Master's thesis

Ohjelmistotekniikka ja ICT

2019

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# PRIVATE LTE NETWORK

*– Design and Suitability for Marine Usage*

TURKU AMK

TURKU UNIVERSITY OF APPLIED SCIENCES

MASTER'S THESIS | ABSTRACT

TURKU UNIVERSITY OF APPLIED SCIENCES

Ohjelmistotekniikka ja ICT

2019 | 73 pages

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## - *Design and Suitability for Marine Usage*

As digitalization evolves, legacy industries and their applications have also moving towards using platforms which requires sophisticated telecommunication solutions and higher data bandwidths. The marine industry can be considered as one of these legacy industries. One of the trends within marine industry is the development toward remote- and autonomous shipping. One of the challenges within this work is embedding modern technologies for marine industry so that classification guidance can still be followed and the required safety level kept when moving functions from man to machine.

This thesis makes a survey in to one of the potential telecommunication systems which could support providing enough bandwidth for limited geographical areas and for certain applications. Private LTE is a technique that will be studied and especially from perspective of remote- and autonomous shipping requirements. LTE network functionality, its functions and ways how to measure performance of LTE network to get objective evidence of the network performance will be presented. An insight into the requirements set by classification societies for telecommunication systems will also be covered. DNV GL, one of the world's best-known classification societies has been used as an example of what kind of rules and guidelines has been set.

Based on the studies within this thesis, private LTE networks can be seen as a potential technological solution to secure required data bandwidth for remote- and autonomous shipping within certain, limited geographical areas. Especially it could be an effective way to arrange secured bandwidth for certain type of marine traffic, such as ferries sailing the same route. In order to be in line with the classification ruling, redundancy would still be required and the most preferably be arranged with some other radio technology or by doubling the equipment and resources of private LTE.

KEYWORDS:

Private LTE, marine, remote operation, autonomous vessels.

OPINNÄYTETYÖ (YAMK) | TIIVISTELMÄ

TURUN AMMATTIKORKEAKOULU

Ohjelmistotekniikka ja ICT

2019 | 73 sivua

Mikko Salokannel

# YKSITYINEN LTE VERKKO

## - *Rakenne ja soveltuvuus meriteollisuudelle*

Digitalisaation edetessä myös perinteiset teollisuuden alat ja niiden käyttämät sovellukset ovat siirtyneet hyödyntämään alustoja, jotka vaativat edistyksellisiä tietoliikenne tapoja ja aiempaa enemmän tietoliikennekaistaa. Yhtenä tällaisena perinteisenä teollisuuden alana voidaan pitää myös laivateollisuutta. Laivateollisuudessa yhtenä selkeänä digitalisaaton trendinä on selvästi nähtävissä alusten etä- ja automaattiohjaus. Tässä työssä yhtenä haasteena on nykyaikaisten tekniikoiden sulauttaminen laivateollisuuden tarpeisiin niin, että luokituslaitosten ohjeistusta saadaan seurattua ja vaadittu turvallisuustaso säilytettyä siirrettäessä toimintoja ihmiseltä koneelle.

Tämä opinnäytetyö kartoittaa yhtä potentiaalista tietoliikennetekniikkaa, jolla voitaisiin tukea tietoliikennekaistan riittävyyttä alueellisesti ja tietyille sovelluksille. Tällaisena tekniikkana tässä tutkitaan yksityisten LTE-verkkojen soveltuvuutta erityisesti etäohjattujen ja autonomisten alusten tarkoituksiin. Tässä opinnäytetyössä esitellään LTE-verkon toimintaa, suorituskyvyn mittaamista ja luokituslaitoksen vaatimuksia tietoliikenteelle. LTE-teknologia esitellään yleisesti ja näkökulmasta, joka taustoittaa mitä pitää huomioida suunniteltaessa yksityisen LTE-verkon hyödyntämistä mainittuun tarkoitukseen. Esimerkkinä luokituslaitoksen säännöistä ja ohjeista käytetään DNV GL:n, yhden maailman tunnetuimman luokittajan laatimia materiaaleja ja niissä käytettyjä referenssejä.

Tämän opinnäytetyön pohjalta voidaan yksityisen LTE-verkon nähdä tarjoavan hyvin potentiaalisen teknologisen ratkaisun, jolla saataisiin alueellisesti turvattua kaivattua kaistaa laivojen etäohjaukseen ja autonomisten alusten toiminnalle. Erityisesti tekniikka olisi soveltuva tietyllä maantieteellisellä alueella toimivalle liikennöinnille, kuten lauttaliikenteelle. Jotta kyseisen tekniikan voitaisiin nähdä olevan linjassa luokituslaitoksen ohjeiden kanssa, pitäisi kuitenkin redundanttisuutta lisätä mieluiten jollakin toisella langattomalla tekniikalla tai kahdentamalla yksityisen LTE-verkon laitteisto ja sen tarvitsemat resurssit.

ASIASANAT:

Yksityinen LTE, meriteollisuus, etäohjaus, autonomiset alukset.

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# FIGURES

# EQUATIONS

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ACK | Acknowledge |
| AP | Access Point |
| APN | Access Point Name |
| CLL | Convention on Load Lines |
| CP | Cyclic Prefix |
| CWND | Congestion Window |
| dBi | decibels over isotropic |
| dBm | decibels over milliwatt |
| DHCP | Dynamic Host Configuration Protocol |
| DNS | Domain Name Server |
| DNV GL | Det Norske Veritas Germanischer Lloyd |
| DUT | Device Under Test |
| E2E | End to End |
| EIRP | Effective Isotropic Radiated Power |
| EPC | Evolved Packet Core |
| E-UTRAN | Evolved Universal Terrestrial Access Network |
| eNB | Evolved Node Base station |
| FDD | Frequency Division Duplex |
| FEC | Forward Error Correction |
| FICORA | Finnish Communication Regulatory Authority |
| FSPL | Free Space Path Loss |
| GI | Guard Interval |
| GPS | Global Positioning System |
| GTP | GPRS (General Packet Radio System) Tunnelling Protocol |
| HARQ | Hybrid Automatic Repeat Request |

| | |
|---|---|
| HSS | Home Subscriber Server |
| IACS | International Association of Classification Societies |
| ICMP | Internet Control Message Protocol |
| IGO | Intergovernmental organization |
| IMCO | Inter-Governmental Maritime Consultative Organization |
| IMO | International Marine Organization |
| IMSI | International Mobile Subscriber Identity |
| IP | Internet Protocol |
| ISI | Inter-symbol Interference |
| LoS | Line of Sight |
| LTE | Long Term Evolution, 4th Gen. Mobile Technology |
| MAC | Medium Access Control |
| MCC | Mobile Country Code |
| MCS | Modulation Coding Scheme |
| MIMO | Multiple Input Multiple Output |
| MME | Mobility Management Entity |
| MNC | Mobile Network Code |
| MSIN | Mobile Subscription Identification Number |
| MU-MIMO | Multi-User MIMO |
| NAS | Non-Access Stratum |
| NAT | Network Address Translation |
| NGO | Non-governmental organization |
| NF | Noise Figure |
| NIST | National Institute of Standards and Technology |
| NTP | Network Time Protocol |
| OFDM | Orthogonal Frequency Division multiplexing |
| OID | Object ID |

| | |
|---|---|
| OS | Operating System |
| PAPR | Peak to Average Power Ratio |
| PC | Personal Computer |
| PDCP | Packet Data Convergence Protocol |
| P-GW | PDN (public Data Network) Gateway |
| PHY | Physical layer |
| QoS | Quality of Service |
| QPSK | Quadrature Phase Shift Keying |
| RAN | Radio Access Network |
| RB | Radio Bearer |
| RB | Resource Block |
| RCC | Remote Controlling Centre |
| RDN | Rapid Deployment Network |
| RE | Resource Element |
| RF | Radio Frequency |
| RRC | Radio Resource Control |
| RS | Reference Signal |
| RSRP | Received Signal Reference Power |
| RSRQ | Received Signal Reference Quality |
| RSSI | Received Signal Strength Indicator |
| RTC | Real Time Clock |
| RTT | Round Trip Time |
| Rx | Reception, Receiver |
| SCTP | Stream Control Transmission Protocol |
| SC-FDMA | Single Carrier Frequency Division Multiple Access |
| S-GW | Serving Gateway |
| SIM | Subscriber Identity Module |

| | |
|---|---|
| SINR | Signal to Interference and Noise Ratio |
| SNMP | Simple Network Management Protocol |
| SNR | Signal to Noise Ratio |
| SOLAS | International Convention for the Safety of Life at Sea |
| SSH | Secure Shell |
| TDD | Time Division Duplex |
| TM | Transmission Mode |
| TRP | Total Radiated Power |
| Tx | Transmission, Transmitter |
| UDP | User Datagram Protocol |
| UE | User Equipment |
| VPN | Virtual Private Network |
| WAN | Wide Area Network |
| WLAN | Wireless LAN (Local Area Network) |

# 1 INTRODUCTION

Remote and autonomous shipping is a trending topic within the marine industry and several projects have been published and also demonstrated within the last few years by shipping companies like Rolls-Royce, Kongsberg, Maersk, and Wärtsilä.

Development toward remote and autonomous shipping requires integrating new technical solutions on board the ships and also into operation centers on shore, as well as taking new working methods into use. Digitalization has been on going in the shipping industry for many years now and classification ruling has been developing to support new technologies and methods, though it is still clear that rules and guidelines are not supporting commercialization of remote and autonomous shipping. Thus, addition to technical development, lot of work is required together with regulatory authorities and classification societies to get certification rules and guidelines in place to allow commercial autonomous shipping in international waters. Currently the demoing and testing of such new technologies takes place in territorial waters and under approval of the flag state authorities.

Autonomous, and especially remote operated vessels, requires telecommunication systems which are capable of delivering required bandwidth, are reliable, and secure. This thesis is looking into one of such technologies, LTE, and especially into private LTE. Private LTE is a small LTE network, typically single cell, and built to serve a certain area and it is not typically meant for public use. This thesis is looking into different aspects of private LTE and seek to respond how it could be made the best to suit for need of marine industry. This is the basis and the rationale for this thesis.

One of the elementary parts of this thesis is the study and analysis of the Rapid Deployment Network (RDN) system provided by Turku University of Applied Sciences (TUAS). This system, TUAS RDN, is built around the light version of LTE Core – EPC (Evolved Packet Core), connected RAN (Radio Access Network) and antennas, which can be chosen based on the area where the system will be deployed. The aforementioned system is presented in a relatively practical level, so that can be used as a part of the evaluation, when considering to choose this system or when designing how to fit it into one’s own architecture. The system is presented in chapter 2.

Closely related to the implementation of a such system, basic link budget calculations are presented as it provides the way to evaluate the system's geographical coverage and which also provides the view for the achievable performance and capacity. These link budget calculations are presented in chapter 3.

Basic tools and techniques to evaluate this kind of a system are presented, as well as simple test plan and actual system performance measurements following the test plan. The measurement results obtained from the evaluation are separately presented and analysed. A simple set of network performance and monitoring tools were developed for this purpose and these tools provides an automated and consistent way of performing measurements also in the future. Network tools and philosophy used for this toolset, as well as measurements, are presented in chapter 4.

In chapter 5, maritime industry standardization bodies are introduced as well as current status of telecommunication specifications regarding marine classification.

The study of the system and development of the toolset used in the system measurements are made partially as daily work for Brighthouse Intelligence Ltd (BHI). Turku University of Applied Sciences (TUAS) has provided their up and running LTE system for the use, as well as required support to use it for testing.

# 2 ARCHITECTURE OF TUAS RDN

## 2.1 Overall architecture

TUAS RDN is based on Bittium Tactical Wireless IP Network. The system is meant to provide IP level data connections between the wireless clients working under the system's coverage area. It provides also backhaul and Internet connection for clients if choose to do so. TUAS RDN can be easily customized based on customer needs. Customization can be for example selection of base station (eNodeB, eNB) and selection of antennas to support the area of operation. Backhaul connectivity can be left out if not needed. Because the system is relatively compact it can be placed on a trailer carrying building crane and which can be pulled by normal car. Previously mentioned transportability makes it easy to move and set up the whole system fast.

In block level, TUAS RDN is a relatively simple solution building up the LTE radio network. Behind the block level simplicity there is mandatory pieces of LTE network, such as LTE core network, which is known as Evolved Packet Core (EPC) and the related Radio Access Network (RAN) parts. The system is controlled by the light version of EPC, which is based on Bittium's Tactical LTE AccessPoint. This light version EPC is a software running on a Linux based minicomputer. The EPC takes care of the radio network, customer's authentication and access to provided services, for example, data connections between the clients or routing for Internet and cloud services.

Backhaul and Internet access for the system can be made via fixed connection or by using a mobile network modem or even with WLAN. The selected carrier for backbone will define the capabilities and performance if it is less than the system's LTE radio performance.

Figure 1 presents the high-level architecture of the TUAS RDN and access to backhaul / Internet.

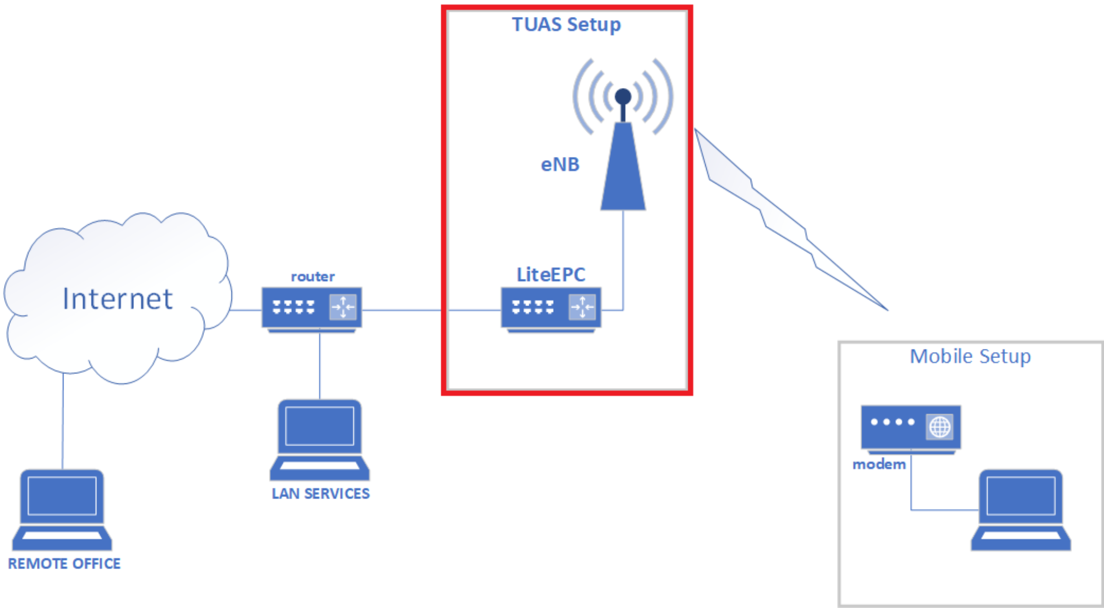


Figure 1. TUAS RDN as part of the whole E2E data path

## 2.2 EPC

The used EPC in TUAS RDN is a piece of software developed by Bittium. It realizes a functionality which can be described as a minimal LTE network core. In TUAS RDN this EPC software is known as LiteEPC. Figure 2 below shows the basic blocks of a typical LTE EPC and not the TUAS RDN LiteEPC specifically.

Mobility Management Entity (MME) is the main control node at the LTE core. It is the endpoint for S1-MME control plane traffic between the Evolved Universal Terrestrial Access Network (E-UTRAN) and EPC. These control protocols are called non-access stratum (NAS) and are used to manage connection related operations. It is also responsible of authentication of the user toward the Home Subscriber Server (HSS). HSS is a database for subscribers and allowed services. Serving Gateway (S-GW) is the termination point at the EPC side for E-UTRAN S1-U communication. S-GW takes care of user packet routing and forwarding, and additionally also charging and inter-eNB handovers. In the case of TUAS RDN where only a single eNB is used, there is no charging functions. Packet Data Network Gateway, PDN-Gateway (P-GW) provides access to external data networks and takes care of packet filtering. P-GW is also responsible for clients/UEs IP address allocations. (Tutorialspoint 2019.)

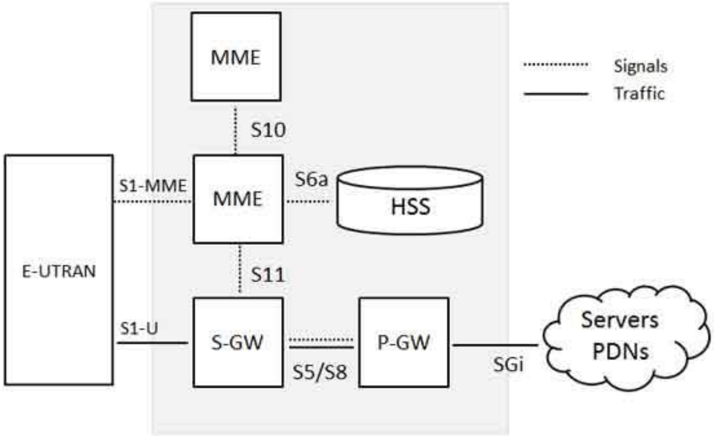


Figure 2. Interconnections between RAN, EPC and PDN (Tutorialspoint 2019).

## 2.3 E-UTRAN and eNodeBase (eNB)

Figure 3 below present the interfaces between the User Equipment (UE), E-UTRAN and EPC. Evolved NodeB (eNB) takes care of the radio resources and is the termination point for radio connection from user equipment (UE) to LTE infrastructure. Whereas S1 interface is the link between eNBs and EPC and were depicted in the previous chapter, Uu is the interface between UE and eNB and presents the radio interface of the LTE. Radio bearer (RB) is divided to data radio bearer (DRB), which is for user plane data and signalling radio bearer (SRB), which is for control plane. SRB is used to carry radio resource controlling (RRC) and NAS messages. NAS was depicted in the previous chapter (2.2). RRC-protocol takes care of the messages used to control physical medium between eNB and UEs. These depicted bearers are logical elements on top of the packet data convergence protocol layer (PDCP) and not actual physical domain elements. (Ahmadi 2014)

Protocol layers between UE, eNB and EPC are depicted in the next chapter (2.4).

