Identity Module (SIM) card is created, two important values will be stored on it. These are the International Mobile Subscriber Identity (IMSI) and the private key [2]. These two numbers are then stored in the Home Subscriber Server (HSS) along with other specifics related to the subscription, such as data allowances and roaming agreements. This private key will not leave the HSS or the SIM and the value of the private key cannot be read from either the SIM card or the HSS as all cryptographic operations are applied in the elements.

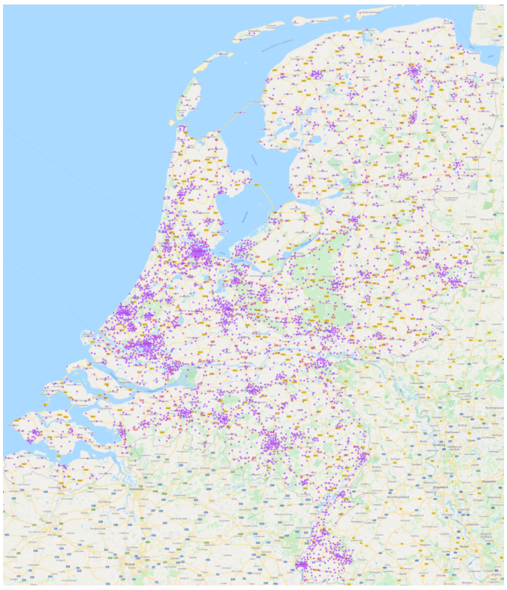


Figure 2.2: Location of all NB-IoT cells utilized by VodafoneZiggo. Each purple dot corresponds to a site, where most have three sectors. This Map was exported from an internal dashboard on the 22nd of July 2020.

The IMSI can be made public, however is somewhat privacy sensitive as it can not be changed. To solve this issue, the Temporary Mobile Subscription Identifier (tMSI) will be used over the radio and interface-specific identifiers in the core. The first three digits of the IMSI generally denote the country of origin and the next two digits denote the operator. The network has an accompanying value called the Public Land Mobile Network (PLMN) identifier, which denotes the country and operator and has the same structure.

Vodafone Group uses the country and operator combination of 90128 to form a range of IMSIs for IoT applications, which makes it harder to find roaming UEs. Due to the fact that all European Vodafone IoT devices can use this range. For non-IoT applications the normally alloted combinations are used such as 20404 for Vodafone NL, where 204 is the country code of the Netherlands and 04, the operator code for Vodafone.

When an UE attempts to set up a connection to the eNodeB, the MME is contacted. The MME handles connections and also manages any data tunnels, which will be explained later. The MME stores information on known devices. When UE is yet unknown or de-registered, the MME will contact the HSS.

Upon contacting the HSS, the first thing that will happen is that the MME will update the HSS on the location of the UE. The second part is the generation of a cryptographic challenge based on the private key of the SIM card, where a value is given and the expected response when encrypted with the private key. The MME will supply the eNodeB with this challenge and the desired result to interrogate the UE. If the result matches the expectation the UE is allowed on the network and authenticated.

2.1.4 Packet Access

The moment a connection has been established a Packet Data Network (PDN) tunnel will be created between the UE towards the Packet Data Network GateWay (PDN-GW). This tunnel

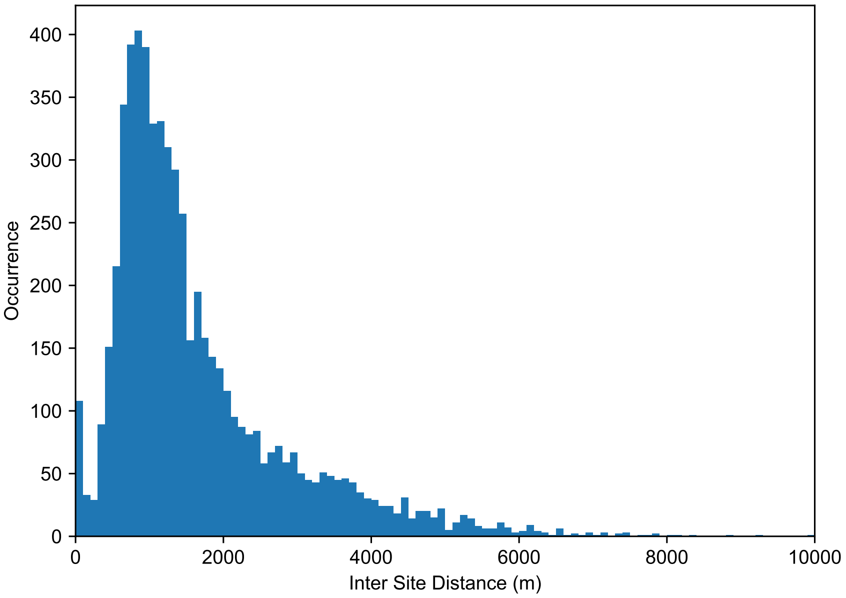


Figure 2.3: Inter Site Distance for all NB-IoT cells. Average distance between cells is 1660 meter and the mode is 800 meter. Site locations have been gathered from SQL table `site_location_and_azimut` and post processed to find distances.

allows for mobility of UE between eNodeBs, for applying Quality of Service (QoS) limits such as throughput throttling and data cap monitoring.

The tunnel will take a route along multiple different NE and each provides different functionality. The first step will be from the eNodeB towards the SGW from the network that is being attached to. This network is also called the visited network. The next step is to extend the tunnel towards the Packet Data Network GateWay (PDN-GW) in the home network, which is schematically drawn up in fig. 2.4. In the current network configuration, VodafoneZiggo always uses the Vodafone Group network as the home network.

The Access Point Name (APN) defined in the UE determines the behavior of the PDN-GW, along with the subscription data received from the HSS. The APN can be an IP address or a name that can be resolved via Domain Name System (DNS). The simplest option is to allow direct access to the Internet. For IoT applications several different security measures can be added.

Specific IP-addresses can be white listed for access, to provide an extra layer of security. An additional feature that can be applied is an additional Virtual Private Network (VPN) between the PDN-GW and the application server. The application server is often provided by the customer of NB-IoT services and host the code to receive measurements or send commands. The PDN-GW also supplies the connection to the IP Multimedia Subsystem (IMS) which supplies packet switched call and SMS services, however this is not needed for NB-IoT.

The last remaining NE to be discussed is the Policy and Charging Rule Function (PCRF). The PDN-GW, keeps a state model of the device and transitions in this state model can be monitored. Most transition can be set to trigger events. The PCRF defines what triggers to set up in the PDN-GW. These triggers can be based on time, connection set-ups, volume of data and many

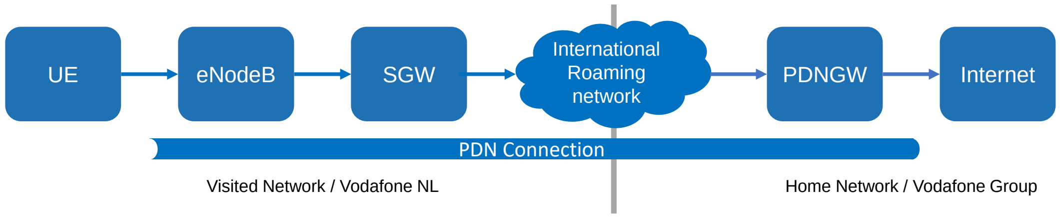


Figure 2.4: Diagram to show the path of the PDN connection and the transfer from the visited network to the home network.

more precise events. The PDN-GW notifies the PCRF each time the trigger is reached. The PCRF will also communicate the QoS profile that needs to be applied.

2.2 Radio Access

2.2.1 Physical Channels

Vodafone makes use of Frequency Division Duplexing (FDD) to separate the uplink (UL) and the downlink (DL) of LTE, instead of Time Division Duplexing (TDD). Along with this, the uplink and the downlink of NB-IoT are situated in the guard-band of the uplink and downlink of LTE respectively.

The following paragraphs will show how these parts of the spectrum are split up into usable and meaningful sections. A more general and formal overview of the different layers can be found in the paper [89].

The bandwidth per direction is 180 kHz and this is split up using OFDM in 12 sub-carriers with a bandwidth of 15 kHz. In the uplink a sub-carrier spacing of 3.75 kHz can also be used, leading to longer symbols and more sub-carriers. Vodafone uses 15 kHz spacing. On top of these symbols within the sub-carriers, physical channels can be constructed. This grouping is used to convey that similar information is being transmitted and how to decode it [6, 7]. A quick reference for physical channels can be found in fig. 2.5.

The uplink makes use of four different physical channels. The first being the Demodulation Reference Signal (DMRS) which is closely inter-weaved with other physical channels to provide information to aid the demodulation process. The next channel is the Narrowband Physical Random Access CHannel (NPRACH) which forms the Radio Access CHannel (RACH) and contains the moment in which UEs can transmit messages to start a new session.

Finally data needs to be transmitted too, thus there are two different Narrowband Physical Uplink Shared CHannel (NPUSCH) formats. These consists of small blocks of various sizes and spread over various number of sub-carriers. The first and generally larger format carries all communications about the connection in the Uplink Control Information (UCI) and the payload itself on the Uplink - Shared Channel (UL-SCH). The second format is smaller and carries information on the radio state.

The downlink operates mostly based on the principle of sub-frames of one millisecond. The first channel of interest is the Narrowband Physical Broadcast CHannel (NPBCH) which carries information on the cell and where to find the NPRACH. Then there are two different synchronization channels called the Narrowband Primary Synchronization Signal (NPSS) and the

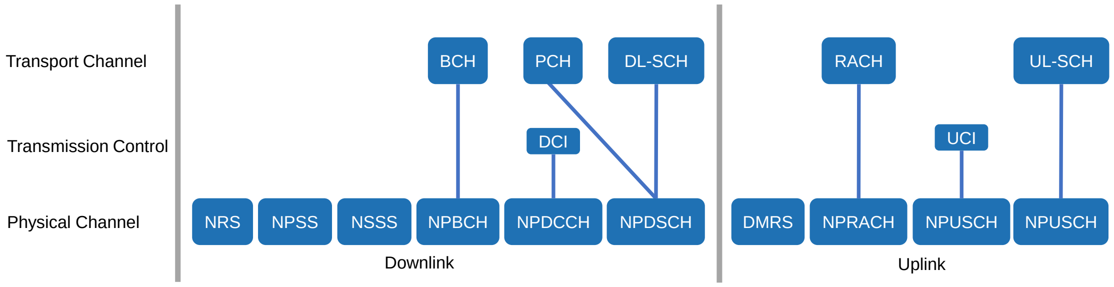


Figure 2.5: Diagram to show the different physical channels and to what transport channels they map.

Narrowband Secondary Synchronization Signal (NSSS), which are used to find the correct offset for transmissions. However these synchronization channels can also be used for positioning and movement measurements. Some symbols are used to carry the Narrowband Reference Signal (NRS), which is similar to the DMRS and is used as an aid in demodulation.

The remaining resources are used for data, which is transmitted via the Narrowband Physical Downlink Control CHannel (NPDCCH) and Narrowband Physical Downlink Shared CHannel (NPDSCH). The first of the two carries scheduling information and radio link control in the Downlink Control Information (DCI). The second carries the payload on the Downlink - Shared Channel (DL-SCH) and the Paging Channel (PCH). Imperfect scheduling of these channels can lead to higher overhead [122].

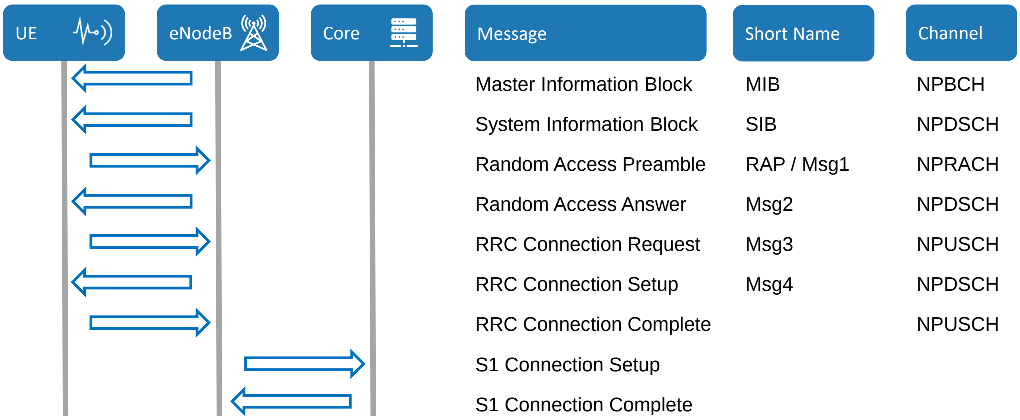
2.2.2 Attachment Procedure

When an unconnected UE wants to connect, it will monitor known frequency bands to find potential cells. During this sweep it checks for the NPSS, as this is a repeating signal that can easily be decoded. From the NPSS sequence the time until the broadcast messages will be transmitted, can be calculated. The broadcast channel contains the Master Information Blocks (MIBs) and the NPDSCH contains further System Information Blocks (SIBs). Within the MIB information is given on the operator, the status of the cell and when the NPRACH is scheduled.

The NPRACH is denoted by the periodicity and the start time. On top of the scheduled moment, certain sub-carriers will be reserved for different CE. CE is one of the features specifically introduced for NB-IoT and LTE-M and will be further explained in the following section.

With the information on the correct moment and sub carriers, the UE can calculate all the available Random Access Preambles (RAPs) and pick one. This will be a hopping sequence over 5 different sub carriers where a single symbol will be transmitted in the NPRACH. This is a slotted ALOHA process, which means that there is a large chance of collisions [106]. Thus, the message is as short as possible and contains no information.

The RA procedure is visualized in fig. 2.6 and will be detailed below [8, 10, 69]. This procedure will be investigated thoroughly in Chapter 6. The moment the eNodeB receives the RAP, which is also known as Msg1, the connection handshake will be started. Each preamble will correspond to a specific ID. The response to the RAP will be the ID of the RAP and a scheduled moment in the Random Access Answer (Msg2). The UE will respond in RRC Connection Request and Contention Resolution (Msg3) with a temporary identifier, which will be used for the rest of the communications. This temporary identifier is the same as the tMSI. This step is part of the resolution of the random access as multiple devices could have used the same RAP leading to



Message	Short Name	Channel
Master Information Block	MIB	NPBCH
System Information Block	SIB	NPDSCH
Random Access Preamble	RAP / Msg1	NPRACH
Random Access Answer	Msg2	NPDSCH
RRC Connection Request	Msg3	NPUSCH
RRC Connection Setup	Msg4	NPDSCH
RRC Connection Complete		NPUSCH
S1 Connection Setup		
S1 Connection Complete		

Figure 2.6: Successful handshake between UE and eNodeB to establish S1 connection for NB-IoT [58].

a collision on Msg3. Msg3 can also be seen as the request to start another Radio Resource Control (RRC) connection, which is the dialog between the UE and the eNodeB.

RRC Connection Setup (Msg4) will confirm the set up of the RRC connection. From now on the eNodeB can set up a S1 connection with the MME and when this successfully completes the connection is ready. This is either a short process if the tMSI is recognized by the eNodeB or the attachment procedure is started as detailed before. The S1 connection is the dialog between the eNodeB and the MME.

2.2.3 Coverage Enhancement and Path Loss

Coverage is generally uplink constrained, as the UE has a much lower transmit power than the eNodeB. Coverage is often denoted in the term of Maximum Allowable Path Loss (MAPL) or Maximum Coupling Loss (MCL), which is given in decibels (dBs) and are used interchangeably. The term MAPL is used to denote the highest amount of attenuation at which a reliable connection can be achieved. The reasoning behind MCL can be found in the book Cellular Internet of Things in table 8.2 [68], however a short primer is given in the following text box. To increase the MAPL a lower target Signal to Interference plus Noise Ratio (SINR) needs to be achieved.

NB-IoT uses two methods for CE, which can also be found in section 7.2 of [68] and in the specifications in 36.213 in chapter 16 [9]. The first being an even lower modulation order, as the modulation can switch to Binary Phase Shift Keying (BPSK) from Quadrature Phase Shift Keying (QPSK) as modulation for the sub-carriers in the uplink. QPSK is also known as Quadrature Amplitude Modulation (QAM). This results in the bit rate being halved, but an increase in MAPL of about 3 dB. The other method of increasing the SINR is to use transmission repetitions. The different levels of CE allow for different amount of repetitions, however these mappings are unknown at the moment. Repetitions allow for transmitting more energy per symbol, as more time is spent per symbol and thus decreasing the signal power needed.

The usage of these different measures are determined by the policies set for the CE level in the eNodeB. These three classes will be denoted as CE 0, CE 1 and CE 2. Without CE the MAPL is 144 dB and with CE 2, 164 dB is feasible. This claim will be further investigated in Chapter 4.

What is path loss?

For a successful reception, the device needs to reliably decode the received signal into bits. The targeted bit error rate can be achieved by having a large enough SINR. The SINR is defined in two parts. The first part is the signal (P_r or S) which is transmitted with a certain power (P_t), an antenna gain for both antennas (G_{tx}, G_{rx}) and attenuated as it traverses from antenna to antenna. This attenuation is called the path loss (PL) and captures effects such as free space loss and shadowing. The second part is defined by the interference from other similar transmissions (I) and other noise sources (N). Some literature omits the interference term, as it can not be assumed to be Gaussian.
This can be summarized in the following equation, where addition and subtraction can be used due to fact that decibels are used.

$$SINR = S - I - N, \qquad S = P_r = P_t + G_{tx} + G_{rx} - PL \tag{2.1}$$

2.2.4 Battery Saving

Battery savings are one of the key features of NB-IoT. This enables devices to operate for many years on small batteries. Previously with GSM this was done by shutting down the modem and waking it up periodically. This meant that the device needed to register with the network every time.

NB-IoT uses two different techniques to create the battery savings [20, 108]. The first being Power Saving Mode (PSM) and the second is Extended Discontinuous Reception (eDRX). From the name of the second technique, we can learn that it is an enhanced version of a similar technique in LTE. Below the capabilities of the two will be detailed.

When a device is unresponsive to the network it will be unregistered from the eNodeB. If the device then wants to communicate with the network the entire authentication procedure needs to be repeated. To combat this PSM is introduced. PSM is a timer that determines how long a UE can be in deep sleep mode before being unregistered. Before this timer runs out, the devices needs to reconnect.

Continuously listening for incoming communications can cause quite the battery drain. This was already noticed in LTE and thus it became standard practice to switch the receiver off for a fraction of a second. This downtime, would often not lead to a degraded service. With NB-IoT this behavior is extended to much longer periods of time with eDRX. The accompanying timer accurately determines when the UE will wake and listen for paging messages.

Details on optimizing energy efficiency of these two mechanisms can be found in [16, 23, 79, 91, 109, 112] and a large scale measurement campaign has been done in [83].

It has to be noted that both of these values can be overruled by the eNodeB. The policies for this are determined by Ericsson and can not be changed at the time of writing. Thus, it is key to monitor how these values are changed to understand the behavior of the UE. There are still

some shortcomings to both of these techniques. This is due to the fact that both are focused on reducing time listening to the network. However, in IoT applications the uplink is just as important. For uplink transmissions, it will always be required to use the RA procedure.

2.3 Measurement Methods

A modern cellular network has multiple methods of investigating the performance and troubleshooting configuration errors. For this thesis, access was granted for all tools that VodafoneZiggo has access to. This access was available from the start of February 2020 until the end of July 2020, which mas made possible due to an internship position. This section will discuss different methods of gathering data with Network Element Counters, Core Traffic Analysis, Call Data Records and the usage of active probes.

2.3.1 Network Element Counters

The basics of performance management is an integrated part of the specifications and thus this section will be relatively similar to other operators. This is based primarily on counting specific events and thus each reported value is also called a counter. For every element in the network the 3GPP defines which counters should be available for exporting from the NE, however more can be added by the hardware vendor [4].

These counters will be exported to a file on the storage of NE every measurement period for every NE. This measurement period is defined to be 15 minutes at VodafoneZiggo for each NE, but this can be different per operator. This file format is based upon Extensible Markup Language (XML) and is further defined in 3GPP specification 32.435 [5] and needs to be downloaded by the Operation System (OS) to be analyzed. The operator can define which counters need to be saved and if filters need to be applied during the collection of the data. Thus it can be that different operators would not have all the data to perform similar measurements as in this thesis. For the analysis there is no specific method defined by the 3GPP and is up to the operator.

While there are counters available for every network element, for this thesis the choice was made to only use eNodeB counters for NB-IoT based on two reasons. The first being that the activity on the eNodeB reports on the behavior of the radio link and no other NEs do. The second is that there are only a handful of separate entities per type of network element. This causes many more devices to be aggregated and thus the behavior is averaged, which results in less clear results.

At VodafoneZiggo this counter data is stored in various SQL databases, which can be accessed by VodafoneZiggo and by Vodafone Group for back office management. Depending on the amount of data added per day, different retention policies are utilized. Two different types of counters exist: standard counters and vectorized counters. Standard counters simply count events, while vectorized counters can show more specific results. A vector counter could be used to keep a histogram of recorded path loss values or to differentiate usage over different CE levels.

Data retention is mostly governed by the data storage capacity. The standard counters per 15 minutes create 9.6 GB per day per network and are stored for around a hundred days by VodafoneZiggo. The vector counters need much more storage as this takes 68.5 GB per day for the entire network and will be stored for just thirty days. However to save data the counters are also aggregated per day.

By summing the 15 minute counters, the storage needed per day is reduced by a factor 96. The normal counters aggregated per day can be stored indefinitely and the vector counters are currently retained for a hundred days.

There are 1906 standard counters and 543 vector counters. Each counter is stored as a column in the table. The counters used are detailed in the following sections. In Appendix C a collection of all available NB-IoT counters at VodafoneZiggo are cataloged, however a large portion of the counters are not used in this report. Most counters correspond to very specific parts of the state model and either are never used or used in similar manners as more logical counters.

