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REDUCTION OF REDUNDANCY IN LTE CA IOP PERFORMANCE TESTING

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REDUCTION OF REDUNDANCY IN LTE CA IOP PERFORMANCE TESTING

The purpose of this thesis was to reduce the test run times in interoperability testing. Carrier Aggregation, a functionality of LTE-Advanced, increases test run times. In this thesis, the redundancy in test cases and it’s reduction was studied.

The test measurements were conducted with an external interferer for better repeatability. The test cases were designed to be as comprehensive and as close to the actual interoperability cases as possible. To study the redundancy in Carrier Aggregation measurement results, four test cases were designed.

Redundancy was found in Carrier Aggregation tests. In these cases, the test results are interchangeable with other results and do not need to be separately measured. According to the findings, the test run times were reduced by 69 % for a product in R&D phase. The evaluation of reduction was based on test plan.

KEYWORDS:

RF, LTE, LTE-Advanced, Carrier Aggregation, interoperability, nonlinear distortion, testing, sensitivity, R&D

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PÄÄLLEKKÄISYYDEN VÄHENTÄMINEN LTE CA IOP PERFORMANCE –TESTAUKSESSA

Opinnäytetyön tavoitteena oli interoperability-testauksen vaatiman testien ajoajan vähentäminen. LTE-Advancediin sisältyvä Carrier Aggregation lisää testien ajoaikaa. Opinnäytetyössä tutkittiin, onko testitilanteissa päällekkäisyyttä, jonka voi jättää erikseen mittaamatta.

Työ toteutettiin suorittamalla mittauksia ulkoisesti tuotetuilla häiriöillä toistettavuuden parantamiseksi. Testitilanteet suunniteltiin mahdollisimman kattaviksi ja vastaamaan mahdollisimman tarkasti todellista interoperability-tilannetta. Testeiksi valikoitui 4 tilannetta, joiden avulla Carrier Aggregationin mittatuloksien päällekkäisyyttä voitiin arvioida.

Carrier Aggregation –testeissä löytyi päällekkäisyyttä, joka voidaan jättää erikseen mittaamatta. Tällaisissa tapauksissa mitattujen testien tuloksia voidaan tietyin ehdoin yleistää mittaamatta jätettyjen testien tuloksiksi. Tulosten perusteella T&K-vaiheessa olevan tuotteen testien ajoaika väheni 69 %. Vähentyminen arvioitiin testiaikataulun perusteella.

ASIASANAT:

RF, LTE, LTE-Advanced, Carrier Aggregation, yhteensopivuus, epälineaarinen särö, testaus, herkkyys, T&K

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LIST OF ABBREVIATIONS

2G	2^{nd} generation mobile cellular technology
3G	3^{rd} generation mobile cellular technology
3GPP	3^{rd} generation partnership project, a partnership group with many standardization organizations
4G	4^{th} generation mobile cellular technology
BLER	Block error rate, rate of correctly received data blocks vs. all transmitted data blocks
BTS	Base transceiver station, a base station in 2G access network
CA	Carrier Aggregation, LTE-A technology where multiple downlink carriers are aggregated to expand transmission bandwidth
CC	Component carrier, one of the aggregated carriers in CA
cdma 2000	Code division multiple access 2000, a standard for a 3^{rd} generation mobile cellular technology specified by 3GPP2 as competition to UMTS by 3GPP
CP	Cyclic prefix, guard period between symbols to prevent inter-symbol interference
CW	Contiguous wave, a sine wave of specific amplitude at specific frequency
DFT	Discrete Fourier transform, calculation used to transfer signal between time domain and frequency domain
DL	Downlink, transmission from network to user
DwPTS	Downlink pilot time slot, one of 3 special fields in TDD frame structure
EARFCN	E-UTRA absolute radio frequency channel number, frequency notation in E-UTRA
EDGE	Enhanced data rates for GSM Evolution, a standard for transitional 2G mobile cellular technologies and networks
EMC	Electromagnetic compatibility, in this context the ability of RF modules to coexist without interfering each other
eNB	Evolved Node B, or eNodeB, an E-UTRAN base station
EPC	Evolved packet core, the core network in LTE system

EPS	Evolved packet system, overall LTE network system, including E-UTRAN and EPC
E-UTRA	Evolved universal terrestrial radio access, LTE air interface
E-UTRAN	Evolved universal terrestrial radio access network, network of LTE base stations into which UE connects
FDD	Frequency division duplex, technique of dividing spectrum frequency-wise between uplink and downlink
FFT	Fast Fourier transform, algorithm that calculates DFT
GERAN	GSM EDGE radio access network, 2G access network
GP	Guard period, one of 3 special fields in TDD frame structure
GPRS	General packet radio service, a standard for transitional 2G mobile cellular technologies and networks
GSM	Global system for mobile communications, a standard for 2G mobile cellular technologies and networks
H3	3^{rd} harmonic, a nonlinear distortion product
HSPA	High-speed packet access, an enhancement to WCDMA based mobile protocols
HSS	Home subscriber service, database with subscriber information
IFFT	Inverse fast Fourier transform
IMD	Intermodulation distortion, a distortion caused by nonlinearity of amplifiers
IOP	Interoperability, the ability of RF modules to coexist
IP address	Internet protocol address, address given to device according to which IP packets are delivered
ITM-A	International Mobile Telecommunications – Advanced, ITU requirements for 4G radio technology
ITU	International Telecommunication Union, a United Nations agency specialized in ICT
ITU-R	ITU Radiocommunication sector, unit in ITU responsible for usage and development of radio technologies and spectrum
LNA	Low noise amplifier, an amplifier at the receiver
LTE	Long term evolution, standard for 4^{th} generation mobile cellular technologies. Usually refers to E-UTRAN air interface

LTE-A	LTE Advanced, an enhancement to the LTE specification that meets the original requirements for 4th generation mobile cellular standard set by ITU. Usually refers to E-UTRAN air interface
MAC layer	Medium access control, protocol stack layer responsible for scheduling physical channel
ME	Mobile equipment, abbreviation for mobile device in GSM
MIMO	Multiple input multiple output, antenna technology where multiple paths are used
MME	Mobility management entity, a part of EPC responsible for tracking idle UEs and security issues
MU-MIMO	Multiple user MIMO, where MIMO is used to enable connection for multiple users
NB	Node B, a base station in UTRAN
OFDMA	Orthogonal frequency division multiple access, a multiple access scheme used in LTE downlink where orthogonality of signals allows denser spectrum usage
PA	Power amplifier, an amplifier at the transmitter
PAR	Peak-to-average ratio, the ratio between signals peak power and average power
PCC	Primary component carrier, the carrier in CA which handles uplink communications
P-GW	Packet data network gateway, a part of EPC responsible for IP address allocation of UE
RAT	Radio access technology, the technology in mobile cellular network used for device to connect with base station
RCT	Radio communications tester, a device used to test the performance of DUT. Emulates the eNB
Rel	Release, notation used by 3GPP on released specifications
RRC	Radio resource control, a protocol responsible for connection between UE and eNB
RX	Receiver
S1-interface	An interface through which eNB connects with EPC
SA	Spectrum analyzer, a device used to study frequency spectrum
SC	Single carrier, LTE without Carrier Aggregation

SCC	Secondary component carrier, the aggregated carrier in CA with only downlink
SC-FDMA	Single Carrier Frequency Division Multiple Access, a multiple access scheme used in LTE uplink
SG	Signal generator, a device used to introduce wanted signals into the system
S-GW	Serving gateway, part of EPC responsible for routing IP packets of UE
SNR, S/R ratio	Signal-to-noise ratio, the dynamic range between signal power and noise power
SU-MIMO	Single user MIMO, a MIMO technique used to give UE better bit rate by using multiple paths
TDD	Time division duplex, technique of dividing spectrum time wise between uplink and downlink
TDMA	Time division multiple access, a multiple access scheme used to connect as many devices to network as possible at limited frequency resources by reusing time domain
TTI	Transmission time interval, time cycle during which eNB evaluates cell state
TX	Transmitter
UE	User equipment, abbreviation for mobile device in LTE
UL	Uplink, transmission from user equipment towards network
UMTS	Universal mobile telecommunications system, 3^{rd} generation mobile cellular network system
UpPTS	Uplink pilot time slot, one of 3 special fields in TDD frame structure
UTRAN	Universal terrestrial radio access network, 3G radio network
V-MIMO	Virtual MIMO, technique of reusing frequency by virtually creating multiple paths by orthogonality
WCDMA	Wideband code division multiple access, a standard for 3G mobile cellular technologies
WiMAX	Worldwide interoperability for microwave access, a standard for wireless hotspot networks
X2-interface	An interface through which eNB connects with other eNBs

1 INTRODUCTION

In 2013, the first commercial Long Term Evolution – Advanced (LTE-A) network was launched in South Korea. It is continuation to the evolution of wireless mobile technologies as a response to growing demand for coverage and capacity of mobile data services.

The total number of mobile subscriptions is predicted to go from 7.1 billion in 2014 to 9.5 billion in 2020, of which 90 % will be mobile broadband. Mobile phone data is estimated to grow 40 % each year in the same time span. Penetration of LTE is expected to be over 70 % of world's population, while 90 % of the world's population over 6 years old are expected to have a mobile phone. [1]

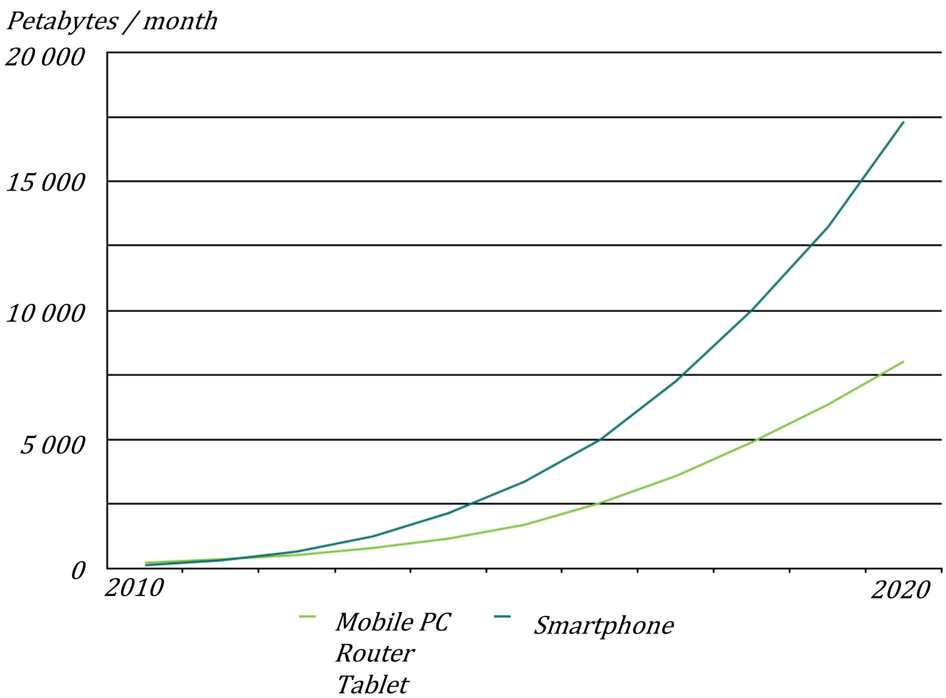


Figure 1. Expected data traffic growth per device in petabytes from 2010 to 2020. [1]

To meet the growing demand for mobile data, 3GPP introduced a new feature called Carrier Aggregation (CA) in Release 10, a technical document describing the new feature, in 2009 [2]. In CA more frequency resources are allocated to mobile user in order to meet the growing demand for mobile data.

This thesis focuses on downlink CA, i.e. traffic from network to user equipment. Although uplink CA was introduced in Rel-10 as well, it's not equally deployed. Developing uplink CA test procedure will be topical in a couple of years, but it is not in the scope of this thesis. Downlink CA is being actively developed and deployed by both network providers and user equipment manufacturers.

As always, new technology requires R&D. Quality products need thorough testing throughout the R&D process. As new test cases are being adopted, the necessity of each should be evaluated to avoid unproductive procedures. In this thesis, the redundancy of testing is researched in order to reduce the testing effort.

The addition of CA band configurations increases the test burden for R&D phase significantly, as it is not enough to measure reception only at specific frequency but with frequency combinations as well. The redundancy in the results of these measurements is evaluated.

Test device manufacturers and mobile phone manufacturers have published white papers where the theory behind the technology is studied, e.g. [1], [2], [12], and [15]. White papers are reliable source of information as manufacturers are usually actively participating in the writing of specifications for technologies. 3GPP publications are used widely, e.g. [25] and [29]. 3GPP publishes the actual specifications used by the industry. Along with the white papers and specifications, books about relevant technologies and businesses were used as well, e.g. [3], [7] and [9]. A few times magazines of relevant domain were used as reference material due to their popularizing approach to explaining mathematics, e.g. [28].

In the next chapter, previous mobile technology generations are presented and a structure of LTE network is presented. In the Chapter 3, the air interface of LTE is introduced to better understand sensitivity, band configurations and basics of tests conducted in this thesis.

In the Chapter 4, interoperability testing's purpose to find internal interference that degrades reception is laid out. Carrier Aggregation increases the tested spectrum and possibly introduces new phenomena. Necessity of tests and interchangeability between test results are considered. Calculation for the most economic measurement is presented.

In the Chapter 5 test plan is formed, and 4 test cases are designed to find out whether there is redundancy in testing. Nonlinear distortion used in the measurements is explained. Transceiver block diagram and device setup in test stack are introduced. Sensitivity search as a test case is explained.

In the Chapter 6 the measurement setups, results and observations are presented. Measurements are conducted with FDD bands, so applying the results for TDD bands is considered. Validity of the measurements is evaluated.

In the end, plan for implementation based upon Chapter 6 findings is presented. Steps to successfully implement the reduction are presented and argumented.

2 EVOLUTION OF CELLULAR NETWORKS

2.1 2nd generation mobile telecommunications technology

In GSM and GPRS, GSM EDGE radio access network (GERAN) consists of base transceiver stations (BTSs), see Table 1 and Figure 3. The BTS is controlled by radio network controller (RNC). Time division multiple access (TDMA) is used as access scheme. Mobile equipment (ME) connects to the BTS. A network of BTSs is called GERAN, and GERAN connects to the core network. In GSM, circuit switching is used. GPRS uses circuit switching for real time services (e.g. phone calls) and packet switching for data services. GSM is referred to as 2G and later introduced GPRS is also referred to as 2.5G. [3], [4]

2.2 3rd generation mobile telecommunications technology

In UMTS technologies, a user equipment (UE) connects to a NodeB (NB), which is controlled by a radio network controller (RNC), see Table 1 and Figure 3. An access network of NBs is called UTRAN [5]. In Rel-99 and Rel-4, GSM's TDMA was replaced by wideband code division multiple access (WCDMA) as access scheme [4]. In Rel-5 and Rel-6, high-speed packet access (HSPA) was introduced [4]. Both circuit switching and packet switching are used in UMTS [6]. IP address is allocated upon establishing data service and released upon closing the service [6]. MAC protocol layer, which is responsible for scheduling physical layer for UE, is located in the RNC in UMTS and in the NB in HSDPA [7], [8].

2.3 4th generation mobile telecommunications technology

In 2008, 3GPP published Rel-8, the first specification for evolved packet system (EPS). In the EPS, core network, access network and user equipment are specified, see Table 1 and Figure 3. They are referred to as the EPC (evolved packet core), E-UTRAN (evolved universal terrestrial radio access network) and UE, respectively [9]. See Figure 2. In 2009, additions such as MIMO and public warning system were introduced in Rel-9 [10].

The term E-UTRAN is used to describe the base station and the network side of LTE, and E-UTRA (evolved universal terrestrial radio access) is used to describe the LTE air interface [9]. In the next chapter, the air interface is described in more detail.

