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MASTER’S THESIS

IMPLEMENTATION AND AUTOMATION OF BEAM MANAGEMENT TEST SYSTEM

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ABSTRACT

The mobile network technologies nowadays have come to a point where transferring data as much as possible, as fast as possible and as reliable as possible has become to the main requirement and this has led to the development of the capacity to become one of the main aspects in mobile technology. The 5G mobile technology with millimetre-wave frequency range combined with beamforming technology is currently answer to the capacity question of the networks. Beamforming in millimetre-waves requires a beam management technology, which basically handles the controlling of the beams. As a new feature the beam management requires testing and verification. In this thesis the environment which is capable to test beam management technology with the MediaTek the prototype UE was created. The beam management was tested with the help of a linear actuator which can traverse UE sideways in front of 5G NR millimetre-wave antenna. The main task in this thesis was to create controlling solutions for the linear actuator so that it can be controlled manually and to integrate the test system to the test automation later. The test automation was implemented in python programming language, so the controlling solution was created using python making the integration easier. After the completing the controlling solution, the beam management tests were executed. There were two test scenarios completed in this thesis, the first one tested beam management while prototype UE was connected to test network and sending ping requests. The second scenario tested the UE while connected to test network and data was transferred to UE from the network. Both scenarios completed successfully resulting the beams to be switched while the UE traversed back and forth with the linear actuator. The manual testing of beam management was successful according to the results. Finally, the existing automation, beam management environment integration to the automation and possible test scenarios to run with the automation were introduced.

Key words: 5G, beam management, millimetre-waves.

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TIIVISTELMÄ

Nykypäivän mobiiliverkkoteknologiat ovat tulleet siihen pisteeseen, että datan siirtäminen nopeasti, luotettavasti ja paljon kerralla on tullut pääkehityksen kohteeksi ja johtanut kehitystyön kohdistumisen mobiiliverkon kapasiteettiin. 5G mobiiliteknologia ja millimetriaaltoihin pohjautuva taajuusalue yhdessä keilanhallintateknologian kanssa ovat vastaus verkkojen kapasiteettikysymykseen. Keilanmuodostus millimetriaalloilla vaatii avukseen keilanhallintateknologiaa, joka käytännössä hallitsee keilojen kontrolloinnin. Uutena ominaisuutena keilanhallinta vaatii paljon testausta ja todentamista. Tässä työssä luotiin ympäristö, joka kykenee testaamaan keilanhallintateknologiaa käyttäen MediaTekin prototyyppipuhelinta. Keilanhallintaa testattiin lineaarisen toimilaitteen avulla, joka kykenee kuljettamaan prototyyppipuhelinta sivuttaissuunnassa 5G NR antennin edessä, joka toimii millimetriaaltoalueella. Työn päätehtävänä oli luoda ohjausratkaisu lineaariselle toimilaitteelle, jotta sitä voitaisiin ohjata manuaalisesti ja myöhemmin integroida testijärjestelmä automaatioon. Testiautomaatio oli luotu käyttämällä python ohjelmointikieltä, niinpä ohjausratkaisu luotiin käyttäen pythonia, tehden näin integraation testiautomaatioon helpommaksi. Kun ohjausratkaisu oli saatu valmiiksi, suoritettiin keilanhallintatestit. Tässä työssä ajettiin kahta erilaista testiskenaariota, ensimmäisessä skenaariossa testattiin keilanhallintaa, kun prototyyppipuhelin oli yhdistettynä testiverkkoon ja lähetti verkolle ping -paketteja. Toisessa skenaariossa testattiin keilanhallintaa, kun puhelin oli yhdistettynä testiverkkoon ja datansiirto testiverkolta puhelimelle oli aktiivisena. Molemmat skenaariot suoritettiin onnistuneesti tuloksena keilojen vaihtuminen, kun puhelinta liikutettiin edestakaisin lineaarisen toimilaitteen avulla. Tulosten perusteella keilanhallinnan manuaalinen testaaminen suoritettiin onnistuneesti. Lopuksi esiteltiin olemassa oleva automaatio, keilanhallintaympäristön integroiminen automaatioon ja mahdolliset testiskenaariot, joita automaatiolla voidaan ajaa.

Avainsanat: 5G, keilanhallinta, millimetriaallot.

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FOREWORD

This thesis was done in MediaTek Wireless Finland and there was up and downsides during the work. Luckily there was numbers of qualified colleagues working in the same industry helping me during the work whenever needed. First, I want to thank my manager Esa Viitanen for coming up with the idea for this thesis. Thanks to everyone from the company for great support during the thesis work, especially my technical advisor Sami Tuisku and my colleague Antti Hyalines deserve thanks for the continuous support and for keeping up the motivation. I'd also like to thank Otto Koskela for the programming support and for great inspiration.

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Oulu, February 02, 2022

Tomi Rahkola

LIST OF ABBREVIATIONS AND SYMBOLS

3G	Third Generation Mobile network
3GPP	Third Generation Partnership Project
4G	Fourth Generation Mobile network
5GCN	5G Core Network
ADU	Application Data Unit
BM	Beam Management
BS	Base Station
CA	Carrier Aggregation
CC	Component Carriers
CDMA	Code Division Multiple Access
CLI	Command Line Interface
CP	Cyclic Prefix
CP-OFDM	Cyclic Prefix OFDM
CSI-RS	Channel State Information Reference Signal
DFT-s-OFDM	Direct Fourier Transform spread OFDM
DL	Downlink
eMBB	Enhanced Mobile Broadband
eNB	evolved NodeB
EN-DC	E-UTRAN New Radio Dual Connectivity
en-gnB	enhanced next generation NodeB
EPC	Evolved Packet Core
EPCSIM	EPC Simulator
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FR1	Frequency Range 1
FR2	Frequency Range 2
GHz	Gigahertz
gNB	next generation NodeB
GSM	Global System for Mobile communications
IA	Initial Access
IFFT	Inverse Fast Fourier Transform
IoT	Internet of Things
IP	Internet Protocol
kbps	Kilobits per second
kHz	Kilohertz
L1	Layer 1
L2	Layer 2
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
Mbps	Megabits per second
MCG	Master Cell Group
MHz	Megahertz
MIMO	Multiple-Input and Mutliple-Output
mMIMO	Massive MIMO

MN	Master Node
MO	Mobile Originated
NR	New Radio
NSA	Non-stand Alone
NW	Network
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average-Power-Ratio
PBCH	Physical Broadcast Channel
PC	Personal Computer
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PRACH	Physical Random-Access Channel
PSS	Primary Synchronization Signal
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RA	Random Access
RAR	Random Access Response
RB	Recourse Block
RE	Resource Element
RLF	Radio-Link-Failure
RS	Reference Signal
RSRP	Reference Signal Received Power
SA	Stand Alone
SCG	Secondary Cell Group
SCS	Subcarrier Spacing
SMS	Short Message Service
SN	Secondary Node
SRS	Sounding Reference Signal
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
TCI	Transmission Configuration Indication
TCP	Transmission Control Protocol
TRP	Transmit-Receive-Point(s)
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication Service
USB	Universal Serial Bus

f_n	Number of sub-carriers per channel
N	Variable indicating the numbers of sub carriers

1 INTRODUCTION

Nowadays Wireless Communications plays a big role in everyone’s life. Most of the people do have a thing called smartphone in their pockets which is not only capable to make voice calls or send text messages but also to do a plenty of other things where the wireless communication is required. For all this to be possible, there is a huge amount of complex technology behind these obvious things we can do with our smartphones.

First generation mobile network was launched in the early 1980s. Back then the only need for mobile networks was to deliver voice over-the-air. The technology of 1st generation was vulnerable to eavesdropping since there was not any kind of security associated with the connection. Data rates were measured in kilobits per second (kbps). In the 1990s, the 2nd generation technology Global System for Mobile communications (GSM) was introduced. There was a lot of enhancements with this generation such as digitalization, channel access method called code division multiple access (CDMA) and short message service (SMS) was also introduced. This new technology was also more secure than its predecessor, data rates were still measured in kbps but the data rate in GSM was many times faster than in the 1st gen technology.

Later when moving on to the 3rd (3G) and 4th (4G) generation technologies the old circuit switching method used in the 1st generation and GSM was slowly replaced with packet switching method. The data rates began to be measured in megabits per seconds (Mbps).

The intended use of the mobile network was turning from voice centric to data centric during the evolution of the 3G and above technologies such as 4th generation, also known as 4G or LTE (Long Term Evolution). At the same time smartphones began to be popular, allowing to make it possible to use various applications and services such as web browsing, video streaming, social media, and cloud services within them. All this and the increased amount of mobile network users created a requirement for bigger data rates and quality for mobile networks. Now this is where the 5th generation technology which is known as 5G or NR (New Radio) steps in.

5G is designed to have better spectral efficiency and larger bandwidth, which makes it possible to transfer larger amounts of data at time. The latency of NR is designed to be notably lower than its predecessors, also technologies such as Internet of Things (IoT) are part of the 5G. Those things (high data rate, low latency) are required to satisfy the needs of growing amount of mobile network users and devices.

During decades, the frequencies of used radio waves has been increasing. Increasing frequency to higher level is an easy way to get more bandwidth, which means larger data rates. However, in the 5G, frequencies have been taken so high that we are talking about millimetre-waves. This means that the wavelength of used radio waves is in millimetres. One of the technologies required with the millimetre-waves is called beam management.

As a brand-new technology, 5G includes several new technologies to make everything work together, one of these technologies is the beam management. The beam management needs to be tested and validated in upcoming new devices to make sure it functions correctly and works as expected. This is where we get to the topic of this thesis.

We have an equipment including the latest mobile technology which means mainly 5G and its aspects. As discussed before, millimetre-waves have a big role in 5G. When we talk about millimetre-waves they are very sensitive to attenuation, and they cannot reach very long distances. The short distance is one of the main reasons for the beamforming and beam management. These techniques make it possible maximize the distance and performance. Alongside the validation of 5G -mobile network functionality, the validation of the beam management comes into the question. How the beam management can be tested and validated? What does the beam management mean, what techniques it includes?

These are the questions to be answered in this thesis. In chapter 2, a short peek into the 5G technology and its aspects will be taken. In chapter 3, the beam management technology will be introduced, and the main properties of it will be inspected. In chapters 4 and 5, the test system implementation for beam management and the automation for the system will be represented. [1]

2 5G NR TECHNOLOGY

The new 5G NR technology has certain requirements regarding to capability and performance of the mobile network technology. These requirements are provided by the 3GPP (3^{rd} Generation Partnership Project). 3GPP is an organization which consists of seven different telecommunication organizations from all around the world, it defines the standards for mobile telecommunication technologies, such as 3G, LTE and NR. 3GPP offers a complete specification for the mobile telecommunication system. These specifications are then followed by different companies that are dedicated to mobile telecommunications industry. This way it can be confirmed that the mobile devices and networks are functioning correctly. And can interwork together without problems [5, 6].

2.1 Requirements for NR technology

As mentioned earlier, when there is a need for bigger data rates and lower latency due to growing group of mobile network users, setting certain goals for the new mobile technology is needed to make it capable to achieve the needs of the mobile network users. The 3GPP Release 15 specifies the following requirements for the New Radio technology:

- **Enhanced Mobile Broadband:** This enhancement means the better performance than the predecessor technology: LTE. The specification states the requirements for multiple scenarios. This includes service areas, the requirement for example indoors and outdoors performance is different. Special deployments have been considered such as requirements for high-speed trains or even planes are specified.

- **Ultra-Low Latency and Reliability:** There is some aspects in 5G where the extremely low latency and reliable connection is needed. Few examples could be an automation of an industry or a remote control of something important.

- **Massive Internet of Things:** The two previous requirements are needed to achieve this requirement. This requirement includes support for massive amount of IoT devices. Low latency and Enhanced Mobile Broadband (eMBB) are important when it comes to high density of devices in the same network.

- **Flexible Network operations:** A certain flexibility is required from the 5G network. Things such as network slicing, scalability, security, and interworking are specified separately.

Short descriptions for the main requirements of the 5G Network is listed above. The development of the 5G technology is following those requirements and they should be reached to make the network capable and suitable for the present demands. [4, p. 9-10]

2.2 5G System Architecture

As stated in previous chapter, the 5G technology is designed to be capable to handle massive density of devices, very high throughputs and very low latency. It also offers a different kind of flexibility compared to the predecessors. All these features are possible because of the new radio interface.

One of the most remarkable things in NR is that its 5G Radio Access Network (RAN) is designed to be able to connect both 4G and 5G core networks. This creates two deployments of 5G network. If the 5G RAN is used with the 5G core the deployment is so called Stand Alone (SA) architecture. If the 4G core network is used, the architecture is then called Non-Stand Alone (NSA). Both deployments will be introduced in this chapter [4, p. 9-15][7].

2.2.1 Stand Alone (SA)

The SA –architecture can be considered as full deployment of the 5G, and it is completely independent of the 4G network parts and features. SA deployment consists of the User Equipment (UE), 5G RAN and 5G core network (5GCN). The 5G RAN in the SA deployment means one gNB (next generation Node-B) at minimum, but also multiple gNBs could be configured.

The gNB or gNBs are connected to the 5GCN with so called NG –interface and multiple gNBs can be connected to each other via interface called Xn –interface. This means that multiple gNBs can be connected to each other and the same core network, but they can also be connected to other 5G Core Networks. The UE can then connect to gNB and through that to the 5GCN. Connectivity, handovers, and other mobility functions are configured through NR interface directly, meaning that the gNB is so called master node (MN) and the signalling between the UE and the gNB goes straight between them. Figure 1 illustrates the functionality of the SA –architecture.