2.3.2 Core Traffic Collection Tools

Another valuable data set is the collection of traffic in the core network and between the core network and the eNodeBs. On all interfaces between the NEs, probes are situated to record all traffic, which creates a very powerful tool to troubleshoot issues on the control plane. These probes are mostly implemented as taps on the Ethernet connection.

Due to the nature of the NB-IoT network only a some of these can be recorded, which are the S1-MME, S1-U and the S11 interface. This is due to the fact that a large part of the EPC is managed by Vodafone Group. These traffic logs can be accessed via two different proprietary tools from NetScout, formerly Tektronix.

The first tool is called the Iris Session Analyzer excels in filtering very precisely, only 1500 traces can be exported [92]. The second tool is the Iris Protocol Analyzer, which seems to be discontinued [110]. The second option has less capable filtering options, however given enough time large amounts of packets can be saved.

The first tool is very well suited to investigating specific behavior and the second is well suited to gather statistics. The downside for both is that the extraction can only be manipulated via the GUI and thus the functionality can not be extended. This downside is the major reason that these tools will not often be used in this report.

2.3.3 NB-IoT Development Kit

VodafoneZiggo has made available a SODAQ SARA R410M development kit [107], along with a SIM card providing access to NB-IoT and LTE-M. The device uses a modem developed by u-blox, namely the SARA-R410M-02B [114] and a rudimentary PCB antenna.

The device itself was set up to run AT commands sent over a serial link, such that it can be controlled from a computer. More information on the AT commands and specifics for connecting to the VodafoneZiggo NB-IoT and LTE-M network can be found in Appendix D.

This module does have some downsides, which are common in other devices as well. It does not provide commands to read out the CE used, the distance towards the cell and the number of repetitions used for data transmissions. These values are key to understand the behavior of the device and the power consumption. The modem does however show the Received Signal Strength Indicator (RSSI), which can be used to predict the previously named values.

The traffic generated by the development kit can be found in both the eNodeB counters and the core traffic logs, which makes it a valuable tool. The home office is situated in a cell without other users during testing, thus the traffic created can directly be related to the values found in the eNodeB counters. This was used to explore the behavior and get a better understanding of NB-IoT traffic. The results based on the generated traffic can be found in Section 3.2.

2.3.4 Limitations on Call Data Records

Most research on cellular networks makes use of Call Data Records (CDRs). Some research uses the term Data Detail Record (DDR) or eXtended Detail Record (xDR) as an updated version due to the decrease in number of calls and the increasing data traffic. However all refer to the same records.

These CDR contain logs on the location of users, traffic patterns and more. These are stored in the HSS. For NB-IoT this element is managed by Vodafone Group, thus access was not possible for this project due to business politics and privacy reasons.

A solution based on the analysis of APNs was used before [74], where keywords were used to categorize devices. This has some downsides, as the APNs could be privacy sensitive. The APNs can only give a guess on whether Machine to Machine (M2M) or Human to Human (H2H) traffic is expected and does not give insight on the Radio Access Type (RAT) used.

2.4 Data Collection and Analysis

This section will give a basic overview of the techniques and programming languages used in this report. Full description of the methods for analysis will be included in the following chapters, as the methods differ between experiments.

This report makes use of data collected from eNodeB counters, core network traffic logs and development kit activity logs. The counters were situated on SQL servers, which also allowed for processing the data before downloading it. The SQL queries used can be found in the GitHub Repository at `https://github.com/TUDSSL/nb-iot-measurements`.

Most analysis of network data at VodafoneZiggo is done using Excel, however this was not well suited to the investigations in this thesis. Off line processing was mainly accomplished using Python, due to the wide collection of libraries and earlier experience. The most used library is matplotlib [56] for the visualization of data. Other often used libraries include numpy [49] for simplifying calculations and pandas [118] for importing the data. When other libraries are critical, it will be included in the applicable section.

The GDPR is taken into account during the analysis for this thesis. Most investigations used the cell counters, which are inherently anonymized as data is aggregated per cell. Core traffic logs always used temporary identifiers, except for an investigation to the number of devices on the network. For this all unique IMSIs needed to be analyzed during two 10 day periods. Since IMSIs can be used to identify devices and in some cases the corresponding owner, these values need to be handled as private data. These values were available, as an employee of VodafoneZiggo, to monitor the state of the network. Logs containing IMSIs have been deleted after processing.

2.5 Hardware and Software

Vodafone has a long-standing cooperation with Ericsson who delivers both core network components and eNodeBs for the NB-IoT network. The hardware used is up-to-date due to the roll-out of 5G via Dynamic Spectrum Sharing (DSS). For eNodeB antennas mostly passive Huawei antenna systems are used. More specifics on hardware and software can not be shared due to business sensitivities.

Features are based on software and no longer on hardware capabilities. During the course of this project the eNodeBs were running the software version 19Q3, which implements the features for Rel-13 for NB-IoT. Ericsson provides add-ons that can extend the functionality of the cell. NB-IoT is an add-on that can be installed on recent version of the eNodeB software. New features are often gated behind licenses which need to be purchased. NB-IoT is an optional feature, but has other optional extensions itself such as extending the maximum cell range to 100 km [37].

2.6 Absence of LTE-M

NB-IoT is implemented as a separate network from LTE, which shares hardware only with eNodeB hardware. LTE-M however is such an integrated part of LTE that the same cells can be used. Furthermore the core network does not have to know it carries LTE-M traffic. This makes it harder for both NE counters and Core Traffic Analysis.

The first obstacle is the counters. NB-IoT shares the eNodeB hardware with LTE, but the cell itself is separated via software. Thus the behavior is measured separately. LTE-M uses the same cell as LTE where some PRBs are reserved for machine type traffic, thus LTE-M and LTE are intertwined. This results in the fact that the LTE counters include the activity of LTE-M. To solve this filters can be applied to a special group of counters to measure just LTE-M traffic. This special group of counters is called the Flex Counters and consists of a subset of all available counters. At the moment of research these were not implemented to the same level as NB-IoT and thus could not provide enough insight.

The second obstacle is the core network. Due to the current implementation for the core network LTE-M traffic cannot easily be separated from LTE. This needs be achieved manually. The eNodeB notifies the MME that LTE-M is being used after the initial connection set up in the same packet only the temporary identifier is used. By searching previous packets this could be matched to the associated UE. The MME should communicate this further with the SGW and the HSS [3], but this does not happen. This is due to the fact that at the time of writing the core network did not support the appropriate signaling.

3

Analysis of Traffic

To answer questions about the potential limits of the capacity go the NB-IoT network, first it is necessary to investigate the current situation of the Vodafone NB-IoT network.

Section 3.1 will use two methods to discuss the number of the devices on the network. Section 3.2 will capture the characteristics of the traffic generated by NB-IoT. Finally, in Section 3.3 an investigation will be held into the changes in traffic over the hours of the day in which the behavior will be compared between NB-IoT and LTE.

3.1 NB-IoT Device Count in Network over Time

Before research can be done on the behavior of devices, it is important to know the number of the devices on the network and how this grows over time. Without direct access to information from the HSS, this number can not directly be found. This section will take a look into two different methods for finding the number of active devices.

The first method involves aggregating counters from all eNodeBs. Unfortunately, there is no counter available for the number of unique devices connected per measurement period. Implementing this would cause issues when a device visits multiple cells within a measurement period. There are two counters that keep track of the number of devices on the cell `pmRrcConnMax` and `pmRrcConnSum`. The first counter keeps track of the maximum number of devices connected at the same time, however due to the fact that NB-IoT devices tend to stay connect for only 10 to 20 seconds this is not a reliable method for finding the number of users. The second counter accumulates the number of connected users every five seconds, which can give imprecise results due to the varying lengths of connections.

One possible solution is to count the number of S1 connections per day. This value can be traced back to the beginning of the deployment of NB-IoT. The S1 connections show the number of successful starts of data transmissions. This will not be synonymous with the number of devices, but can answer growth based questions.

In fig. 3.1 the number of S1 connections per day is shown. With information from the next section an estimate can be derived for the number of active devices. Large scale implementation started in 2019 in Amsterdam where NB-IoT is mostly used in Schiphol to track suitcases [115] and as smart meters in certain neighborhoods.

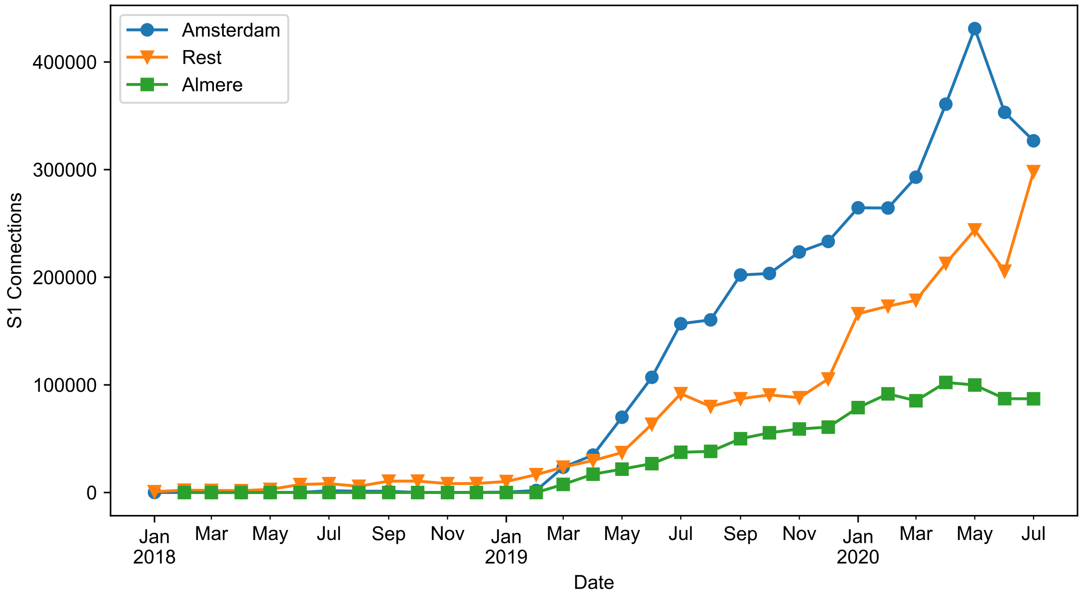


Figure 3.1: Shows the average number of S1 connections being made per day over certain areas since the start of 2018. Grown mainly started at the beginning of 2019 in Amsterdam, which is still the main contributor of connections.

In August 2020 the average number of S1 connections per day was 711992. LTE receives 860514063 connections per day. This large disparity can be attributed to two factors. The first being the large difference in the number of devices. The second reason is that phones often change cells as people move around.

Another method of determining the number of users is by counting the number of unique IMSIs on the control plane in a large time window. Two periods of 11 days have been taken in March and June to record all IMSIs. The period of March was from the 5th until the 16th. The period in June was from the 10th until the 21th. This process is laborious as the captures need to be restarted per day and can often crash during exporting, which is the reason behind having only two measurement periods.

Vodafone Group has decided to use the 90128 IMSI range for M2M solutions. Thus, a probe can be used on the S11 interface to monitor the creation of new sessions. In this same message information is given on whether NB-IoT is used or LTE. When the latter is reported it will be assumed to be LTE-M traffic as it uses a M2M contract. The equivalent filter is defined for GSM, however adjustments were made for the different protocols.

The IMSI is visible during the start of a new session in the Create Session Request (CSREQ). Not all devices start a new session every day, as sessions could theoretically last infinitely and some UE report less than once per day. This then depends on the uptime of the device, eNodeB and the programming of the UE. What is expected is that with a longer period of capturing packets more unique IMSIs will be found.

Due to business sensitivities absolute numbers can not be displayed. Table 3.1 shows the relative number of IMSIs when compared to the IMSIs using NB-IoT in March. In a period of three months a growth is found with a factor of 1.26 when looking with a window of 11 days for

RAT	Month	Relative Size
NB-IoT	March	100
NB-IoT	June	126
LTE-M	March	202
LTE-M	June	277
GSM	June	973

Table 3.1: Number of unique IMSIs can be found in the 90128 IoT range during a period of 11 days relative to March for NB-IoT. A growth factor of 1.26 is observed, but GSM still has a much larger market share.

NB-IoT. It is also clear that there are more than double the devices using LTE-M, which is also experiencing a bigger growth during three months of 1.37. The market share of M2M devices operating on GSM is still much larger.

The result can be compared to fig. 3.1 where in the period from March until and including June a growth factor of 1.46 can be found across the nation. This disparity can be due to the different methods of defining the range, but is mostly due to the fact that the number of S1 connections per device is variable. These values are all much higher than the predicted growth values in literature. There are still relatively few devices in the network, which means that multiplicative growth is not hard to achieve.

3.2 Traffic Type

The previous section discussed the growth and usage of the network mostly in the terms of S1 connections. This section will give some insight on what happens during an S1 connection and how often devices connect.

3.2.1 Measurement Method

To find out how much data is transferred per S1 connection the counter `pmRadioThpVolUl` can be used to find the number of kilo bits transferred. The documentation of this counter specifies that the data volume on the Media Access Control (MAC) level is reported. There is no clear source on the relation between this quantity and the payload transmitted by the UE. Thus this relation needs to be found first.

This mapping can be found with an experimental approach using a NB-IoT development kit. The device was reprogrammed to allow a connected PC to send ATtention (AT) commands and echo the response. The PC ran a script that transmitted several payloads of differing sizes and differing number of repetitions within 15 minutes. These transmissions and their size were logged. The size and number of repetitions are compared with the counter of `pmRadioThpVolUl` for the cell `08N063283`. This cell had no other users and thus a direct relation could be made between transmissions and counter values.

When the relation between the MAC layer and the throughput is known, it is possible to find the average payload size per cell per moment from the earlier mentioned counter. This is done by dividing the MAC layer throughput by the number of connections in a moment. Finally, the relation found earlier can be applied. Each occurrence can then be logged in a histogram.

To find the period in between messages, devices need to be monitored instead of the cells in general. For this the packets on the S1 interface are being sniffed such that all Modify Bearer

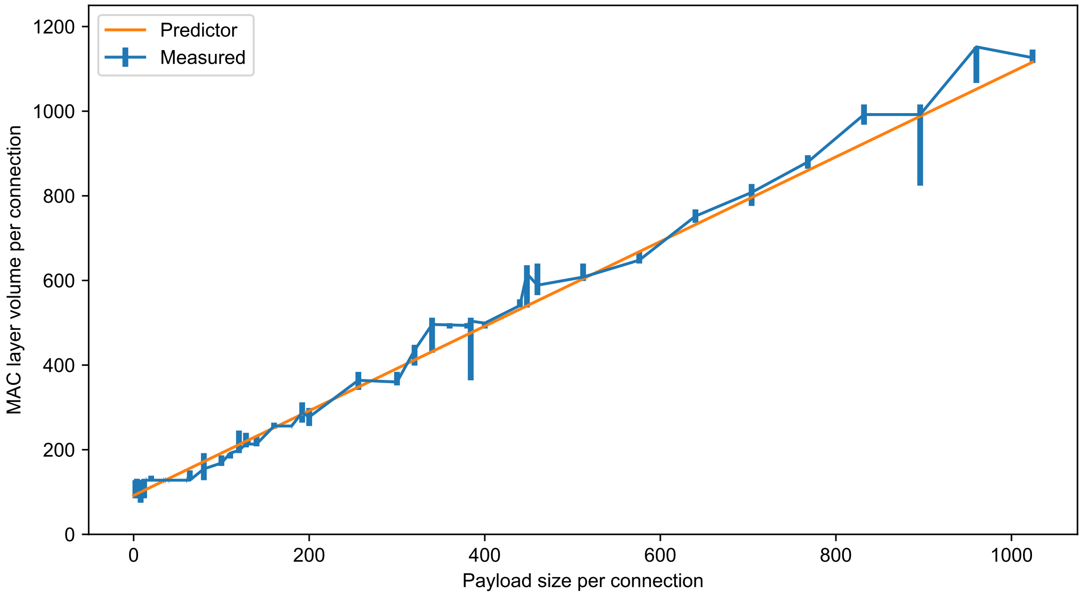


Figure 3.2: Data volume transferred from UE versus reported data transfer on MAC layer of network, based on 1911 measurements over a period of 10 days. An offset of 92 bytes was found between the payload and the MAC layer throughput reported by the eNodeB.

Request (MBREQ) are gathered. This contains a Tunnel Endpoint IDentifier (TEID) that identifies the current session and the endpoint. Then it is simple to find the time in between messages with the same TEID. These are logged in various time bins for better plotting. This method is however not completely flawless, as devices that start new sessions regularly do not retain the same TEID. Unfortunately, devices with a low frequency in reporting may not be counted in this method.

Improvements can be made by linking IMSI to TEID values, but this significantly increases the storage needed and can not be prolonged over a long enough period.

3.2.2 Results

The results of the mapping between the data payloads and the MAC layer volume can be seen in fig. 3.2. This plot includes a linear prediction of the relation. This line has an offset of 92 bytes on top of the actual size of the payload, which is a fairly accurately description of the relation. 28 bytes are explained by the fact that data from the device is encapsulated by IP and UDP headers, which have of size of 20 and 8 bytes respectively. This leaves an additional 64 bytes that are overhead on the MAC layer.

With the relation known the average payload sessions per 1 minutes per cell can be found in fig. 3.3. The highest amount of packages is being sent with a payload around the 128 bytes and the majority of all messages are smaller than 1 kB. This is to be expected as most devices only transfer some measurements in a few floats or integers in a small binary format. There is however a fairly long tail of payload sizes. There is no upper limit on the payload size that can be transmitted. Most LTE session are in the range of 10 kB to 1 MB, which is roughly the size of optimized images and small websites.

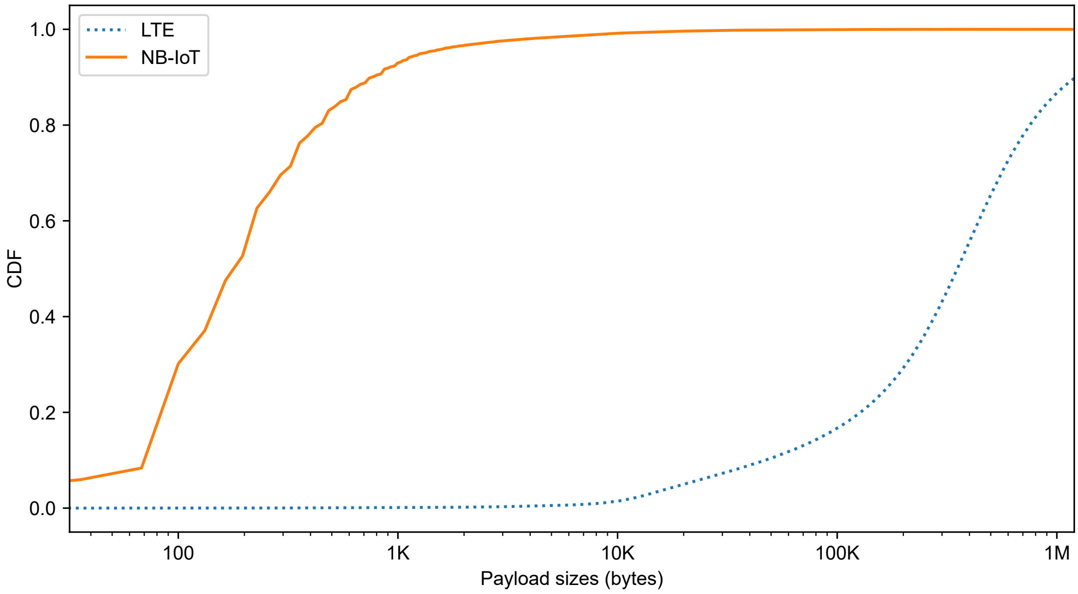


Figure 3.3: The average size of packets encountered shown for LTE and for NB-IoT indexed on the maximum value. Captured data over a hundred days. NB-IoT and LTE both have a peak at 128 bytes payload. However LTE is also used for much larger payloads. The average payload for LTE is 0.9 MB and for NB-IoT 0.6 kB KB. This is disparity is logical as NB-IoT mainly transmits sensor data, while LTE is mainly used to fetch websites and pictures of cats.

For LTE multiple flows per session are needed [127], as browsing web pages often requires connections to other servers. For NB-IoT this is generally not the case as there is only a single application and thus a single flow. Combining the information of the fact that multiple flows are needed and each one is larger. It is but natural that more data is utilized. A similar result has also been found per Transmission Control Protocol (TCP) session in research at the beginning of the utilization of LTE [54]. When taking into account the fact that most devices have multiple TCP flows [29] concurrently the results are fairly similar.

The result of the scan for periods in between messages can be found in fig. 3.4. What is interesting is that a fairly large portion is instructed to connect every five minutes, which is not recommended behavior. A larger portion of devices connect every two hours. The higher value bins also represent a larger period of hours, which distorts the results somewhat. Relatively few devices connect less than twice per day.

The average period in between messages is 16 minutes and 28 seconds. This may seem contradictory with the results from fig. 3.4, however the graph shows the time spent in each waiting period until the next message. The average shows the time between messages over all, for which low period devices contribute more. This is due to the fact that they transmit more.

CE was added to provide more devices coverage by lowering the modulation and increasing the number of repetitions. In the vector counter `pmS1SigConnEstabSuccCe`, measurements on the data volume and number of S1 connections can be found per CE level. Similarly the volume of the data can also be compared using `pmRadioThpVolDlCe` and `pmRadioThpVolUlCe`. These values can be summed and compared to one another.