In the case of TUAS RDN, only one base station, eNB, is used and so is the E-UTRAN part of the system. Single cell Nokia Mini Macro has been used as an eNB for TUAS RDN. Nokia Mini Macro is not presented any further, but a basic structure of the eNB and protocol stack used in LTE is presented to give an overview of the LTE RAN and to provide some insight to the data flow from the IP networking perspective.

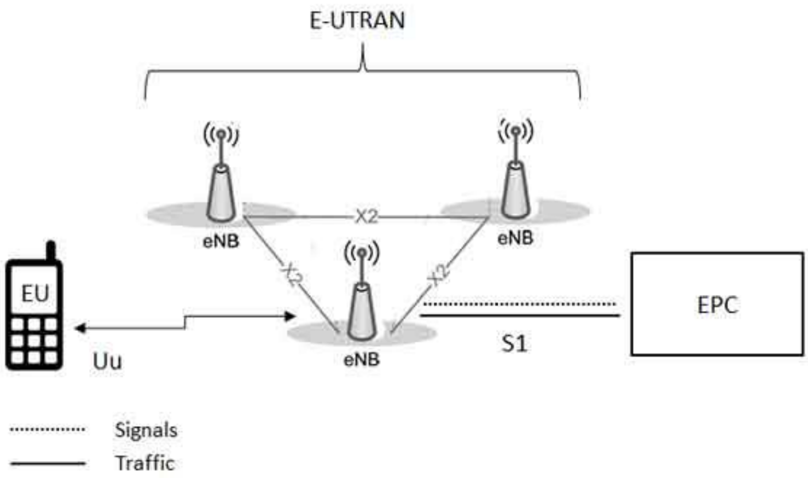


Figure 3. Interconnections between UE, RAN and EPC (Tutorialspoint 2019).

## 2.4 LTE network protocol stack

In the LTE infrastructure, the user plane data between EPC and eNB is transferred within the GPRS tunneling protocol (GTP). GPRS is an acronym for general packet radio service and was originally a technique developed for data services in the 2$^{nd}$ generation mobile technology known as GSM (Global System for Mobile communication). So, in that sense it is a kind of a relic and referring to the first digital mobile generation as such. GTP packets for user plane data are referred with GTP-U. GTP-U messages are transferred with UDP packets. Figure 4 below presents the protocol stack for user plane data and where GTP-U packets are transferred between eNB, SGW and PGW. (3GPP 2018.)

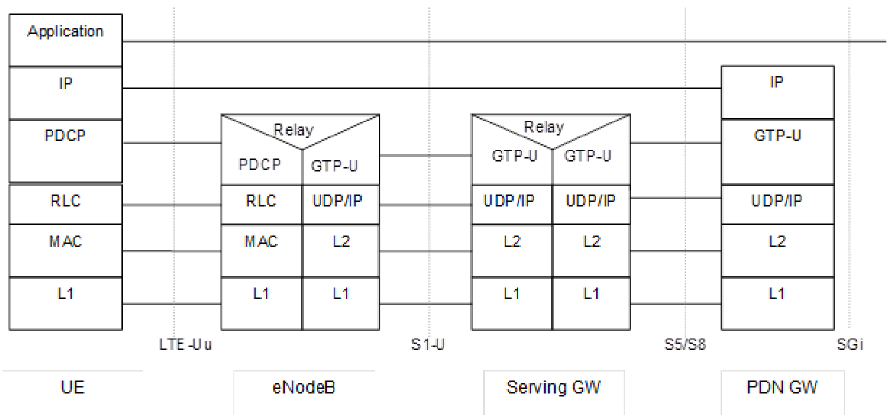


Figure 4. LTE protocol stack for user plane (3GPP 2018).

The control plane between S-GW and MME in the EPC is carried with GTP-C protocol over UDP whereas control plane messages between MME and eNB are carried with S1-AP protocol over SCTP. (3GPP 2018.)

As mentioned in the previous chapter (2.3), control plane and user plane bearers between radio interface of eNB and UE, are both working on top of the Packet Data Convergence Protocol (PDCP) layer. User plane application data is transferred within IP, working above the PDCP layer, whereas control plane data uses Radio Resource Control (RRC) protocol above the PDCP layer. The protocol stack structure at the LTE radio interface is shown in Figure 4. The main functions of the PDCP layer are header compression and decompression, and in-sequence delivery of upper layer packets and detection of duplicates of lower layers. It also takes care of ciphering. RLC layer takes care of packet segmentation according to factors of physical medium. The MAC layer takes care of multiplexing of packets to transport blocks and also mapping of logical channels to transport channels and their prioritization. The MAC layer also takes care of Hybrid Automatic Repeat Request (HARQ) process which handles packet repeat request combined with the forward error correction (FEC) functions. The physical layer (PHY) transfers the transport block over the physical channels meaning LTE radio interface. Physical layer controls the radio interface parameters and takes care of RF related parameter processing such as modulation and coding, frequency utilization and time synchronization, radio interface measurements and indication for higher layers. (NXP 2008.)

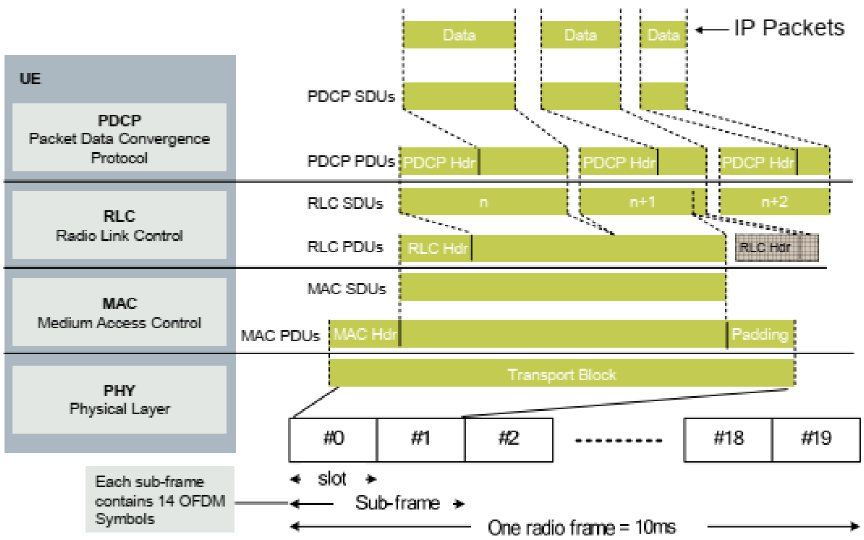


Figure 5. Data flow in eNB protocol stack (NXP 2008).

## 2.5 LTE radio interface

Figure 5 in the previous chapter (2.4) shows the eNB protocol stack where physical layer at the bottom of the picture shows one radio frame constituting twenty 0.5 ms slots. In case of frequency division duplex (FDD) multiplexing, a single frame consists of ten 1 ms sub-frames, which is further divided in to two slots. In FDD technique, downlink and uplink has dedicated frequency allocation and therefore transmission and reception can be simultaneous. In time division duplex (TDD) technique, frame length is still 10 ms but it consists of two 5 ms half-frames which are divided into five 1 ms sub-frames. In the case of TDD, sub-frame allocation for uplink or downlink can be made based on required need and according to predefined uplink-downlink configurations. However, uplink-downlink configurations might be relatively static in single cell as this will help to mitigate co-operation with neighbor cells.

Downlink and uplink are defined so that transmitting data from eNB to UE refers to downlink and where uplink refers to the case UE transmitting toward eNB. For LTE, RF Modulation used for downlink is OFDM, orthogonal frequency division multiplexing. OFDM is a modulation technique where data is modulated to several subcarriers which are orthogonal to each other. Orthogonality is achieved by placing the parallel subcarriers according to their sin(x)/x behavior. This means that as subcarriers are modulated with a specific rate, which defines the shape of the spectrum, parallel subcarriers are placed to these minimums of the particular carrier. Subcarrier distance in LTE is 15 kHz and it defines the OFDM symbol length (or vice versa, depending on the point of view). 15 kHz subcarrier spacing leads to a 66.67 µs symbol length. Typically, some padding is added after the symbol to achieve tolerance for multipath effects and to prevent inter-symbol-interference (ISI). This padding is a copy from the beginning part of the symbol and something that can be used, for example, to allow spectrum shaping or to benefit FEC. This added padding is called cyclic prefix (CP) or guard interval (GI). In LTE it is agreed that in basic scheme, seven symbols are transmitted within one time slot so that the first symbol has a CP of 5.2 µs and rest of the symbols has a CP of 4.7 µs. LTE also allows usage of an extended CP of 16.7 µs and where only six symbols per slot are transmitted.

OFDM has several dB Peak-to-Average Ratio (PAPR, aka crest factor) and therefore requires linear amplifiers in order to keep the modulation parameters in shape. This is not a problem for eNBs having fixed power supply instead of batteries. For uplink, single carrier frequency division multiple access modulation (SC-FDMA) is used and it only has a 2 dB PAPR and enables the use of much more energy efficient amplifiers. Therefore, it is much better for mobile devices which runs on battery. Due to these facts, it also better supports uplink coverage as such. This is an important aspect in the sense that allowed transmit powers are much more limited in UE side, both by regulations and due to mobility antenna options. in sense of frame format, SC-FDMA modulation used for uplink works as OFDM used for downlink, and so frame structure is also very similar what is described for downlink.

In LTE, frequency allocation within the band is built around resource blocks (RB). In frequency domain one resource block consists of 12 subcarriers and in time domain of one 0.5 ms slot including seven modulated symbols. One symbol within one subcarrier is called a resource element (RE). One resource block is the minimum entity that can be allocated. One resource block consumes 180 kHz of spectrum. LTE band with allocated band of 10 MHz consists of 50 resource blocks and 20 MHz band with 100 resource blocks. Whereas OFDM resource blocks for downlink can be allocated more freely, SC-FDMA resource blocks for uplink are limited to be allocated as consecutive resource blocks. (Geßner 2011.)

## 2.6 Configurations of the LiteEPC

LiteEPC software runs on top of the Linux Ubuntu PC and is using Ubuntu version LTS 14.04, version LTS 16.04 should also be supported. The PC is a mini PC equipped with two ethernet interfaces and has no other particular requirements. One ethernet interface is required for eNB S1 connection which carries S1-MME and enables for Mobile Management Entity (MME) control communication link toward E-UTRAN. The same S1 works as S1-U interface for eNB and is seen in the PC as Linux TUN device (IP level tunnel). The second ethernet interface is for the WAN connection and so for external data routing and from EPC perspective it is an external input for P-GW.

LiteEPC configurations are preferred to be made locally or via SSH from WAN/Router side network. It is also possible to configure it from the eNB port. Network configuration for LiteEPC is normal Ubuntu based configuration where network parameters are defined in */etc/network/interfaces* -file. Dynamic Host Configuration Protocol (DHCP) can be used for IP-addressing but it is recommended to use static IPs set explicitly. DHCP usage may lead to problems within system startup where EPC is obtaining different IP than previously and thus destroying routings made by EPC. There are basic IP settings for both Ethernets: for eNB and for WAN. At this phase it is important to notice that IPs for mobile clients are (to be) defined in LiteEPC specific settings and not in OS based settings.

Most of the EPC specific configurations are stored at */etc/epc/config.cfg* -file. Mobile Country Code (MMC) settings are defined also in this file. MMC is a country specific code and defines the country where operating. It also defines Mobile Network Code (MNC), which uniquely defines the network operator. MCC and MNC together defines a home network. If MCC and MNC values in the connected mobile client's SIM card matches to the network, it is connected to its home network instead of roaming. In Finland MCC is 244 and MNC for Bittium is 34.

Access Point Name, APN, is the name for the gateway to access from a cellular network to a public network. For TUAS RDN this is *Bittium* by default. If domain name resolution is required, Domain Name Server (DNS) need to be specified as well. LiteEPC can be configured to provide, via DHCP, the same DNS for clients as EPC PC is using.

IP addressing for the mobile clients can be dynamic via DHCP, or it can be static and based on mobile device International Mobile Subscriber Identity (IMSI) code. IMSI is stored in the SIM card and it constitutes of aforementioned MCC and MNC and additionally individual MSIN (Mobile Subscription Identification Number). MSIN part is 9 to 10 digits long depending of the length of the MNC. IMSI is stored as a 64-bit field. (Bittium 2017.)

## 2.7 Required License to operate LTE band

In order to operate on official LTE band, which is a piece of radio frequency spectrum allocated for LTE usage, a license is required. Typically, frequency allocations are provided by country specific telecommunication authorities. In Finland this authority is FICORA, Finnish Communication Regulatory Authority. FICORA has licensed allocated LTE frequencies for different telecommunication operators and there are usually no free pieces of spectrum available for third parties. One way to obtain a piece of spectrum to use, is to ask if any operator can loan or rent part their spectrum. Operators are most probably not using all their bands at every location and are possibly willing to temporarily loan or rent it.

The LTE B28, 700 MHz band, was specifically under an interest for this thesis as it would provide the most suitable link budget from its nature and also being the most tolerable for obstacles in the line-of-sight. On the other hand, only 10 MHz spectrum bandwidths are available for B28 and this leads automatically to half of the available data bandwidth compared to full 20 MHz spectrum bandwidth cases. This was not considered to be a problem, since the planned operation area in the Finnish archipelago was not too large and based on link budget calculations, full performance should be available for the entire area.

Current situation for licenses can be seen from FICORAs web pages. Currently B28 frequency allocations are shared between three operators and those licenses are covering the whole country, excluding Ahvenanmaa.

FICORA web-pages show that DNA Oyj, Elisa Oyj and Telia Finland Oyj each has 10 MHz of bandwidth for uplink and downlink at B28. Uplink frequencies are from 703 MHz to 733 MHz and downlink frequencies are from 758 MHz to 788 MHz. Each operator has basically the same rules and for example Telia has UL frequencies 723…733 MHz and DL frequencies 778…788 MHz. The same license defines also the maximum Equivalent Isotropic Radiated Power (EIRP) levels allowed to be used by an operator and is basically 64 dBm / 5 MHz. The same license also specifies maximum allowed Total Radiated Power (TRP) or EIRP levels for client devices for uplink and it is 23 dBm with exception that this can be exceeded if the client device is statically mounted and it is confirmed that it does not interfere other devices and systems. (Traficom 2017.)

# 3 LINK BUDGET ESTIMATION

Link budget, as the name indicates, is adding up all amplification and losses occurring on the radio path between transmitter and receiver. The calculations take into account transmitter power and receiver sensitivity and also includes antenna gains. Air interface is frequency dependent and, in most cases, maximum allowed transmission powers are limited by regulatory rules. On the other hand, sensitivity is dependent on used reception bandwidth and used modulation (bits per Hz utilization) which defines required signal to noise ratio (SNR). Chapter 3.1 presents basic parameters which enables to calculate simplified link budget for line-of-sigh (LOS) links. Chapter 3.2 presents example calculations for 700 MHz LTE B28.

## 3.1 Parameters required for link budget

### 3.1.1 Effective Isotropic Radiated Power, EIRP

EIRP defines the maximum directional radiated power toward a single direction measured over the whole spherical and with vertical and horizontal polarizations. If antenna gain G, used conducted RF power P, and losses L (=efficiency & matching) are known, EIRP can be calculated by:

$$EIRP = P + G + L$$

Equation 1. EIRP

Typically, maximum allowed EIRP for a certain band is defined on a national level by official telecommunication authority. In Finland this authority is Finnish Transport and Communications Agency, also known as Traficom.

Current radio license decisions in Finland for 700 MHz / B28, for example for operator Telia, allows uplink frequencies for 723-733 MHz and downlink frequencies for 778-788 MHz. According to admitted license, an operator is allowed to use maximum EIRP of 64 dBm / 5 MHz per antenna. For uplink the same license defines maximum TRP of 23 dBm but it is not as strict, as it allows EIRP to exceed that value if it is confirmed that the system does not disturb normal network operation. (Viestintävirasto 2017; Räsänen & Lehto 2003.)

### 3.1.2 Antenna Selection

Antenna selection is an extremely important part of the link budgeting. The antenna needs to be selected to match wanted operational area in horizontal and vertical plane, meaning beamwidths in aforementioned dimension. Beamwidth affects antenna gain, which is one of the key factors for link budget. Antenna gain is a figure which depicts maximum directional power compared to the value which an ideal isotropical antenna would provide. So, whereas ideal isotropical antenna radiates equally to all directions and has 0 dBi gain, directional antenna concentrates its beam in a certain direction and is has gain in a certain direction over isotropical antenna. That is what dBi is depicting. In some cases, antenna gain might be specified as dBd which is gain compared over half-wave dipole antenna, which already has 2.1 dBi gain. Over all, the smaller the beamwidth, higher the antenna gain and vice versa. (ARRL 2010.)

For link budget, as antennas are reciprocal, meaning they work equally for transmission and reception, it is beneficial for both directions (uplink and downlink).

### 3.1.3 Modulation Coding Schemes and required SNR

For both directions, uplink and downlink, different Modulation Coding Schemes (MCS) are used to optimize the throughput and link quality. In other words, different MCSs are not able to carry equal amounts of data and are not equally tolerant for Signal-to-Noise Ratio (SNR). Lower the MCS index, a simpler and more SNR tolerant modulation is used.

As described above, the used MCS defines required SNR. This is what needs to be taken into account in link budget estimations. This can also be seen from the fact that different MCS has different receiver sensitivity. SNR requirements for different modulations are show in 3.1.4. (Geßner 2011; Zarrinkoub 2014.)

### 3.1.4 Noise floor, Bandwidth, Sensitivity, and Shannon theorem

If sensitivity figures for different modulations are not provided. The following method can be used to estimate the required sensitivity levels.

At first, the noise floor needs to be calculated, which can be done in following way:

$$N = k \times T \times B$$

Equation 2. Noise floor (ARRL 2010).

where $N$ is noise, $k$ is Boltzmann's constant (1.3806485279) ×10$^{-23}$ J/K), $T$ is ambient temperature in Kelvins, and $B$ is used Bandwidth in Hz.