The EPS utilizes packet switching for all services. IP address is allocated upon device switch on and released upon device switch off [6]. In the EPS basic architecture, the UE connects to the EPC over E-UTRAN. See Figure 2. [11]

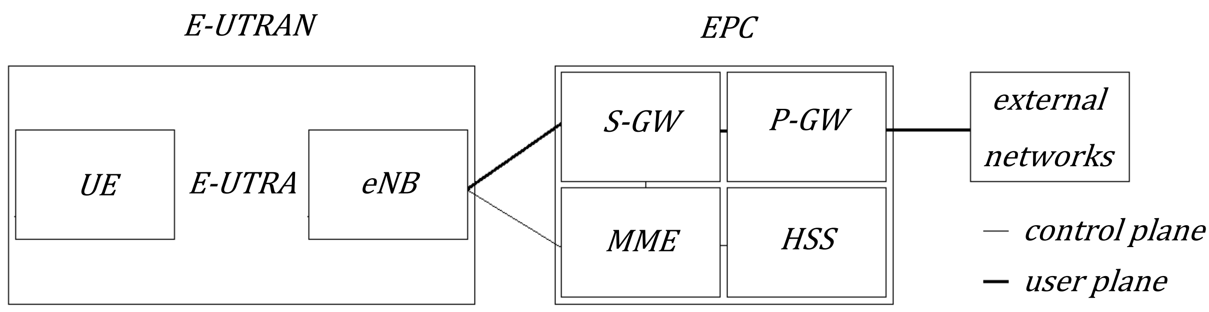


Figure 2. Basic EPS architecture. [11]

EPC consists of 4 elements: HSS, S-GW, P-GW and MME. [11], [12]

- Home subscriber service (HSS) is a database that manages user and subscriber information. It handles user authentication and access authorization.
- Serving gateway (S-GW) routes IP packets of UE between the EPC and E-UTRAN. Between EPC and the eNB, there is S1-interface.
- Packet data network gateway (P-GW) connects the EPC to outside IP networks. P-GW is responsible for IP address allocation.
- Mobility management entity (MME) tracks and pages idle UEs and deals with mobility and security in E-UTRAN.

EPC was designed to support E-UTRA, but also other radio access technologies (RAT) and handovers between them are supported. The EPC is fully backwards compatible with GERAN and UTRAN access technologies. The EPC is also compatible with IP based non-3GPP specified access technologies, e.g. WiMAX, WLAN, CDMA2000 and fixed networks. [11]

E-UTRA uses single carrier frequency division multiple access (SC-FDMA) for uplink and orthogonal frequency division multiple access (OFDMA) for downlink. In downlink, high modulation schemes (up to 64QAM), large bandwidths (up to 20 MHz) and spatial multiplexing (up to 4x4) are utilized. This allows Rel-9 specification to achieve one of the main goals set for 4G: theoretical peak data rate is 75 Mbps in uplink and 300 Mbps in downlink. In Rel-10, peak data rate reaches 600 Mbps with 8x8 spatial multiplexing, and with maximum bandwidth of 100 MHz, 3 Gbps is reached. [13]

Another main goal for E-UTRAN was flatter network architecture. Significant change to GERAN and UTRAN is the absence of separate controllers in E-UTRAN. The functionality of controllers is mainly shifted to the evolved NodeBs (eNB). In Figure 3, the controller between base station and core network is therefore missing, and its functionality is spread to the bordering equipment. The eNBs connect via X2-interface to each other and via S1-interface to the EPC. With distributed intelligence E-UTRAN is faster in connection setup and handover. [13]

Having MAC layer in the eNB is also an advantage gained by distributed intelligence. Scheduling physical channel between UE and the eNB is responsibility of the eNB, making communication and decisions quicker. Time in which the eNB evaluates radio channel quality and decides modulation and coding scheme, prioritizes QoS requirements for UEs, and informs UE which radio resources were being allocated to it takes only 1 ms. Connection is fast to adapt to environment and requirements. [6]

Table 1. Cellular network generations. [3], [4], [5], [6], [9], [11]

Technology	GSM	GPRS	WCDMA	LTE
Network system	GSM	GPRS	UMTS	EPS
Generation	2G	2.5G	3G	4G
Core network switching	Circuit	Circuit/ Packet	Circuit/ Packet	Packet
Base station	BTS	BTS	NB	eNB
Controller	Yes	Yes	Yes	No
Access network	GERAN	GERAN	UTRAN	E-UTRAN
Multiple access scheme	TDMA	TDMA	WCDMA	OFDMA/ SC-FDMA
Device	ME	ME	UE	UE

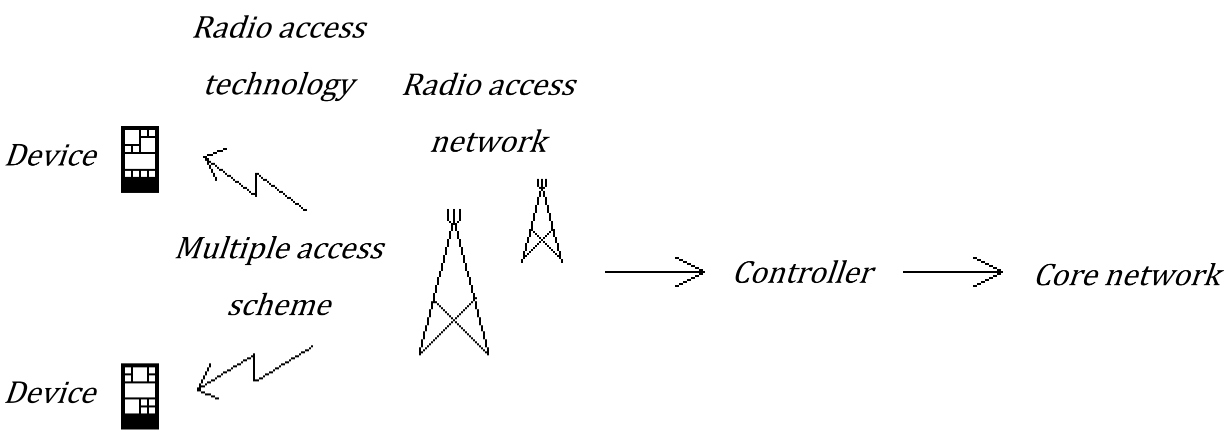


Figure 3. Architecture of generic mobile network. Relation between the parts of the network, itemized in Table 1, depicted. [6]

3 LONG TERM EVOLUTION AIR INTERFACE

3.1 ITM-Advanced requirements and 3GPP specification

In 2010, ITU decided to allow marketing Rel-8 and Rel-9 as 4G, although they technically do not meet the original requirements set for 4th generation mobile technology specified in ITM-Advanced in ITU-R [14]. The technology that actually meets the requirements is specified in Rel-10 and is called LTE-Advanced [2]. In 2010, ITU-R evaluated 3GPP's suggestion, and decided it fulfills the requirements for ITM-Advanced [15].

ITU-R specified key features for IMT-Advanced as follows: [16]

- Peak data rate of 100 Mbps for high mobility and 1 Gbps for low mobility in downlink and 675 Mbps in uplink.
- Peak spectral efficiency for downlink 15 bit/s/Hz with 4 antennas and uplink 6.75 bit/s/Hz with 2 antennas.
- Scalable bandwidths up to 40 MHz.
- User plane latency (time between IP packet at UE/the eNB IP layer and IP packet at the eNB/UE IP layer) less than 10 ms.
- Support for high speed vehicular mobility up to 350 km/h.
- Compatibility with other radio access systems.
- Worldwide roaming capability.

3GPP specified key features for LTE-Advanced as follows: [13]

- Peak data rate of 3 Gbps for low mobility in downlink and 1.5 Gbps in uplink.
- Peak spectral efficiency for downlink 15 bit/s/Hz with 4x4 MIMO and 30 bit/s/Hz with 8x8 MIMO.
- Bandwidth configuratins of 1.4, 3, 5, 10, 15 and 20 MHz and with Carrier Aggregation up to 100 MHz.
- User plane latency 10 ms.

It is evident that LTE-A does not only meet the requirements of ITM-A but also exceeds them.

3.2 Resource allocation

3.2.1 LTE bands

As LTE is evolution of UMTS, the frequency bands of UMTS are usable for LTE as well. Because LTE-A is an evolution of LTE, LTE-A uses same frequency bands as well. Of all specified LTE bands, usable bands for UE are country specific. [12]

There is overlap in spectrum with legacy technologies, but in these cases LTE is capable of coexistence [9]. These so called legacy bands are actively being freed for LTE [17]. Multiple channel bandwidths were specified to take better advantage of the existing gaps in spectrum [9]. ITU-R specified low bands for coverage and high bands for capacity [9]. See Appendix 1.

3.2.2 Channel numbering

Channel numbers can be regarded as spectrum notation. Frequency can be directly converted to channel number, by which allocated channel center frequency is informed to UE. The channel numbers by which spectrum is allocated are named E-UTRA Absolute Radio Frequency Channel Number (EARFCN) with numbers ranging from 0 to 65535. Channel raster is 100 kHz. [9]

During testing, EARFCN is used instead of frequency to control the connection. One frequency can be used in many bands, but EARFCNs are unique. [18]

3.2.3 Radio frames

LTE has designated bands for Time Division Duplex (TDD) and Frequency Division Duplex (FDD) modes. FDD and TDD are consistent modes. Both utilize similar framework, e.g. OFDMA in downlink, SC-FDMA in uplink and sub-frame structure. [9]

FDD divides uplink and downlink traffic to different frequency bands, and is therefore paired. Bands for downlink and uplink traffic are fixed, making FDD suitable for symmetrical traffic, e.g. phone calls (voice over LTE, or VoLTE). Between the bands there is spacing called guard bands to prevent interference. [9]

In the time domain, traffic is based on radio frames. Radio frame type 1 is used in FDD, see Figure 4. 10 ms frame is divided into 10 sub-frames of 1 ms, each further divided into 2 slots of 0.5 ms. Each slot contains 7 OFDM symbols. [9]

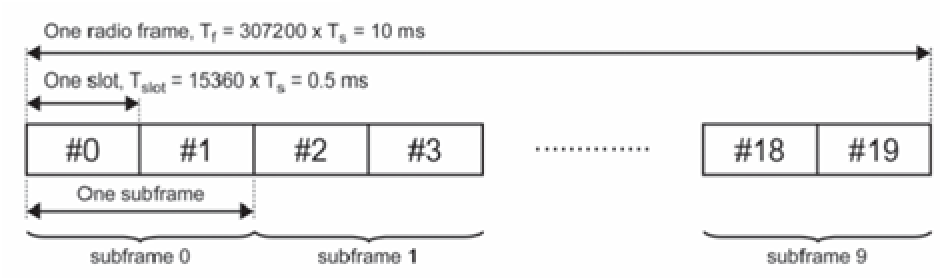


Figure 4. Radio frame type 1 (FDD). Radio frame is divided in its components in time domain. [19]

TDD divides uplink and downlink traffic in respect with the time domain. TDD uses one band for uplink and downlink traffic, and is therefore unpaired. There is no need for uplink and downlink to be symmetrical. This makes TDD more adaptable to reallocate radio resources. [9]

Radio frame type 2 is used in TDD, see Figure 5. 10 ms frame is divided into 2 half-frames of 5 ms, both further divided into 5 sub-frames of 1 ms. Sub-frames consist of 2 slots of 0.5 ms. TDD has 3 special fields: DwPTS, GP and UpPTS, with total length of 1 ms. Special fields are used flexibly for longer guard period, control information and payload. [9]

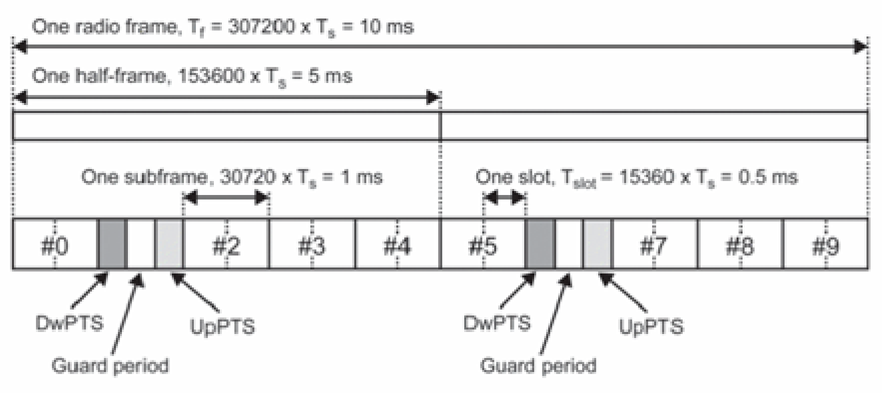


Figure 5. Radio frame type 2 (TDD). Radio frame is divided in its components in time division. [19]

3.2.4 Resource blocks

Resource block is the minimum entity in frequency domain allocated to UE. Resource block is a set of 12 subcarriers in frequency domain and 1 slot in time domain, see Figure 6. As 1 slot contains 7 OFDM symbols, resource block is a grid of 12 subcarriers and 7 OFMD symbols. A single grid item is called resource element, occupying 1 subcarrier for 1 OFDM symbol. Since spacing between subcarriers is 15 kHz, the minimum allocated bandwidth is 180 kHz. [9]

A number of resource blocks in 1 RB steps is allocated to UE every 1 ms according to the cell traffic and UE needs [9]. Transmission bandwidth can therefore be anything between 180 kHz and 20 MHz in 180 kHz steps [9]. For uplink, the RBs are contiguous unlike in downlink, where RBs need not be adjacent [12].

E.g. 5 MHz channel has 25 RB at maximum. As each RB contains 12 subcarriers of 15 kHz, the total occupied bandwidth is 4.5 MHz. This leaves 0.5 MHz for guard bands. See Table 2 for more examples.

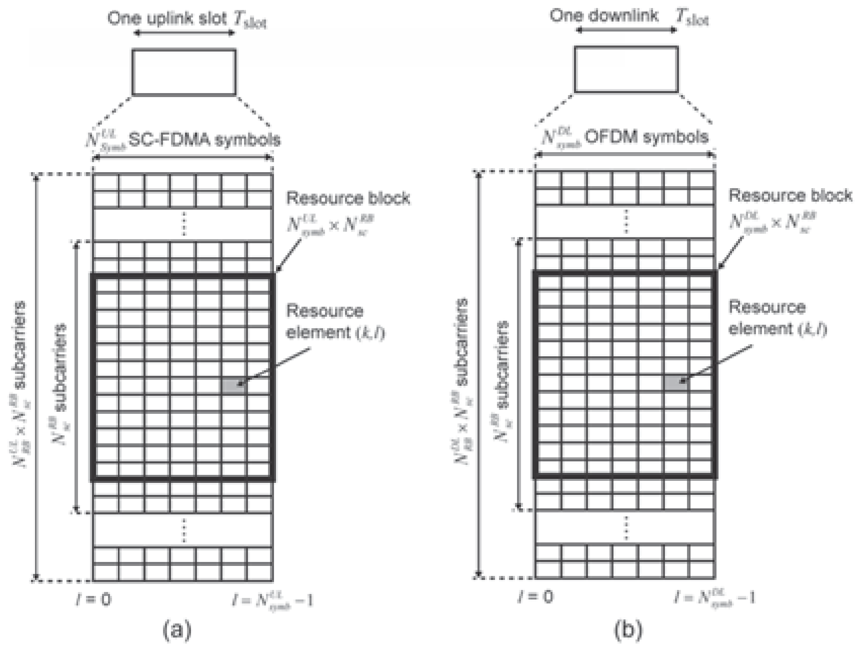


Figure 6. Resource grid for (a) uplink and (b) downlink. Resource block consists of 7 symbols and 12 subcarriers. Slots are similar in uplink and downlink. [19]

Table 2. Transmission bandwidths. [12], [13]

Bandwidth (MHz)	1.4	3	5	10	15	20
Number of RB	6	15	25	50	75	100
Number of subcarriers	72	180	300	600	900	1200
Transmission bandwidth (MHz)	1.08	2.7	4.5	9	13.5	18

Narrow bandwidths were specified to enhance the usage of legacy bands [18]. Because adjacent-channel interference limits are stricter than in-band interference limits, it was not possible for operator to buy a 10 MHz channel with top 5 MHz overlapping with a channel of another operator, and only assign RBs from the 5 MHz that doesn’t overlap [18]. Therefore the ability to buy small piece of spectrum enhances the efficiency of spectrum usage. For an interesting read, see [20].

