FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
DEGREE PROGRAMME IN ELECTRONICS AND COMMUNICATIONS ENGINEERING

MASTER'S THESIS

mmWAVE RX INTERFERENCE TEST CONSIDERATIONS AND CHALLENGES IN OTA ENVIRONMENT

Author	Antti-Jussi Lesonen
Supervisor	Risto Vuohtoniemi
Second Examiner	Juha-Pekka Mäkelä
Technical Advisor	Tuomas Jääskö / Jukka Sutinen

September 2019

Lesonen A-J. (2019) mmWave RX Interference Test Considerations and Challenges in OTA Environment. University of Oulu, Faculty of Information Technology and Electrical Engineering, Degree Programme in Electronics and Communication Engineering. Master's Thesis, 69 p.

ABSTRACT

Verifying equipment using the OTA (Over the Air) techniques is a recent addition in telecommunication testing. With the addition of new frequency bands, mmWave (millimetre wave) technology and massive MIMO (Multiple-Input-Multiple-Output), the 3GPP (3rd Generation Partnership Programme) has cemented OTA testing as the focus for verifying future equipment. However, these verifying methods are still in development, or stated as general ideas of how they are meant to be done. The main goal of this thesis is to study and design a system for receiver radio testing, according to 3GPP specifications. The test system must operate in mmWave frequency range and must be integrated to a pre-built antenna testing environment. The motivation is to verify the testing method proposed by 3GPP for mmWave receiver testing and analyse it thoroughly.

This thesis aims to answer such research questions as: Is the testing method proposed by 3GPP valid for verifying mmWave frequency products? What are the major challenges, when designing test setup for high frequency devices? How can the method be improved and how it can be applied in the future?

This thesis answers the first question by applying the proposed test methods in practical scenario and testing an actual eNB/gNB (eNodeB / Next generation eNodeB). Since the proposed test method has only general outline of what equipment to use, the actual test scenario will have additional pieces of testing equipment.

For the second question, this thesis discusses the theory behind 5G and mmWave challenges, and how the use of these techniques is justified for practical usage. This theory is based on former research as well as current specifications applied by the 3GPP.

The third research question is part of the final analysis, where the test results are analysed, and the major parts are discussed in depth. These discussions are then further expanded on with the purpose of suggesting possible areas of improvement as well as how to apply these findings into future use.

The final outcome of the study is that the suggested test method is workings as it was presented by the 3GPP. However, there are some areas of improvement that should be discussed as a future work.

Key words: mmWave, RX, OTA.

Lesonen A-J. (2019) Millimetriaaltojen RX interferenssi RF-testit OTA-ympäristössä. Oulun yliopisto, tieto- ja sähkötekniikan tiedekunta, elektroniikan ja tietoliikennetekniikan tutkinto-ohjelma. Diplomityö, 69 s.

TIIVISTELMÄ

Tuotteiden testaaminen ilmateitse on melko uusi lisäys tietoliikennetestauksen tekniikoihin, joita käytetään tuotteiden varmentamiseen. 3GPP on osoittanut OTA-testauksen keskeiseksi osaksi tulevien tuotteiden verifiointia. Osaksi tämä johtuu uusien taajuuskanavien käyttöönotosta, millimetriaaltoteknologiasta sekä massive MIMO tuotteiden yleistymisestä. Vaikka testaustapoja on jo ehdotettu, ne ovat vielä mahdollisesti vain yleisiä ideoita kuinka testejä tulisi suorittaa. Työn tarkoituksena on tutkia ja suunnitella vastaanottimen testaamiseen tehty testijärjestely. Testijärjestelyn tulee toimia millimetriaalloille tarkoitetulla taajuusalueella, ja työ tulee integroida valmiiksi suunniteltuun CATR- antennikammioon. Työn motivaationa on verifioida 3GPP:n ehdottama testausmetodi, millimetriaaltotaajuuksilla toimivien vastaanottimien toimivuus ja analysoida tämä tarkemmin.

Tämä työ pyrkii vastaamaan tutkimuskysymyksiin kuten: Onko 3GPP:n ehdottama testimetodi pätevä verifioimaan millimetriaaltotaajuuksilla toimivia tuotteita? Mitä ovat suurimmat haasteet, kun suunnitellaan testijärjestelyä korkeataajuuksisille laitteille? Kuinka tätä metodia voidaan parantaa, ja kuinka sitä voidaan hyödyntää tulevaisuudessa?

Työ vastaa ensimmäiseen tutkimuskysymykseen ottamalla käyttöön 3GPP:n ehdottamat testausmetodit käytännön testijärjestelyssä, ja testaamalla näillä metodeilla oikean tuotteen. Tällä tavoin ehdotettu testausmetodi pyritään verifioimaan. Tulee kuitenkin ottaa huomion, että ehdotetussa metodissa esitetään vain yleisellä tasolla mitä testaamiseen käytettävää laitteistoa käytetään. Tämän takia testeissä tulee olemaan joitain lisälaitteita, jotka ovat kuitenkin osa kokonaista testiympäristöä.

Toiseen tutkimuskysymykseen perehdytään käymällä läpi teoriaa 5G:n ja millimetriaaltoteknologian haasteista, ja kuinka näitä tekniikoita tullaan hyödyntämään tulevaisuudessa. Teoria perustuu aiempaan tutkimukseen, sekä nykyisiin spesifikaatioihin jota 3GPP on kehittänyt.

Kolmas tutkimuskysymys on osa lopullista analyysiä, jossa testien tulokset analysoidaan ja niiden pääkohdista keskustellaan tarkemmin. Tämän jälkeen keskusteluja täsmennetään liittyen mahdollisiin parannuksiin tietyllä aihealueilla, sekä mahdollisuuksista käyttää kyseisiä tuloksia tulevaisuudessa.

Lopullinen päätelmä on, että ehdotettu testausmetodi toimii kuten se oli esitetty 3GPP:n dokumentoinnissa. On kuitenkin joitain osa-alueita, joita voitaisiin käsitellä tarkemmin tai jopa parantaa tulevaisuutta varten.

Avainsanat: millimetriaalto, vastaanotin, OTA.

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FOREWORD

When I started my studies at the University of Oulu, I was full of passion and excitement. Throughout the years, that excitement faded and the possibility of changing my major came into mind. However, after one of my technical advisors Jukka Sutinen presented me with the possibility of working for RF Performance unit in Nokia, that excitement returned with additional eagerness to prove myself. During my time working, I have learned many valuable skills and assets that I have been using in my studies as well as every day life. So, I'd like to thank all my co-workers from Nokia that shared their experiences, helped me when I was unsure what I was doing, and cheered for me through dark winter days.

Lastly, I want to thank my parents who have been cheering me on for my whole life. Special thanks to my sister, who guided me with my later studies when I had trouble expressing certain aspects of this thesis.

Oulu, August 16, 2019
Antti-Jussi Lesonen

LIST OF ABBREVIATIONS AND SYMBOLS

3GPP	3rd Generation Partnership Project
AAS	Active Antenna array System
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
ADC	Analog to Digital Conversion
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
BW	Bandwidth
CATR	Compact Antenna Test Range
CPRI	Common Public Radio Interface
CW	Continuous Wave
DAC	Digital to Analog Conversion
DDC	Digital Down Conversion
DL	Down Link
DUT	Device Under Testing
EIRP	Equivalent Isotropic Radiated Power
EIS	Equivalent Isotropic Sensitivity
EVM	Error Vector Magnitude
FR	Frequency Range
gNB	Next generation NodeB
IoT	Internet of Things
IoV	Internet of Vehicles
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MIMO	Multiple Input Multiple Output
mmWave	Millimetre Wave
MU-MIMO	Multiple User-Multiple Input Multiple Output
ng-eNB	Next generation eNodeB
NR	New Radio
OTA	Over-the-Air
PL	Path Loss
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
REFSENS	Reference Sensitivity
RE	Radio Equipment
REC	Radio Equipment Control
RF	Radio Frequency
RIB	Radiated Interface Boundary
RoAoA	Rotation of Angles of Arrival

RX	Receiver
SCS	Subcarrier Spacing
SGH	Standard Gain Horn
SU-MIMO	Single User- Multiple Input Multiple Output
TBC	Transmission Bandwidth Configuration
TDD	Time Division Duplex
TRP	Transmission Reception Point
UE	User Equipment
UL	Uplink
VNA	Vector Network Analyzer

d	Distance between antennas
dB	Decibel
f	Frequency
f_c	Centre Frequency
FSPL	Free space path loss
Hz	Hertz
N_{RB}	Number of resource blocks
D_r	Directivity of the receiver antenna
D_t	Directivity of the transmitter antenna
L_{FS}	Loss caused by free space
L_M	Miscellaneous losses
L_T	Total gain/loss calculated from components
P_{OUT}	Power at the wanted measurement surface
P_r	Available power at the receiver
P_t	Power delivered to transmitter antenna

θ	Elevation angle
ϕ	Azimuth angle
λ	Wavelength
Δ	Delta
π	Pi
c	Speed of light

1 INTRODUCTION

When measuring the performance of any DUT (Device Under Testing) there are certain specifications that the tests themselves must follow. These guidelines are formatted by one of many telecommunication standards. The most common one is 3GPP (3rd Generation Partnership Project), which unites seven organizational partners [1] and their telecommunication standards.

In this section the two introductory parts are presented. The motivation and goals of the thesis are discussed in the first part, and the full structure of the thesis is explained in the second part describing the fundamental ideas behind the thesis.

1.1 Motivation and goals

The motivation of this thesis is to design, analyse and verify a test setup for receiver radio testing in OTA (Over-the-Air) environment. This project will be used in the future as a reference, when performing OTA RX (receiver) tests in mmWave frequency bands. The designed receiver measurement setup used in this thesis was built based on the current 3GPP standards and research carried out by other researchers. There are however multiple complications that arise when we take in account the frequency range, component non-linearity, power budget and complexity of the design. The complexity includes additional attenuation caused by component path loss as well as free space path loss. Additional path loss also affects the dynamic range of the measurement equipment, which is limited due the typical characteristic of OTA measurements. Due to the limited dynamic range of measurement equipment, another layer of complexity is present when selecting each component as well as designing the power budget for the measurement setting.

MmWave radios are becoming more common day by day, since previous frequency bands are becoming more crowded. By expanding the frequency range of the communication equipment, it is possible to have larger operating bands for increasing bandwidth and data rate requirements. However, there are some drawbacks when operating in such high frequencies. Such as the previously mentioned path loss, as well as the fact that the performance measurements have not been tested in mmWave environment. The goal of the thesis is to elaborate on the possible challenges and aspects related to the mmWave technology. To achieve this goal, practical tests will be done according to the suggested test methods defined by the 3GPP.

1.2 Structure of the thesis

The thesis is built around four major components: theory, design, test execution and analysis. In chapter 2 the thesis presents an overview on the theoretical portion of 5G technology. The chapter also includes the short explanation of the evolution from LTE to 5G. In chapter 3, the typical test environment of receiver tests is explained. The performance aspects of receiver tests are also presented. Chapter 4 includes the design process for the tests, as well as the written plan for each test. The test execution is explained in detail, as well as the test metrics used for each measurement. Chapter 5 describes the overall test process in order of execution and includes the final measurement results. In Chapter 6, a short discussion on the findings of the research is given. Chapter 7 summarizes the thesis.

2 5G TECHNOLOGY

With the significant increase of mobile data traffic, the main challenge of 5G networks is to provide full coverage to everyone as well as provide quality solutions in data transfer, without compromising from other areas like coverage and latency. With the average mobile user downloading around 1 terabyte of data annually by 2020 [2] and the number of connected devices growing exponentially every year, the data rates of today would not be sufficient to support the future demand. In the future there will be multiple new applications demanding increasing amount of traffic i.e. IoT (Internet of Things), IoV (Internet of Vehicles), Smart Home and E-Healthcare.

This chapter discusses the technological background of wireless 5G telecommunications. This includes the evolution from LTE to 5G, the suggested requirements for a 5G system to the applications of what the future 5G systems will use.

2.1 5G applications and requirements

With the exponential growth of data transfer in sight, there should be a common goal for telecommunication industry. In "Next Generation 5G Wireless Networks: A Comprehensive Survey" by Mamta Agiwal, Abhishek Roy, and Navrati Saxena, the writers combine different research initiatives from multiple industries and academies to identify eight major requirements and goals for 5G systems [3]:

1) 1 ~ 10 Gbps data rates, which increases the theoretical peak data rate of LTE by tenfold.
2) 1 ms round-trip latency: The round-trip time of 4G is nearly 10 ms, which makes the latency drop to a tenth.
3) High bandwidth in unit area: Higher bandwidths are required to ensure that all of the connected devices are enabled in highly populated areas.
4) Enormous number of connected devices: With multiple applications like IoT and IoV, the new 5G networks need to have the connectivity to work with these new applications.
5) Perceived availability of 99.999%: The plan is to have networks always available, wherever the device is.
6) Almost 100% coverage for ‘anytime anywhere’ connectivity: The 5G network user needs to have complete coverage anytime and anywhere.
7) Reduction in energy usage by almost 90%: Reducing the energy usage in production phase with more green technology, as well as reducing the overall power consumption of user equipment is a crucial part of 5G.
8) High battery life: Lower power consumption is regarded as an important topic in 5G network planning.

When comparing these requirements to previously set ones for LTE and LTE-A (Long Term Evolution-Advanced), it is clear that 5G is largely more demanding. However, when LTE was first drafted as an idea, the requirements then might have been as alien as 5G requirements are thought to be now.

2.1.1 From LTE to 5G

LTE was first proposed as a standard in 2004 by a Japanese telecommunications company NTT Docomo. LTE was built on the foundations of GSM (Global System for Mobile

Communications) and UMTS (Universal Mobile Telecommunications System). The basis for LTE releases today was frozen on December 2008 as the release 8 was put out by the 3GPP. [4]

Just like LTE was built around already existing technologies, 5G continues the trend by improving and adding to the already existing releases like LTE and IMT-Advanced. The important thing in 5G is that it is supposed to be backwards compatible, meaning that previously designed telecommunication solutions are supposed to work in the newly planned architecture. 5G uses NG-RAN (Next Generation Radio Access Network) nodes, which work either as a gNB (Next generation NodeB) or ng-eNB (Next generation eNodeB). For NR access (5G) a gNB node is used, whereas ng-eNB provides E-UTRA access (LTE) [5]. The 5G radio access network architecture is illustrated in Figure 1. [5]

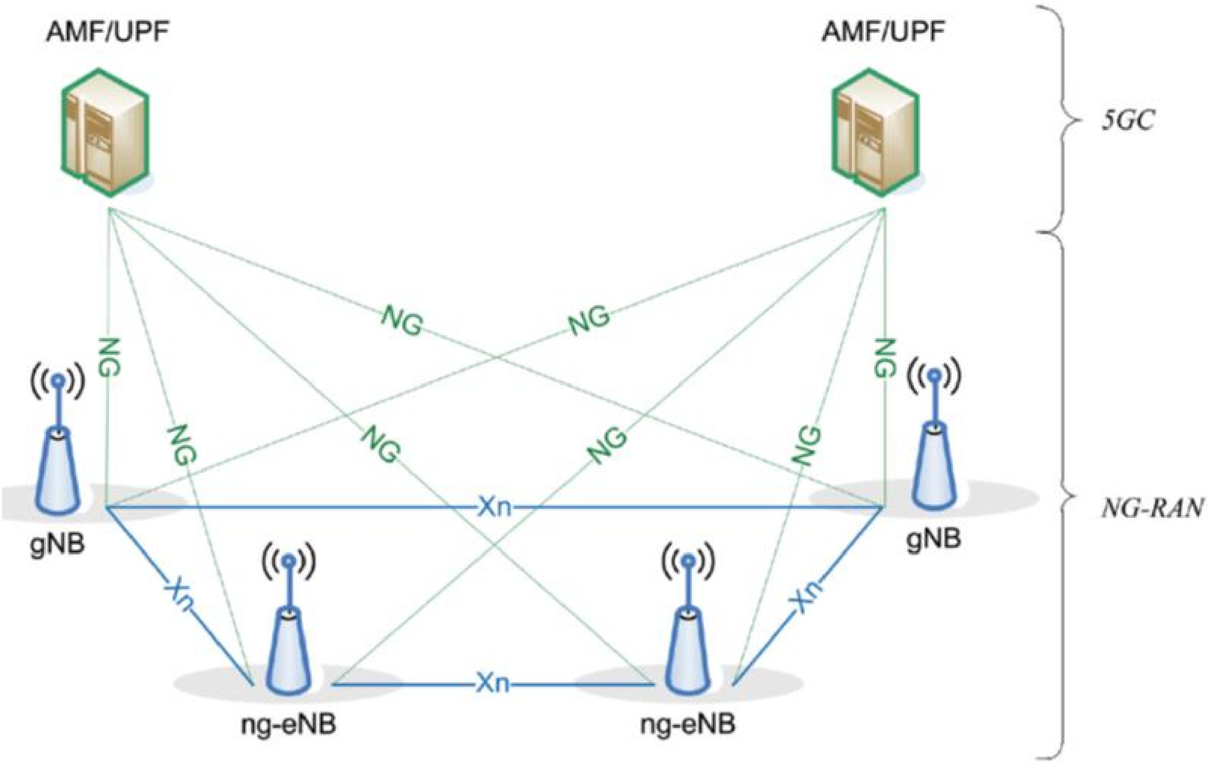


Figure 1. Next Generation Radio Access Network.

The backward compatibility requirement of 5G technology necessitates the support for all the previously implemented technologies. As new additions to technological advancements, there are new frame structures (reduced guard band, multiple SCS, overhead reduction), massive MIMO and flexible spectrum utilization and multiple CC (component carrier) variations for both NR and LTE [6].

Frequency range of LTE compared to 5G is a major part why 5G is set to supposedly achieve 10 times higher data rates compared to traditional LTE. In 5G the usable frequency range varies from 3 GHz all the way up to 300 GHz compared to the maximum frequency standardized on LTE which is 3.5 GHz. The frequency spectrum up to LTE is largely in use, which makes it difficult to allocate any new wideband areas in the spectrum. In case of 5G, the standardization of the spectrum allocation for 5G is still ongoing. There are open slots in higher frequencies, but some of them are not usable due to physical phenomena. [7, 8]

2.1.2 Key technologies

In this section, the concept of MIMO, mmWave and beamforming techniques are briefly discussed. These technological advancements are meant to provide the increased coverage and capacity needed in the future. While testing receiver performance, these technologies are also taken in consideration.

2.1.2.1 MIMO

MIMO stands for Multiple-Input-Multiple-Output technique, in which the operating antenna has multiple input and output ports. In MIMO the system uses multipath propagation to its advantage, in which phenomena like reflection, shadowing and jitter causes the transmitted signal to reach the receiver from multiple different paths. By using different coding and multiplexing functions in the designated transmitter and receiver, the transmitted high-power signal can be split into multiple low-power signals which are then processed in the multiple receiver system.

In 5G, massive MIMO was introduced as part of the greatly increasing number of antennas per site, as well as large scale antenna arrays in use. Typical antenna quantities under consideration for the base station vary from 256 to 1024 for the mm-wave bands. The antennas consist of cross polarized elements arranged in a two-dimensional array. The array may also consist of constituent sub-arrays [9, 10].

The term MIMO typically comes in part with beamforming. Since legacy LTE it has been used to describe variants of adjusting set beams for single users (SU-MIMO) as well as multiple users (MU-MIMO). In SU-MIMO both the base station and the UE (User Equipment) have multiple antennas and multiple data streams concurrently interacting with each other to provide maximum throughput to the user [11]. In MU-MIMO, the base station is sending multiple data streams for the current cell, one for each UE. Operating base station is using multiple antenna ports to form beams for UE's, but UE only needs one port to receive the data [11]. The link between MIMO, beamforming and large-scale arrays are visually presented in Figure 2 [12]. In the figure the BS (Base Station) is operating with MU-MIMO principle, where it has multiple data streams for each UE in the cell.

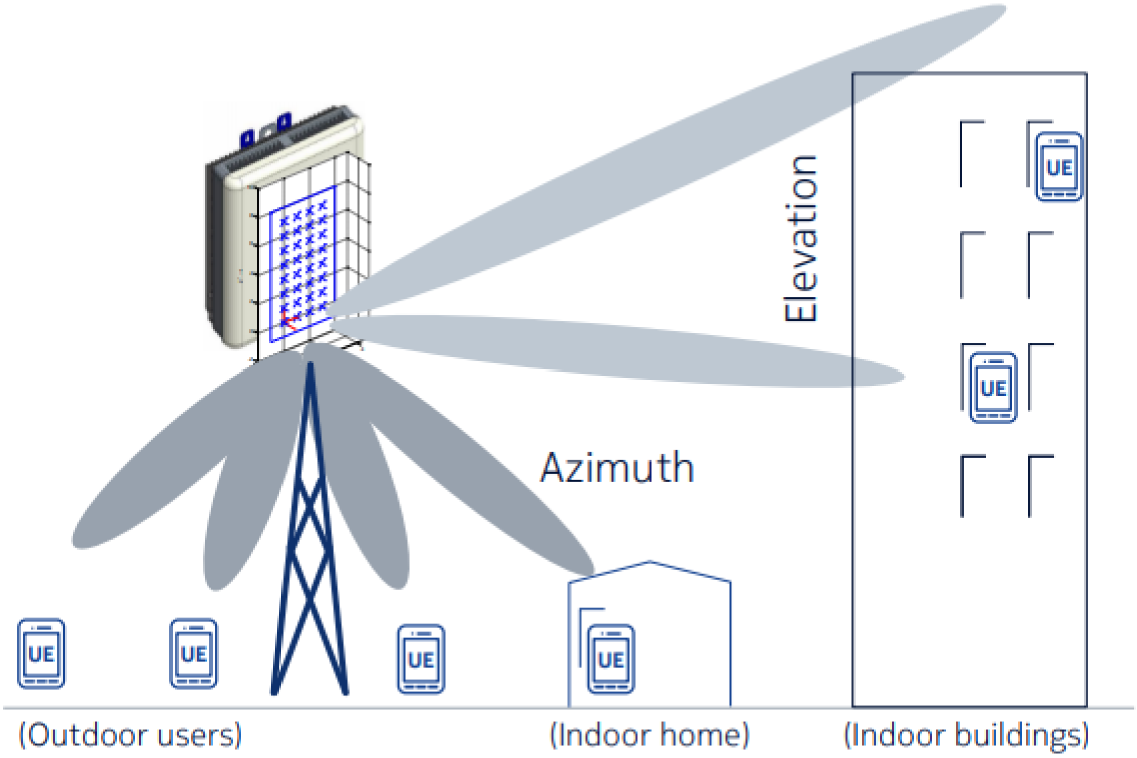


Figure 2. A typical BS uses MIMO in a real-life setting.

2.1.2.2 Millimetre wave frequencies

Nearly all current wireless mobile communication systems are operating under so called "Beachfront Spectrum", which allocates all the frequency bands below 3 GHz [3]. This frequency spectrum has become extremely crowded, due to the favourable propagation conditions provided in those bands [13]. In recent years the technological advancements in antenna design and 5G architecture has made it possible to explore higher, previously thought to be unconventional, frequency spectrum [3]. The spectrum allocated between 30 GHz up to 300 GHz is called millimetre wave spectrum, in which the usable spectrum availability comes in three different areas: 24-57 GHz, 65-164 GHz and 201-300 GHz [3]. All together the potential usable bandwidth would be 252 GHz, since the Oxygen Absorption Band (57-64 GHz) and Water Vapor Absorption Band (164-200 GHz) allocate their own frequency spectrum. This frequency spectrum allocation is presented in Figure 3 [3].

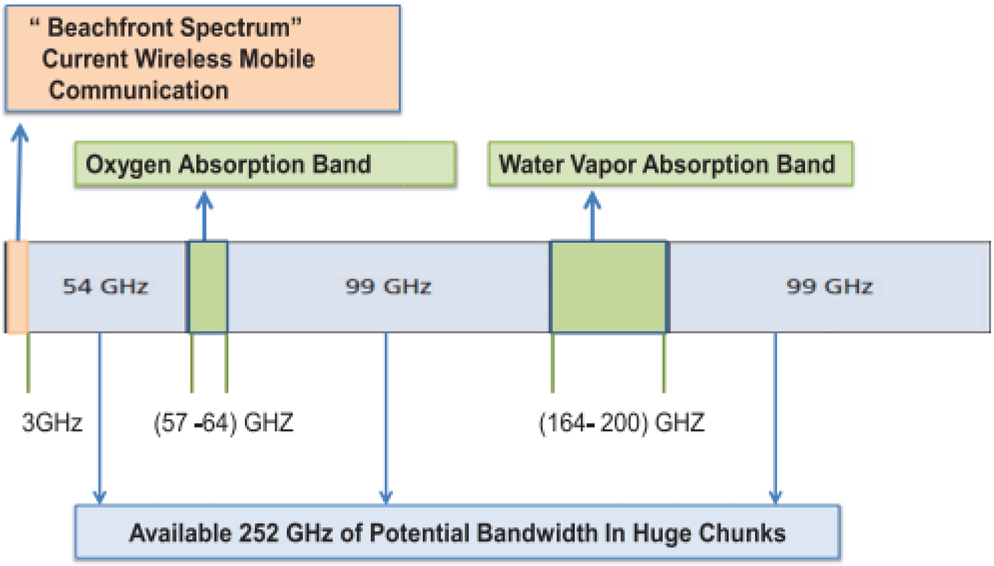


Figure 3. Millimetre-wave spectrum allocation up to 300 GHz.

Sub 3 GHz frequency spectrum has favourable propagation conditions. This means that the electromagnetic waves transmitted by the antenna at these frequencies are less likely to be affected by the distance and interference, and more likely to be affected by reflection-, refraction- and diffraction propagation characteristics [14]. In millimetre wave frequency spectrum, the wavelength of electromagnetic waves is reaching down to the range of 10-1.0 millimetres. By increasing the carrier frequency, the penetration loss of the signal increases. This causes challenges, where previously mentioned propagation characteristics don't act as in lower frequencies. Diffracted signals become very weak, so reflected- as well as LOS (Line-Of-Sight) signal importance grows [13]. Since wavelength of the carrier is so small, scattering from rain can also be considered to affect millimetre wave propagation, since raindrops are roughly the same size as the travelling signal wavelength. In Figure 4 the average atmospheric absorption is presented as a function of frequency. Reduction in wavelength appears as an increase in attenuation in the figure [15]. In the case of curve, A (sea level) and curve B (4 km elevation), the trend stays the same.