Typically used reference temperature is 290 K. When using 1 Hz for bandwidth, it leads to the value of -174 dBm/Hz (after comparing it to 1 mW and changing presentation format to dBm). -174 dBm/Hz can be considered a constant in the field of RF technology. (ARRL 2010; Räsänen & Lehto 2003.)

Factor for the bandwidth in decibel-units can be calculated from: $10 \times log_{10}(B)$. If using 10 MHz band, it leads to factor of 70 dB ($10 \times log_{10}(10^7) = 70\ dB$). So now we can conclude that noisefloor for 10 MHz band is:

$$\text{-}174\ dBm/Hz + 70\ dB = \text{-}104\ dBm$$

Equation 3. FSPL [dB] for full path.

Figure 6 below shows one interpretation of required SINR (Signal to Interference and Noise Ratio) vs. modulation schemes. This data can now be used together with the above-mentioned noise analysis to estimate required link budgets.

| CQI index | Modulation | Coding rate | Spectral efficiency (bps/Hz) | SINR estimate (dB) |
|---|---|---|---|---|
| 1 | QPSK | 0.0762 | 0.1523 | −6.7 |
| 2 | QPSK | 0.1172 | 0.2344 | −4.7 |
| 3 | QPSK | 0.1885 | 0.3770 | −2.3 |
| 4 | QPSK | 0.3008 | 0.6016 | 0.2 |
| 5 | QPSK | 0.4385 | 0.8770 | 2.4 |
| 6 | QPSK | 0.5879 | 1.1758 | 4.3 |
| 7 | 16QAM | 0.3691 | 1.4766 | 5.9 |
| 8 | 16QAM | 0.4785 | 1.9141 | 8.1 |
| 9 | 16QAM | 0.6016 | 2.4063 | 10.3 |
| 10 | 64QAM | 0.4551 | 2.7305 | 11.7 |
| 11 | 64QAM | 0.5537 | 3.3223 | 14.1 |
| 12 | 64QAM | 0.6504 | 3.9023 | 16.3 |
| 13 | 64QAM | 0.7539 | 4.5234 | 18.7 |
| 14 | 64QAM | 0.8525 | 5.1152 | 21.0 |
| 15 | 64QAM | 0.9258 | 5.5547 | 22.7 |

Figure 6. SINR estimate for different MCS (Zarrinkoub 2014).

If expecting over 20 Mbps data throughput, what is wanted, we select a SINR value of 10.3 dB, as that, spectral efficiency is 2.4 and with 10 MHz bandwidth it leads to over 20 Mbps data throughput. Now we can estimate that the required RF power at the receiver would need to be:

$$-104\ dBm + 10.3\ dB = -93.7\ dBm$$

Equation 4. Sensitivity for 20 Mbps with 10 MHz band.

Additionally, receiver Noise Figure (NF) and possible cable losses needs to be added which would lead to additional loss of several dB.

The best reference to estimate LTE sensitivities would be ETSI specifications which defines type approval acceptance criterias for devices. In this particular case it would be ETSI TS 136 101 where latest version is V14.7.0 (2018-04). For example, for B28 working at 700 MHz, which is now under our interest, it defines -95.5 dBm for minimum sensitivity for QPSK with coding rate of 1/3 which would correspond to a data rate that requires ~ 0 dB SINR in the table shown in Figure 6. In this case, the data rate of requiring 10 dB SINR is pursued, and so it would lead to about -85.5 dBm sensitivity leaving space for about 8 dB margin for NF. Typically, receiver’s NF at the UEs is around 5…7 dB which will leave few dB margin for UE to pass type approval testing or having “integration losses” at design. In this presentation 7 dB NF is considered which lead to: -93.7 dBm + 7 dB = -86.7 dBm sensitivity. To simplify things -87 dBm is going to be used.

In case sensitivity and SNR/SINR values are not available, it is possible to estimate theoretical sensitivity by using Shannon theorem (also known as Shannon-Hartley theorem). Shannon theorem defines minimum SNR required for a certain bitrate per Hz. Shannon theorem is widely accepted and typically shown as:

$$C = B \times log_2(1 + \frac{S}{N})$$

Equation 5. Channel capacity (ARRL 2010).

where $C$ is channel capacity, $B$ is used bandwidth, $S$ is signal power and $N$ is noise power.

This leads to the conclusion that theoretically, within 1Hz band, it is possible to deliver 1 bit per second with 0 dB SNR. So, as it was calculated previously that noise floor with a receiver having 10 MHz bandwidth, is -104 dBm, it can be concluded that with RF power of -104 dBm we could get theoretically throughput of 10 Mbps. But as over 20 Mbps was required, it is possible to achieve with cost of 3 dB (according to Shannon theorem) and so required RF power would be actually -101 dBm. This is a theoretical value and with modulations and codings used in LTE this level is not achieved. As mentioned earlier, receivers add also some amount of noise which is depicted with the Noise Figure and which is typically around 5…7 dB at typical UE LTE devices. So, in this case the difference between theoretical and actual is about 7 dB (depending on which SINR value selected from the Figure 6).

### 3.1.5 Free Space Path Loss, FSPL

In order to simplify link budget calculation, Free Space Path Loss (FSPL) is the easiest point to start. Fresnel zones are used to estimate Line of Sight (LoS) FSPL propagation effects. Different zones are calculated so that particular zone’s surface is presenting the points where reflected signal would have certain phase shift to the direct transmission. The first zone is considered the most important as blockages or reflection from this zone can do the most harm for the signal. The surface of the first Fresnel zone represents the plane from where reflected signal would be seen 180° off phase compared to directly travelled signal while reflection within the second Fresnel zone would have 180°…360° phase shift and so stronger phase cancellation. Reflection itself causes also 180° phase shift and so for reflection from the first Fresnel zone's edge would cause 360° phase shift which could even aid the link budget by gaining the signal. Similarly, reflection from the second Fresnel zone's edge would actually cancel the signal being in 540° (180°) phase shift with directly travelling signal. Significance For higher order Fresnel zone numbers are considered less important as signal travelling distance increases further and so the signal spreads wider area making significant reflections less likely and leaving the phase cancelling effects less meaningful. (Microwave Link 2015.)

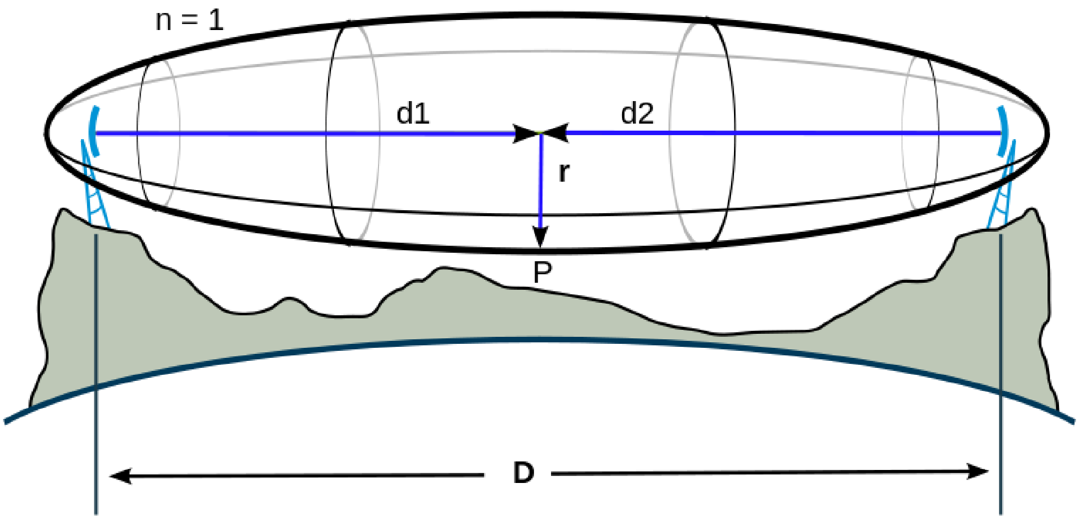


Figure 7. Fresnel zone (Microwave Link 2015).

Following equation can be used to calculate Fresnel zone radius for different zone indexes with different frequencies.

$$r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}, d_{1,} d_2 \gg n\lambda$$

Equation 6. Fresnel zone radius (Räsänen & Lehto 2003).

where $r_n$ is Fresnel's zone radius for nth zone, $n$ is zone index, $d_1$ and $d_2$ are distances from the transmitter and receiver respectively and $\lambda$ is the wavelength of the used frequency.

Very often Fresnel zone analysis is bypassed just by calculating the Fresnel zone radius $r_n$, and then comparing calculated Fresnel zone radius for available LoS conditions by using following generalizations:

1. Maximum obstruction allowable within the first Fresnel zone is 40% without significant loss (Proxim Wireless 2019; Microwave Link 2015).
2. Recommended obstruction within the first Fresnel zone is 20% or less to keep attenuation minimal (Proxim Wireless 2019; Microwave Link 2015).
3. If an obstruction reaches just to the direct line, attenuation is 6 dB (Räsänen & Lehto 2003).

Considering this toward the TUAS RDN where LTE operation is planned at band B28 (750 MHz), Figure 8 presents the $1^{st}$ and 2nd Fresnel zone radiuses for different link distances.

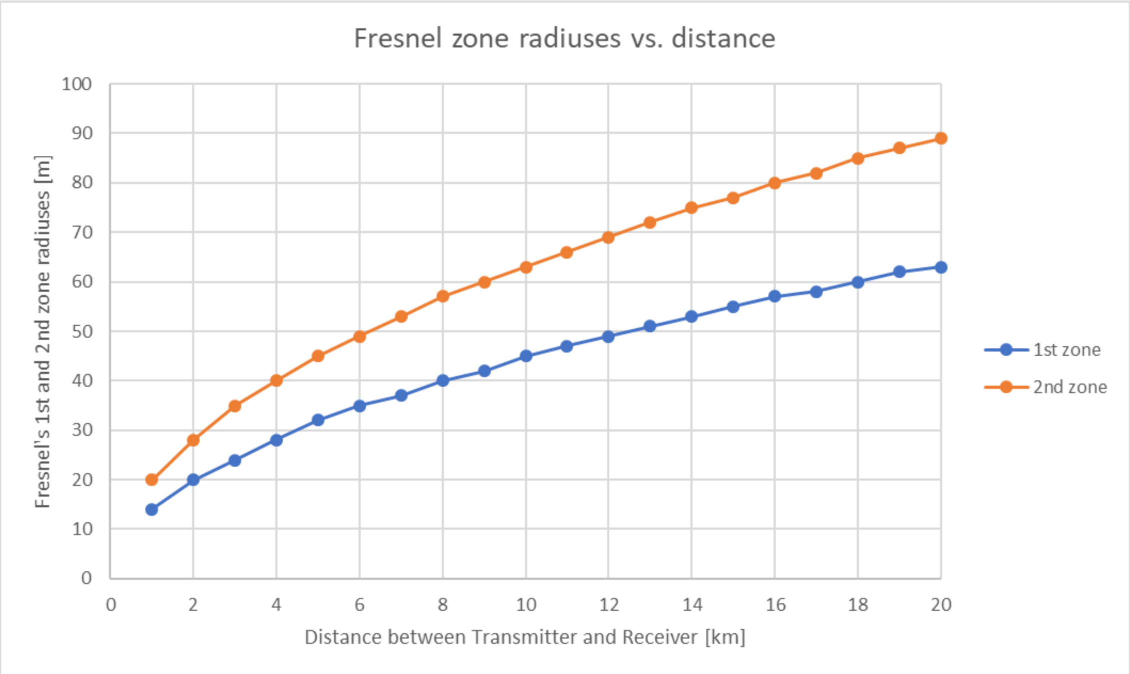


Figure 8. The first and second zone radiuses compared to the link distance.

After Fresnel zone is taken into account, Free Space Path Loss (FSPL) can be analysed for link budget calculations. Link budget is the budget of all gains and losses within a transmission path. Link budget need to be estimated in order to obtain knowledge of link capacity.

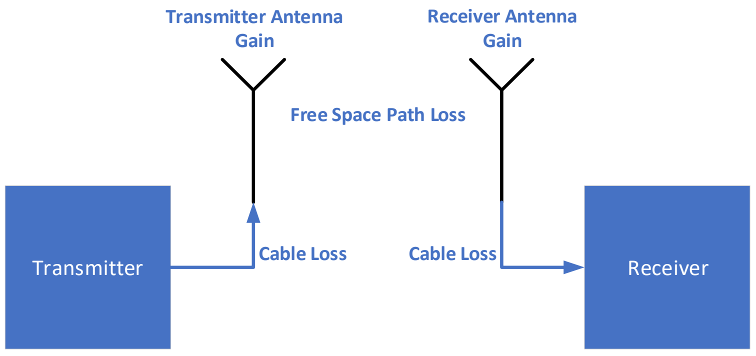


Figure 9. Transmission path losses

FSPL for the air interface, without taking antenna gains into account, can be calculated with the following formula:

$$FSPL = (\frac{4\pi d}{\lambda})^2$$

Equation 7. FSPL (Electronics Notes 2019).

where $d$ is distance and $\lambda$ is wave length of the signal. This formula depicts the fact that radiation follows inverse-square law. In other words, when distance is doubled, the surface area of the radiation sphere has increased quadruple making power density to drop to one fourth. As RF signals are handled usually in form of decibels (dB), FSPL can be calculated simply in the following way:

$$FSPL[dB] = 10\log_{10}(FSPL)$$

Equation 8. FSPL [dB] (Electronics Notes 2019).

To simplify calculations, link budget calculations can be extracted in to the following format and where parameters are distinguished to simplify calculations and now with antenna gains included:

$$FSPL[dB] = 20log_{10}(d) + 20log_{10}(f) + 20log_{10}\left(\frac{4\pi}{c}\right) - G_t - G_r$$

Equation 9. FSPL[dB] for full path (Electronics Notes 2019).

## 3.2 LOS link budgets

In this chapter estimations for TUAS RDN are presented for LOS scenario where LTE B28 (700 MHz band) is utilized with a goal to achieve 20 Mbps data rate. The assumption is that 10 MHz radio bandwidth is available from the operator. Based on chapter 2.1.1. 67 dBm is used for downlink EIRP and estimated to be achieved with help of 12 dBi antenna gain. 12 dBi is estimated as a realistic gain with directional antenna which would still allow adequate beamwidth for the purpose. For uplink device conducted RF power of 23 dBm is used with additional antenna gain of 3 dBi. Uplink client is considered as moving vehicle which requires omni-directional antenna, meaning 360° horizontal plane beamwidth. Used sensitivities for link budget calculations are -87 dBm at UE based on analysis in chapter 2.1.4 and for eNB -90 dBm as base station receivers actually has lower NF and therefore better sensitivity.

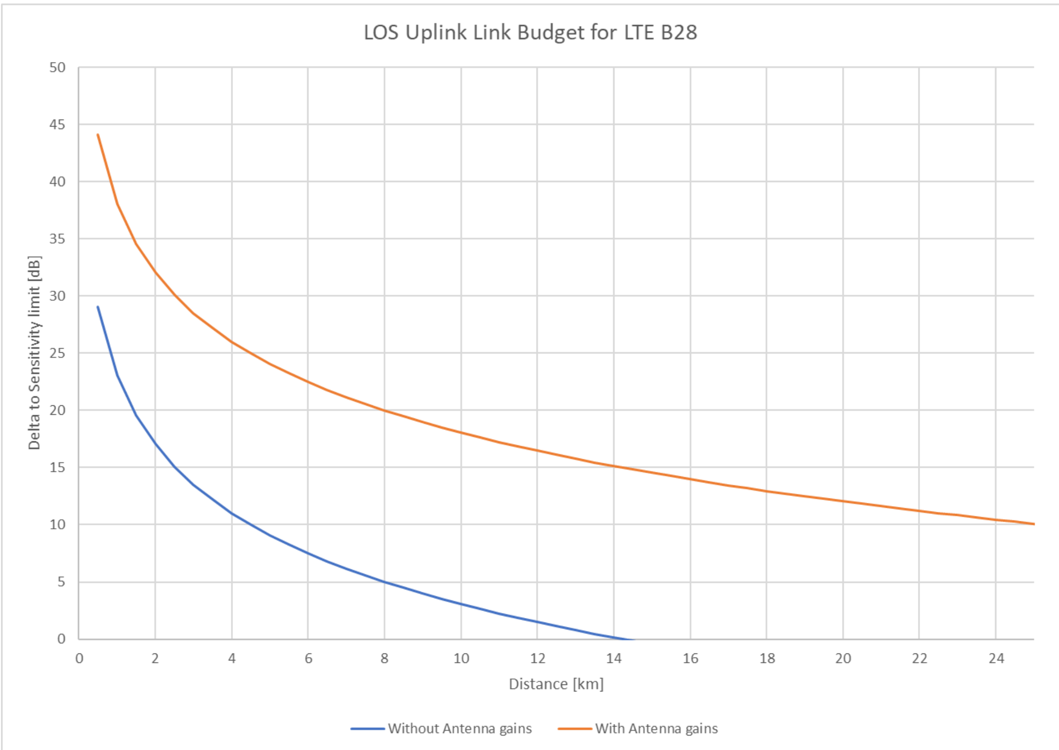


Figure 10. Transmission path losses

From the Figure 10 above it can be seen that theoretical FSPL figures are very favourable for 700 MHz band allowing several kilometre links even with omnidirectional antennas. Reserving a minor 6 dB margin would drop the estimated link to half but a modest 12 dB margin would be somewhat tolerable, but dropping estimated link to one fourth of original. Reserving an 18 dB margin would lead to dropping the estimated distance to one eight of the original. From the Figure 10 above it can also be understood why proper antenna planning is very important.

In the case of LTE B28 and by using presented antenna gain, where customer end device would have 3 dBi antenna gain and 26 dBm EIRP and operator side would have 13 dBi antenna gain, cautious estimation can be made that over 10 km link distances should be reachable with 20 Mbps uplink data rates when considering purely line of sight propagation model. This is with limitations of assumed 10 MHz radio bandwidth and channel reservation for single user.

Comparing these results to the shown Fresnel ellipsoid radius in Figure 7, it can be seen that pure line of sight connection is not feasible considering several kilometre links and when having relatively small vehicles where achievable antenna height is basically limited to below 20 m, or in case of very small vehicles even to few meters.