3.3 Uplink multiple access scheme

Single carrier frequency division multiple access is the uplink multiple access scheme that was designed to optimize range and power consumption [19]. SC-FDMA has low peak-to-average ratio [19]. This is beneficial for mobile device due to lower power consumption.

QPSK, 16QAM or 64QAM is mapped to a constellation. Data is projected to I- and Q-axes at *M* times faster than SC-FDMA symbol rate, see Figure 7 top left. This leads up to having *M* consecutive symbols with 66.7 µs/*M* duration (SC-FDMA symbol length is 66.7 µs), see Figure 7 top middle and top right. These *M* data symbols are then converted to frequency domain with DFT, see Figure 7 bottom left. DFT sampling rate is chosen so that *M* data symbols, with the length of 66.7 µs, is fully represented in frequency domain with *M* DFT bins. The faster the data rate, the wider the bandwidth. The process is illustrated in Figure 7. [19, 21]

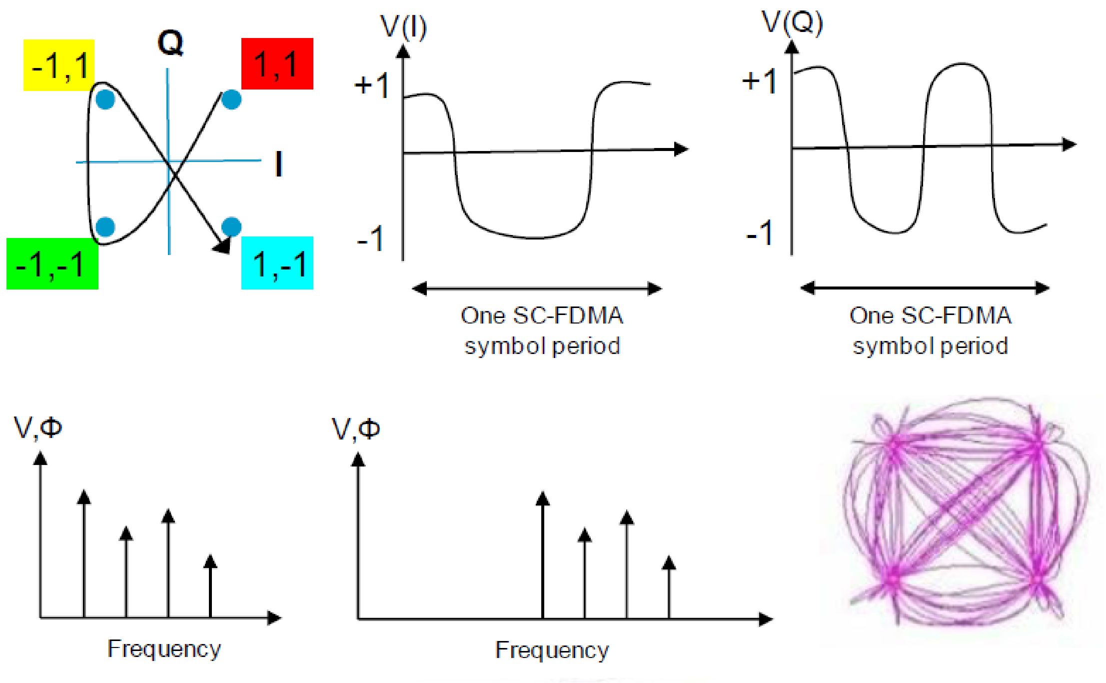


Figure 7. SC-FDMA signal generation. The projection of symbols at I/Q axes in top left picture and resulting I- and Q-graphs. Symbol length is 4 times the SC-

FDMA symbol length, incorporating 4 data symbols into one SC-FDMA symbol. [19]

After the conversion, the *M* baseband DFT bins are shifted to the entire wanted bandwidth, see Figure 7 bottom middle. As opposed to having one data symbol per one subcarrier, SC-FDMA symbol carries the information of *all* the input data symbols. [19], [21]

Amplitude and phase of DFT bins are no longer directly relative to the original data symbols. Subcarriers are time-invariant during the symbol duration, representing time-variant data symbols. This means that *M* bins, representing *M* data symbols, are invariant for 66.7 µs. [19], [21]

Then SC-FDMA symbols are converted back to time domain with inverse DFT and cyclic prefix is inserted to the beginning of the transmission, see Figure 7 bottom right. End of each symbol is duplicated to the beginning to the symbol. Cyclic prefix is a guard period used to prevent multipath problems. Copying cyclic prefix that is longer than the delay spread, inter-symbol interference can be overcome totally. Using cyclic prefix causes 7 % reduction in data rate. Although the data rate is fast, the symbol rate isn't. If SC-FDMA symbol is partially lost, the missing data is still available during the whole symbol duration. [19], [21]

3.4 Downlink multiple access scheme

Downlink multiple access scheme was designed to optimize receiver complexity and flexible resource allocation [9]. OFDMA signal generation is simpler than that of SC-FDMA as can be seen from Figure 8. OFDMA is based in OFDM technology with main difference being OFDMA's ability to dynamically allocate resources for users [19]. For this function, features from TDMA are incorporated in OFDMA [19].

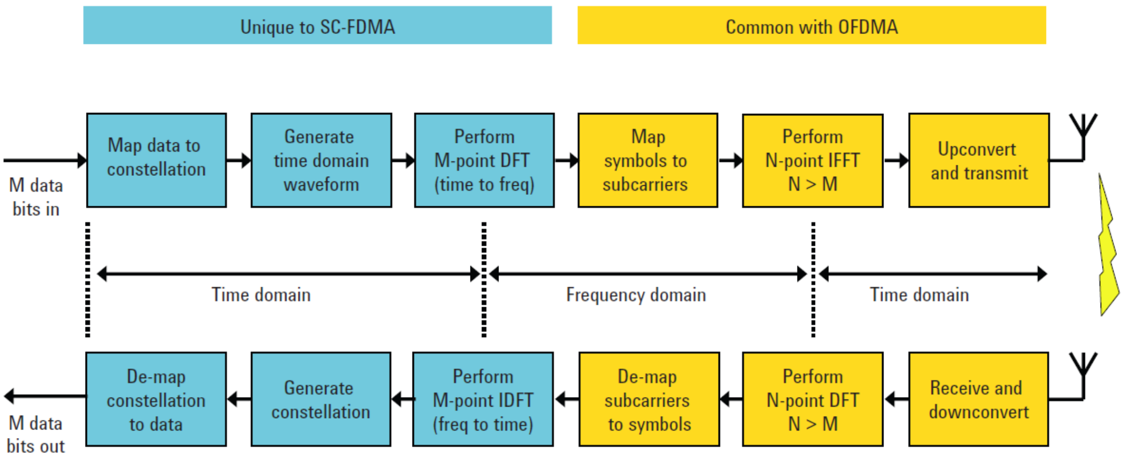


Figure 8. SC-FDMA and OFDMA signal generation. Procedures unique to SC-FDMA and common with OFDMA are separated. [19]

In OFDMA, orthogonal subcarriers are deployed over transmission bandwidth [19]. In frequency domain, each subcarrier's spectrum is a sinc function, and orthogonality in subcarriers means that x-intercept point for sinc function lies at adjacent subcarrier's vertex, see Figure 9. Subcarriers don't interfere, and spectrum is used more efficiently because the lack of need for guard bands. High data rate stream can be divided into multiple low data rate streams, each on separately modulated subcarrier [19].

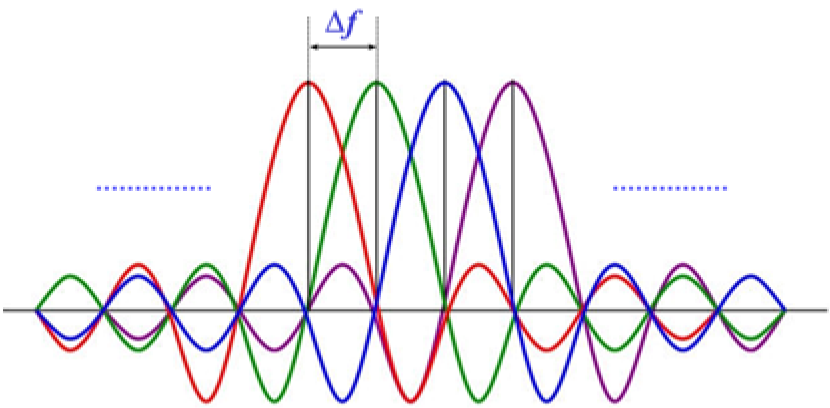


Figure 9. Orthogonal subcarriers with Δf. As orthogonality requires, the spectrum of a specific subcarrier has Δf between vertex and x-intercept point and with next subcarrier's vertex. [30]

Because orthogonality enables denser placement of subcarriers, frequency-selective fading is easier to deal with. Fading is on wider band than single subcarrier that is affected. Signals are equalized by interpolating neighboring reference signals. Another feature increasing robustness is the usage of cyclic prefixes similar to SC-FDMA. [9]

QPSK, 16QAM or 64QAM data is mapped to constellation. *M* adjacent 15 kHz subcarriers are modulated with *M* data symbols, each symbol modulating specific subcarrier for 66.7 µs. Signal is turned to time domain with IFFT, resulting to *M* time-domain symbols. Cyclic prefix is added before transmission. [19]

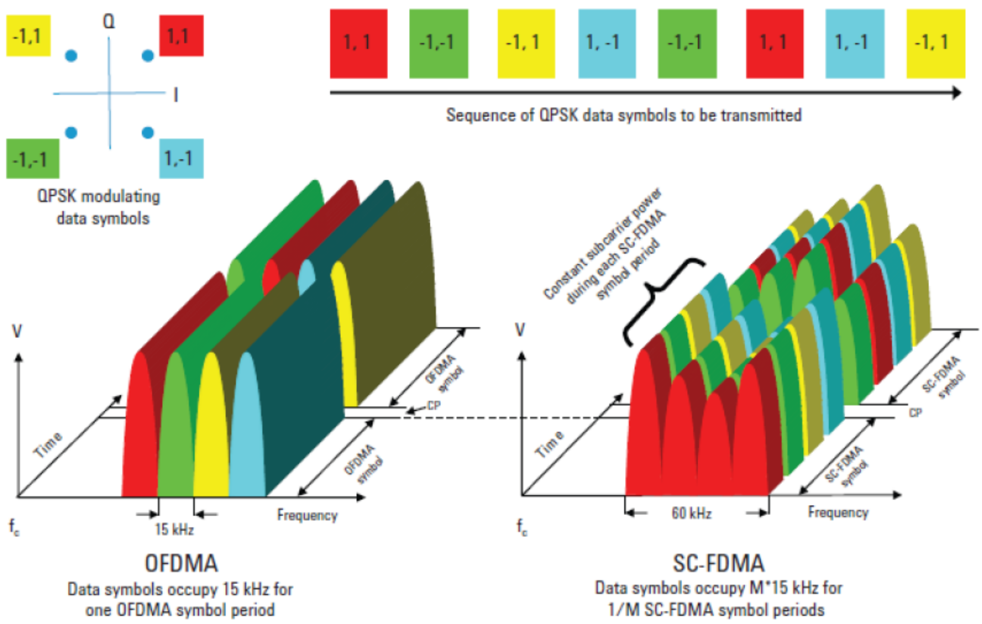


Figure 10. OFMA AND SC-FDMA signals in time domain. Empty gaps between the symbols are actually filled with cyclic prefixes. [19]

As now can be seen, the foremost difference between SC-FDMA and OFDMA is precoding used in SC-FDMA that unites *M* data symbols into 1 single-carrier symbol for 66.7 µs, where amplitude and phase of original data symbols no more correlate directly with SC-FDMA symbols unlike in OFDMA, whose symbols are formed with directly modulating subcarriers with data symbols. Symbol time and subcarrier frequency spacing have the following dependency

$$\Delta f = \frac{1}{T_s} \quad (1)$$

where $\Delta f = 15\ kHz$ and $T_s = 66.7\ \mu s$. The empty gaps between symbols in Figure 10 are used for cyclic prefixes. [19]

3.5 Downlink physical channels

In LTE downlink, there are PDSCH, PDCCH, PCFICH, PHICH, PBCH and PMCH and primary and secondary synchronization signals and reference signals. [12]

- PDSCH (physical downlink shared channel) is the actual payload. These channels can be dynamically allocated between users in time domain and can be individually modulated and coded.
- PSCCH (physical downlink control channel) is channel used by the eNB to control UE. It notifies resource allocation, modulation and coding scheme. Unlike PDSCH, PDCCH is mapped to resource elements as opposed to resource blocks.
- PCFICH (physical downlink format indicator channel) is used to help UE to detect PSCCH.
- PHICH (physical hybrid automatic repeat request indicator channel) is used by eNB to send ACK and NACK to the UE.
- PBCH (or physical broadcast channel) is used to broadcast information needed during UE cell search.
- PMCH (or physical multicast channel) is similar to PDSCH except it broadcasts to multiple users.
- Reference signals are used in channel estimation, scattered evenly across resource grid to pre-defined resource elements.
- Primary and secondary synchronization signals' functions differ, but both participate in the cell synchronization and cell search.

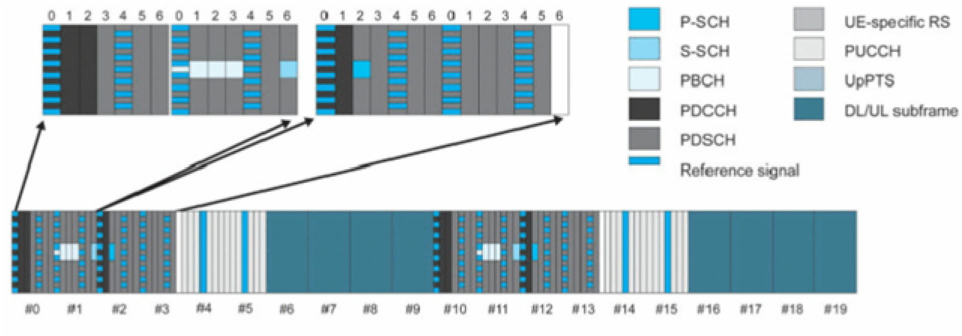


Figure 11. Example of downlink mapping in FDD. [22]

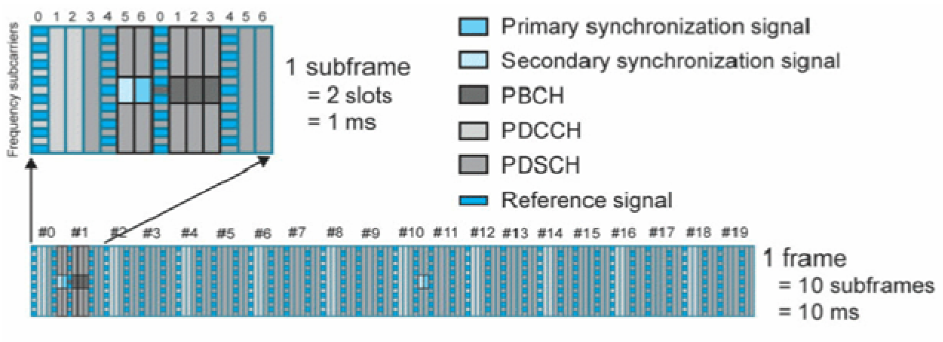


Figure 12. Example of downlink mapping in TDD. [22]

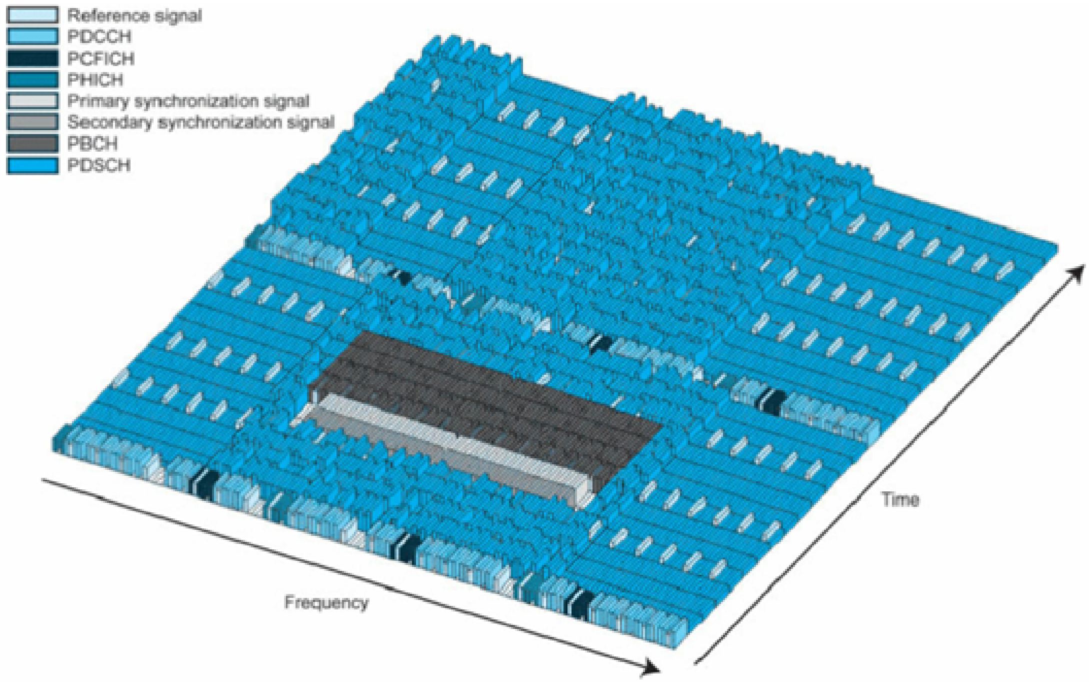


Figure 13. TDD downlink mapping in 3D. Each plate represents a resource element. [22]

Spread of the control channels makes LTE robust. Therefore contiguous wave makes little damage to LTE transmission. LTE is far more sensitive to wide-band noise. In the later test cases, CW is not used as interferer per se for this reason. 3 MHz AWGN signal and 5 MHz intermodulation product are used instead.