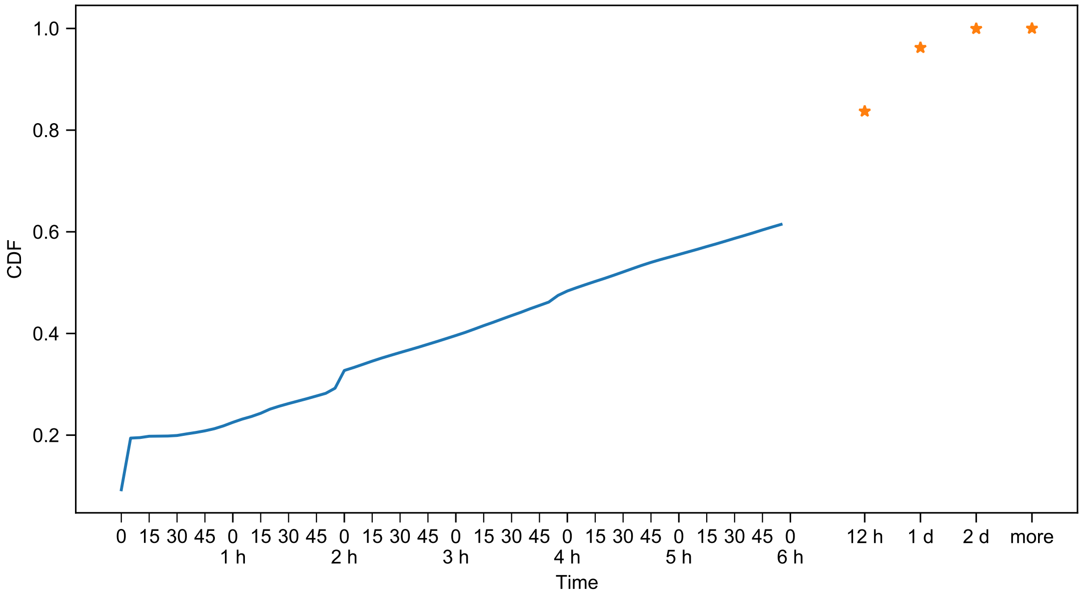


Figure 3.4: Period between messages, captured over five days. Most devices communicate every five minutes, while the average is 16 minutes. Data collected during a period of three days. There are two specific periods that are the most popular, which are 5 minutes and 2 hours. More than 95 % of the devices transmit more than once per day.

The results can be found in fig. 3.5. The figure shows that Coverage Enhancement is only used for less than 95 % of all connections. Next to this the data volume behaves according to the same relation.

3.3 Distribution Over Day

The capacity of a H2H network is not planned for the average use case but for the busy hour values. Human data traffic patterns are closely related to their daily schedules [117]. M2M traffic experiences different effects, as their behavior is not dictated by the position of the sun. One can however be expected to find peaks, as many devices belong to the same project. This section will be used to investigate how the behavior of NB-IoT devices changes during the different hours of the day.

From the standard 15 minute counters, values can be aggregated and averaged over the months of May, June and July in separate bins for each period of 15 minutes. Five sets of Key Performance Index (KPI) will be used in this analysis. The first being the number of kilo bits transmitted as payload, as this is a commonly used metric for H2H networks. To complement this the number of S1 connections will also be recorded.

These two values are fundamental for the usage of the PRBs that are available per cell. NB-IoT shows for the uplink the percentage of available PRBs for the NPUSCH and for the downlink the available PRBs for NPDCCH and NPDSCH. The cell varies in activity and outside interference also changes over the day, so variances in the success rates of various processes are also expected.

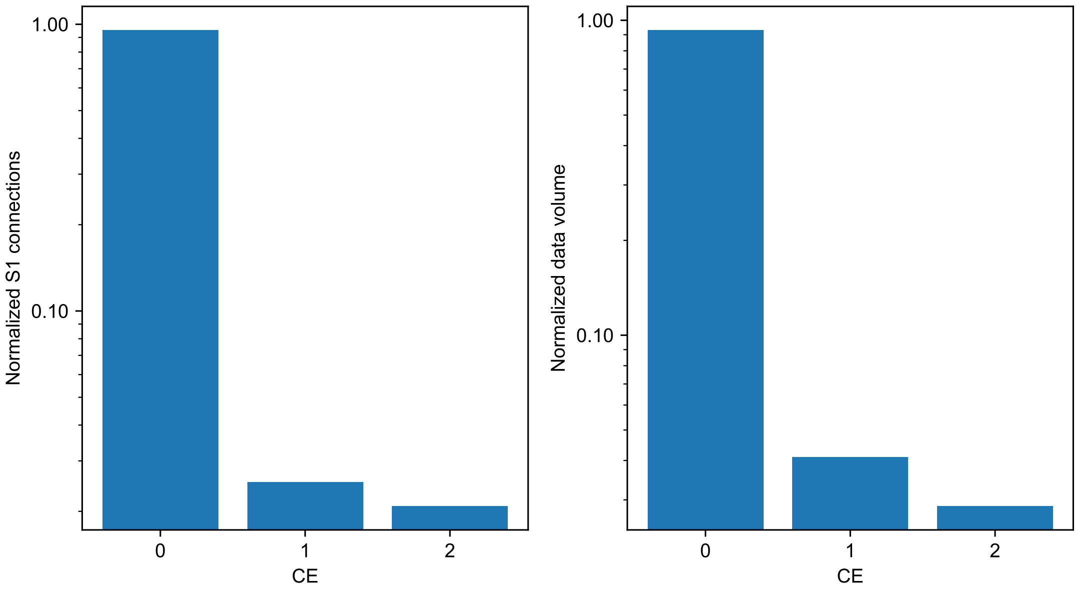


Figure 3.5: Distribution of S1 connections and data volume over CE levels, based on total connections during June 2020. CE is used for less then 95 % of all connections.

The first pair of of KPIs can be investigated in fig. 3.6 where the throughput and number of S1 connections over the day are plotted for both LTE and NB-IoT. The LTE volume and S1 connections do not just represent the behavior of cellular networks but also the Dutch population. The throughput rises, as the people rise from their bed and return at about 11 PM. Similar results can be found in [111, 127].

In between there are two other phenomena happening. The first being the lunch break at noon, where people are more active on their phones [100]. The lunch break was more noticeable before the COVID-19 lock down. At the proper Dutch dinner time of 6 PM traffic a small decrease in traffic is experienced. The evening shows a decline in S1 connections, as people will be less likely to be on the move.

A different story is told when looking at the results from NB-IoT. Generally all KPIs stay relatively flat over the day, as the y-axis is scaled to magnify the effects. In data volume an increase at around two PM can be noted, which can be attributed to certain smart electricity and gas meters. The S1 connections experience a smaller deviation, but has sharper peaks as specific wake-up times are reached. From this it can be concluded that one or more projects exchange a bigger amount of messages than normal at a fixed moment.

In fig. 3.7 related KPIs for LTE and NB-IoT can be seen. The first being the usage of PRBs, which seems to fluctuate less for NB-IoT than for LTE along with the throughput. The changes in traffic are managed well by the network and no success rate issues arise during busy hours over the day for both the attachment process and data transmissions for LTE. The random access success rate for NB-IoT, will be further explored in Chapter 6.

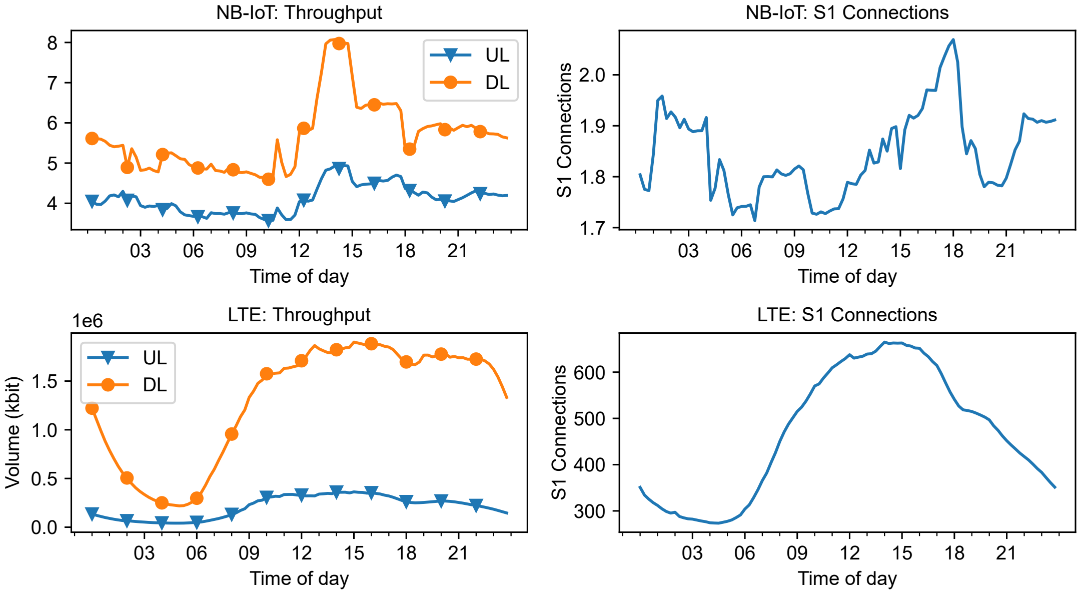


Figure 3.6: Change in data volume and S1 connections over the day for both NB-IoT and LTE, measured nation-wide over the period of a month. LTE shows clearly the hours of activity of the population and the usage of the network. NB-IoT has much more defined peaks in the traffic, but is generally closer to the average.

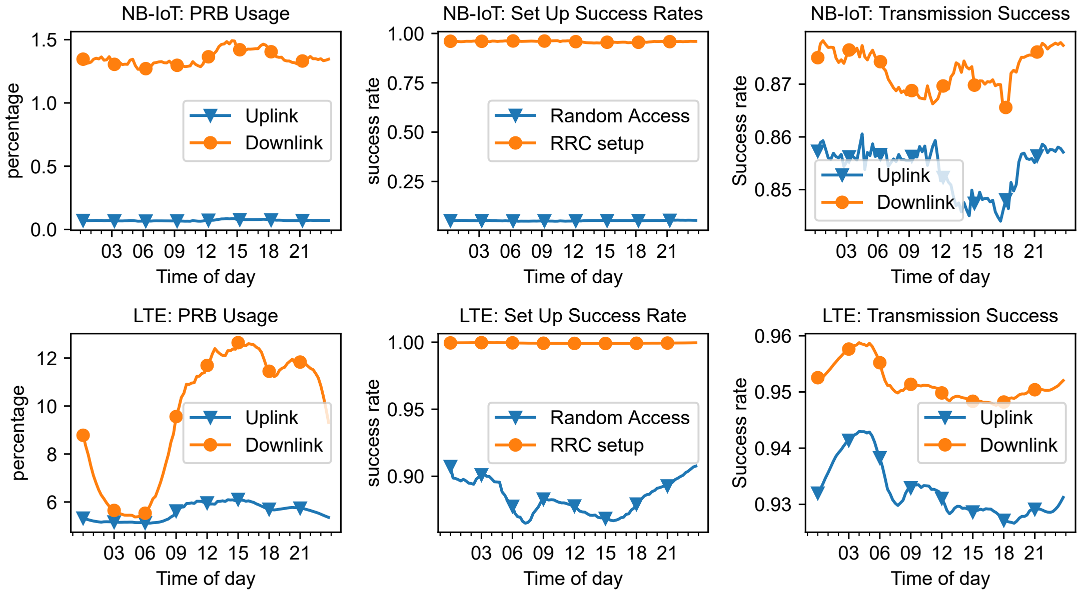


Figure 3.7: Changes in PRB usage and success rates over the day for both NB-IoT and LTE, measured nation-wide over the period of a month. The usage directly correlates with the usage found in the previous plots. During more busy moments the transmission success rate is some what lowered. NB-IoT shows an alarming Random Access success rate. This will be investigated later.

3.4 Summary of Results

This chapter set out to investigate the following question: *What type of traffic is generated by NB-IoT and how is it different from LTE?* With the above results, this question can be answered as follows.

The Usage of the NB-IoT is growing. Steady growth can be noted since the start of 2019. Expectations mostly give a growth factor per year, which is matched and exceeded. However due to the relatively low number of devices, procentual growth only adds a few devices per month. This rather slow growth of modern CIoT is also seen by data from Finnish operators [41]

The average payload size is 0.6 KB. During each connection messages of 64 bytes or 128 bytes were most commonly exchanged, most containing multiple headers and authentication keys. CE allows five percent extra devices to connect from difficult to reach areas. Using this information a good profile can be made of the average usage.

The average period between messages is 16 minutes. This is much higher than what has been expected with most literature. A large set of devices operate on a period of 5 minutes. Devices operating with such a period will have an expected battery lifetime, which is much lower than the advertised 10 year period. However a better measurement method might be needed to better capture the behavior of very low frequency reporting UE.

H2H traffic is uniformly distributed over the day. H2H traffic experiences large changes over the day and can be quite predictable, due to the large number of users. NB-IoT does not have behavior directly linked to the hour of the day. However variances can still be seen, due to the relatively low number of devices.

4

Effects of Coverage Enhancement

This chapter will investigate the effects of path loss on the NB-IoT connection performance. Coverage Enhancement (CE) can be used to improve the success rates of transmissions for devices in low coverage environments such as indoors or underground.

The method that will be executed for these experiments, will first be detailed in Section 4.1. Then the impact of the path loss on the success rates of payload transmission and the set up of the connection will be investigated in Section 4.2. Section 4.3 will focus on what methods are employed to ensure a stable connection. In Section 4.4 the effect of the cell size on the path loss experienced is investigated.

4.1 Path Loss Measurement Method

For the results in this chapter, the distribution of measured path loss values by the eNodeB will be used. These are stored as a histogram in the vectorized counter `pmUlPathlossNbDistr`, which comes from each eNodeB. This distribution will then be compared to various KPIs in the following sections. These KPI can be the success rate of setting up a connection or the probability of a successful data transmission.

The results will be grouped in bins distributed per whole decibels based on the average path loss. This averaging step hides the fact that a single cell can experience a wide distribution of path loss values, but only a single success rate value can be calculated. To solve this the average will be weighted by the inverse of the variance [65]. This will reduce the the impact of cells with a wide distribution and emphasize the results of the cells with values close to the average.

To retrieve the most samples, the data has been gathered from the raw vectorized counters which have a resolution of 15 minutes. All stored data for this collection is used, thus 30 days of data has been used for the following plots.

4.2 Success Rates for Set-up and Data

With increasing path loss, transmission becomes harder as the signal-to-noise ratio will drop. To help decode the transmission CE is used, as this adds more energy per bit. The application of CE is governed by the eNodeB to maintain a target success rate for network use. The following measurements in this section and following sections, look into this algorithm.

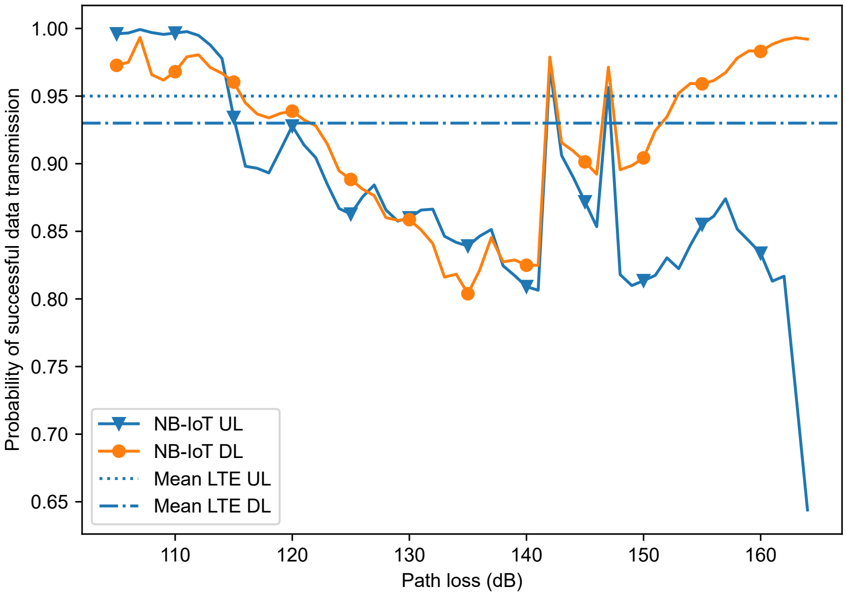


Figure 4.1: Plot showing the average experienced path loss in a cell compared to various success rates and also includes the average success rates for LTE. The plot shows a decline in UL and DL success rate as path loss increases. Acronyms: Long Term Evolution (LTE), uplink (UL) and downlink (DL).

Network use can be divided up into the process of random access, setting up the RRC connection and the up and downlink transmission of the payload. Set up is done with less information on the radio state and thus a different process is used to determine CE. So this section will measure these processes separately.

The counters for the uplink keep a count of successful transmissions and for failed transmissions. Transmissions with BPSK and QPSK are counted separately. The successful transmissions are thus given by the sum of `pmMacHarqUlSuccQpskCe` and `pmMacHarqUlSuccBpskCe`. To get the success rate the successful transmissions are divided by the total number of transmissions. This total is given by the earlier calculated successful transmission summed with the failures, which are retrieved from `pmMacHarqUlFailQpskCe` and `pmMacHarqUlFailBpskCe`.

The downlink only utilizes QPSK, this is due to the fact that the eNodeB can use more energy when transmitting. The successful transmissions are found in `pmMacHarqDlAckQpskCe`, while the failed transmissions are found in `pmMacHarqDlNackQpskCe`. For the success rate the number of successful transmissions is divided by the total of both.

The effects of path loss on transmission can be seen in fig. 4.1. The probability of a successful transmission drops with the path loss. Around 140 dB, Coverage Enhancement will be used to increase the success rate of transmission. Beyond 160 dB the success rate for the uplink drops off. The figure also shows the success rate experienced by LTE on average, which is much higher in most cases.

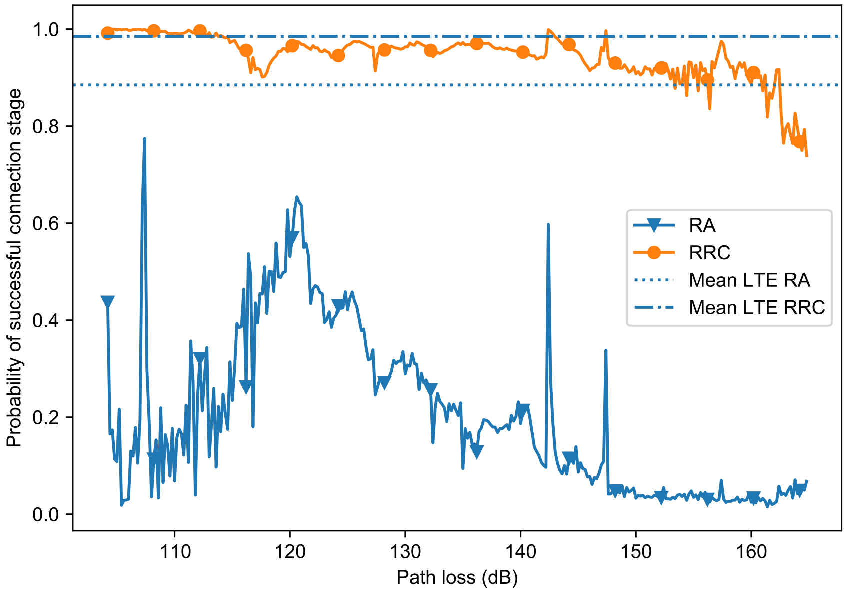


Figure 4.2: Similar plot as in fig. 4.1. This plot shows the success rate during the connection set up. In the best scenario with 120 dB path loss, only 60 success rate is achieved during RA. Both plots contain spikes at the same location. The reason for this is unclear, but these pathloss bins are overrepresented and might correspond to reporting errors. Acronyms: Long Term Evolution (LTE), Random Access (RA) and Radio Resource Control (RRC).

Connection start up consists of a few different steps, as detailed in Chapter 2. For this section two stages of this multi-stage handshake have been picked to represent a part of the set-up. One part with relatively low amount of information about the radio state and a part where more information is available. The first stage is RA contention and shows how often a answer is received to a Msg2. The second selected stage is the set up of the RRC connection, as this is the last step in set up.

The first stage is the ratio between the number of scheduled Msg3 packets and the number of received Msg3 packets. The number of scheduled packets can be found in four different counters that need to be summed: `pmRaMsg3SingleToneDistr`, `pmRaMsg3SixToneDistr`, `pmRaMsg3ThreeToneDistr` and `pmRaMsg3TwelveToneDistr`. The number of received messages is captured by `pmRaSuccNbCbra`.

The success chance for the RRC connection is found by the ratio of successful connections over the number of attempts. The first value is found in the counter `pmRrcConnEstabAttCe` and the second value in the counter `pmRrcConnEstabSuccCe`.

The success rate during set up can be found in fig. 4.2, along with the average values for similar activities in LTE. The RRC setup has a better success rate than the success rate for the uplink and the downlink data transmissions. The setup process is quicker to use higher repetition values for the messages, as a failed message means the entire procedure needs to be restarted. This values also stays relatively flat over the the different path loss values encountered.