## 3.3 Different propagation models

In most cases, line of sight analysis is not enough, as propagation path is just not pure line of sight. Addition to LOS mode, also other propagation effects needs to be at least understood and often also taken into account.

Typically, the most significant effect is caused by multipath propagation, where the same signal is reflected on the surfaces within the transmission path and summed to the signal travelled directly. Depending on the phase of the reflected signal summing at receiver, it may assist the transmission or attenuate the signal. In marine cases two-ray propagation model is often used to depict the effect of reflected signal from the sea. Figure 11 below presents the two-ray model with H- and V-polarizations at sea environment. Figure 11. Two-ray model with H- and V-polarizations as sea (Hubert et al. 2012).It is showing the example of the case calculated for sea environment with two-ray model for 2.4 GHz. Used EIRP has been 1 Watt for the case where both antennas, receiver and transmitter are located at 6 meters above the sea level. (Hubert et al. 2012.)

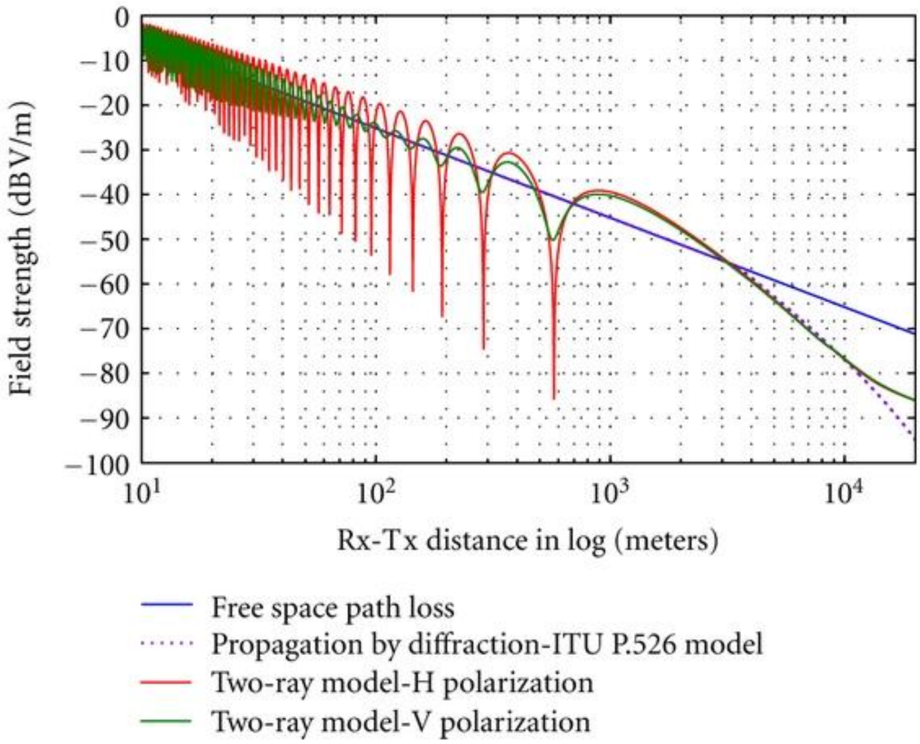


Figure 11. Two-ray model with H- and V-polarizations as sea (Hubert et al. 2012).

As shown in Figure 11, vertical and horizontal polarizations behave very differently, where horizontal polarization shows steep attenuation dips. To avoid problems caused by these steep and deep dips, vertical polarization is often considered more practical over horizontal polarization in sea environment. (Hubert et al. 2012; Anwar et al. 2012.)

In marine environment, effects of ship movements, rolling, pitching and heave, has also been studied for radio communication. Based on these studies heave (ship up and down movement) is seen as the most critical. This can be considered also from the perspective that height of the waves can be several meters and significant compared to the wavelength. (Huang et al. 2015.)

Additionally, frequency specific atmosphere effects, mainly in troposphere, may need to be considered. These effects include additional attenuations from different weather phenomenon like fog, rain, snowing, etc. In case of lower frequencies, VHF and below, also ionosphere effects start to be something which need to be taken into account.

This chapter is not showing any formulas related to multipath propagations as these subjects are beyond this thesis. Main purpose was to indicate that line of sight model for propagation is usually not sufficient but providing good indication what can be achieved.

## 3.4 Diversity, MIMO and Beamforming

Link budget calculations in previous chapters for line of sight was presented to provide the basic insight to estimate link budget. It is still a usable way to start to estimate link performance, especially for LTE uplink where in most cases only one stream is used. This is particularly the case for the researched topic where planned usage is for marine industry on sea environment. Single stream usage is still the case with many of the industrial level LTE devices which are typically category 4 device and do not support MIMO for uplink. Multiple Input Multiple Output (MIMO) was presented in 3GPP Rel 10. For Downlink, 3GPP Rel 8 already defined seven different transmission modes (TM) which includes diversity, MIMO and beamforming. Diversity, MIMO and beamforming are depicted in this chapter, just to provide overview of the techniques.

Diversity techniques are the techniques which utilizes the benefit of multiple antennas and sending the same data via multiple antennas with different coding to gain better signal to noise ratio.

MIMO is a technique in radio communication where same piece of radio spectrum in the same time slot is used to carry multiple individually coded streams. These streams are often called spatial streams and technique to re-use the spatial domain is also called a spatial multiplexing. Maximum number of usable streams depends on the number of antennas used by the transmitter and receiver. Every stream must have its own antenna at transmitter and receiver. So, for example, with four antennas at transmitter end and four antennas at receiver end, it is theoretically possible to use four different simultaneous, spatial streams. Channel conditions are evaluated by the receiver and by using a channel matrix which contains channel impulse responses for all antenna combinations. This information is provided to the base station via uplink control signaling. If the radiation path between different antenna combinations are too correlated, all possible spatial streams cannot be used. So, MIMO is actually taking the benefit out of the multipath propagation. In line of sight communication where multipath propagation does not have significant effect, antenna polarizations are typically used to achieve distinguishable radiations paths. By using polarization, maximum isolation (minimum correlation) can be achieved by making a 90-degree alignment between the antennas. In LTE, downlink MIMO is widely used as complexity lies on the base-station side and user equipment complexity can be kept at a feasible level. Addition to LTE modulation techniques where downlink modulation allows higher data rates compared to uplink, heavier MIMO utilization for downlink side just increases the asymmetricity of the link. This can be considered as a logical approach as demand for downlink capacity has been typically increased more heavily due to increasing download streaming (YouTube, Netflix, Spotify, etc.).

Beamforming is a technique where two or more antennas are used to amplify the signal toward certain direction(s) and attenuate it toward the other direction(s). This can be achieved by phasing the transmissions for antennas so that they amplify each other a certain direction and canceling each other in a certain direction. In LTE, beamforming does not play an important role but particularly for TDD band where Tx and Rx works at the same frequency and as propagation path is assumed reciprocal meaning channel characteristics are the same for both directions, UE-specific reference signals for beamforming has been specified as a mandatory feature to be supported.

Multi-User MIMO (MU-MIMO) is a technique which can benefit from both above mentioned techniques, MIMO and beamforming. In MU-MIMO the base station is transmitting for two (or more) UEs within the same time slot and the same piece of spectrum. For this, a base station is required to have channel matrix for individual UEs by utilizing multipath propagation for individual UEs. (Geßner 2011.)

## 3.5 RSSI, RSRP and RSRQ

Due to their importance for actual field testing and system tuning, LTE Received Signal Strength Indicators (RSSI) are covered here specifically.

LTE radio frame structure is explained in chapter 2.5. It was noted that LTE signal consists of 10 ms radio frames which are divided to 1 ms subframes and which are divided further to 0.5 ms slots each carrying seven OFDM symbols. One OFDM symbol is an ensemble of orthogonally modulated subcarriers and in LTE, 12 subcarriers constitutes a unit called Resource Block (RB). The piece of OFDM symbol in one subcarrier is called Resource Element (RE) and it is the smallest information unit in the time-frequency domain in LTE. Some of the resource elements are needed to use for channel estimation and synchronization in order to keep the receiver synchronized and optimized for reception. Signals used for channel estimation are called Reference Signals (RS) and these are carried on frequency domain in pre-defined subcarriers and on time domain in predefined resource elements. On frequency domain every sixth subcarrier and on time domain two OFDM symbols per 0.5 ms slot are used to carry reference signals for the first two antenna ports. (Geßner 2011.)

RSSI is a Received Signal Strength Indicator. Traditionally it depicts the RF-power received over full reception bandwidth including noise and interferences. This is also how it is defined within LTE: RSSI is a measure of RF-power received over full reception bandwidth. RSSI is reported from -25 dBm to -100 with a 1 dB resolution. (ETSI 2018b.)

RSRP is Received Signal Reference Power and it is the average power of all reference signals (RS) over all subcarriers and so depicting the average power for single RS. Values can vary from -44 dBm to -156 dBm and it is reported with resolution of 1 dB. (ETSI 2018b.)

RSRQ is Received Signal Reference Quality indicator and it is a quality indicator which depicts relation of RSRP to RSSI so that RSRP is calculated to match the same bandwidth as RSSI. So RSRQ is calculated from RSSI and RSRP following way:

$$RSRQ = {}^{N\ x\ RSRP}/_{RSSI}$$

Equation 10. RSRQ (La Rocca 2016).

where $N$ is the number of resource blocks, $RSRP$ is measured average power for a single RS, and $RSSI$ is received power over full bandwidth.

For 20 MHz bandwidth where 100 RBs are used this would lead to a theoretical 30.79 dB difference between RSRP and RSSI. In the case of 10 MHz band difference is logically 3 dB smaller. With a single reception antenna, maximum RSRQ would be -3 dB when there is no traffic addition to RSs on the channel, as then only 2 x RS power is measured per RB for RSSI compared to single RS power for RSRP. On the other hand, minimum RSRQ without additional interferences and for single antenna reception would be -10.8 dB due to a minimum ratio of 1/12. With two reception antennas, in case of dual stream MIMO, maximum RSRQ would be -6 dB due to doubled amount of RS increasing measured RSSI. Minimum RSRQ for two antenna case, without additional noise, would be -13 dB due to relation of 1/20. This relation of 1/20, in the case of dual stream MIMO, is because both spatial streams has two RSs but they are not overlapping between the streams in the frequency domain. When antenna 1 (stream 1) is transmitting its RSs, corresponding REs in frequency domain at antenna 2 (stream 2), are not transmitting and vice versa. This leads to the situation where four RS are occurring on 24 possible REs (12 REs for both streams) and so four are contributing RSSI as carrying RS and four are not sending at all. (La Rocca 2016; Christina Geßner 2011.)

## 3.6 Antenna Temperature and interferences

Effects of possible interferences has not been taken into account in the shown link budget calculations.

Commonly used standard temperature of 290 K for earth has been used for presented noise-based calculation shown in chapter 3.1.4. Sometimes additive noise coming from external sources such as atmosphere or galactic sources are presented as antenna noise temperature $T_A$ and thus summing up to the noise load:

$$T_S = T_A + T_R$$

Equation 11. Antenna noise temperature.

Where $T_S$ is combined noise temperature and $T_R$ is receiver noise temperature. This is purely consuming $S/N$ ratio and affecting the link budget. However, it is to be noted that when assuming 290 K as base level for the receiver, additional 290 K of $T_A$ from antenna or air interface would cause an additional 3 dB loss of $S/N$. (Räsänen & Lehto 2003.)

# 4 APPLICATION LEVEL MEASUREMENTS

This chapter depicts the basic application level measurements, tools and methodologies used for TUAS RDN verification. Following sub-chapters also depict basic network tools used and which are well known from Unix / Linux toolbox and are widely used for different network related analysis, configuration and problem solving.

### 4.1.1 Time synchronization

Time synchronization is mandatory for devices used for network measurements and where a time domain based analysis of the results is expected. With proper time synchronization it is possible to use computer time to timestamp result files and keep results comparable for the time domain analysis. Typically, it is also mandatory to keep clock synchronized for cryptographic and logfile usage.

Chrony is an application for Linux, BSD, macOS, and Solaris systems and can be used to obtain or provide time synchronization over a network. By default, it works as a client and polls time from specified time sources. Time sources can be NTP servers, PC Real Time Clocks (RTC) and other sources providing reference clocks like GPS. Chrony can be configured to work as an NTP server and enables it to be used as a time source for other devices located on the same network. Chrony constitutes a pair of programs where one is *chronyd,* a daemon working as a background application, and the other is *chronyc,* a command-line tool. (Chrony 2019.)

As Ubuntu based Linux distros (mainly Linux Mint 19) have been used for network measurement and testing, it is to be noted that since Ubuntu release 16.04, the default time synchronization application has been *timedatectl.* However, *timedatectl* does not provide NTP server functionality so chrony was used instead. It is also to be noted that according to Ubuntu documentation (Time Synchronization): ”*If chrony is installed timedatectl steps back to let chrony do the time keeping*” (Ubuntu 2019a).

In case of TUAS RDN measurements, Chrony is used as an NTP client at both measurement PCs as both can access public Internet and fetch time from the public NTP server. Used public NTP server was time.mikes.fi. Chrony was selected to be used for time synchronization to prepare the solution for future usage, where closed network structure without access for Internet would be used. In a closed network structure, Chrony would be used to connect the PC to a modem working as an NTP server, providing time to clients. Modem's own clock would be synchronized from the integrated GPS receiver.

### 4.1.2 Iperf

Iperf is the most used tool to perform network performance measurements and testing. It is also suitable to assist in different network performance and parameter optimizations. In addition to throughput measurements, by default, it can also be used to analyze jitter, packet loss, packet order errors, TCP windowing and retransmissions. With iperf, it is possible to select between TCP and UDP, and with iperf3 also SCTP. In addition to protocol selection, it is possible to select IP port for the iperf traffic, which is a very handy feature for firewall and QoS testing. Iperf can also be used to check the effects of multiple parallel streams, in which case different stream are handled in different IP ports at client side.

There are two versions of iperf. The first one is iperf2 which has reached version 2.0.13 (SourceForge 2019) and the second one is iperf3 which has reached version 3.7 (ESnet 2019). Iperf2 and iperf3 are not compatible, but both versions carry the same basic set of features and usage of them is almost the same. Usually, both iperf versions are used from the command line but there are also graphical user interfaces available which reuse the shell binaries. It is also possible to build own scripts which utilizes the iperf binaries and this is how it is used in the measurements performed.

For the basic use where relatively low data rates are used, it does not make a difference which version is used. However, iperf2 is officially supported in Windows and the latest version is available as binary version whereas iperf3 is not officially supported for Windows. There are Windows binaries available till version 3.1.3, but as the latest version is 3.7, it is missing some error correction and interesting and useful features. Available iperf binaries should also be possible to build for Mac OS. Based on this, iperf2 is recommended for Windows and for Linux (and Mac OS) either one can be used and selection can be made based on specific need.

The most obvious differences between iperf2 and iperf3 are multithreading in iperf2, which means that the iperf server can serve several clients simultaneously whereas iperf3 is only able to serve one client at a time due, to being single threaded. Another significant difference is that iperf3 uses so called controller connection to start, stop and exchange results between the server and client. This is done via the same port numbers as used for measurement traffic but data exchange is always with TCP regardless of selected protocol for actual testing. This makes it impossible to establish a connection between the server and client in cases where only UDP traffic is allowed, like in firewall testing for example. Another case where iperf3 usage is not possible is the case where only single directional traffic is possible. Typical examples of this kind of tests would be port mirroring testing and also some specific routing testing. One of the advantages of iperf3 is a feature called reverse-mode. Iperf client initializes the connection and is typically the one which sends data to the server. With iperf3 reverse mode, the client is still used to initialize the connection but with an argument it can command the server to be the one that sends data. This is an especially good feature when measuring in the case where another end is behind a NATted network. (SourceForge 2019; ESnet 2019.)

### 4.1.3 Ping

Ping is the basic network tool which is used to check the reachability of active network elements which have IP-addresses, like servers, hosts, routers and managed switches. Ping utilizes the ICMP protocol on the IP-layer and particularly *ICMP echo request* and *ICMP echo reply* -messages. The ping initiator sends an ICMP echo request packet targeted to the IP address, which reachability is wanted to test. An ICMP echo request consist of an 8-byte header and typically a 56-byte payload. The packet header has an identifier number which is specific for a started ping process and increasing sequence number. These are copied by the receiver to the ICMP echo reply message in addition to the received payload. Based on this information, the ping initiator knows to which request the received reply belongs to and then knows if part of the packets have been lost. This will also cause linear data flow in both directions as data payload is also copied and sent back to the initiator. Even it is basically meant to be used to check reachability and round-trip time (RTT) for network elements, possibility to affect payload size and transmission interval, it can also be used for loading the network with certain fixed amount of data flow. (Ubuntu 2019b.)

For example, the following command:

*sudo ping 192.168.1.1 -i 0.01 -s 16384* would cause continuous data flow of around 13 Mbps for both, uplink and also for downlink, assuming the device pinged is responding to ICMP queries.

Ping tool is meant for checking network element reachability and round-trip time like mentioned before, but it can also be used to check clock offsets between the devices when using timestamp options. With this mode, raw timestamps at different phases at ICMP echo message are stored in the payload part. (University of Delaware 2012; Ubuntu 2019b.)

For example, the following command:

*sudo ping 192.168.1.1 -T tsandaddr -i 0.5*

would produce the following output:

*PING 192.168.1.1 (192.168.1.1) 56(124) bytes of data.*

*64 bytes from 192.168.1.1: icmp_seq=1 ttl=64 time=1.57 ms*

| | | |
|---|---|---|
| *TS:* | *192.168.1.211* | *70359943 absolute* |
| | *192.168.1.1* | *-121* |
| | *192.168.1.1* | *0* |
| | *192.168.1.211* | *123* |

where 70359943 is the absolute timestamp at sending end depicting milliseconds since midnight. -121 is receiver’s time difference to sender’s timestamp. 0 is receiver timestamp for ICMP echo reply message, and 123 is sender’s time difference to receiver’s timestamp. Offset and delay can be calculated as following:

$$offset = [(T2 - T1) + (T3 - T4)] / 2$$

$$delay = (T4 - T1) - (T3 - T2)$$

Equation 12. Offset and delay from ping timestamps (University of Delaware 2012; Ubuntu 2019b).