3.6 Multiple input multiple output

Multiple input multiple output, or MIMO, is a setup where more than one antenna are transceiving. MIMO systems consist of *m* transmit antennas and *n* reception antennas. MIMO setup is used for two main purposes: increasing data rate and increasing robustness. As a third MIMO technique, beam forming is used to increase the cell coverage by adjusting the radiation pattern. [22]

Multi-antenna techniques are key features in LTE-A. LTE-A has 9 different Transmission Modes, or TMs, for downlink, each being a different MIMO setup. [22]

An increase in data rate is achieved by sending multiple data streams, or layers, over multiple antennas. When this technique is used to increase single user's data rate, it is called single-user MIMO. When this technique is used to increase cell data rate, it is called multi-user MIMO. [22]

Increase in robustness is achieved by sending identical layer over multiple antennas. Adding redundancy in such manner enhances S/R ratio. This is called transmit diversity. Transmit diversity is MIMO default mode, and a fallback option for more complex modes. Later in Chapter 6, measurements are executed in TM2. [22]

3.7 Carrier Aggregation

LTE-Advanced is designed to meet the throughput requirements by increasing the transmission bandwidth. Because LTE-A was supposed to be fully backwards compatible, bands specified in Rel-8 (and UMTS) were used. A reasonable method of increasing bandwidth is Carrier Aggregation (CA), a technique where downlink carriers are aggregated up to 100 MHz bandwidth. The LTE receiver can tune to only one LTE carrier, but LTE-A receiver can benefit from the aggregated component carriers (CCs) and eventually wider downlink bandwidth. See Appendix 2. [2]

According to specification of TDD, bandwidths and amount of CCs are equal in uplink and downlink. In FDD, uplink and downlink can have a different number of CCs, with uplink having always less. Moreover, the carriers may vary in transmission bandwidth. Supported bandwidths for TDD and FDD are the usual 1.4, 3, 5, 10, 15, and 20 MHz with adjustable amount of resource blocks. As maximum of 5 CCs can be aggregated, the total aggregated transmission bandwidth is 100 MHz. [24]

Carrier aggregation can be divided into 3 categories according to carrier placement, see Figure 14: [24]

- In contiguous intraband CA, CCs are neighbouring. Carriers merely seem to continue over wide bandwidth

- In non-contiguous intraband CA, CCs are within the same band but, as the name suggests, not contiguous
- In the interband CA, CCs are on different bands

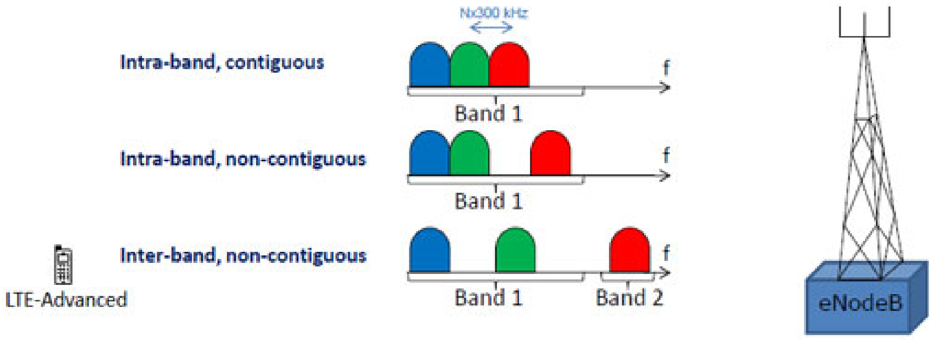


Figure 14. Carrier Aggregation categories illustrated. [24]

In CA, there are always primary component carrier (PCC) and secondary component carrier(s) (SCC(s)). PCC is responsible for maintaining the connection [24]. PCC is changed only during handover, SCCs are changed according to needs [24]. Carriers are on respective cell: PCC is on primary cell (Pcell) and SCC on secondary cell (Scell) [13].

According to 3GPP, one of the key measurements for UE is receiver reference sensitivity. Reference sensitivity is defined to be met with both carriers, regardless of which CC is PCC. In specification sheets, more detailed requirements are laid out [25]. Receiver sensitivity is discussed in more detail in Section 5.5.

4 RATIONALE FOR REDUCTION

4.1 Interoperability testing

A part of EMC is RF interoperability (RF IOP), the ability of different RF modules to operate in close proximity without causing degradation in performance [26]. 3^{rd} harmonic of WCDMA 850 transmission landing on WLAN reception channel and degrading sensitivity, or increase in noise floor by display are exemplary IOP problems. IOP is in some contexts referred to as in-device coexistence, and usually the terms are used interchangeably. After interference is found it is suppressed or the source is isolated with different methods.

It is not only transmitters that can cause interference in the device. All alternating currents with sufficiently high frequency have RF characteristics that can reduce performance. Therefore running e.g. a camera, a display or a wireless charger can produce electromagnetic fields within the device that can become induced in the receiver chain and reduce performance. Even if the modules themselves do not introduce high enough frequencies, their harmonics and intermodulation products can still disrupt the receiver.

It is worth a notion that only the type of interference that degrades reception is of interest in IOP. A multitude of interfering signals might be found in the device but as long as it does not exceed the emission limits or disrupt the reception, the interference is not important.

Although antennas are separately tested, IOP is the first measurement where device performance is tested with antenna in the configuration. While some in-device interference problems might be caught in the earlier phases of testing, in IOP the antenna adds substantial variable. IOP is the first test where RX is connected to the antenna through which interference, e.g. wideband noise by display, might be induced.

4.2 Overlap in band configurations

In IOP tests, LTE bands are tested multiple times with device-specific Carrier Aggregation configurations. This causes significant amount of overlap in tested LTE bands, but whether the information is redundant or not is another matter.

IOP testing is not used to find malfunction in device's CA performance but to find the interference from within the device that could possibly harm the reception. The configurations themselves are not what is tested but the interference that lands on their receivers. The effect of interference in the RX with Carrier Aggregation enabled is not well studied subject, and there are no tests done on whether the same bands should or should not be tested in multiple configurations to detect interoperability problems.

Different CA configurations might lift different interference out even when measuring the same bands. Depending on the interference and band configurations, e.g. intermodulation distortion products from transmission and baseband harmonic might degrade reception. The overlap is redundant only if the additional tests do not provide additional information. Reducing redundancy is desired outcome but not on the expense of results' comprehensiveness.

4.3 Increase of test channels

Measuring the performance of multiple receivers against multiple sources of interference leads to laborious testing effort. One of the longest measurements is with LTE technology because of fragmented band distribution and because LTE-A introduces multitude of configurations for Carrier Aggregation.

In Equation 2 it can be seen that to the more component carriers there are present in the test, the more test channels are required, and the growth is exponential, as r_s is in the power of *k.*

To calculate the amount of test channels in CA configuration, see

$$m = r_p * {r_s}^k * n * \frac{(n-1)!}{k!\,(n-1-k)!} \qquad (2)$$

$m = number\ of\ test\ channels\ in\ total$
$r_p = number\ of\ test\ channels\ in\ primary\ carrier$
$r_s = number\ of\ test\ channels\ in\ secondary\ carriers$
$n = number\ of\ bands\ in\ the\ original\ configuration$
$k = number\ of\ aggregated\ bands\ in\ the\ test\ configuration$

To find the most economic test sequence for Carrier Aggregation, Equation 4 is examined. Equation 4 predicts that the number of aggregated carriers is the most critical factor in the number of total test channels. In Table 3 test channels of 4 component carrier (4CC) configuration are calculated when the measurement is split down to 2 component carrier (2CC), 3 component carrier (3CC) and original 4CC configuration.

Table 3. Example calculation for channel reduction.

Overall config \ Test config	4CC	- 4 carrier configuration - conf. split down to lower configurations - 20 channels at primary carrier - 5 channels at secondary carriers
2CC	1 200	
3CC	6 000	
4CC	10 000	

In Table 3 one can see that the shorter the configuration, the lesser the number of the test channels required. The most economical solution would be to measure all carrier aggregated configurations split down to 2CCs, and to use 2CC's PCC test result to replace single carrier test result.

The superior economic efficiency of 2CC over 3CC is more diverse than this calculation suggests. The test stack for 3CC is more complex, requiring additional equipment. Ability to avoid the acquisition costs for such device would mean notable savings.

5 TEST SETUP

5.1 Plan for testing interchangeability of measurement results

To reduce CA test burden in IOP, it should be studied if the test results are interchangeable in similar configurations and if differences between the tests should arise, which test case is the most comprehensive. In other words the redundancy of overlap is of interest.

In the tests, narrow-band interferer is used for better validity. Although in most real life scenarios wide-band noise causes most of the trouble, handling such noise is somewhat difficult. CW as the source of interference is on the other hand more unambiguous as its behavior is easier to trace. Hence, narrow-band interference is exploited. Both wide-band and narrow-band interference occurs in devices, depending on the source.

Single carrier and primary carrier are technically identical LTE connections. The results of similar distortion at single carrier and primary carrier should be compared to verify correspondence. If both measurements lead to similar results, overlap is redundant and only other is necessary to measure. This measurement is presented in Subsection 6.1.1.

Secondary carrier is different to single carrier in theory because of the presence of uplink in single carrier. Alternating uplink frequency might lift up or override some interference. Testing in practice if there are some cases where single carrier and secondary carrier do in fact end up in different sensitivity results at the same carrier is presented in Subsection 6.1.2.

If aggregated configurations are split down to shorter configurations, the effects must be carefully studied. As opposed to replacing singe carrier (SC) with PCC where no carriers are set apart from each other, splitting Carrier Aggregation configurations the interaction of now separated carriers will not be tested. There is a possibility to lose information by separating interacting carriers away from each other. Therefore, the tests must focus on examining whether or not there is interaction between component carriers that will be lost after the connections are up separately.

The effect of configuration on primary carrier sensitivity should be studied. Measuring sensitivity degradation of primary carrier with interferer in both 2CC and 3CC should reveal whether the configuration affects sensitivity. The test can be set up according to test in Subsection 6.1.1. Test is conducted in Subsection 6.2.1.

Similarly, the effect of separating downlinks must be carefully studied. Splitting downlinks to separate measurements leads to not testing secondary carriers' downlinks effect on each other. If downlink traffic causes harmonics or intermodulation products that are induced after the filtering, separating them away from each other would prevent finding those interferences. Evaluation of interchangeability is based upon studying the similarity between the sensitivities in both cases, in Subsection 6.2.2.

To find out whether the test results can be generalized, thorough testing must be conducted. The following 4 test cases are conducted

1. An intermodulation product of interferer and uplink is placed on (primary) downlink frequency, and results of single carrier and primary carrier are compared. The similarity of degradation by intermodulation (IMD) products effect is studied.
2. An interferer is placed on (secondary) downlink frequency and results of single carrier and secondary carrier are compared. The similarity of degradation by interferer is studied.
3. An intermodulation product of interferer and uplink is placed on (primary) downlink frequency (as in test 1). The results of 2CC and 3CC are compared. The similarity of sensitivity plots are studied.
4. SCC2 3rd harmonic (H3) with high and low downlink (DL) levels is tuned on SCC1 in 3CC configuration, and similarity between results with 2CC configuration without H3 from SCC2 is compared.

5.2 Nonlinear distortion

A perfectly linear amplifier would have transfer function [32]

$$v_{out}(v_{in}) = c_0 + c_1 v_{in} \tag{3}$$

Output signal is a linear function of input signal amplified by factor of c_1 plus DC offset c_0, see Figure 15.

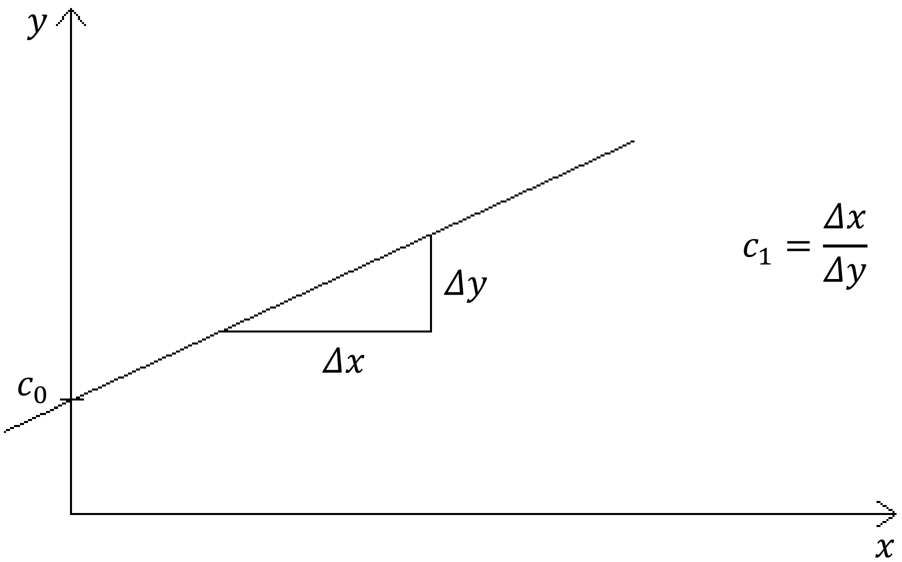


Figure 15. Linear amplifier.

A linear amplifier will not introduce additional components to output, whereas nonlinear amplifier will generate components at output that are not present at input. Well-known example is the harmonic products of the input signal. The nonlinearity of the amplifier can be approximated with Taylor series [32]

$$v_{out}(v_{in}) = \sum_{n=0}^{\infty} c_n v_{in}^n = c_0 + c_1 v_{in} + c_2 v_{in}^2 + c_3 v_{in}^3 + c_4 v_{in}^4 \ldots \tag{4}$$

Nonlinear coefficients c_2, c_3, c_4 etc. and input voltage raised to the 2nd, 3rd and 4th power, respectively, leading to nonlinear transfer function. A graph of a transfer function is no longer linear. From 4th term on, the coefficients are usually small enough to be ignored.