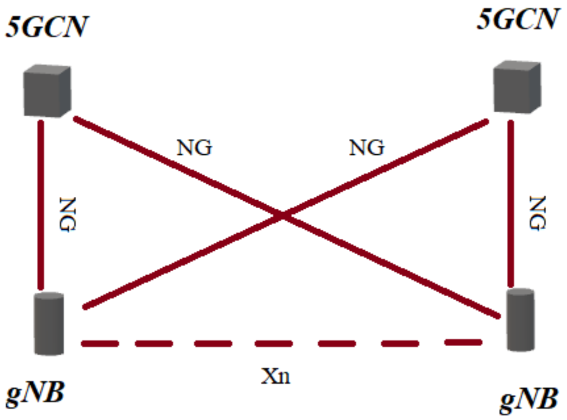


Figure 1. The structure of the SA –architecture.

SA being considered as full deployment of 5G makes it yet rare to exist in a public use. The transition to the 5G is happening slowly step-by-step and thus there is another deployment called NSA and it will be introduced next. [4, p. 9-15][7]

2.2.2 Non-Stand Alone (NSA)

The Non-Stand Alone -architecture implements some capabilities of the NR technology, such as low latency and higher data throughputs. These capabilities will be used parallel with LTE services. In NSA deployment 5G RAN and NR interface will be used with the existing 4G core network and 4G RAN, so the NR interface will be added to the LTE network without a need to replace the entire network.

The first deployments of the 5G networks will be implemented by using the NSA -architecture. It is easier to move slowly towards the 5G with this deployment, since 5G capabilities can be built on existing LTE network structures. In NSA -architecture the 5G RAN will be added to the 4G Core Network which is also known as Evolved Packet Core (EPC). This EPC can already contain 4G RAN meaning eNB or eNBs (evolved Node-B), the additional gNBs so called en-gNBs will be added to the existing architecture.

Additional en-gNBs (enhanced next generation NodeB) will be connected to existing eNBs via so called X2 -interface. This means that when the gNB is configured with eNB with the X2, the eNB will be used as a master node (MN) and the gNB as a secondary node (SN). Figure 2 illustrates the NSA -architecture. [4, p. 9-15][7]

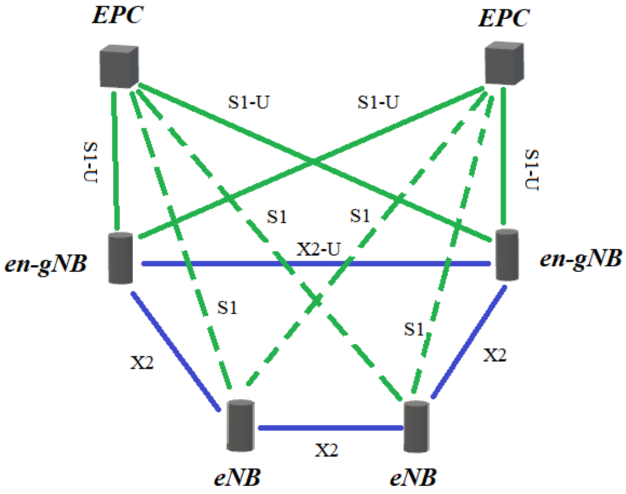


Figure 2. The NSA -architecture structure.

In NSA deployment the connectivity and radio layer configurations will be configured between the UE and eNB (Master Node). So, the connection establishment and other configuring is done via 4G RAN, unlike in SA, where everything is configured via NR interface. Secondary nodes (en-gNBs) will be configured by Master node(s) (eNB).

The eNB forms a Master Cell Group (MCG) and en-gNB forms a Secondary Cell Group (SCG). The SCG can be considered as the 5G part of the network, and it can be used to transport user data with low latency and high throughputs. Whether the SCG is or is not used is up to master node, which can decide if the SCG is used for data transfer or not.

The NSA -architecture also makes it possible to use both MCG and SCG together. This is called 4G and 5G dual connectivity, often shortened as EN-DC. In EN-DC configuration split bearer is used, which means both nodes can be used for data transferring. [4, p. 36-45][7]

For the beam management testing in this thesis, the NSA deployment is used for test environment. The environment includes simulated EPC and 4G RAN. The 5G RAN (gNB) will be used in the environment as a secondary node. Further discussion about the environment will be on chapter 4.

2.3 New Radio NR

As mentioned earlier, a certain set of goals have been specified for the New Radio technology and those goals should be reached. It is obvious that LTE is not capable enough to achieve those goals, thus the new NR technology is required. NR introduces new set of frequency bands, various enhancements and new techniques which will make it capable enough to satisfy the new requirements, and improve the performance compared to LTE.

2.3.1 NR Waveform

The NR technology will inherit the waveform from its predecessor LTE, meaning that the waveform will be OFDM (Orthogonal Frequency Division Multiplexing) with CP (Cyclic Prefix). OFDM with CP has been a very good choice to mobile networks because it has excellent spectral efficiency. There are some differences compared to the LTE. In LTE, OFDM was used only for the DL (downlink) signal, on NR however the OFDM is used for the DL, but also UL (uplink) signal. Since PAPR (peak-to-average power ratio) gets relatively high when using OFDM, the option for uplink waveform is DFT-s-OFDM (Direct Fourier Transform spread OFDM). This improves the coverage in UL, but only single carrier can be used transfer data when using this waveform. [4, p. 25-30][9]

2.3.1.1 CP-OFDM

As mentioned before OFDM has gained popularity among mobile networks due to high spectral efficiency it has. OFDM makes benefit of QAM (Quadrature Amplitude Modulation) and widely used multiplexing method FDM (Frequency Division Multiplexing) together to form a high-data-rate communication system. FDM is known for example from FM Radio. In FDM the frequency spectrum is shared to separate channels by dividing the spectrum to slices for each channel, this way, the multiple data transmissions can be done with different channels simultaneously. However, the channels must not overlap to avoid interference in each channel, this is not very efficient from the spectral point-of-view.

The OFDM uses the basic principle from FDM, but in OFDM one channel consists of an array of overlapping sub-carriers. The sub-carriers are orthogonal to each other, this means that they can be considered statistically uncorrelated with the other sub-carriers. This way the interference is minimized, and bandwidth is maximized. Figure 3 illustrates the OFDM signal represented in frequency domain. [10, 11, 12, 13]

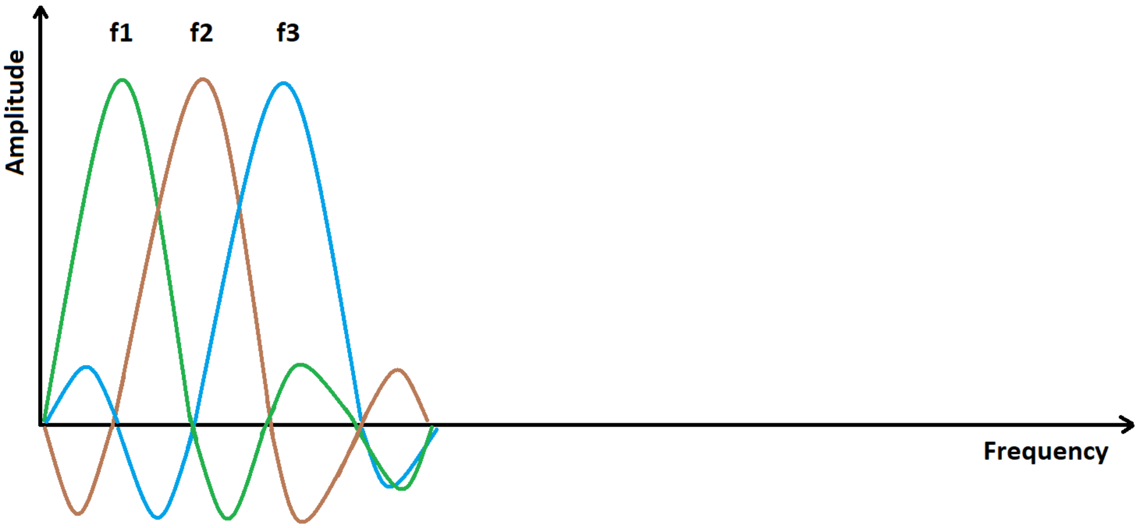


Figure 3. OFDM signal in frequency domain.

There can be N -number of sub-carriers per channel (f_n). Usually, data at the transmitter is converted from serial to smaller parallel segments. Each data segment is then modulated individually using digital QAM. In digital QAM, data is modulated by altering the phase and amplitude of the electromagnetic wave. The product is QAM symbol, one symbol is combination of certain amplitude and certain phase. Now we have multiple parallel QAM -modulated symbols containing the data.

The conversion to the OFDM -signal is done with Inverse Fast Fourier Transform (IFFT). IFFT is an efficient algorithm to convert frequency domain data symbols into the time domain. The QAM -symbols can be represented as series of complex numbers (digital QAM -signal). Those symbols (OFDM -subcarriers) are fed into the IFFT -block which converts the frequency domain symbols into the time domain waveform. The output of IFFT -block is one OFMD -symbol, an orthogonal time domain waveform of combined QAM -symbols containing the data. Figure 4 illustrates the OFDM -signal in time domain. [10, 11, 12, 13]

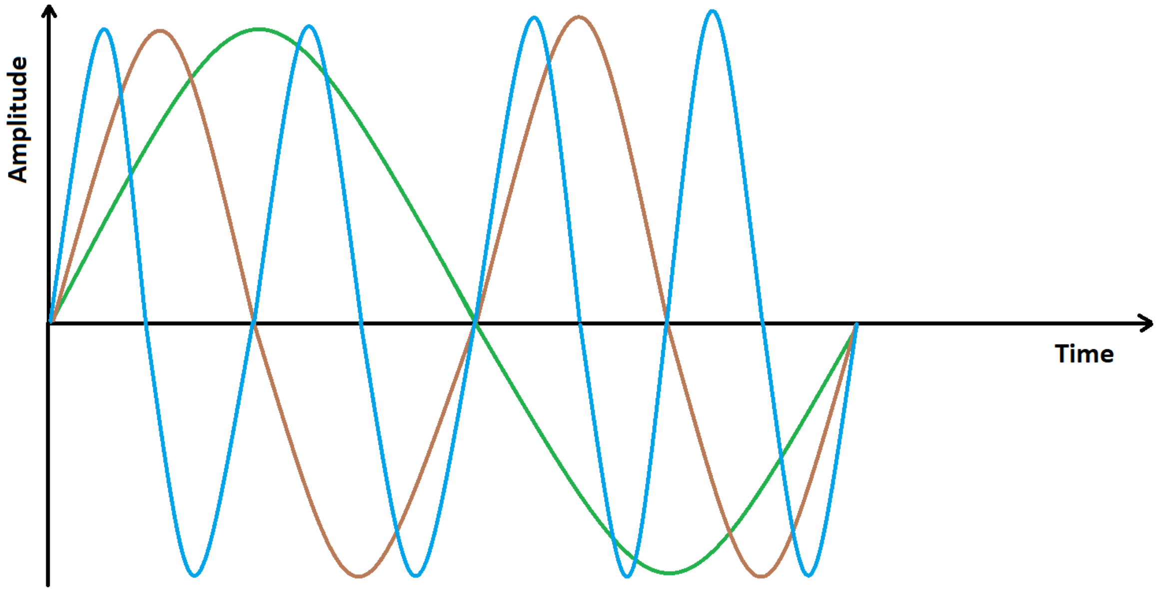


Figure 4. OFDM -signal in time domain.

The same procedure is done in the receiver side, but in inverse order. When receiving OFDM -symbol, it is first converted to the frequency domain symbols using Fast Fourier Transform (FFT). This produces series of QAM -symbols which in turn contain the modulated data. The QAM -symbols will be demodulated to restore the original data segments. Those data segments will then be converted back to the original serial data stream. The Figure 5 represents the function of the OFDM -transceiver. [10, 11, 12, 13]

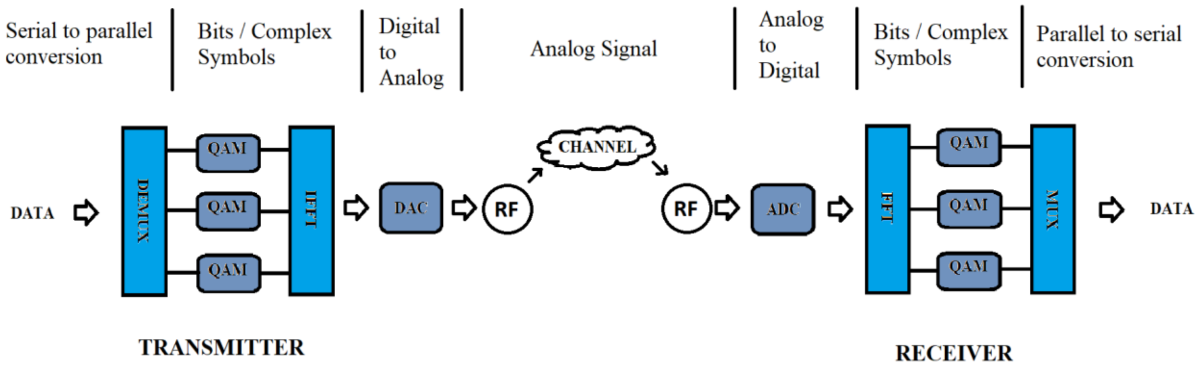


Figure 5. The functions of OFDM transmitter and receiver.