In addition to latency, RTT is important figure as it affects TCP data throughput together with buffer settings as following:

$$Throughput\ [Mbps] = \frac{CWND\ [Mb]}{RTT\ [s]}$$

Equation 13. Effect of RTT to TCP throughput (Johnson 2017).

where $CWND$ is a TCP congestion window and $RTT$ is a round trip time. CWND is a measure which depict how much data can be send to the path without acknowledge from the recipient. CWND is maintained by the sending end and it is dynamically tuned according to feedback from the receiver. If CWND is limited due to low receiving or transmitting buffers, it affects to CWND and so to the TCP throughput performance. (Johnson 2017.)

### 4.1.4 Modem monitoring and SNMP

Advantech SmartFlex SR308 is the modem which was selected to be used for the measurements. Selection was based on previous experience of the same manufacturer's devices. Previous experience is from a different model which used different LTE band configuration but which has the same operating system and same configurability.

The SmartFlex modem is an LTE Category 4 device compatible with 3GPP Rel 11. SmartFlex is specified to be able to deliver Cat. 4 performance meaning 150 Mbps downlink and 50 Mbps uplink. These values are theoretical values and typically referred as L1 level values meaning rates without taking account overhead coming from signaling and coding.

Rationale for selection is based on device's functionality and relatively easy configurability and controllability. Especially important is controllability which makes it possible to configure it to work with an automated measurement system. Equally important are monitoring features available via the control interfaces. With SmartFlex modems, a good range of cellular related parameters are available via SNMP. Selected parameters to monitor and record are: technology, channel, cell, operator, RSRP, RSRQ, status, voltage, temperature, byte counter for incoming data and byte counter for outgoing data. All these values are read every fifth seconds and written to the result file with a timestamp.

### SNMP

Simple Network Management Protocols (SNMP) is a protocol working over UDP and is used for device management. Basic SNMP functionality is based on query-response principle where a separate SNMP manager is polling an SNMP agent in the network device. SNMP agents are programs running on network devices and collecting device specific information and then providing this information if SNMP manager is polling it. Information is sorted based on OIDs, Object IDs and SNMP manager can poll information either based on single OID or by a group of OIDs. It is also possible to use SNMP to configure devices. In such a case, SNMP manager is querying a specific OID with a value it wants to write. A typical example of the write operation, is shutting down a certain switch port and a typical example of the reading operation is polling data counter of a certain switch port.

Currently there are three different version of SNMP: v1, v2c and v3. Version 1 can be considered as obsolete and v3 as recommended, as it provides encryption and authentication. Version 2 does not provide any actual security features, only very light authentication where SNMP manager has to know SNMP community name in order to get its queries to SNMP agent. Typically, read- and write access are separated to have different community names but this does not provide any actual security as all information including community names are transferred as plain text. SNMP version 3 is recommended if any level of security is wanted. UDP port 161 is reserved for SNMP agents to listen for queries from the SNMP managers. (ManageEngine 2019.)

SNMP traps are messages which are sent automatically by SNMP agents if configured to do so. This enables to obtain information about different changes of device states or receiving status report on fixed time intervals without the need to poll them separately and continuously. SNMP traps are sent via UDP and SNMP agents reserve port 162 for this purpose. (ManageEngine 2019.)

## 4.2 Measurement control

Typical test setup used for cellular network measurement is shown in Figure 12. Main role in this kind of arrangement is set to the part which is named here as *Mobile Setup*. This mobile part consists of a PC and a modem. In addition to the modem’s ability to provide required connectivity to the mobile network, it should be capable of providing the required monitoring functions for the network parameters.

Counterpart and endpoint for the measurements initiated from the *Mobile Endpoint* is the PC immediately behind the *TUAS RDN Setup* and the *Router* connected directly to the *LiteEPC*. This PC, *Local Endpoint*, is visible to the mobile setup by the routing of the *LiteEPC* and *Router*. This dedicated *Router* is also used to provide Internet connection for the *TUAS RDN Setup*. Cellular mobile network is NATting the traffic from the external network to the UEs, which is typical behaviour also in the case of public consumer mobile networks. This means that without separate arrangements, for example VPN tunnel or port forwarding, connection initialization can be made only from the *Mobile Setup* side. Due to this reason measurement controlling tasks are set to the PC at the *Mobile Setup*. This PC can initialize the connection for the *Local Endpoint* PC and controlling commands can be simply passed via a separate IP-socket or even via telnet or SSH. In the case of a typical public cellular mobile network, where public service providers are operating the networks, it might be very difficult to have a PC as a measurement endpoint directly connected to the EPC. In this case, a PC working as *Remote Endpoint* is needed and can be reached via public IP. However, in this measurement arrangement, it cannot be known exactly which part of the network is actually limiting factor if it differs from the expected.

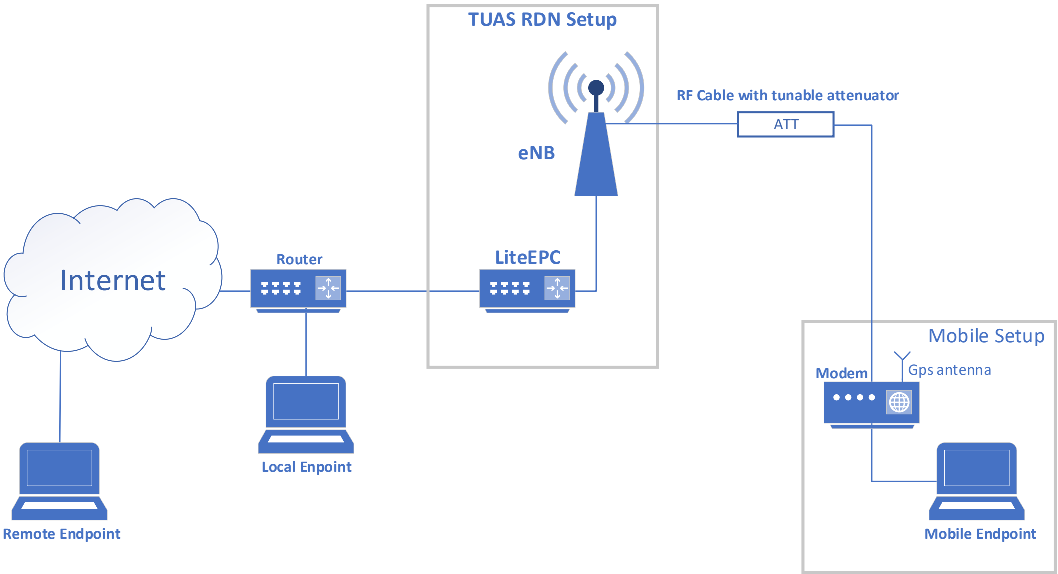


Figure 12. TUAS RDN setup at testing.

Figure 13. depicts the control flow for the measurements. The control flow can be followed manually by initiating tasks separately or it can be automated. An automated method is recommended to guarantee consistent setup and results. Different loggers can be single commands, scripts or applications written specifically to handle the task. Measurements can be set to finish with timeout or in case control flow is automated, it can be stopped by the controlling element. Results can be optionally collected automatically by the element controlling the measurement. *Mobile Setup* uses SSH for controlling tasks at the *Local Endpoint* or at the *Remote Endpoint*. Rsync is used for transferring the scripts and results between the measurement nodes.

In case of iperf, which is used for throughput measurement, server-side application must be started first. For Downlink measurements iperf3 needs to be used as it supports reverse mode. Reverse mode is required to allow iperf client from *Mobile Setup* to initialize connection and to command the server running at *Local Endpoint* to send traffic.

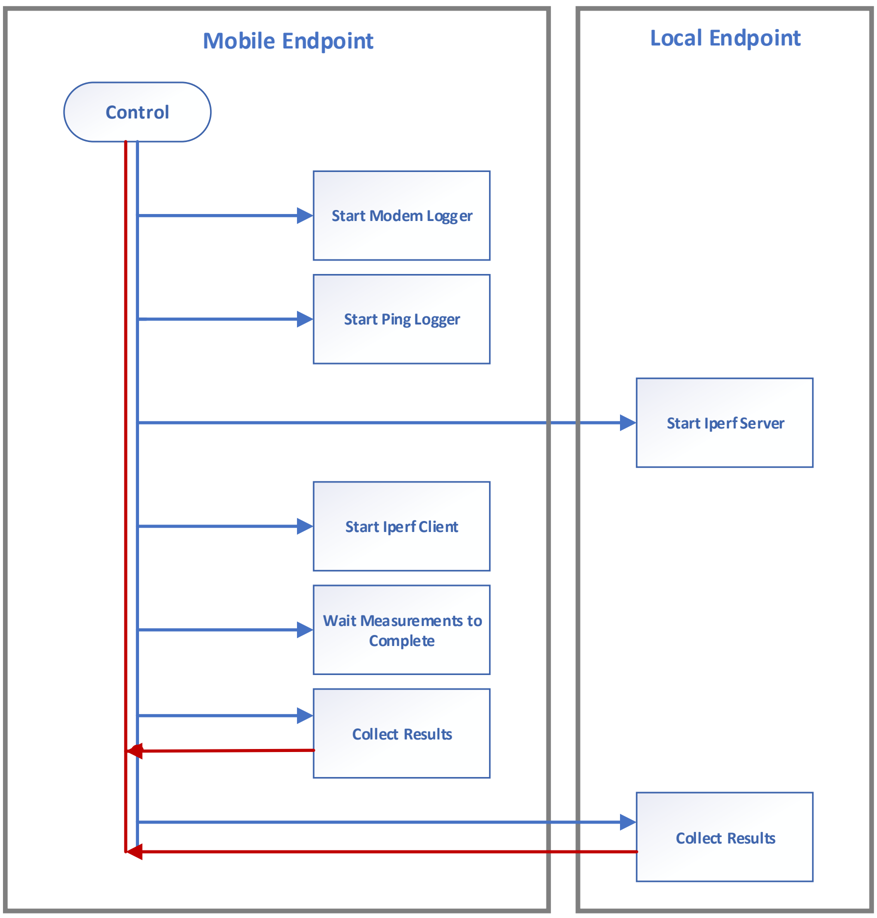


Figure 13. Control Flow for the Measurements.

## 4.3 Test Scenarios and Test Plans

Measurements were originally planned to be performed in the field. Due to licensing issues of 700 MHz B28, it was required to change measurements plan to match performed measurements as conducted measurements inside the TUAS lab. These field measurements were originally planned to show real life performance of TUAS RDN when used with 700 MHz LTE band 28 and to gain insight into how measured values match expected, theory-based values. Secondary purpose was to gain insight into Advantech B28 LTE modem. These measurements were performed at TUAS Radio Laboratory at Turku, Joukahaisenkatu site.

## 4.4 Test Plans

When considering system verification measurements, it is good practice to create a test plan which depicts what the purposes of the measurements are and which also defines exact steps to produce the measurement scenarios. This approach makes it possible to reproduce the measurements later in a consistent manner and is also something that can be interpreted to be required as a part of the quality processes. It also makes it possible to later analyze what was measured. and consider is new type of measurements required when new features are presented and imported to the system.

Certain measurement and related documentation are required by the classification process as described later in chapter chapter 5.5.1. However, these measurements depicted here are research and development type measurements meant for development purposes, even though they could possibly be used to partially cover the official measurements.

The following chapter presents three test scenarios that were planned and executed. Linux bash shell script was used to control the measurements in a way presented in chapter 4.2.

### 4.4.1 Test Case 1: Maximum Downlink and Uplink Throughput

**Rationale:**

- To see maximum realized application level data throughput with given radio resources, at different signal levels.
- To see throughput and latency variations with given radio resources at different signal levels.
- To see RSRP and RSRQ behaviors with different signal levels.

**Test case defaults for measurements:**

- No other UEs connected to the eNB.
- Test time for single measurements is 100 s.
- Measurement Interval for throughput is 0.1 s.
- Measurement Interval for modem logger is 5 s.
- Measurement Interval for ping is 1 s.
- Test is to be repeated for TCP and UDP protocols.
- Test is to be repeated for uplink and downlink directions.
- Test is to be repeated for signal levels producing RSRP values from -80 dBm to -110 dBm with 15 dB steps. These values correspond approximately total average power values at the phone’s antenna port from -53 dBm to -83 dBm and at the base stations from -68 dBm to -98 dBm due to fact that eNB Tx power is +39 dBm and UE Tx power is +24 dBm.

**Measurement steps:**

1. Tune the RF attenuation so that measured RSRP at the modem is according to the test step.
2. Start modem logger script with extended test time of 10 s.
3. Start the ping script with extended test time of 10 s.
4. Start iperf Server.
5. Start iperf Client.

6. Wait for the measurement to complete.
7. Collect the produced log files.
8. Repeat steps 1. – 7. for all signal levels and protocols for uplink and downlink directions.

### 4.4.2 Test Case 2: RSRQ vs. RSRP

**Rationale:**

- To see RSRP and RSRQ behavior with different data loads with high and low signal levels.

**Test case defaults for measurements:**

- No other UEs connected to the eNB.
- Test time for single measurements is 100 s.
- Measurement Interval for throughput is 0.1 s.
- Measurement Interval for modem logger is 5 s.
- Measurement Interval for ping is 1 s.
- Test is to be performed with UDP protocol.
- Test is to be repeated for uplink and downlink directions.
- Test is to be repeated for signal levels producing RSRP values from -80 dBm to -120 dBm with 20 dB steps. These values corresponds approximately total average power values at the phone’s antenna port from -53 dBm to -93 dBm and at the base stations from -68 dBm to -108 dBm due to fact that eNB Tx power is +39 dBm and UE Tx power is +24 dBm.Test is to be repeated for UDP data rates of 0-, 1-, 8-, and 16 Mbps and for maximum data rate (overloading the channel).

**Measurement steps:**

1. Tune the RF attenuation so that measured RSRP at the modem is according to the test step.

2. Start modem logger script with extended test time of 10 s.
3. Start the ping script with extended test time of 10 s.
4. Start iperf Server.
5. Start iperf Client with selected data rate.
6. Wait for the measurement to complete.
7. Collect the produced log files.
8. Repeat steps 1. – 7. for all signal levels and data rates.

### 4.4.3 Test Case 3: Multiple UEs loading the eNB

**Rationale:**

To see RSRP and RSRQ behavior at DUT when other UEs loading the eNB.

- To see effect for maximum throughput for DUT when other UEs are just connected to eNB without loading it.
- To see how capacity is shared between the UEs and DUT when both loading the network.

**Test case defaults for measurements:**

- Test is performed via air interface using antenna after the tunable attenuator.
- Test time for single measurements is 100 s.
- Measurement Interval for throughput is 0.1 s.
- Measurement Interval for modem logger is 5 s.
- Measurement Interval for ping is 1 s.
- Test is to be performed with UDP protocol.
- Test is to be repeated for uplink and downlink directions.
- Test is to be performed with signal level producing RSRP value of -90 dBm. This value corresponds approximately total average power value of -63 dBm at the phone and -78 dBm at the base station due to fact that eNB Tx power is +39 dBm and UE Tx power is +24 dBm.

**Measurement steps:**

1. Place the modem close to eNB’s antenna and tune the RF attenuation so that measured RSRP at the modem shows about -90 dBm. Set the phone so that it is also showing about -90 dBm RSRP.
2. Start modem logger script with extended test time of 10 s.
3. Start the ping script with extended test time of 10 s.
4. Start iperf Server for the DUT and for the Phone at the local endpoint PC.
5. Start iperf Client at phone to send TCP data for 60 s.
6. Wait 30 s. and start iperf Client at modem setup to send TCP data for 60 s.
7. Wait for the measurements to complete.
8. Collect the produced log files.
9. Repeat steps 2. – 8. for download by using iperf3’s reverse mode.

## 4.5 Measurement results

### 4.5.1 Results for the Test Case 1

**Downlink results**

Downlink throughput was measured to be around 35 Mbps with TCP and UDP. UDP provided more stable and consistent data flow showing 35.35 Mbps average throughput with a standard deviation of 0.44 Mbps, which would mean that 99.9 % of results should fit within ± 1.5 Mbps variation of average if considering results are distributed according to standard normal distribution. Results for the TCP showed short 0.1 … 0.3 s “black-outs” and which would destroy statistical evaluation as such. It was noted that data was actually buffered, and then recovered after “black-outs” making the average very close to the same regardless of the “black-outs”. Statistical analysis was made to obtain a comparison between the UDP and TCP results. TCP throughput average shows 34.77 Mbps figures without any data manipulation and 34.78 Mbps average by cleaning the “black-out” periods. For cleaned TCP data, standard deviation is 0.31 Mbps leading to the estimation where 99.9 % of results should fit within ± 1.0 Mbps variation of average if considering results are distributed according to standard normal distribution. For cleaned TCP data, it is shown in Figure 14. below that results are actually following standard normal distribution model quite well.