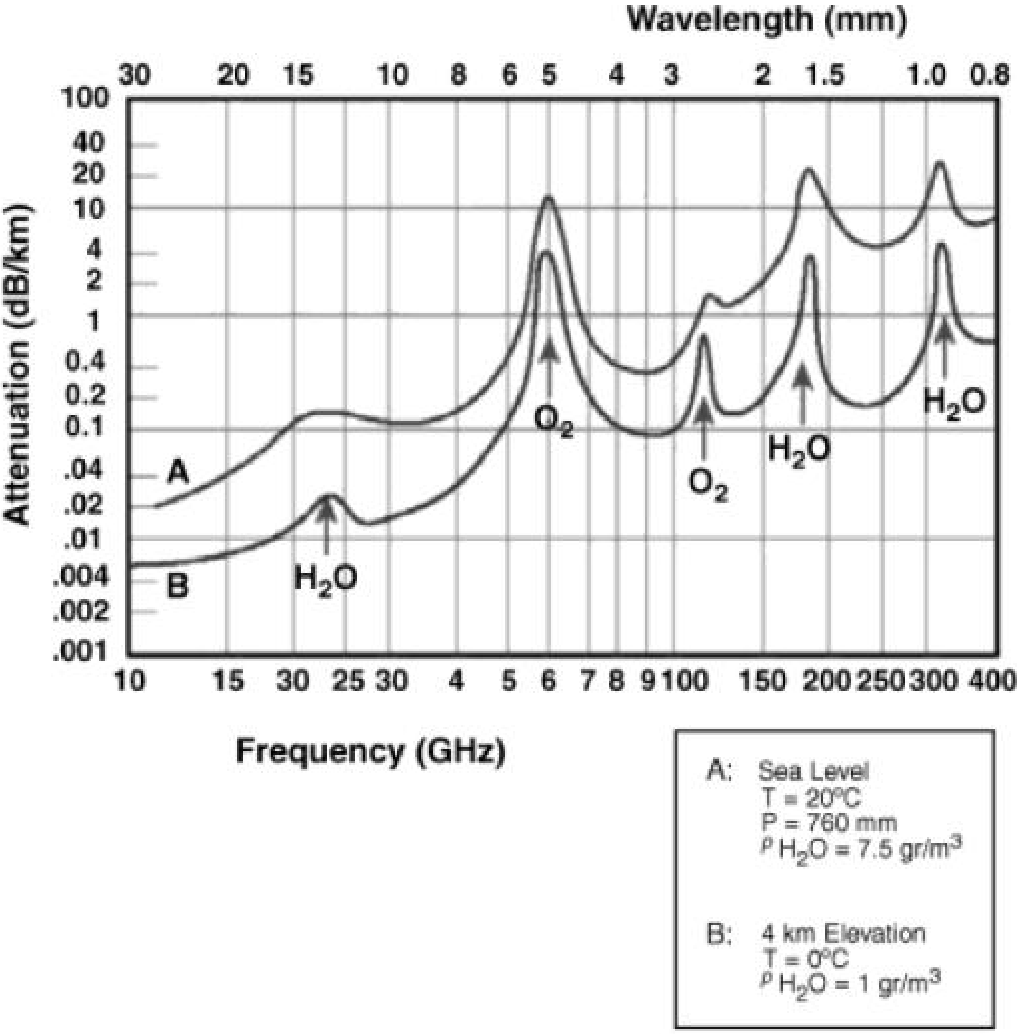


Figure 4. Average atmospheric absorption as a function of frequency.

To combat these vulnerabilities in millimetre wave frequency spectrum, the transmission distance could be minimized so the path loss caused by the distance would be minimal. It is also a possibility to furthermore improve the performance in millimetre wave frequency spectrum by forming large antenna arrays (MIMO / Massive MIMO). These would provide higher beamforming array gain, which could minimize frequency dependent propagation loss. [16, 2].

2.1.2.3 Beamforming in 5G

Beamforming in short means the ability to adjust the direction and shape of radiated patterns with either analog or digital techniques. In analog beamforming, the signal is first modulated and then divided into multiple transmit paths where each signal is met with certain amplitude and phase adjustments. The beamforming is done at the transmit end, whereas in the receiver end every path is assigned a complex weight which enables the signal to be combined in the summation network. In digital beamforming the phase and amplitude adjustments are done before Digital to Analog Conversion (DAC). In the receiving end Analog to Digital Conversion (ADC) and Digital Down Conversion (DDC) is done before the combining of multiple paths. These beamforming techniques are presented in Figure 5 [3].

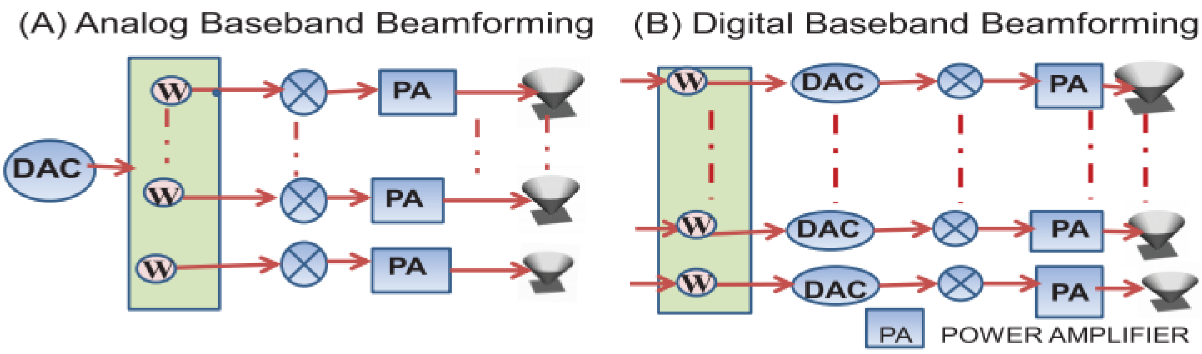


Figure 5. Analog – and digital beamforming.

From technical standpoint, the biggest difference between analog and digital beamforming is the place where the beamforming weights are applied in the process. In analog beamforming the beamforming weights are applied to a modified RF signal in the time domain, where as in digital beamforming the beamforming coefficients are multiplied per RF chain. This is done over the modulated baseband signal and can be done either before or after the Fast Fourier Transformation (FFT) [3].

In legacy LTE both digital- and analog beamforming are being used concurrently. However, due to the massive path loss created in mmWave frequencies it is preferred to use analog beamforming. Because there is increasingly more path loss in mmWave frequencies compared to typical LTE bands, using the beamforming gain achieved from analog beamforming can compensate for that loss. While analog beamforming is suggested to use in 5G NR mmWave frequencies, digital beamforming is still more widely used in sub mmWave bands as well as LTE and LTE-A [11].

3 RECEIVER PERFORMANCE

To ensure that the designed product is fulfilling the required specifications, the working product should always be tested. This applies to radio receivers as well. These tests are specified by multiple telecommunications standard development organizations and the forerunner for these specifications is 3GPP. The role of 3GPP in telecommunication standards is to unite multiple standards created for technology specifications. By doing this, the 3GPP will provide every partner with globally applicable technical specifications for past and future mobile systems.

Verifying the properties specified by the manufacturer is part of a successful product development project. This chapter presents information on different ways to test a radio receiver. Also, the most common receiver performance metrics are explained. The chapter includes the description of testing arrangements and explains what kind of measurement system should be used in OTA testing.

3.1 Receiver testing

Radio receiver testing can be done in multiple different ways, but the tests mainly consist of conductive and radiative measurements. The conductive measurements use a measurement setup, where the DUT is directly connected to the measurement equipment. Typical test that can be done for radios is S-parameter measurement over antenna elements with a VNA (Vector Network Analyzer). These kinds of tests are more often used during the device designing phase, where the design changes rapidly, so testing its performance would not be efficient. Radiative measurements, such as OTA testing, can be used to test a device without a physical connection between the measurement equipment and the device. There are multiple reasons to move from conductive measurements to radiative measurements. To begin with, in 5G NR most of the designed antennas are using massive MIMO design which makes the measurement more complex. The complexity comes from the architectural aspect of the product, in which parts of the unit have been mostly integrated. This means, that physical contact points in the product are scarce or do not exist at all. And if a point of contact would be found in the product, testing or verifying that product based on that contact point would not be sufficient of telling how the actual product works. Since the product is designed as an integrated unit, testing a single contact point does not tell the full picture of how the unit operates.

In conductive measurements, each contact point would be connected to the measurement equipment and measured separately. In radiative measurements, the receiver is connected to the measurement equipment but not to the signal source. Due to the increasing amount of antenna elements, the size of the devices is increasing. Typical direct far field measurement setup is not sufficient for the sheer size of the designed 5G antennas. This means that more room is required to test the devices, such as CATR (Compact Antenna Test Range) chambers.

Radiative measurements can also be either passive or active. Passive measurements are usually done in R&D (research and development) phase with a unit that doesn’t need to active components. In passive testing, RF-cables are connected to the unit ports and measured either directly or with OTA. Since the unit is reciprocal, the radiation pattern information can be measured with either transmitter or a receiver. For the final product evaluation, an active measurement is needed with a fully functioning unit. In active measurements the total radiated power (TRP) and total isotropic sensitivity (TIS) are measured. In active antenna system the transmitter and receiver behaviour may differentiate from each other, which is why it is required to measure the radiation pattern as well as the absolute power information. [17]

In antenna testing, it is required to take in account antenna field region. Depending on the wavelength that the device is operating, measurements can be done in either reactive near-field, radiative near-field or far field. Each of these field regions are operating under certain circumstances, and depending on the measurement distance, a certain amount of calculus is needed to determine the structure of the field. In 5G radio receiver measurements, most of the measurements are done in far-field, since it is much simpler to analyse. To analyse a near-field result, a near- to far-field transformation needs to be carried out through multiple complex mathematical equations. Depending on the measurement type (flat-plane, cylindrical or spherical), a different transformation technique might need to be applied. A fast Fourier transformation (FFT) might work on flat-plane measurements but might be hard to execute on cylindrical or spherical cases [18, 19]. These transformations are not needed in far-field case, where distribution of energy does not deviate depending on the distance, and the power level decreases with distance according to inverse square law.

With mmWave frequencies being used for even larger antennas, the threshold for far field is increasing. The far-field distance follows the formula;

$$R > \frac{2D^2}{\lambda} \tag{1}$$

where R is the minimum far-field distance, λ is the wavelength and D is the diameter of the smallest sphere that encloses the radiating parts of DUT [20]. By increasing the antenna size and decreasing the wavelength, the far-field distance starts to increase as the antenna size starts to gradually get larger with Massive MIMO. Testing facilities like a CATR with a reflector are a prime example of the future for OTA testing, since the size of the chamber does not need to follow the far-field size. For CATR, the far-field distance is seen as the distance between the feed antenna to the reflector [20]. CATR is further explained in section 3.3.

3.2 Receiver performance tests

Receiver performance usually correlate to the test results of the eNB or gNB sensitivity in OTA environment, compared to TRS (Total Radiated Sensitivity) measured from a UE. The term TRS describes the lowest possible power received by the UE, from multiple field combinations much like a spherical surface. The power here is the effective isotropic sensitivity available at the receiver.

Receiver performance tests are specified by 3GPP, with each test case having its own requirements and specifications. Receiver sensitivity, dynamic range, selectivity, blocking, spurious emissions and intermodulation are part of the test cases that describe the DUT radiated receiver characteristics [21]. The motivation behind receiver performance measurements is usually related to these receiver characteristics. Major attributes of these measurements are sensitivity, noise and selectivity.

Receiver tests in OTA environment are usually done with a signal generator setup. A specified signal is transmitted from the signal generator to the feed antenna that works as the TX part of the measurement setup. In some cases, multiple generators are needed to perform certain scenarios for specified measurements. In measurements like channel selectivity, blocking and OTA dynamic range, it is required to have additional signal generator to generate the interference signal. As an exception to the rest, OTA receiver intermodulation requires to have three different signal sources. The generic OTA receiver intermodulation block diagram is presented in Figure 6 [21]. It is also possible to have fewer signal generators in the test setup, if for example a single signal generator can produce two different signals from two RF output ports.

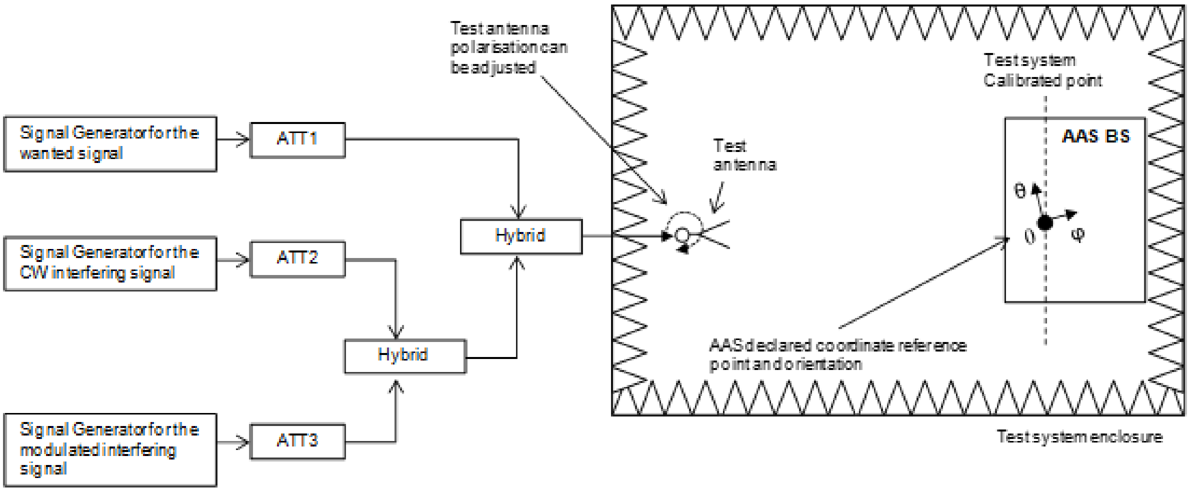


Figure 6. Measurement set up for generic OTA receiver intermodulation.

3.2.1 Receiver sensitivity

The eNB/gNB sensitivity determines the weakest signal level that can be successfully received by the node. Receiver sensitivity testing is performed to verify the eNB/gNB's ability to receive data with a specified throughput [22]. In practice this would mean that if the eNB/gNB product has a bad sensitivity, it would be less likely to detect lower power signals coming from users. This is seen as bad service connection on mobile equipment.

Test method for radio receiver sensitivity has changed over the years, but the principle has remained the same. Idea is to measure the signal throughput over certain time, where the amount of sent data is known. This data is then compared to the received data, and the error rate is told by the number of messages that were failed to be received. With BER (Bit Error Rate), the method is to send certain amount of data and then check the number of not acknowledged bits that were lost during the transmission. This method is used in legacy LTE measurements. In 5G OTA testing, the amount of errors is measured in blocks with BLER (Block Error Rate). A certain number of CPRI (Common Public Radio Interface) frames are captured over the period of measurements, and each frame contains certain number of blocks. These frames are captured and then analysed for failed blocks, where the percentage of failed blocks over all of the transmitted frames is the value used in BLER. For 3GPP, the specification of successful sensitivity measurement is ≥95% throughput of the measured channel. [21]

3.2.2 In-band and out-of-band interference testing

In radio receiver testing it is common to use an interference signal in most cases. These signals can be used as IB (In-band) or OOB (Out-of-band). For IB test cases, the interference signal is set on the same frequency band that the DUT is operating on and usually in the channel adjacent to the wanted channel [21]. These kinds of RX interference tests are meant to evaluate the receiver's ability to filter out unwanted signals, as well as the ability to withstand interference. For OOB interference tests, the interference signal is in a different frequency band rather than using it on the same band. The idea behind both IB and OOB interference tests remain the same. In practice these tests tell how much unwanted data can the eNB/gNB units filter out and sustain a good connection. If the units didn't filter out the unwanted signals, the user connections would be poor since the transferred data would have multiple errors in them.

In telecommunications, IB and OOB are used terms in signalling. In-band signalling is when the control information of a call is transmitted through the same frequency band as the other data. In out-of-band scenario, a separate frequency channel or a band is used to transmit this data. These kinds of signals may generate a certain amount of noise or interference, which is the base of these IB and OOB interference measurements. In Figure 7 the frequencies used for IB and OOB are presented as they were used for this thesis. The DUT has a 3 GHz bandwidth with a centre frequency of 28 GHz, so everything inside that is considered in-band. Out-of-band start after the initial bandwidth stops for the unit and the maximum offset of the out-of-band boundary from uplink operating edge is defined in 3GPP in BS type 2-O as 1500 MHz [21].

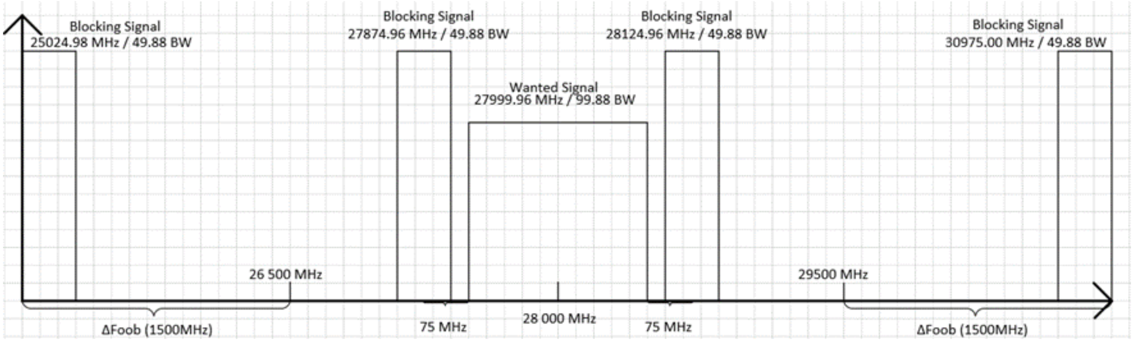


Figure 7. Required frequency channels used in this thesis illustrated in their designated places.

3.2.3 Adjacent channel selectivity

Adjacent channel selectivity (ACS) is a measure of receiver's ability to receive a modulated OTA signal at its assigned channel frequency in the presence of an adjacent channel signal at a given frequency offset from the assigned channel frequency. Adjacent channel selectivity is the ratio of the receive filter attenuation on the assigned channel frequency to the receive filter attenuation on the adjacent channel(s). The test purpose is to verify the ability of the BS receiver filter to suppress interfering signals in the channels adjacent to the wanted channel. The requirement of ACS in 3GPP FR2 is a situation where the BLER shall not exceed 5% error value [23, 21]. In practice if the filtering in the eNB/gNB unit is not functioning properly, it means that it might not reject the unwanted interfering signals that are placed in the adjacent frequency channels. This causes the unit not to be able to separate the wanted and the unwanted signal that it is receiving. So higher ACS values mean that the receiver can reject interference from signals on an adjacent channel better. In Figure 8 is presented the definition of ACS [24].

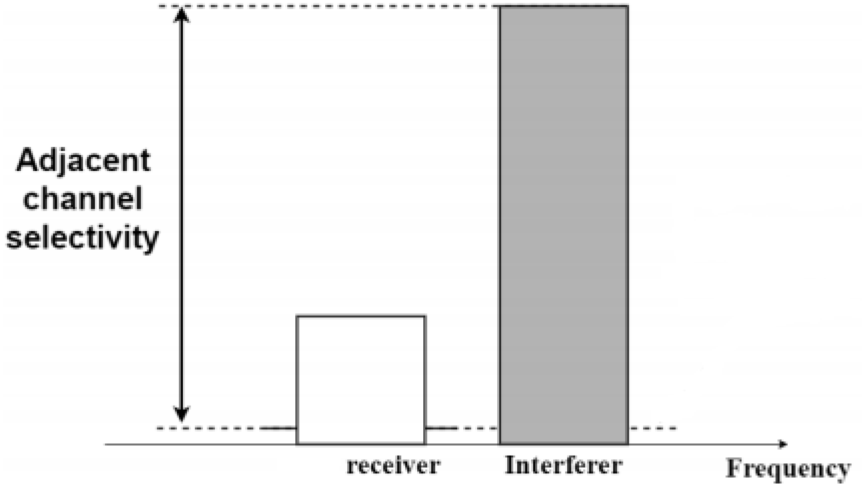


Figure 8. Definition of adjacent channel selectivity.

3.2.4 Blocking characteristics

The OTA in-band blocking characteristics is a measure of the receiver's ability to receive a wanted signal at its assigned channel in the presence of an unwanted interferer. This effect should be measured at the RIB (Radiated Interface Boundary) of a unit specified by the 3GPP. In OTA environment, both wanted- and interferer signals are specified by the 3GPP specifications, where the interferer is either a general blocking NR signal or an NR signal with one RB (Resource Block) for narrowband blocking. [21]. In 3GPP technical specification document 38.141-2, receiver blocking test is described as a test that stresses the receiver's ability to withstand interference coming from unwanted signals at specified bands, which can be within the operating band (IB) or outside of it (OOB). If the unit can withstand the interfering signals without degrading its sensitivity, it means that the unit is operating like it should. These measurements are associated with the RIB of the unit, as it is stated in 3GPP [21]. In Figure 9 the receiver blocking mechanism is illustrated where green graph presents the victim receiver and the red graph illustrates the interfering transmitter [25].

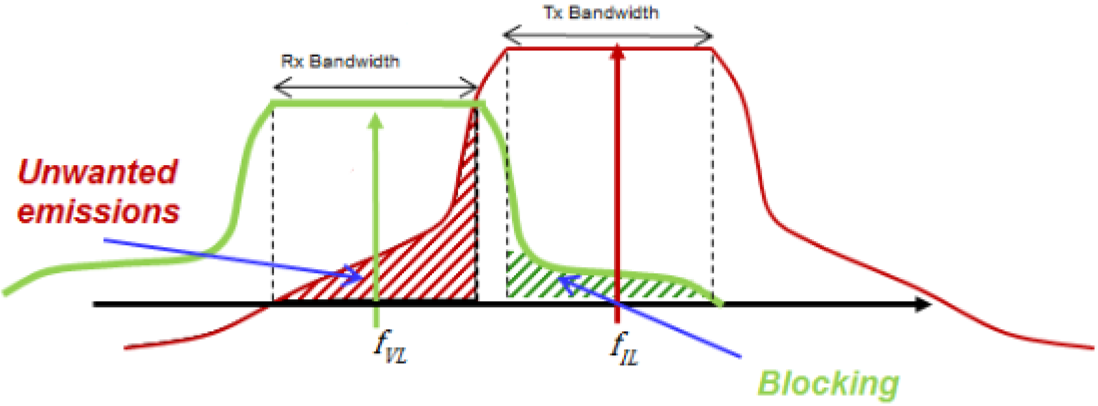


Figure 9. Receiver blocking mechanism, as well as unwanted emissions.

For the general OTA out-of-band blocking the previously stated requirement applies to the wanted signal for each supported polarization, where it is assumed that polarizations match correctly. This requirement is assumed to be the same in in-band case and in out-of-band case.

3.2.5 Intermodulation distortion

Third and higher order mixing of the two interfering RF signals can produce an interfering signal in the band of the desired channel. Intermodulation response rejection is a measure of the capability of the receiver unit to receive a wanted signal on its assigned channel frequency in the presence of two interfering signals which have a specific frequency relationship to the wanted signal. The requirement is defined as a directional requirement at the RIB. To verify that the BS receiver dynamic range, the relative throughput shall fulfil the specified limit. In Figure 10 the placement of 3rd order intermodulation products are illustrated in a single carrier scenario [26]. In a case of poor intermodulation performance, it is possible that the generation of intermodulation products into the own receive band could result in additional noise as well as degrading the receiver's sensitivity [26].

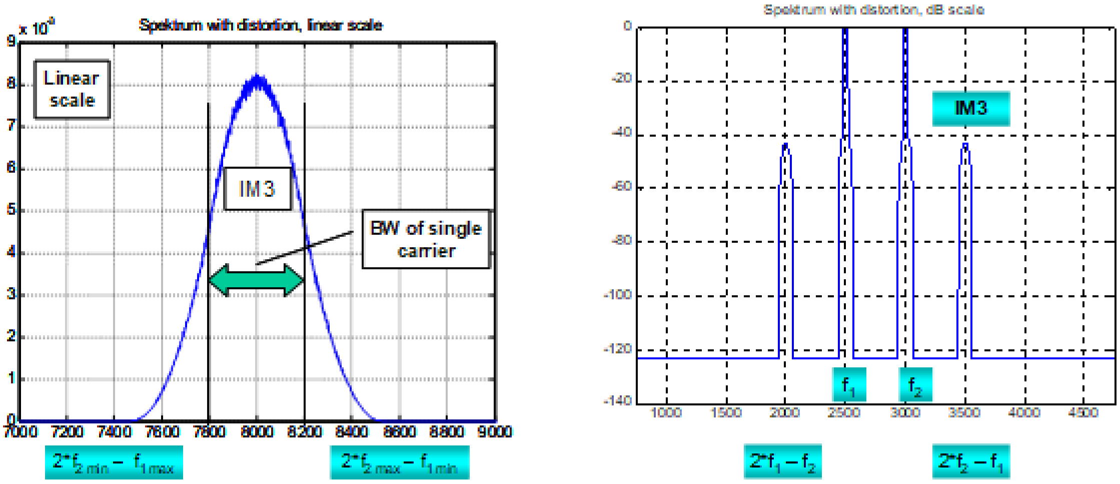


Figure 10. Illustration of IM3 products placing in a single spread spectrum carrier.

3.3 Basics of OTA measurement systems

Over the Air (OTA) measurements were standardized by Cellular Telecommunications Industry Association (CTIA) and the 3GPP to evaluate the end-to-end performance of SISO devices [27]. Focus of OTA system is to create realistic propagation conditions to real life situation as possible. These tests are usually performed in an anechoic chamber, which has its insides covered with absorber material to reduce the signal reflections. A reverberation chamber can also be a possibility; but it is not used for the same purposes as the anechoic chamber to mitigate reflected radio signals. A reverberation chamber works as a natural multipath environment, so simulating different propagation environments can be a possibility. It is impossible to discern the field pattern or directivity from all of the reflected waves from the walls of the reverberation chamber. However, it is possible to measure metrics like antenna efficiency, TRP (Total Radiated Power) and antenna diversity gain.

Commonly in anechoic chambers the DUT is placed on a positioner, which enables the possibility of measuring the operating device from multiple angles, as well as multiple polarizations [28]. In reverberation chamber DUT is placed to a specific spatial point in the chamber, depending on the number of steps measured. The example positioner setup in an anechoic chamber is presented in Figure 11 provided in the Nokia RF performance test matrix. In the figure the spherical coordination system is marked in front of the DUT, where θ is the elevation angle and ϕ is the azimuth angle described on the side of the DUT.