To further illustrate the effects of the transfer function, let us consider input signal representing uplink signal and internal interferer [32]

$$v_{in} = a_1 \cos(\omega_1 t) + a_2 \cos(\omega_2 t) \quad (5)$$

Two components with amplitudes a_n and angular velocities ω_n are introduced to nonlinear amplifier. Let us examine the output components of the first 3 term [32]

$$\begin{aligned}
v_{out}(v_{in}) = {} & c_0 + c_1 v_{in} + c_2 v_{in}^2 + c_3 v_{in}^3 \\
& = c_0 + c_1(a_1 \cos(\omega_1 t) + a_2 \cos(\omega_2 t)) \\
& + c_2(a_1 \cos(\omega_1 t) + a_2 \cos(\omega_2 t))^2 \\
& + c_3(a_1 \cos(\omega_1 t) + a_2 \cos(\omega_2 t))_{in}^3 \\
& = c_0 + c_1(a_1 \cos(\omega_1 t) + a_2 \cos(\omega_2 t)) \\
& + c_2 \left[\frac{a_1^2 + a_2^2}{2} + \frac{a_1^2}{2} \cos(2\omega_1 t) + \frac{a_2^2}{2} \cos(2\omega_2 t) \right. \\
& \left. + a_1 a_2 \left(\cos\big((\omega_1 - \omega_2)t\big) + \cos\big((\omega_1 + \omega_2)t\big)\right] \\
& + c_3 \left[\left(\frac{3a_1^3}{4} + \frac{3a_1 a_2^2}{2} \right) \cos(\omega_1 t) \right. \\
& + \left(\frac{3a_2^3}{4} + \frac{3a_1^2 a_2}{2} \right) \cos(\omega_2 t) + \frac{a_1^3}{4} \cos(3\omega_1 t) + \frac{a_2^3}{4} \cos(3\omega_2 t) \\
& + \frac{3a_1^2 a_2}{4} \left(\cos\big((2\omega_1 - \omega_2)t\big) + \cos\big((2\omega_1 + \omega_2)t\big)\right) \\
& \left. + \frac{3a_1 a_2^2}{4} \left(\cos\big((2\omega_2 - \omega_1)t\big) + \cos\big((2\omega_2 + \omega_1)t\big)\right] \right. \quad (6)
\end{aligned}$$

It should be clear by now that there are frequencies present at output that were not present at input. The components that are generated at the nonlinear amplifier are called harmonics, if the result signal is at integer multiple of fundamental frequency, or intermodulation products, if the result signal is at sum or difference frequency of integer multiple of fundamental frequencies [27].

Mapping some of the resulting intermodulation products on frequency domain are in Figure 16.

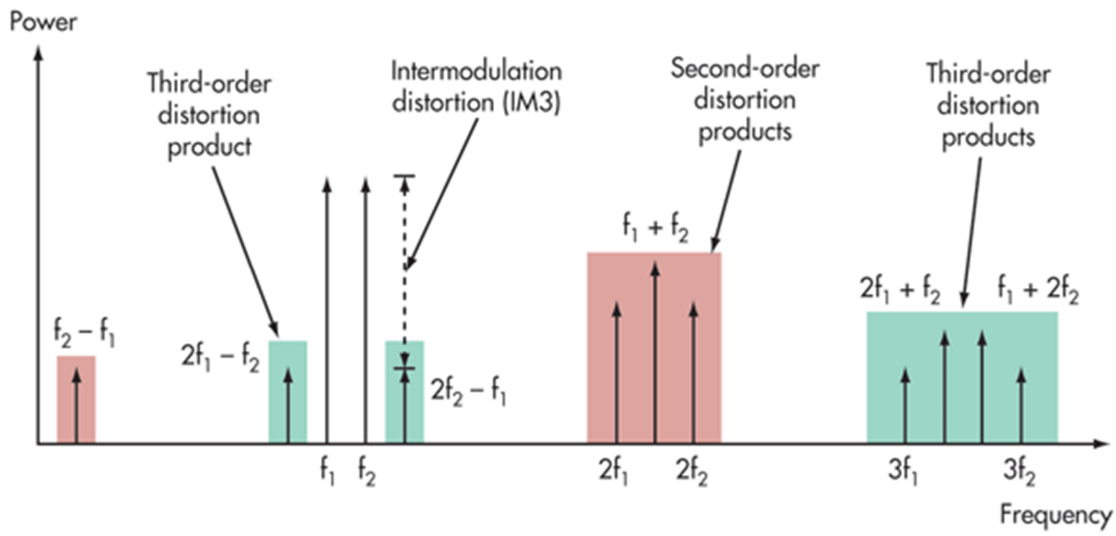


Figure 16. Relevant distortion products. [28]

Some IMD products cause extensive trouble for the receiver filtering because of the proximity in frequency plane, namely $2f_1 - f_2$ and $2f_2 - f_1$ in Figure 16. The IMD products that are used in this thesis are IM3 product and H3 which lands on reception channel. The power of the product is relative to the power of the input signal(s). With low input signal levels, the product will not cause degradation at receiver even on reception channel.

5.3 Transceiver block diagram

Although the interferer in IOP test cases is originated from modules inside the DUT, in this thesis the test case is designed for sufficient repeatability. In this thesis the interferer is introduced to the system from external signal generator, simulating internal interference. While the interferer from the modules can be on any frequency, with external signal generator selecting the interferer frequency is more particular. External interferer must pass through filters that internal interferers do not go through. In Figure 17 is a block diagram of transceiver.

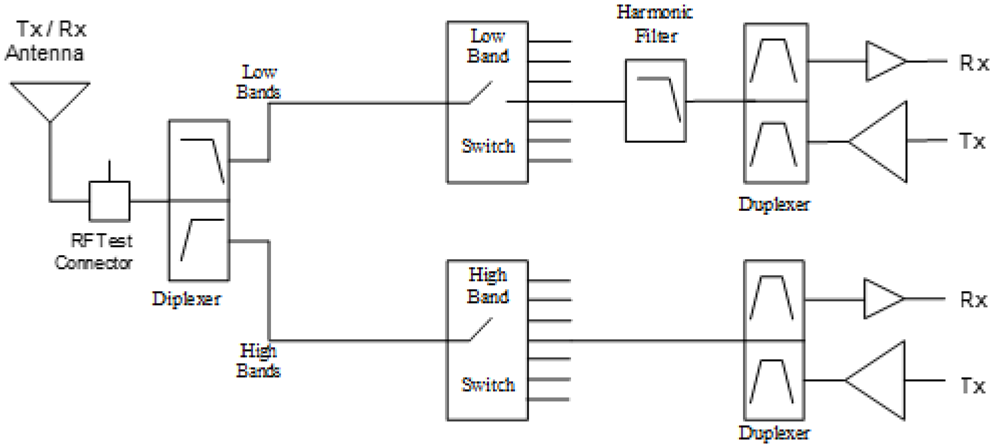


Figure 17. Transceiver block diagram. [31]

The interferer must pass through duplexer so interferer on either reception channel or transmission channel is most reasonable, as attenuation outside band pass is 60 dB. The first method of generating interference is to tune CW on reception channel. The second method is to tune the interferer on a frequency where the interferer itself does not degrade reception but only nonlinear distortion, e.g. intermodulation products, do. See Figure 18. Usable carrier configurations in this test have transmission in lower frequency than reception, see Appendix 2. When half way between lowest transmission frequency and lowest reception frequency lands on transmission channel, the configuration can be used for the setup.

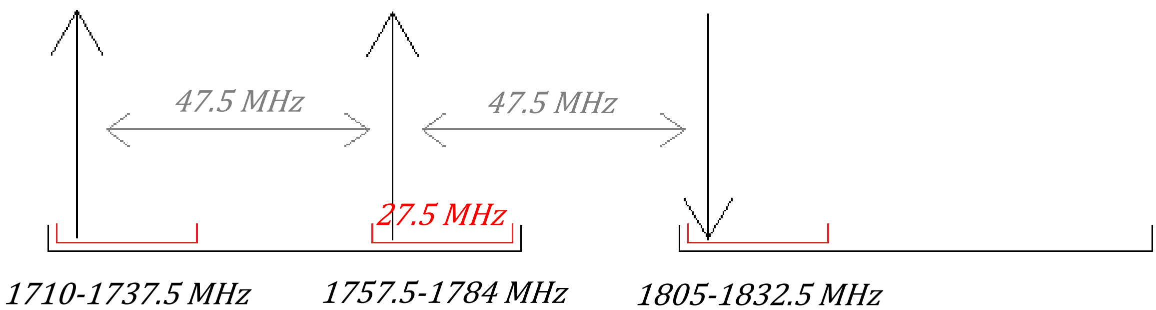


Figure 18. CW in frequency plane. In this exemplary setting, where band 3 is used, transmission is at low limit of uplink band, lowest channel in the figure. 47.5 MHz higher there is CW, still on uplink band, thus passing through the TX filter to PA, in the middle channel of the figure. Another 47.5 MHz higher there is

reception, the specific frequency that is being measured with the specific uplink, at highest channel in figure. Also the IMD lands on this same frequency.

$$f_{IMD} = 2f_{CW} - f_{TX} \quad (7)$$

CW is tuned to appropriate frequency and signal passes through duplex filter to transmitter's PA, although small power levels might leak to LNA. At the PA output, UL and CW IMD products leak over the duplex filter to LNA, with ~60 dB attenuation according to duplexer specification. IMD product degrades sensitivity. This is so called reverse IMD phenomenon, see Figure 19.

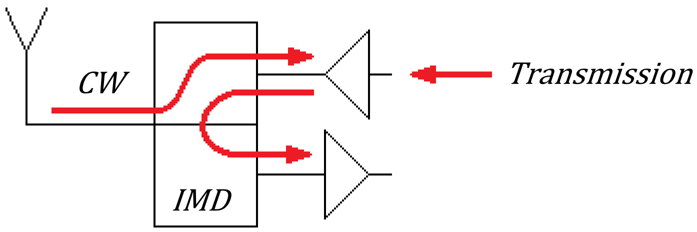


Figure 19. Reverse IMD phenomenon.

Harmonics are generated at LNA. The passing signal produces harmonics that degrade the reception.

5.4 Device setup

The test setup is depicted in Figure 20. The basic setup is RCT and DUT that are connected via cable. RCT is Anritsu M8820C. A splitter is added to divide the RCT output signal between DUT and SA.

An external Agilent E4438C ESG vector signal generator is coupled to the line. Between coupler and generator, there is filtering in order to filter out the DUT transmission from generator output. DUT transmission is at high output level and similarly to distortion at DUT PA, the two signals can cause intermodulation at the generator output.

First filter from the coupler is 5 MHz tunable band reject filter, which is tuned to the transmission bandwidth with attenuation of ~60 dB. Second filter is a transmission band pass filter, which filters out the distortion products at reception channel that might still be generated at generator. Between the two filters, there is a 10 dB attenuator for impedance matching.

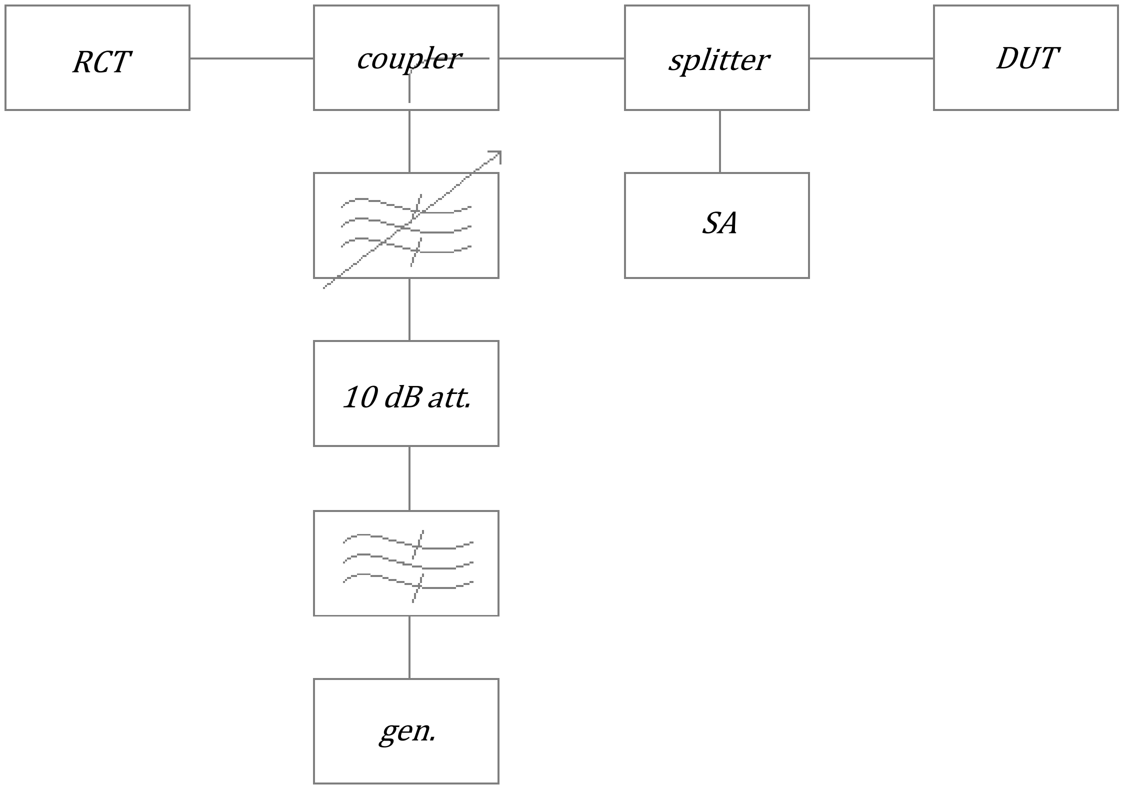


Figure 20. Setup block diagram.

Path attenuation between generator and DUT was measured to be approximately 38 dB at relevant frequencies. Later, generator output level is the level reported at measurements.

5.5 Sensitivity search

In device test specification sheet [29], a reference sensitivity level test procedure is presented. The purpose of the test is

> To verify the UE's ability to receive data with a given average throughput for a specified reference measurement channel, under conditions of low signal level, ideal propagation and no added noise. A UE unable to meet the throughput requirement under these conditions will decrease the effective coverage area of an e-NodeB.

RCT downlink power is set to signal level declared in [29]. DUT transmission is at maximum level during the measurement. RCT sends blocks to DUT sufficiently large amount to get statistically valuable result. Throughput is then analyzed. Throughput should reach 95 %. Uplink and downlink signaling is set to QPSK and reference sensitivity limits for each bandwidth are set separately. Performance tests are usually run with 5 MHz (25 RB) bandwidth, as is the case also in this thesis.

In sensitivity search the test procedure is slightly different. The downlink level for 95 % throughput is iterated. RCT sends blocks to DUT which reports back how many blocks it received. RCT iteratively lowers the downlink power level until BLER is 5 %. The sensitivity search finds the receiver sensitivity floor where as the reference sensitivity level simply tests if the DUT passes the specification limits.

Any internal interference leaking to receiver at reception channel would therefore be visible in sensitivity search where the absolute performance of the receiver is tested. When some sort of distortion is present, to reach 95 % throughput, RCT must raise the downlink level to restore the required S/N ratio. The peaks at downlink power are therefore sign of interference at that frequency. These interferers are traced in IOP, so they can be dealt with in order to improve the sensitivity.