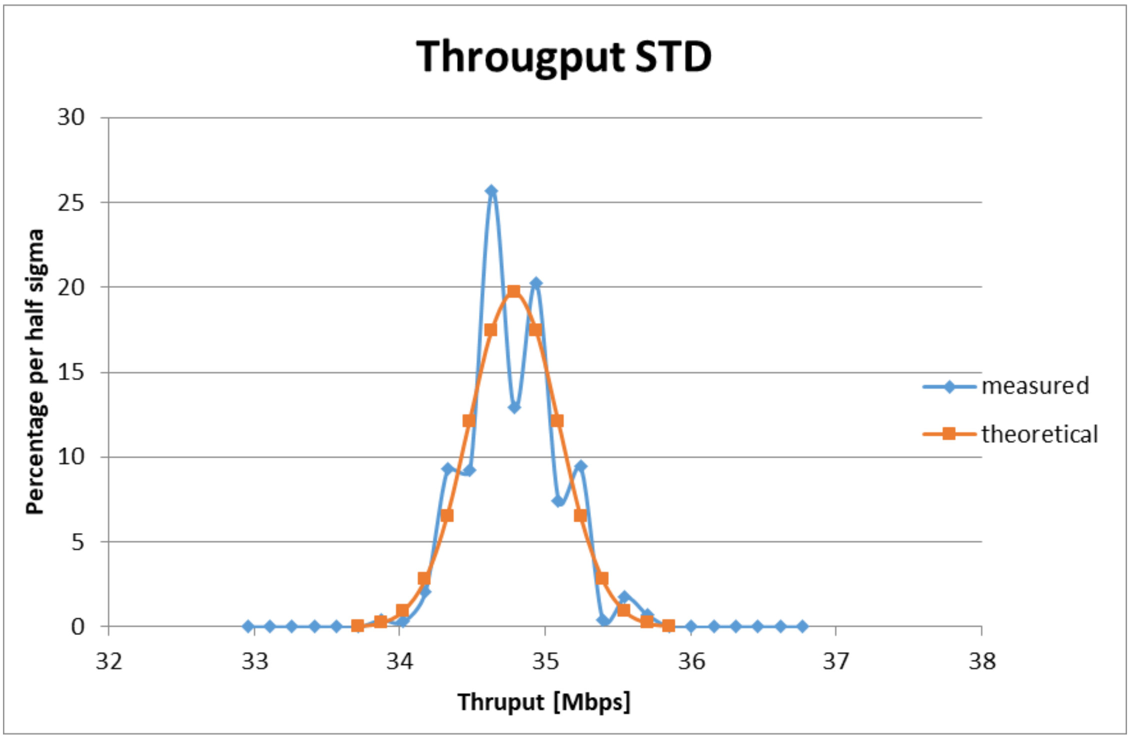


Figure 14. TCP throughput distribution for data cleaned of “black-outs”.

“Black-out” periods during the TCP transmissions were discovered to be independent to signal level and discovered with every signal level. Figure 15. below shows the graph where throughput is a presentation of receiving end data flow and where CWND is a measure of sending ends TCP congestion window (CWND). In detailed graph, in the Figure 16, it can be seen that throughput and congestion window starts to drop exactly at the same measurement cycle. However, it needs to be noted that the CWND is a measure of sending end and the throughput is a measure of receiving end. The Phenomenon is probably caused by the receiving end modem or computer and not the cellular link itself. Receiving end computer or modem can be assumed to be buffering the data before the protocol stack is providing the data to application level. This is assumed by the fact that after the “black-out” all the missing data is received by the application just within one 0.1 second period which corresponds over 100 Mbps momentary throughput rate and which is not possible for the cellular link used for the test. It is also assumed that receiving end buffer starts to fill when application (iperf) is not receiving the data and as the receiving end is actually indicating this to the sending end via ACKs and according to TCP communication procedure, and then starts to mitigate congestion window and amount of data send on the line.

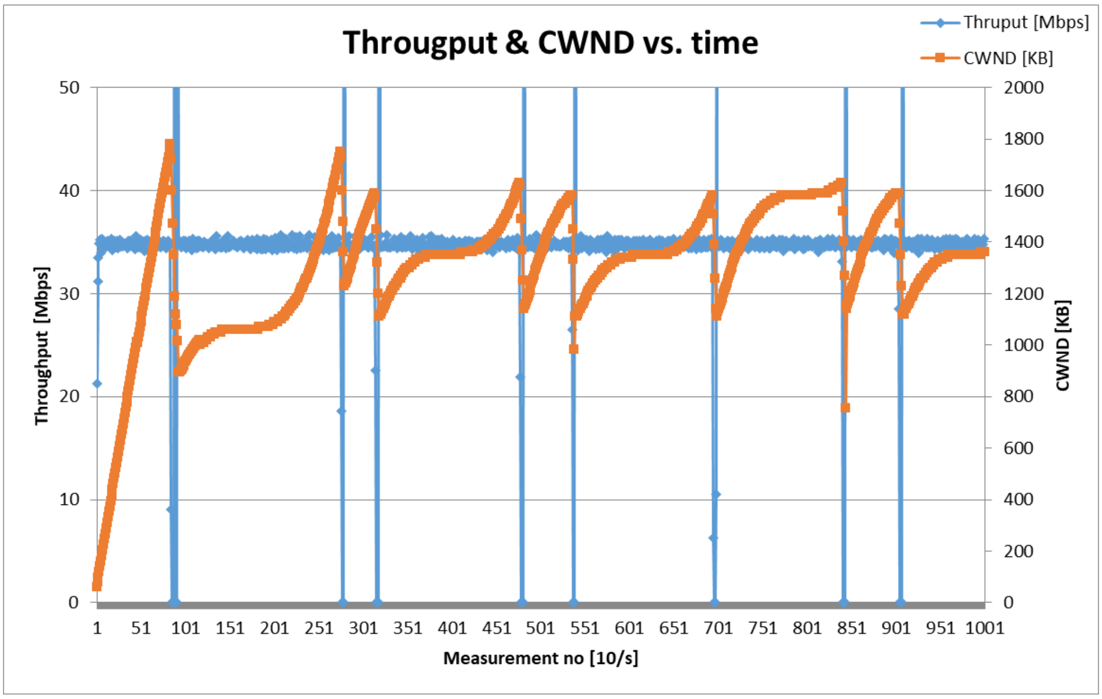


Figure 15. Effect of TCP Congestion Window (CWND) to throughput.

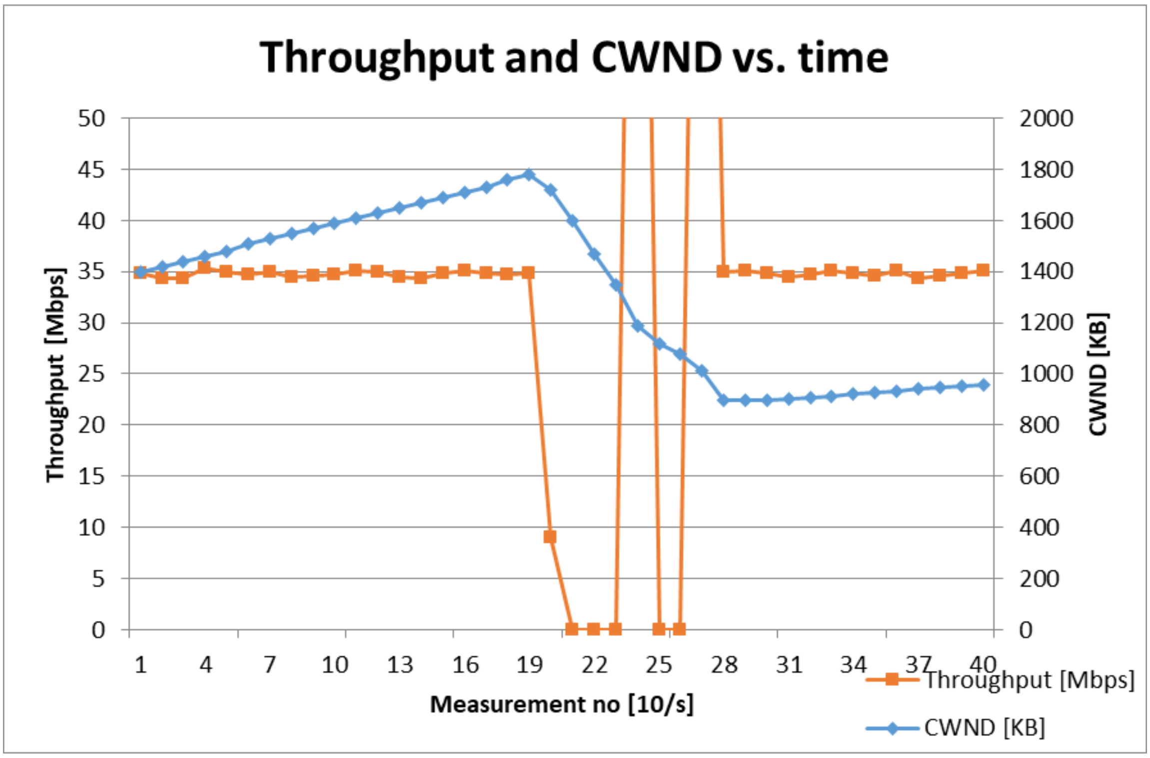


Figure 16. Effect of TCP Congestion Window (CWND) to throughput.

For curiosity, it is noted here that also round-trip-time (RTT) was seen to follow the TCP congestion window behaviour extremely accurately as shown in Figure 17. below.

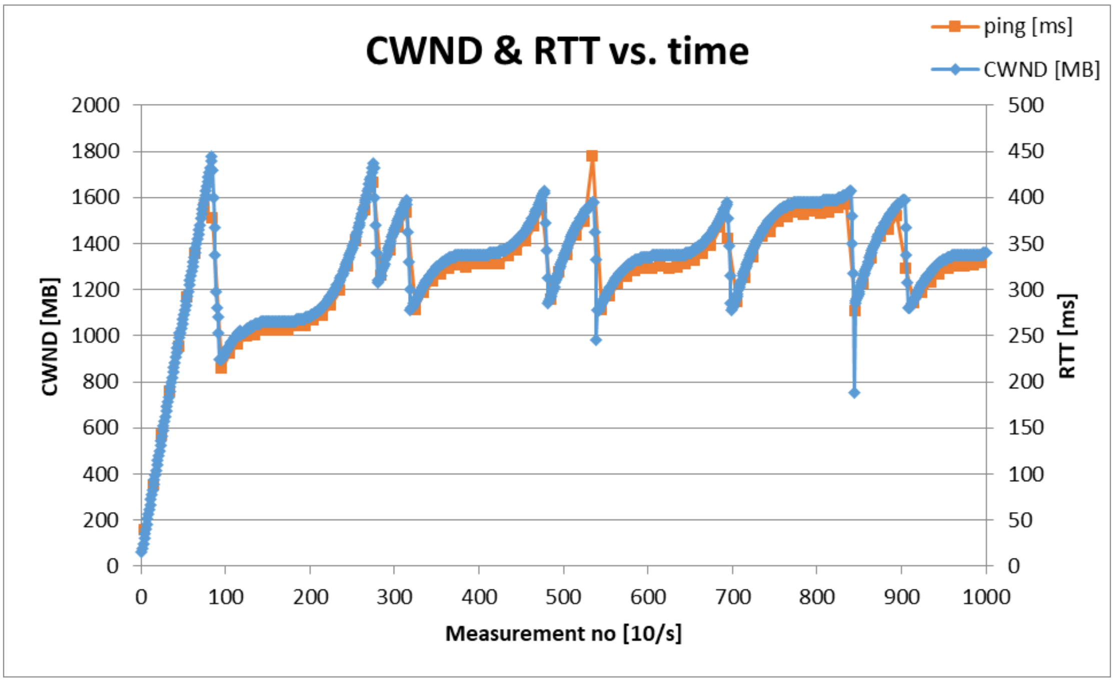


Figure 17. TCP Congestion Window (CWND) vs. Round Trip Time (RTT).

RSRP values were stable over the throughput measurement and remained during the loading situation exactly where it was tuned without data loading. RSRQ figures shows however changes were in most parts direction of the change and magnitude of the change were as expected. A good example is RSRQ figures during TCP downlink, measurement shown in Figure 18 below, and where beginning two measurement are from the case where data loading is not yet started and where RSRQ values drops immediately when maximum download capacity is used. However, it requires some more analysis to explain why RSRQ is not behaving in a consistent manner regarding of the signal level.

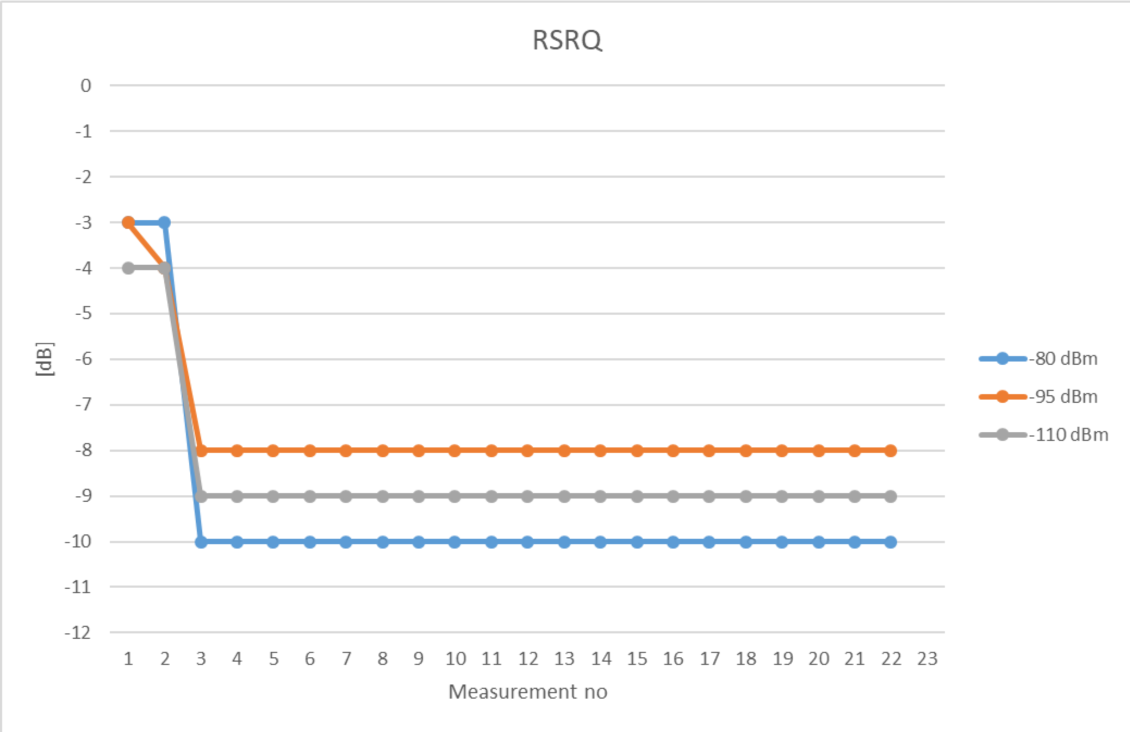


Figure 18. RSRQ behaviour with maximum TCP downlink load vs. different RSRP levels.

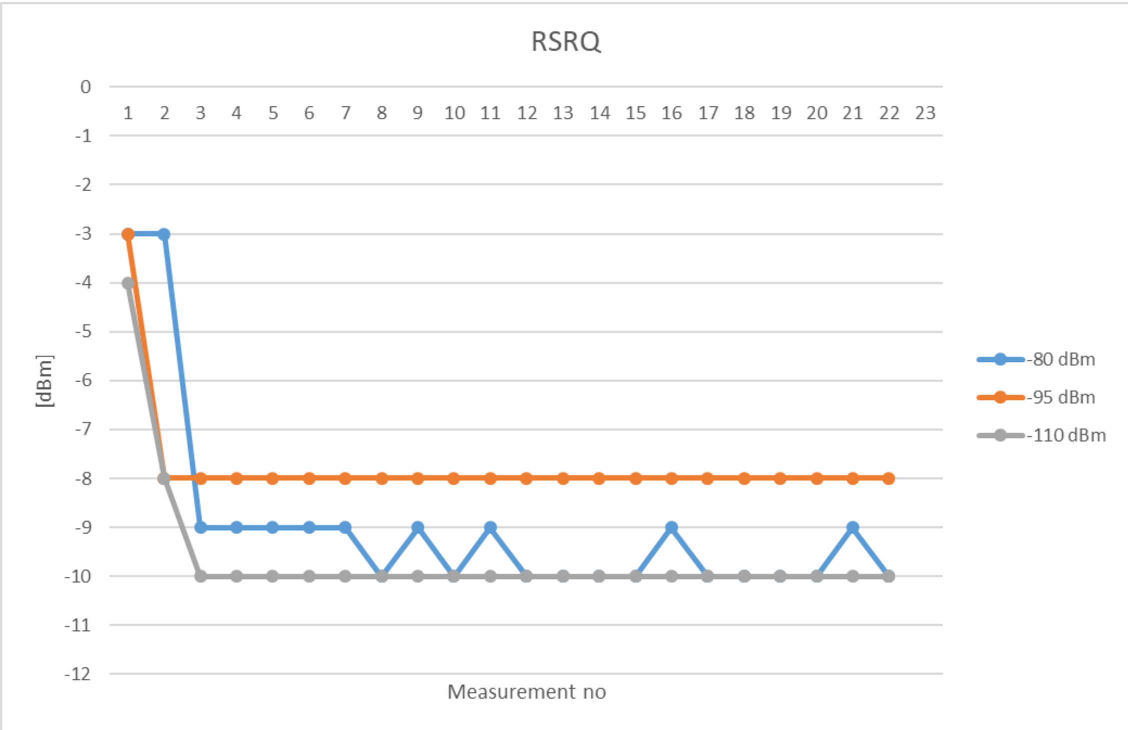


Figure 19. RSRQ behaviour with maximum UDP downlink load vs. different RSRP levels.

**Uplink results**

Uplink throughput was measured to be exactly 16 Mbps with TCP and 16.2 Mbps with UDP. UDP provided a much more stable and consistent data flow also for uplink by showing extremely stable throughput with standard deviation of only 0.05 Mbps. This would mean that 99.9 % of results should fit within ± 0.16 Mbps variation of average if considering results are distributed according to standard normal distribution. Results at the receiving end showed again “black-outs” for TCP reception but in the case of uplink, these “black-outs” were in the order of one second and so 2…3 times longer than in case of downlink measurement. In the TCP download case, it was also noted that data was buffered and then recovered after “black-outs”, meaning that the average is exactly the same regardless if the average is calculated from the raw data or from the data where “black-out” periods and buffering is cleaned. Statistical analysis with cleaned TCP data were made to obtain comparison for UDP results. TCP throughput average shows 16.0 Mbps with and without data manipulation and standard deviation with cleaned data is 0.11 Mbps. This would lead to the estimation where 99.9 % of the results should fit within ± 0.4 Mbps variation of average, if considering results are distributed according to standard normal distribution. Figure 19 below shows one of the observed “black-outs” in the case of TCP uplink measurement.