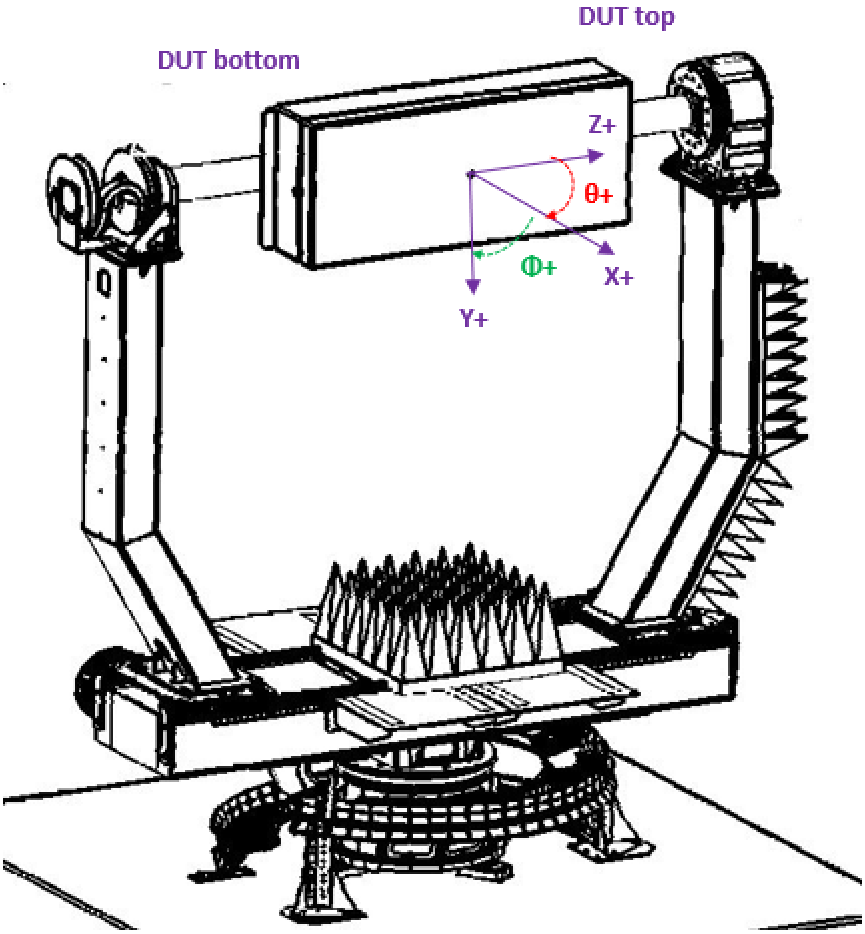


Figure 11. Example positioner system of a CATR.

3.3.1 Compact antenna test range

Compact Antenna Test Range (CATR) is a method of using a parabolic reflector to create a far field test environment within the space of a near field measurement system. The reflector in CATR is used to transform the advancing spherical wave to a plane wave form, while maintaining reciprocal attributes. Typical equipment linked to CATR are position system, measurement probe antenna and a feed antenna. The positioner is used to move the DUT within the calculated quiet zone in a way, that allows the tester to measure the whole 3D radiation pattern, as well as test different beamforming sets and polarizations of the antenna. CATR is used for both FR1 as well as FR2 frequencies, and it has been standardized as a valid test method by the 3GPP for Active Antenna System (AAS) Base Station (BS) RF measurements [29].

One of the core attributes of CATR is the reflector, and how it is designed to work. The reflector edges are usually treated to combat the diffraction caused by the reflection. One of the treatments is usage of serrated edges. The design creates an effortless transition between the parabolic reflector surface and the free space. This reduces the diffraction effect as well as directs the diffracted field to the surrounding absorbers. Typically, the serrations are 5 times the length of wavelength, which defines the lowest operating frequency. The rolled edge design slightly bends the edges of the reflector backwards, which decreases the possible reflected energy at the edges of the reflector [29].

As previously mentioned, a key component on OTA testing is the position/rotation system. In addition to adjustment of the two axes of rotation (azimuth / elevation) freely, it is also used to adjust the angle between the dual-polarized measurement antenna. The quiet zone that the DUT is placed inside of depends on the size of the reflector installed in the chamber [29].

When comparing CATR to a Direct Far Field method, the main benefits are the shorter test distance as well as the amount of path loss. The large amount of path loss caused by the free space in OTA measurements is a key challenge, especially when transitioning in mmWave tests. In 3GPP technical report TR38.810, there are criteria for the CATR test method. These include things like the shape and size of the quiet zone, possible tests to be performed with the set up and the multitude of DUTs that can be tested. In Figure 12 is presented the simplified CATR eNB/gNB test setup in a CATR [29].

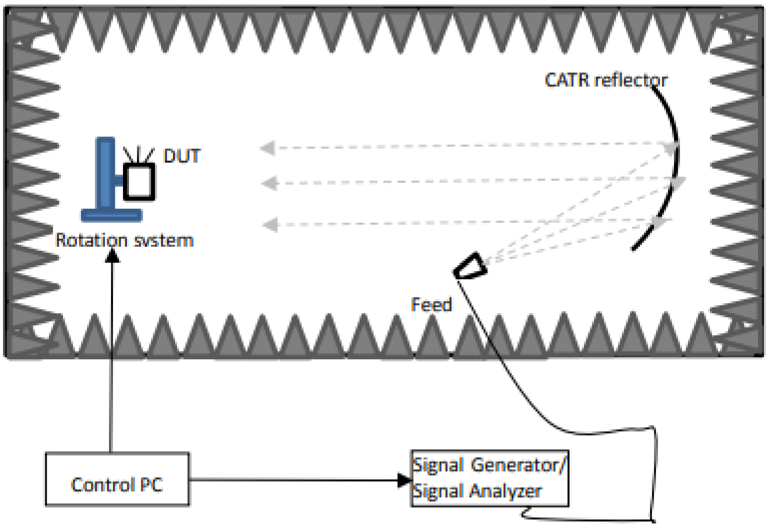


Figure 12. Basic eNB/gNB RF measurement setup illustrated in CATR.

4 TEST SETUP

This chapter describes the test setup, and what metrics were chosen for the design process. Power budget part consists of path loss calculator design, block diagram design as well as reasoning behind the measurement system component selection. Test plan part explains the chosen receiver test and explains the test metrics used for the test. Execution strategy part describes the management component of the practical work, which includes the approximation of the total time for all the tests, how each tests step will be prepared, and how they are executed. Test result analysis part describes the steps and metrics for the final analysis.

4.1 Power budget

In this thesis the goal of using a power budget was to calculate the estimate of how much attenuation there will be in higher frequencies in the proposed measurement system. These estimates will be used to determine the calibration value of the measurement setup in the chosen frequencies. Since the work is done in mmWave frequencies, there is higher path loss as well as cable loss, which is why it is important to determine set calibration estimates. By measuring the actual path loss value, and comparing it to the estimate, it will determine the uncertainty of the estimate.

Power budget or link budget is the calculated estimate of all the gains and losses within the test setup. It is used as a simulation tool for signal strength between the transmitter and the receiver, as well as a tool to calculate losses caused by multitude of things. Vital point of doing a power budget calculation is to determine whether it is possible to perform wanted measurements in the current test setup. Signal generators used in RX interference measurements are limited to certain power level. Rhode & Schwartz SMW40 for example, can output signal levels between -120 dBm to +18 dBm. By doing power budget calculations, it can be determined if this signal generator can be used to perform the wanted interference measurements.

There are many ways of forming a power budget, but the simplest way is to use Friis transmission equation as a base of the calculations. Friis transmission equation can be used to characterize antenna performance via gain metrics [30], which forms the basic power budget formula presented as

$$P_r = P_t + D_t + D_r + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right). \tag{2}$$

Here P_r is the available power at the receiver, P_t is the power delivered to the transmitter antenna, D_t is the isotropic directivity of the transmitting antenna, D_r is the directivity of the receiver antenna, λ is wavelength and d is the distance between the antennas. If one wishes to calculate the received power of the receiver antenna in another way, it can be done by calculating the gains and losses of the test setup. The power at the wanted measurement surface can be indicated as P_{OUT}, which was used in this thesis. The power is calculated by equation (3) as

$$P_{OUT} = P_T - L_T - L_{FS} - L_M \tag{3}$$

where P_{OUT} is the power at the wanted measurement surface, P_T is generator output power, L_T is the total gain/loss calculated from different components, L_{FS} is the loss caused by free space path loss and L_M is miscellaneous losses that are caused by replaceable components (i.e. if a coupler was changed to a splitter).

Free space path loss is the main contributor to the massive attenuation in mmWave frequencies. Free space path loss is the attenuation of signal with free LOS (Line-Of-Sight) path between the transmitter and the receiver. Formula for FSPL in decibels can be written as [30];

$$FSPL = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}(\frac{4\pi}{c}) \tag{4}$$

where d is the travelled distance, f is the frequency, and c is the speed of light. By increasing the distance travelled, and/or the utilized frequency, the amount of path loss increases.

4.1.1 Drawings and test setup planning

For OTA RX interference tests, the first step for planning the test setup was to confirm what kind of tests would take place during the testing period. The testing setups can be designed such way that they can be reused in other tests and thus saving planning time. Using these criteria, the selected measurement case was in-band blocking.

The base of the block diagram can be found for each measurement in 3GPP documents like TS 38.141-2. In this thesis the focus is on in-band blocking test case, which is described in section 3.2.4 and seen in Figure 13. [21]

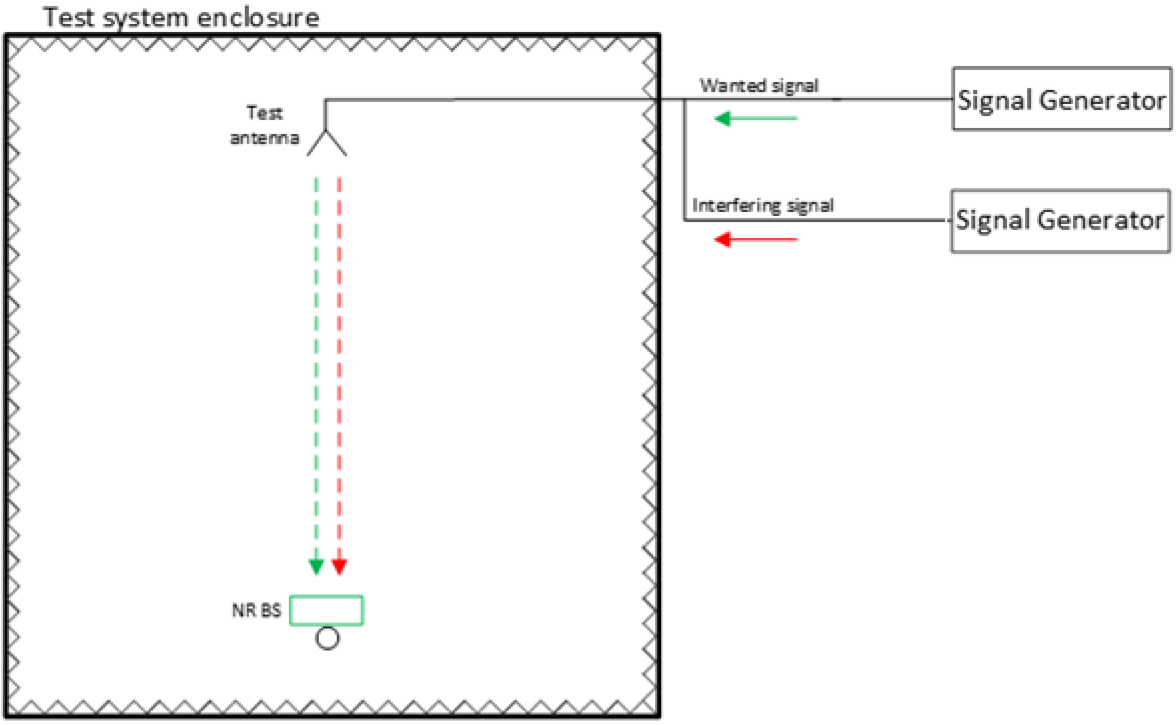


Figure 13. General OTA blocking measurement setup in a direct far field test environment.

The test system enclosure is an anechoic chamber built in Nokia testing facilities, which has been used for OTA TX tests previously, so the difficulty of the test setup comes from the testing equipment prior to the test antenna. Using the previously calculated power budget, it can be determined which kind of measurement components could be included to the measurement setup. It was possible to test out different component values in the power budget, after including all of the essential components first i.e. cables, RF-units and test equipment.

The test environment for the planned measurements was the CATR #2 (Compact Antenna Test Range) OTA chamber located in Nokia facilities in Oulu. This chamber provides the possibility of measuring devices from sub 1.7 GHz frequencies up to 40 GHz. The list of essential components for the measurement was as follows;

- 2x SMW40 vector signal generator, B140 option
- 1x FSW Spectrum analyser
- 1x X-step DRT8i baseband emulator
- 1x DC power source (Delta power)
- 4x 2.92mm RF cable
    - 2x RADIALL 2000PJ SS
    - 1x RADIALL 5000PJ SK
    - 1x SUCOFLEX 101
- 1x MVG RF-Unit OFR-OTA40-1
- 1x 28GHz Nokia mmWave radio (DUT)

Each component listed has an essential part of the measurements. Each signal generator in this setup transmits different signal. The spectrum analyser is used for measuring the EIRP level for calibration purposes, as well as verifying the test beam direction for each conformance test direction. X-step baseband emulator is used for capturing the received frame and transferring it to the analysis tool, which takes in the In-phase Quadrature (IQ) data. X-step can also be used as a baseband waveform generator if the DUT was to be tested in downlink. The MVG RF-Unit works as a switch between uplink and downlink measurements. And the mmWave unit is the DUT that works as the receiver for in-band-blocking tests.

For each component, the loss/gain value was considered in the power budget calculation, and then the replaceable component values were filled in the calculator excel (Appendix 2). By doing this, the total loss value could be calculated for each measured frequency and be compared to the specifications by 3GPP.

4.1.2 Component selection

The only options for choosing variable components, were the part for mixing signals and the RF cables. For RF cables, the ones with optimal length were chosen, while comparing the total loss of all cables. And for signal mixing, there were three possible scenarios discussed;

- Directional 4-port coupler
- Power combiner
- Single signal generator with multiple rf output ports

The requirements for the selected method was to minimize the total attenuation of the system, while attaining a fitting difference between the interference signal and the wanted signal. By process of elimination, it was decided that a directional coupler was to be used for the tests. Reasoning behind this was based on the selected test case, as well as the component specifications which were more suitable than rest of the options.

With the power combiner, there would not have been any attenuation difference between the two input ports. This means that the attenuation difference would be compensated by using the signal generators to create that gap. However, when operating in mmWave frequencies the total path loss is large enough that the dynamic range of the operating signal generator wouldn’t have been enough to properly execute the planned tests. As for the option of sending multiple signals from a single signal generator, there is a problem of availability. It is possible to mix two modulated baseband signals using a single signal generator. However, that option is valid only for sub 20 GHz signal generators that were available. Another possible candidate for mixing the signal that was brought up was a circulator. Only problem with a 4-way circulator used for mixing signals is that in order to be able to mix the wanted- and interfering signals, you would have to pass one of the signals through the other signal generator. This might break the input port of the generator in high power scenarios, which makes the circulator impractical in this case.

After selecting the mixing component for the measurements, the S-parameters of the components were measured separately on the planned/selected frequency range using a vector network analyser (VNA). These measurement results were compared to the specifications found in the datasheet of the component. A Marki C-0250 directional coupler was used, and the measurement results of its S21-parameters are shown in Figure 14, and the corresponding manufacturer determined values in Table 1.

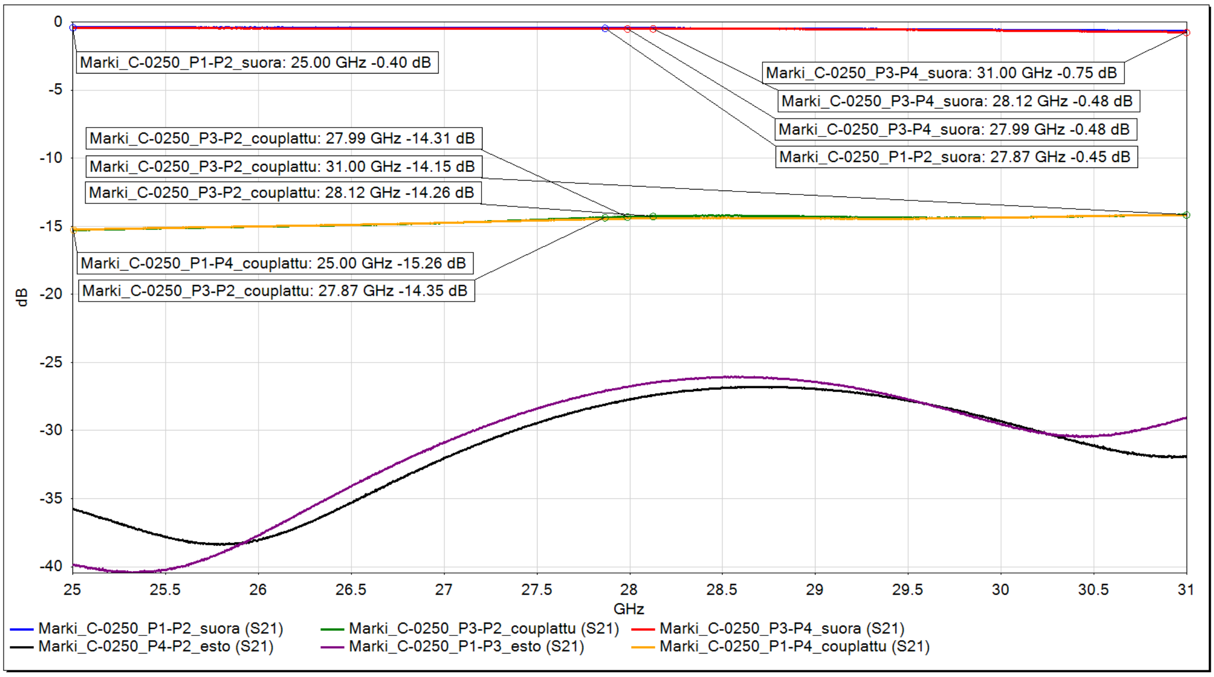
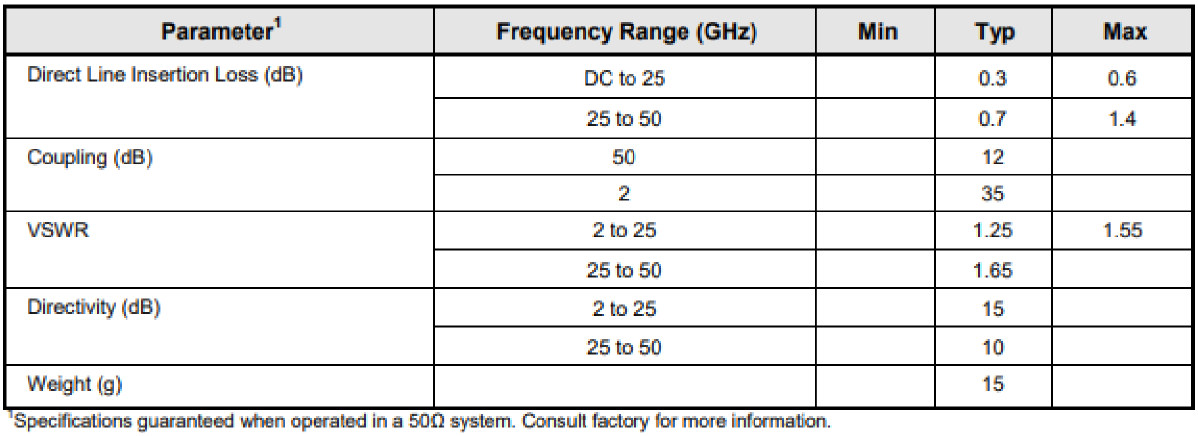


Figure 14. Measured Marki C-0250 coupler S21-parameters.

Table 1. Manufacturer determined directional coupler specifications (Appendix 1)



Parameter[1]	Frequency Range (GHz)	Min	Typ	Max
Direct Line Insertion Loss (dB)	DC to 25		0.3	0.6
	25 to 50		0.7	1.4
Coupling (dB)	50		12	
	2		35	
VSWR	2 to 25		1.25	1.55
	25 to 50		1.65	
Directivity (dB)	2 to 25		15	
	25 to 50		10	
Weight (g)			15	

[1] Specifications guaranteed when operated in a 50Ω system. Consult factory for more information.

In these tests, the direct line, coupled line and the isolation between ports were measured using S-parameters. When compared to the specification data, there is a noticeable difference in the typical values of direct line insertion loss (~ -0.512 dB) and coupling (~ -14.466 dB). With less insertion loss and more coupling, the requirements for signal generator dynamic range decrease with in-band blocking case.

4.2 Test plan

This test plan describes the testing approach and overall preparation for receiver in-band blocking measurements in mmWave frequencies. The overall test plan includes two major parts:

- Test Strategy: The theory that the measurements are based on, assumptions, description from calibration to the actual test process including all calculations and specific tasks to perform.
- Execution Strategy: Describes how the test will be performed and how the actual measurements might deviate from the planned ones. Includes the preparations up to the point where the actual measurements are about to begin.

The measurement that this thesis is focused on, is in-band blocking in the receiver end (Uplink). This kind of measurements have been done before, but not in OTA (Over-The-Air) environment in mmWave frequencies. The main goal of these measurements is to validate the testing method of using OTA, as well as provide valuable data on how this test follows the expected results. Previous information about the results of these measurements are not available, but all of the specified test methods and requirements are provided by 3GPP (3rd Generation Partnership Project) in multiple documents. These documents explain the minimum requirements for all aspects in depth.

The OTA in-band blocking characteristics is a measure of the receiver's ability to receive an OTA wanted signal at its assigned channel in the presence of an unwanted OTA interferer. The wanted signal used simulates the data traffic that the receiver is supposed to receive, whereas the interfering signal simulates an interfering signal generated by external causes such as nearby transmitter or noisy equipment. The interfering signal is an NR signal for general blocking or an NR signal with one RB (Resource Block) for narrowband blocking [21].

The objective of the test is to verify that the measurements in question works according to the specifications provided by the 3GPP standard. The test will be executed and verified by the

3GPP standards, as well as analysed for future use of the DUT in testing. The outcome of the test is twofold: A finalized test report on in-band blocking characteristics of the measured DUT, as well as a written test plan as a piece of the final diploma thesis regarding these measurements.

One of the key assumptions for the planned tests was, that the tests should be completed in the given time period of 25.-30.3.2019. The other is that the results acquired from the DUT should resemble the specified results provided in the eNB/gNB specification document. Taking these into consideration, the total scope and level of testing was written as:

- The purpose of this test is to test the measurement method proposed by 3GPP for in-band blocking case in FR2 via OTA environment.
    - The measurement is a sensitivity measurement, and the data we want to collect is the signal level of the signal as well as the BLER (Block-Error-Rate) value of our signal.
        - These values can be determined from captured IQ-data, which we have available via X-step baseband emulator.
- Tests are made semi manually, so the minimum requirement for these measurements is to measure the middle (M) frequency channel with four different blocking frequency channels. Bottom (B) – and top (T) channels can be included but are not the primary objective of this thesis. These values are pre-determined by the manufacturer.
    - Here B is the bottom of the declared frequency range of the DUT operating band, M is located in the middle (centre) frequency and T is the top of the frequency range.
- The primary focus of the measurements is to research the observations and limitations of 3GPP suggested OTA In-Band blocking test methods. One of the objectives is to verify the suggested method and draw conclusions of the measured results. The results about the radio receiver performance are only the secondary objective of this plan
- The tests are done with single frequency channel method. By using two signal generators (both for their individual signals) and a directional coupler for combining the two, we can perform the desired in-band blocking case with enough dynamic range.
- The tests are planned to begin on 25th of March, and the planned end is on the 29th of March.

Before starting any measurements, there were the general guidelines that were agreed upon. These guidelines are;

- Testing will begin once the first official version of this test plan has been accepted.
    - This plan includes entrance and exit criteria.
    - Test procedures should be well documented so anyone can repeat each step after reading the document.
- The tests will be done with the 3GPP requirements as a foundation.
    - Testing will be focused on meeting the minimum requirements of 3GPP specifications.
- The measurements only focus on one test case, but with little modifications we can test other receiver aspects as well.
- The tests will be done semi manually, since there is no software support for these measurements.
    - Frequency channels are appointed manually with each signal generator.

  - IQ-data capture is done automatically with supported software and hardware combination
  - Rotation of DUT with the rotation equipment, and controller software automatically.
- The CATR chamber will be calibrated before testing starts with a spectrum analyser and a signal generator.
- The 3GPP requirement shall apply at the RIB, when the AoA of the incident wave of a received signal and the interfering signal are from the same direction and are within the OTA REFSENS RoAoA. [21]
  - OTA REFSENS RoAoA (Range of Angles of Arrival) is the RoAoA equivalent to the 3dB beam width of a non-AAS base station passive antenna providing the same coverage area as the AAS (Active Antenna System) base station.
  - “OTA REFSENS RoAoA: Is the RoAoA determined by the contour defined by the points at which the achieved EIS is 3dB higher than the achieved EIS in the reference direction” [21].
- The test setup will follow the accepted block diagram, that will be included in section 4.2.1.

4.2.1 In-band blocking

The method of calibration was chosen with the fact in mind, that we want to keep the previous measurement setup as close as it can be to the one we need. Therefore, the chosen method was to setup a single signal generator and a spectrum analyser setup, which is used to determine the loss value from the signal generator input to the RIB of our DUT. In Figure 15 the block diagram of the desired wanted signal calibration method is presented. And in Figure 16 is presented the calibration method for the interference signal.