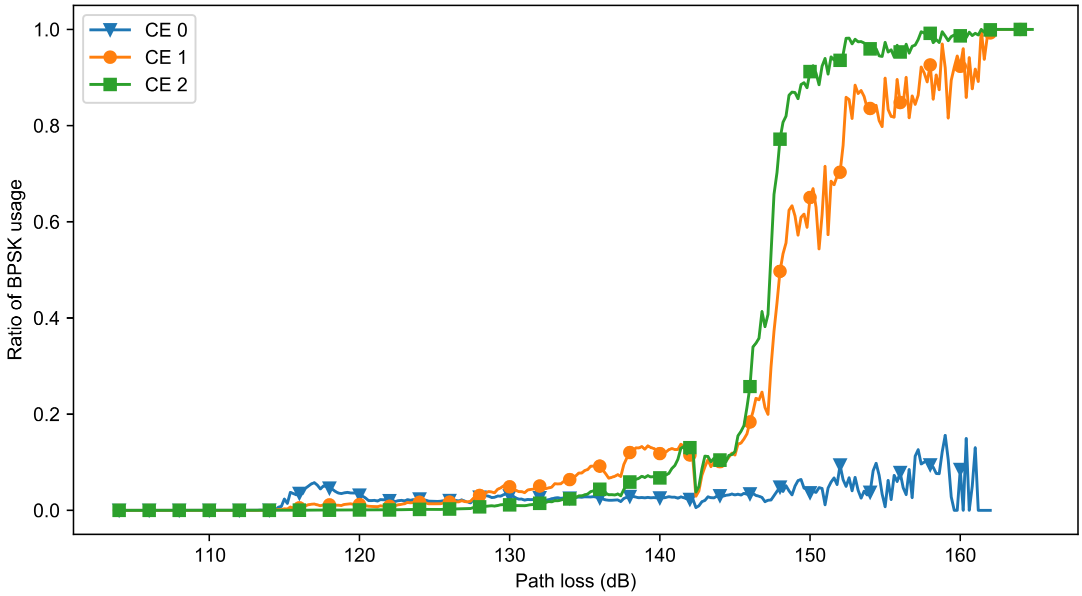


Figure 4.3: Utilization of the lower order modulation BPSK depending on the experienced path loss in the cell. This measured during July over all cells. CE 1 reaches 50 % usage at 148 dB path loss and CE 2 reaches 50 % usage at 147 dB. Devices that do not utilize CE never use BPSK.

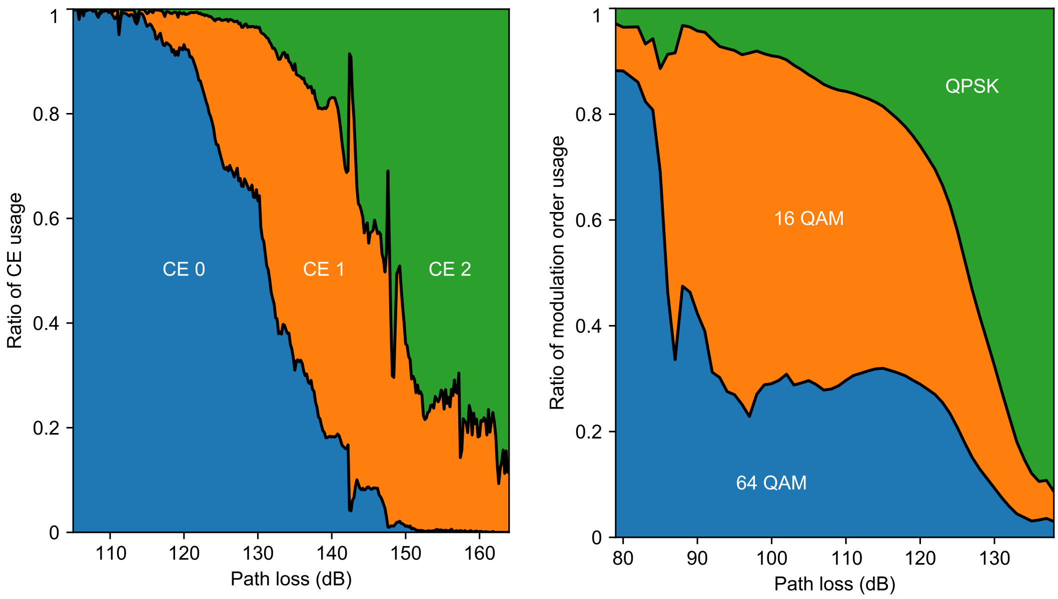
Both plots in figs. 4.1 and 4.2 show spikes at the same locations. The reason for this is not to be found from theory. When looking at how often each bin is represented in the data set, these bins are ten times more popular than their neighboring bins. This might suggest a reporting error.

Figure 4.2 shows that Random Access requires broader discussion later on. It seems that the eNodeB experiences random access procedure failures often. An explanation of this behavior and its mitigation will be given in Chapter 6 and the impact on the capacity of the network will be discussed in Chapter 7.

4.3 Usage of Coverage Enhancement

NB-IoT provides two main methods to increase the coverage. The first being the choice of modulation between QPSK to BPSK in the uplink. The other method is repetition of all transmitted data. Using these methods results in more radio time being needed to transmit messages and more battery usage is experienced [15, 22, 73]. There are no known documents describing the relation between this path loss and the CE used, thus this will be investigated for the VodafoneZiggo network.

Based on the method detailed in Section 4.1, the usage of BPSK can be investigated. To achieve this, we need the know the number of transmissions done using BPSK and QPSK, which can be found in the counters `pmMacHarqUlSuccBpskCe` and `pmMacHarqUlSuccQpskCe` respectively. To find the ratio of BPSK usage the total number of BPSK transmissions is divided by the total using both modulation types.



(a) Usage of CE for NB-IoT.

(b) Usage of modulation in LTE Uplink.

Figure 4.4: Methods to adapt the uplink to trade off capacity for coverage. Data collected over 30 days nationwide. For both LTE and NB-IoT there does not seem to be clear definitions on the utilized CE or modulation.

In fig. 4.3 the relation between the path loss in the uplink and the usage of BPSK can be seen. When the coverage is good, QPSK is used. This will lead to higher bitrates and lower radio utilization. With CE 1, half of devices at 148.2 dB will use BPSK. The transition is fairly sharp. For CE two a similar result can be found, however half of the devices is reached at 147.4 dB. The difference between the two is not significant. It is clear that the decision to use BPSK is directly linked to the path loss value.

Unfortunately, the number of repetitions can not directly be found from the counters or from the UE. Most devices do not support commands to retrieve this information and for some this information can only be retrieved via debug ports. Within VodafoneZiggo there are no tools to investigate the repetitions and adjust them.

The closest information is the CE level, where every level corresponds to a different set of allowed repetition counts. For the distribution of Coverage Enhancement the number of S1 connections per CE is recorded. This is possible due to the fact that the CE level is established during the RA process. The counter used is `pmS1SigConnEstabSuccCe`.

Figure 4.4a shows the relation between the path loss and the CE. There is no distinct point at which CE is switched, but it happens more gradually. The CE is determined by the success rate during the attachment process, subsequent data transmissions and not specifically by the path loss experienced.

The process of picking a modulation order or coding scheme is done in most modern radio systems. During this section a comparison will be made between the selection of CE with the modulation selection in LTE. LTE is mostly meant to have high throughput, which is also reflected in the various choices of QAM. The LTE counters for 64-QAM `pmMacHarqUlSucc64Qam`, 16-QAM `pmMacHarqUlSucc16Qam` and QPSK `pmMacHarqUlSuccQpsk` all store the number of successful transmissions and are used to determine the distribution of usage.

The distribution of modulation for the LTE uplink is shown in fig. 4.4b. This shows a similar relation between path loss and chosen modulation as with NB-IoT in fig. 4.4a The modulation index is chosen based on the experienced success rate and the device type. The modulation index is generally less important for the user, as the only key metric for the user is the throughput and the latency.

4.4 Effects of Cell Size on Path Loss

The placement of a device, together with its surroundings determine the experienced path loss. Path loss measurement campaigns are abundant [33, 77, 93], however the quantity of data is key. A maritime study can be found in [102], however this lacks macro scale testing as does most current research. A recent study has already found that the utilization of existing infrastructure leads to good coverage [61]. The following experiment will validate this result from the position of the MNO instead of the user.

For this experiment the cells have been grouped according to the distance towards the next cell. For larger cell size, larger bins were used to aggregate data from more cells.
The x-axis shows this grouping of cells. The y-axis shows the path loss values. Every data point is normalized over all path loss occurrences in the cell size bin. The data used for this has been gathered from all cells over a period of 100 days.

Based on the data from these measurements a log-distance model can be fitted, similarly as in the maritime study [102]. This follows the form:

$$PL = PL_0 + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) \tag{4.1}$$

This formula takes the distance between the UE and the eNodeB. For this, an approximation is needed for the average device in the cell. This can be done in a two step method. First the border of a cell needs to be found. This can be modeled as $\frac{1}{\sqrt{2}}$ of the ISD. Then the average position of the UE within the cell can also be approximated as $\frac{1}{\sqrt{2}}$ of the cell border. With this approximated distance between UE and eNodeB the parameters of the formula can be recovered trivially using least squares.

fig. 4.5 shows the result of this aggregation and the fitting of this function. The density and the fitted model show that the cell size has next to no effect on the experienced path loss. This can easily be explained by the fact that NB-IoT was deployed on a network of cells, that was already optimized for coverage over the entire country. It can also be seen from the map of cells that cells are nearer to each other in cities, where buildings increase the path loss values. The result is similar to what was found in the previous research cited [61]. The exponent recovered is much lower than the more commonly found values that range from two till five.

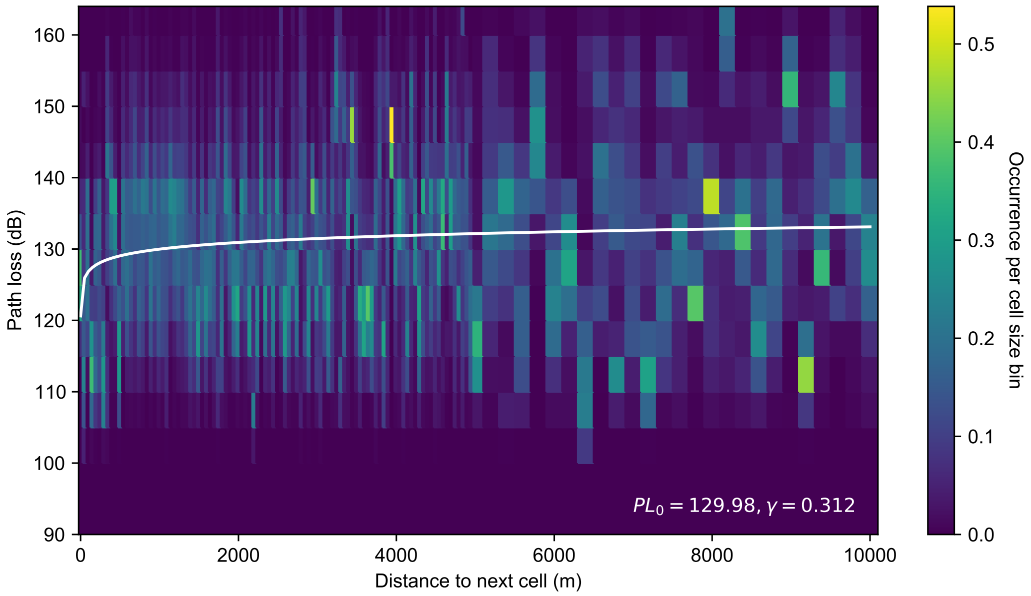


Figure 4.5: Effect of cell size on path loss in the uplink. The plot shows a marginal shift in the distribution of path loss when using larger cells. Data from July. Distance bins close to 10 km, are wider as less cells are in these bins. It can be expected that all cells will generally have similar measured path loss distributions. A path loss formula has been fitted, to find a very low exponent value of 0.3.

4.5 Summary of Results

This chapter results have been gathered in order to answer the following question: *Does CE provide additional coverage, and what techniques are used?*

CE provides reliable data transmission. Figure 4.1 shows that transmission success rates are kept above 80 % until 160 dB. The success rate for the uplink does fall to 65 % when the path loss worsens to 164 dB.

Random Access has a low success rate. This section also discovered issues in the RA procedure, as in fig. 4.2 it could be seen that the random access success rate was generally very low. In Chapter 6 this will be investigated further.

It is unclear when CE is used. The second section uncovered information on when BPSK is used for transmissions. Around 147 dB the switch is made when using CE. Harder to find are the exact rules on the repetition values, as these are not directly related to the CE. Furthermore, from fig. 4.4a no clear relation between the CE and the path loss could be derived.

Coverage is plentiful in the Netherlands. Lastly the relation between cell size and average experienced path loss was investigated. The same conclusion as a paper from the summer of 2020 could be drawn [61]. Due to the deployment of NB-IoT on existing LTE hardware coverage was well planned. This is caused due to the higher density of cells in cities, which pose a more difficult radio environment. The reverse is also true as there is a lower density of cells in rural areas, which contain few obstacles.

5

Characterizing Usage

Data connectivity via LTE has become an integral part of life for many. People have autonomy in choosing how their LTE device operates and when data is being used, however generally people have similar times at which they work, hold breaks and sleep. These different activities will have an impact on the usage of the smartphone and also the utilization of the network.

NB-IoT on the other hand is primarily used for sensors and actuators, and devices often have tasks which include periodic reporting or communicating warnings. This is often not influenced by the time of the day, but by the policies created by the companies using NB-IoT. These behaviors will be explored further in this chapter based on a Machine Learning approach.

First, in Section 5.1 a report will be shown on the distribution of devices over the Netherlands. Section 5.2 will be featuring an investigation on grouping cells based on similar usage patterns. Following this in Section 5.3 the validity of the Poisson model for traffic models is tested. Finally, a Markov based model will be tested in Section 5.4.

5.1 Spatial Distribution of Devices

The process of the placement of sites is a two phase process. To reduce Capital Expenditure (CAPEX) operators can not infinitely place towers and have to measure the usage and interest. The first part will consist of placing cell towers to provide coverage over the area such that a sufficient portion of the population can be served [38]. The second part primarily consists of enhancing existing sites, by adding extra cells. Another method used in the final part is acquiring and constructing new sites.

Currently, the LTE network has existed for a long period and occasionally additional sites are created to match the growing usage. The location of NB-IoT sites are not based on the current distribution UE or interest. This is due to fact that they are deployed on top of all existing LTE 800 MHz cells.

The distribution of LTE UEs over the LTE cells can be expected to be quite even. This is due to two different phenomena. The first being that areas with a lower amount of users, will have correspondingly a lower amount of cells. On the other side in busy areas, the load can be actively distributed over multiple cells. This load sharing is possible due to handovers between cells.

Unfortunately handovers and load sharing are not possible in NB-IoT, as this feature is removed. NB-IoT devices are often not linked to the population, but to projects ran by companies. The distribution of devices over the cells can be different. By analyzing the difference in the distributions and the room possible for growth, we can validate the current approach of piggybacking all NB-IoT cells on LTE 800 MHz cells.

To investigate the differences in the distribution of the devices over the cells for the different RATs, we will utilize the number of S1 connections. This value will be recorded per cell and per RAT during July 2020. From this data, the Cumulative Distribution Function (CDF) of the usage for a tower can be generated.
In Chapter 7 simulations will be created to investigate the capacity. To simplify these simulations the CDF can be approximated using a two-parameter distributions. This section will find the best suited CDF out of a selection of three.

The Probability Density Function (PDF) of the Gamma distribution is given by the following:

$$f(x;k,\theta) = \frac{x^{k-1}e^{-\frac{x}{\theta}}}{\theta^k\Gamma(k)} \quad \text{for } x > 0 \text{ and } k,\theta > 0. \tag{5.1}$$

The PDF of the Weibull distribution is given by the following function:

$$f(x;k,\lambda) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} \mathrm{e}^{-(x/\lambda)^k} & x \geq 0, \\ 0 & x < 0. \end{cases} \tag{5.2}$$

The two above mentioned distributions are both generalizations of the exponential distribution function. Thus the parameters describe similar effects. The k value denotes the shape of the distribution. The θ or λ show the scale of the distribution. Finally, the x value is used to select the index of the eNodeB.

The PDF of the Zipf-MandelBrot distribution is given by the following expression:

$$f(x;N,q,s) = \frac{1/(x+q)^s}{H_{N,q,s}} \quad \text{, where} \quad H_{N,q,s} = \sum_{i=i}^{N} \frac{1}{(i+q)^s}, \tag{5.3}$$

The Zipf-Mandelbrot distribution is a generalization of the power law distribution. In the formula the N denotes the number of items, which in this case is the number of cells. There are two parameters which define the shape of the CDF. The first being the q which defines the plateau of the distribution and s, the power factor and defines the slope of the function.

The result can be seen in fig. 5.1 for NB-IoT and for LTE on 800 MHz during July 2020. The measured distribution was also fitted to the three different distribution functions. The fitting of these functions was achieved using the `curve_fit` function from the scipy library [116]. The fit is evaluated by calculating the sum of the squared error. In the legend of the plot, the parameters found and the total squared error can be found.

Based on the square error it can be determined that the most suitable function to show the current distribution of NB-IoT devices is the Weibull distribution. As this has a error of 0.1 and this same distribution has the second best fit with LTE. It becomes evident that distributions based on the exponential distribution are well suited to reduce the error.

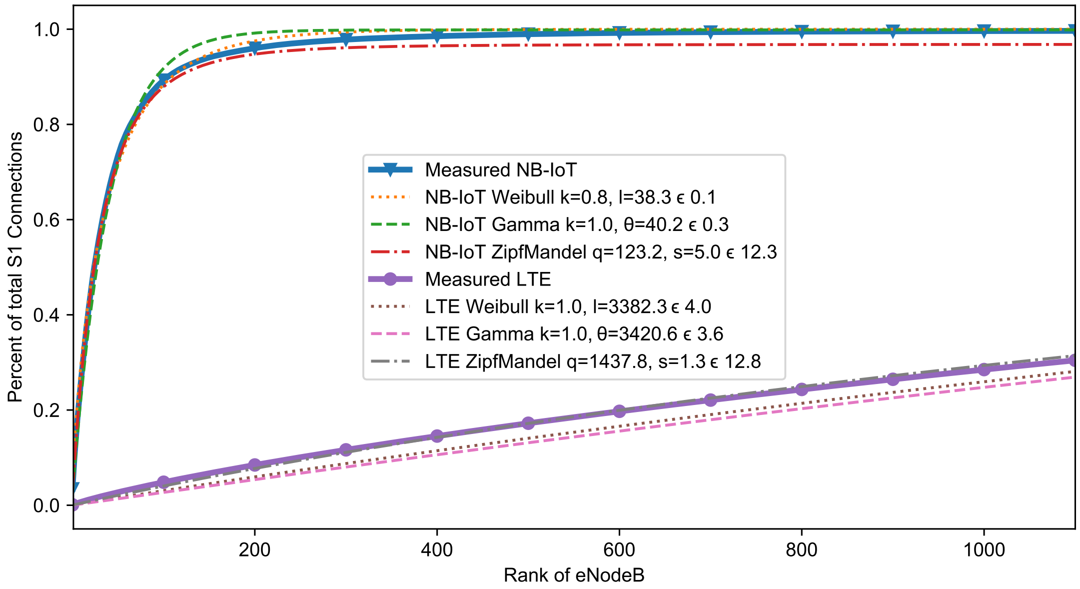


Figure 5.1: This plot shows the distribution of S1 connections over the network, where the eNodeBs are sorted by number of S1 connections and the rank is the index. Few cells generate most of the S1 connections, measured during July 2020. NB-IoT has a very skewed distribution with a Zipf-Mandelbrot k-factor of 5.7, while LTE is spread more evenly with a factor of 1.3. This signifies that a lot of NB-IoT cells are unused.

However the Zipf-Mandelbrot distribution can also be used, as the scale s parameter behaves better. This is due to the fact that the uniform distribution can be simulated using the value zero, which the other distributions can not.

From the figure, it can be inferred that NB-IoT is currently centered around a few cells as there is a the sharp rise of cumulative connections of NB-IoT. This means that a significant portion of traffic can be analyzed with data from fewer than all cells.

At the moment of measurement 95 % of all S1 connections for NB-IoT can be attributed to the 175 most used cells and half of all traffic is generated in just 25 cells. For comparison LTE the necessary number of cells are 2350 and 9348 respectively. This uneven usage of cells can lead to growth issues, which will be further investigated in Chapter 7.

5.2 Grouping of Cells

Earlier research has shown that the traffic patterns within an LTE cell can be used to determine the type of district the cell is in [117]. Inversely, the type of district could also be used to estimate the behavior. This can be useful during the design of network changes.

However, NB-IoT is generally not determined by the behavior of people but by companies. IoT creates similar patterns which are either localized to specific areas or spread out over the entire country. Overlapping traffic patterns that have similar transmit times can create issues long before the total capacity is reached [124]. Therefore, we will analyze similarity between cells in the generation of traffic in the VodafoneZiggo network.

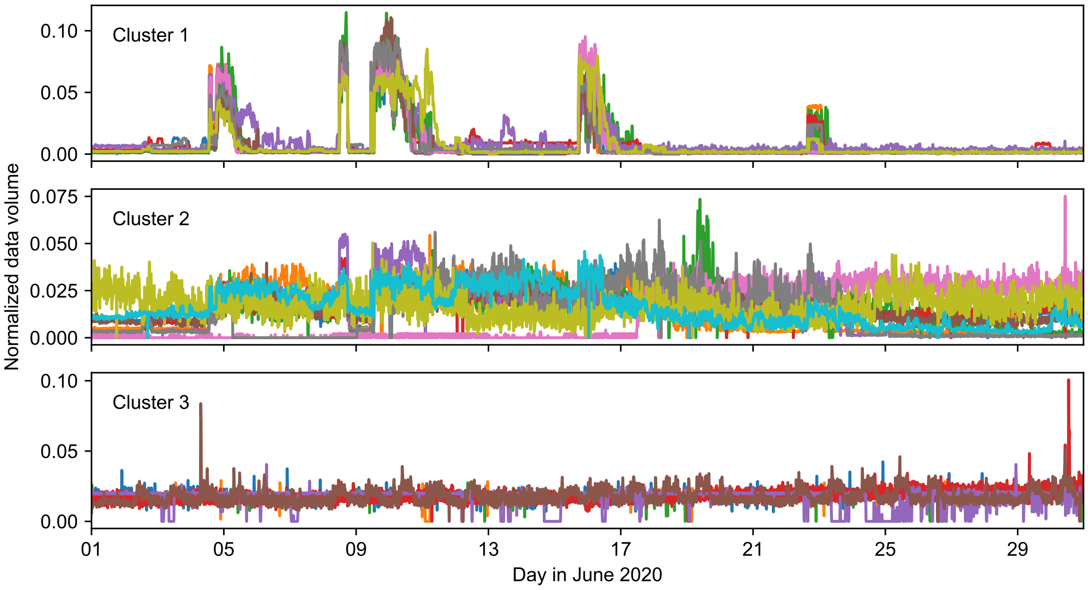


Figure 5.2: Clustering of cells based on similar frequency domain signals, shows three different groupings of similar projects during June 2020. Each line shows the data volume of a grouped cell. The first cluster shows cells which are highly impacted by firmware updates. The second cluster shows cells that operate sporadically and each cell is active during different weeks. The third cluster shows cell exhibiting a more uniform utilization.