2.3.1.2 Cyclic Prefix

It is known that the wireless communication systems are sensitive to the phenomenon called multipath propagation. Multipath propagation causes inter-symbol interference (ISI) in the radio channel. Cyclic prefix is a method to prevent the interference between OFDM -symbols and thus the loss of data. When cyclic prefix is used in OFDM, the waveform is called CP-

OFDM. In CP-OFDM, the last samples of the symbol are copied and appended in the front of that same symbol. So, each symbol has a guard interval between them, and the guard interval is this repetition of the first section of each individual symbol. This guard interval is then called 'Cyclic Prefix'. In the Figure 6 the Cyclic Prefix insertion is illustrated. [11][18]

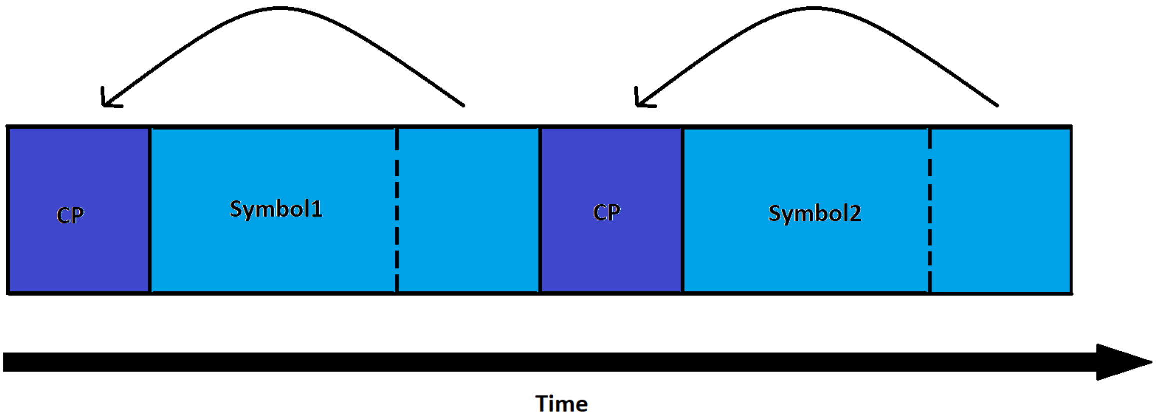


Figure 6. Insertion of cyclic prefix between the symbols to prevent ISI.

2.3.2 NR Frame Structure

As one of the main aspects in NR is flexibility, the frame structure is designed to support multiple subcarrier spacing (SCS) options. The term SCS refers to a distance between the centres of each subcarrier. There are 5 different possible values for SCS in NR. Those are 15 kHz, 30 kHz, 60 kHz, 120 kHz, and 240 kHz. Each subcarrier corresponds one Resource Element (RE) in frequency domain, and one OFDM -symbol in time domain. One Resource Block (RB) consists of 12 consecutive subcarriers in frequency domain and 14 OFDM -symbols in time domain.

Figure 7 represents the frame structure in time domain, 14 OFDM -symbols form a one 1ms slot, which is one subframe. Together 10 subframes form a 10ms long radio frame which is 1 RB in time domain. The number of symbols in each subframe depends on the used SCS and the size of the used CP. For some SCS options it is possible to use extended CP, a cost for this will be the lower number of OFDM -symbols in the subframe. [4]

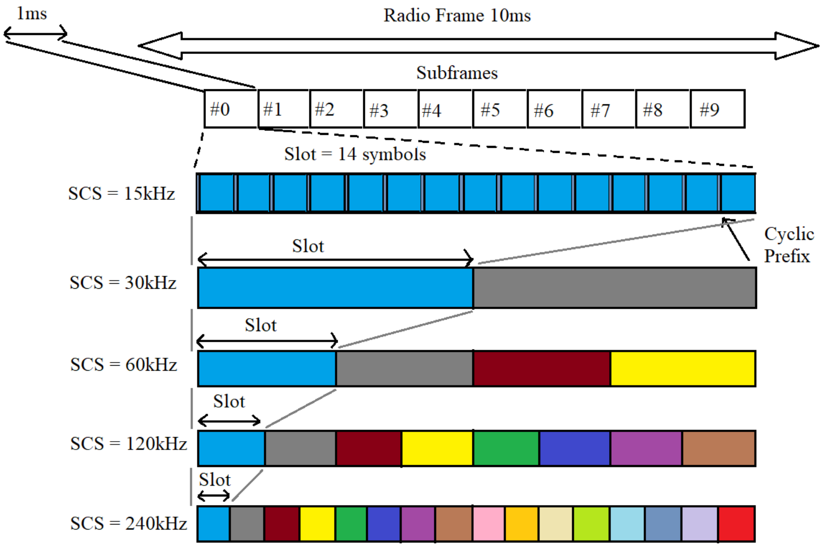


Figure 7. NR frame structure.

2.3.2.1 *Frequency Ranges*

The NR supports multiple carrier frequencies and the frequencies have been divided into two ranges called frequency range 1 (FR1) and frequency range 2 (FR2). Different possible bandwidths are supported depending on the frequency range. Table 1 represents the range specific information and supported bandwidths. [4]

Table 1. Frequency Ranges in NR.

Frequency Range	**Frequency**	**Supported Bandwidth (MHz)**
FR1	410 MHz – 7125 MHz	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, 100
FR2	24250 MHz – 52600 MHz	50, 100, 200, 400

As seen from the Table 1, FR1 covers frequencies approximately from 410 MHz to 7.1 GHz. The FR2 covers much higher frequencies approximately from 24 GHz to 52 GHz meaning it is within millimetre-wave range. Since different types of SCS, frequencies and bandwidths are supported, there are a lot of options to implement NR. In total all those things combined is often referred to as “multiple numerologies in NR”.

Precise definitions for each numerology have been specified by 3GPP. The numerologies supported in NR are presented in the Table 2. [4]

Table 2. Multiple numerologies in New Radio technology.

Cyclic Prefix (CP)	**Subcarrier spacing (SCS)**	**Number of subframes / radio frame**	**Number of slots / subframe**	**Number of OFDM symbols / slot**	**Usable Frequency Range**
normal size	15	10	1	14	FR1
normal size	30	10	2	14	FR1
normal size	60	10	4	14	FR1/FR2
extended size	60	10	4	12	FR1/FR2
normal size	120	10	8	14	FR2
normal size	240	10	16	14	FR2

From the Table 2 we can see that the extended CP could be applied to SCS of 60 kHz but the number of OFDM symbols would be decreased due to this. Note that some of the SCSs are not applicable for FR1, and some of them not for FR2 either. [4]

3 BEAM MANAGAMENT

As mentioned before, in NR technology, especially in FR2, the beam management (BM) is essential. As a term “beam management” is quite wide. It includes techniques such as beam sweeping, beam measurement, beam determination/selection, beam reporting, beam maintenance and beam recovery. Those techniques will be introduced and discussed in the section 3.2. Beamforming technique is the base for everything related to beam management and it is needed to form beams at the first place. Short peek into the beamforming technique will be taken, but the main subject will be the beam management and its aspects.

3.1 Beamforming in general

The terms MIMO (Multiple-Input and Multiple-Output) or Massive MIMO (mMIMO) have been heard in the discussions about 5G technology. In general, MIMO refers to a technique where multiple antennas are used to transmit and receive information, in other words capacity of a cell is increased. This makes higher throughputs possible.

In NR technology, the term Massive MIMO is more familiar, but the term in the context of NR technology is bit of a misleading. In NR, and especially in FR2 frequencies, mMIMO is used for beamforming. If there are enough antennas on transmitter side, it is possible to use multiple of them (more precisely, a set of antenna elements) to form beams and point them to a specific location. This is called ‘Analog beamforming’, this technique impacts to the radiation pattern and the antenna array gain. With one set of antenna elements, one beam can be formed with this technique. Analog beamforming compensates the high path loss in FR2 frequencies and is mandatory for the efficient implementation of the millimetre-wave networks.

Another technique is called Digital beamforming. In digital beamforming, the modification of the amplitude and phase are done in the baseband processing on the transmitter side before data transmission. Digital beamforming has one downside in it, it is very hardware costing and thus power hungry to use if it would be the only beamforming technology used in transmitter. Due to this, there is a method called hybrid beamforming, where both mentioned techniques are combined and used together. Hybrid beamforming compensates the hardware costs and in FR2 it is the method expected to be used mostly. [14]

3.2 Why Beam management?

In the introduction of this chapter, it was mentioned that the beam management is essential for FR2 frequencies. This is because the beamforming is used, and beam management is needed to fulfil the low latency and fast data transfer requirement set for NR.

Forming beams means that instead of circular coverage, beam-shaped coverage is formed. The radiation pattern of beam is completely different comparing to the cell. Its width is narrow, but the length is many times longer than it would be with circle radiation pattern. The differences of the cell coverages between the cells with beamforming enabled and disabled are more precisely illustrated in the Figure 8.

Beamforming and thus beam management is used in NR to maximize the signal quality on UE side without the need to raise transmitting signal power levels at the transmitter side. Beam switching, configuring and other tasks related to beam management will be discussed next. [20]

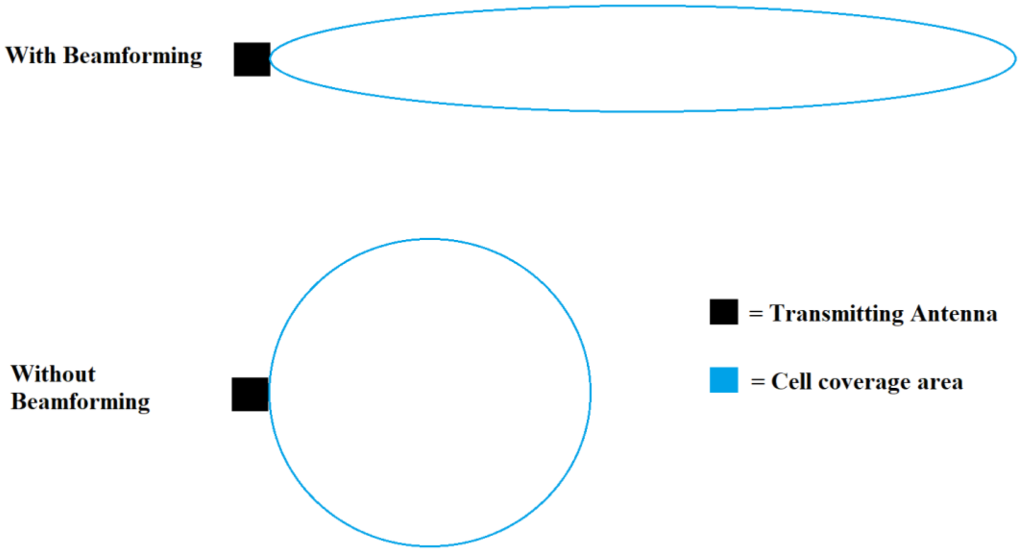


Figure 8. Beamforming disabled vs. beamforming enabled.

3.3 Beam Management Procedure

Beam management includes numerous tasks to establish and maintain the connection between the UE and the transmit-receive-point(s) (TRP) on base station (BS) side. A set of Layer 1 (L1, Physical Layer) and Layer 2 (L2, Medium Access Control, MAC) procedures are defined for beam management. With the help of BM procedure, the beam pair links can be established between the UE and the TRP(s). Six aspects included in the BM procedure are shown in Table 3 below. [15][16]

Table 3. Beam management procedure.

Operation	Purpose
Beam Sweeping	Transmit/Receive beams covering spatial area during predetermined time interval. TRP(s) and/or UE can make this procedure.
Beam Measurement	For UE or TRP(s) to measure the signal quality of received beams transmitted by UE or TRP(s).
Beam Reporting	UE reports information of received beam(s) to the BS based on the information from Beam measurement procedure.
Beam Determination	For UE or TRP(s) to decide the best suitable beam(s) for transmission/reception.
Beam Adjustment	For UE/TRP(s) to adapt to the channel changes due to changing environment or UE/TRP(s) blockage. This operation consists of sweeping, measurement, reporting and determination.
Beam Recovery	For UE to detect new candidate beams in the case of beam failure. UE informs TRP(s) about the beam failure with separate beam recovery request.

As mentioned before, the main purpose of the procedures shown in Table 3 is to form a suitable beam pair which means beam pointing from transmitter to receiver and vice versa. Together the beams provide a good connectivity. The beam pair can be used for uplink or downlink data transmission.

Usually, the BM procedure is done either in TRP(s) or in UE side. However, should the BM procedure be done in TRP or UE side, the resulting beam pair is usually suitable for the bi-directional data transmission. This means that beam pair link configured for downlink can be used for uplink. 3GPP refers this as ‘beam correspondence’. This makes the beam management easier and faster. For example, if BS has determined a certain beam pair to be used in downlink, and this pair also happens to be suitable for uplink transmission, there is no need to perform another beam sweeping procedure on UE side since the already existing beam pair link can be used for uplink and downlink data transmission.

There are some minor differences in the BM operations depending on the state of the UE. If the UE is not connected to the network (*IDLE/DEREGISTERED mode*), meaning it must perform initial access to the network, there is some differences in the procedures compared to the case where the UE is already registered to the network (*CONNECTED mode*). The beam management procedure also known as beam establishment before the connection to the network will be discussed next. [15][16]

3.3.1 During Initial Access

Whenever UE is entering coverage area of a new cell, the procedure called cell search is carried out. It is also carried out continuously when the UE is in IDLE/INACTIVE –state and moving within the cell coverage areas.

In general, initial access (IA) requires certain tasks from UE and network. The procedure with and without beam management contains similarities, thus the steps from initial access without BM will be explained first.

3.3.1.1 IA without BM

In normal initial access, BS is broadcasting synchronization signal within the cell coverage area. Synchronization signal is transmitted by BS periodically which varies from 5ms to 160ms, the signal consists of a primary synchronization signal (PSS) and a secondary synchronization signal (SSS). Together those two signals combined with physical broadcast channel (PBCH) form a synchronization signal block (SSB) also often referred as SS block. The SSB is transmitted to cell area periodically, the PBCH included in the SSB carries information UE needs to know before establishing connection to a network. When the device (UE) gets information about cell, it may start to establish connection. Connection establishment procedure is called Random-Access (RA) procedure.