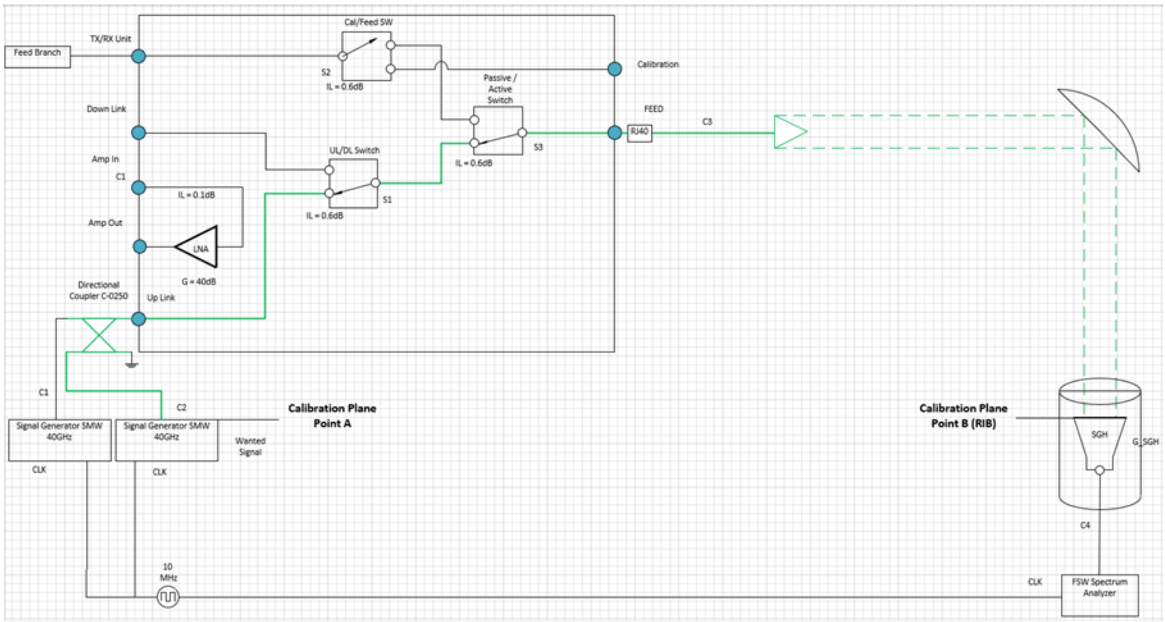


Figure 15. Calibration method of CATR #2 chamber for FR2 in-band blocking wanted signal.

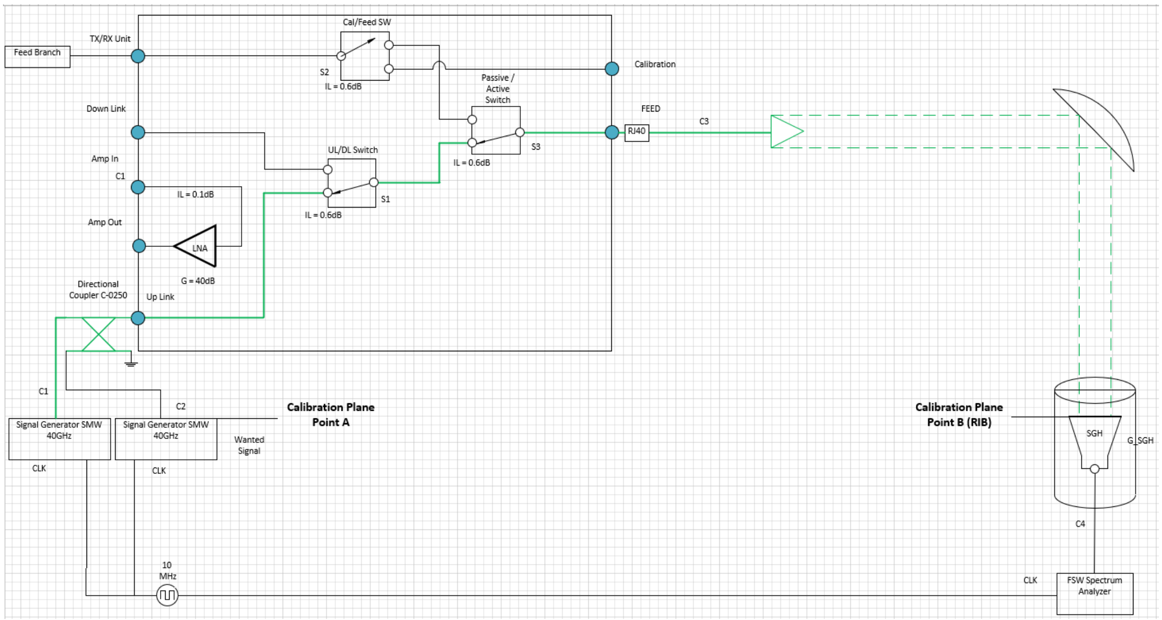


Figure 16. Calibration method of CATR #2 chamber for FR2 in-band blocking interference signal.

Signal generator shall be connected to OTA box up link input via a directional coupler. In OTA Box the switches have been set up like they are presented in Figure 15 and 16. The antennas for calibration are reference antennas SGH, which has pre-determined values saved for each frequency. These values are provided by the antenna manufacturer technical report of each antenna. This way we can compare the measured signal level value of each frequency to the reference value provided by the SGH reference sheet. The frequency channel that should be measured is the middle channel of the determined DUT operating range. For each channel, value of signal level should be saved and compared to the theoretical value of the signal calculated by the link budget excel (Appendix 2). If the measured signal level is within the specifications of 3GPP uncertainty levels of +/-3.4 dB, the calibration is marked as successful.

In the calibration, the components in use are the same as in the final measurement. There will be two SMW40 signal generators with B140 option, which provides a RF path from 100 kHz up to 40 GHz. In addition to that, there was one FSW spectrum analyser and two standard gain horn antennas. Calibration will be done with the middle channel of the operating range of the DUT, as well as four selected blocker signal frequency channels. These frequency channels will be further explained in subclause 'Desired frequency channels and signal modulation'.

The setup for the actual measurement does not vary much from the one we used for calibration. This is presented in Figure 17.

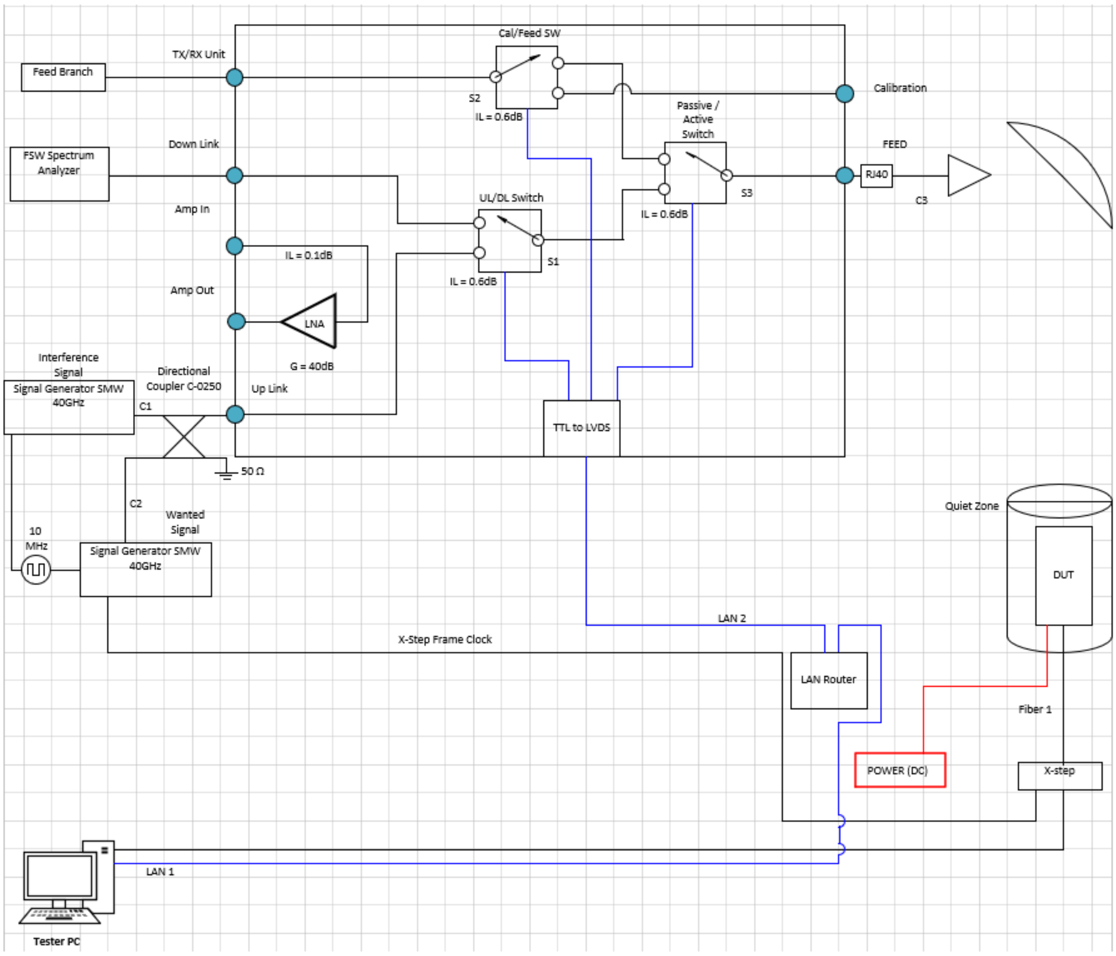


Figure 17. Measurement setup used for in-band blocking test case in FR2 with OTA environment.

The path for the interference signal and the wanted signal is identical to the path of the calibration, but the only difference is that the wanted signal and the interference signal are fed through the same path via a directional coupler. The total loss of this measurement setup can be calculated with the link budget excel provided in the attachments (Appendix 2).

The measured frequency points are the same for the calibration as well as the final measurement. These are determined by the operating range of our DUT, which is operating in FR2 frequency range. The radio in use is a 28 GHz mmWave product, which operates in frequency range of 26500-29500 MHz. The initial conditions provided in 3GPP document TS 38.141-2-f00 subclause 7.5.2.4 states that the RF channels to be tested for single carrier is the middle channel (28000 MHz). For the single frequency channel measured, there will be four frequency channels appointed to the blocking signal according to the 3GPP specifications calculated later in this subclause.

After determining the frequency points to be measured, the test model was decided on. From Nokia DUT test matrix, the pre-determined uplink test model for 100 MHz single carrier signal specified by 3GPP TS 381.41-2 is; “Uplink, Rank1, mmWave (120 kHz subcarrier spacing), 100 MHz, full-UL-frame, 1x50 MHz - QPSK, 16QAM, 64QAM and 256QAM modulations [21]”. Here the subcarrier spacing (SCS) is determined for supporting a 120 kHz spacing. Therefore, the wanted signal positioning is calculated with that in mind. For each frequency point, calculations are done for transmission bandwidth configuration;

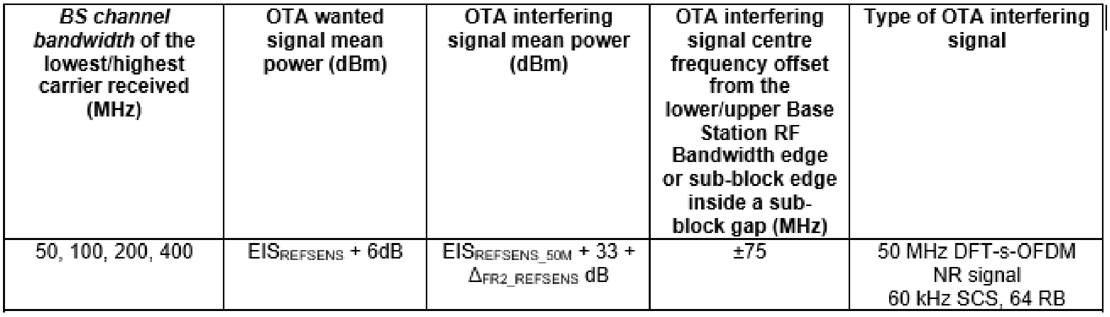
$$TBC = N_{RB} * SCS * Number\ of\ Subcarriers. \tag{5}$$

Where N_{RB} is the number of resource blocks in use for the determined signal by the 3GPP specifications provided in document TS 38.141-2-f00 annex A, SCS is the subcarrier spacing for the wanted signal and number of subcarriers is a pre-determined constant of 12. Therefore, we have calculated based on equation (5);

$$TBC = 66 * 0.12\ \text{MHz} * 12 = 95.04\ \text{MHz}.$$

For the interference signal we have the specifications included also in the same document as presented in Table 2 [21].

Table 2. General OTA blocking requirements for BS type 2-O



BS channel bandwidth of the lowest/highest carrier received (MHz)	OTA wanted signal mean power (dBm)	OTA interfering signal mean power (dBm)	OTA interfering signal centre frequency offset from the lower/upper Base Station RF Bandwidth edge or sub-block edge inside a sub-block gap (MHz)	Type of OTA interfering signal
50, 100, 200, 400	$EIS_{REFSENS}$ + 6dB	$EIS_{REFSENS\_50M}$ + 33 + $\Delta_{FR2\_REFSENS}$ dB	±75	50 MHz DFT-s-OFDM NR signal 60 kHz SCS, 64 RB

Now for 50 MHz, SCS 60 kHz, 64 RB signal we calculate the value based on equation (5);

$$TBC = 64 * 0.06\ \text{MHz} * 12 = 46.08\ \text{MHz}.$$

For the guard band we have specifications in 3GPP document TS 38.101-2-f40 subclause 5.3.3 as presented in Table 3 [31];

Table 3. Minimum guard band for each UE channel bandwidth and SCS

SCS (kHz)	**50 MHz**	**100 MHz**	**200 MHz**	**400 MHz**
60	1210	2450	4930	N. A
120	1900	2420	4900	9860

For wanted signal with SCS 120 kHz, and interference signal with SCS 60 kHz the guard band for a single carrier signal is;

$$GB = 2 * 2.42\ \text{MHz} = 4.84\ \text{MHz}, \tag{6}$$
$$GB\ (IF) = 2 * 1.21\ \text{MHz} = 2.42\ \text{MHz}. \tag{7}$$

Now the total bandwidth channel is the sum of our transmission bandwidth configuration and the guard band of the signal;

$$Wanted\ Signal = 95.04\ \text{MHz} + 4.84\ \text{MHz} = 99.88\ \text{MHz}, \tag{8}$$
$$Interference\ Signal = 46.08\ \text{MHz} + 2.42\ \text{MHz} = 48.5\ \text{MHz}. \tag{9}$$

As for the placement of the wanted and interference signals, the interference signal is location is determined in Table 2 as +/-75 MHz from the centre of interfering signal to the lower/upper bandwidth edge or sub-block edge of the wanted signal. For wanted signal, the location is calculated in the provided Nokia DUT test matrix as follows;

Table 4. DUT calculated frequencies for Uplink middle channel

5G 1x100	
Middle Frequency	
Downlink (TX)/Uplink (RX)	
Frequency	NR-ARFCN
27999.96	2079165.00

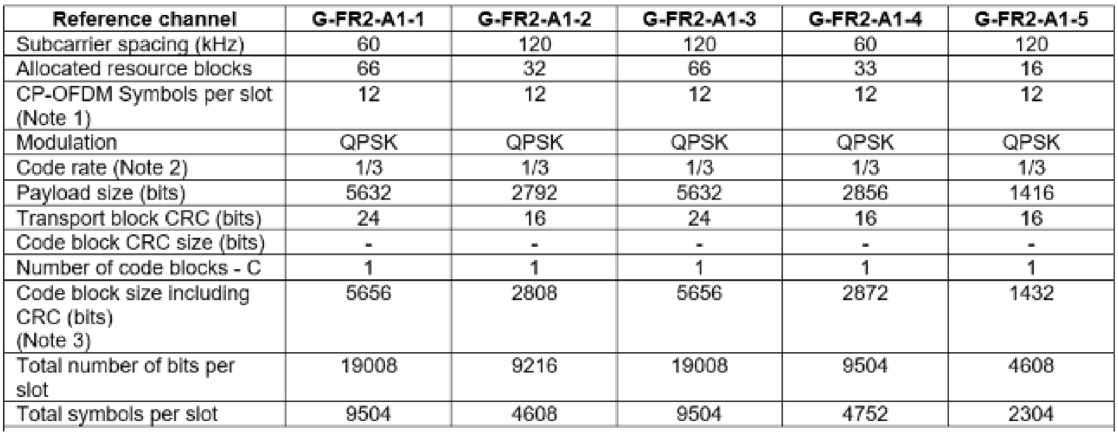
For the four frequency channels appointed for the blocking signal, they are calculated in Table 5. These frequency channel locations were previously illustrated in Figure 7, where the four blocker signals are set up according to the calculated table.

Table 5. DUT calculated frequency channels for four blocker signals

5G 1x50 Blocker			
Lower Blocker	Middle Blocker		Upper Blocker
Downlink (TX)/Uplink (RX)	Downlink (TX)/Uplink (RX)		Downlink (TX)/Uplink (RX)
Frequency (MHz)	Frequency (MHz)	-/+75	Frequency (MHz)
25024.98	27999.96	27874.96 / 28124.96	30975.00

As for the modulation for the measurements, it is specified in 3GPP document 38.141-2-f00 annex A for the wanted signal, and for interfering signal in 7.5.2.5.3. Depending on the test, the reference channel for the wanted signal changes according to the specifications. The reference channel table is presented in Table 6 [21].

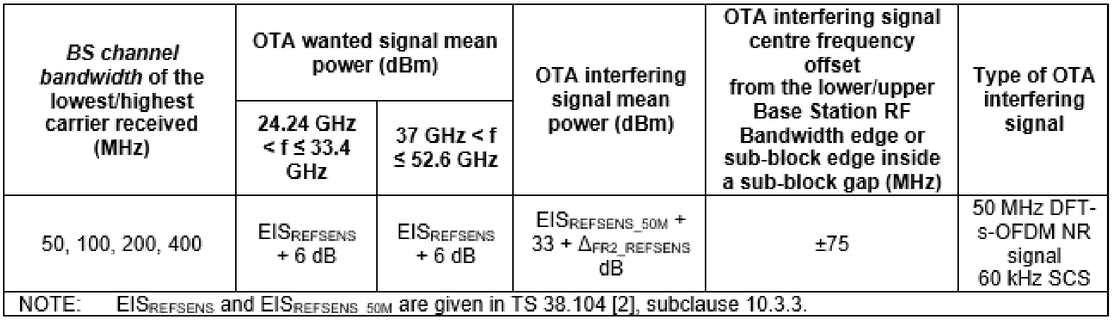
Table 6. FRC parameters for FR2 receiver sensitivity (wanted signal) and in-channel selectivity / blocking



Reference channel	G-FR2-A1-1	G-FR2-A1-2	G-FR2-A1-3	G-FR2-A1-4	G-FR2-A1-5
Subcarrier spacing (kHz)	60	120	120	60	120
Allocated resource blocks	66	32	66	33	16
CP-OFDM Symbols per slot (Note 1)	12	12	12	12	12
Modulation	QPSK	QPSK	QPSK	QPSK	QPSK
Code rate (Note 2)	1/3	1/3	1/3	1/3	1/3
Payload size (bits)	5632	2792	5632	2856	1416
Transport block CRC (bits)	24	16	24	16	16
Code block CRC size (bits)	-	-	-	-	-
Number of code blocks - C	1	1	1	1	1
Code block size including CRC (bits) (Note 3)	5656	2808	5656	2872	1432
Total number of bits per slot	19008	9216	19008	9504	4608
Total symbols per slot	9504	4608	9504	4752	2304

Now that the reference channel is established, frequency channels used for blocker- and wanted signal and total bandwidth channel size for both signals is done, focus is switched to the blocking requirements. These requirements are presented in Table 7. [21]

Table 7. General OTA blocking requirements for BS type 2-O



BS channel bandwidth of the lowest/highest carrier received (MHz)	OTA wanted signal mean power (dBm)		OTA interfering signal mean power (dBm)	OTA interfering signal centre frequency offset from the lower/upper Base Station RF Bandwidth edge or sub-block edge inside a sub-block gap (MHz)	Type of OTA interfering signal
	24.24 GHz < f ≤ 33.4 GHz	37 GHz < f ≤ 52.6 GHz			
50, 100, 200, 400	$EIS_{REFSENS}$ + 6 dB	$EIS_{REFSENS}$ + 6 dB	$EIS_{REFSENS\_50M}$ + 33 + $\Delta_{FR2\_REFSENS}$ dB	±75	50 MHz DFT-s-OFDM NR signal 60 kHz SCS
NOTE: $EIS_{REFSENS}$ and $EIS_{REFSENS\_50M}$ are given in TS 38.104 [2], subclause 10.3.3.					

In the table, the value for the $EIS_{REFSENS}$ is not given. This value is presented in another TS document as a value based on a reference channel measurement, which is then used as a declared basis level. Usually $EIS_{REFSENS}$ reference channel measurement is done with a 50 MHz BS channel bandwidth, and the result is told as $EIS_{REFSENS\_50M}$. If the BS does not support 50 MHz channel bandwidth, it doesn't matter since the requirements don't imply that the BS has to support that given channel bandwidth. [32]

In the same document, values for $EIS_{REFSENS\_50M}$ are given as a range for each BS type as seen on Table 8 [32].

Table 8. Values for $EIS_{REFSENS\_50M}$ depending on the BS type

BS Type	Maximum (dBm)	Minimum (dBm)
Wide Area BS	-96	-119
Medium Range BS	-91	-114
Local Area BS	-86	-109

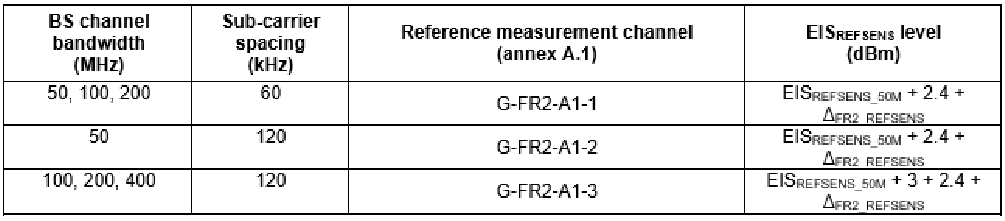
Now by declaring the limitations of $EIS_{REFSENS\_50M}$, we can calculate the OTA interfering signal mean power for each BS type. The equation is presented in Table 7 as $\mathrm{EISREFSENS}_{50M} + 33 + \Delta_{FR2\_REFSENS}$ dB, where $\Delta_{FR2\_REFSENS}$ is opened in technical specification 38.141-2-f00. In the specification $\Delta_{FR2\_REFSENS}$ is specified as -3 dB for the reference direction, and 0 dB for all other directions [21]. Therefore, the calculated values in Table 9 work as a maximum / minimum limit of our interfering signal [32].

Table 9. Values for $EIS_{REFSENS\_50M}$ depending on the BS type

BS Type	Maximum (dBm)	Minimum (dBm)
Wide Area BS	-63 (-66 for ref.)	-86 (-89 for ref.)
Medium Range BS	-52 (-55 for ref.)	-65 (-68 for ref.)
Local Area BS	-47 (-50 for ref.)	-76 (-79 for ref.)

As for EISREFSENS, the reference values for 50 MHz channel bandwidth are the same as in Table 7, but the requirements are opened in TS 38.141-2 subclause 7.3.5.3 as presented in Table 10 [21];

Table 10. FR2 OTA reference sensitivity requirements



BS channel bandwidth (MHz)	Sub-carrier spacing (kHz)	Reference measurement channel (annex A.1)	$EIS_{REFSENS}$ level (dBm)
50, 100, 200	60	G-FR2-A1-1	$EIS_{REFSENS\_50M}$ + 2.4 + $\Delta_{FR2\_REFSENS}$
50	120	G-FR2-A1-2	$EIS_{REFSENS\_50M}$ + 2.4 + $\Delta_{FR2\_REFSENS}$
100, 200, 400	120	G-FR2-A1-3	$EIS_{REFSENS\_50M}$ + 3 + 2.4 + $\Delta_{FR2\_REFSENS}$

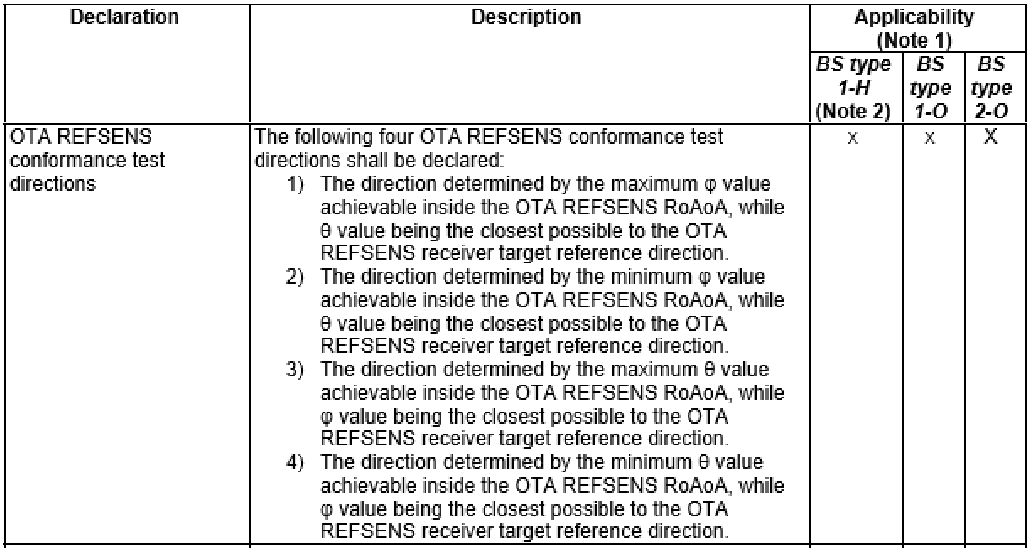
Since the wanted signal in use is 100 MHz with sub-carrier spacing of 120 kHz, the level in use will be of $EIS_{REFSENS\_50M} + 3 + 2.4 + \Delta_{FR2\_REFSENS}$, and the reference measurement channel is G-FR2-A1-3. As for the interfering signal, the channel bandwidth is 50 MHz and SCS 60 kHz. Therefore, the measurement channel in use is G-FR2-A1-1 and the corresponding EIS reference sensitivity value would be;

$$EIS_{REFSENS} = EIS_{REFSENS\_50M} + 2.4 + \Delta_{FR2\_REFSENS}.$$

However, in the actual test scenario, sensitivity is measured with the same setup as in the in-band blocking case. This data is used to get the exact value of the measured reference sensitivity, and it will be used as $EIS_{REFSENS}$.

Since $EIS_{REFSENS}$ should be measured for each conformance test direction appointed in 3GPP specifications, it is required to determine the values for each test direction. In this case, to optimize the time used in the measurements, it is advised to use pre-existing data of the DUT in question, provided by Nokia under NDA. Measurement directions specified by 3GPP, the requirements to be followed are in the OTA RoAoA specifications. OTA Refsens RoAoA was already discussed in general test assumptions, however the limitations were not specifically explained. For OTA RoAoA the declarations are explained in TS 38.141-2 subclause 4.6, part D.55 as seen on Table 11 [21].