In the machine learning world the notion of grouping unlabeled data is called clustering and is what we will be doing in this section. From the 50 most used cells the number of S1 connections and data volume per 15 minutes for June 2020 will be used to group similarly behaving cells. This selection of 50 cells is used to ensure enough devices are connected to make meaningful conclusions. A technique based on the work in [117] will be used, however the following changes will be made to better fit the nature of M2M cells.

The first step in any clustering process is to define a function which shows the distance or dissimilarity between two different cells. The second and last step is to choose an algorithm which applies this distance metric to build up groupings of similar nodes.

Most IoT devices have dominant timer-driven peaks [41] due to the prevalent use case of periodic reporting. Thus, it is important to create a distance function that takes this into consideration. To do this the vector of number of S1 connections per 15 minutes is transformed into the frequency domain using the Fast Fourier Transform (FFT). This vector in the frequency domain, will be the vector with all the features.

From the vector of features we need to move to a distance value between cells. To do this the correlation between the two different frequency domain vectors is taken. From this we receive a measure of similarity from -1 until 1, where 1 means completely similar. However, a value is needed that is zero when the vectors are the same and higher when the vectors are different. Thus the distance is to be taken as one minus the correlation.

Many different algorithms exist to cluster based on distances. For this specific experiment a clustering algorithm is needed that also takes into account that there might be cells that do not belong to a cluster. Thus, the selection of possible algorithms reduces to either DBSCAN

[103] or OPTICS [17]. The latter was chosen due to the fact that fewer parameters need to be hand tuned. The implementation of the algorithm was provided by scikit-learn [94] and more information can be found on `OPTICS`.

The results of this clustering process can be seen in fig. 5.2, where three clusters are shown with their respective traffic pattern for June 2020. The first cluster probably shows a group of cells that were used to update the firmware of smart meters for gas and electricity, as learned from discussions within VodafoneZigo. The second cluster is mode difficult to explain. The middle cluster shows NB-IoT devices where the volume fluctuates slowly over the weeks. This might be due to devices moving in and out of the range of the cells. The third cluster has an exceptionally uniform connection rate over the month.

Further improvements in clustering will mostly be found in the kernel. The kernel is the function that takes the raw data and transforms it into vectors from which a dissimilarity value or pairwise distance value can be taken. More information on the time of the day should also be included, as messages tend to be generated at similar moments in the day and not only at similar intervals.

5.3 Validity of Poisson Modeling

Network traffic is often modeled as a Poisson process [82, 88]. This results in simple algebraic solutions. The Poisson traffic model assumption for NB-IoT might hold true when the behavior of a very large pool of devices are summed that behave independently. However, currently there are still relatively few devices on the network.

There are two more issues that might have an impact on the validity of a Poisson process assumption. Firstly, the load needs to be investigated as individual cells only, as there are no handovers to distribute UEs over nearby eNodeBs. This creates the first issue, as even fewer devices operate per cell. Secondly, device behavior is often not uniform over the day. As there are often set moments on the day that are used for reporting.

To check the validity of a Poisson model, the index of dispersion can be used [44]. For this analysis, we have used traffic from the 250 most used cells for both NB-IoT and LTE from July 2020.

The index of dispersion is given by the variance over the mean of the signal under investigation. When the index of dispersion is close to one, the underlying process can be modeled as a Poisson process. When the index of dispersion is lower than one, the set can be called underdispersed and acts even more uniformly than a Poisson process. This index of dispersion is calculated for each cell and the input vector for each cell is the number of S1 connections aggregated per 15 minutes.

$$IoD = \frac{E[X]}{\mathrm{Var}[X]}. \tag{5.4}$$

The results are presented in fig. 5.3 in a logarithmic plot. The dot in the middle denotes the average values and the lines cover 80 % of all cells. The crosses denote the highest and the lowest value found. These are displayed for the number of connections and the data volume for both NB-IoT and LTE.

For LTE, the data volume and S1 connections are highly overdispersed, which is to be expected due to the day and night cycle. When investigating NB-IoT, some cell towers were found that do experience Poisson-like traffic or underdispersed traffic. However, it can clearly be seen that most cells have a index of dispersion much larger than one. NB-IoT generally has a lower

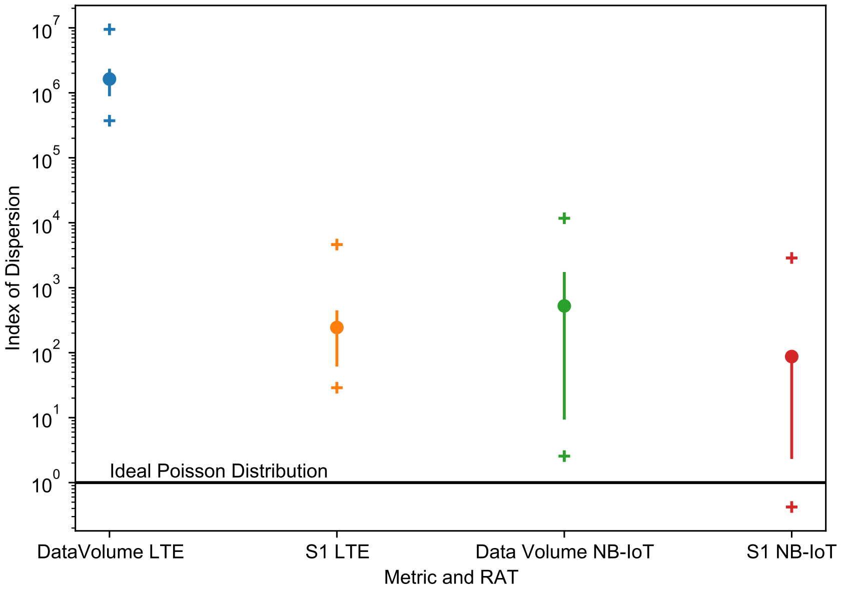


Figure 5.3: Index of dispersion of S1 connections, which shows the accuracy of a Poisson model. Data gathered during the July 2020 for the 250 most used cells. The dot shows the average, the line denotes the region in which 80 % of cells operate and the pluses the out most values. Most cells can not be modeled using a Poisson model.

index of dispersion than LTE. However, this plot also shows that this method is not well suited for both RATs.

5.4 Modeling Firmware Updates

The previous section showed that IoT traffic could not be modeled using a Poisson process per cell. Thus, a more sophisticated model is needed to describe the traffic patterns. From fig. 3.6, we found that there are different states, that a group of UEs could be in. This section sets out to identify the differences between these states and how often these change. These can then be used to better anticipate future peaks in the network. This information will also be used in Chapter 7 to model the impact of simultaneous firmware updates.

The process of labeling data can still be seen as a clustering or unsupervised machine learning task. However, we do have the knowledge of the sequences and the previous state, thus it seems logical to incorporate a Markov Model in the clustering model. Luckily, this has already been created and is called Hidden Markov Models (HMMs) [97] and has been used previously for similar tasks [25, 67].

The HMM consists of two different parts. The first being a Markov model to simulate the transitions between different states. This has previously been used for LTE traffic modeling [111]. These transitions of the Markov model contain information on the average time spent in each state and how often a state is reached. The second part of the HMM is a Gaussian model for each state that describes the behavior in that state.

These factors make HMM a method that is easier to interpret [62]. Which allows for a more

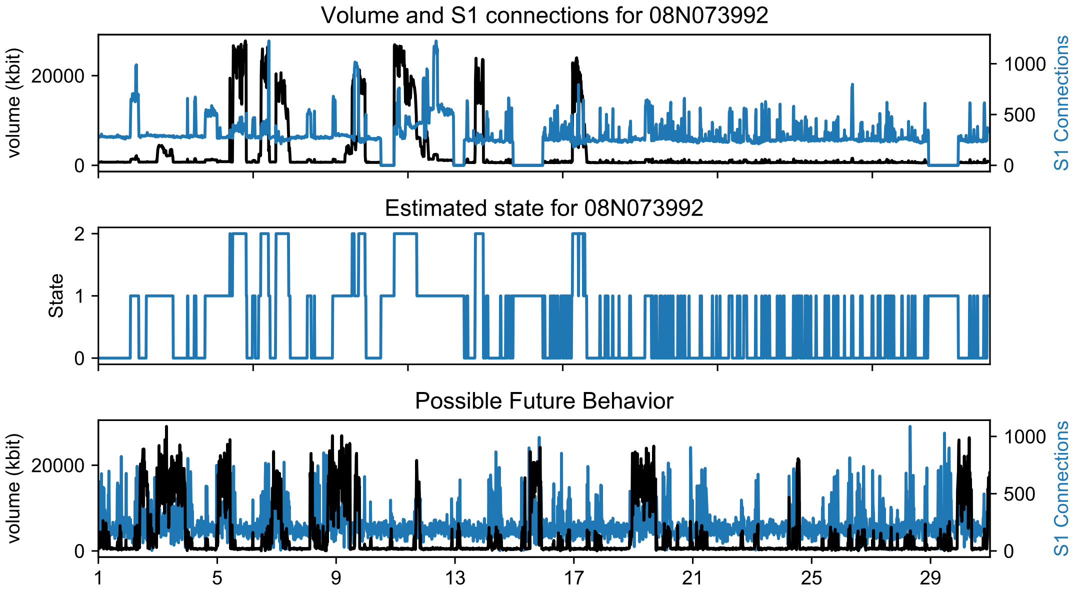


Figure 5.4: HMM model trained on different smart meter cells, used to predict the state and create a similar traffic pattern. Traces used were from June 2020. This plot shows the prediction of state and a potential realization of the traffic for cell `08N073992`. State two accurately depicts the moments that a firmware update happens, state one denotes a slightly higher than normal amount of S1 connections and volume and state one shows the normal state.

detailed simulation of the average traffic and outliers for each state. Training and estimating states is accomplished using the hmmlearn library [53].

In Section 5.2 a group of eight cells has been found which have large firmware updates during June. The data and S1 connections have been recorded and stored, similar to in Section 5.3. The model can then be created from these activity traces. In this analysis, the model has been trained on seven out of the eight cells. This model can then have two different uses.

The first is the possibility to recognize state changes on current measurements. This is often interesting to know and can be used to automatically provision the right resources. The second use is to create a possible realization of the signal. This predicted trace is not a prediction, however can still be used for more accurate modeling.

The results of this can be found in fig. 5.4, where the trained model predicts the state and shows a potential realization for cell `08N073992`. The top plot shows the behavior of the test cell which has been kept from the training set during June 2020. The moments when firmware updates happen can clearly be seen, as the volume per fifteen minutes rises sharply.

The middle plot shows the prediction of which state the device is in. The state zero applies when the default behavior is shown. The state one applies when slightly less S1 connections are being made. The state two shows when firmware updates happen. Due to the nature of clustering unlabeled data, it is quite hard to verify the correctness.

Finally, the bottom plot uses the HMM to show a potential realization of the behavior of the cell in the future. Important lessons can be learned from such a model are the difference in data volume transmitted in different state. We can also learn how often these state changes happen.

5.5 Summary of Results

This chapter explored different methods to model the behavior of UEs connected to the same cell and tried to to answer the following question: *Can NB-IoT usage be characterized and grouped based on traffic patterns?* The answer to this question can be summarized as follows.

25 cells currently serve half of all NB-IoT UEs. The H2H network has evolved over the past two decades to fit the needed capacity for the density distribution of the Dutch population. However, M2M devices are currently mostly situated around a few differently located cells and traffic is not shared with other cells. Since the NB-IoT cells are linked to the LTE cells optimizing for capacity for both RATs will be challenging.

Dominant NB-IoT projects can be recognized. Using the traffic patterns found at different cells, large projects can be recognized using a clustering approach based on machine learning. From our measurements and analysis we found that in the context of VodafoneZiggo network, that there is one dominant traffic generating set of NB-IoT UEs on a group of eight cells.

M2M traffic can be modeled using Hidden Markov Models. We have shown that traffic at a single cell can not be modeled using a Poisson process. A better option to model NB-IoT UE behavior per cell is by using HMM. This captures not just the average behavior, but also how often from this default behavior is deviated.

6

Impact of Random Access

In Section 4.2 we found that the RA procedure has a low success rate as seen from the eNodeB. This chapter will dive into the specifics of the procedure to determine the cause of this problem and how to solve it.

6.1 Random Access Success Rate

In fig. 4.2 we have shown that RA is not working correctly during the set up of a connection. We will take a look at the counter values that corresponds to each stage in the handshake. These value will give a perspective on how the eNodeB experiences the connection process. Effects measured by the eNodeB might not be experienced by the noticed by the UE.

There are five important steps for which the chances that the next step are taken can be measured.

1. A RAP is received and needs to be scheduled by the eNodeB for a Msg2. To measure this, the ratio between the counters for the number of transmitted Msg2 `pmRaMsg2AttCbra` and the number of detected RA attempts `pmRaAttCbra` will be used.
2. The reply with the Msg3 to the Msg2. The counter that stores the successful receptions of Msg3 is `pmRaSuccCbra` and this will be compared to the number of scheduled contention messages from `pmRaMsg2AttCbra`.
3. RRC connection start upon successful reception of Msg3. To find the number of RRC connection attempts counter `pmRrcConnEstabAtt` will be used and divided by the number of successful RA procedures from `pmRaSuccCbra`.
4. Completing the process of RRC connection. The number of successful finishes of the RRC connection set up will be divided by the number of attempts, which can be found in counters, `pmRrcConnEstabSucc` and `pmRrcConnEstabAtt` respectively.
5. The process of setting up the S1 connection and finalizing it. To investigate this, the start and finish of the S1 connection set up are needed and these can be found in the following two counters, `pmS1SigConnEstabSucc` and `pmRrcConnEstabSucc`.

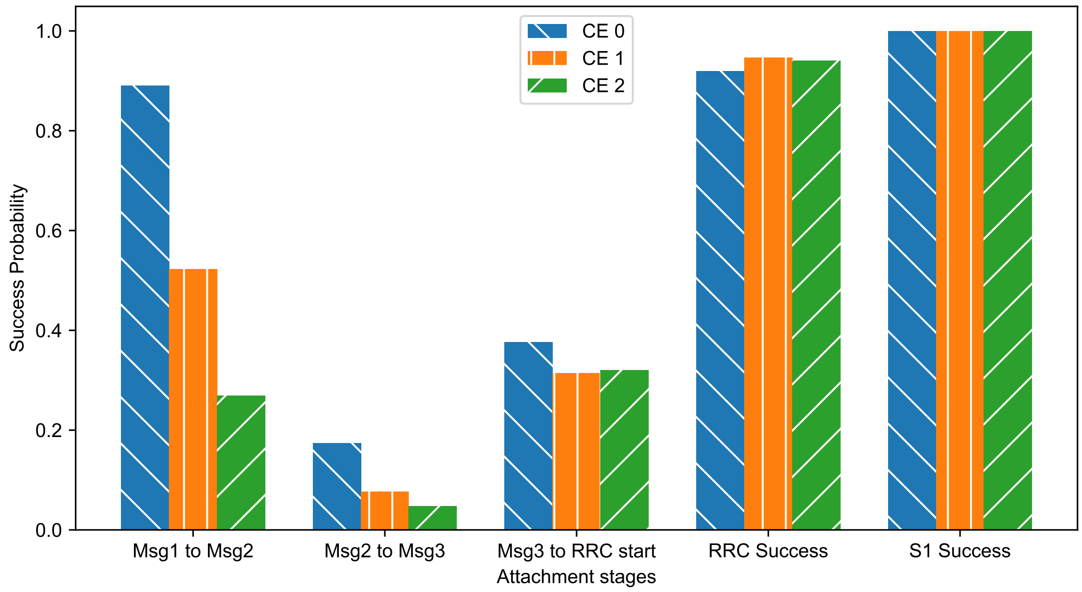


Figure 6.1: Dissection of attachment to eNodeB success rates based on data gathered during June 2020 nation wide. The first three stages have a significantly low success rate and are also heavily impacted by the CE level. The last two stages show acceptable success rates. Acronyms used: Random Access Preamble (Msg1), Random Access Answer (Msg2), RRC Connection Request and Contention Resolution (Msg3), Radio Resource Control (RRC) and Interface between eNodeB and MME (S1).

These five different stages in the connection can be reviewed in fig. 6.1 per CE level. The first three stages each exhibit very low success rates and show worse results when higher CE is used. These stages will be further discussed in the next section. The fourth stage resembles the average success rate of data transmission and thus performs as expected. The fifth grouping shows the S1 connection results, these should generally not fail due to the fact that this is only core network traffic.

6.2 Correlations Between eNodeB in Random Access

The Netherlands is densely packed with cells. Thus, with a high MAPL due to CE a single UE can interfere with the reception of many other cells. When there are not enough measures taken to distinguish transmissions for different cells, this can lead to issues where multiple cells respond. To investigate these issues a match need to be found between the received RAP at different eNodeBs and the actual devices wanting to connect.

The simplest method for investigating this behavior would include core network logs and extensive logs from the eNodeB. This would allow attempts to be grouped based on their arrival times and proximity. On top of this the intended recipient could be determined. As discussed in Section 2.3 the tools in place during the beginning of 2020 would not allow for such large-scale data analysis. Thus, a different method needed to be developed.

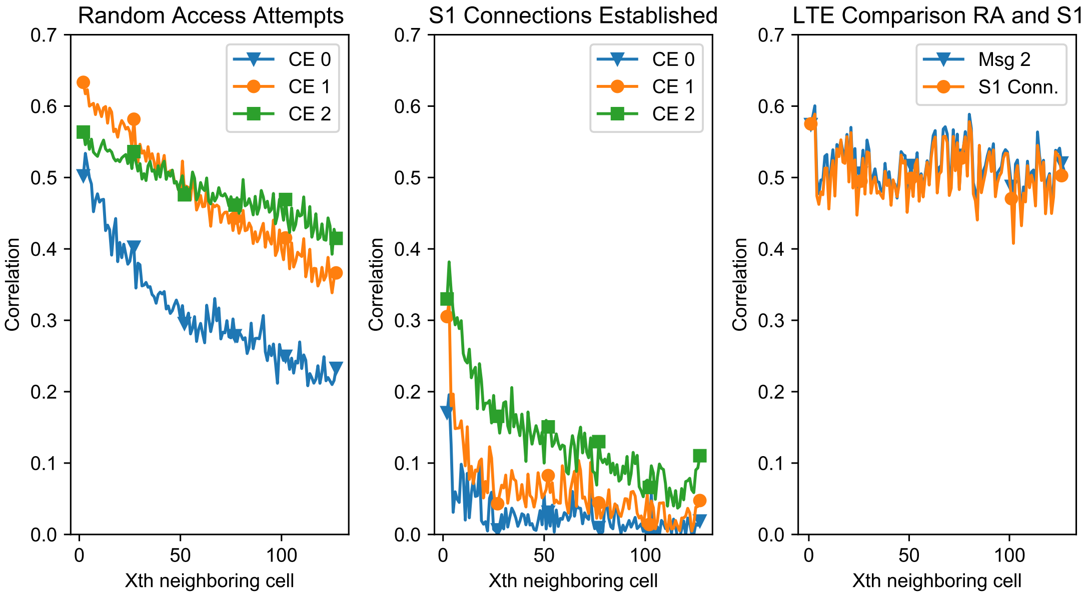


Figure 6.2: Correlation between traffic patterns for nearby cells. The left-most plot shows the correlation in RA attempts per CE. The center plot the correlations in successful S1 connections per CE. The right-most figure shows the correlation for S1 and for RAP for LTE. As expected the difference between RA and S1 is almost negligible for LTE. NB-IoT does show a larger shared amount of RA traffic than of shared S1 connections. The decrease in correlation does show that location is a factor.

The method used in this thesis is based on correlations between access patterns. If a group of UE in a cell have a specific pattern of traffic, then this same pattern would be detected by multiple cells that share the same parameters for their NPRACH scheduling. Overlapping RAP will cause the arrivals to have similar patterns, as they reach the same cells. The number of valid connections can be measured by the number of S1 connections, as it can be assumed that a device retries until a successful attachment to the network.

For this investigation, the 50 most popular cells and their traffic patterns are compared with their neighboring cells. The most popular cells are selected based on the number of S1 connections in June 2020. The next step is to find 100 cells which are situated in the right direction from the location of the site. This directionality is included to take into accounts the effects of sectorization where cells only cover certain directions. The cells are then ordered based on their distance.

The correlation between traffic will be based on the number of successful S1 connections using the counter `pmS1SigConnEstabSucc`. For the correlation between the random access attempts the counter `pmRaAttCbra` will be used. Finally, the average is taken to create a plot that shows the change in correlation as the distance increases between the popular cells and the neighboring cells.

Figure 6.2 shows the average correlation between cells for the S1 connections and the received RAPs. The x-axis denotes the number of other cells between the two cells that are being compared. The y-axis shows the average correlation between the cells. We observe that S1 connections are not correlated over cells that are further away. This can be attributed to smaller projects and that devices behave independently. However, RAPs are more strongly correlated even if there are 120 cells in between. This shows that random access has widespread impact on surrounding cells, especially on higher CE levels.

The figure also shows the same analysis for LTE. We observe that LTE traffic patterns are more similar over different cells. LTE traffic is more governed by human behavior [127]. The gap between S1 connections and random access attempts is much smaller, which is expected as the success rate for the entire random access process is much higher. This is what a functioning network should look like.

6.3 Suspected Reason of Abnormal RA Impact

What can be seen in fig. 6.1 is that there are three stages at which the eNodeB experiences failures.

- The failure to respond to a RAP
- Devices failing to respond to the second message
- The failure to start the RRC procedure.