To make better sense of sensitivity search results, comparison with calculated reference sensitivity for 5 MHz bandwidth is useful (according to Table 2 transmission BW is 4.5 MHz). In the exemplary calculations, noise factor NF is set to 9 dB, S/N is set to -1 dB, implementation margin IM is 2.5 dB, and diversity increases gain by 3 dB, see Figure 21. [9]

$$P_{dBm} = -174 + 10log_{10}(\Delta f) + NF + \frac{S}{N} + IM - G_{div} \qquad (8)$$

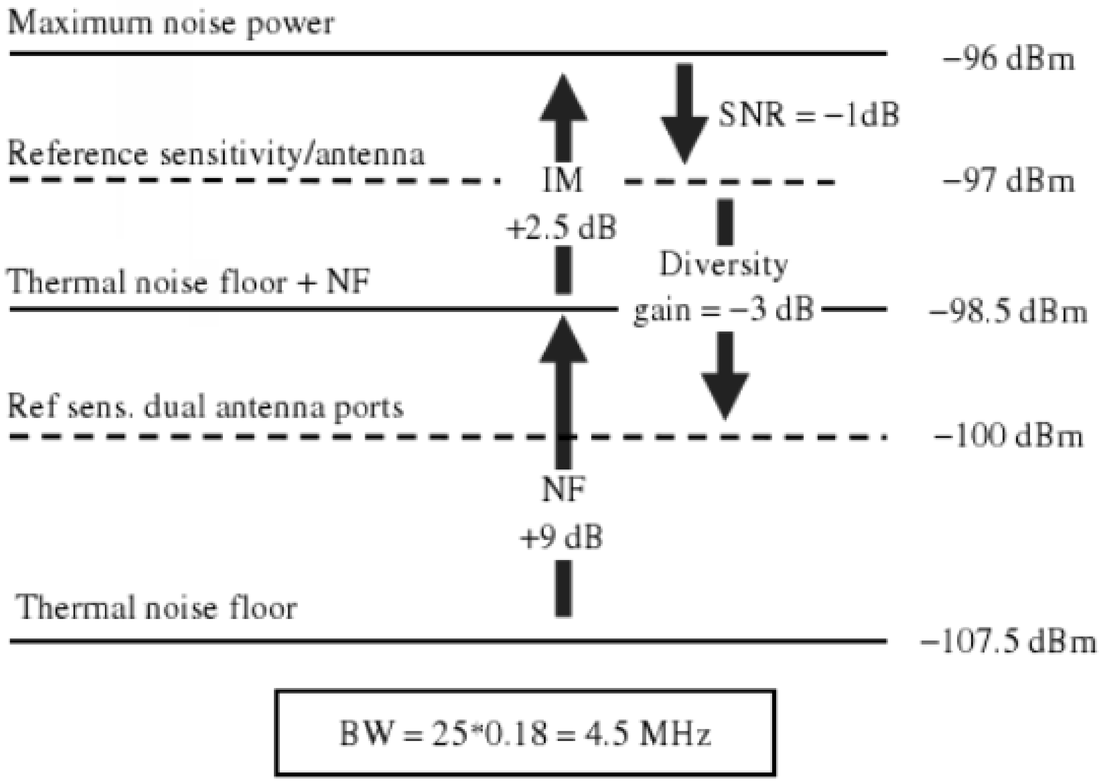


Figure 21. Reference sensitivity budget for 5 MHz bandwidth. [9]

The result is -100 dBm [9]. The actual measurements differ from calculated reference sensitivity because of device-specific NF and error correction algorithms that can tolerate lower S/N ratio.

6 MEASUREMENTS

6.1 LTE and LTE-A 2CC comparison

6.1.1 Comparing LTE SC to LTE-A PCC with IM3 as interferer

In this test, CW (output level 20 dBm) was introduced to the system according to Figure 20. The CW frequency was selected in a manner where DUT transmission and CW generates an intermodulation product at reception frequency, see Figure 18. Intermodulation distortion product was chosen for the test to ensure that the externally generated interferer is technically as close as possible to internally generated interferer.

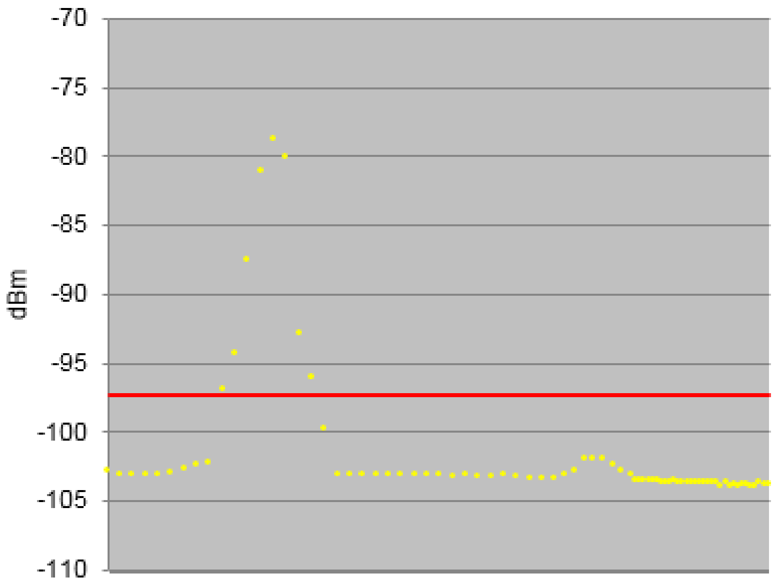
The signal level at the DUT was measured as -27.5 dBm which is in line with the path attenuation. For the signal to pass through the filtering, it is necessary to select CW at transmission frequency. Reception and transmission have fixed duplex spacing meaning that IMD3 product needs to be in the middle of the duplex spacing, see Figure 18. Using band 2, CW frequency of 1899 MHz reasonably fulfils requirements. When transmission is 1859 MHz and CW at 1899 MHz, the intermodulation product appears at reception frequency 1939 MHz, see Equation 7. The frequencies are in Table 4.

Table 4. Frequencies used in measurement in Subsection 6.1.1.

Band	Mode	EARFCN DL	DL (MHz)	EARFCN UL	UL (MHz)
2	FDD	690	1939.0	18690	1859.0
17	FDD	5790	740.0	23790	710.0
29	FDD	9715	722.5	-	-

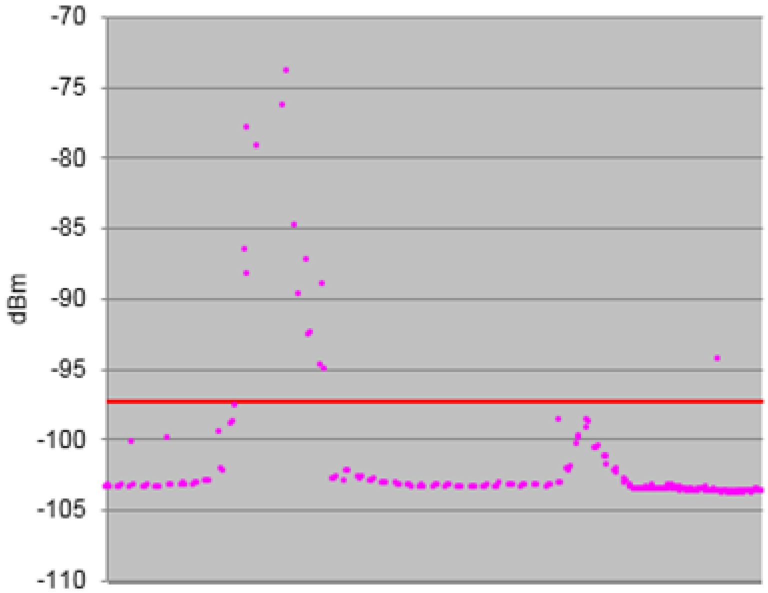
In the following Graphs, frequency is on x-axis and power level is on y-axis. Red lines are limits given in specification.

In Graph 1, there is visible degradation at band 2 sensitivity.



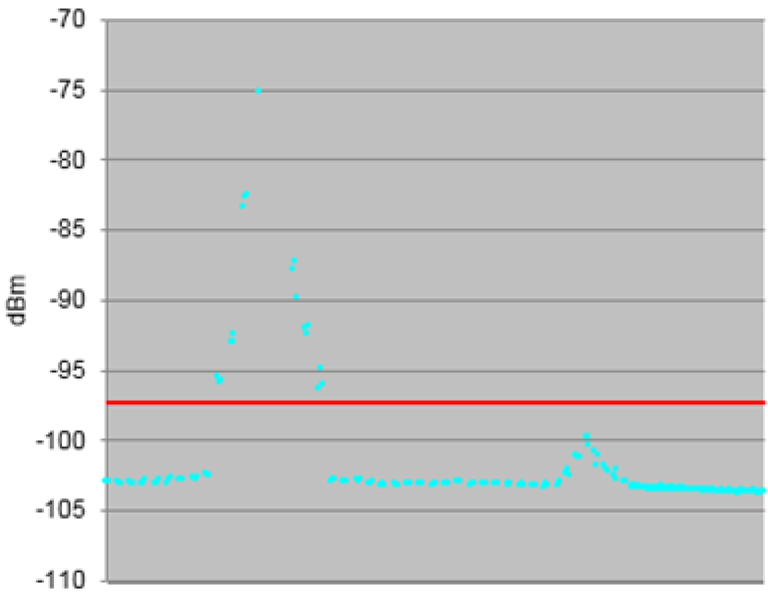
Graph 1. Band 2 sensitivity. Clear degradation where IMD is present. Incidentally, a 5th order IMD product appears at low right in the plot.

Band configuration 2+17 with degradation in band 2 in Graph 2.



Graph 2. Band 2 sensitivity in 2+17. Similar degradation to Graph 1 plot.

Band configuration 2+29 with degradation in band 2 Graph 3.



Graph 3. Band 2 sensitivity in 2+29. Degradation in sensitivity is similar to those depicted in Graph 1 and Graph 2.

Within the limits of measurement accuracy and taking the varying nature of uplink into consideration, the sensitivity graphs are similar. Each measurement was run 5 times for better validity. The plot is band 2 sensitivity with approximate sensitivity of -103 dBm. The sensitivity is clearly degraded at 1939 MHz, reaching -87 dBm at worst in SC case and -73 dBm at worst in 2CC cases. Also, at frequency 1952.5 MHz, an IM5 product of UL at 1872.5 MHz and CW degrades sensitivity, and even more visibly in CA case.

When DUT is measured multiple times consecutively, the temperatures inside the DUT rises. The rise in temperature has complex effects on receiver, e.g. in filters' frequency response. This has an effect on degradation.

The degradation of sensitivity is close to identical in each measurement. The sensitivity degradation caused by out-of-band interfering signal is equally distinguishable regardless of the band configuration. LTE single carrier measurement results are interchangeable with LTE-A primary carrier measurement results in IOP.

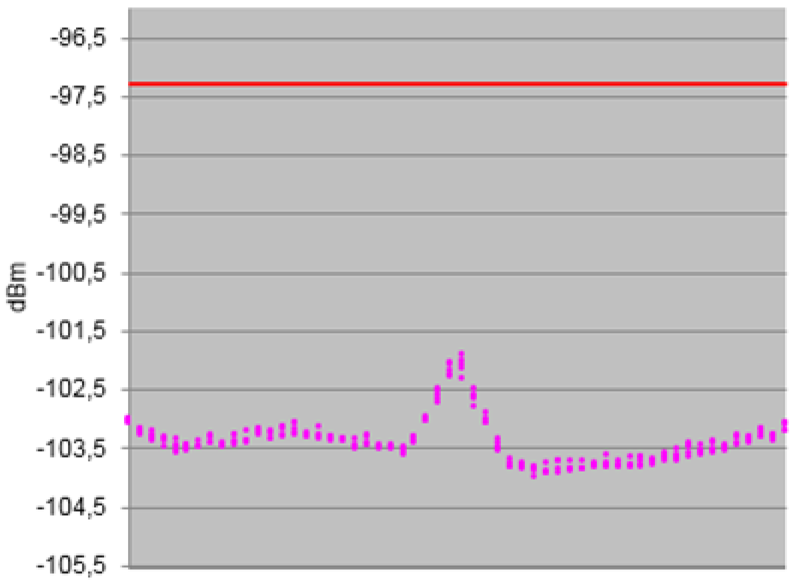
6.1.2 Comparing LTE SC to LTE-A SCC with AWGN as interferer

In this test, an AWGN with 3 MHz bandwidth (output level -82 dBm) is introduced to the system, according to Figure 20. AWGN was selected due to LTE's tendency to be more vulnerable to wide-band noise than to CW, due to the spread physical channel grid in downlink. Band configuration in the test is 17+2, see frequencies in Table 5. The frequency of AWGN was selected to the middle of band 2 DL at 1960 MHz, so no intermodulation is present in this test.

Table 5. Frequencies used in the first measurement in Subsection 6.1.2.

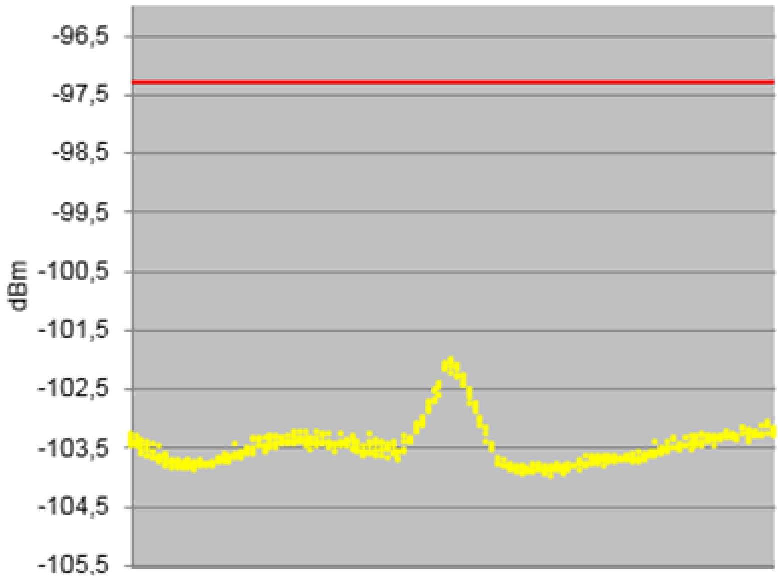
Band	Mode	EARFCN DL	DL (MHz)	EARFCN UL	UL (MHz)
2	FDD	900	1960.0	18900	1880.0
17	FDD	5825	743.5	23825	713.5

Graph 4 shows band 2 sensitivity with degradation at 1960 MHz caused by AWGN interferer.



Graph 4. Band 2 sensitivity with AWGN. Degradation caused by interferer is clear.

Graph 5 shows band 2 sensitivity degradation in 17+2 at 1960 MHz.



Graph 5. Band 2 sensitivity in 17+2 with AWGN. Degradation is similar to Graph 4.

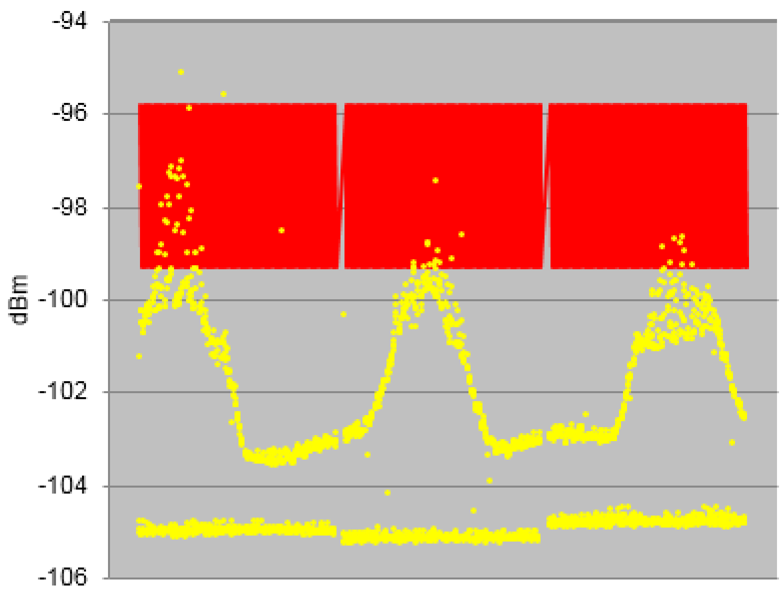
Each test was run 5 times for better validity. Sensitivity degradation in the AWGN frequency is similar in both cases, with sensitivity reaching -101.9 dBm at worst in both tests. The plots are close to identical: both have similar rippling throughout the band. The sensitivity degradation caused by in-band interferer is equally distinguishable regardless of the band configuration.

However, along with 17+2 test it is necessary to repeat the measurement with 17+4 where H3 of UL lands on secondary carrier's reception channel. Frequencies are in Table 6. Specification gives separate requirements for such band configurations with similar phenomenon, see [29]. With up to 10 dBm lower sensitivity requirement for such bands, using secondary carrier test result interchangeably with single carrier result might lead up to losing significant interferer to the risen noise. Using AWGN level of -82 dBm it should verify whether the peak in plot is visible in aggregated configuration as clearly as in band 4 alone.