Table 11. Manufacturer declaration for OTA Refsens RoAoA conformance test directions



Declaration	Description	Applicability (Note 1)		
		BS type 1-H (Note 2)	*BS type 1-O*	*BS type 2-O*
OTA REFSENS conformance test directions	The following four OTA REFSENS conformance test directions shall be declared: 1) The direction determined by the maximum φ value achievable inside the OTA REFSENS RoAoA, while θ value being the closest possible to the OTA REFSENS receiver target reference direction. 2) The direction determined by the minimum φ value achievable inside the OTA REFSENS RoAoA, while θ value being the closest possible to the OTA REFSENS receiver target reference direction. 3) The direction determined by the maximum θ value achievable inside the OTA REFSENS RoAoA, while φ value being the closest possible to the OTA REFSENS receiver target reference direction. 4) The direction determined by the minimum θ value achievable inside the OTA REFSENS RoAoA, while φ value being the closest possible to the OTA REFSENS receiver target reference direction.	x	x	X

These directions are given in the manufacturer declaration of NOKIA DUT OTA Peak directions set as seen on Figure 18 [33]. To limit the required tests, the plan is to measure the minimum directions required by 3GPP specifications as they are stated in the OTA REFSENS conformance test directions. In this case, the tested conformance directions would be the boresight, maximum of elevation and azimuth angles as well as the minimum of azimuth and elevation angles. The azimuth and elevation angles are specified as the measurement directions of a positioner in OTA measurements spherical coordination system. These directions are marked in Figure 18 as a red cross. The red dots are part of the peak direction set, which include theoretical -3 dB points for each conformance direction beam. These points are marked as red circles around the specified conformance directions. The red outline of the figure is a visual presentation of the redirection range of the AAS BS.

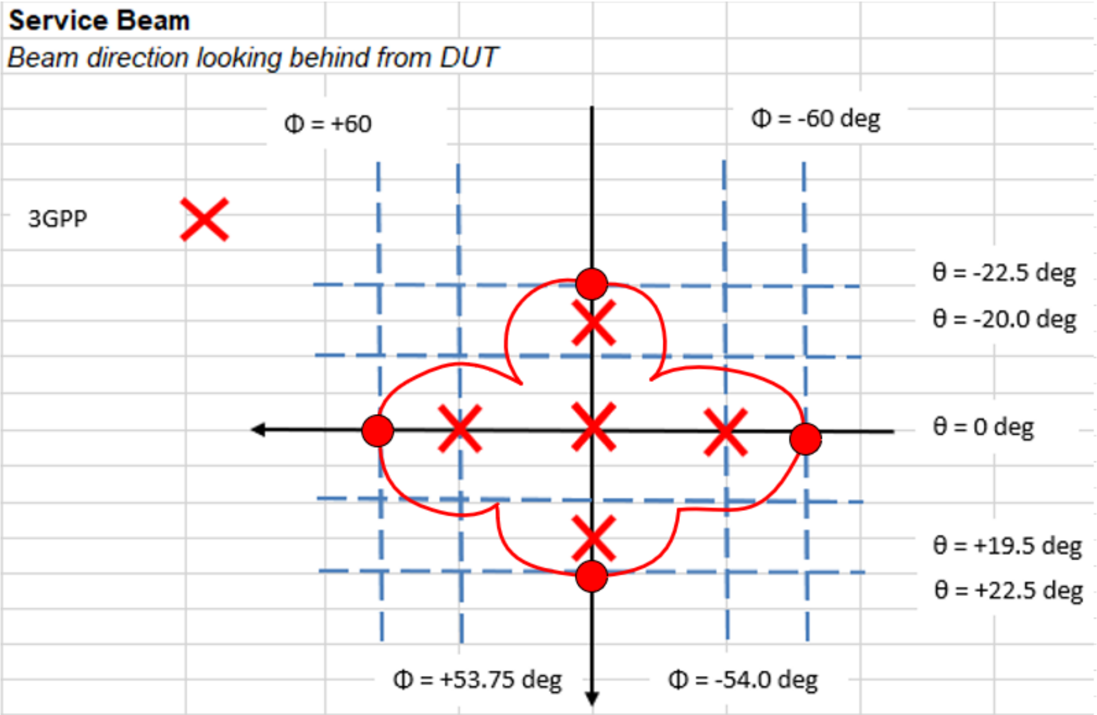
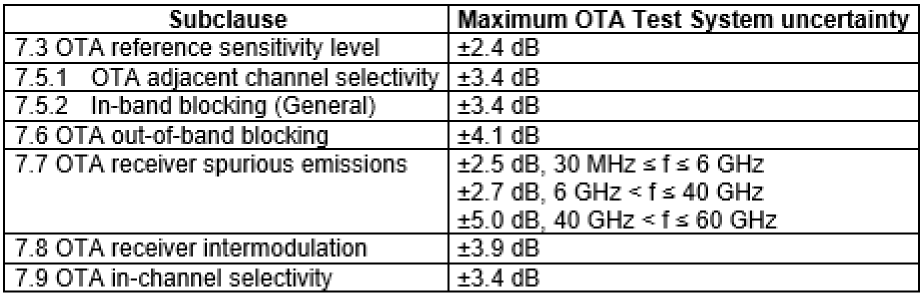


Figure 18. Manufacturer declaration of the measurement directions calculated for DUT, with 3GPP conformance test direction illustration.

As for uncertainties, the 3GPP specifications state that the maximum OTA test system uncertainty for FR2 OTA receiver tests are presented in Table 12 [21]. For the thesis, the focus would be on the maximum OTA test system uncertainty on OTA reference sensitivity level, as well as the In-band blocking (General).

Table 12. Maximum OTA system uncertainty for FR2



Subclause	Maximum OTA Test System uncertainty
7.3 OTA reference sensitivity level	±2.4 dB
7.5.1 OTA adjacent channel selectivity	±3.4 dB
7.5.2 In-band blocking (General)	±3.4 dB
7.6 OTA out-of-band blocking	±4.1 dB
7.7 OTA receiver spurious emissions	±2.5 dB, 30 MHz ≤ f ≤ 6 GHz ±2.7 dB, 6 GHz < f ≤ 40 GHz ±5.0 dB, 40 GHz < f ≤ 60 GHz
7.8 OTA receiver intermodulation	±3.9 dB
7.9 OTA in-channel selectivity	±3.4 dB

4.3 Execution strategy and test management process

The execution strategy was designed with an entry – and exit criteria in mind. The entry criteria, described as initial tasks to do before initiating the actual measurements, were agreed upon with the technical advisors for this thesis. This was also the case with exit criteria. These both are listed as bullet points below as such;

- For the measurements to begin, an accepted test plan should be able to be presented.
- Successful calibration is required, accompanied with a working link budget calculator to verify the calibration.
- To begin in-band blocking measurements, it is required to measure the OTA EIS-REFSENS of the DUT (See next chapter for more information)
    - For wanted signal only, using 100 MHz BW channel, Middle channel and SCS 120 kHz.
- For exit criteria, the success of reference sensitivity as well as in-band blocking is considered to be the final criteria.
    - In case of measurements are unsuccessful, they are not considered to be invalid results. In this case a deep analysis is required to explain the final results.

For test management purpose, a simplified test design process is presented in Figure 19. For calibration of OTA Chamber, the process is described in subclause 3.2.1. Calibration verification is done by comparing the calculated theoretical result of the signal level in RIB to the actual measured value with the calibration setup. Since 3GPP has not made specifications for this instance, the tester should determine the uncertainty of these measurements as close as possible to the maximum OTA test system uncertainty as described in Table 12. In case of in-band blocking measurements, the allowed limit for uncertainty is +/-3.4 dB.

To finalize the calibration verification, it is advised to test out if the test setup for in-band blocking is working as intended. After successful calibration for both wanted- and interfering signal, setup both signal generators to generate their designated signals and verify the received signal on the spectrum analyser.

Furthermore, it is advised to test the measurement setup and the DUT before starting the final measurements. One way to verify the setup is to compare the measured DL (Down Link) test results from previously measured TX side performance tests. Setup the OTA RF unit switches in a way, that the signal is fed through the downlink side of the unit, and measure EIRP at 3GPP Boresight Peak Direction. Compare the measured value to the one provided by the Nokia performance excel to see if the DUT is working as expected.

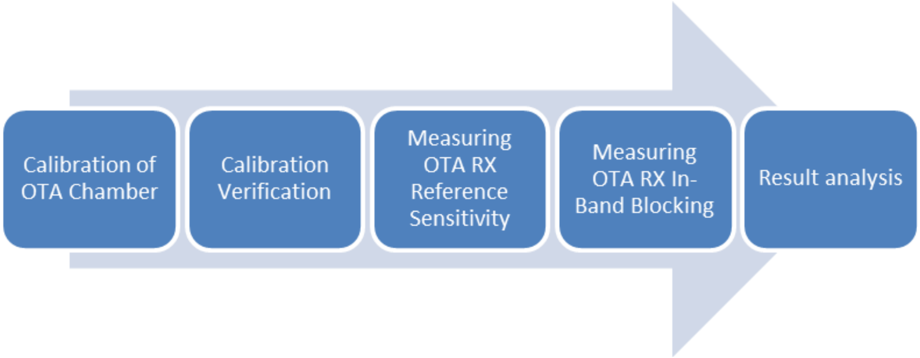


Figure 19. Simplified testing process.

The number of tests planned is limited to the amount of time available to fully execute all of the required tests. For example, measuring the beam width for each OTA peak direction would take considerable amount of time and resources. These measurements can be compensated by analysing earlier data from the manufacturer, and trusting the pre-determined values offered in these documents. Since the DUT under question has been tested on TX side, these results can be repurposed as RX results. The operating DUT that will be measured is specified to work in 5G TDD networks, RX and TX data are reciprocal, meaning It behaves identically in the transmission and reception. TX gain equals RX gain $Gt = Gr$, and radiation patterns is similar in transmission and reception.

Test execution is distributed between five whole work days, between 8:30 am to 4:30 pm. Since previous measurement data can be used again, the only measurements remaining are the $\mathrm{EIS}_{\mathrm{REFSENS}}$ on boresight, and in-band blocking measurements for each conformance test direction. According to previous research, each sensitivity measurement step will take around 10 minutes (data capture, IQ-data demodulation and calculations). For each measurement, there will be around 5 to 6 measurement steps, so it will take around 50 to 60 minutes to complete one full sensitivity measurement. In the measurement, the goal is to find the minimum value for the signal level that passes the BLER test. In the example seen in Figure 20, the measurement starts at a value that is known for having greater rates for successful measurement.

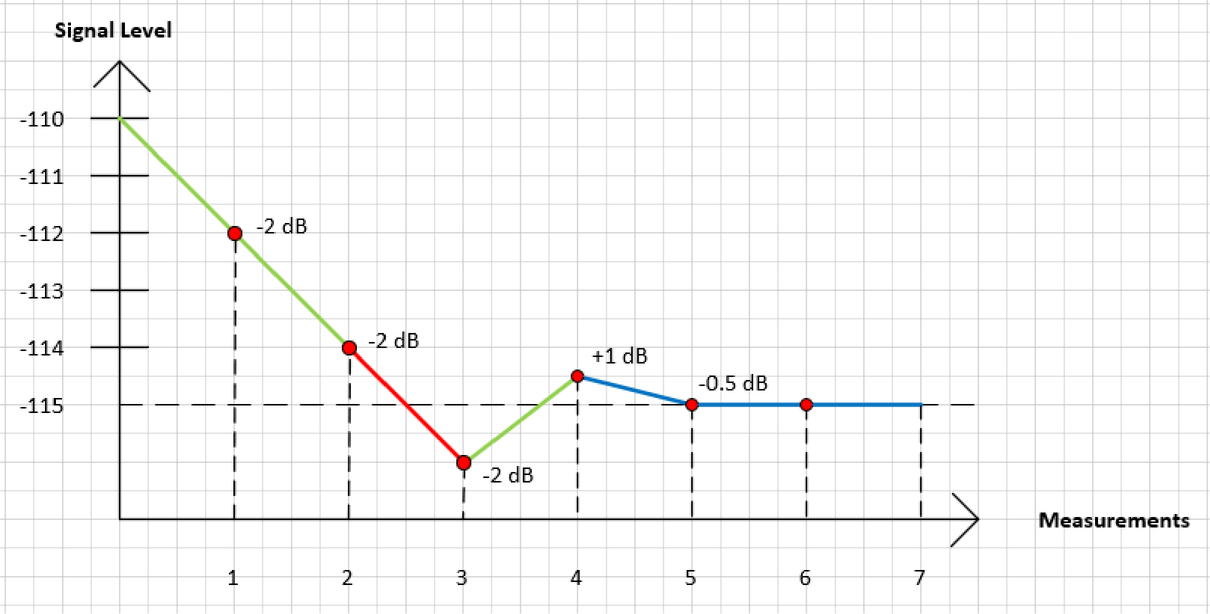


Figure 20. Measurement step method visualized.

After the first test, the signal level is then decreased after each measurement until the BLER test fails. When the lower limit is found, the signal level is then adjusted to a point where the BLER measurement fulfils the 3GPP specified requirements of BLER being equal or less than the specified limit.

By calculating every step for each measurement needed, the total estimated time required is presented in Table 13. However, this is merely an estimate of the total time that the measurements will take. The values were selected based on previous test measurement performed in a similar setting. In a case that the measurement duration or measurement type changes, these values will be calculated again according to the amount of time that the new type of measurements will take.

Table 13. Estimate of total measurement duration

Measurement	Directions	Minimum Steps	Maximum Steps	Total min (Directions * Steps*10)	Total max (Directions * steps *10)
EIS Refsens	5	5	6	250	300
In-band blocking (wanted + 75)	5	1	3	50	150
In-band blocking (wanted -75)	5	1	3	50	150
In-band blocking (wanted + lower blocker)	5	1	3	50	150
In-band blocking (wanted + upper blocker)	5	1	3	50	150
TOTAL	5 directions	9	18	450 min / 7h 30 min	900 min / 15h

With the total maximum being 15 hours, it is possible to increase the testing steps in the possibility of more detailed testing data. However, these calculations have not taken in account the calibration of the system, as well as every other uncertainty that these measurements may present during the testing phase. In Table 14 is presented the week-long plan for these measurements;

Table 14. Weekday plan estimate for measurements

Weekday	Daily Plan
Monday	Hardware and software familiarization. Measurement equipment / component installation + Calibration.
Tuesday	OTA chamber calibration finish + Test setup verification via DL + $\text{EIS}_{\text{REFSENS}}$ measurements.
Wednesday	$\text{EIS}_{\text{REFSENS}}$ measurement finish + In-band blocking for +/-75 MHz blocker.
Thursday	Finish In-band blocking for +/-75 MHz blocker, start measuring lower + upper blocker
Friday	Finish everything left on Thursday, DOUBLE CHECK EVERYTHING IS DONE BY TODAY.
(Saturday)	In case of missing data / complications during the measurements, use this day to finish work.
(Sunday)	In case of missing data / complications during the measurements, use this day to finish work.

4.3.1 Calibration strategy

For calibration, the process follows the previously calculated frequency channel values so, that we check each frequency channel separately and compare it to the expected value calculated in the link budget excel.

1. Start by calibrating the wanted signal frequency channel; Middle 27999.96 MHz, BW 100 MHz, SCS 120 kHz.
    a. Set the correct ARB file to the SMW40 signal generator.
    b. Feed the set signal through the wanted signal path presented in Figure 1.
    c. Compare the value displayed in FSW spectrum analyser to the one calculated in the link budget excel.
    d. If the displayed value and the excel do not exceed the 3GPP specified uncertainty values, the calibration is defined as successful.
2. After calibrating the wanted signal, we calibrate the four interfering signal paths; 4 frequency channels, BW 50 MHz, SCS 60 kHz.
    a. Set the correct ARB file to the SMW40 signal generator.
    b. Feed the set signal through the interfering signal path presented in Figure 2.
    c. Compare the value displayed in FSW spectrum analyser to the one calculated in the link budget excel.

Calibrations are to be done to the reference directions (0degree azimuth, 0degree elevation), since there is no calculated data of the values for each beam direction.

4.3.2 OTA reference sensitivity

For OTA Reference Sensitivity, the suggested procedure by 3GPP with personally specified edits is followed.

1. Place the BS with its manufacturer declared coordinate system reference point in the same place as calibrated point in the test system.
    a. Set DUT to the same point the SGH was calibrated on.
2. Align the manufacturer declared coordinate system orientation of the BS with the test system.
    a. Start by setting DUT to the reference direction.
3. Align the BS with the test antenna in the declared direction to be tested.
4. Ensure the polarization is accounted for such that all the power from the test antenna is captured by the BS under test.
    a. For these tests, only one polarization will be measured to ensure that the time appointed to complete these measurements are met. The polarization chosen is “Vertical”.
5. Configure the beam peak direction of the BS according to the OTA REFSENS RoAoA for the appropriate beam identifier.
    a. Given previous data, the beam peak of DUT in question is set on 0-degree azimuth / 0-degree elevation.

6. Set the BS to transmit beam(s) of the same operational band as the OTA REFSENS RoAoA being tested according to the appropriate test configuration in clause 5.
7. Start the signal generator for the wanted signal to transmit.
    a. G-FR2-A1-3, ARB file
8. Set the test signal mean power so the calibrated radiated power at the BS Antenna Array coordinate system reference point is specified in subclause 7.3.5
    a. Table 9
9. Measure throughput for each supported polarization.
    a. Only for previously determined polarization "Vertical"
10. After measuring throughput for supported polarization, adjust the signal level with a step of -2 dB until sensitivity level reaches / goes over the given limit of EIS_REFSENS.
    a. After adjusting step, depending if the level is under / over, adjust the step size so +/-1 dB and measure throughput again. Finally reduce the step size to +/-0.5 dB to get the final result.
11. Repeat steps 3 to 10 for all OTA REFSENS conformance test directions of the BS (D.55), and supported polarizations.
    a. Previously determined conformance test directions, and only the earlier determined polarization "Vertical". [21]

For OTA reference sensitivity case, measure the sensitivity needed in the specified directions for OTA in-band blocking test case. Anything not related to those measurements are not the primary objective of this thesis.

4.3.3 OTA receiver in-band blocking

For OTA RX In-Band Blocking measurements, the 3GPP suggested method will be followed step by step, to ensure that the validation process is as close to the suggested one as possible.

1. Place the BS with its manufacturer declared coordinate system reference point in the same place as calibrated point in the test system.
2. Align the manufacturer declared coordinate system orientation of the BS with the test system.
3. Align the BS with the test antenna in the declared direction to be tested.
4. Align the NR BS to that the wanted signal and interferer signal is polarization matched with the test antenna(s).
    a. Previously determined polarization of "Vertical"
5. Set the test signal mean power so that the calibrated radiated power at the BS Antenna Array coordinate system reference point is as follows:
    a. Set the signal generator for the wanted signal to transmit as specified in Table 4 for BS type 2-O.
    b. Set the signal generator for the interfering signal at the specified frequency offset from the wanted signal to transmit as specified in Table 5 for BS type 2-O.
6. Measure throughput for each supported polarization, for multi-carrier and/or CA operation the throughput shall be measured for relevant carriers specified by the test configuration i.e. wanted signal.
7. After measuring throughput for supported polarization, verify whether measured wanted signal sensitivity aligns with the 3GPP specification limits.

   a. (Optional; After confirming that the wanted signal sensitivity is within the 3GPP specifications, adjust the interfering signal level in similar fashion to the sensitivity measurements.)

8. Repeat steps 3 to 7 for all the specified measurement directions. [21]

4.4 Test result analysis

The test analysis will be done with two separate tools; IQ-data analysis software and an excel sheet that has 3GPP specifications inserted in it. The analysis software used is VSE from Keysight Technologies, which uses custom IQ-modulation analysis to streamline the signal quality measurements. As the results are presented in the analysis software, the results are then combined in a performance excel which is based on the specifications based on 3GPP TS 38.141-2 document.

4.4.1 Common public radio interface

Common Public Radio Interface, also known as CPRI is a publicly available specification for the key internal interface of radio base stations between the Radio Equipment Control (REC) and the Radio Equipment (RE) [34]. It is an industry cooperative effort to allow base station manufacturers to share a common protocol to make it easier to adapt different platforms from one customer to another [34]. The basic principle of CIPRI is to focus on simplifying the radio base station architecture by dividing it to two separate parts; radio part and a control part. This is made possible by specifying a Digitalized Radio Base Station Internal Interface, as seen on Figure 21 [34].

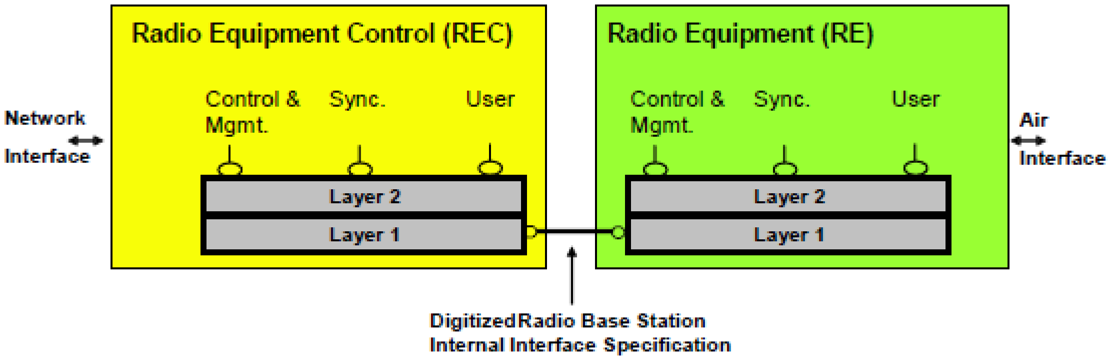


Figure 21. CPRI system and interface definition.

In Figure 21 there are two layers on REC and RE. These layers are defined by their protocols as seen on Figure 22 [34].

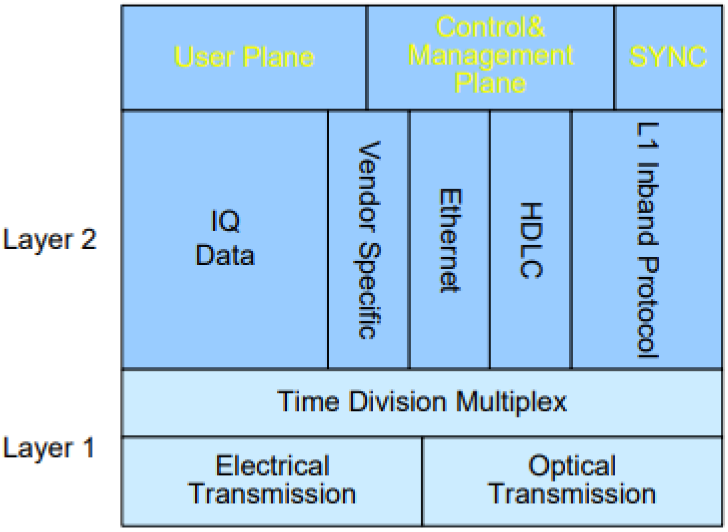


Figure 22. Defined layers of CPRI.

Layer 1 supports the electrical interface, which would be the one used in the traditional radio base stations, as well as an optical interface which is accustomed to remote radio equipment. Layer 2 supports the flexibility and scalability of the CPRI interface. Both layers operate on certain planes. The user plane information is presented in IQ-data, which is either transferred to from the radio base station to the mobile station or the other way around. Synchronization plane is for the data that which relays the timing and synchronization information between different nodes. Control & management plane is for controlling the flow of data usage in call processing, and management contains information of for the operation, administration and maintenance of the CPRI link and the nodes. [34]

4.4.1.1 IQ-data

IQ-data is the in-phase and quadrature modulated data, which is used to denote the complex format of RF data. Mathematically speaking, IQ data tells the amplitude and phase data of a sine wave translated from a polar coordinate system to a Cartesian (X, Y) coordinate system [35]. By expanding the sine wave formula of $A_c\cos(2\pi f_c t + \phi)$ where A_c is the amplitude f_c is the frequency and ϕ is the phase, the formula can be presented in IQ form of;

$$A_c\cos(2\pi f_c t + \phi) = Icos(2\pi f_c t) - Qsin(2\pi f_c t), \tag{10}$$

where I is used for the amplitude of the in-phase carrier and Q is for the amplitude of the quadrature-phase carrier [35]. This means that by controlling the amplitude of both I and Q signals, it can vary the values of frequency and phase as well. When modulating this kind of signal, it is important to remember that sine and cosine are separated by a 90-degree phase difference, which is seen on the I/Q modulator hardware in diagram on Figure 23 [35].

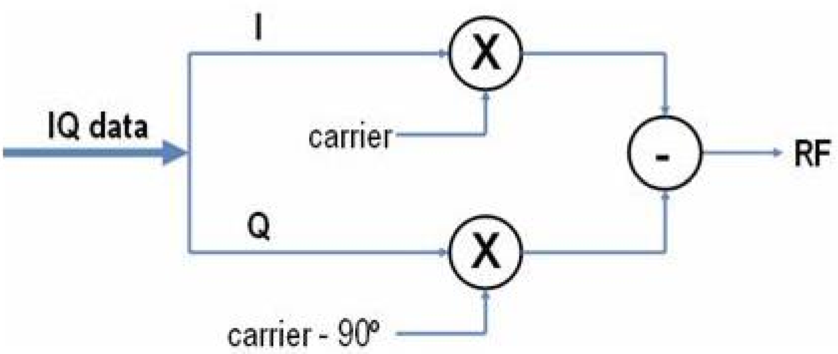


Figure 23. Hardware diagram of an I/Q modulator.

In this thesis, a baseband emulator is used to transfer IQ data through CPRI frames. A CPRI frame consists of 16 words, where the word size is dependent on the link rate, which is comparable to the total line bit rate. The basic frame structure is presented in Figure 24 [34].