An interesting observation is that all these conversion rates are worse for higher CE levels.

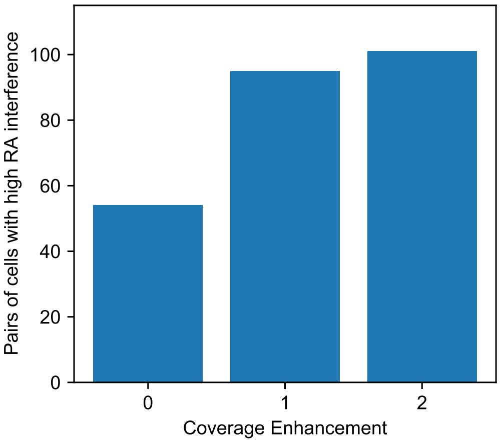
Let us first briefly recall the RA procedure. Each cell dedicates some time in the uplink channel for the NPRACH in which multiple RAP opportunities are created. The start time, periodicity and duration are used to denote a time slot. Furthermore, it is possible to define which sub carriers are used for which CE level. A UE listens for the MIB and SIBs which are broadcast to learn these parameters, then it picks one RAP. Due to improper planning it can happen that a UE can pick a RAP that belongs to multiple cells that are in the vicinity.

There are two reasons why a eNodeB would not respond to a RAP. The first being that the cell is overloaded, however this should not be the case at the moment for most NB-IoT cells.

The second reason is that the UE is outside the configured maximum cell range. At the moment this is a fixed number for all cells, more than double the size of even the largest cells. This cell range is currently under investigation at VodafoneZiggo. Due to the extended coverage there is a higher probability that cells can still receive RAP from outside of this cell range.

From fig. 6.2 it could be seen that the with high CE many cells could be reached. Looking at LTE , power control enables the device to only reach a handful of nearby cells, which greatly reduces the need for Random Access planning [9]. The number of received RAP is generally not detrimental to performance. If there is a collision with a device in range, the eNodeB will continue the procedure and schedule a Msg3. This costs extra radio resources, however the UE will not be negatively impacted.

Comparing the number of scheduled Msg3s and the amount of received Msg3s, all UEs are within cell range. However, this can still mean that there can be many of such cells. It turns out that on average twenty cells respond to a single random access attempt when CE 2 is used. This can cause an enormous PRB overhead, as will be discussed in Chapter 7. Better RA planning can solve this issue, however this is no small task. Specific mitigations could not be



(a) 250 pairs with highest gap between Msg2 and S1 correlations categorized by CE. We see that the higher the CE, the more worst pairs are visible. Note that the higher the CE, the lower the amount of traffic sent (see fig. 3.5).

Distance between pair			Correlation type	
Cells	km	CE	Msg2	S1
4	1.8	1	0,99	0,05
13	1.8	0	0,97	0,01
4	1.8	2	0,94	0,01
111	5.2	1	0,92	0,08
53	4.2	1	0,91	-0,10
2	0.5	1	0,88	0,12
5	4.6	1	0,87	0,16
121	4.0	0	0,86	-0,07
6	1.6	2	0,86	-0,02
4	1.6	2	0,86	-0,02

(b) Example of cells that have highly correlated Msg2 patterns indicating overlapping RAP chosen out of the set of pairs with high usage cells and their 128 neighbors. Interference happens over long distances and with many cells in between, as a pair has 120 different cells between and a different pair has a distance of 5 km between them.

Figure 6.3: Investigation on cell tower pairs that interfere in their RA procedure. The plot on the left shows high correlation gaps for higher CE values. the plot on the right shows the 10 worst offenders and the distance between the cells.

investigated as the implementation details of the planning could not be provided at the time of writing by VodafoneZiggo.

Finally, it became evident in fig. 6.2 that not all received Msg3 result in the start of a RRC connection. The reason behind this could not be found in literature and also not be provided by VodafoneZiggo or Ericsson engineers. This is still an open question at the time of writing and deserves to be investigated further.

6.4 Solution to RA Interference

RA planning is somewhat difficult as radio coverage is not easily modeled and being overly careful reduces capacity. Lately a lot of development has been put into Self Organizing Network s (SONs) to solve these issues [78] and is being applied for LTE planning for VodafoneZiggo. For LTE planning is mostly based on the principle that all neighboring cell pairs are known. However, with NB-IoT the number of reached cells is much larger. Cells with similar settings for RA need to be discovered out of a much larger set.

Another problem with applying SON is that a completely different set of KPI need to be used. With SON most of the attention is put on handovers and interference limitation, which are easy to measure effects. Knowing which pairs interfere in the RA is much harder.

One method to find these similarly configured pairs is to look at the difference between the correlation in Msg2 and S1 connections. As this will allow for changing these parameters to remove possible collisions. This can also be done for different CE methods separately.

The ten cells with the highest correlation on Msg2 can be found in fig. 6.3b, which also show the large variance in distance between these cells. An automated system could take a look into the assigned RA parameters and adjust them to reduce these correlations. This task is too large to do manually as the number of pairs grows near quadratically with the number of cells.

The 250 cells with the highest difference in correlation between Msg2 and S1, can often be attributed to higher CE traffic. This is shown in fig. 6.3a. This underlines the importance of better random access planning for higher CE. The reason behind this is clear, as transmissions with CE have a much greater chance of influencing cells further away and there are less RAP for higher CE values.

6.5 Summary of Results

This chapter investigates the RA procedure of NB-IoT. In particular, this chapter tried to answer the following question: *What impact does the new RA design have on the performance of the NB-IoT network?* We answer this question as follows.

RA planning needs to be improved. There is much to be improved in the RA procedure. Cell ranges and CE usage need to be further optimized to reduce the number of cells that respond to a single UE. Responding to RAP costs PRBs and also cost energy. The influence of this overlap and interference will be further investigated in the next chapter.

UEs experience a low RRC connection success rate. We found that the probability of starting a RRC connection is rather low. An UE can experience a roughly 1 in 3 success rate in setting up a connection, which reduces battery life [121, 126]. This phenomena needs to be further investigated, but this is out of the scope for this thesis.

7

Analysis of Potential Growth

VodafoneZiggo has seen growth in the number of users on the NB-IoT network since 2018, as can be seen in fig. 3.1. The question that will be answered in this chapter is how much further the current technology can scale and how it compares to LTE. To answer the question of scalability, few other issues that have arisen in earlier chapters need to be addressed as well.

The first step in Section 7.1 will be to find the associated cost of several key network actions that are part of network usage. From the cost of different activities, the number of potential M2M devices are estimated for NB-IoT and LTE in Section 7.2. The impact of the repetitions for CE will be investigated in Section 7.3. The next step in Section 7.4 is to investigate the number of supported devices when the UEs are spread better over the cells. This will be followed in Section 7.5 by an investigation on the impact of firmware updates and the potential maximum throughput of a cell. With each of these measurements, thus chapter will give some insight on the future of NB-IoT and how this can be improved.

7.1 Radio Resource Usage

The first step to finding the capacity of the network is to find out how much PRBs different network activities consume. The set of actions that will be used are Msg2, S1 connections, uplink and downlink transmissions (measured in kilobit). The cost of these actions will be measured in terms of percentage of available PRBs. The number of connections and the data volume are the fundamental metrics of any communications system, while the Msg2 represents the RA procedure. The RA procedure needs extra attention due to the high failure rate.

The percentage of available uplink PRBs in the NPUSCH can be found in the vectorized counter `pmNpuschUtilDistr`. The information on the available PRBs in the downlink can be found split over the counters `pmNpdcchCceUtil` and `pmNpdschUtilDistr`, as both the NPDCCH and the NPDSCH are used for messaging and thus need to be summed for total usage. The number of Msg2 transmitted, S1 connections set up, upload volume and download volume can be found in `pmRaMsg2AttNbCbra`, `pmS1SigConnEstabSuccCe`, `pmRadioThpVolUlCe` and `pmRadioThpVolDlCe`, respectively.

`pmNpuschUtilDistr` and the other channel usage counters behave slightly different than in the specifications provided by Ericsson. The specifications dictate an increment of the bin corresponding to the usage each second. Contrarily, the bin representing the lowest amount of

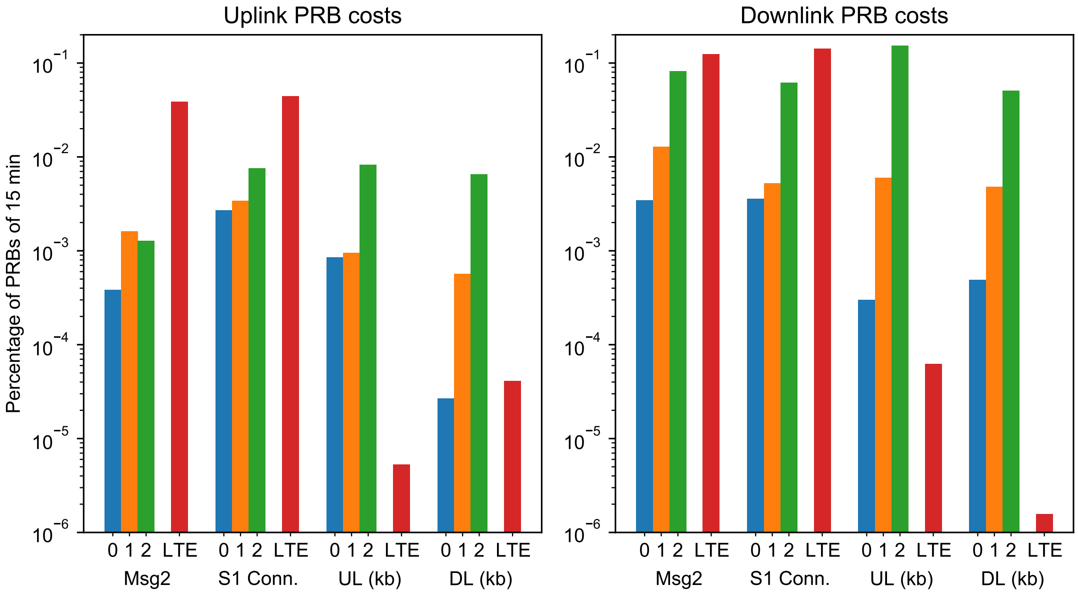


Figure 7.1: Percentage of PRBs for a 180 kHz bandwidth carrier used per network activity, based on data from June 2020. The x-axis shows the cost for different actions for different CE values and LTE. CE has a large impact on action cost. LTE is more efficient in data transmission, however has a bigger connection start overhead.

usage is not incremented by the eNodeB when there is no PRB usage. The upside of this is that the analysis has become more accurate as the value zero can be measured instead of the bin for values between zero and five percent.

The data for this analysis was sampled from the 15 minute vector counters which are retained for 30 days. Entries without activity were pruned to reduce the size of the data set. This resulted in over 10 million data points that can be used. Thus we have 10 million entries that a regression can be calculated from. As the output parameter we use the utilized PRBs and the input parameters are the different activities detailed above. The model has been chosen to make use of as few as possible features, to remove collinearity [34]. The results of the linear regression will then estimate the number of PRBs used per activity.

This linear regression was repeated for the different CE values to show the differences in PRB cost and network activities. For comparison these PRB costs were also calculated for LTE, however the results needed to be compensated for the different bandwidths available. LTE as used by VodafoneZiggo, makes use of 10 MHz or 20 MHz carriers depending on the base frequency. This compensation leads to a better comparison of the spectral efficiency. To compensate for the larger bandwidth the costs from LTE found, needed to be divided by the bandwidth of LTE and multiplied by the bandwidth of NB-IoT.

The result of this linear regression can be seen in fig. 7.1 for LTE and the different CEs. It can be seen that LTE has a more involved connection procedure than NB-IoT, but more efficient data transmission due to higher order modulation and larger packets. The impact of repetitions can also be seen in the large increase of resource use as each CE adds an order of magnitude in PRB costs. A key observation is that downlink data also costs resources in the uplink and vice versa, as data needs to be scheduled and reception needs to be confirmed.

7.2 Maximum Number for Connected UEs

This section sets out to investigate the maximum number of UE that will be supported in the current configuration of the network. For this, we first want to analyze the current situation before any changes. This section sets out to create a system to analyze the network. In the coming sections the effects of various changes will be further investigated.

To investigate the current situation a model of the current network is needed. However, for this model the load on a single cell is calculated and extrapolated to the rest of the network. To calculate the load on a single cell we need to know the number of devices connecting. For this access rate we take a fixed number per fifteen minutes. This will not give us a detailed view of the network, where access patterns fluctuate. However, this will give us capacity boundaries of a single cell.

Next, there are two components we need to know the total load. The first component is the load created by devices connected to the cell under investigation. The second component is the load created by RA attempts in neighboring cells. Below will be detailed how both of these are found.

The first step to find the network actions by the average device. To model this the number of network actions for a single S1 connection are needed. These values can be found by taking the total number of occurrences for each action and dividing this by the total number of S1 connections. This process is repeated for the different CE values to create separate profiles for CE users. The counters are used for this as in the previous section, namely `pmRaMsg2AttNbCbra`, `pmS1SigConnEstabSuccCe`, `pmRadioThpVolUlCe` and `pmRadioThpVolDlCe`. The results are the average network usage pattern of a NB-IoT connection. The average network usage pattern by a UE can be multiplied by the PRB cost for each action to find the cell load generated by an average device.

To accurately model the load created by RA interference, we need to know the number of devices utilizing the neighboring cells. Building on top of the assumption that all devices behave similarly, we can calculate the number of Msg2 if it is known how many devices connect to surrounding cells. For the remainder of this chapter we will assume the neighboring cells have an average load. Thus, the cost created by Msg2 needs to be calculated partly based on the number of devices wanting to connect to the cell under investigation and the number of devices connecting to neighboring cells.

In this section two types of cells are taken for evaluation. The first we call ‘Max’ and is the cell that is the most used and will be used to show the worst case scenario. The second cell will be called ‘Mean’ and shows the situation for a averagely utilized cell and this shows the utilization experienced on average in the entire network. To calculate the number of devices on the most loaded cell, the Zipf-Mandelbrot distribution will be used with the values found in Section 5.1.

The first result we would like is to find the utilization of the most loaded cell when a reasonable number of devices is connected. Thus, we make the simplification that 10.000 devices want to connected in a period of 15 minutes distributed over all cells. This simplification thus only gives an average load of the network and does not take into account any arrival distribution.

The next result we need to find is how many devices can connect to the entire network, before the capacity is exceeded of the most loaded cell. In NB-IoT this point is crucial, as load sharing via handovers is not possible. When the capacity is exceeded reliable transmissions can no longer be guaranteed.

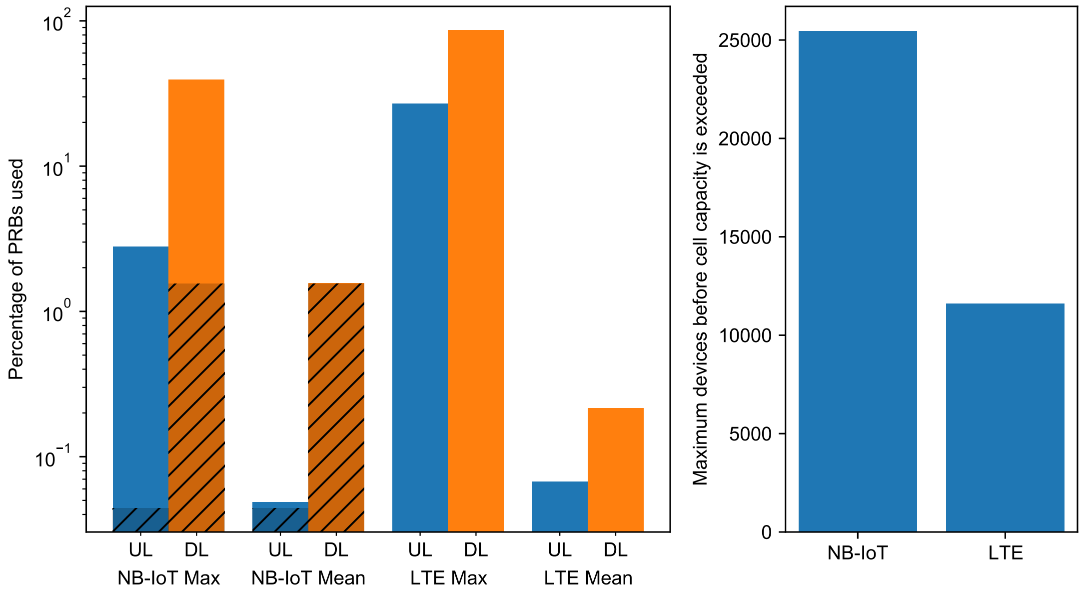


Figure 7.2: The figure describes the utilization for two different types of cell, The first is called 'Max' and shows the cell that has the most connected UE, and the second is 'Mean' and shows the utilization of an averagely loaded eNodeB. The plot on the left shows the utilization for both types of cells and for the two RATs, when there are 10.000 devices connecting per 15 minutes. The figure also shows in the shaded area the load created by just Msg2. The figure on the right shows the maximum number of devices connected to the network before the capacity of the most used cell is exceeded. NB-IoT allows for more devices to be connected with the current usage pattern. However the utilization of the average cell is higher, due to the fact that there is more RA interference. LTE has a set up procedure with larger messages, but it does interfere less with the surrounding cells and thus has a lower utilization on cells with a low amount of traffic.

The results on this are provided in fig. 7.2. When comparing 'NB-IoT Max' and 'LTE Max', we learn that NB-IoT is generally more efficient than LTE. This is mostly due to the larger messages exchanged during the set up of a connection for LTE. The number of total UE supported by NB-IoT is 2.2 times higher than LTE, when serving M2M traffic.

A more averagely used cell has a lower utilization for LTE, as LTE experiences less RA interference. The cell load created just by RA from other cells is represented by the dashed section of the NB-IoT results. When looking at the average cell, this is a significant part of the load. However, care needs to be taken to include the logarithmic scale.

7.3 Impact of Coverage Enhancement on Cell Capacity

The comparison in fig. 7.2 is not completely fair. This is due to the fact that NB-IoT offers Coverage Enhancement and needs to trade in extra resource blocks for far away or badly situated devices. Providing a similar coverage as LTE would only require CE 0. The question then becomes: how much extra resource blocks are needed for this extra coverage?

Using the information gathered in Section 7.1, we can analyze the PRB cost for different CE further. In this analysis ten devices connect each fifteen minutes per cell. This is more than the current number of connections to NB-IoT network at the time of measurement, however this

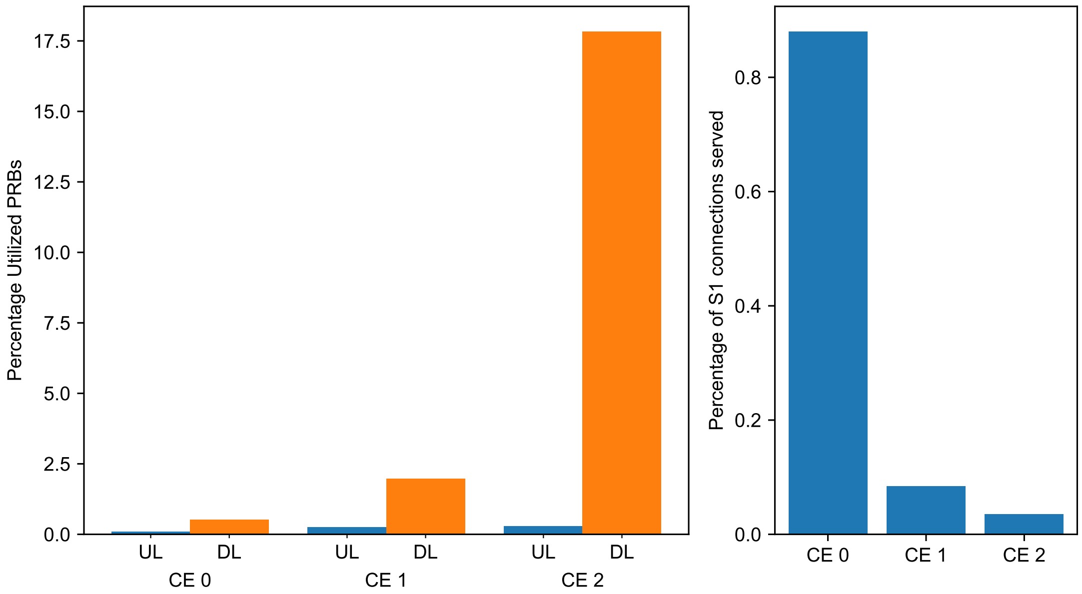


Figure 7.3: The left plot shows the average utilization of resource blocks per CE, when there are 10 devices connected to each cell. The right plot shows the distribution of devices over different CE values. While the higher CE values only represent a small number of devices, they correspond to a large share of the used PRBs. Usage of repetition directly impacts the number of needed PRBs.

number is not impossible. In this experiment neighboring cells also have ten connected devices per fifteen minutes that all generate RA interference. From `pmS1SigConnEstabSuccCe` we can learn the distribution of devices over the different CE values. With the model created in the previous section, we can find the PRB needed per CE level to serve the UE.

The result is presented in fig. 7.3. The left subplot shows how much of the available resource blocks are needed for each CE level. The right subplot shows what percentage of devices are connected using different CE levels.

From the right subplot we learn that four percent of devices connect via CE 2, while from the left subplot we learn that to connect so few devices 17.5 % of all downlink resources are needed. This imbalance is less pronounced in CE 1. As CE 1 sees double the use, however needs only one seventh of the resource blocks to serve all devices in CE 1 when compared to CE 2. Moving down to CE 0, this accounts for eleven times as many devices and uses just a fifth of the resources as needed for CE 1.

The reason behind this is two-fold. The first being that in higher CE more RA interference is found. The second is that the methods used for CE, do cost extra PRB. The method of extending coverage using repetition may be successful, however it is clear that this reduces capacity significantly. This trade-off needs to be actively monitored as the network grows.