In NR, there is a physical channel provided for RA which is called Physical Random-Access Channel (PRACH) and is also known as preamble transmission sent by the UE to the network, before camping to the cell. Network responds to the preamble by sending Random-Access Response (RAR) back to the UE. RAR indicated the successful reception of the preamble and provides some information to UE. UE and NW then send the uplink and downlink messages, known as ‘Message 3’ and ‘Message 4’ to make sure there will not be any collisions during simultaneous transmissions of the similar preambles from other possible devices within the cell. After UE receives Message 4 successfully, its state changes from DEREGISTERED/IDLE mode to CONNECTED mode. The IA -procedure, without BM is illustrated in the Figure 9. [15][16][17]

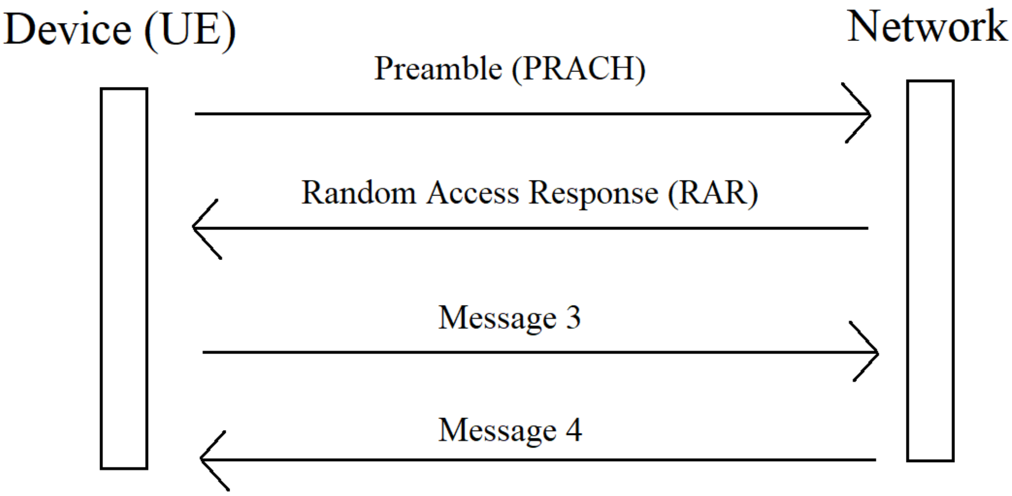


Figure 9. Random-Access procedure between UE and NW.

This is the basic procedure in Random-Access without BM. The same procedure will remain with the BM initial access, but there will be some differences to make it possible to form suitable beam pairs between UE and the BS. The IA with BM will be discussed next.

3.3.1.2 IA with Beam Management

With BM, the same procedure is used but it is slightly altered. The first step in the IA procedure with BM and its features enabled is the beam sweeping. The beam sweeping is done in the BS side (TRP). In the case without BM, the BS would be transmitting the SS Block with certain periodicity whereas in the case with BM enabled, the multiple SSBs with different time indices are being transmitted. Those multiple SSBs are being divided between downlink beams so that each beam has its own SSB. The UE within the beam area can then receive the beam specific SSB and respond with preamble. The subsequent preamble transmission following the reception of SSB is received by BS. BS can then identify the downlink beam which has the UE located within its range based on time index of received uplink preamble. This way an initial beam pair can be established, and NW can assume that the beam pair will be valid for further uplink and downlink transmissions. Eventually, the beam pair established during IA will in some point become unusable, then a procedure called 'Beam Adjustment' will handle the situation. The beam adjustment basically includes BM operations during the UE is in CONNECTED mode.

If the UE is in the IDLE mode within the cell coverage area, then whenever the connectivity is needed, UE will start Random Access procedure and the best beam pair will be established based on the PRACH preamble sent by UE, so basically the procedure is the same as before the initial access to the cell.

The beam pair that provides good connectivity does not always mean the beams pointing directly to each other from the UE and TRP(s) point-of-views. There may be obstacles and blockages in the environment, and when there is, UE and TRP(s) should be able to handle this kind of situation. The beam pairs can also be established via reflection, which helps to overcome the situations when there is no direct line of sight (LOS) between TRP(s) and UE. In the Figures 10 and 11 beam pairs are illustrated. [15][16][17]

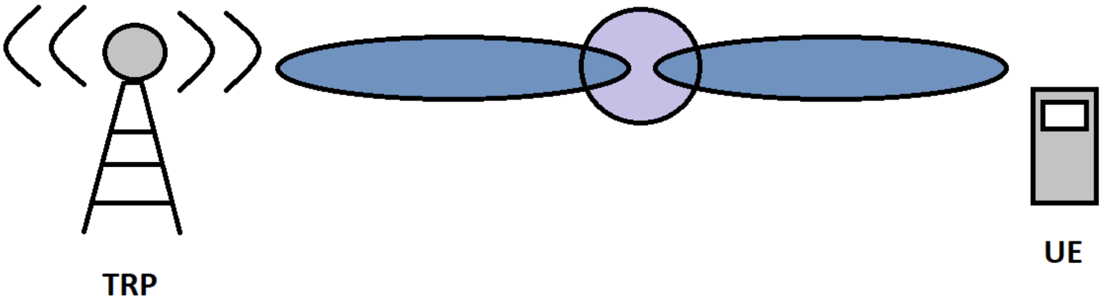


Figure 10. Direct beam pair between TRP and UE.

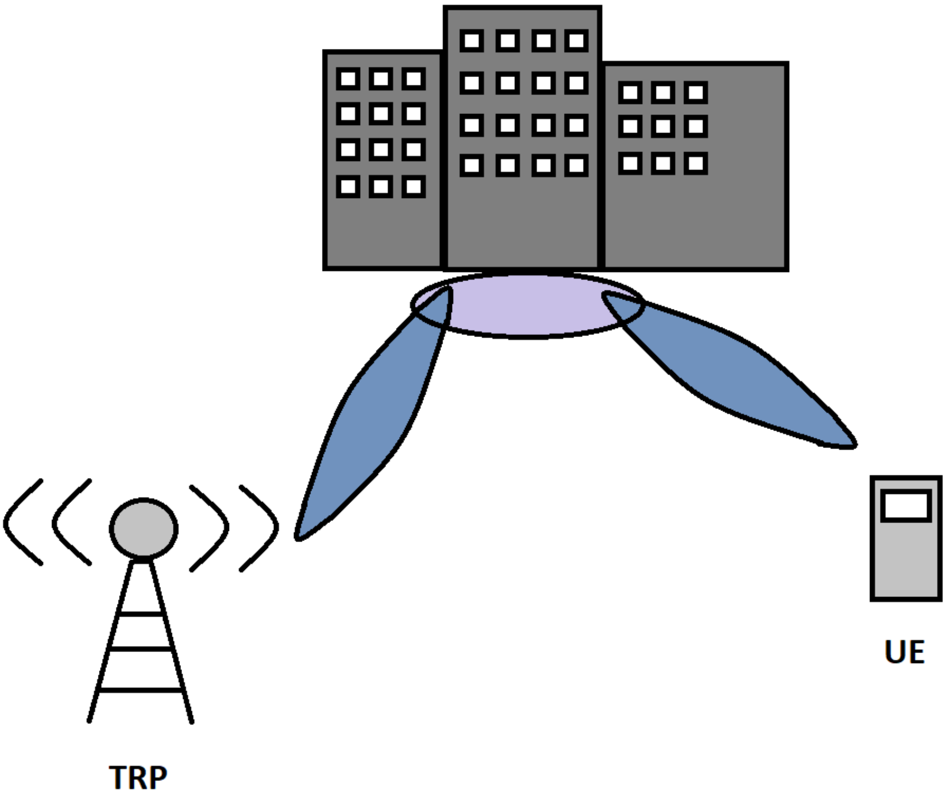


Figure 11. Reflecting beam pair between TRP and UE.

3.3.2 During Tracking

Beam management during tracking also referred as 'beam adjustment' contains the operations listed in Table 3. In this chapter the actual operations of beam management during tracking (CONNECTED mode) will be inspected more closely. The beam sweeping operation will be discussed first.

3.3.2.1 Beam Adjustment

The beam sweeping, measurement, reporting and determination operations are done continuously with certain periodicity on BS or on UE side to maintain the already existing beam pairs between UEs and TRPs. These operations, also known as beam adjustment, contain several procedures which are as follows: transmitter-side beam adjustment and receiver-side beam adjustment. Both of those can be performed either in downlink or in uplink.

Beam adjustment needs to be done regularly since the moving of UE or effects of the changing environment will impact on the transmitter and receiver-side beams. [15][17]

3.3.2.2 Transmitter-side beam adjustment on downlink

In CONNECTED mode, the UE is generally using CSI-RS (Channel State Information Reference Signal) for measurements and for beam selection, but SS Blocks can also be used while in CONNECTED mode. UE performs CSI-RS measurements for the beams transmitted by the BS periodically (sweeping) and selects the best beam to be used for data transmission. UE then reports the beam ID which corresponds the CSI-RS index associated with the selected beam and the Reference Signal Received Power (RSRP) to the BS. Basing on the received information BS may select the best beam.

Receiver-side device (UE) can measure and report up to 4 reference signals (either CSI-RS or SSB), practically this means 4 beams. In addition to the previous, IDs of the beams and the differences in the RSRPs between the best beam and the rest of the beams are reported to BS. These multiple reference signals can be seen as a one CSI-RS resource set, which then can be used by the receiver-side device. Basing on the information reported by the receiver-side device, the BS may then adjust the beam(s) if needed meaning re-directing beam, re-forming beam, or selecting a new beam to be used.

As mentioned before these procedures can be referred as beam adjustment. The case described above is called downlink beam adjustment and more specifically transmitter-side downlink beam adjustment, meaning that the transmitter-side (BS) beams are to be adjusted. The sweeping operation is done on the transmitter-side (BS) and the measuring is done on the receiver-side (UE). After the procedure, one set of reference signal beams (CSI-RS resource set) and selected beam within it will be configured for use. The figure 12 represents the transmitter-side beam adjustment. [17]

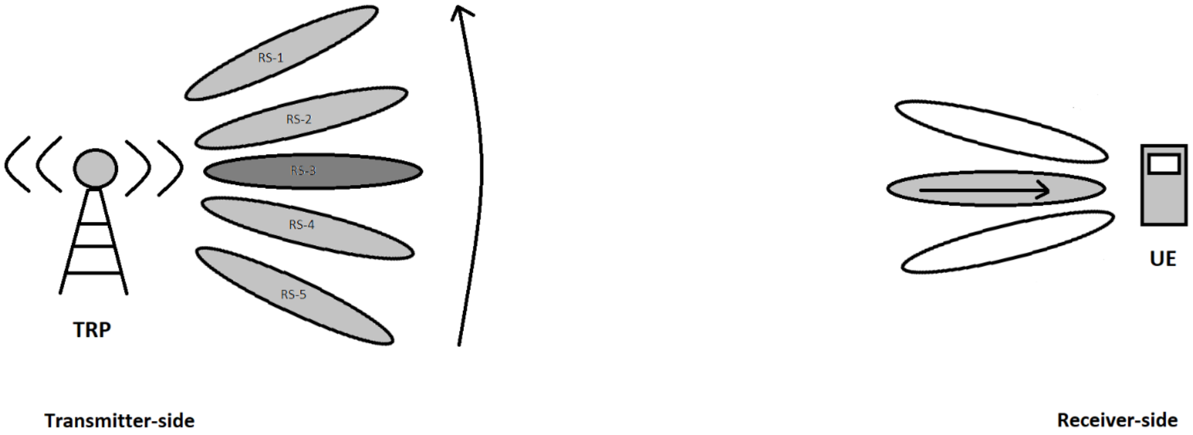


Figure 12. Transmitter-side beam adjustment on downlink.

3.3.2.3 Receiver-side beam adjustment on downlink

Beam adjustment will also be done on receiver-side. This is logically called receiver-side downlink beam adjustment. When the receiver-side downlink beams are adjusted, the selection of the best beam is up to device and the beam switching and/or adjusting is done internally on the device (UE) side. Compared to the transmitter-side beam adjustment, there is not any kind of reporting to the BS during receiver-side beam adjustment.

In the receiver-side beam adjustment, sweeping operation will be done on receiver-side (UE) over the multiple reference signals transmitted by the BS. Also, the receiver-side should be able to recognize the beams included in the configured beam resource set consisting of multiple CSI-RS’s or SSBs while performing the beam sweeping operation. This is solved by including ‘repetition’ –flag within the configured resource set, with the help of this flag UE can assume that the measured reference signals are transmitted using the same spatial filter. The figure 13 represents the receiver-side beam adjustment operation. [17]

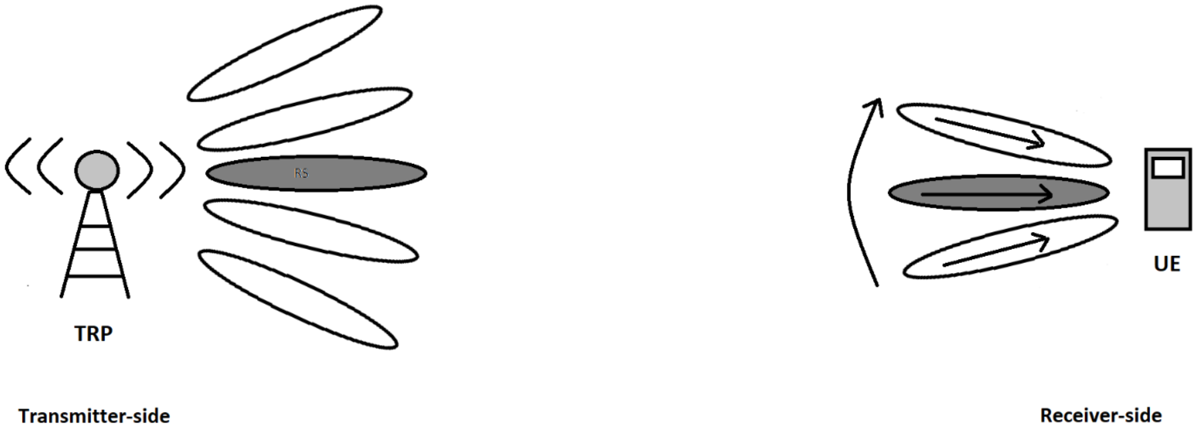


Figure 13. Receiver-side beam adjustment on downlink.