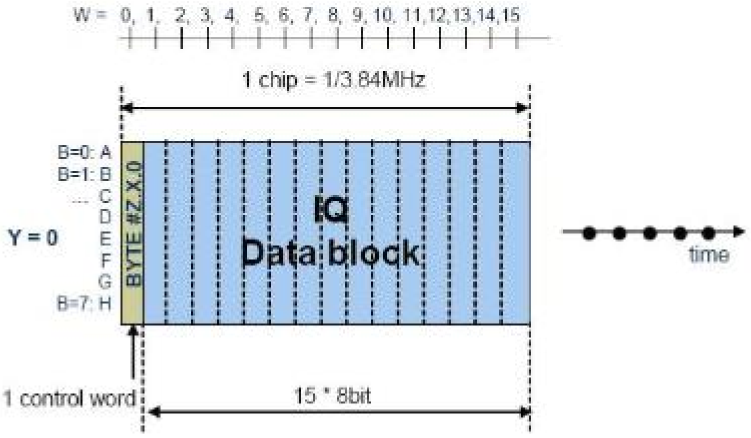


Figure 24. Basic frame structure for 614.4Mbps CPRI line rate.

In the basic frame, there are six different indexes for different parts; B is for bit index, W is the word index, Y is for the byte index within a word, X is for basic frame number, Z is for hyper frame number and Z.X.Y is the control words definition. These frames are then captured within the radio and sent to the custom IQ modulation analysis software.

Analysis is done by capturing wanted number of frames and then analysing the blocks inside the frame. The Block Error Rate (BLER) measurements is defined as the ratio of received blocks with errors, to the total number of received blocks. Here a block is a transport block, and it has an error when the cyclic redundancy check (CRC) of the block is incorrect. [36]. When the link quality decreases, the number of failed blocks increase as well.

5 TEST PROGRESS AND RESULTS

This section describes the final test process in depth and includes the progression of each step listed in this chapter. Measurement progression describes the overall process of how each measurement step took place, and what were the final measurement steps to complete each test. Sections from 5.2 to 5.5 are written in order of execution, and include the measurement results as well as the measurement steps and observations for each measurement.

5.1 Measurement progression

The measurements did not start until two days after the planned date (27.3.2019) and ended on 3.4.2019. There were some changes to the measurements due to software compatibility issues. First subject to change was the measurement block diagram. In the original block diagram, we are using X-step DRT8i baseband emulator, as well as the frame clock from the baseband emulator to synchronize the sent signal with the measurement software. However, due to the discontinuation of DUT support on the renewed software version, we were unable to measure directional measurements while using the baseband emulator. Because of that, the original analysis software 89600 VSA that was in use could not be used, due to Nokia 5G OTA measuring tool being integrated with the commands to use it with the baseband emulator. This was however fixed, with a workaround that made it possible to capture the IQ data from the DUT itself. By using hardcoded commands embedded in the DUT, as well as writing certain values to the register, we managed to capture the IQ data straight from DUT and analyse it using the newer Keysight VSE software. This drastically decreased the measurement time, as well as increase the amount of measurements made.

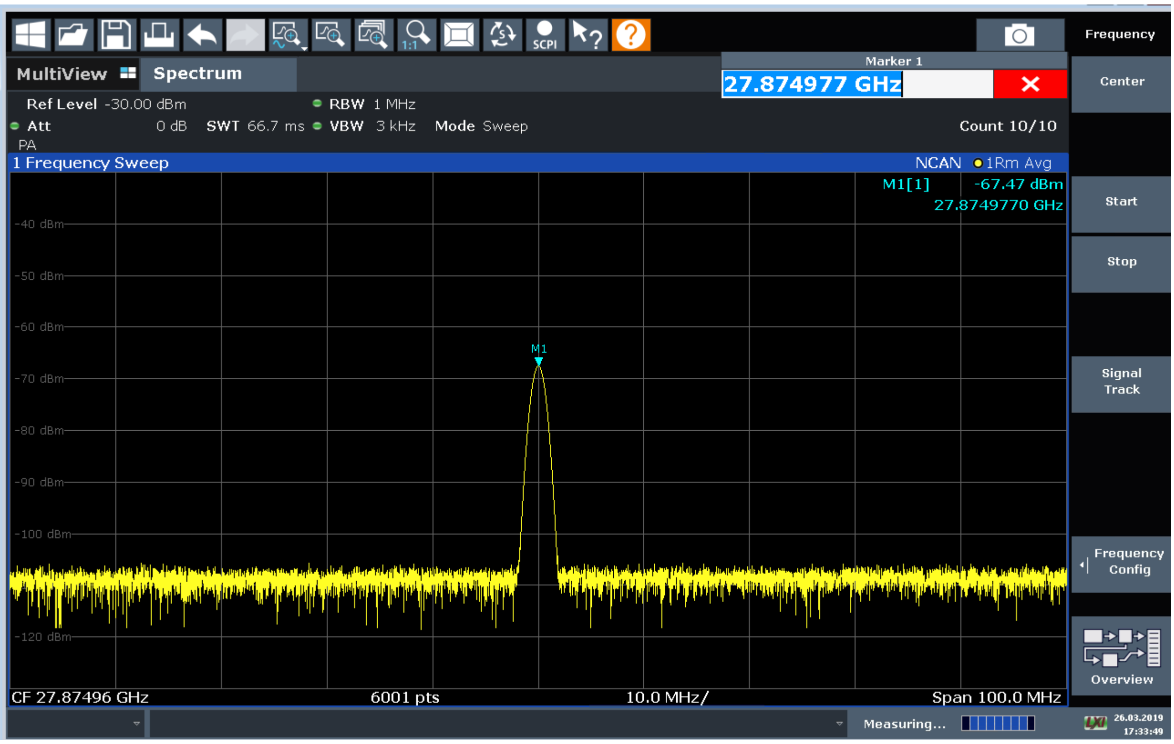
Other than problems with software, there were no exceptions to the planned measurements. Calibration took around two days to complete, and the actual measurements took around three days with the software problems included. The simplified measurement steps were as follows;

1. Setup DUT
    a. 48V / 10A from Delta power source
    b. Using python shell and code provided, run DUT setup command list with Frmon commands.
    c. Load the desired beamforming file from SSH connection and run beams for both RX and TX.
    d. Turn positioner in a way, that it faces directly to the reflector (i.e. 0deg Azimuth / 0deg Elevation) and set the desired beam from the register to 0 / 0.
        i. Repeat steps for all turns to ensure that each beam is facing the right direction after being set.
        ii. If TX is set on DUT, measure the maximum EIRP value for each turn, and find the equivalent -3dB turn (this will be needed in In-Band blocking case). Use downlink path on switches as well as FSW ACLR measurement settings.
2. Test RX BLER (Block Error Rate)
    a. Load slot 1 from VSE for the right window positioning for blocking / sensitivity measurements.
    b. Setup signal generator to send G-FR2-A1-3 signal with auto trigger for wanted signal. Use measured OTA PL value as level offset.

        i. For interference signal, setup 3GPP requirement-based interference signal with auto trigger, and with the required offset.
   c. Run test.py as Python shell and use rx_bler(x) command to measure inserted x number of frames for each test.
        i. Measurement and capture time can be adjusted inside the code. Depending on the number of frames measured and the capture time, it will increase the time needed for the measurements.
   d. The command ran on python shell will present you with information of each measured frame, and in the end give a detailed percentage of total failed blocks i.e. BLER.
   e. After measuring one point correctly, reference to "Setup DUT" part c and d. Load new beam and turn positioner to the right direction. Repeat RX BLER measurement.

5.2 Calibration

Calibration was done with two different horn antennas with wanted signal as well as the interference signal. For upper portion of the measurement frequency (31 GHz – 26.5 GHz), SGH 2650-40 horn antenna was used to determine the path loss value. For the lower portion of planned frequencies (25 GHz – 28 GHz), A-info LB-60670-1.85F horn antenna was used in the same sense as previous SGH. Calibration was done on all the previously determined centre frequency points of selected frequency channels i.e. 25024.98 MHz / 27874.96 MHz / 27999.96 MHz / 28124.96 MHz / 30975 MHz. The calibration method used was to measure the total path loss between the signal generator output to the RIB of the DUT as well as to the input of FSW. Using the link budget excel, these values were calculated in advance as a reference of how much there would be path loss. These values were listed for each frequency point with CW signal, as well as the modulated signal used for the actual measurement. As for the uncertainty limit, the 3GPP specified In-Band blocking uncertainty was used (+/-3.4 dB). For FSW the settings were pre-set with detector of RMS as well as an averaging factor of 10 for CW signal. For modulated signal, ACLR measurement settings were used with the previous additions for detector and averaging factor. These settings are presented in Figures 25 and 26.



Marker 1 27.874977 GHz

Ref Level -30.00 dBm RBW 1 MHz
Att 0 dB SWT 66.7 ms VBW 3 kHz Mode Sweep Count 10/10
PA

1 Frequency Sweep NCAN 1Rm Avg

M1[1] -67.47 dBm 27.8749770 GHz

CF 27.87496 GHz 6001 pts 10.0 MHz/ Span 100.0 MHz

Figure 25. Calibration with CW signal for interfering frequency for 27874.96 MHz.

Frequency Span 462.0 MHz

Ref Level -30.00 dBm RBW 1 MHz
Att 0 dB SWT 500 ms (~5.4 s) VBW 1 MHz Mode FFT
PA

1 ACLR NCAN 1Rm Clrw

M1[1] -112.10 dBm 27.8709600 GHz

CF 27.99996 GHz 10001 pts 46.2 MHz/ Span 462.0 MHz

2 Result Summary None

Channel	Bandwidth	Offset	Power	
Tx1 (Ref)	98.000 MHz		-76.82 dBm	
Tx Total			-76.82 dBm	
Channel	Bandwidth	Offset	Lower	Upper
Adj*	49.880 MHz	125.000 MHz	-95.90 dBm *	-62.10 dBm *

Figure 26. Calibration with modulated signal for middle channel and +75 IF channel.

The calibration results are presented in Tables 15 and 16.

Table 15. Calibration results for SGH 2650-40

Frequency (MHz)	27999.96	28124.96	27874.96	30975	27999.96	28124.96	27874.96	30975
SG Level (dBm)	6	6	6	6	6	0	0	0
Simulation result at FSW	-73.461	-58.97	-58.913	-60.341	-73.462	-65.051	-64.914	-66.341
Measured result (FSW)	-71.3	-58.2	-56.9	-58.15	-71.2	-62.25	-61.97	-63.32
Simulation result (RIB)	-88.281	-73.922	-73.748	-74.806	-88.281	-79.923	-79.749	-80.806
Measured result (RIB)	-86.119	-73.072	-71.734	-72.615	-86.019	-77.122	-76.805	-77.785
ΔSignal Level (RIB)	2.161652	0.850697	2.013628	2.191273	2.261652	2.800697	2.943628	3.021273
RIB offset	14.81955	14.87215	14.83492	14.46471	14.81955	14.87215	14.83492	14.46471
Modulation	CW	CW	CW	CW	QPSK	QPSK	QPSK	QPSK
Measured OTA Path loss	92.11955	79.07215	77.73492	78.61471	92.01955	77.12215	76.80492	77.78471

Table 16. Calibration results for A-info LB-60670-1.85F

Frequency (MHz)	27999.96	27874.96	25024.98	27999.96	27874.96	25024.98
SG Level (dBm)	6	6	6	6	0	0
Simulation result at FSW	-84.146	-69.528	-68.778	-84.146	-69.528	-68.778
Measured result (FSW)	-82	-67.45	-64.68	-82.32	-72.84	-70.64
Simulation result (RIB)	-88.156	-73.533	-72.557	-88.156	-73.533	-72.557
Measured result (RIB)	-86.01	-71.455	-68.46	-86.33	-76.845	-74.42
ΔSignal Level (RIB)	2.145714	2.078363	**4.096632**	1.825714	3.311637	1.863368
RIB offset	4.01	4.005	3.78	4.01	4.005	3.78
Modulation	CW	CW	CW	QPSK	QPSK	QPSK
Measured OTA Path loss	92.01	77.455	74.46	92.33	76.845	74.42

When comparing the simulation results to the measured results, an observation can be made that the average uncertainty between all frequencies is around ~2.4 dB, which is within the given limit. However, in 3GPP specifications it is perceived that the maximum / minimum system uncertainty is checked after every measurement. In this case, the chamber in use would not qualify for this kind of measurement. However, the maximum uncertainty was achieved by using CW signal, rather than the modulated signal used during the actual measurements. When both CW and QPSK signal level difference is averaged, the uncertainty drops to 2.98 dB which is within the specifications. Addition to this, the measured gain values of A-info LB-60670 do not seem to be as accurate as SGH 2650-40. With these observations, the current CATR in use would be sufficient to use in RX interference measurements.

Calibration setup from the previously shown block diagram only changed in such way, that the 10 MHz clock signal was deemed not necessary. This simplified the installing process of measurement equipment and save some time as well. The calibration setup is presented in Figures 27 and 28. In the actual calibration, the positioner is turned in a way that the SGH is facing the CATR reflector as seen on Figure 28.

Figure 27. Calibration installation setup of SGH 2650-40.

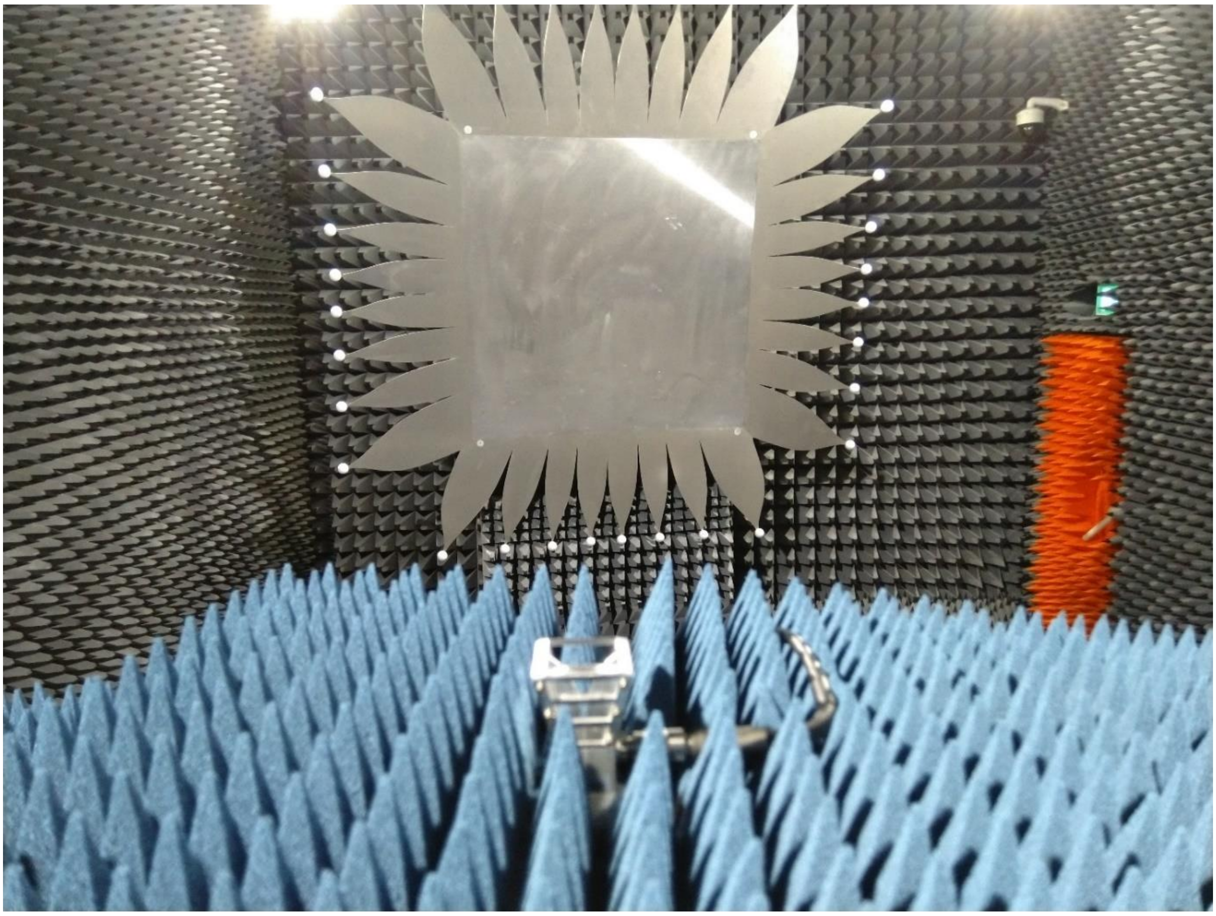


Figure 28. Calibration installation setup of A-info LB-60670-1.85F from antenna point of view.

5.3 Sensitivity in OTA environment

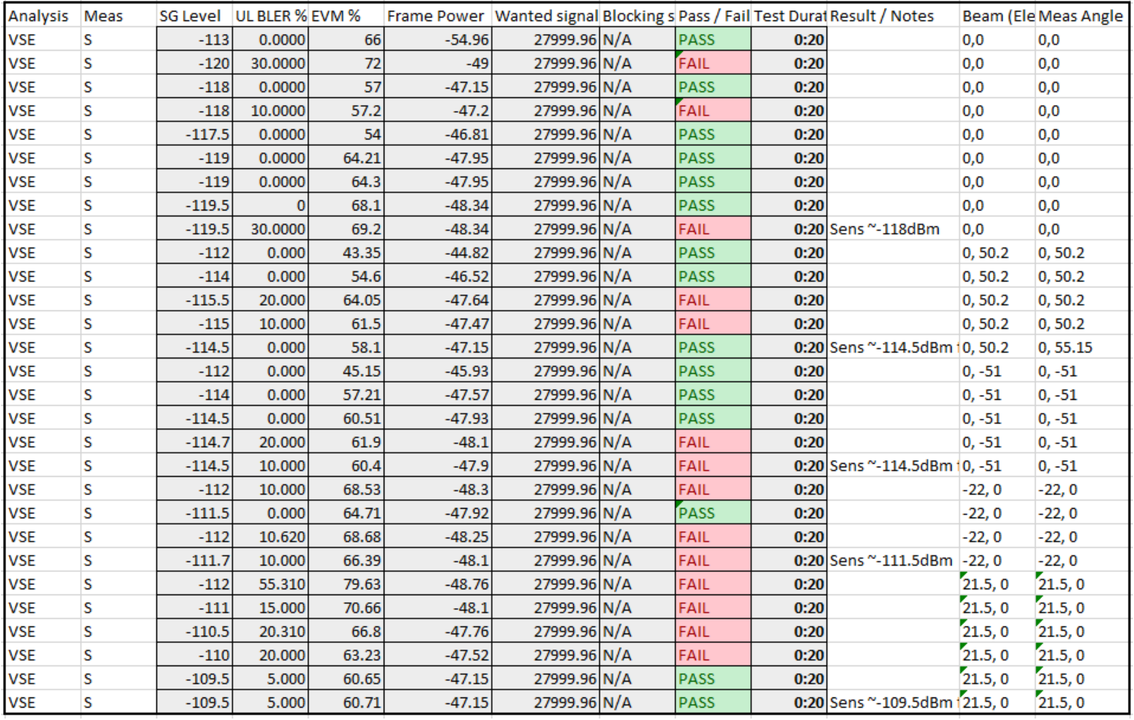
For sensitivity measurements, it is required to have the 3GPP specified OTA REFSENS conformance directions, in which the 3GPP RoAoA will be applied with in-band blocking test case. In the original plan, it was supposed to use the angles given by the manufacturer. But during the testing phase, it was discovered that the angles fed to the radio did not fully correspond to the wanted direction. To ensure that the angles used were in fact within the 3GPP specified conformance directions, as well as 3GPP RoAoA, these angles were measured again with downlink side. The fed angles were the ones that were originally planned, and the corrections were made after manually searching the maximum of the angle, as well as the 3-dB point for RoAoA. These findings are presented in Table 17.

Table 17. Measured conformance direction angles for reference sensitivity and in-band blocking

Azimuth / Elevation	Original beam (deg)	Measured maximum (deg)	Measured value (dBm)	Measured 3dB angle (deg)	Measured -3dB value (dBm)
Elevation	20	22	45.6	23.2	42.4
Elevation	-19.5	-21.5	46.44	-23.26	43.4
Azimuth	54	51	49.9	56.5	46.88
Azimuth	-53.75	-50.2	50.26	-55.15	47.2

After measuring the conformance directions over downlink side, the switches are positioned to uplink position to prepare for sensitivity measurements. The measurement procedure that was planned beforehand was followed as originally planned. Measurement results are presented in Table 18.

Table 18. Sensitivity measurement results for selected Nokia DUT



Analysis	Meas	SG Level	UL BLER %	EVM %	Frame Power	Wanted signal	Blocking s	Pass / Fail	Test Durat	Result / Notes	Beam (Ele	Meas Angle
VSE	S	-113	0.0000	66	-54.96	27999.96	N/A	PASS	0:20		0,0	0,0
VSE	S	-120	30.0000	72	-49	27999.96	N/A	FAIL	0:20		0,0	0,0
VSE	S	-118	0.0000	57	-47.15	27999.96	N/A	PASS	0:20		0,0	0,0
VSE	S	-118	10.0000	57.2	-47.2	27999.96	N/A	FAIL	0:20		0,0	0,0
VSE	S	-117.5	0.0000	54	-46.81	27999.96	N/A	PASS	0:20		0,0	0,0
VSE	S	-119	0.0000	64.21	-47.95	27999.96	N/A	PASS	0:20		0,0	0,0
VSE	S	-119	0.0000	64.3	-47.95	27999.96	N/A	PASS	0:20		0,0	0,0
VSE	S	-119.5	0	68.1	-48.34	27999.96	N/A	PASS	0:20		0,0	0,0
VSE	S	-119.5	30.0000	69.2	-48.34	27999.96	N/A	FAIL	0:20	Sens ~-118dBm	0,0	0,0
VSE	S	-112	0.000	43.35	-44.82	27999.96	N/A	PASS	0:20		0, 50.2	0, 50.2
VSE	S	-114	0.000	54.6	-46.52	27999.96	N/A	PASS	0:20		0, 50.2	0, 50.2
VSE	S	-115.5	20.000	64.05	-47.64	27999.96	N/A	FAIL	0:20		0, 50.2	0, 50.2
VSE	S	-115	10.000	61.5	-47.47	27999.96	N/A	FAIL	0:20		0, 50.2	0, 50.2
VSE	S	-114.5	0.000	58.1	-47.15	27999.96	N/A	PASS	0:20	Sens ~-114.5dBm	0, 50.2	0, 55.15
VSE	S	-112	0.000	45.15	-45.93	27999.96	N/A	PASS	0:20		0, -51	0, -51
VSE	S	-114	0.000	57.21	-47.57	27999.96	N/A	PASS	0:20		0, -51	0, -51
VSE	S	-114.5	0.000	60.51	-47.93	27999.96	N/A	PASS	0:20		0, -51	0, -51
VSE	S	-114.7	20.000	61.9	-48.1	27999.96	N/A	FAIL	0:20		0, -51	0, -51
VSE	S	-114.5	10.000	60.4	-47.9	27999.96	N/A	FAIL	0:20	Sens ~-114.5dBm	0, -51	0, -51
VSE	S	-112	10.000	68.53	-48.3	27999.96	N/A	FAIL	0:20		-22, 0	-22, 0
VSE	S	-111.5	0.000	64.71	-47.92	27999.96	N/A	PASS	0:20		-22, 0	-22, 0
VSE	S	-112	10.620	68.68	-48.25	27999.96	N/A	FAIL	0:20		-22, 0	-22, 0
VSE	S	-111.7	10.000	66.39	-48.1	27999.96	N/A	FAIL	0:20	Sens ~-111.5dBm	-22, 0	-22, 0
VSE	S	-112	55.310	79.63	-48.76	27999.96	N/A	FAIL	0:20		21.5, 0	21.5, 0
VSE	S	-111	15.000	70.66	-48.1	27999.96	N/A	FAIL	0:20		21.5, 0	21.5, 0
VSE	S	-110.5	20.310	66.8	-47.76	27999.96	N/A	FAIL	0:20		21.5, 0	21.5, 0
VSE	S	-110	20.000	63.23	-47.52	27999.96	N/A	FAIL	0:20		21.5, 0	21.5, 0
VSE	S	-109.5	5.000	60.65	-47.15	27999.96	N/A	PASS	0:20		21.5, 0	21.5, 0
VSE	S	-109.5	5.000	60.71	-47.15	27999.96	N/A	PASS	0:20	Sens ~-109.5dBm	21.5, 0	21.5, 0

Based on previous information provided by manufacturer information, the required sensitivity for DUT with 100 MHz carrier is -107 dBm. With this information, the starting point of signal level was set to -113 dBm. During the sensitivity measurement in boresight, the measurement step was set with a rough estimate at first. After the first failing result was found, the step was reduced to 2 dB, and after that the step was reduced all the way to 0.5 dB. Reference sensitivity was measured for each designated conformance direction, as seen on Table 18.

Channel throughput was measured with BLER (Block Error Rate). The pass and fail criteria were based on BLER value provided by the vector signal analysis software VSE. Other values that were used to determine the desired step were EVM (Error Vector Magnitude) and frame power, as seen in Figure 29.

Ref Level 0.00 dBm **Freq** 0.0 Hz **Mode** Uplink, 100 MHz **Capture Time** 20.0 ms **BWP** All **SGL**
Frame Count 1 of 1(1) **Frame** 1
Inp: File

Frame Results Selected	Mean	Limit	Max	Min
EVM PUSCH QPSK (%)	26.32	17.50		
EVM PUSCH 16QAM (%)		12.50		
EVM PUSCH 64QAM (%)		8.00		
EVM PUSCH 256QAM (%)				
EVM DMRS PUSCH QPSK (%)	17.73	17.50		
EVM DMRS PUSCH 16QAM (%)		12.50		
EVM DMRS PUSCH 64QAM (%)		8.00		
EVM DMRS PUSCH 256QAM (%)				
EVM PUCCH (%)		17.50		
EVM DMRS PUCCH (%)				
EVM All (%)	25.77			
EVM Phys Channel (%)	26.33			
EVM Phys Signal (%)	17.77			
Frequency Error (Hz)	-8.04			
Power (dBm)	-48.52			

BWP/Sf/Slot	Allocation ID	Code-word	Mod	# Bits	Bitstream [Compact]
0 / 1 / 8	PUSCH 0	1/1	QPSK	5632	00100100100101000100011110011111000011001101010 ... #Bits 19008 #Bit Errors 10
0 / 1 / 9	PUSCH 0	1/1	QPSK	5632	001011110101000111011110010101110011010100001000 ... #Bits 19008 #Bit Errors 4
0 / 2 / 18	PUSCH 0	1/1	QPSK	5632	001010001000100001110011101110110000010111100100 ... #Bits 19008 #Bit Errors 6
0 / 2 / 19	PUSCH 0	1/1	QPSK	5632	101010011010010110000100010110101000000111111100 ... #Bits 19008 #Bit Errors 8
0 / 3 / 28	PUSCH 0	1/1	QPSK	5632	011000010111001110010001000110101101110001100110 ... #Bits 19008 #Bit Errors 3

Figure 29. Keysight VSE data window with wanted signal level -105 dBm at boresight, from which all the parameters are exported.