Table 6. Frequencies in the second measurement in Subsection 6.1.2.

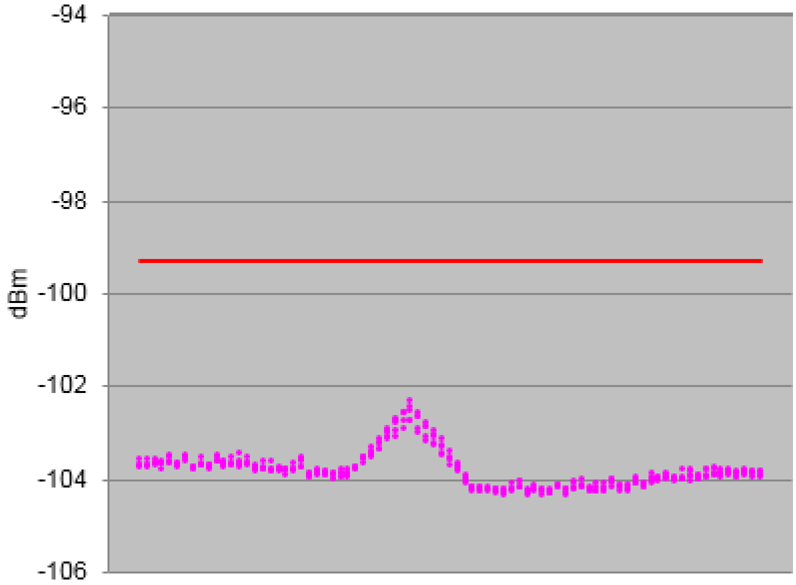
Band	Mode	EARFCN DL	DL (MHz)	EARFCN UL	UL (MHz)
4	FDD	2150	2130.0	20150	1730.0
17	FDD	5825	743.5	23825	713.5

In Graph 6, the effect of UL H3 is clearly perceivable. The secondary was measured on 3 primary channels (hence, 3 different frequencies), thus three plots with similar degradation at three frequencies. The sensitivity degradation is 1-2 dB where harmonic is not directed to, and 5-6 dB where harmonic lands to.



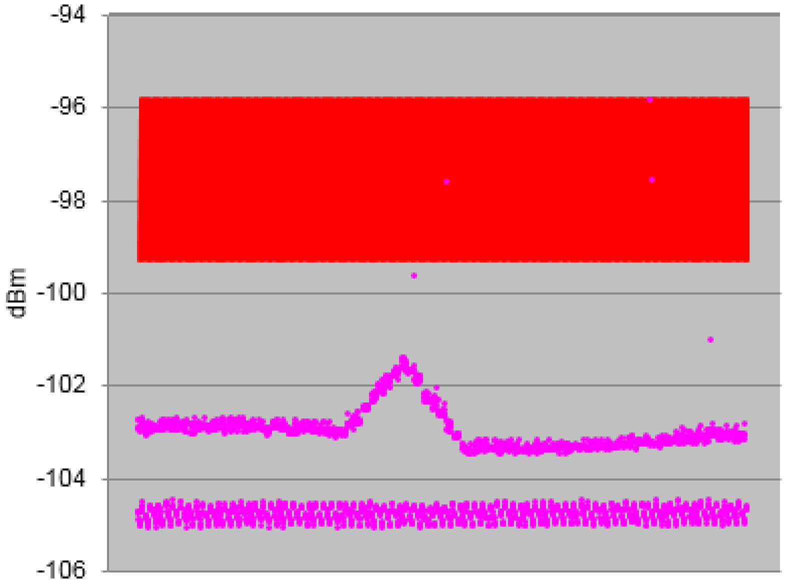
Graph 6. Configuration 17+4 with AWGN. UL third harmonics cause significant degradation in band 4 sensitivity. There are three peaks as PCC was set to 3 different channels as SCC was measured, leading to 3 UL frequencies.

In Graph 7, only band 4 alone was measured with same AWGN as used in previous measurement. As opposed to previous measurement, now the possible interferer is visible. The interchangeability between these results is nonexistent.

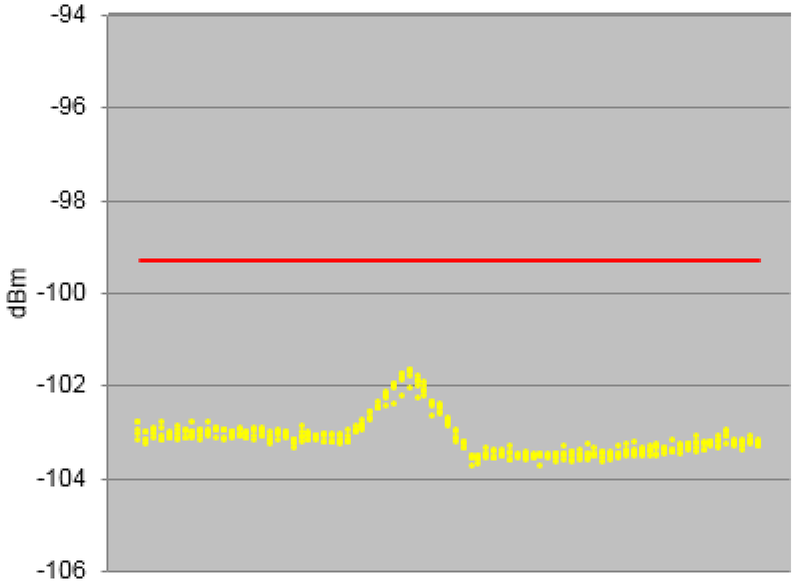


Graph 7. Band 4 sensitivity with AWGN. The degradation is nothing like in Graph 6.

Using the same band configuration but changing primary from band 17 to band 4 results in a plots in Graph 8 and Graph 9. As can be seen, the same carriers have different sensitivity when uplink frequency changes, compare Graph 6 and Graph 8.



Graph 8. Configuration 4+17 with AWGN. The same bands as in previous measurement, but uplink was changed from band 17 to band 4.



Graph 9. Band 4 with AWGN. Resulting plot is similar to that in Graph 4.

The take on this one is that measuring sensitivity with only other band as primary may result in incompetent results. The possible distortion is lost in Graph 6, and the effect of harmonics is lost in Graph 8. While the distortion in Graph 6 is well-known harmonic, the cause might be any uplink originated interference, including IMD product. Therefore each secondary carrier is important to be measured with all possible uplinks. Configurations should be measured with switching primary and secondary bands.

6.2 LTE-A 2CC and LTE-A 3CC comparison

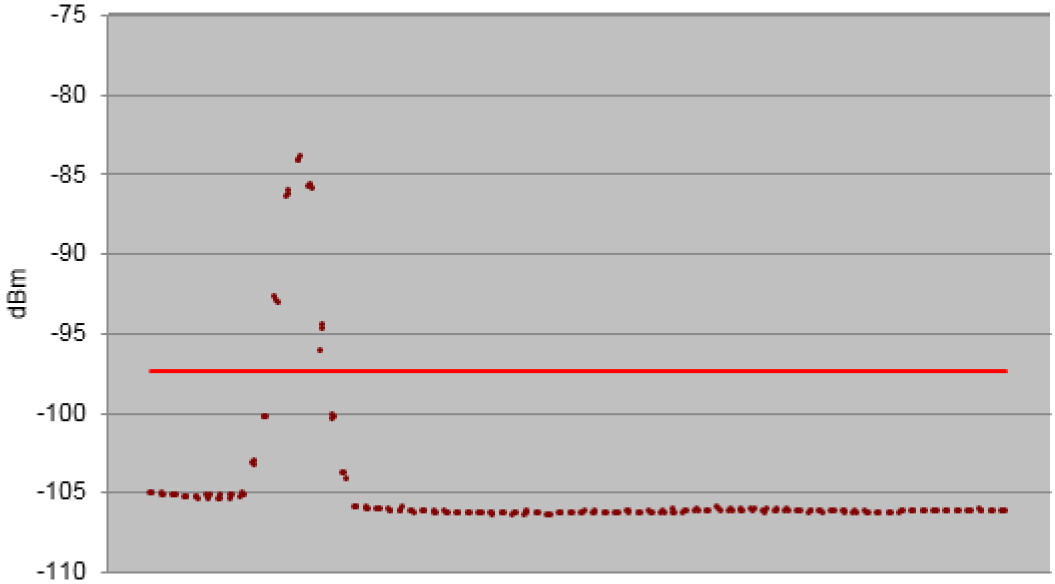
6.2.1 Comparing 2CC PCC to 3CC PCC with IM3 as interferer

Using the results in Subsection 6.1.1, it is reasonable to assume that primary carrier sensitivity search results are interchangeable. Only difference between primary carrier on 2CC and 3CC is increased overhead, which should not have an effect on sensitivity. To confirm this assumption, a measurement was devised.

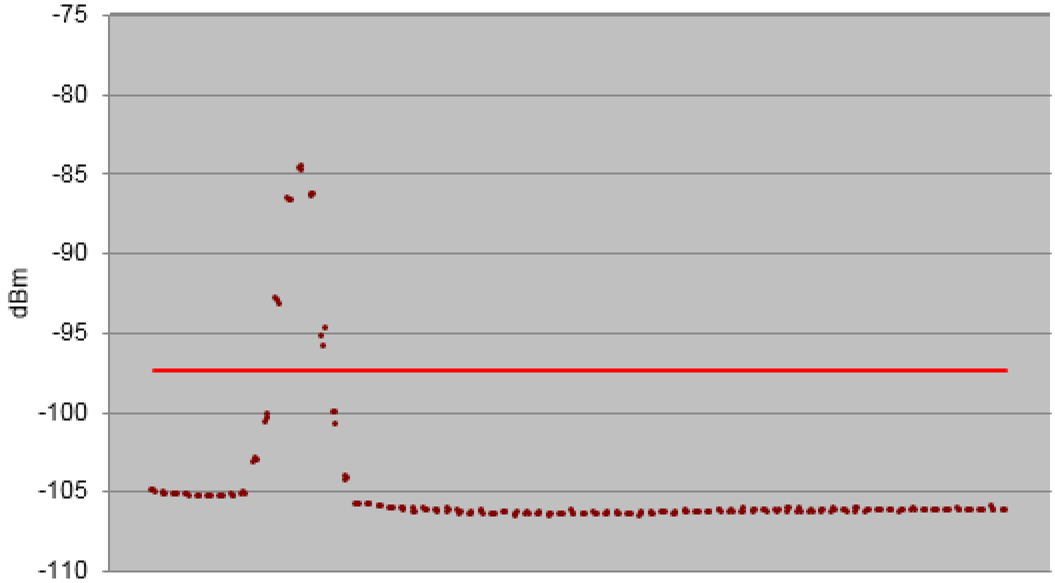
According to test setup in Subsection 6.1.1, an intermodulation distortion was targeted at primary carrier reception frequency. Measurement configurations were 2+12 and 2+30 in 2CC and 2+12+30 in 3CC. Frequencies are presented in Table 7. In 3CC, to make test run time reasonable only the middle channel on both secondary carrier were measured. Only primary carrier is of interest but secondaries were measured to ensure they are active at all times.

Table 7. Frequencies in measurement in Subsection 6.2.1.

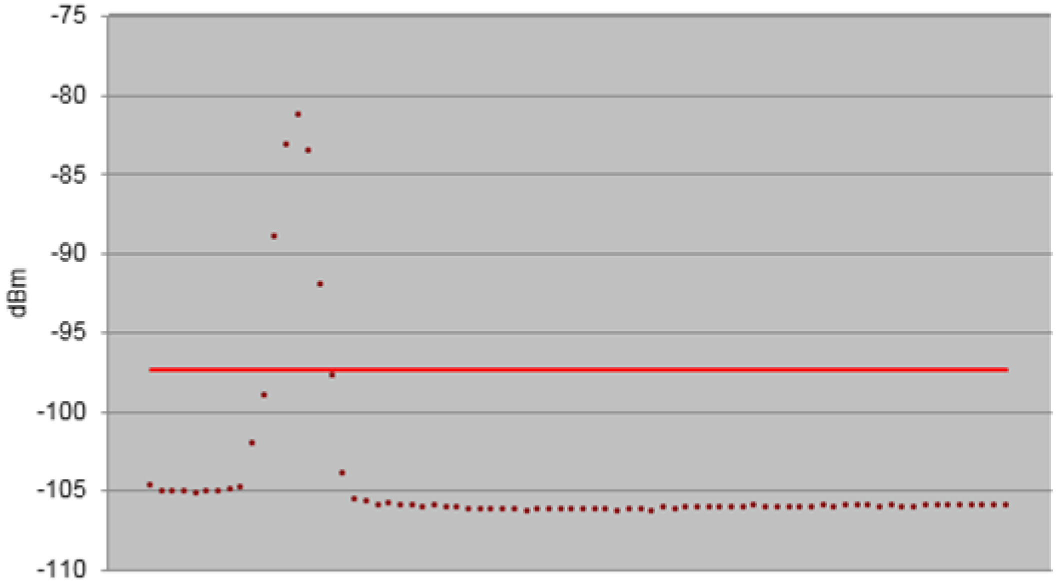
Band	Mode	EARFCN DL	DL (MHz)	EARFCN UL	UL (MHz)
2	FDD	690	1939.0	18690	1859.0
12	FDD	5095	737.5	23095	707.5
30	FDD	9820	2355.0	27710	2310.0



Graph 9. Band 2 sensitivity in 2+12. Degradation by IMD is clear.



Graph 10. Band 2 sensitivity in 2+30. Degradation is similar to that in Graph 10.



Graph 11. Band 2 sensitivity in 2+12+30. Degradation is similar to that in Graph 10 and Graph 11.

The results in this case remind the results in Subsection 6.1.1. The results themselves are not comparable, as different DUT was used. Sensitivity plot shows clear degradation at suspected frequency, resulting plot to shift from approximately -105 dBm to -81.3 dBm at worst in 3CC case and from -105 dBm to -84 dBm at worst in 2CC cases.

However, the variance in the degradation does correlate with measured transmit level, resulting in higher IMD level, and therefore in higher degradation in reception. In Table 8, the average measured transmitted level at channels corresponding to IMD is in Table 8.

Table 8. Average transmit level.

Band configuration	Average measured transmitted level (dBm)
2+12+30	23.3
2+12	20.2
2+30	20.2

2CC measured transmit level is approximately 3 dBm lower than in 3CC. Accordingly, degradation in 2CC is approximately 3 dB lower than in 3CC. As can be seen in Equation 6, 1 dBm increase in uplink signal level leads to 1 dBm increase in IMD. The degradation in sensitivity is similar in both cases considering the uplink level. The possible interference at PCC is as visible in 2CC case as in 3CC case, and similar results are expected with consistent uplink level.

6.2.2 Comparing 2CC SCC to 3CC SCC

The levels of DL signals are presumably low enough to not cause any degradation in other carrier's reception. This is due to the networks tendency to try to use as little power as possible while still maintaining reliable connection.

The possible information loss is caused by missing simultaneous DLs: the separation of CCs must be validated by testing their effect on each other. If DL signal at high level causes intermodulation products with internal interference or harmonics, they might be missed.

See Table 9 for different interband carriers A, B and C in 3CC configuration A+B+C etc. and in 2CC configurations A+B, A+C etc. As stated in Section 6.1., sensitivity is measured with varying uplink (UL) frequencies in order to test if UL brings new distortions to DL frequency. Therefore, just like 3CC should be measured with each carrier as primary, and eventually with alternating UL frequency, also 2CC should be measured with each carrier as primary.