3.3.2.4 Uplink beam adjustment

The uplink beam adjustment is usually not needed since usually during the downlink beam adjustment the beam correspondence can be assumed. However, the situation when the uplink beam adjustment comes into the question is possible.

The beam adjustment in uplink works the same way as in downlink, but instead of CSI-RS or SS Blocks, the sounding reference signal (SRS) transmitted by UE is used to measure the signal of UE. Network then reports the results to UE so it can perform the selection/adjustment procedure. Also on uplink beam adjustment, beam correspondence can be used instead of performing uplink and downlink beam adjustments separately meaning that if the uplink adjustment procedure is done and the beam correspondence can be assumed, and the downlink adjustment procedure is no longer needed. The figure 14 represents the beam adjustment on receiver-side uplink. [17]

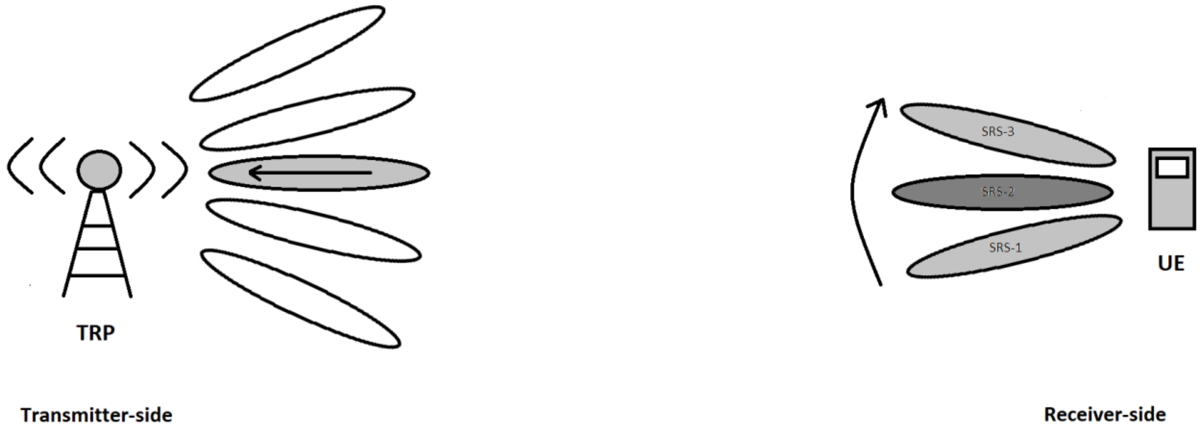


Figure 14. Receiver-side beam adjustment on uplink.

3.3.2.5 Beam Recovery

A situation where the UE is getting blocked either totally or temporarily but rapidly, the beam pair might become unusable, and the beam adjustment might not be enough to maintain the beam pair to keep connectivity. Such event is called beam failure, also referred to as beam recovery.

As a concept, beam recovery is almost like radio-link-failure (RLF). In RLF, the UE loses the connectivity to the serving cell which initiates cell search and a re-establishment procedure to a new cell within the coverage area. The RLF procedure could be applied to the beam recovery, but there are reasons to introduce a new procedure for beam recovery separately. The RLF involves high-layer functionality which makes it a slow process. This would not be good with the beam failure event, since the beam failures might be occurring rapidly. This would result a failed connection establishment to the cell because another beam failure might happen before recovering the earlier beam failure event.

Another point in RLF is that often when the UE loses the coverage of the serving cell, and eventually finds a cell within coverage area, the found cell is usually different than the cell which the UE lost. In beam failure event, the cell usually remains the same, but the beam pair is re-established rather than a new cell. Since the cell remains the same, establishing a new beam pair does not require as high-layer functionality as RLF does. This allows faster lower-layer functionality to be used, which suits the purpose of the beam recovery. Generally, the beam recovery consists of steps shortly described and listed on Table 4. [17]

Table 4. Beam recovery event steps.

Step	Function
Detection of beam failure	Device detects beam failure when one has been occurred.
Identification of candidate beams	Device identifies new beam pair to restore connectivity.
Recovery-request transmission	Device transmits recovery-request to the network.
Recovery-request response	Response to the recovery-requests from the network.

3.3.2.6 Detection of Beam Failure

In NR, the beamforming can be done on transmitter side in a way that the receiving device does not know what beam is used at the transmitter. NR do also support so called beam indication in which the beam is indicated to the receiving device. The beam indication bases on the downlink signalling of transmission configuration indication (TCI) –states. Each TCI state includes information about transmission configuration, which also covers the information about reference signals (CSI-RS/SSB). When there is data transmission on downlink, either physical downlink shared channel (PDSCH) or physical downlink control channel (PDCCH) is being used. The PDSCH/PDCCH can then be associated with the certain TCI. Based on the TCI associated with the downlink channel, the device can then assume that the data transmission is done by using the same beam as the beam used for reference signal informed in the TCI.

It can be assumed that the beam failure has happened if a certain value of error probability in PDCCH exceeds. But the device just bases the declaration of beam failure to the quality of the reference signal, meaning the RSRP of the periodic CSI-RS/SSB associated with the PDCCH TCI state. If the measured RSRP of the reference signal goes below the configured value, it is defined as ‘beam failure instance’. If the number of beam failure instances exceed the configured value, the beam failure can be assumed, and the beam recovery can be initiated. [17]

3.3.2.7 Identification of candidate beams

Identification of new candidate beams after beam failure is first step in beam recovery procedure. This procedure shares similarities to initial beam establishment discussed earlier. In this procedure, the device tries to find a new beam pair which could be used to restore connectivity. As in the initial beam establishment the device is configured with a set of reference signals (a resource set) each signal corresponding specific downlink beam. Either CSI-RS or SSB is used in resource set. This resource set then forms a set of candidate beams for the device.

The device is then measuring the RSRP on the reference signals of the configured resource set. There is a configured target value for the RSRP of the reference signal, which when exceeded is assumed to correspond the beam which can be used to restore the connectivity. The device should also consider different directions of the receiver-side beams when applicable. This will affect to the decision of the beam pair selection. [17]

3.3.2.8 Recovery-request transmission and response

When the declaration of a beam failure is done and suitable beam pair has been identified for restoring connection, a beam recovery request is sent. The purpose of recovery request is to inform the NW side that the beam failure has been detected by the receiving device. The information about candidate beam may also be included in the request, to inform NW.

The beam recovery request is basically a random-access request consisting of preamble transmission and RA –response. Preamble should be transmitted using the preamble configuration associated with the identified beam. The uplink beam, which is being used to transmit the preamble, should be the beam which coincides with the identified candidate downlink beam.

Depending on the configuration on NW side, the candidate beams may or may not be associated with unique preamble configurations. There are three options for this listed below.

1) Each candidate beam has unique preamble configuration. With this option the network can identify which downlink beam is used based on the preamble transmitted by the UE.

2) There are a group of candidate beams and all beams within the group have a unique preamble configuration. There might be multiple beam groups with unique preamble configuration as well. With this option the preamble received by NW only indicates the beam group which the candidate beam belongs.

3) All beams are associated with the same preamble configuration. With this option NW is only informed that the beam failure has happened, and the recovery has been requested by the UE.

When the beam recovery-request has been carried out, the device starts monitoring the downlink for a response. If the response is received, the device can assume that NW is transmitting PDCCH TCI associated with the candidate beam (CSI-RS associated with the candidate beam). The monitoring of the response starts four slots after the recovery-request transmission. If the response is not received within a certain time window, the device will retransmit the request. [17]

4 TEST SYSTEM IMPLEMENTATION

Beam management as a part of the network means that gNB (next generation Node-B) and UE (User Equipment) both have responsibilities to do to everything to work correctly. In this thesis the focus is on UE side, and functionality will be mostly from the UE point-of-view since the UE is the one being tested/validated.

The next question will be: How beam management can be tested?

Well, the simplest test environment would be just UE and the gNB both supporting beam management and the UE would be placed towards the antenna of the gNB. Testing could be done with this environment and at least basic features of beam management could be tested, when the placement of UE is fixed.

Think about the scenario that the UE is being moved, there would be not any guarantees that UE (or gNB) would function correctly. By moving the UE, it would move through the different beams and both UE and gNB should handle beam switching and other stuff what is happening during this procedure. This is the reason why in this thesis, we build an environment which has an ability to move UE from side to side to make it sure that beam management and its features will still function correctly, independent on whether the UE is moving or standing still.

4.1 Test Equipment

The first problem which comes into question when building this kind of environment is: How to implement a system which will move the UE? Well, obviously there would be many options for this, but in this thesis, I have ended up using linear actuator. So, we have a toothed belt axis with moving guide, which is moved by a stepper motor. Stepper motor makes it possible to make very small and precious movements if needed but also fast continuous movement is possible.

The stepper motor is controlled by the separate servo controller. The servo controller is programmable controller, and it can be configured and controlled with PC via Ethernet. The direct parametrization and control of the linear actuator can be done with servo controller via specific software. The actuator can also be controlled with different kind of protocols directly, thus the need of a specific software is not necessarily needed to control the guide. This is the perfect option if we are taking an automation into account.

The other equipment needed of course are the UE and the test network supporting 5G, millimetre-waves and beam management. Then we need a computer to trace the logs from UE side, so we can see in real time what happens inside UE (quality of signal, data throughput, and beam related things). For the UE and test network part, the environment is already set up and verified to be working, so the linear actuator is the only thing to be added to the setup. The list of each test equipment is represented in the Table 5.

Table 5. List of test equipment.

Test Equipment	Usage
Test UE	The UE which will be tested. MediaTek prototype UE supporting NR FR2 and beam management features. Will be used in Beam Management tests.
Enhanced Next Generation Node-B (en-gNB)	Secondary node integrated to Master Node (enB) via X2 -interface. Will be used as FR2 radio part in Beam Management tests.
Simulated Evolved Packet Core (EPCSIM)	EPC Simulator simulates the LTE core network. Used as a core NW for test network including test node.
Linear Actuator	Toothed Belt Axis with Guide. Will be used to move the UE back and forth in front of RF -antenna.
Stepper Motor/Servomotor	Integrated to linear actuator, will be used to power the toothed belt axis which in turn will move the guide.
Servo Controller	Connected to Stepper Motor. Programmable controller that will be used to control the stepper motor.
Data/Logging PC	PC for transferring data through UE to network. Will also be used to record UE –side logs and control servo controller.

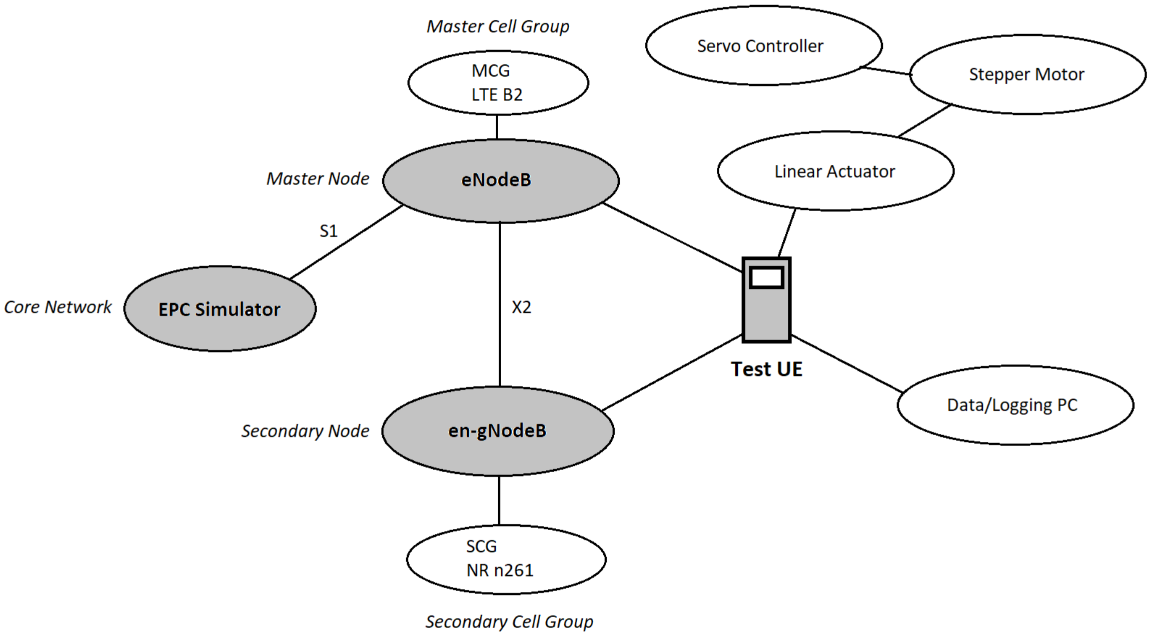


Figure 15. Test setup structure map

4.1.1 Test UE

MediaTek prototype UE is the device of interest in this thesis. The test UE is NR capable and supports FR2 –range and beam management. The results of the BM tests will be taken from the UE point-of-view and the BM feature functionality will be validated with the Test UE. The logs from the tests can be saved from UE for later inspection after the tests, but it is also possible to see the real time trace from the UE during the test execution. The picture of the Test UE can be seen from the Figure 15.

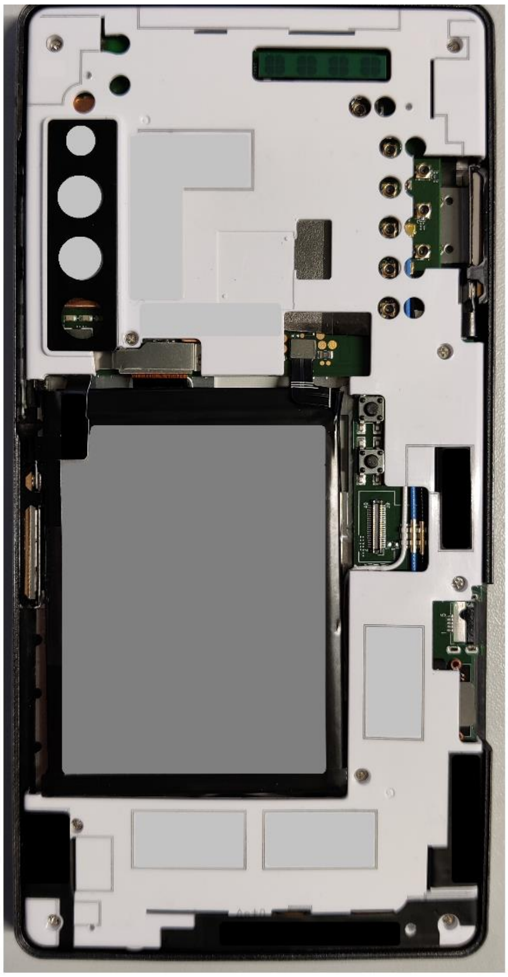


Figure 16. MediaTek Test UE.