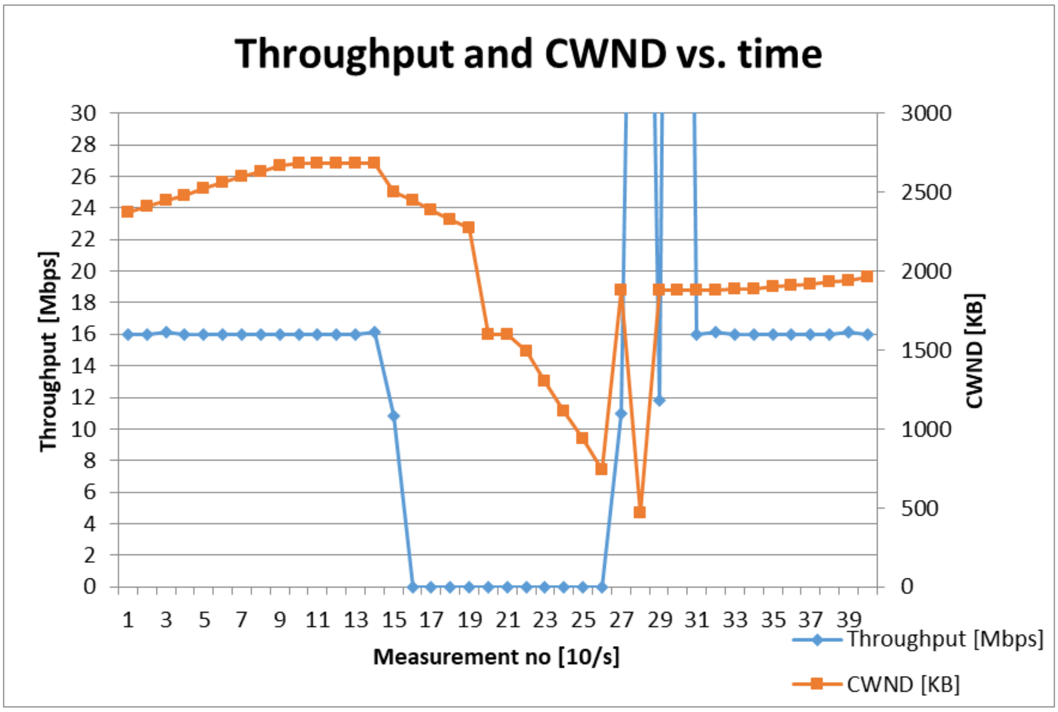


Figure 20. “Black-out” effect in case of TCP uplink throughput.

RSRP values were stable over the throughput measurement and remained under load, exactly where it was when tuned without data loading. For UDP uplink, RSRQ figures remained stable over the measurement period and did not change from the reference without data loading. For TCP uplink measurement, RSRQ shows a minor 1…2 dB drop during the data loading compared to reference without loading. This behaviour is expected to cause by TCP protocol, which causes some downlink traffic due to sending ACKs.

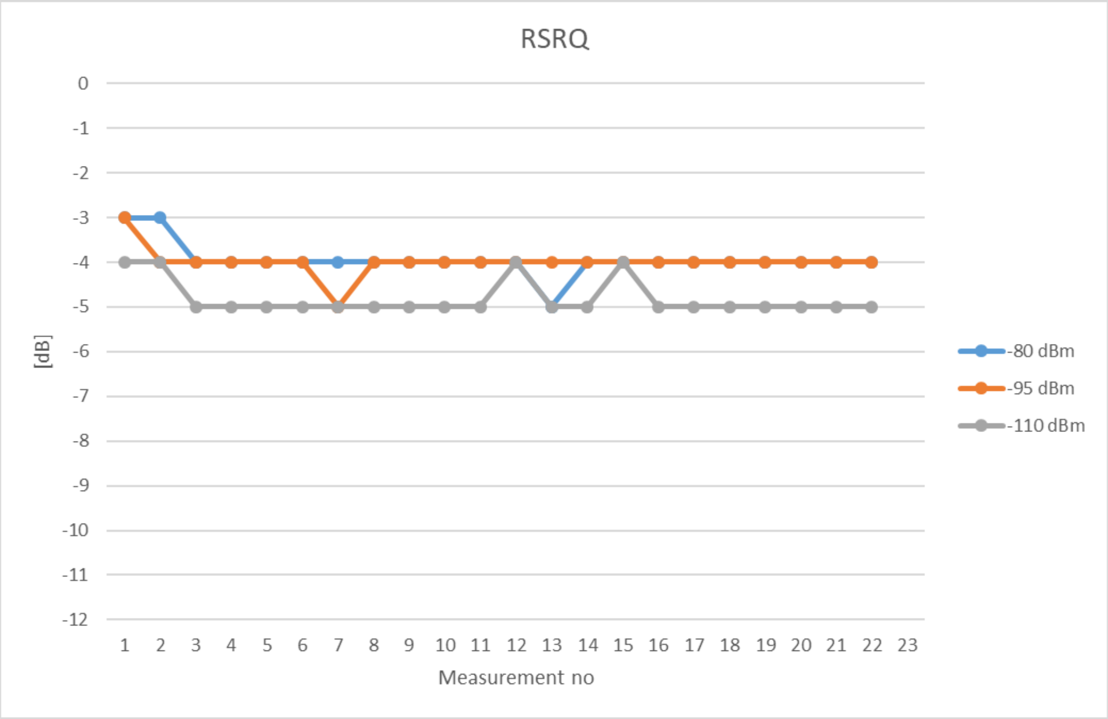


Figure 21. RSRQ behaviour with maximum TCP uplink load vs. different RSRP levels.

### 4.5.2 Results for the Test Case 2

RSRQ measurement for different data rates was originally planned to be performed with 0, 1, 8, and 16 Mbps data rates and also for maximum achievable data rate which was measured to be around 35 Mbps. Results for UPD case with RSRP level -80 dBm are shown below in Figure 22.

During the data analysis it was noticed that the measurements for 8 Mbps were corrupted and result file was missing, and therefore results for 8 Mbps are not shown.

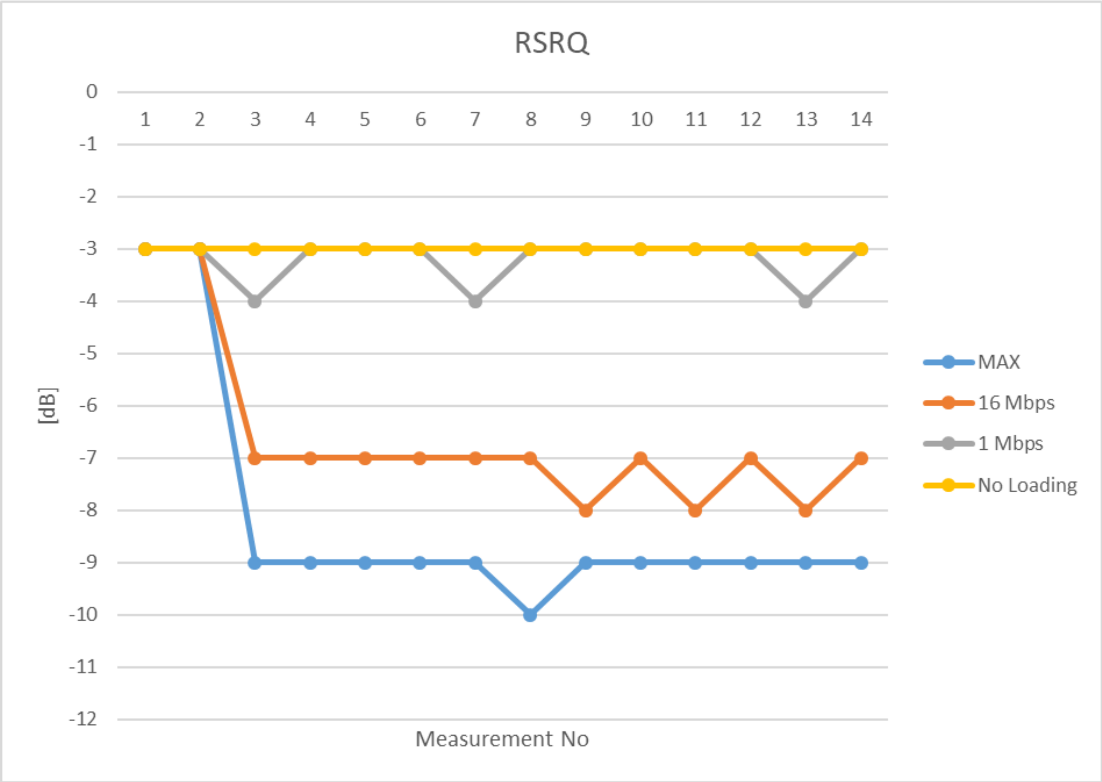


Figure 22. RSRQ behaviour for UDP downlink with different data loading.

### 4.5.3 Results for the Test Case 3

Collecting result from several different iperf servers needs to be designed carefully so that the results are actually stored in a distinguishable way and are easily collectible from all the places where stored. If running several servers in different hosts, separate hosts must be accurately synchronized so that results are time stamped properly, making it possible to later matched in the time domain. With iperf2 it would be possible to initialize several DUTs to be attached to a single server, but during the data analysis it is simpler to handle the iperf3 data, where different DUTs are distinguished by separate iperf3 processes and which are running on different TCP/UDP ports.

Measurements showed that data bandwidth is shared evenly between the DUTs in the downloading case and even though it is not shown in the Figure 23 below, the DUT station labeled as “Rogue” was also receiving equal amount of data compared to DUT1 when both stations where downloading simultaneously.

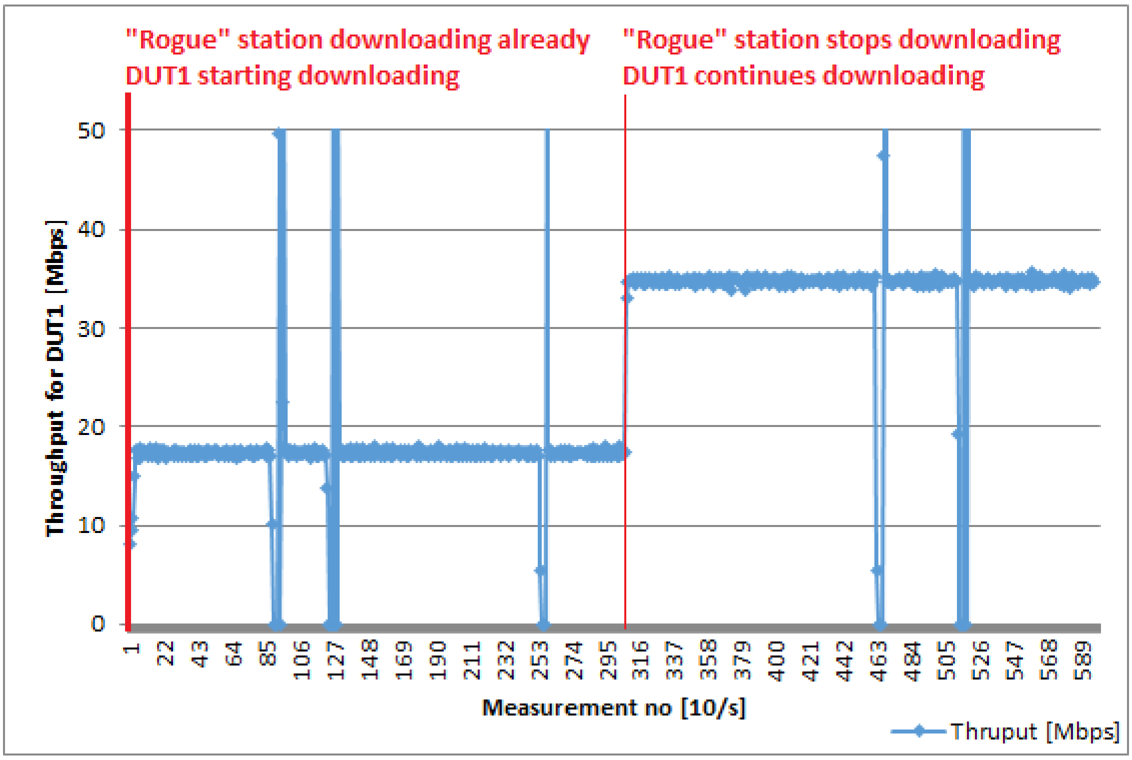


Figure 23. Data bandwidth sharing between DUTs in case of TCP downloading.

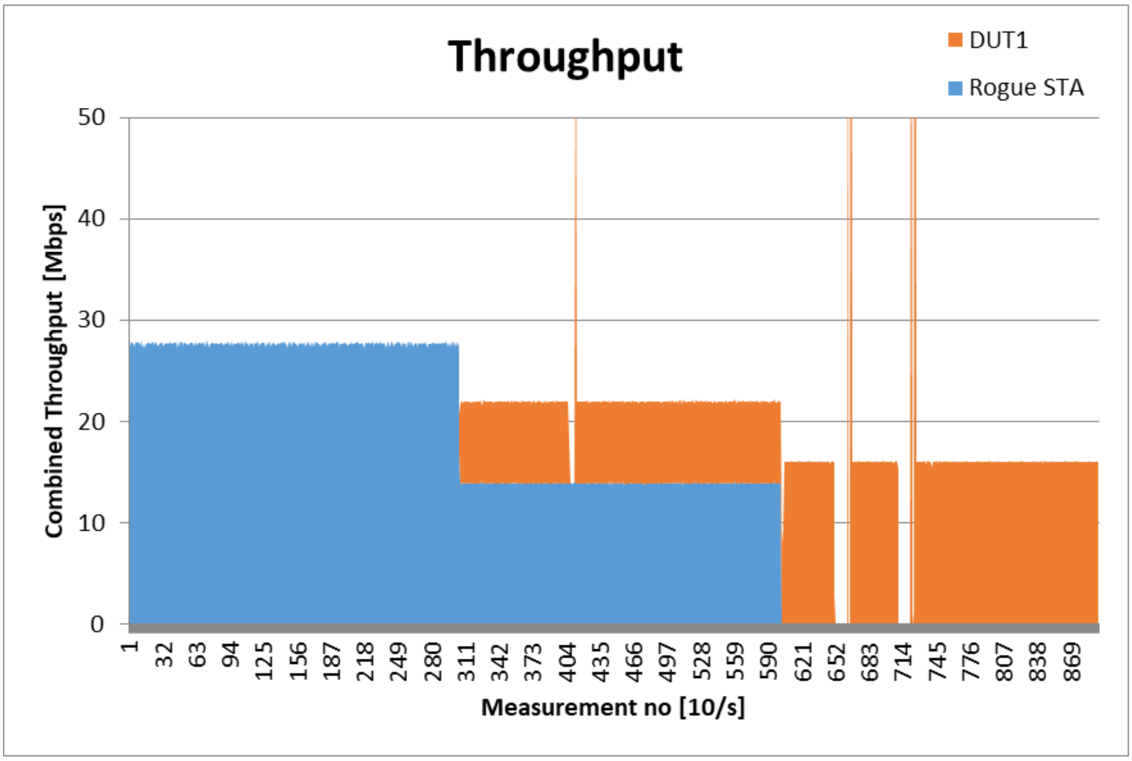


Figure 24. Data bandwidth sharing between DUTs in case of TCP uploading.

Interestingly, the device used as a Rogue station showed clearly better uplink performance than the DUT used for measurements. As maximum uplink data rate was measured to be around 16…17 Mbps for DUT, for the rogue station this figure was 27…28 Mbps. The difference between the uplink capabilities can be explained by the features supported by the device. While DUT supports 16 QAM modulation for uplink, the rogue station supports 64 QAM and is capable of delivering roughly 1.5 times more data just using that and without taking coding rate into account.

Another interesting issue is that the “black-outs” discovered within the TCP throughput measurements of Test Case 1, reported in Chapter 4.5.1, was not discovered within the rogue station. This gives a hint that the problem lies either in the sending end machine, in the mobile setup PC or in its modem, and not in the used LTE EPC + eNB combination.

# 5 MARINE CLASSIFICATION

This thesis concentrates mainly in the area of telecommunication but the driver for the covered topics has been to seek ways to verify presented solution for marine industry purposes. Marine industry has its own certification process which is depicted in general level in this chapter. DNV GL, one of the classification societies has been taken into closer look and as an example of globally known classification society. DNV GL rules and recommendations has been opened in parts relating to telecommunications concerning remote and autonomous.

## 5.1 Classification Societies

Need to classify ships raised from the opportunity to take part of the insuring the individual voyages. This kind of insurance was basically writing a deal, called *underwriting*, where it was promised to take part of the losses if individual voyage didn't make it and in return part of the profits was promised. This raised a need for participating to assessing the risks case by case. The first classification society, Register Society, was founded in England in 1760 to serve this purpose. Later this Register Society became to known as Lloyds Register based on the coffee house where London merchants, shipowners and captains gathered to make deals including *underwriting.* Register Society published the first annual register of the ships in 1764 as an attempt to classify ships. At this phase classification was purely to evaluate risk level for the ship without assessing its safety or seaworthiness.

Today: "*marine classification is a system for promoting the safety of life, property and the environment primarily through the establishment and verification of compliance with technical and engineering standards for the design, construction and life-cycle maintenance of ships"* (Wikipedia 2019a).

Addition to class certificate, classification societies provides also *Load Line Certificates*, which defines maximum draught of the ships according to commonly agreed standard known as International Convention on Load Lines (CLL 66/88) by International Maritime Organization (IMO).

Ships need to be certified in order to be registerable and able to obtain insurance. Classification is also required for ship to enter certain waterways or ports. Classification certification is a process where ship is inspected against rules and standards set by classification society. This inspection is made by classification society representative. Classifications societies have their own specific standards and guiding which need to be applied when obtaining classification from that society. According to Wikipedia there is currently more than 50 organizations which describe marine classifications as part of their offering. International Association of Classification Societies, IACS, was founded to ease collaboration between classification societies and to have uniformity within the standards between them. Currently IACS has twelve classification society members which are representing classification of over 90 % of the world's cargo-carrying ships' tonnage. (Wikipedia 2019a; Wikipedia 2019b.)

## 5.2 IMO

International Maritime Organization, IMO, is a specialized agency of the United Nations, UN. Until 1982 it was known as Inter-Governmental Maritime Consultative Organization (IMCO) and which was founded in 1948.