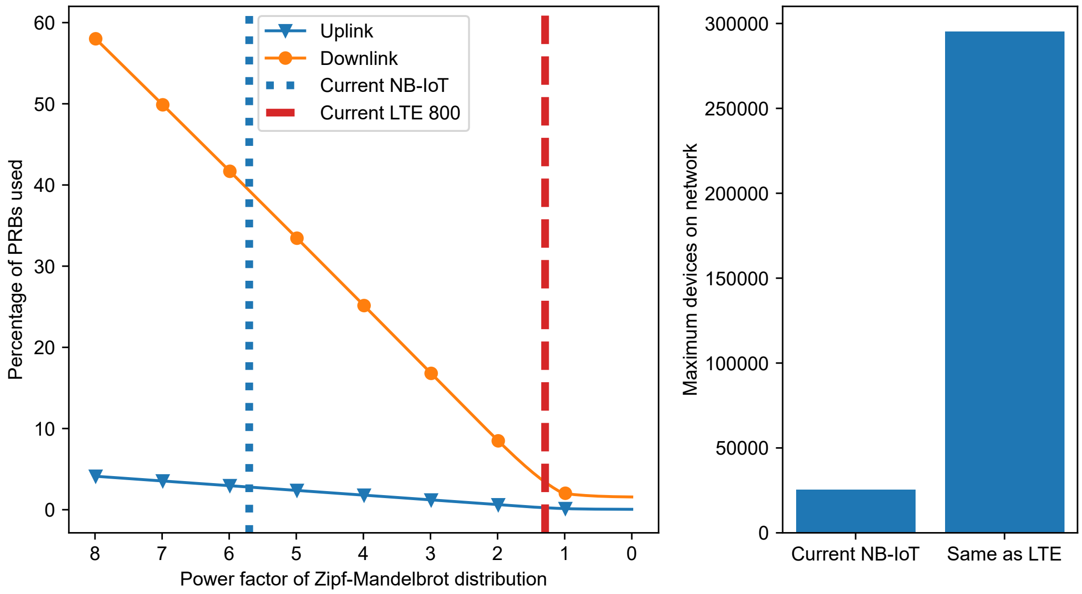


Figure 7.4: Analysis of different spatial distribution of 10000 devices with varying power factors for the Zipf-Mandelbrot distribution. The left plot shows the load of the most popular cell. The vertical lines show the current power factor for NB-IoT and LTE. The right plot shows the current power factors for the different RATs, the maximum number of devices before the capacity of the most loaded cell is exceeded. From the difference between NB-IoT and LTE in the right subplot, we learn that by spreading the devices better over the network the total capacity increases twelve fold.

7.4 Distribution of Users over Cells

In Section 5.1 it was discussed that NB-IoT devices are not spatially distributed similarly as LTE devices. If all devices were situated within a small set of cells, problems would arise quickly. Therefore, it is beneficiary to monitor the spatial distribution and see if capacity issues arise. These issues can often be solved by VodafoneZiggo by reconfiguring cell ranges or by adding cells.

To analyze this effect we make use of the Zipf-Mandelbrot distribution and the earlier found scale parameters for NB-IoT and LTE. However we would also like to know how the network behaves in distributions that have a different scale parameter. Thus, the scale parameter is swept from seven all the way down to zero to investigate different scenarios. From this distribution the number of UE connecting to the most popular cell can be calculated.

The interference from surrounding cells was found by taking the average value of experienced interference. The load of the most popular cells can be extrapolated to find the maximum number of devices before the first cell exceeds its capacity. This point was chosen, as this NB-IoT does not feature load sharing via handovers.

The results of this analysis can be found in fig. 7.4, where the different power factors for the Zipf-Mandelbrot distribution are investigated. The power factor of the distribution will get better when more devices are started and when the network is further optimized. When the power factor of NB-IoT becomes as low as the current power factor for LTE, a twelve times increase of devices on the network is possible.

In the left-hand sub-figure of fig. 7.4 a flattening of both curves for uplink and downlink is seen as the power factor reaches 1. This is where the random access of surrounding cells will have more effect on the load than the devices on the cell itself. This is due to the fact that the interference is a constant value and is not dependent on the distribution in this analysis.

7.5 PRB Cost of Firmware Updates

One of the features of NB-IoT that is advertised by operators is the maximum throughput of a cell of 250 kbps on the link layer [85]. Based on this claim, customers of the NB-IoT service have implemented Firmware Over The Air (FOTA) [31, 42]. FOTA is not the only feature that can be created that would periodically have a higher than normal data use during a connection. Two examples of such features are database synchronization or public key updates. This section will investigate the effects of the larger payloads than average on the PRB capacity of the cell.

To investigate this a prediction will be made based on the data found in Section 7.1. In this thought experiment the data volume in the downlink and the uplink will be increased. From this we can find the maximum average download throughput and the number of devices supported within the same fifteen minute window.

For this analysis the current download payload size is multiplied by a factor, while the square root of the factor is applied to the volume of the uplink data. This square root is chosen to approximate the behavior during large downloads, where a lot of data needs to be downloaded and the uplink is mostly used for confirmations of reception. This imbalance between download and upload is inverted from LTE, where the downlink is more utilized to stream video and download pictures.

After multiplying the payload with the factors mentioned above, a new average usage pattern is found. This usage pattern can be multiplied with the costs in the same operation as mentioned in the previous sections. This process relies on the assumption that the traffic generated by other UEs have the same payload size. For this analysis we will take a look into the behavior of the average cell, and thus have the same number of UE connected as their neighbors.

From the PRB cost for a single UE, the number of devices for a single cell can be calculated. This calculation is achieved by inverting the fraction of PRBs used. The average amount of kilobits can be multiplied by the number of devices in the cell and the increase in payload to find the data volume transmitted by the cell. When dividing by the the amount of seconds in 15 minutes, the throughput of the cell can be found.

The effects on the load of cell created by the larger payload is presented in fig. 7.5. The left-most graph shows how much PRBs will be used for a single device. The dotted line is used to denote the increase in payload found for the firmware update as found from Section 5.4. From this left-most plot the maximum number of users is calculated and shown in the center plot of fig. 7.5. On the right hand side plot the throughput is shown, where a maximum of 43 kbps can be found on the right edge of the plot.

This throughput is lower than the advertised maximum cell throughput of 250 kbps as advertised by operators. The reason for this discrepancy in download throughput is the CE that needs to take place for a small amount of devices. When only CE 0 is used, then the maximum downlink throughput of a single cell would be 230 kbps.

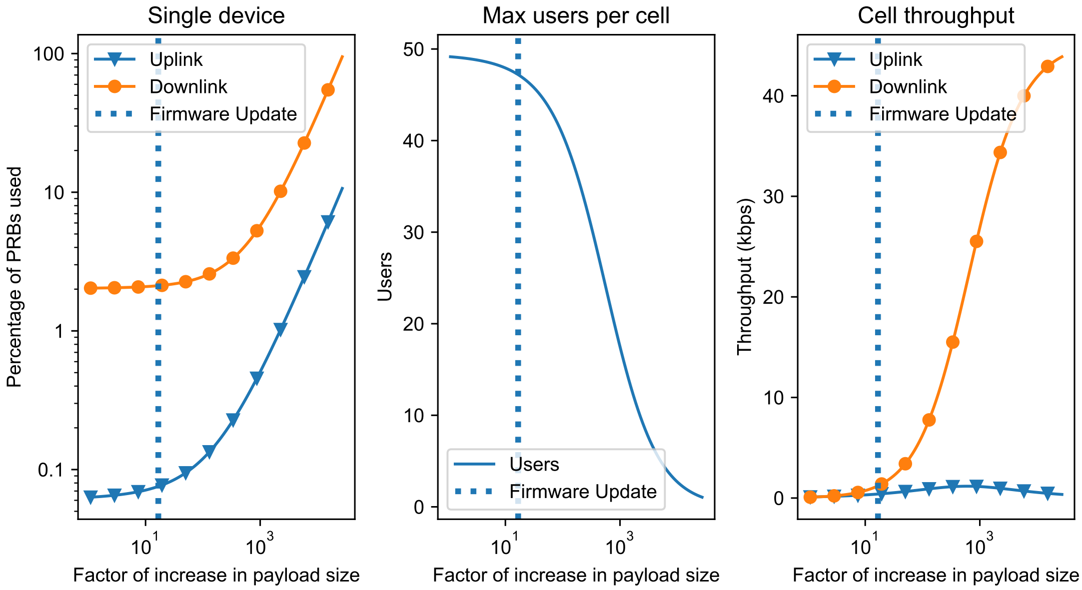


Figure 7.5: This figure shows the behavior of the average cell, as the payload transmitted increases multiplicatively from the average value based on data from July 2020. The plot on the left shows the utilization of resource blocks if larger payloads are sent per device and the dotted line denotes the increase in payload found in Section 5.4. The middle plot shows how much devices will be supported, which is calculated by inverting the PRB cost of a single device. The plot on the right shows the throughput per cell if the maximum number of devices is connected, as the payload increases. When the payload size increases, less users can be served by the same cell as can be seen in the middle plot. However this reduces overhead from connection set up and RA interference. With the current CE distribution an average data rate of 43 kbps is to be expected, as can be seen in the right-most plot.

7.6 Cell Capacity Loss due to Random Access Interference

In Chapter 6 we have shown that RAP are detected and acted upon by multiple eNodeBs. This costs PRB and is a detriment to the total capacity of the surrounding cells. Above we have found values for cell capacity that have not yet been satisfactory.

Finding a RA planning which reduces this interference, will be much harder than normal due to the higher allowable path loss than previously with LTE. This section will investigate the results of improving this interference step by step, as a good solution will be found also in steps.

In Section 7.1 we found how many Msg2 are transmitted currently per S1 connection. This is currently much higher than can be attributed to the normal transmission failure rate. Reducing the interference in the RACH can be done by reducing the overlapping RAP from cells that are close together.

In the ideal scenario only 1.1 times the number of S1 connections would be the number of received Msg2. In this section we investigate the number of connections per fifteen minutes per cell that would be possible if the interference is solved. This is solved by reducing RA parameter overlapping, without decreasing the capacity of the RACH too much. However finding this ideal balance is not trivial so, analyzing only the ideal is not enough.

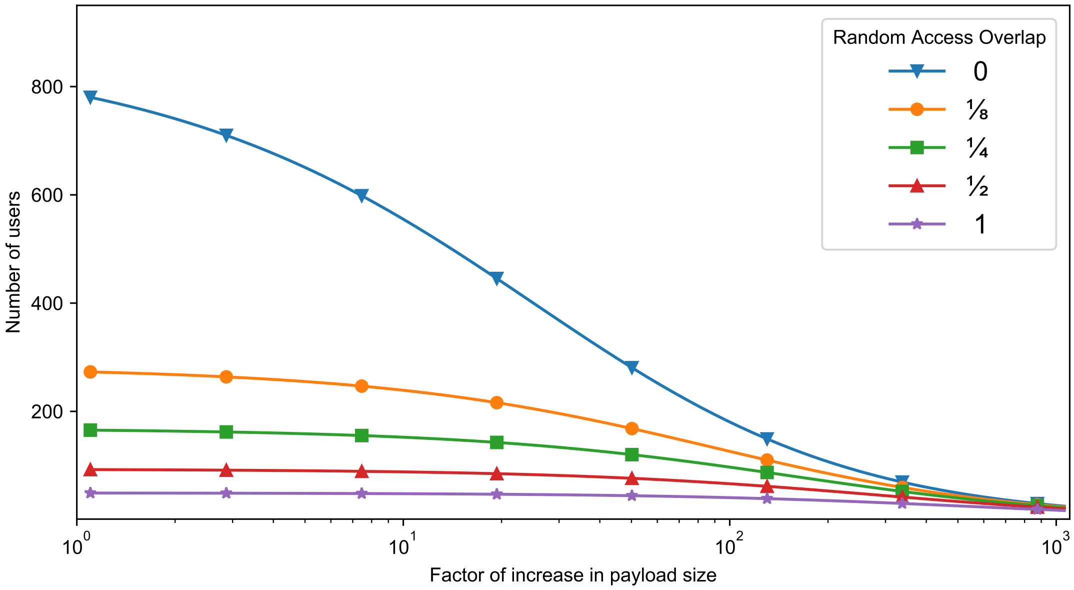


Figure 7.6: The impact of fixing the random access interference measured by the maximum number of devices for the average cell before the capacity is exceeded. The current amount of interference is denoted by a factor of 1. Factor 0 shows the ideal situation with as little as possible overlap in the RA planning. Ideal interference planning will allow 16 times more devices to be connected to a cell.

Several points in between the current and the ideal scenario have been chosen for fixing the random access overlap. With these the PRB costs for a single device at each cell per 15 minutes are calculated. The ratio between the total PRB available to the PRB cost per device is than taken to find the maximum number of users per cell for varying payload sizes.

The results of this analysis are presented in fig. 7.6. The different lines show a different situation based on how ideal the planning of the RA is. A factor of one denotes the current situation in which the VodafoneZiggo network resides, while a factor of zero denotes the ideal situation. With a standard traffic pattern 16 times more devices will be supported than currently possible, however this ratio diminishes as larger payloads are transmitted.

7.7 Summary of Results

This chapter set out to answer the remaining subquestion: *How many devices will be able to make use of the NB-IoT network?* Below are the observations that stem from our experiments performed in this chapter. The results from the different sections can also be combined, which shows the potential of NB-IoT.

NB-IoT can serve more M2M devices than LTE. NB-IoT allows for 25000 devices connected per fifteen minutes to the network at this moment. When comparing LTE with a similar bandwidth this results is 2.2 times more connected devices. This is mainly due to the more efficient set up procedure.

CE needs a significantly large amount of PRBs. CE allows UEs in bad coverage to make a connection. The downside of CE is the high PRB costs due to transmission repetitions. UE utilizing CE 2 use more than 17 times as many PRBs in the downlink. At the same time this represents a group as small as five percent of the number of CE 0 devices.

Broader spatial distribution of UEs allows for more connections. The current LTE network is optimized for the spatial distribution of H2H devices. NB-IoT devices might not follow the same distribution as LTE. A different planning of radio resources might be needed to spread the load of NB-IoT devices. When this distribution becomes more uniform a twelve times increase in capacity can be found.

Large payloads are possible, but at a cost. NB-IoT allows for larger payloads to be transmitted. Due to CE, the expected maximum throughput of a single cell will only be 43 kbps, with a single device connected. A higher throughput can be achieved when disabling CE, as 230 kbps can be reached.

With proper RA planning capacity is increased. RA interference is currently a a large part of the load on the network. Reducing this interference will allow up to 800 connected devices per 15 minutes, which is a significant increase of 16 times from the current situation.

8

Conclusion

The information, results and lessons from this report are intended for a wider audience. In the previous chapters answers to all of the subquestions can be found. The main research question will be answered below, along with recommendations.

First a summary of the results and answers to the research question will be given in Section 8.1. Section 8.2 will discuss the impact for the academic world and for further engineering efforts on cellular networks and LPWANs. A few lessons for those who want to start developing NB-IoT devices are next in Section 8.3. Section 8.4 is mainly intended for VodafoneZiggo, however these lessons are universal and also apply for other MNOs. Finally, this chapter will be rounded out in Section 8.5 with a discussion on the limitations of this work.

8.1 Discussion of Results

This thesis set out to answer the following question. *How is a NB-IoT network used and will the capacity match the expectations?* The following are the main results:

Low number of users but steady growth. There are currently a lower amount of users than expected and predicted by many parties, this can be seen in fig. 3.1. The average user transmits a message of 128 bytes every 16 minutes, which is a higher reporting rate than most sources recommend. Some NB-IoT use cases also implement FOTA to update the UE and knowledge of these updates are key for capacity modeling.

Coverage Enhancement provides plenty of coverage, in exchange for significant extra cell load. The stand out feature of NB-IoT is the deep coverage provided due to CE. From fig. 4.1, we learn that sufficient performance can be expected up until 163 dB. One aspect of the cost of CE becomes clear in fig. 6.1 and fig. 6.2, as the RA planning becomes much more difficult. On top of this a significant number of PRBs need to be dedicated to serving UE utilizing CE, as can be seen in fig. 7.3.

Capacity is lacking, but improvements can be made. The number of users per cell is currently not as high as expected, as can be seen in fig. 7.5. This can be attributed to two different phenomena. The first being the addition of CE, which generate a significant portion of all traffic. The second is improving the planning for RA as this currently translate to a large PRB overhead. The effects of reducing collisions can be seen in fig. 7.6.

8.2 Recommendations for Science and Engineering

During the writing of this thesis several topics have been uncovered that need further research and investigation. Below this is summarized in the three main components.

Better Self Organizing Network algorithms. Future research is needed on the topic of cells influencing each other over longer distances. As with CE 2, RAP travel much further and many more cells are reached. Path loss and coverage models have in the past only been developed for a handful of devices in the range of the cell. The large increase of towers within similar ranges poses new research topics.

Modeling using more realistic patterns. Currently, most theoretical analysis is done with the assumption that traffic arrives according to a Poisson model. Variance has been shown to be orders higher than the mean for both the start of connections and the volume of traffic. Furthermore, NB-IoT is also used in even more non-uniform ways, such as firmware updates. Firmware Updates can be triggered over a significant amount of devices. This provides much more uncertainty on the utilization and thus the capacity of the system.

High amount of RRC connection failures. In Section 6.1 we learned that only one in three attempts to set up a RRC connection actually completes. This causes a need for UE needing to restart the connection procedure multiple times. The connection procedure has a bigger impact on the battery life, than the transmission of data.

8.3 Recommendations for Consumers

While this report has focused on measurements from the viewpoint of the MNO, lessons can be extracted for consumers. More detail is needed for customers wanting to utilize NB-IoT to connect their IoT appliances to the Internet.

Distance is not important for path loss, however the immediate surroundings are. What can be surprising is that the distance towards the closest cell does not determine the path loss. The biggest influence is the more immediate surroundings. The effects of path loss are generally not reflected in various success rates, as this is managed by different methods of coverage enhancement. The impact of this coverage enhancement is increased battery consumption, which reduces overall lifetime of the device.

Reduce reporting period to conserve battery. Generally, it is advisable to reduce the frequency of transmission as much as possible. This will reduce the effects overhead by connection protocol and the headers in the data payload. When coverage enhancement is used this is even more important, as transmissions take significantly longer. Currently, the coverage enhancement value or the number of repetitions can not be requested from most chip-sets, while this should be key for managing life span.

Spread firmware updates to reduce active listening time. NB-IoT makes it possible to perform firmware updates. However, it is not ideal to update multiple devices at the same time in the same cell. Earlier it became evident that the maximum throughput of an average single cell lies around 43 kbps with a single user. With more users on the cell, the total throughput drops quickly. This average maximum throughput can be much higher, when no CE is allowed. Another option is to connect to LTE or LTE-M for large transfers.

8.4 Recommendations for Operators

This work has measured the performance of the VodafoneZiggo NB-IoT network. Lessons can be drawn from this that should apply for most NB-IoT operators.

Coverage is good due to the reuse of existing cells. Initial deployment can generally be seen as successful in providing service and coverage. This is mainly due to the utilization of all current LTE 800 MHz cells, which were already optimized for coverage over the Netherlands. This link has recently been found by others, but has also been reaffirmed in this report.

RA Planning is more difficult. As stated before the current RA planing poses capacity issues for NB-IoT due to the extended coverage. This is important to solve, as this will increase the maximum capacity by a factor of 13. The main method to solving this problem is finding a more extensive SON algorithm. One of the biggest challenges is to find the extra neighboring cell pairs created due to CE.

SC-PTM is needed to support large scale firmware updates. Another method to increase capacity is to implement Single Cell-Point To Many (SC-PTM), which is a solution for multi-cast [20]. This can solve capacity issues, when customers also adopt this technology for firmware updates. At the moment there are no reports of usage of this technology.

Creating a better overview of CE. At the moment it is hard to find the number of repetitions or the modulation order. This often requires debug access to the radio module of the UE. Meanwhile this has a large impact on the power consumption and the utilization of PRBs. Providing a dashboard with these insights towards the consumers can let them make more informed decisions on their reporting frequency.

This information can also be used to create different costs for different CE values. As billing and pricing models can be used to convince consumers to adapt their current communication patterns. This has previously also been used to better shape the traffic and reduce busy hours for H2H subscriptions [59]. Reducing the CE allowed will increase the total capacity of the network significantly.

8.5 Limitations of this Work

This thesis has been the result of a long project and during this project certain choices were made and circumstances encountered. The result of these will be detailed below.

This thesis makes heavy use of cell counters for most investigations, which inherently causes the behavior of one or more devices to be summed and some details will be lost. The counters provide a view which is integrated over 15 minutes in which it could happen that multiple connections are made by the same device. This further reduces the accuracy of the analysis.

The current network currently has a low number of users, with the expectation to grow. Making extrapolation between different orders of magnitude brings many uncertainties. This is exaggerated by the fact that a single project dominates the results, which skews many of the results towards the tendencies of that single project. Many of the investigations can be repeated with more users to test for the validity of the conclusions.

During the investigation of growth currently the traffic is assumed to be uniform over 15 minutes. Before it has been observed that on a timescale of 15 minutes there was a much higher variance than mean and this can be extrapolated with the self-similarity principle [12]. Nonuniformness is however countered by eNodeBs that can delay the access of some devices and that the load can be shared among multiple towers. For further work this needs to be investigated in a much more extensive simulator which is aware of surrounding cells.

Many results in this report depend on snapshots of different databases and a lot of data has been lost from the beginning of the investigation due to retention policies. This is mostly due to inexperience with the intricate details of the NB-IoT protocol and the overwhelming number of counters available. On top of this some time needed to be taken for furthering the knowledge of SQL to retrieve the information.

Lastly, COVID-19 has had a major impact on us all. This entire project has been completed within lock down, which has had a somewhat negative impact on motivation and work ethic. The opportunity for coffee chats with fellow students was sorely missed for inspiration and motivation. Let us all hope, that this will all be resolved soon.