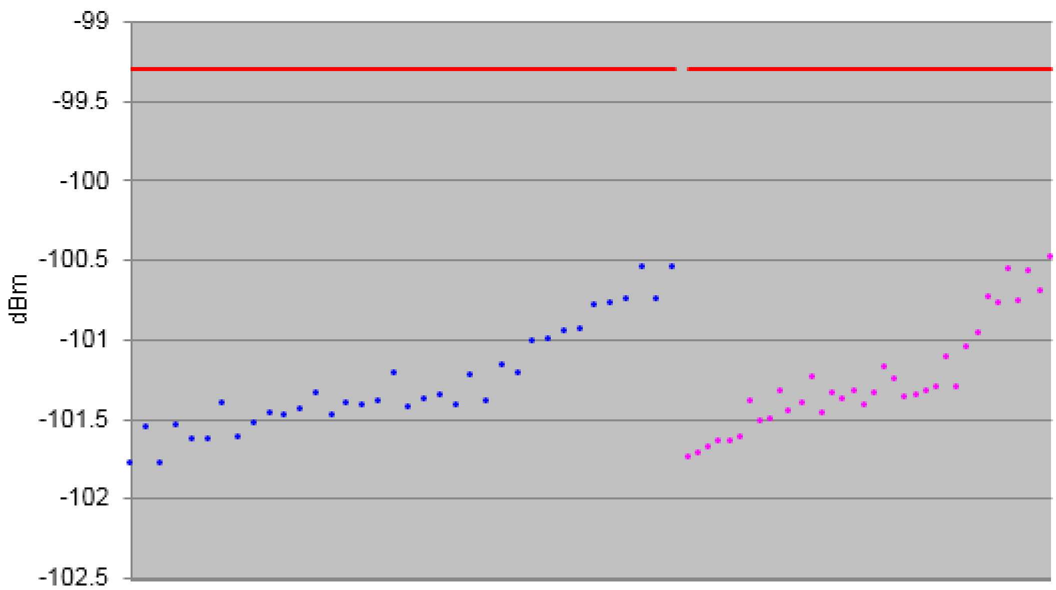
If secondary carrier C lifts up interference at carrier B that is visible in configuration A+B+C, it is visible in configuration C+B, as C and B downlinks are similarly present at both cases and B is correspondingly secondary. The possible interference is present in both 2CC and 3CC configurations.

Table 9. 3CC configurations and corresponding 2CC configurations.

	3CC	2CC	
1st primary	A+B+C	A+B	A+C
2nd primary	B+A+C	B+A	B+C
3rd primary	C+A+B	C+A	C+B

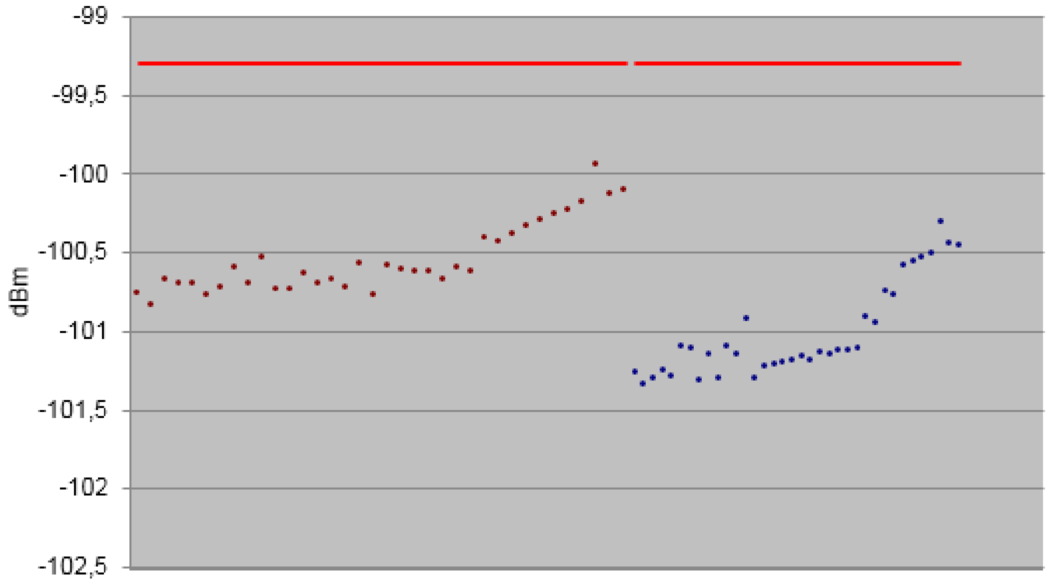
Interference is present in both cases, and tests are carried to verify that both configurations measure it equivalently.

If 3CC configuration has better sensitivity than 2CC, interference might be lost. A test is carried out to test whether the secondary carrier sensitivity is identical in 2CC and 3CC. Configurations 30+4 and 30+4+29 were chosen for test purpose. H3 of band 29 DL lands on upper limit of band 4.



Graph 12. Band 4 in 30+4+29 and 30+4 with low DL power.

In Graph 13, band 4 sensitivity from configurations 30+4+29 (left) and 30+4 (right) is depicted. DL level is -100 dBm for band 30 and -97 dBm for band 29. As can be seen, the sensitivity is similar in both cases. According to this plot, it's reasonable to assume that band 4 sensitivity is same with low DL power regardless of the configuration.



Graph 13. Band 4 in 30+4+29 and 30+4 with high DL power.

In Graph 14, similar plots as in Graph 13 is depicted. DL level is -27 dBm for both bands 30 and 29. Sensitivity degrades across the frequency range. Sensitivity in 3CC is approximately 0.5 dBm worse than in 2CC. The change in the sensitivity is evident throughout the band, not only where H3 lands.

Two conclusions can be drawn. On one hand, high DL causes perceivable degradation in the sensitivity. DL is high enough to possibly lift up interference. On the other hand, the risen sensitivity level by the DL might cover up some minor degradation. Because high DL levels such as in here are unlikely in realistic situations, the possibility of losing degradation peak in the risen sensitivity is more relevant setback.

After considering the two possible speculations, the latter is weighted as more realistic. Lower priority is given to DL originated interference, and DL level is kept low in order to measure more precise measurements with other types of interference. The SCCs can be divided away from each other, because in the unlikely event that SCCs affect each other, testing the possibility might cloak something more urgent.

6.3 Applying the results to Time Division Duplex

Test cases in chapter 6 were implemented with FDD mode. The results can be applied to TDD. PCC will not suffer from transmission originated interference, as transmission and reception on PCC are never simultaneous in TDD. Therefore the problem depicted in Subsection 6.1.2 with H3 of transmission on RX is not topical for TDD. However in-band interference is as much of a problem for TDD carriers, so these carriers should be similarly measured. As CA configurations for present DUTs are mainly in intra-band category, measuring the band with only one DL is sufficient.

Support for simultaneous reception and transmission for inter-band TDD band configuration is device specific. If CCs are on different bands and device does not support simultaneous RX-TX, aggregated downlinks are scheduled in unison. This means that device cannot receive at the same time it transmits. If transmission is never simultaneously active with SCC reception, it won’t be affected. According to test results in 6.2.2., the effect of DL is not worth mentioning. This means there is no actual need to measure TDD in CA configurations at all, and TDD bands can be tested as single carrier.

If device does support simultaneous RX-TX for CA configuration, SCCs scheduling is independent from PCC. Transmission might affect secondary carrier’s reception. Assuming that all devices do support simultaneous RX-TX, same rules for TDD and regular FDD are applied.

6.4 Evaluation of reliability

The most notable compromise to reliability is caused by the inductive nature of the study. Problem of induction is ever-present, and there is little to do about it. Planning the tests in this study were crucial, and comprehensive measurements were conducted. In Subsections 6.1.1., 6.1.2., and 6.2.1. proofing that similar phenomena happen across the measurements was easier to argument. Subsection 6.2.2. revealed to be especially tricky, as the point of the measurement was to prove that no other phenomenon happens. The results were as anticipated, and convincing arguments backed up the conclusion. All in all, the conclusions drawn from the measurements seem reliable and reduction legitimate.

7 IMPLEMENTATION OF REDUCTION

Uplink frequency seems to be determinant factor when it comes to the possible visibility of interferer. Measuring reception channels with all relevant transmission channels seems necessary and sufficient measurement. Single carrier (SC) test results are interchangeable with primary component carrier (PCC) test results, when equivalent bands are measured. 3 component carrier (3CC) test results are equivalent with 2 component carrier (2CC) test results, when equivalent bands are measured in equivalent roles.

By the following changes redundancy is reduced to minimum

- SC is replaced with PCC
- 3CC, 4CC and onwards is split down to 2CC

Under the following conditions the previous changes are legitimate

- PCC is used as SC result as such
- All carriers that are configured as primary in 3CC are primary in 2CC as well. Same applies for secondaries
- All SCCs affiliated with specific PCC in 3CC are affiliated with the said PCC in 2CC

For sufficient accuracy, PCC carriers should be measured with a raster of 20 channels (higher raster for PCC since each carrier is measured only once as PCC), and SCC carriers should be measured with a raster of 45 channels (precise enough considering time savings). Measurements are conducted with 5 MHz bandwidth with full 25 RB.

According to preliminary calculations, test run time of an exemplary product was reduced by 69 % compared to test run time with redundancy intact.

8 CONCLUSIONS

In this thesis, redundancy of IOP test results were studied. Redundancy was defined with interchangeability: if a result from one test exposes the same or more interference as a result from another test, the results are interchangeable and the latter test can be left out. In order to research the redundancy of results, 4 test cases were devised. All tests aimed to find possible phenomena that would appear only on specific Carrier Aggregation configuration. Tests were ran according to test plan laid out in Section 5.1.

In Subsection 6.1.1., a CW interferer was tuned on a frequency where the CW and the device uplink produced an intermodulation product. The IMD product landed on band 2. Band 2 was measured as such and as a primary carrier in 2 different 2CC configurations. The degradation of sensitivity was similar regardless of the configuration. Therefore single carrier and primary carrier tests give similar results, and are therefore interchangeable.

In Subsection 6.1.2., single carrier and secondary carrier results were compared. This was done by tuning CW directly onto the downlink channels. The results were different depending on uplink frequency. The third harmonic of primary carrier uplink was clearly perceiveable in secondary carrier in some cases. If uplink has this type of contribution to degradation, it could also cause degradation of different origin, that is to say degradation caused by two-tone nonlinear distortion. SCC must be measured separately.

Because of the results in 6.1.1. and 6.1.2., the implementation of the reduction was done by leaving separate measurements for single carrier out and replacing the results with PCC results of the same band. This led to savings in test run times.

In Subsection 6.2.1., interchangeability of primary carriers of 2CC and 3CC was studied using 3rd order intermodulation product as interferer. Tests were ran with 2 different 2CC configurations and a 3CC configuration. The tests had a glitch because of the unstability in uplink power, but the numbers checked out. PCC results are interchangeable between 2CC and 3CC.

In Subsection 6.2.2., the significance of two simultaneous SCCs was studied. This was performed by conducting 4 different measurements: 2CC and 3CC with high and low downlink power. The bands were chosen in a manner where third harmonic from one secondary in 3CC would land on another secondary, in this case band 4. 2CC lacked the secondary that was the origin of the harmonic. In the low-power example, band 4 results were similar. In the high-power example, the sensitivity across band 4 in 3CC was decreased. The high-power example was evaluated of lesser significance.

Because of the results in 6.2.1. and 6.2.2., the implementation of the reduction was done by replacing the results of 3CC configurations with the results of lowest common 2CC configurations.

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Operating bands

Table 5.5-1 E-UTRA operating bands

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
	F_{UL_low} – F_{UL_high}	F_{DL_low} – F_{DL_high}	
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD
5	824 MHz – 849 MHz	869 MHz – 894MHz	FDD
6[1]	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD
11	1427.9 MHz – 1447.9 MHz	1475.9 MHz – 1495.9 MHz	FDD
12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
15	Reserved	Reserved	FDD
16	Reserved	Reserved	FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	FDD
20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
21	1447.9 MHz – 1462.9 MHz	1495.9 MHz – 1510.9 MHz	FDD
22	3410 MHz – 3490 MHz	3510 MHz – 3590 MHz	FDD
23	2000 MHz – 2020 MHz	2180 MHz – 2200 MHz	FDD
24	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD
25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
26	814 MHz – 849 MHz	859 MHz – 894 MHz	FDD
27	807 MHz – 824 MHz	852 MHz – 869 MHz	FDD
28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
29	N/A	717 MHz – 728 MHz	FDD[2]
...			
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
41	2496 MHz 2690 MHz	2496 MHz 2690 MHz	TDD
42	3400 MHz – 3600 MHz	3400 MHz – 3600 MHz	TDD
43	3600 MHz – 3800 MHz	3600 MHz – 3800 MHz	TDD
44	703 MHz – 803 MHz	703 MHz – 803 MHz	TDD

NOTE 1: Band 6 is not applicable

NOTE 2: Restricted to E-UTRA operation when carrier aggregation is configured. The downlink operating band is paired with the uplink operating band (external) of the carrier aggregation configuration that is supporting the configured Pcell.

[25]

Operating bands for CA

Table 5.5A-1: Intra-band contiguous CA operating bands

E-UTRA CA Band	E-UTRA Band	Uplink (UL) operating band BS receive / UE transmit			Downlink (DL) operating band BS transmit / UE receive			Duplex Mode
		F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
CA_1	1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
CA_7	7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD
CA_38	38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	TDD
CA_40	40	2300 MHz	–	2400 MHz	2300 MHz	–	2400 MHz	TDD
CA_41	41	2496 MHz		2690 MHz	2496 MHz		2690 MHz	TDD

Table 5.5A-3: Intra-band non-contiguous CA operating bands

E-UTRA CA Band	E-UTRA Band	Uplink (UL) operating band BS receive / UE transmit			Downlink (DL) operating band BS transmit / UE receive			Duplex Mode
		F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
CA_25-25	25	1850 MHz	–	1915 MHz	1930 MHz	–	1995 MHz	FDD
CA_41-41	41	2496 MHz	–	2690 MHz	2496 MHz	–	2690 MHz	TDD

Table 5.5A-2: Inter-band CA operating bands

E-UTRA CA Band	E-UTRA Band	Uplink (UL) operating band BS receive / UE transmit			Downlink (DL) operating band BS transmit / UE receive			Duplex Mode
		F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
CA_1-5	1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
	5	824 MHz	–	849 MHz	869 MHz	–	894 MHz	
CA_1-18	1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
	18	815 MHz	–	830 MHz	860 MHz	–	875 MHz	
CA_1-19	1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
	19	830 MHz	–	845 MHz	875 MHz	–	890 MHz	
CA_1-21	1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
	21	1447.9 MHz	–	1462.9 MHz	1495.9 MHz	–	1510.9 MHz	
CA_2-17	2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
	17	704 MHz	–	716 MHz	734 MHz	–	746 MHz	
CA_2-29	2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
	29	N/A			717 MHz	–	728 MHz	
CA_3-5	3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
	5	824 MHz	–	849 MHz	869 MHz	–	894 MHz	
CA_3-7	3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
	7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	
CA_3-8	3	1710 MHz		1785 MHz	1805 MHz		1880 MHz	FDD
	8	880 MHz		915 MHz	925 MHz		960 MHz	
CA_3-20	3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
	20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	
CA_4-5	4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
	5	824 MHz	–	849 MHz	869 MHz	–	894 MHz	
CA_4-7	4	1710 MHz		1755 MHz	2110 MHz		2155 MHz	FDD
	7	2500 MHz		2570 MHz	2620 MHz		2690 MHz	
CA_4-12	4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
	12	699 MHz	–	716 MHz	729 MHz	–	746 MHz	
CA_4-13	4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
	13	777 MHz	–	787 MHz	746 MHz	–	756 MHz	
CA_4-17	4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
	17	704 MHz	–	716 MHz	734 MHz	–	746 MHz	
CA_4-29	4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
	29	N/A			717 MHz	–	728 MHz	
CA_5-12	5	824 MHz	–	849 MHz	869 MHz	–	894 MHz	FDD
	12	699 MHz	–	716 MHz	729 MHz	–	746 MHz	
CA_5-17	5	824 MHz	–	849 MHz	869 MHz	–	894 MHz	FDD
	17	704 MHz	–	716 MHz	734 MHz	–	746 MHz	
CA_7-20	7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD
	20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	
CA_8-20	8	880 MHz	–	915 MHz	925 MHz	–	960 MHz	FDD
	20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	
CA_11-18	11	1427.9 MHz	–	1447.9 MHz	1475.9 MHz	–	1495.9 MHz	FDD
	18	815 MHz	–	830 MHz	860 MHz	–	875 MHz	

[25]