Each measurement was done with 20 frames, with each frame containing 16 blocks. The 3GPP specification for passing and failing is described in the technical specifications. The limit described is ≥ 95% of the maximum throughput of the reference measurement channel, when the test signal is set to the correct $\mathrm{EIS}_{\mathrm{REFSENS}}$ level. In other words, the measured BLER shall be ≤ 5% in order to pass. These limits apply to all conformance test directions within the OTA REFSENS RoAoA [21]. Based on this criterion, the measurement would be marked as a fail if 17 or more blocks would be deemed as errors. The measurement setup is presented in Figure 30 and Figure 31.

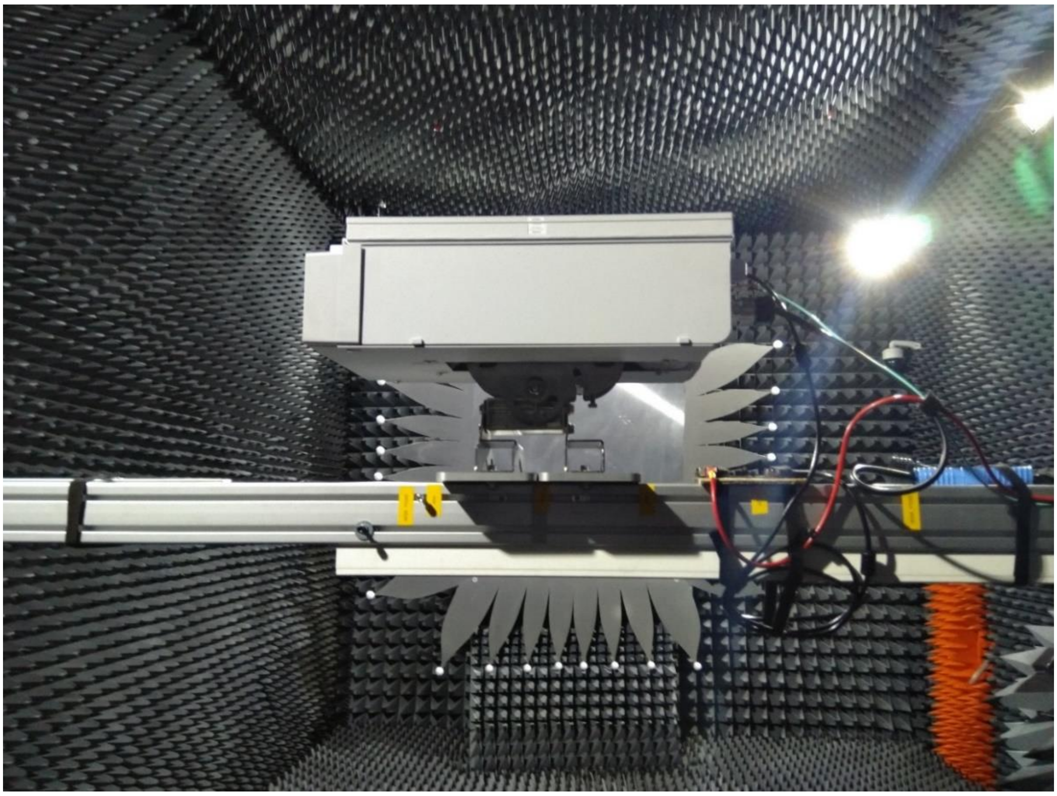


Figure 30. Positioned DUT after installation.

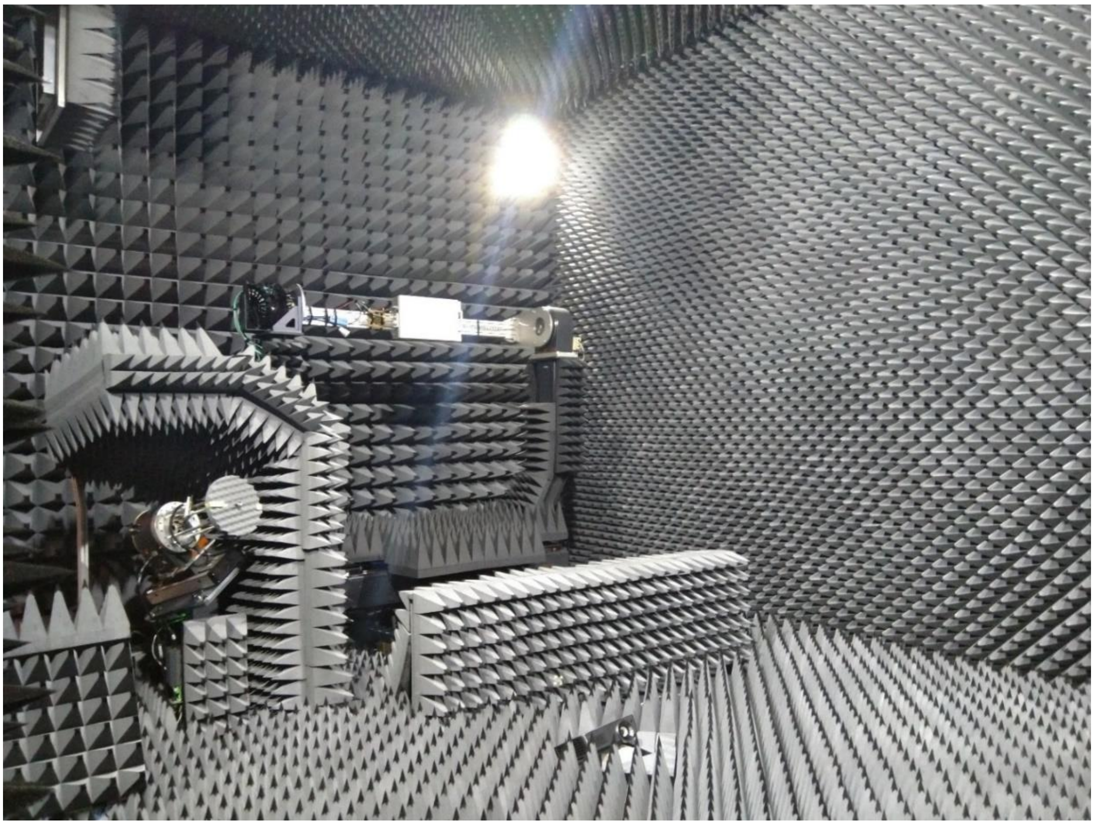
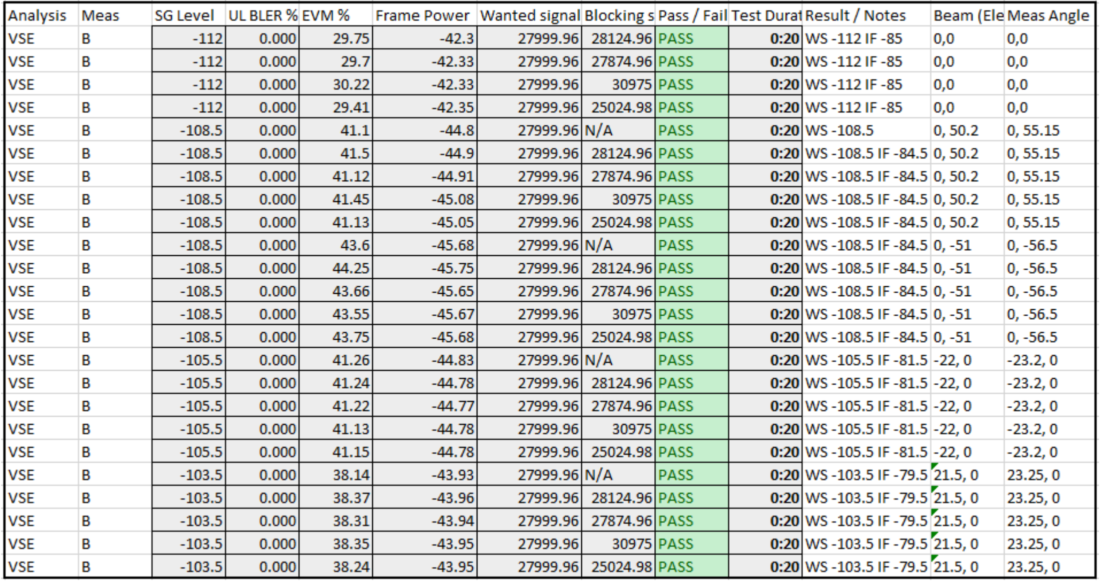


Figure 31. DUT position during boresight measurements.

5.4 In-band blocking

Similar to sensitivity measurements, in-band blocking measurements were done in a similar fashion. Measurement order for each direction was the following; Measure the sensitivity of the maximum azimuth / elevation angle of the DUT, and after that turn the positioner to the measured -3 dBm angle that was previously determined. For this angle, measure the blocking test case for each specified blocking signal channel. Each measurement was done over 20 frames as the sensitivity measurements, so the criteria for failure is the same as before. The test results are presented in Table 19. In this table, the parameters that should be focused on are UL BLER (Uplink Block Error Rate), which tells the amount of failed block as a percentage over the course of measured frames. EVM gives the tester an idea of how high can the EVM value get before the BLER test fails. In this case, the threshold would be around 64%. Frame power tells the total power over the received frame. Wanted signal and blocking signal are set for the indicated frequencies that each signal is using. In result / notes column, WS and IF values are for the wanted – and interfering signal level values. Beam column is for the selected beam direction in which the order is (elevation, azimuth), and measurement angle is the corresponding angle that is used for measuring the set beam.

Table 19. In-band blocking tests for operating DUT



Analysis	Meas	SG Level	UL BLER %	EVM %	Frame Power	Wanted signal	Blocking s	Pass / Fail	Test Durat	Result / Notes	Beam (Ele	Meas Angle
VSE	B	-112	0.000	29.75	-42.3	27999.96	28124.96	PASS	**0:20**	WS -112 IF -85	0,0	0,0
VSE	B	-112	0.000	29.7	-42.33	27999.96	27874.96	PASS	**0:20**	WS -112 IF -85	0,0	0,0
VSE	B	-112	0.000	30.22	-42.33	27999.96	30975	PASS	**0:20**	WS -112 IF -85	0,0	0,0
VSE	B	-112	0.000	29.41	-42.35	27999.96	25024.98	PASS	**0:20**	WS -112 IF -85	0,0	0,0
VSE	B	-108.5	0.000	41.1	-44.8	27999.96	N/A	PASS	**0:20**	WS -108.5	0, 50.2	0, 55.15
VSE	B	-108.5	0.000	41.5	-44.9	27999.96	28124.96	PASS	**0:20**	WS -108.5 IF -84.5	0, 50.2	0, 55.15
VSE	B	-108.5	0.000	41.12	-44.91	27999.96	27874.96	PASS	**0:20**	WS -108.5 IF -84.5	0, 50.2	0, 55.15
VSE	B	-108.5	0.000	41.45	-45.08	27999.96	30975	PASS	**0:20**	WS -108.5 IF -84.5	0, 50.2	0, 55.15
VSE	B	-108.5	0.000	41.13	-45.05	27999.96	25024.98	PASS	**0:20**	WS -108.5 IF -84.5	0, 50.2	0, 55.15
VSE	B	-108.5	0.000	43.6	-45.68	27999.96	N/A	PASS	**0:20**	WS -108.5 IF -84.5	0, -51	0, -56.5
VSE	B	-108.5	0.000	44.25	-45.75	27999.96	28124.96	PASS	**0:20**	WS -108.5 IF -84.5	0, -51	0, -56.5
VSE	B	-108.5	0.000	43.66	-45.65	27999.96	27874.96	PASS	**0:20**	WS -108.5 IF -84.5	0, -51	0, -56.5
VSE	B	-108.5	0.000	43.55	-45.67	27999.96	30975	PASS	**0:20**	WS -108.5 IF -84.5	0, -51	0, -56.5
VSE	B	-108.5	0.000	43.75	-45.68	27999.96	25024.98	PASS	**0:20**	WS -108.5 IF -84.5	0, -51	0, -56.5
VSE	B	-105.5	0.000	41.26	-44.83	27999.96	N/A	PASS	**0:20**	WS -105.5 IF -81.5	-22, 0	-23.2, 0
VSE	B	-105.5	0.000	41.24	-44.78	27999.96	28124.96	PASS	**0:20**	WS -105.5 IF -81.5	-22, 0	-23.2, 0
VSE	B	-105.5	0.000	41.22	-44.77	27999.96	27874.96	PASS	**0:20**	WS -105.5 IF -81.5	-22, 0	-23.2, 0
VSE	B	-105.5	0.000	41.13	-44.78	27999.96	30975	PASS	**0:20**	WS -105.5 IF -81.5	-22, 0	-23.2, 0
VSE	B	-105.5	0.000	41.15	-44.78	27999.96	25024.98	PASS	**0:20**	WS -105.5 IF -81.5	-22, 0	-23.2, 0
VSE	B	-103.5	0.000	38.14	-43.93	27999.96	N/A	PASS	**0:20**	WS -103.5 IF -79.5	21.5, 0	23.25, 0
VSE	B	-103.5	0.000	38.37	-43.96	27999.96	28124.96	PASS	**0:20**	WS -103.5 IF -79.5	21.5, 0	23.25, 0
VSE	B	-103.5	0.000	38.31	-43.94	27999.96	27874.96	PASS	**0:20**	WS -103.5 IF -79.5	21.5, 0	23.25, 0
VSE	B	-103.5	0.000	38.35	-43.95	27999.96	30975	PASS	**0:20**	WS -103.5 IF -79.5	21.5, 0	23.25, 0
VSE	B	-103.5	0.000	38.24	-43.95	27999.96	25024.98	PASS	**0:20**	WS -103.5 IF -79.5	21.5, 0	23.25, 0

The 3GPP specifications mentions the following criteria for the wanted signal and the interfering signal [21];

$$OTA\ WANTED\ SIGNAL_{Mean\ Power} = EIS_{REFSENS} + 6\text{ dBm}, \tag{11}$$

$$OTA\ INTERFERING\ SIGNAL_{Mean\ Power} = EIS_{REFSENS\_50M} + 33 + \Delta_{FR2\_REFSENS}. \tag{12}$$

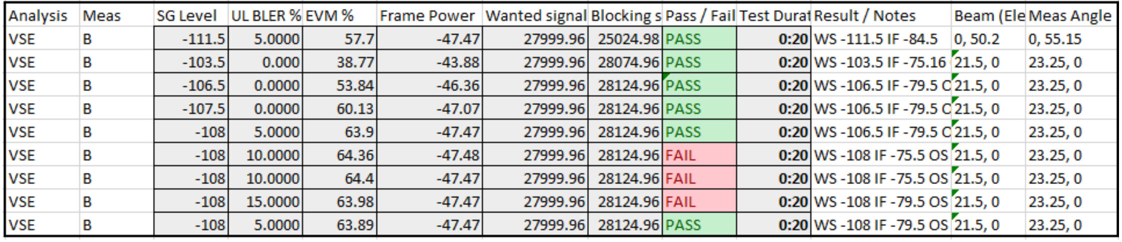
$EIS_{REFSENS}$ is specified by 3GPP as the minimum mean power received at the RIB for the specified reference measurement channel [21]. Therefore, we are using the measured sensitivity as $EIS_{REFSENS}$. As for interfering signal, $EIS_{REFSENS\_50M}$ is used. This was specified earlier in section 4.2.1. Since the reference measurement is done with the 50 MHz signal, the measured reference sensitivity will be used as $EIS_{REFSENS\_50M}$.

As for $\Delta_{FR2\_REFSENS}$, the presumption was that for reference direction the value would amount to 0 dBm and for each 3-dB angle, the compensation would be made on the interfering signal with -3 dBm. This would mean that for every conformance direction RoAoA angle, OTA interfering signal mean power would amount to +30 dBm. This assumption was used during these tests, however after further research this would not seem to affect the result (Further info in subclause 5.5).

5.5 Additional measurements

During in-band blocking measurements, a question was raised about the effect of wanted signal vs. interferer signal level in blocking measurement. With the limited time left for the measurements, the goal was to compare the effect of wanted signal – and interferer signal level to the BLER value. With a small sample size, there were 9 measurements made. The results are presented in Table 20.

Table 20. Additional measurements made for research purposes with AEUF-A101



Analysis	Meas	SG Level	UL BLER %	EVM %	Frame Power	Wanted signal	Blocking s	Pass / Fail	Test Durat	Result / Notes	Beam (Ele	Meas Angle
VSE	B	-111.5	5.0000	57.7	-47.47	27999.96	25024.98	PASS	**0:20**	WS -111.5 IF -84.5	0, 50.2	0, 55.15
VSE	B	-103.5	0.000	38.77	-43.88	27999.96	28074.96	PASS	**0:20**	WS -103.5 IF -75.16	21.5, 0	23.25, 0
VSE	B	-106.5	0.0000	53.84	-46.36	27999.96	28124.96	PASS	**0:20**	WS -106.5 IF -79.5 C	21.5, 0	23.25, 0
VSE	B	-107.5	0.0000	60.13	-47.07	27999.96	28124.96	PASS	**0:20**	WS -106.5 IF -79.5 C	21.5, 0	23.25, 0
VSE	B	-108	5.0000	63.9	-47.47	27999.96	28124.96	PASS	**0:20**	WS -106.5 IF -79.5 C	21.5, 0	23.25, 0
VSE	B	-108	10.0000	64.36	-47.48	27999.96	28124.96	FAIL	**0:20**	WS -108 IF -75.5 OS	21.5, 0	23.25, 0
VSE	B	-108	10.0000	64.4	-47.47	27999.96	28124.96	FAIL	**0:20**	WS -108 IF -75.5 OS	21.5, 0	23.25, 0
VSE	B	-108	15.0000	63.98	-47.47	27999.96	28124.96	FAIL	**0:20**	WS -108 IF -79.5 OS	21.5, 0	23.25, 0
VSE	B	-108	5.0000	63.89	-47.47	27999.96	28124.96	PASS	**0:20**	WS -108 IF -79.5 OS	21.5, 0	23.25, 0

As seen on the table, in the first measurement the wanted signal level was decreased by -3 dBm (in the official measurement signal level was -108.5 dBm) and the interfering signal level stayed the same. With this change, there is a noticeable increase in EVM, and it can be seen as the BLER value reached the limit of 5%. As for interfering signal level, the effect did not seem to be as volatile as it was with wanted signal. During the last four measurements, the interfering signal was on the maximum level that the signal generator was able to send. The wanted signal was set to a point, where on average the result would end up being a failure (i.e. more than 5% BLER). After that, the signal was dropped by -4 dB to see the effect. The only difference between that -4-dB shift is seen on EVM value, where it shifted from ~64.4% to ~63.9%. Based on the previous measurements made, the average failing measurement had around ~66.44% EVM, when the passing measurement was around ~58.57%. So, the 0.5% shift seen on EVM after interfering signal was dropped, does not seem to have a drastic effect to the official measurements, where EVM is around 40%. This kind of shift might not even be because of interfering signal, but the measured DUT operating time and temperature deviation over the course of the measurements.

6 DISCUSSION

The measurement setup can be reused for multiple RX-interference tests. These test cases include In-channel selectivity, Adjacent-channel selectivity, OTA reference sensitivity and OTA Dynamic Range. Depending on the test case, it the specifications or signal level and frequency offset are changed from both sources. Other than that, the setup remains similar.

The planned time window for these measurements were based on previous measurements as well as assumptions of how much it would optimally take. This however changed due time, since there were multiple problems with software integrations as well as hardware discontinuation problems. Two major pieces were switched, X-step baseband simulator was only there to establish connection to the DUT and the original vector signal analysis tool VSA was changed to the variant of VSE. After all the previously mentioned changes were made, and the measurement process was pinpointed to the one in use, the tests themselves did not last as long as originally planned. Compared to the 5 minutes and 30 seconds it took to measure with the baseband emulator to the 20 seconds that It took with directly capturing the IQ data from the radio, the amount of time saved for these measurements were enormous. With baseband emulator the measurement over one block took 5 minutes 30 seconds. Since all of the VSE measurements were made over 20 blocks, that would mean the total amount of time used for one measurement with VSA would take 110 minutes. In total there were 87 measurements made to complete the necessary measurements, so the total time would be 9570 minutes, or 159 hours and 30 minutes. Compared to the radio capture, over 20 blocks the test took around 20 seconds. This would amount to total of 29 minutes.

In most receiver interferer tests, the common interfering signal is specified as “50 MHz DFT-s-OFDM NR60 kHz SCS” signal [21]. As a NR signal can be either TDD or continuous, it is important to pay attention of the way that the test equipment is setup. If a TDD interferer signal is used, it is required to synchronize the wanted- and the interfering signal. While further receiver interferer tests were being done, it was noticed that in cases where interferer signal was a TDD signal, it had to be synced with the wanted signal via a frame clock input. While test signals were triggered with the internal clock signal of the signal generators, there were times when the interferer signal and the wanted signal did not synchronize and it would result to a failing measurement. When the signal generators are not synchronized, it is possible that the transmission from one input may overlap with any other frame, it being either the receiving radio capture frame or one of the transmitted signals from the generators. In the analysis software, this would be seen as an excessive signal burst in the capture buffer time frame. If there were multiple excessive signal bursts within the captured frame, it is possible that the frame capture could be skewed in a way that causes the capture start point to shift. This adds to the uncertainty of the interferer measurements, since the synchronization is not specified in any 3GPP document. The case may also be, that the intended way for interferer signal to work is to send it out of sync since the method is not specified. If that is the case, then the frame capture timing adds more to the uncertainty of the measurement. This Tx/Rx timing has been noted as a key test challenge on previous research papers, but there has not been a universal solution to solve this challenge. [8]

The test cases that can’t be done with the same setup include receiver out-of-band blocking as well as OTA receiver intermodulation. For intermodulation case, the only difference would be an additional signal generator and hybrid coupler that would be required. Depending on the signal level required for the test case, it might require an additional amplifier if the dynamic range of the signal generators don’t fill the requirements. For out-of-band blocking additional filtering is required to ensure, that the actual interfering signal is filtered out and the intermodulation products are the only ones left to be transmitted. With the additional filtering, it also means that there will be additional attenuation caused by the input loss of filtering. In this case the additional amplifier could be needed, if the losses of the measurement system were similar to the one in this thesis. In Figure 32. is presented a concept of how the additional filtering block diagram for out-of-band blocking test would be made.

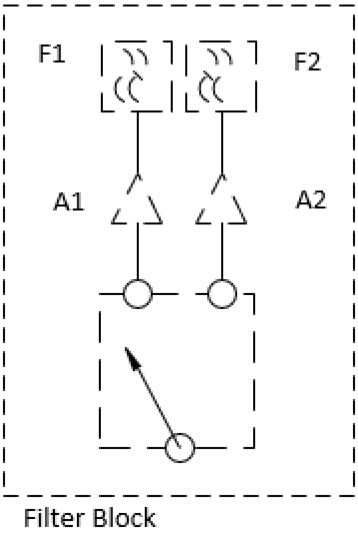


Figure 32. The concept for additional block for interfering signal in out-of-band blocking test case.

There are several variable factors in verification as well as uncertainty in these measurements. The verification process was done by calibrating the wanted signal band by hand, in which the measured SGH gain values were compared to the ones measured with the RX test setup. This way the values that the manufacturer of SGH has provided are supposedly 100% accurate and trustworthy. However, it is not completely sure if the values provided reflect the performance of the radio in different chambers. This is paired up with calculating the link budget with an excel file, in which the attenuation values of each frequency are inputted by hand. This makes human error a major uncertainty in this method. By completely removing the need to input attenuation values by hand, it would remove the uncertainty of human error as well as the need to calculate the link budget every time. This can be achieved by having an option in the signal generators for using S-parameter files to adjust the offset according to the S-parameter files inserted to the generator. This would only add additional measurement step for the signal generator side, in which each component would be measured for its S-parameter value.

The uncertainty of OTA system can be caused by poor calibration, human error or hardware faults. Most common uncertainty is the varying attenuation value that has to be taken into account in every measurement. In addition to this, previously mentioned synchronization may also cause some uncertainty in some measurement cases. Since the synchronization is not specified in 3GPP documents, some testers may interpret the need for synchronization in a different way. The simple solution for this is to specify the need for synchronization for each measurement in the technical specification documents of 3GPP.

7 SUMMARY

In this thesis, a measurement setup for RX OTA testing is presented, designed and analysed. The 3GPP specified measurement method seems to work as it was planned. However, according to the measurements made it is highly unlikely that a DUT would fail an in-band blocking test with the specifications made by the 3GPP. The effect of interfering signal in OTA environment has minimal impact on the wanted signal quality. With the amount of frequency channels tested, it is possible that the worst-case scenario was not found within the determined frequency channels. With that in mind, it is also possible that the DUT in use was a great quality product. If that is the case, then it would be beneficial to test a product, which has worse RX side qualities. This way the effect of interfering signal can be confirmed, which would solidify the specifications set by the 3GPP.

There was one minor detail to highlight regarding the measurements. Even though the measurements were a success, they were almost limited by the dynamics of the measurements setting. When comparing the signal generator level of Tables 18 and 19, the difference between the maximum output of both tables are only 4 dB apart. This means, if the reference sensitivity measured from DUT would have been more than 4 dB worse, the measurements would not have been successful. This can be improved by optimizing the total path loss caused by components and cables.

The planned measurements were successfully completed within the limits calculated based on the 3GPP technical document specifications. Hence, this setup can be used for mmWave RX in-band blocking measurements. The proposed testing method works, and with minor adjustments it can be used for most of mmWave receiver tests. With out-of-band blocking, it can be difficult to integrate this exact setup due to the extra loss caused by the filter block. This can be improved with a LNA that fits the required specifications of the desired measurement setup. In the future, it would be beneficial to specify the need for synchronization for each measurement to reduce the uncertainty that it might cause.

8 REFERENCES

[1] 3GPP. About 3rd Generation Partnership Project (read January 2019). URL: http://www.3gpp.org/about-3gpp

[2] S. Han, C. I, Z. Xu & C. Rowell. (2015) Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G. IEEE Communications Magazine, vol. 53, no. 1, pp. 186-194.

[3] M. Agiwal, A. Roy & N. Saxena. (2016) Next Generation 5G Wireless Networks: A Comprehensive Survey. IEEE Communications Surveys & Tutorials, vol. 18, no. 3, pp. 1617-1655.