Alongside with the Test UE there will be data/logging PC for tracing the UE logs. Test UE is connected to the PC via USB (Universal Serial Bus) 3.0 –cable. In the PC, there is separate logging tool, which will help to trace UE logs in real time via the USB. Also, the prototype UE itself doesn’t have the functionality to transfer data independently, so the PC is used for data transfers over the USB via UE to the network, this is similar to the USB tethering (internet connection sharing) feature included in the present smart phones. The same exact PC is used to communicate with the servo controller to control the servomotor. The Figure 16 illustrates the Test UE and PC setup.

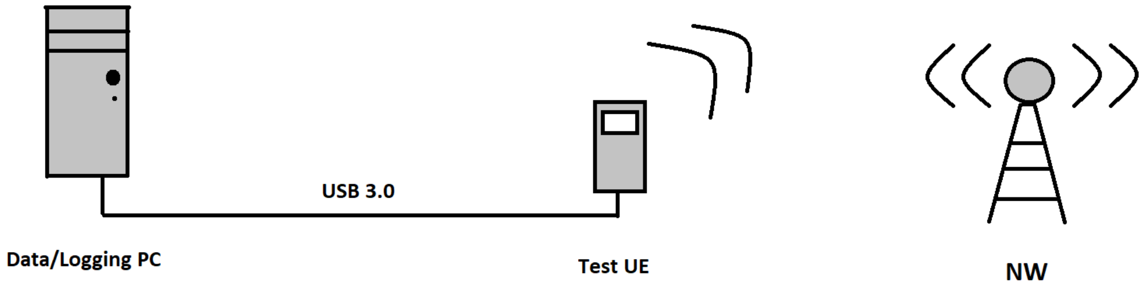


Figure 17. Test UE and Data/Logging PC setup.

4.1.2 Test Network

The test network for the BM tests will be NSA setup with LTE Band 2 anchor cell which will be used as the master cell. The FR2 NR Band 261 cell(s) will be used as secondary cell(s). The eNB (Master Node), en-gNB (Secondary Node) and simulated core (EPCSIM) together form the test network. The secondary cell (FR2 Band 261) is responsible for data transferring and beam management functionality and it will be used to run the tests. The LTE cell will be connected to UE via conducted Radio Frequency (RF) cable, and the NR cell(s) over-the-air (OTA). The NSA setup is partly similar to the NSA environment earlier presented in Chapter 2.

The network and the Test UE support carrier aggregation (CA) up to 8 component carriers (8CC) and 2x2 MIMO for downlink. For uplink, 2CC and 2x2 MIMO is supported. This means that 8 cells can be used for downlink data transfers and 2 cells for uplink data transfers making the network alongside the simulated core capable of 4 Gbps of downlink throughput and 250 Mbps of uplink throughput. This allows high throughput and beam management tests to be combined. Detailed illustration of the NW configuration and how UE is related to it is presented in the Figure 17.

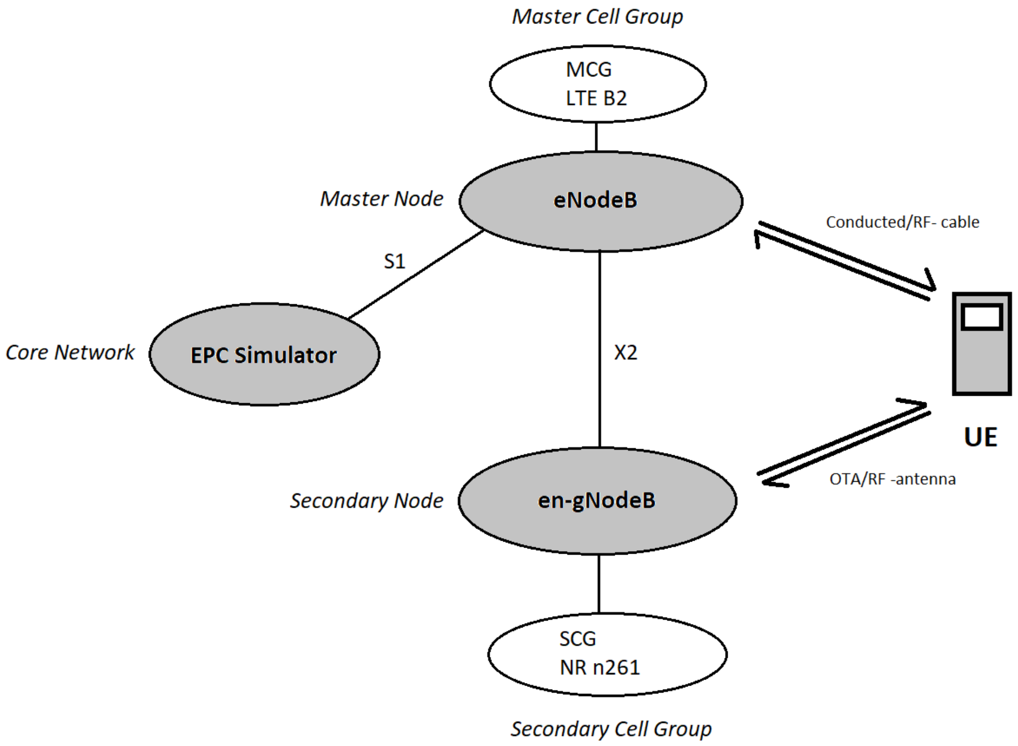


Figure 18. The test network structure with UE.

4.1.3 Final setup

The Test UE will be integrated to the guide of the linear actuator; this will be done with the proper jig which will be fitted to the guide with screws. Power supply and the servo controller will be connected to the servo motor of the actuator to power the movement of the guide. The UE and the servo controller will be connected to the data/logging PC which will also be used to control the movement of the guide. Once the UE is fitted to the actuator and cabling for the UE and actuator has been set up, the setup is ready for the first test runs. First the guide needs to be calibrated, further discussion about the calibration and guide usage will be on the 'Implementation' -section. The Figure 18 illustrates the linear actuator setup and its idea.

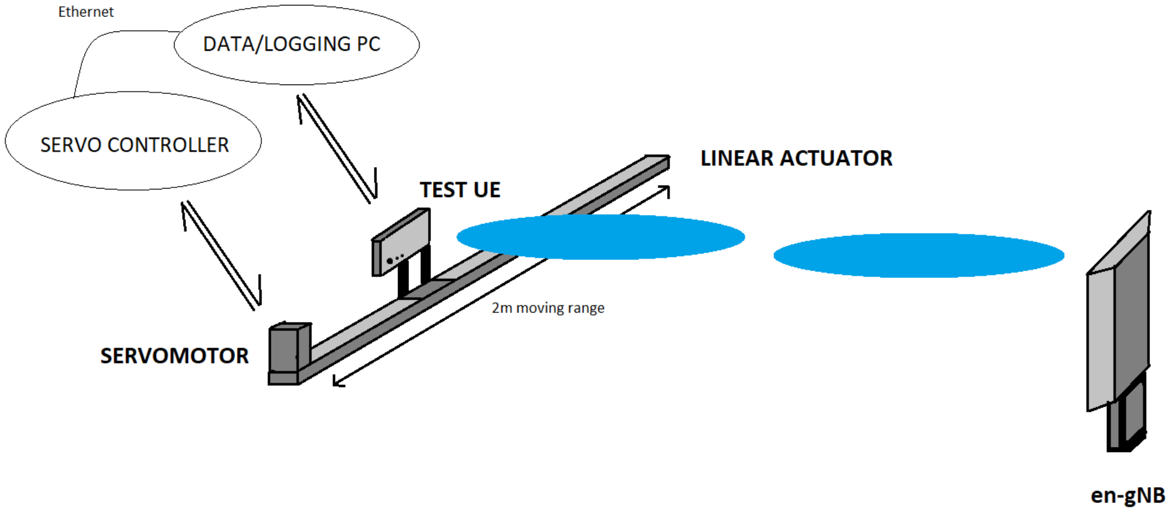


Figure 19. Test UE integrated to the linear actuator. UE and NW beams illustrated with blue colour.

4.2 Implementation

Controlling the linear actuator was the most demanding part in the implementation of the test system. As discussed earlier, the network and UE were already set up in the environment and verified to be functioning correctly. The addition of the actuator made the beam management testing possible. The main goal in the implementation was to make the controlling of the UE and the actuator to work smoothly without errors. This chapter will mostly introduce the implementation of the actuator control.

4.2.1 Linear actuator

As described in the Figure 18, the final setup consists of the linear actuator, Test UE fitted into actuators guide, servomotor, servo controller, data/logging PC and the en-gNB. The servo controller is used to control the servomotor which moves the guide. The servo controller is controlled with data/logging PC via Ethernet. The calibration and configuration can be done via Ethernet with separate configuration web interface but controlling the motor via servo controller will be done using a Modbus protocol over Ethernet, also known as Modbus TCP.

4.2.1.1 Modbus TCP

Modbus is a messaging protocol operating on application layer, Modbus TCP means that the protocol is used on TCP/IP stack over Ethernet. Modbus makes the client/server type communication possible between the devices connected to each other. Different bus/network types are supported. General Modbus frame consists of protocol data unit (PDU) which includes the Modbus function code and Modbus data. Specific network/bus can introduce additional fields on the application data unit (ADU) which includes PDU.

There are several different ways to organize data in the device, this is usually defined by the manufacturer of the device. The Modbus data model is represented in the Table 6.

Table 6. Modbus data model.

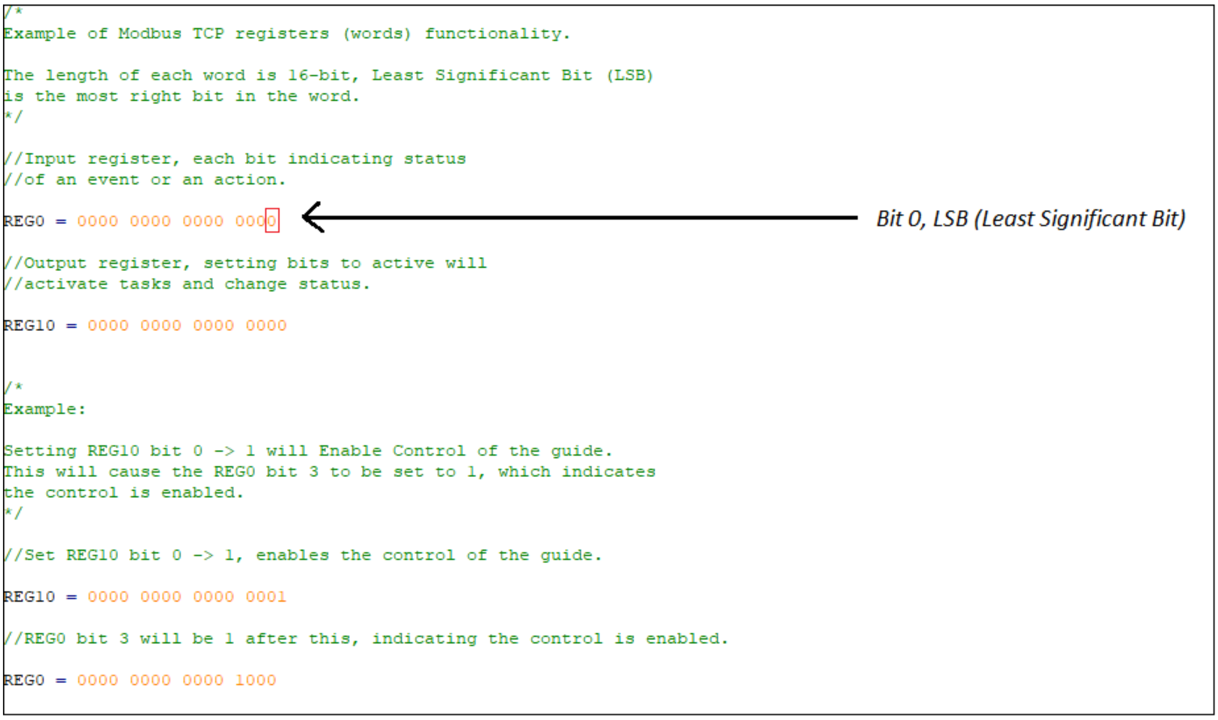
Tables	Object type	Modification
Discrete input	Single Bit	Read-Only
Coils	Single Bit	Read/Write
Input Registers	16-bit Word	Read-Only
Holding Registers	16-bit Word	Read/Write

In this case, the servo controller uses Input/Holding registers, 12 readable input words (Input registers) and 12 writable output words (Holding registers). There are different word types for events and actions on the servo controller. The input words are indicating the status/on-going events of the servo controller and the output words are writable registers which can be used to control the guide. [19]

4.2.1.2 Guide Control

Controlling the servo can be done through the web interface which is used to configure the guide. From the automation point-of-view, this is clumsy. The second option, as discussed in the previous chapter, is the Modbus TCP protocol. This is better option taking automation into account, since the automation bases on python and Modbus TCP libraries are available for python.