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A

Acronyms Used

This appendix contains all acronyms that are reused along with the location of their first mention.

3GPP	3rd Generation Partnership Project (Governing body for cellular standards.)	1
5G	Fifth Generation	3
APN	Access Point Name	9
AT	ATtention (Command Language for modems.)	21
BPSK	Binary Phase Shift Keying (Transmits one bit of information per symbol.)	12
CDF	Cumulative Distribution Function	38
CDR	Call Data Record	16
CE	Coverage Enhancement	1
CIoT	Cellular Internet of Things	1
DL	downlink	10
DMRS	Demodulation Reference Signal	10
eDRX	Extended Discontinuous Reception	13
eNodeB	Evolved Node B (NE that hosts the cell.)	6
EPC	Enhanced Packet Core	6
FDD	Frequency Division Duplexing	10
FOTA	Firmware Over The Air (Update method for software on UEs)	57
GSM	Global System for Mobile communication (2G)	6
H2H	Human to Human	16
HMM	Hidden Markov Model	42
HSS	Home Subscriber Server	6
IMSI	International Mobile Subscriber Identity	7
IoT	Internet of Things	1
IP	Internet Protocol	6
ISD	Inter Site Distance	7
KPI	Key Performance Index	24
LPWAN	Low Power Wide Area Network	1
LTE-M	LTE-Machine (Changes to LTE to allow for lower power devices to connect.)	1
LTE	Long Term Evolution (4G)	3
M2M	Machine to Machine	16
MAC	Media Access Control	21
MAPL	Maximum Allowable Path Loss	12
MCL	Maximum Coupling Loss	12
MIB	Master Information Block	11

MME	Mobile Management Entity	6
MNO	Mobile Network Operator	1
Msg1	Random Access Preamble	46
Msg2	Random Access Answer	11
Msg3	RRC Connection Request and Contention Resolution	11
NB-IoT	Narrowband Internet of Things	1
NE	Network Element	5
NPBCH	Narrowband Physical Broadcast CHannel	10
NPDCCH	Narrowband Physical Downlink Control CHannel	11
NPDSCH	Narrowband Physical Downlink Shared CHannel	11
NPRACH	Narrowband Physical Random Access CHannel	10
NPSS	Narrowband Primary Synchronization Signal	10
NPUSCH	Narrowband Physical Uplink Shared CHannel	10
NRS	Narrowband Reference Signal	11
NSSS	Narrowband Secondary Synchronization Signal	11
OFDM	Orthogonal Frequency Division Multiplexing	3
PCRF	Policy and Charging Rule Function	6
PDF	Probability Density Function	38
PDN-GW	Packet Data Network GateWay	6
PLMN	Public Land Mobile Network (Used to denote the operator)	8
PRB	Physical Resource Block	7
PSM	Power Saving Mode	13
QAM	Quadrature Amplitude Modulation (Bits per symbol depends on the prefix.)	12
QoS	Quality of Service	9
QPSK	Quadrature Phase Shift Keying (Can send two bits of information per symbol.)	12
RACH	Radio Access CHannel	10
RAN	Radio Access Network	6
RAP	Random Access Preamble	11
RAT	Radio Access Type	16
RA	Random Access	3
RRC	Radio Resource Control	12
RSSI	Received Signal Strength Indicator	15
S1	Interface between eNodeB and MME	46
SC-PTM	Single Cell-Point To Many (This is similar to multicast.)	63
SGSN	Serving GPRS Support Node	6
SGW	Serving GateWay	6
SIB	System Information Block	11
SIM	Subscriber Identity Module (Usually a little plastic card in your phone.)	7
SINR	Signal to Interference plus Noise Ratio	12
SON	Self Organizing Network (Depends on smart algorithms to configure network parameters.)	49
SQL	Structured Query Language (Common database interfacing language)	7
TCP	Transmission Control Protocol	23
TDD	Time Division Duplexing	10
TEID	Tunnel Endpoint IDentifier	22
tMSI	Temporary Mobile Subscription Identifier	8
UDP	User Datagram Protocol	6
UE	User Equipment	1
UL	uplink	10
UMTS	Universal Mobile Telecommunication System (3G)	6

B

Analysis of Abbreviations

When reading this report many abbreviations are mentioned. The goal was to keep the number of abbreviations at a minimum. However, when reading the original specifications many more can be encountered. Luckily TErms and Definitions Database Interactive (Teddi) provides a place to find definitions on all telecommunication abbreviations used in cellular specification documents and can be found on `https://webapp.etsi.org/Teddi/`. This appendix will investigate the abbreviations and the timing of their introduction.

This website unfortunately does not provide an Application Program Interface (API) or downloadable database. A small web scraper was written to retrieve all different abbreviations by looking up all letters from the alphabet, downloading all the results found per letter and removing the duplicates. This is can be done with the python module Requests and Beautiful Soup. If any one is interested in this data or the script used, it can be shared when asked.

The 3GPP had 9798 definitions, but only 5512 of these are different abbreviations. Some of these duplicates are conflicting definitions, however there are also misspellings in the definitions. Removing spelling mistakes and cleaning the data was not done for this analysis.

Fortunately not all abbreviations are needed for this thesis. Int this report only 117 different abbreviations are used. From which only 22 abbreviations are specific for NB-IoT, as many are reused from LTE or come from a more general background.

In fig. B.1 several different plots can be found.

The top left plot shows the number of new abbreviations per release. Each release generally takes about a year to be prepared. Some notable releases are Release 3 which introduces UMTS. Release 4 includes the IP core for the 3G systems. Release 8 introduces LTE and thus has a spike in new definitions. Release 13 introduces NB-IoT, however this did not require many new abbreviations. Release 15 contains the first phase of 5G specifications, however more needed to be added yet in Release 16. Release 16 was not finished at the time of measuremetn.

The top right figure shows the average size of the added abbreviations per release. On average the abbreviations become 0.05 letters longer per release. This happens as new technologies often prepend a letter to denote a new version. Furthermore the amount of available short abbreviations is slowly running out.

The bottom left plot shows the different abbreviations categorized per length. What is interesting is that there are more two letter abbreviations than possible combinations, which is due to spellings errors or differing definitions. The most common acronym is the Three Letter Abbreviation (TLA), however this acronym is not even in the database. The next most common is the four letter acronym, which is also given the name extended Three Letter Abbreviation (eTLA).

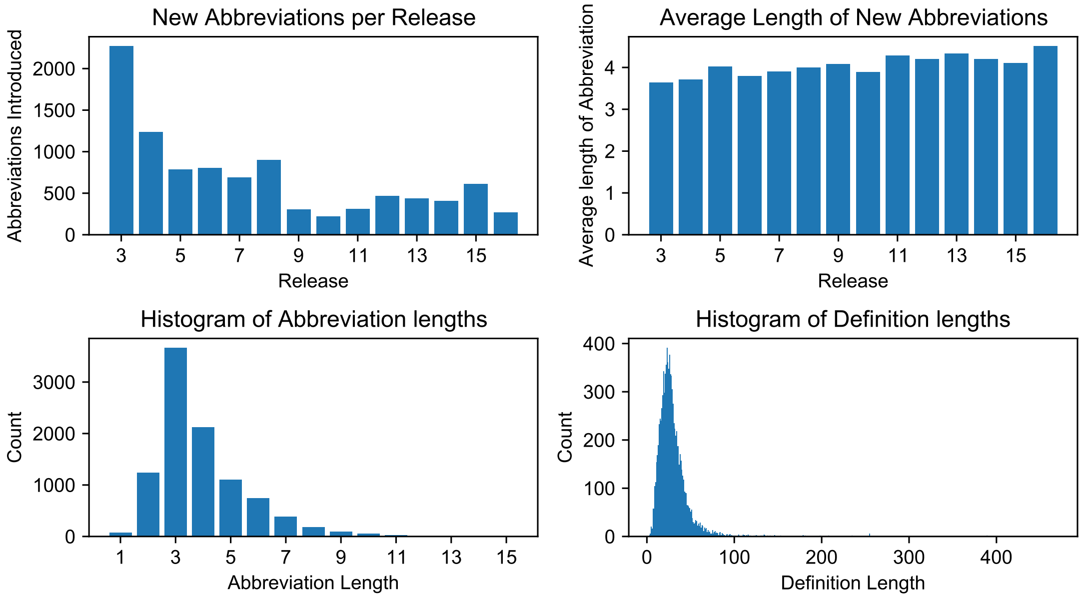

Figure B.1: Analysis of Abbreviations. The most common length of abbreviations is 3 and there are on average 623 new abbreviations per release. With each release the new abbreviations become on average 0.05 letters longer.

Definitions of abbreviations can become quite long, where most definitions are 32 letters long. This can be seen in the plot on the bottom right. However the tail extends past 400 letters, as in some definitions sentences are used to further define concepts.

In table B.1 can be seen what the most popular abbreviations are. This is measured by the amount of documents the abbreviation is used in. There are no surprises in this list and thus provides a nice collection to start learning cellular networks. Most of these concepts are also explained in Chapter 2.

In table B.2 all new abbreviations for NB-IoT can be found. This list is surprisingly short. However it shows how many concepts have been borrowed from LTE. Half of the abbreviations are concepts from LTE, but have a N prepended to denote the difference. This practice can be quite confusing as many 5G abbreviations also have a letter N added. This is due to the fact that the 5G RAT has received the brilliant name of New Radio. The trend does not include the new version of the eNodeB, which will be called gNodeB, where the g stand for Generation.

Abbreviation	Definition	Occurrence
UE	User Equipment	8623
IP	Internet Protocol	5010
FDD	Frequency Division Duplexing	3823
PLMN	Public Land Mobile Network	3496
RRC	Radio Resource Control	3353
UMTS	Universal Mobile Telecommunication System	3287
TDD	Time Division Duplexing	3201
QoS	Quality of Service	3132
CN	Core Network	3122
RNC	Radio Network Controller	3042
DL	downlink	2888
UL	uplink	2844
PDU	Packet Data Unit	2635
RACH	Radio Access CHannel	2576
IMSI	International Mobile Subscriber Identity	2438

Table B.1: Most often used Abbreviations in 3GPP Documents

Abbreviation	Definition
NPUSCH	Narrowband Physical Uplink Shared CHannel
NPDSCH	Narrowband Physical Downlink Shared CHannel
NPDCCH	Narrowband Physical Downlink Control CHannel
NPBCH	Narrowband Physical Broadcast CHannel
NPRACH	Narrowband Physical Random Access CHannel
NPSS	Narrowband Primary Synchronization Signal
NSSS	Narrowband Secondary Synchronization Signal
NB-IoT	Narrowband Internet of Things
IoT	Internet of Things
NRS	Narrowband Reference Signal
CIoT	Cellular Internet of Things
CE	Coverage Enhancement
SC-PTM	Single Cell-Point To Many
NRSRP	Narrowband Reference Signal Received Power
NRSRQ	Narrowband Reference Signal Received Quality
eDRX	Extended Discontinuous Reception
NPRS	Narrowband Positioning Reference Signal
NSCH	Narrowband Synchronization Channel
CP-CIoT	Control Plane CIoT

Table B.2: NB-IoT Abbreviations introduced in release 13 and 14

C

Summary of Important Counters

Counter	Type	Description
`pmMacHarqDlAckQpsk`	Transmission	The total number of successful HARQ transmissions in the downlink direction using a QPSK modulation.
`pmMacHarqDlNackQpsk`	Transmission	The total number of unsuccessful HARQ transmissions in the downlink direction using a QPSK modulation.
`pmPagDiscarded`	Paging	Counts the number of S1AP Paging messages discarded and not broadcast in this NB-IoT cell. This counter is a subset of pmPagReceived. (old version)
`pmPagDiscardedNb`	Paging	Counts the number of S1AP Paging messages discarded and not broadcast in this NB-IoT cell. This counter is a subset of pmPagReceivedNb. (new version)
`pmPagEdrxDiscarded`	Paging	Number of S1AP eDRX Paging messages discarded and not broadcast in this cell. This counter is a subset of pmPagEdrxReceived.
`pmPagEdrxReceived`	Paging	Number of S1AP eDRX Paging messages routed to this cell. This counter is a subset of pmPagReceived.
`pmPagReceived`	Paging	Counts the number of S1AP Paging messages routed to this NB-IoT cell.
`pmPagReceivedNb`	Paging	Counts the number of S1AP Paging messages routed to this NB-IoT cell.
`pmRadioThpVolDl`	Volume	The total successfully transferred data volume on MAC level in the downlink. This counter includes possible padding bits.
`pmRadioThpVolUl`	Volume	The total successfully transferred data volume on MAC level in the uplink. This counter includes possible padding bits.
`pmRrcConnCe0Max`	RRC	Peak number of NB-IoT UEs in RRC-Connected mode using coverage enhancement level 0.
`pmRrcConnCe0Sum`	RRC	Sum of all sample values recorded for number of NB-IoT UEs in RRC-Connected mode using coverage enhancement level 0.

`pmRrcConnCe1Max`	RRC	Peak number of NB-IoT UEs in RRC-Connected mode using coverage enhancement level 1.
`pmRrcConnCe1Sum`	RRC	Sum of all sample values recorded for number of NB-IoT UEs in RRC-Connected mode using coverage enhancement level 0.
`pmRrcConnCe2Max`	RRC	Peak number of NB-IoT UEs in RRC-Connected mode using coverage enhancement level 2.
`pmRrcConnCe2Sum`	RRC	Sum of all sample values recorded for number of NB-IoT UEs in RRC-Connected mode using coverage enhancement level 0.
`pmRrcConnEstabAtt`	RRC	The total number of NB-IoT RRC Connection Request attempts.
`pmRrcConnEstabAttReatt`	RRC	The total number of RRC Connection Request attempts that are considered as re-attempts.
`pmRrcConnEstabSucc`	RRC	The total number of successful NB-IoT RRC Connection Establishments.
`pmS1SigConnEstabAtt`	S1	This measurement provides the number of S1 Signaling connection establishment attempts for any establishment cause.
`pmS1SigConnEstabSucc`	S1	The total number of successful S1 signaling connection establishment

Table C.1: Important single value counters that can be used for analysis of NB-IoT networks.

Counter	Length	Type	Description
`pmMacHarqDlAckQpskCe`	3	Packet Succes rate	Number of successful HARQ transmissions in DL using QPSK modulation.
`pmMacHarqDlNackQpskCe`	3	Packet Succes rate	Number of unsuccessful HARQ transmissions in DL using QPSK modulation.
`pmMacHarqUlFailBpskCe`	3	Packet Succes rate	Number of successful HARQ transmissions in UL using BPSK modulation.
`pmMacHarqUlFailQpskCe`	3	Packet Succes rate	Number of unsuccessful HARQ transmissions in UL using BPSK modulation.
`pmMacHarqUlSuccBpskCe`	3	Packet Succes rate	Number of successful HARQ transmissions in UL using QPSK modulation.
`pmMacHarqUlSuccQpskCe`	3	Packet Succes rate	Number of unsuccessful HARQ transmissions in UL using QPSK modulation.
`pmNpdcchCceUtil`	20	Utilization	PDF of percent of the resources utilized for NPDCCH compared with total amount of resources available (and accessible for both NPDCCH and NPDSCH, not counting non-available subframes) each subframe, considering bandwidth and antenna configuration.

`pmNpdschUtilDistr`	20	Utilization	PDF of percent of the resources utilized for NPDSCH compared with total amount of resources available (and accessible for both NPDCCH and NPDSCH, not counting non-available subframes) each subframe.
`pmNpuschSingleToneDistr`	3	Utilization	Distribution of scheduled single tone NPUSCH from NB IoT devices.
`pmNpuschSixToneDistr`	3	Utilization	Distribution of scheduled six tone NPUSCH from NB IoT devices.
`pmNpuschThreeToneDistr`	3	Utilization	Distribution of scheduled three tone NPUSCH from NB IoT devices.
`pmNpuschTwelveToneDistr`	3	Utilization	Distribution of scheduled twelve tone NPUSCH from NB IoT devices.
`pmNpuschUtilDistr`	20	Utilization	PDF of percent of the resources utilized for NPUSCH compared with total amount of resources available, not counting non-available subframes.
`pmPagDiscardedCe`	3	Paging	Number of S1AP paging messages discarded and not broadcasted in this NB-IoT cell. This counter is a subset of pmPagReceivedCe.
`pmPagReceivedCe`	3	Paging	Number of S1AP paging messages routed to this NB-IoT cell.
`pmPagRecordNbDistr`	16	Paging	Number of NB-IoT paging records (UEs paged for each paging occasion) included in an RRC paging message sent on anchor carrier of cell.
`pmRaAttNbCbra`	3	Random Access	Distribution per NB-IoT NPRACH resource of detected contention-based random access preambles from NB-IoT devices.
`pmRadioRecInterferencePwr`	16	Interference	The measured Noise and Interference Power on NPUSCH, according to 36.214.
`pmRadioThpVolDlCe`	3	Throughput	Transferred data volume on MAC level in DL. Includes possible padding bits.
`pmRadioThpVolUlCe`	3	Throughput	Transferred data volume on MAC level in UL. Includes possible padding bits.
`pmRaMsg2AttNbCbra`	3	Random Access	Distribution per NB-IoT NPRACH resource of contention-based random access Msg2 attempts for each NB-IoT cell.
`pmRaMsg3SingleToneDistr`	3	Random Access	Distribution of scheduled random-access single tone Msg3 from NB IoT devices
`pmRaMsg3SixToneDistr`	3	Random Access	Distribution of scheduled random-access six tone Msg3 from NB IoT devices
`pmRaMsg3ThreeToneDistr`	3	Random Access	Distribution of scheduled random-access three tone Msg3 from NB IoT devices
`pmRaMsg3TwelveToneDistr`	3	Random Access	Distribution of scheduled random-access twelve tone Msg3 from NB IoT devices

`pmRaSuccNbCbra`	3	Random Access	Distribution per NB-IoT NPRACH resource of successfully detected random access Msg3 for CBRA from NB-IoT devices.
`pmRrcConnEstabAttCe`	3	Connection	Number of attempted NB-IoT RRC connection requests.
`pmRrcConnEstabAttReattCe`	3	Connection	Number of attempted RRC connection resume requests.
`pmRrcConnEstabSuccCe`	3	Connection	Number of established NB-IoT RRC connections.
`pmS1SigConnEstabAttCe`	3	Connection	Number of attempted S1 signaling connection establishments for any cause.
`pmS1SigConnEstabSuccCe`	3	Connection	Number of Successfull S1 signaling connection establishments for any cause.
`pmSinrNpuschDistr`	9	Path Loss	Distribution of the SINR values calculated for NPUSCH.
`pmUlPathlossNbDistr`	25	Path Loss	Distribution of the uplink pathloss.

Table C.2: Vectorized counters that can be used to analyze NB-IoT networks.

D

AT-Commands

The method to control any radio device for cellular communication is with AT commands. However, these are notorious for their bad documentation and many magic numbers. The basic set of commands that are required by the 3GPP are being extended by the different manufacturers in different ways. On top of this, each operator has specific instructions for connecting to the network.

This section will give a small overview of the different commands that are needed for the Sara R4 series to connect to the Vodafone network for both NB-IoT and LTE-M. These commands were also used to achieve manual control over the development kit and mostly uses information from the documentation of the modem [113].

Connect to Vodafone NL network

The first step is to define the APN that will be used for the connection. The default value for this is `nb.inetd.gdsp`, however clients can get their own APNs if requested. This is defined using the following command `AT+CGDCONT=1,”IP”,”nb.inetd.gdsp”`.

The next step will be to define which network to connect to. This can be used in several ways. The standard way is to force the right operator value. Vodafone is defined by 20404 and this can be selected using `AT+COPS=1,2,”20404”`. This makes sure that the Vodafone network is used. When roaming this can also be set to automatic using `AT+COPS=4,2,”20404”`, but this will still set a favorite value.

Connecting to the correct RAT

Some devices from the Sara R4 series can connect to both NB-IoT and LTE-M. NB-IoT is denoted by the number 8 and LTE-M by 7. The RAT can be selected using `AT+URAT=7` or `AT+URAT=8`. Some devices also support connecting over LTE with the value 3 and some may also support GSM with the value 9. Vodafone SIM cards do not make a distinction between the different RATs possible. This is partly due to the fact that the core network can not distinguish LTE-M from LTE.

The next step is to start the network registration. However, this works slightly different for NB-IoT and LTE-M. For NB-IoT `AT+CEREG=2` is needed, but for LTE-M `AT+CEREG=3` needs to be used. After the command has been given to register with NB-IoT, the device should wait roughly 9 seconds before being connected. The reasoning behind the different registration parameters is not quite obvious, as it should only adjust the error reporting. This command can also be used to check the status with `AT+CEREG?`.

The coverage can be checked with the command `AT+CSQ` which can be decoded to the RSSI with the following formula.

$$dBm = -113 + (2 * x) \tag{D.1}$$

Keep in mind that this formula gives the RSSI and not the path loss value, which has been used in this report. The coverage enhancement, number of repetitions or modulation type can not be checked directly.

Sending Data

The standard way of transmitting data is over IP. While Non-IP Data Delivery (NIDD) is possible, it is not recommended for starters by VodafoneZiggo. For IP functionality a socket needs to be used. The basic commands for this are `AT+USOCL=0` for closing the zero socket, as multiple sockets can be used in tandem. Opening a socket is done with `AT+USOCR=17,1463` which opens a socket on port 1463 for UDP as denoted by the 17.

UDP is the recommended technique as handshakes can stop functioning due to the high latency[119]. Sending data can be done with the command `AT+USOST=0,”80.112.163.254 ”,1463,12,”Hello, World”`. This command sends 12 bytes of information to the specified IP address. Similarly, data can be read from a socket using `AT+USORF=0,12` which reads twelve bytes from the zero socket.

Often the radio itself also has supported for higher layer protocols such as Message Queuing Telemetry Transport (MQTT) and File Transfer Protocol (FTP). These work in similar ways and can be more efficient to use, depending on the application.

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W.A. Kayser, Electrical Engineering Master Student TU Delft
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