[4] 3GPP. Long Term Evolution (read January 2019). URL: https://www.3gpp.org/technologies/keywords-acronyms/98-lte

[5] Gino Masini (2018) NR Architecture RWS-180009. In: Workshop on 3GPP Submission Towards IMT-2020, October 24-25, Brussels, Belgium.

[6] WU Yong (2018) Self evaluation: Enhanced Mobile Broadband (eMBB) Evaluation results RWS-180018. In: Workshop op 3GPP submission towards IMT-2020, October 24-25, Brussels, Belgium.

[7] Michael Wang (read April 2019) 5G, When Will We See It?. URL: https://medium.com/@miccowang/5g-when-will-we-see-it-7c436a4ad86c

[8] Gr. Y. Mihaylov, T. B. Iliev, T. D. Bikov, E. P. Ivanova, I. S. Stoyanov, V.P. Keseev & A.R.Dinov (2018) Test cases and challenges for mobile network evolution from LTE to 5G. 2018 41st International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, pp. 0449-0452.

[9] Mansoor Shafi, Andreas F. Molisch, Peter J. Smith, Thomas Haustein, Peiying Zhu, Prasan De Silva, Fredrik Tufvesson, Anass Benjebbour & Gerhard Wunder (2017) 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice. IEEE Journal on Selected Areas in Communications, vol. 35, no. 6, p. 1201-1221

[10] 3rd Generation Partnership Project (2018) Technical Specification Group Radio Access Network; Study on channel model for frequency spectrum above 6 GHz (Release 15). 3GPP TR 38.900, 85 pp.

[11] Matti Passoja (read April 2019) 5G NR: Massive MIMO and Beamforming – What does it mean and how can I measure it in the field?. URL: https://www.rcrwireless.com/20180912/5g/5g-nr-massive-mimo-and-beamforming-what-does-it-mean-and-how-can-i-measure-it-in-the-field

[12] Kamil Bechta & Christophe Grangeat (2017) RF exposure impact on 5G rollout, A technical overview. ITU Workshop on "5G, EMF & Health" December 5th, Warsaw, Poland, 12 p.

[13] D. Choudhury (2015) 5G wireless and millimeter wave technology evolution: An overview, IEEE MTT-S International Microwave Symposium, Phoenix, AZ, 2015, pp. 1-4.

[14] Renato Lombardi (2018) Microwave and Millimetre wave for 5G Transport. ETSI White Paper No. 25. 16 p.

[15] Huang, Kao-Cheng; Zhaocheng Wang (2011). Millimeter Wave Communication Systems. John Wiley & Sons. pp. Sections 1.1.1–1.2

[16] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta and P. Popovski (2014) Five disruptive technology directions for 5G. IEEE Communications Magazine, vol. 52, no. 2, pp. 74-80.

[17] Foegelle, Michael. (2002). Antenna Pattern Measurement: Concepts and Techniques. Compliance Engineering.

[18] Hirokazu Kobayashi, Yoshio Yamaguchi & Yi Cui (2012) Simple Near-field to Far-field Transformation Method Using Antenna Array-factor, Journal of Wireless Networking and Communications 2012, 2(4): 43-48

[19] S. Costanzo & G. Di Massa (2007) Near-field to Far-field Transformation With Planar Spiral Scanning, Progress In Electromagnetics Research, PIER 73, 49–59, 2007

[20] 3rd Generation Partnership Project (2019) Technical Specification Group Radio Access Network; NR Study on test methods (Release 16). 3GPP TR 38.810 V16.3.0, 168 p.

[21] 3rd Generation Partnership Project (2019) Technical Specification Group Radio Access Network; NR; Base Station (BS) conformance testing Part 2: Radiated conformance testing (Release 15). 3GPP TS 38.141-2, 261 p.

[22] Keysight Technologies (2015) Performing LTE and LTE-Advanced RF Measurements with the E7515A UXM Wireless Test Set, Application Note, 128 p.

[23] Il-kyoo Lee, Dong-han Lee, Jae-young Kim, Hyun-jin Hong & Seung-hyeub Oh (2002) Analysis of UE RF parameters for 3GPP specifications. Proceedings IEEE 56th Vehicular Technology Conference, Vancouver, BC, Canada, pp. 559-562 vol. 1.

[24] Juha Kalliovaara (2017) Field Measurements in Determining Incumbent Spectrum Utilization and Protection Criteria in Wireless Co-existence Studies, TURUN YLIOPISTON JULKAISUJA, Sarja – ser. AI osa – tom. 559.

[25] European Communications Office (read May 2019) SEAMCAT Handbook Edition 3. URL: https://ecocfl.cept.org/display/SH/SEAMCAT+Handbook

[26] 3rd Generation Partnership Project (2013) Technical Specification Group Radio Access Networks; Passive Intermodulation (PIM) handling for Base Stations (Release 12), 3GPP TR 37.808 V1.0.0, 31 p.

[27] Ya Jing, Xu Zhao, Hongwei Kong, Steve Duffy, & Moray Rumney. (2012) Two-Stage Over-the-Air (OTA) Test Method for LTE MIMO Device Performance Evaluation. International Journal of Antennas and Propagation, vol. 2012, Article ID 572419, 6 p.

[28] Lee, Kian Seng and Mats X. Andersson. (2009) Overview of Antenna and Over The Air (OTA) Measurements in Reverberation Chambers. The 2009 International Symposium on Antennas and Propagation (ISAP 2009) October 20-23, Bangkok, Thailand, 4 p.

[29] Hao Hu, Honggang Sui, Yifan Liu, Zheng Zhang, Meng Hou, Yujuan Ma, Ya Jing, Jinqiang Xing, Bin Han, Sijia Gu, Yueting Cai, Qing Xu, Tao Liu & Anmin Xu. (2019) GTI 5G Device OTA Performance White Paper. 70 p.

[30] Shu Sun, Theodore S. Rappaport, Timothy A. Thomas, Amitava Ghosh, Huan C. Nguyen, István Z. Kovács,Ignacio Rodriguez, Ozge Koymen, and Andrzej Partyka. (2016) Investigation of Prediction Accuracy, Sensitivity, and Parameter Stability of Large-Scale Propagation Path Loss Models for 5G Wireless Communications. IEEE Transactions on vehicular technology, vol. 65, no. 5, 2846 p.

[31] 3rd Generation Partnership Project (2018) Technical Specification Group Radio Access Network; NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone (Release 15). 3GPP TS 38.101-2 V15.4.0 131 p.

[32] 3rd Generation Partnership Project (2019) Technical Specification Group Radio Access Network; NR; Base Station (BS) radio transmission and reception (Release 15). 3GPP TS 38.104 208 p.

[33] 3rd Generation Partnership Project (2017) Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and Universal Terrestrial Radio Access (UTRA; Radio Frequency (RF) requirement background for Active Antenna System (AAS) Base Station (BS) (Release 13). 3GPP TR 37.842. 131 p.

[34] Ericsson AB, Huawei Technologies Co. Ltd, NEC Corporation, Alcatel Lucent, and Nokia Networks (2015) Common Public Radio Interface (CPRI); Interface Specification. CPRI Specification V7.0. 128 p.

[35] National Instruments (read February 2019) What is I/Q Data?. URL: http://www.ni.com/tutorial/4805/en/

[36] 3rd Generation Partnership Project (2016) Technical Specification Group Radio Access Network; Terminal conformance specification; Radio transmission and reception (TDD) (Release 11). 3GPP TS 34.122. 594 p.

9 APPENDICES

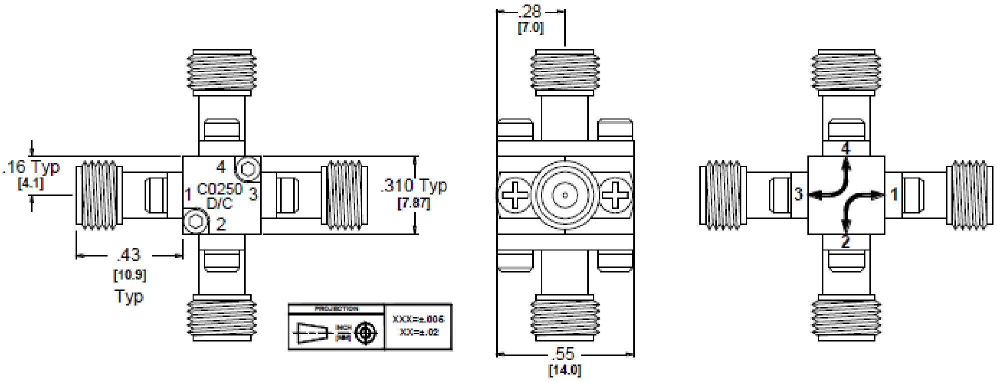
Appendix 1	Marki Directional Coupler datasheet
Appendix 2	Link budget excel for CATR#2
Appendix 3	Measured losses for MVG OTA BOX and Radiall cables
Appendix 4	Close-up of directional coupler setup

Appendix 1 Marki Directional Coupler datasheet

Electrical Specifications

Parameter[1]	Frequency Range (GHz)	Min	Typ	Max
Direct Line Insertion Loss (dB)	DC to 25		0.3	0.6
	25 to 50		0.7	1.4
Coupling (dB)	50		12	
	2		35	
VSWR	2 to 25		1.25	1.55
	25 to 50		1.65	
Directivity (dB)	2 to 25		15	
	25 to 50		10	
Weight (g)			15	

[1] Specifications guaranteed when operated in a 50Ω system. Consult factory for more information.



DIRECTIONAL COUPLER C-0250

Page 2

Typical Performance

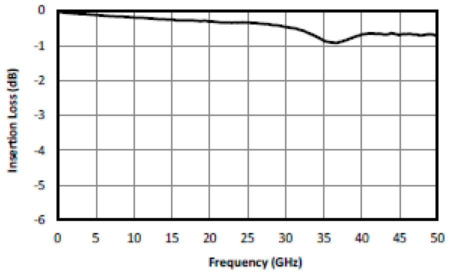


Fig. 1. Direct line insertion loss.

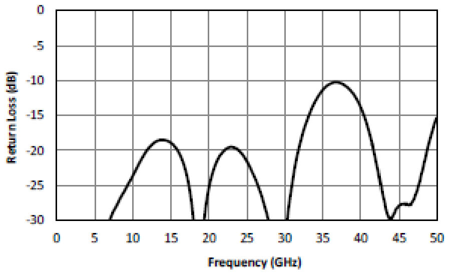


Fig. 2. Typical port return loss.

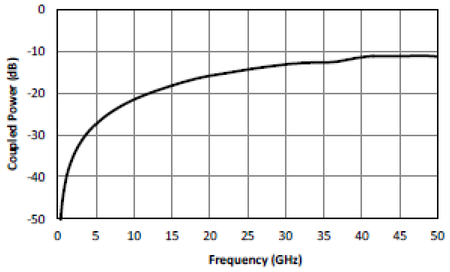


Fig. 3. Coupled port power.

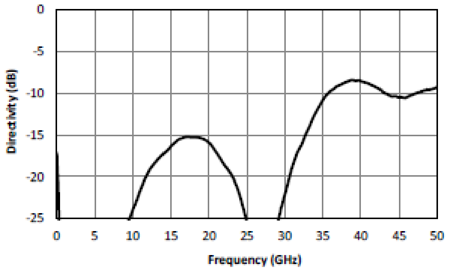
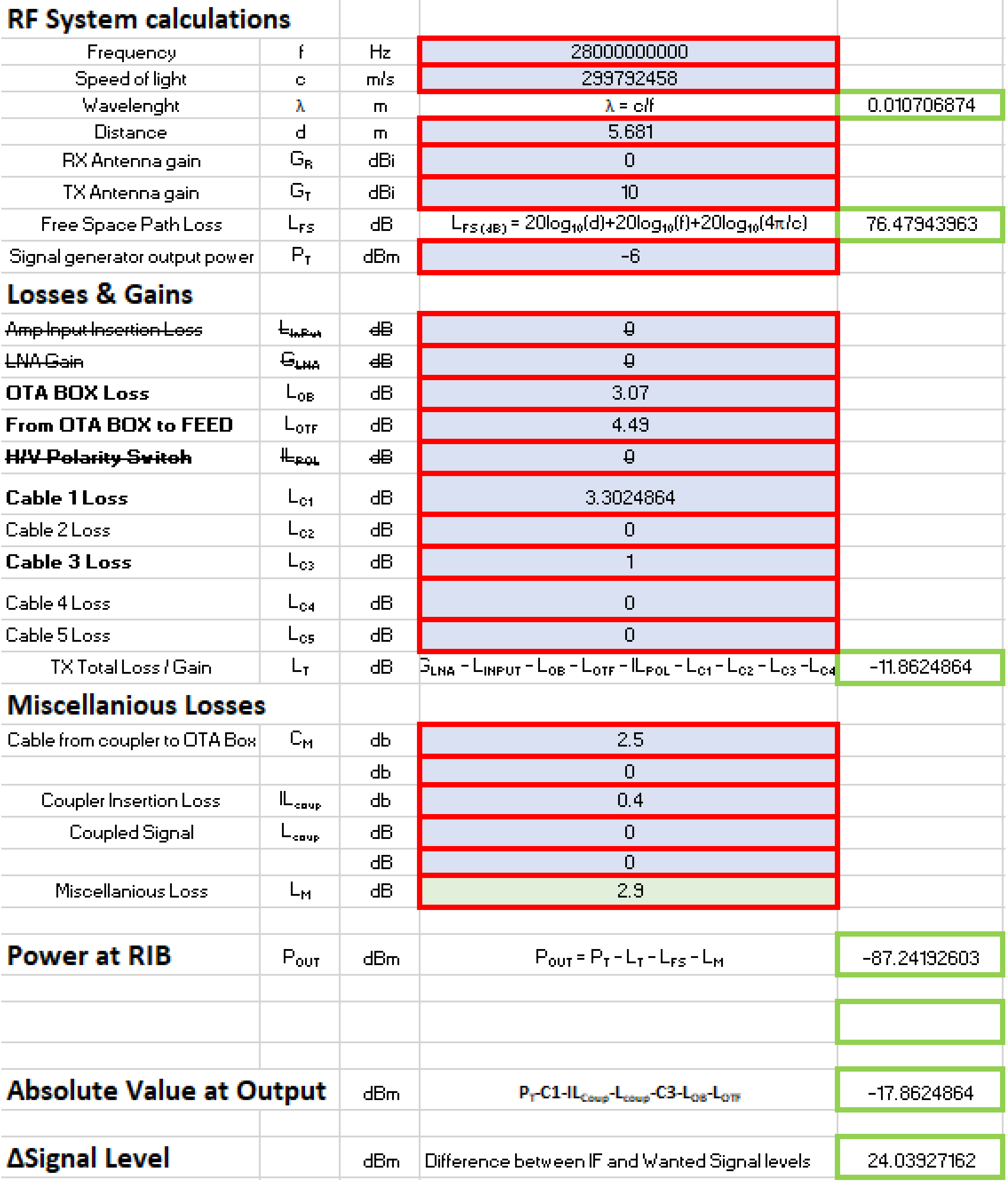


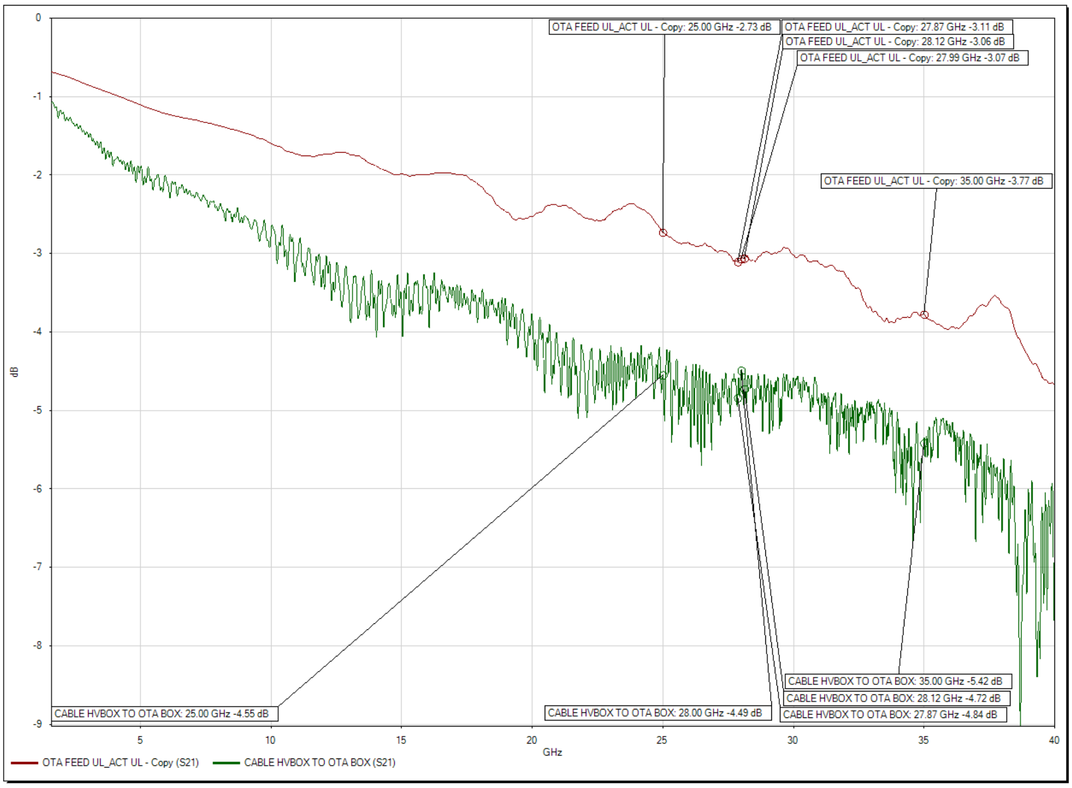
Fig. 4. Typical directivity.

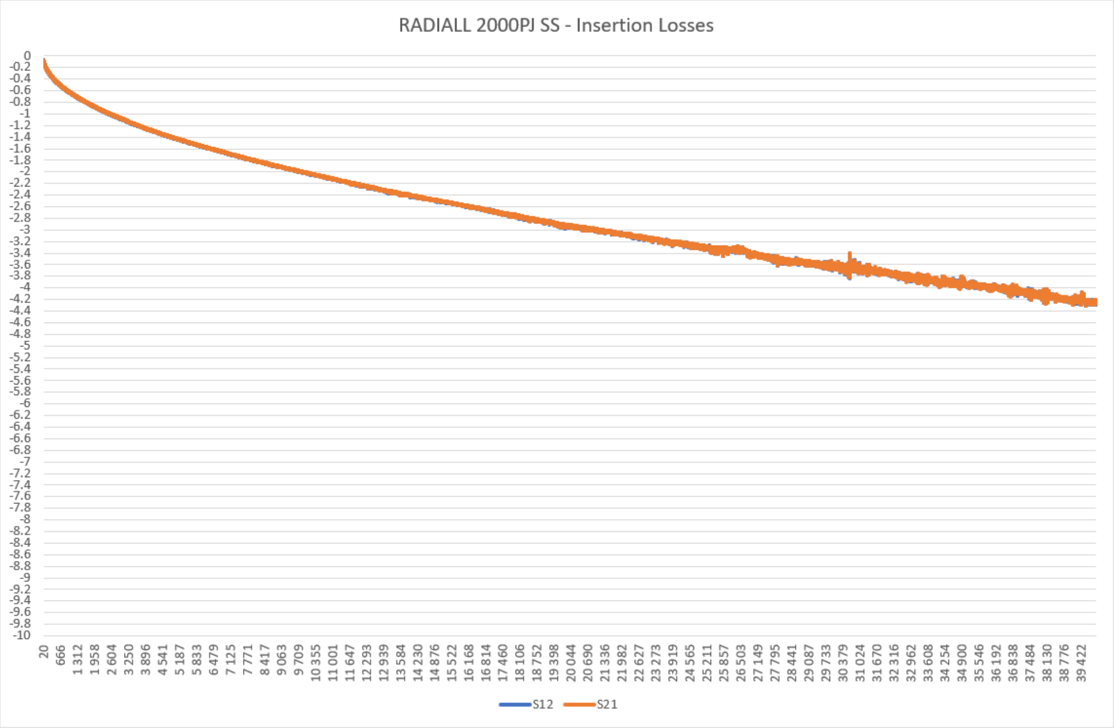
Appendix 2 Link Budget excel for CATR#2

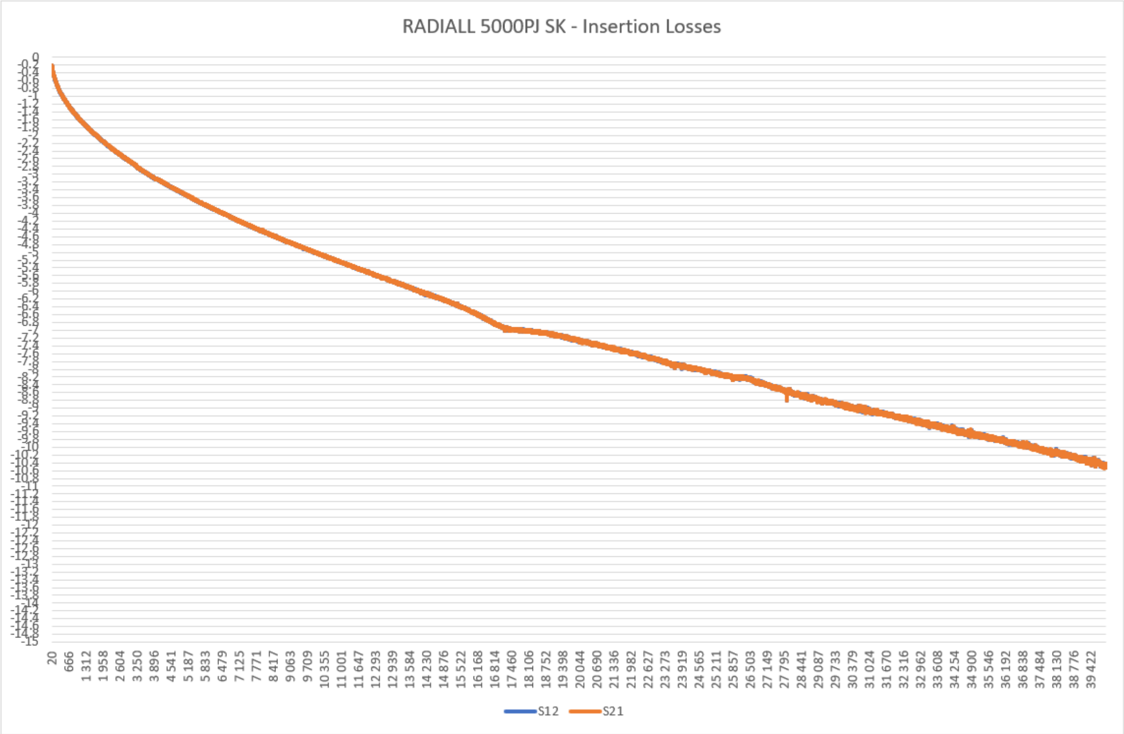


RF System calculations				
Frequency	f	Hz	28000000000	
Speed of light	c	m/s	299792458	
Wavelenght	λ	m	λ = c/f	0.010706874
Distance	d	m	5.681	
RX Antenna gain	G_R	dBi	0	
TX Antenna gain	G_T	dBi	10	
Free Space Path Loss	L_{FS}	dB	$L_{FS\,(dB)} = 20\log_{10}(d)+20\log_{10}(f)+20\log_{10}(4\pi/c)$	76.47943963
Signal generator output power	P_T	dBm	-6	
Losses & Gains				
~~Amp Input Insertion Loss~~	~~L_{INPUT}~~	~~dB~~	~~0~~	
~~LNA Gain~~	~~G_{LNA}~~	~~dB~~	~~0~~	
OTA BOX Loss	L_{OB}	dB	3.07	
From OTA BOX to FEED	L_{OTF}	dB	4.49	
~~**H/V Polarity Switch**~~	~~IL_{POL}~~	~~dB~~	~~0~~	
Cable 1 Loss	L_{C1}	dB	3.3024864	
Cable 2 Loss	L_{C2}	dB	0	
Cable 3 Loss	L_{C3}	dB	1	
Cable 4 Loss	L_{C4}	dB	0	
Cable 5 Loss	L_{C5}	dB	0	
TX Total Loss / Gain	L_T	dB	$G_{LNA} - L_{INPUT} - L_{OB} - L_{OTF} - IL_{POL} - L_{C1} - L_{C2} - L_{C3} - L_{C4}$	-11.8624864
Miscellanious Losses				
Cable from coupler to OTA Box	C_M	db	2.5	
		db	0	
Coupler Insertion Loss	IL_{coup}	db	0.4	
Coupled Signal	L_{coup}	dB	0	
		dB	0	
Miscellanious Loss	L_M	dB	2.9	
Power at RIB	P_{OUT}	dBm	$P_{OUT} = P_T - L_T - L_{FS} - L_M$	-87.24192603
Absolute Value at Output		dBm	P_T-C1-IL_{Coup}-L_{coup}-C3-L_{OB}-L_{OTF}	-17.8624864
ΔSignal Level		dBm	Difference between IF and Wanted Signal levels	24.03927162

Appendix 3 Measured losses for MVG OTA BOX and Radiall cables






RADIALL 5000PJ SK - Insertion Losses
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
-2.8
-3
-3.2
-3.4
-3.6
-3.8
-4
-4.2
-4.4
-4.6
-4.8
-5
-5.2
-5.4
-5.6
-5.8
-6
-6.2
-6.4
-6.6
-6.8
-7
-7.2
-7.4
-7.6
-7.8
-8
-8.2
-8.4
-8.6
-8.8
-9
-9.2
-9.4
-9.6
-9.8
-10
-10.2
-10.4
-10.6
-10.8
-11
-11.2
-11.4
-11.6
-11.8
-12
-12.2
-12.4
-12.6
-12.8
-13
-13.2
-13.4
-13.6
-13.8
-14
-14.2
-14.4
-14.6
-14.8
-15
20
666
1 312
1 958
2 604
3 250
3 896
4 541
5 187
5 833
6 479
7 125
7 771
8 417
9 063
9 709
10 355
11 001
11 647
12 293
12 939
13 584
14 230
14 876
15 522
16 168
16 814
17 460
18 106
18 752
19 398
20 044
20 690
21 336
21 982
22 627
23 273
23 919
24 565
25 211
25 857
26 503
27 149
27 795
28 441
29 087
29 733
30 379
31 024
31 670
32 316
32 962
33 608
34 254
34 900
35 546
36 192
36 838
37 484
38 130
38 776
39 422
S12
S21

Appendix 4 Close-up of directional coupler setup.