However, there is not any specific software to control the guide which uses Modbus, so the implementation of the control program was essential. Implementing the control program with python was one of the biggest challenges in this thesis. The functionality of Modbus TCP with the guide was discussed earlier, a small example of the Modbus TCP functionality is illustrated on the Figure 20.



```
/*
Example of Modbus TCP registers (words) functionality.

The length of each word is 16-bit, Least Significant Bit (LSB)
is the most right bit in the word.
*/

//Input register, each bit indicating status
//of an event or an action.

REG0 = 0000 0000 0000 0000

//Output register, setting bits to active will
//activate tasks and change status.

REG10 = 0000 0000 0000 0000


/*
Example:

Setting REG10 bit 0 -> 1 will Enable Control of the guide.
This will cause the REG0 bit 3 to be set to 1, which indicates
the control is enabled.
*/

//Set REG10 bit 0 -> 1, enables the control of the guide.

REG10 = 0000 0000 0000 0001

//REG0 bit 3 will be 1 after this, indicating the control is enabled.

REG0 = 0000 0000 0000 1000
```

Figure 20. Modbus register functionality example.

As can be seen from the Figure 20, performing actions with the guide is done by activating a specific bit in a specific register. More precisely, sequential activation of specific bits in a correct order is needed for some actions to be made, at the same time, status and events can be monitored by observing the active bits of readable input registers. This is the way to communicate with servo controller and perform guide actions.

4.2.2 Modbus Control Program

The implemented control program is a simple command line interface (CLI) –styled application, which provides options for different linear actuator actions. The structure of the program is the main function, the Modbus control –class and the ModbusTCP –library which is basically class as well. The ModbusTCP library can be seen as a bottom layer of the program, which directly communicates with the servo controller using the Modbus protocol. The Modbus control –class is self-implemented class including the control methods such as powering on the guide, getting and setting the guide position and moving the guide. The control –class can be seen as a middle layer of the program since it uses the ModbusTCP class methods to communicate with servo controller. The final top layer of the program, which is also self-implemented, is the main function which is user controllable CLI –styled menu containing the options of possible commands to be send to the servo. The main program uses the Modbus control –class and its methods to perform actions. The structure of the program is illustrated in the Figure 21.

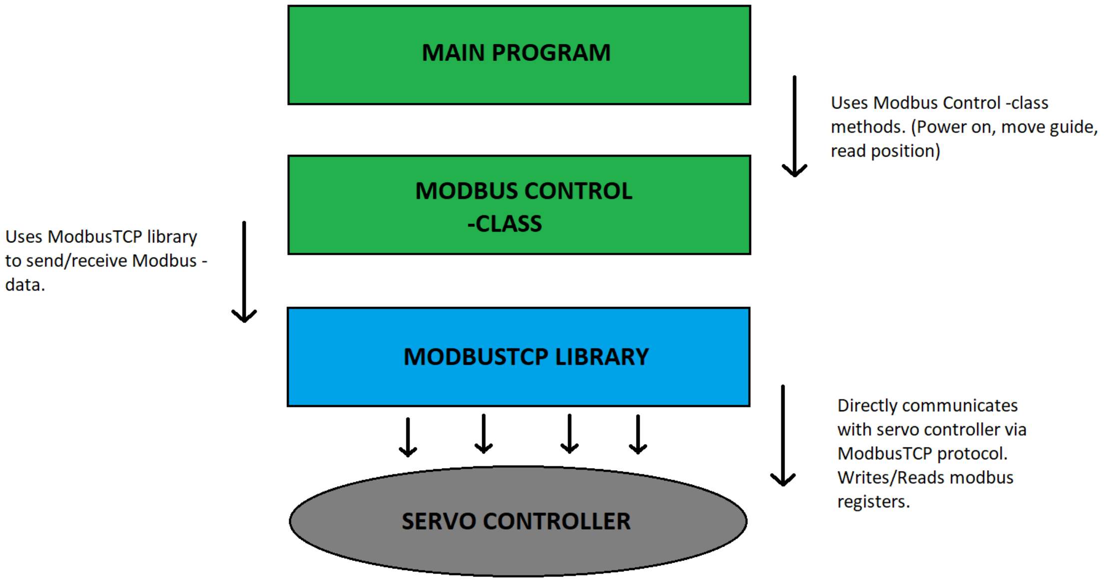


Figure 21. Modbus Control Program structure. Green parts are self-implemented, blue part is the publicly available ModbusTCP library.

The control program was designed in a way that it would be easy to integrate to the automation, thus the structure is as described in the Figure 21. Main program could be easily replaced with any other function or class which could use control class methods, such as class responsible for the test automation. The main program in the early phase was mostly used to debug and test the Modbus control –class. After the control class was verified to be working, the features of it were reduced to the actions needed for manual control of the guide and the program itself suits to manual testing perfectly alongside the web interface control. The view from the main program window with some options listed in the program is presented on the Figure 22.

```
= = = = = = = = = = = = = = = = = =
|                                 |
|  _ ___ _ _______ _ ___ ______   |
| | |/ /| ||  ____|| |/ /|  __  | |
| |   / | || |___  |   / | |  | | |
| |   \ | ||___  | |   \ | |__| | |
| |_|\_\|_||_____| |_|\_\|______| |
|                                 |
= = = = = = = = = = = = = = = = = =
| MODBUS Testing software         |
= = = = = = = = = = = = = = = = = =
-----------------------------------------------------------
Therads running: ['ModbusPollingThread']
-----------------------------------------------------------
Connected to Servo controller: True
-----------------------------------------------------------
Software limits active: False
-----------------------------------------------------------
Actual Position: 0.04mm
-----------------------------------------------------------
Error: No Fault (0)
-----------------------------------------------------------
Warning: No Fault (0)
-----------------------------------------------------------
1) Init Powerstage

2) Reset Control Word
3) Acknowledge Faults
4) Set position/velocity

5) Activate traversing task

6) Reset Output Registers
7) Set homing point
8) Jogging control

9) Show Modbus Registerlist

10) PLC Master Control
11) Enable Drive

12) Travel to homepoint

E) Exit
R) Refresh


Choose:
```

Figure 22. View from the main screen window of the main program.

The linear actuator can be controlled manually with the Control program. This is typically done in a way that user inputs the position coordinates to the control program, and they will be sent to the servo controller via ModbusTCP, after this the moving of the guide can be started via the control program. Also, when using the actuator first time, the reference coordinates need to be determined to the controller (guide calibration), this is done by moving the guide manually (via web interface or the control program) and setting reference point in desired position. After this, when the UE is installed into the guide and the test environment is configured, the testing can be started.

4.3 Tests and results

First beam management tests were done with the MediaTek –prototype UE introduced earlier in the Figure 15. The first test was run manually with the help of Modbus Control program and several other tools used to configure and control the prototype UE.

The test environment consists of the LTE Band 2 + NR Band 261 NSA setup and simulated core network and the capable prototype UE. The beam management with this test environment uses SS Blocks to determine beams, the CSI- Reference Signals are not supported by this environment. SSB is thus used in CONNECTED/IDLE mode. The first test procedure is described next.

4.3.1 Test Procedure

1. Attach test UE to the network, this is done with data/logging –PC using several tools.

2. Verify that FR2 attach is successful and MCG and SCG are configured by checking the logs from the data/logging –PC.

3. After successful FR2 call, initiate MO (Mobile Originated) Ping from UE to NW using data/logging –PC.

4. When the ping is ongoing, start moving the linear actuator guide using Modbus Control Program.

5. Check that the UE doesn't crash and that the SSB Beam ID is changing while the guide is traversing.

6. Save logs from UE using data/logging -PC for further inspection. In the end detach UE from the network and move guide back to the reference point via Modbus Control Program.

4.3.2 Results

During this test procedure UE was first moved from home point to the end of the actuator, total length of about 1.8m. While moving towards the end point the velocity was set to 200mm/s and when moving back towards home point the velocity of the guide was set to 330mm/s, so it is slightly faster. This was done to make the test case more versatile. Table 7 includes the test results, which in this case will be the measured SSB beam indices from the UE log.

4.3.2.1 Beam management during MO ping

Table 7. Beam indices during the test procedure.

SSB index	13	12	14	15	20	15	12	13
Guide direction	Towards end point	Towards end point	Towards end point	Towards end point	Towards home point	Towards home point	Towards home point	Towards home point

From the Table 7 we can see that 5 different beams were used during the test case. Since this case was run with the MO ping ongoing, the UE side beam adjustment during tracking was tested on this case. This was first BM test run with the prototype UE in this environment and no UE crashes were seen during the test run, beams were also adjusted successfully, this was verified also by watching a real time log from the data/logging –PC and verifying that SSB indices were changing during the case.

According to the results, it can be assumed that the UE side beam management is working as expected without crashing. By the time when the new features are added to the UE side, this same case can be used to verify the UE again and again. Also, there is a lot of different cases possible to run with this environment such as BM during IDLE or BM during data transfer. Those cases, including this one (BM during ping) can be added to the automation.

4.3.2.2 Beam management during DL data transfer

The Beam Management during data transfer was additionally tested manually to see if the BM affects to the downlink data transfer performance when using 8 contiguous carriers (8CC). The test procedure is like what is stated in the section 4.1.3, but instead of ping data is transferred from NW to Test UE after successful FR2 call. The SSB indices during this case were the same as in previous case (see Table 7.) and no crashes were seen. However, throughputs per carrier were recorded during the test case to see the performance during BM operations. The results were plotted separately and can be seen from Figure 23.

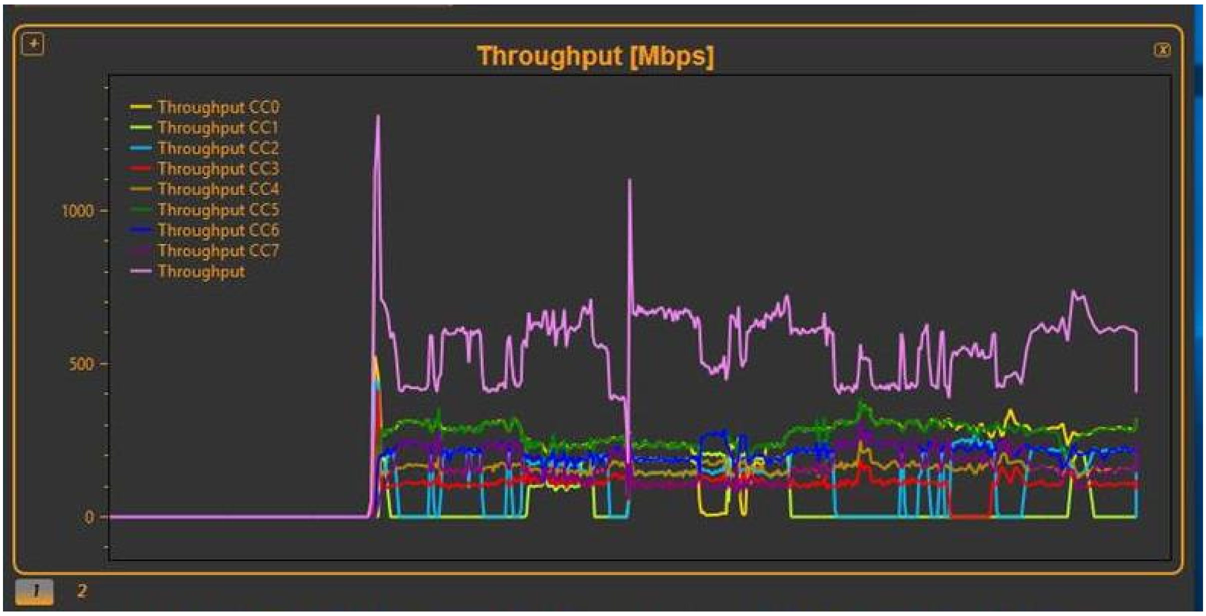


Figure 23. Downlink throughput per carrier during BM.

As can be seen from the Figure 23 the throughput varies a lot when the UE is being moved. This is probably because the beams are switched many times during the data transfer, so the maximum downlink speed is not reached before switching to the next beam. Generally, data transfer works during BM operations and there were no crashes on UE side during the test, this is good news from our point of view and the logs provide important information for further development of the UE. The UE is also prototype which means a slightly better performance is expected from the commercial UE.

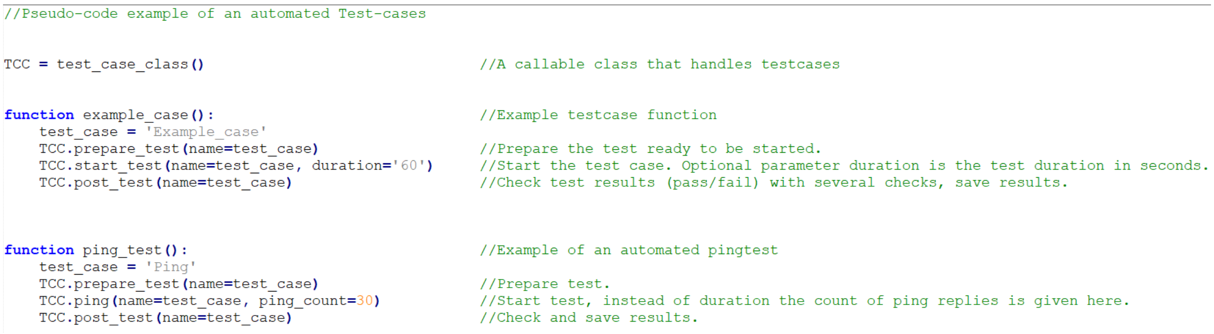
5 TEST SYSTEM AUTOMATION

In previous chapter the beam management test setup was introduced and discussed. Two test cases were executed, and several cases introduced. In this chapter the automation of those and several other cases will be studied. First, the existing automation structure will be introduced and after that beam management test integration to the automation will be discussed.

5.1 Existing Automation

As discussed before, automation is built on python. Python is an open-source programming language that is designed to run on multiple platforms, and it suits perfectly on automation and integration of multiple systems. The existing automation is capable to handle multiple Test UE's and several other hardware such as attenuators and relay boxes. It consists of numerous self-made classes and publicly available python libraries. Because of the flexibility of python, it is easy to add libraries or write new classes to the automation.