IMO is truly global organization having 174 Member States, three Associate Members, 81 international non-governmental organizations and 64 intergovernmental organizations. Member States are independent countries where as Associate Members are autonomous or special administrative areas of certain countries. Non-governmental organizations (NGOs) are international organizations which has expertise and capability to make substantial contribution to the work of IMO and which has Consultative Status. Intergovernmental organizations (IGOs) has established cooperation agreements with IMO to ensure maximum conformity with IMO and which has Observer Status.

IMO is a global standard setting authority for international shipping. It is working on areas of safety, security and environmental matters including prevention of marine and atmospheric pollutions caused by shipping. IMO has 174 member states and three associate members.

IACS (International Association of Classification Societies) is one of the NGOs and so has a Consultative Status in IMO. IACS provides knowledge of the classifications societies to support developing unified interpretations from country specific regulations. After unified interpretations are adopted and applied by IACS classification societies, compliance for flag state regulations is certified by classification society. So IACS with its classification society members are developing and actually applying technical rules which reflects the aims embodied within the IMO conventions.

International Convention for the Safety of Life at Sea (SOLAS) is maritime treaty assigned by 164 countries (Nov-2018) which defines minimum safety standards for merchant ships and can be seem as the link between regulations developed by the IMO and the classifications standards set by classification societies. (Wikipedia 2019a; IMO 2019.)

## 5.3 DNV GL

DNV GL is taken here as an example of classification society. DNV GL is selected as it is only classification society which has head office in Scandinavia and also its roots strongly in Scandinavia and in Europe.

History of DNV GL lead to 1860th Oslo, Norway. In 1864 DNV, Det Norske Veritas was founded by Norway’s marine insurance clubs to standardize rules and processes for assessing vessels and to provide uniform classification and taxation for Norwegian ships. In 1867 at Germany, group of 600 different parties from marine industry gathered to establish Germanische Lloyd (GL) to improve transparency within merchants, ship owners and insurers and to evaluate the quality of ships and provide this information to stakeholders.

DNV and GL can be seen collaborating from the very beginning of their existence but officially DNV and GL merged in 2013 and became to known as DNV GL Group. Nowadays it operates over 100 countries and is presenting itself as ”*globally leading quality assurance and risk management company with 100,000 customers across the maritime, oil and gas, energy, food and healthcare industries, as well as a range of other sectors, DNV GL helps companies to become safer, smarter and greener.”* (DNV GL 2019a).

## 5.4 DNV GL rules and standards for maritime

DNV GL rules and standards for maritime includes different type of documentations which covers rules for classifications (short as RU), standards (ST), offshore standards

(OS), class guidelines (CG), class programmes (CP), statutory interpretations (SI), service specifications (SE), and recommended practices (RP).

There are dedicated rules for classification for different types of vessels like inland vessels, high speed vessels, naval vessels, yachts, floating docks, offshore units and underwater technology. Regarding ship class certifications, DNV GL rules and standards doesn't only specify requirements for different functionalities and materials, but also working methods related for fabrication and testing.

In addition to ship class certification and certifications of different equipment meant for maritime usage, these rules and standards covers wide area of different maritime functions such as used processes and working methods in industry generally. These standards include also specifications for competences for different roles like key technical personnel, craft, operators and even teaching professionals.

Following presents how above-mentioned different type of rules and standards are depicted by DNV GL. (DNV GL 2019b.)

"***DNV GL rules for classification*** *contain procedural and technical requirements related to obtaining and retaining a class certificate. The rules represent all requirements adopted by the Society as basis for classification.*" (DNV GL 2019b).

"***DNV GL class programmes*** *contain procedural and technical requirements including acceptance criteria for obtaining and retaining certificates for objects and organizations related to classification.*" (DNV GL 2019b).

"***DNV GL statutory interpretations*** *contain the Society's own interpretations of statutory regulations. These are valid when not instructed otherwise by the flag or coastal state administration, and when no interpretations exist from IACS or regulatory bodies. The publication covers only selected relevant topics and shall under no circumstances be taken as the Society's complete interpretations of such regulations.*" (DNV GL 2019b).

"***DNV GL class guidelines*** *contain methods, technical requirements, principles and acceptance criteria related to classed objects as referred to from the rules.*" (DNV GL 2019b).

"***DNV GL standards*** *contain requirements, principles and acceptance criteria for objects, personnel, organizations and/or operations.*" (DNV GL 2019b).

In next chapters, it is presented the parts of the DNV GL rules and standards, which can be considered the most relevant for telecommunication systems, especially from the functional perspective.

## 5.5 DNV GL rules and standards relevant for telecommunication

Regarding classifications rules relevant for the telecommunication systems, main documents to look at are under *DNV GL rules for classification*: *Ships (RU-SHIP)* – category. Documents particularly under interest regarding electrical equipment locates under its *Part 4 Systems and components.* Interesting chapters are eight and nine, *Ch.8 Electrical installations* (DNVGL-RU-SHIP-Pt4Ch8) and *Ch.9 Control and monitoring systems* (DNVGL-RU-SHIP-Pt4Ch9). (DNV GL 2018a; DNV GL 2018b.)

Document of Part 4 Chapter 8 covers different aspects related to electrical installations and are not directly under interest of this thesis but mentioned as it covers important topics when planning onboard systems and powering and power controlling for those. Topics of this document includes rules for system design and related main supply system, emergency supply and battery systems. It covers also closely related topics for electrical installations such as cable selections, protections and filtering of the circuits and controlling of the electrical equipment, and also including aspects of monitoring. (DNV GL 2018a.)

Document of Part 4 Chapter 9 covers rules for control, monitoring and safety systems. This document is also valid for equipment and features which falls to control and monitoring category but which are not necessarily required on board the vessel by the rules. This document is particularly under interest for the telecommunication systems as it covers the topics of computer systems, control system networks and data communication links. DNVGL-RU-SHIP-Pt4Ch9 is referring to IACS UR E22 document when it comes to use of wireless communications systems. IACS UR E22 is a document of International Association of Classification Societies (IACS) of Unified Requirements (UR) regarding the rules related to electricity (E). IACS UR E22 is document titled as “On Board Use and Application of Computer based systems” and covering minimum requirements for computer-based systems and which are unified between IACS member class societies. Overview for DNVGL-RU-SHIP-Pt4Ch9 is provided in chapter 5.5.1. (DNV GL 2018b; IACS 2016.)

*DNV GL class guidelines (CG)* for *Autonomous and remotely operated ships* (DNVGL-CG-0264), covers guidelines for ships implementing novel technologies such aiming towards autonomous ships. This document covers wide area of different topics related to remote and autonomous ships. Overview for this document is provided in chapter 5.5.2. (DNV GL 2018b, DNV GL 2018c.)

### 5.5.1 Control and monitoring systems (DNVGL-RU-SHIP-Pt4Ch9)

In DNVGL-RU-SHIP-Pt4Ch9, systems are categorized to three groups based on potential excessiveness failure could cause. Failure in systems belonging to *non-important* group would not cause dangerous situation for humans, vessel or environment. Failures on systems belonging to *important* group could possibly eventually cause danger some of aforementioned parties, and failures on systems belonging to *essential* group would cause immediate danger. One of the major solutions mitigating the risk levels is building redundancy to important systems. Redundancy means having actual spare component in parallel with actual primary component and which can replace functions of primary component without noticeable breakage in operation. Having alternative back-up solution may also affect to the risk category of the system.

In DNVGL-RU-SHIP-Pt4Ch9 it is clearly noted that the main components of the *essential* and *important* systems shall be type approved. Type approval processes for the components are specified in dedicated DNV GL class programmes and for example document DNVGL-CP-0203 describes type approval scheme for "*Electronic and programmable equipment and systems*" and it can be considered to be applicable for devices listed above. DNVGL-CP-0203 describes relevant requirements and refers to DNVGL-CG-0339 which is DNV GL class guide and a guideline for "*Environmental test specification for electrical, electronic and programmable equipment and systems*". Basis for the basic environmental testing specified in DNVGL-CG-0339 comes from the IEC and its specialized sub-group CISPR standards. These standards are defined explicitly in DNVGL-CG-0339. Performance tests are specified to be performed according to relevant EN, IEC, ISO standards. Regarding the unit specific type approval requirements, it is mentioned that case-by-case approval may be accepted as an alternative to the actual DNV GL specific type approval of separate units.

The some of the main points of DNVGL-RU-SHIP-Pt4Ch9 for telecommunication includes the following rules:

- The main components of the *essential* and *important* systems shall be type approved.
- *Essential* and *important* systems shall be arranged so that single failure in one system or unit cannot spread to another unit. To prevent failure spreading, segregation or segmentation is required between separate systems.
- Within *Essential* and *important* systems an integrated system redundancy and/or segregation need to be arranged to mitigate single failure situations.
- *Essential* and *important* systems shall have methods to detect the most probable failures that may cause reduced or erroneous system performance.
- The most probable failures shall result in the least critical of any possible new conditions and total loss of power to any single control system should not result in loss of propulsion or steering.
- A redundant system upon failure shall transfer of active mission execution to the standby unit without interruption that jeopardizes safe operation or even the most time critical functions.
- On the process level, controllers based on computers are required to have deterministic response time.
- Computers used for this kind of *essential* and *important* functions shall not be used to serve any other than relevant purposes.
- Computers used for *essential* functions shall not depend on rotating based bulk storages and should not have forced ventilation. In case they require that, alarm for ventilation failure and high temperatures shall be implemented addition to self-diagnostics.
- *Essential* systems are specified to have diagnostic system to support maintenance in sense of finding and repairing failures.
- Networks of control and monitoring systems shall be single point of failure-tolerant and networks are required to be segmented and secured and able to work independently.
- Network monitoring capabilities are required and functions to allow possibility to intervene if data amount of the network is exceeding the level of safe operation.
- It is required to have triggers for alarms for cases of network faults or degraded performance and network nodes shall be time synchronized to allow a uniform time tagging of alarms and events to enable a proper sequential logging.

- Any remote connections for network, weather it is for service, diagnostics or maintenance, shall be acknowledged by ship responsible and authorized onboard the vessel.
- Communication links are required to establish normal operation after restoration of the power failure.
- It is required that failure analysis shall be made for control, monitoring and safety network and which concentrates on main network components and functions integrity distributed over network segments.

(DNV GL 2018b.)

### 5.5.2 Autonomous and remotely operated ships (DNVGL-CG-0264)

It is noted by DNVGL-CG-0264 that currently IMO does not have a safety framework for vessels equipped with technology enabling reduced manning or no manning. Also, it is noted that:

"*The area of autonomy and remote operation of vessels is still an immature field where new ideas and technical solutions are being introduced. It is therefore currently not possible or desirable to provide detailed rules for all areas and combinations of concepts.*

These two issues together prevent such technologies to enter into international shipping. However, national and regional regulators may approve these technologies on their territorial waters. It is still stated that same level of safety is expected as with normal ships and this particular guideline, DNVGL-CG-0264, is developed to support to achieve this when implementing and introducing such novel technologies enabling path towards autonomous shipping.

Related to the telecommunication and networking, DNVGL-CG-0264 is in some parts referring to documents *SOLAS III/6: Communication (to personnel)* and *SOLAS IV/4: Radiocommunications*. SOLAS requirements are mentioned as a baseline for autonomous and remotely operated vessel and valid as such for conventional vessels. DNV GL has its own interpretation for SOLAS regulations and it is in DNV GL statutory interpretations documents labeled as DNVGL-SI-0364. (DNV GL 2018d.)

SOLAS III/6 defines communication system requirements for vessel internal communication and particularly for human to human communication and human to public/passengers communications as well alarming system. (DNV GL 2018d.)

SOLAS IV/4 Radiocommunications, functional requirements are not actually interpreted in DNV GL interpretation document DNVGL-SI-0364. These requirements are covering radio communications for global maritime distress and safety system (GMDSS). (DNV GL 2018d.)

Few different references are mentioned in DNVGL-CG-0264 for cyber security closely related to telecommunication. DNVGL-CP-0231 is a class programme specification for *Cyber security capabilities of control system components*. It is noted in DNVGL-CG-0264 that the network components on-board and in the Remote Control Centres (RCC) should be type-approved according with DNVGL-CP-0231. This document covers different cyber security aspects such as authentication, encryption, required monitoring capabilities, and etc. Similarly, it is noted that design for novel technologies reaching toward autonomous and remote-controlled ships should follow DNVGL-RP-0496 *Recommended practices for cyber security resilience management for ships and mobile offshore units in operations*. Two additional standards mentioned in DNVGL-CG-0264 related to telecommunication and are International Electrotechnical Commission’s IEC 62443 series and NIST cybersecurity framework. Both of those are referred regarding the cybersecurity assessments items where it is guided to map incidents which should be prevented or mitigated by applying a recognized framework, e.g. based on the IEC 62443 series of standards or the NIST cybersecurity framework. (DNV GL 2018c; NIST 2018.)

Following list summarizes some of the main parts of DNVGL-CG-0264:

- System should be single-point-of-failure tolerant. Telecommunication and networking system should be able to operate at 100 % capacity even in case of single component failure.
- Communication link between the vessel and RCC should consist of at least two independent communication systems/channels.
- The data bandwidth usage and latency figures should be monitored and anomalies and capacity limitations should be noticed independently on-board the vessel and in the RCC.

- Traffic between the vessel and the RCC should be possible to prioritize based on communication types to secure the most important communication types in case of limited network capacity.
- Operator should be able to select which data is transferred in case of limited telecommunication situations.
- The operator should be able to test and diagnose all functionality and characteristics of one communication channel while the other(s) are used for actual operations.
- Telecommunication and networking functionality should be logged. It is actually mentioned that: "*The communication should be recorded"*. This could be interpreted that while cybersecurity is doing packet inspection for every ingress and egress packet, operational system should log the given commands and connectivity system should monitor the link states.
- The network components on-board and in the RCC should be type-approved according to DNVGL-CP-0231 Type approval programme for cyber security and DNVGL-CP-0203 Type approval programme for electronic and programmable equipment and systems.
- Cybersecurity policy should follow up-to-date cybersecurity management framework like IEC 62443 series of standards or the NIST cybersecurity framework.
- Network segmentation should be used to segregate different functional networks. Methods could include the use of air-gap, firewalls, DMZ, VLAN and/or layer 3 network devices.
- Component running own software should have policy for updates.
- Failure analysis for communication systems and functions need to made.

(DNV GL 2018c; IACS 2018.)

# 6 CONCLUSION

LTE is a well-known system as it is developed in open forums (like 3GPP) and has its system standards and specifications freely available. Many device manufacturers have been providing industrial level devices for several years already, some of them have even been certified against marine class programmes. Certification gives indication that it has been in someone’s interest to have device certified for the marine industry and to match, at least in the sense of environmental aspects, for marine use. These device level class programmes, which specifies the requirement to be fulfilled in order to get device certified, is only one aspect. Another completely different aspect is set by the system level requirements, classification rules, for full systems that integrates the set of devices. Marine classification rules set also high demands for network functionality, reliability and security, especially when used for vital operational functions. Especially regarding remote and autonomous operation, the highest level of requirements is set. For example, for remote operations it is indicated that in case of a single point of failure, 100 % operational capability must retain. Essentially, this could be interpreted so that, in case of a telecommunication system that is vital for operation, having a single LTE router is not enough. Duplicating the LTE router only on board the vessel is essentially not enough, but also the shore side infrastructure should have also redundant devices in this case. This could be reflected in the case where usage of parallel modems, utilizing different operators, automatically provides redundancy to a certain extent.

Regarding the LTE 700 MHz B28-band, it can be noted that a too high data rate demand was set for the link budget estimation. This is especially valid for the particular case where only 10 MHz bandwidth was available and 20 Mbps was defined as the ”required” data rate for the uplink. It was shown that 20 Mbps can be achieved with certain devices, if the device’s LTE category is supports higher order modulations than 16QAM. With selected reference device, which supports only Cat. 4, only 16 Mbps was achieved even though the theoretical speed is 25 Mbps. Acknowledging the fact that the control and coding causes certain overhead, lowering the actual achievable data rate, the achieved result was still a bit of a disappointment as, 20 % overhead would have still produced 20 Mbps. For downlink, the maximum theoretical data rate for a single stream is 37.5 Mbps, and 35 Mbps was the measured value, which is an overhead of less than 10 %. Due to limited resources, it was not possible to study any further why the uplink data rate was showing so low values and why TCP showed 0.3 to 1 second ”black-outs” on the application level.

Modern cellular mobile phone networks are asymmetric in sense of downlink vs. uplink data bandwidth. Specified downlink performance is typically two times higher than uplink performance with the same number of spatial streams. The difference is even bigger if taking into account the fact that more spatial streams are typically supported for downlink. The rationale for such a design is based on the fact that typically downlink capacity has been seen as much more important, due to typical network use cases (media streaming: music and videos). This approach also allows usage of more cost-effective technology within consumer terminals, as the same level of uplink performance is not required from terminals. Balance in radio transmission powers also favours downlink performance, as base stations are allowed to use much higher powers than terminals. With these limits, it is easy to conclude that as the network is not optimized for uplink usage, and when planning to use private LTE in a solution which will load the network more heavily in uplink direction, careful design becomes even more important than for downlink cases.

Generally, private LTE can be seen as a potential solution for certain marine operations which are limited to a certain geographical area and a certain amount of users. TUAS RDN type single cell solution can be estimated to become crowded very quickly, especially if users require bandwidth of several Mbps. However, it could fit very well for solutions for ferry operations, where only one or two ferries operating in certain, few km, routes, would share the capacity of the cell and where the backbone connection for the system is arranged in a way that it is not the limiting factor. To make the whole communication system compliant with regulatory rules for remote and autonomous systems, it would require the vessel to have prioritization logic built into the system, which would be able to transfer the data traffic seamlessly to a secondary connection in case of the primary connection (private LTE) fails.

One of the challenges regarding the private LTE is frequency allocations. Essentially, there are no free frequencies available (at least in Finland) as spectrum allocations have already been shared. This means that obtaining a piece of frequency spectrum would mean either renting or buying it from the mobile operator. It can also be seen out of interest for shipping companies, to manage and take care of private LTE networks and its related infrastructures and devices. With all this in mind, it can be estimated that providing special networks for certain future marine operations can open up new business models and opportunities for current mobile operators and entrepreneurs.

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