A single test case is basically a callable python function which has at least following steps: preparation of the test case, execution of the test case and post-test actions such as result checking and log collecting procedures. A few examples described on the Figure 24.



```
//Pseudo-code example of an automated Test-cases


TCC = test_case_class()                               //A callable class that handles testcases


function example_case():                              //Example testcase function
    test_case = 'Example_case'
    TCC.prepare_test(name=test_case)                  //Prepare the test ready to be started.
    TCC.start_test(name=test_case, duration='60')     //Start the test case. Optional parameter duration is the test duration in seconds.
    TCC.post_test(name=test_case)                     //Check test results (pass/fail) with several checks, save results.



function ping_test():                                 //Example of an automated pingtest
    test_case = 'Ping'
    TCC.prepare_test(name=test_case)                  //Prepare test.
    TCC.ping(name=test_case, ping_count=30)           //Start test, instead of duration the count of ping replies is given here.
    TCC.post_test(name=test_case)                     //Check and save results.
```

Figure 24. Pseudo-code example of the automated test cases.

The Figure 24 describes the basic automation steps and are presented to give example of the existing automation and its functionality. There are three basic steps in one test case: pre-test, actual test and post-test. The pre-test function includes required actions such as register UE to the network, start log capturing and other required checks. After pre-test is successfully executed the actual test can be started. The test function includes all the actions needed to run the test. These are usually defined by the tester and can vary a lot. One example is the test duration and ping count from the ping test case as described above. As a last step, there is post-test, which handles the result checking and the log collecting. Structures of pre and post tests are presented in the Figures 25 and 26 respectively.

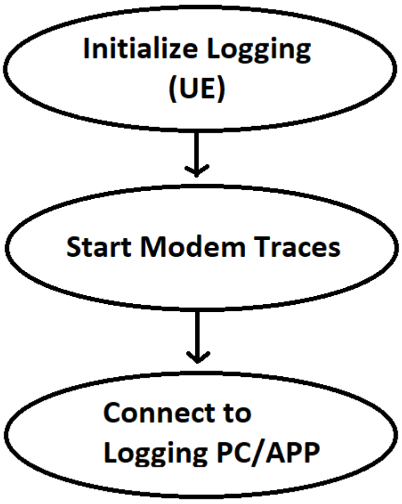


Figure 25. Structure of the pre-test function. All the steps above will be executed during pre-test if unless they are already running.

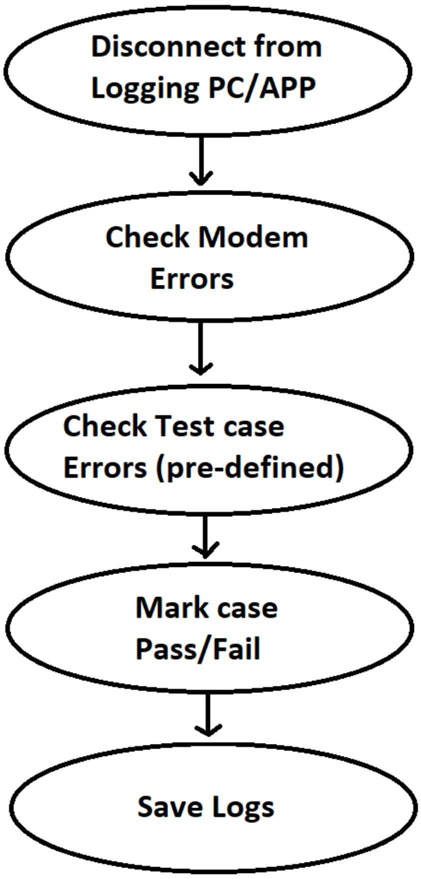
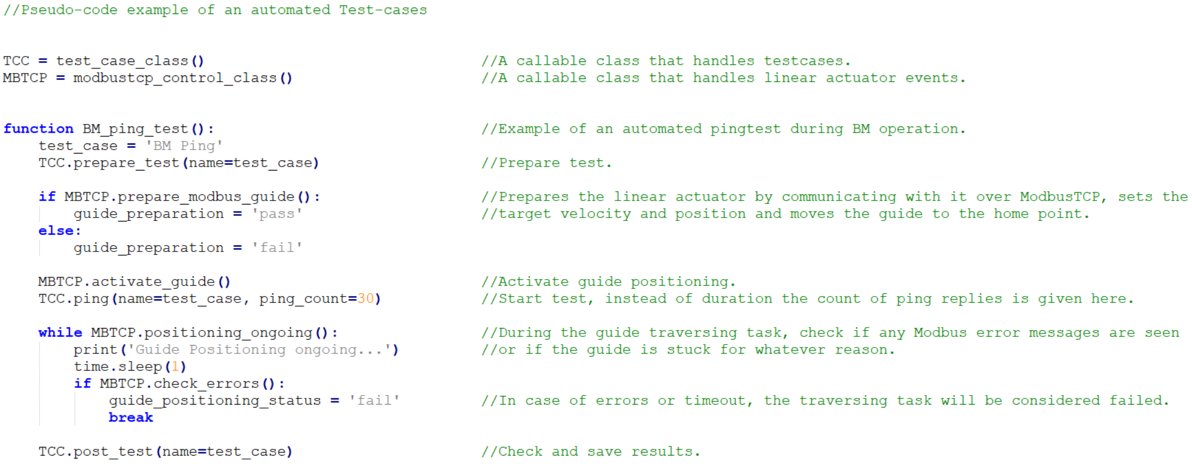


Figure 26. Structure of the post-test function. Test case errors are pre-defined steps which need to be passed during the case, these can be added by the user depending on the test case.

5.2 Integration

Automation of the beam management testing will be discussed next. As discussed before, the program which was designed to control the linear actuator was written in python to make it easier to integrate the guide controlling functions to the existing automation. This means that to automate BM test case(s), the earlier mentioned ModbusTCP control –class could be directly used in the automation since it already includes most of the methods to control the linear actuator.

In addition to normal test case, the steps for moving the guide during the test only needs to be added to the test case, also since this is an automation being designed, the functions that will check that the guide actually moves and gets to the set positions are necessary. The Figure 27 represents the test case where beam management testing features are included.



```
//Pseudo-code example of an automated Test-cases


TCC = test_case_class()                               //A callable class that handles testcases.
MBTCP = modbustcp_control_class()                     //A callable class that handles linear actuator events.


function BM_ping_test():                              //Example of an automated pingtest during BM operation.
    test_case = 'BM Ping'
    TCC.prepare_test(name=test_case)                  //Prepare test.

    if MBTCP.prepare_modbus_guide():                  //Prepares the linear actuator by communicating with it over ModbusTCP, sets the
        guide_preparation = 'pass'                    //target velocity and position and moves the guide to the home point.
    else:
        guide_preparation = 'fail'

    MBTCP.activate_guide()                            //Activate guide positioning.
    TCC.ping(name=test_case, ping_count=30)           //Start test, instead of duration the count of ping replies is given here.

    while MBTCP.positioning_ongoing():                //During the guide traversing task, check if any Modbus error messages are seen
        print('Guide Positioning ongoing...')         //or if the guide is stuck for whatever reason.
        time.sleep(1)
        if MBTCP.check_errors():
            guide_positioning_status = 'fail'         //In case of errors or timeout, the traversing task will be considered failed.
            break

    TCC.post_test(name=test_case)                     //Check and save results.
```

Figure 27. Pseudo-code example of automated ping test with BM operations.

As can be seen from the Figure 27, the steps for the guide control are preparing the guide, activating the traversing task and error checking during the guide is moving. The self-implemented ModbusTCP control -class is used for guide related actions.

In a normal test case, there are certain tasks that needs to be passed to pass the test case for example starting logging from the Test UE and connecting UE to Test/Logging application. Similarly, the linear actuator guide preparation and positioning must be successful, these actions are checked during the test, and any of them fails, the test case will be marked as fail too. The Figure 28 illustrates the test case with linear actuator.

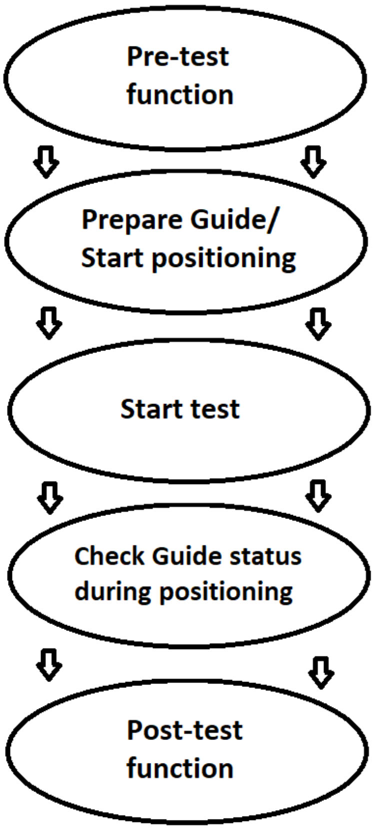


Figure 28. Structure of the automated beam management test case with linear actuator.

The pre-test and post-test functions seen in the Figure 28 are presented in the Figures 25 and 26 respectively with more details. If any of the steps in the Figure 28 fails, the test case will be considered as failed case, and the post-test function will mark the case as fail and save logs. If no errors are seen and no single pre-defined step fails, the case will be marked as pass and logs will be saved. The reason for the failed/passed case will be in the results too.

The automation run overnight and thus designed to save results from the day to the specific folder which, the failure and pass -logs are separated into different folders and each test case result folder will be named with the name of the test case and the date and time. This is an easy way to keep track of the results. The failed cases will also be listed into text file, since mostly failed results are most important.

6 DISCUSSION

The goal of this thesis was to create an environment capable to run FR2 beam management tests to MediaTek prototype UE(s) supporting this feature. The beam management in FR2 being a reasonably new feature created a demand for this kind of test environment. The idea of the test environment itself is not very complex, it was known what is needed to run beam management tests. The actual problem in this thesis was the implementation of that system. How to build this kind of environment? What equipment are needed, and which are the best for this purpose? How to control the environment? Is it possible to automate the test environment? These were the main problems when planning the implementation.

The guided linear actuator being chosen for the environment was probably the most suitable option for this kind of environment. The guide could be pre-configured via web interface which also provides the possibility to control, but also direct control via ModbusTCP was possible. The ModbusTCP made the idea of automation possible making this the best option for the environment. Since there was not any kind of program providing the control of the guide other than web interface, one needed to be self-implemented.

The implementation of control program for the environment was probably the hardest part in this thesis. The communication with the guide controller over ModbusTCP required a lot of studying the protocol structure and the way messages are sent to controller. Also, performing specific actions with the controller, specific bit sequences needed to be sent to the controller. This required a lot of familiarizations to the documents of the guide and bit manipulation; in other words, the implementation of the control program gets as close to low level programming as could be by using python as a programming language. This was the most challenging part in the thesis, but also interesting since it is now the base for all the future improvements.

The basic tests with the current existing environment can now be executed and are useful for the prototypes. However, the development potential of this environment is huge. There is a plenty of different test cases that could be done without adding any hardware to the environment. This could include the case where the guide moves random distances within the limits during the data transfer is ongoing. The case could be modified so that in sometimes UE randomly detaches the connection from the network and re-establishes it later during the UE is moving. There is a lot of cases that could be done with the existing environment to make the testing more versatile.

The further development of the environment is also possible. The equipment used makes it possible to combine actuators so that the vertical movement would also be possible in addition to the horizontal movement. This would make the environment even more versatile and creating more than one this kind of environments takes the stability and performance testing of the smartphones to a new level. Another point of development is to add hardware that can rotate UE. This would make the antenna used in UE side to change. This is already possible since there was another thesis worker in the company who was researching the switching of antenna of arrival on UE side and implemented a test environment for that case. Together these two environments could be combined to one, creating again a whole new test environment.

7 SUMMARY

The goal of this thesis was to create an environment for MediaTek prototype UE to test the UE side beam management features. The requirement was to run the tests in environment manually but also to make the integration to test automation possible. The implementation of the environment was done with the help of linear actuator which is controlled by a separate controller. The linear actuator moves the UE back and forth in front of FR2 antenna making it travel across the beams, this generally makes the testing of beam management possible.

The environment created in this thesis was first of a kind in this company, meaning that the controlling of the environment had to be developed. The controller supported ModbusTCP protocol for communication and the existing test automation was created with python. The conclusion was to create a python class including all the needed libraries capable to communicate with the controller which in turn controls the linear actuator. The python class was implemented in a way it could be easily added into the existing automation. This was not an easy task since the ModbusTCP protocol needed to be studied first.

After the functionality of the ModbusTCP was studied, the planning and writing of the python class for the servo controller could be started. The goal was to create a program that could be used to move the linear actuator attached with the MediatTek prototype UE. By moving the UE in front of FR2 antenna would result UE to trigger different beam management operations. This would result a successful beam operation or a crash in UE side depending on how the feature works.

By the time python class was finished, it was time for the first test runs. The results for the first test run were promising. During the first test case, the UE was moved back and forth in front of the antenna while in CONNECTED mode and MO ping. According to the UE-log the SSB index of the beam was changing during the UE was traversing, this indicated that the beams were switched successfully and the beam switching operation on UE side is working. After the first test, a couple of more tests were executed and results were good, logs indicated that the beams were switching. A different kind of scenario where data transferring was involved indicated that the beam management was working as expected, but performance was not good as expected, this is important finding. It is critical to find the reasons for the lack of the performance and this can be studied by examining the logs more closely.

The planning of an automation was the next step. The automation is needed as it may require several hundred of runs to trigger a bug on UE side. The results of the manual trials were good, but they are not yet bullet proof, since only couple of runs were executed. With the help of automated cases, which could be run overnight the results will be more realistic. The test automation already existed, and the python class created for could be integrated to the existing automation directly. The automation will be running always when there are no other tests pending and the UE software will be updated daily, in this way the UE and its beam management features can continuously be verified. The environment is now in active use, and its further development potential is huge.

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