Master's Thesis

Investigating Power Amplifier behavior in User Equipment terminals

By

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Abstract

In this thesis work, experiments have been carried out to study the behavior of radio frequency power amplifier which is the one of the largest power consumers in a user equipment which is a mobile phone in this case. A CMW-500 which is a Rohde and Schwarz equipment has been used to emulate the base station. A user equipment has been chosen that operates in accordance with cat12 LTE. The input path of the power amplifier from the device driver has been surgically intruded to introduce signals of interest.

The design of the experimental set up has been challenging. Introducing signals of interest to measure linearity and third order modulation products, with the user equipment being connected to the CMW-500, took lot of planning and preparation. A very high frequency switch has been introduced to switch between the input signals from the device driver and the signals introduced for the purpose of the experiments. The switch also has a low insertion loss. Efforts have also been made to check that the signals introduced into the input of the power amplifier are of the same level as the input signal to the power amplifier from the device drivers. So, additional attenuators and amplifiers have also been introduced in a manner that the noise figure is as low as possible. Experiments have been conducted to understand the linearity characteristics and efficiency of the power amplifier.

After conducting the experiments, it has been observed that because of varying supply voltage it is very difficult to understand the behavior of the amplifier in a high-power mode. The measurements made for measuring efficiency of power amplifiers clearly showed that the power amplifier behaves in 2 power modes: a low power mode with constant supply power and a high-power mode where envelope tracking sets in and the supply voltage varies. The specifications of the power amplifier read that the behaviour of the power amplifier is controlled digitally. So, while conducting experiments, there has almost been no control over the mode in which the power amplifier would operate.

Acknowledgments

I would like to thank:
My mentor and guide at Ericsson: Lars Peter Künkel, who has always been a driving force in making this thesis work possible and guiding with all the technical know-how needed to design and perform the experiments

My supervisor at LTH: Henrik Sjöland, for all the discussions and the thesis update sessions especially during the development stage of the thesis work. I have thoroughly enjoyed the sessions and the valuable inputs have been very useful during the thesis work.

I would like to thank Ericsson for providing me the resources and facilities to design and conduct the experiments.
I would also like to thank family and friends who have been supporting me throughout.

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CHAPTER 1

1 Introduction

The power amplifier is the largest power consumer in the mobile terminal radio. It is important to understand its behavior with latest standards and advanced architectures to save power. Thus, measurements in real devices are very valuable and experiments have been designed to perform such measurements.

In LTE (Long Term Evolution), DFTS-OFDM (Discrete Fourier Transform - Orthogonal Frequency Division Multiplexing) was the only candidate for uplink modulation. But in the 3GPP NR Radio Standardization, both OFDM (Orthogonal Frequency Division Multiplexing) and DFTS-OFDM will be used for uplink modulation. Both have their advantages and disadvantages. The biggest disadvantage of OFDM is large variations in instantaneous power of the transmitted signal which affects the linearity requirements and efficiency. This is especially very disadvantageous in a UE (User Equipment) terminal since it drains off the battery of the terminal. It also poses a limitation on the performance of the power amplifier in the terminal. This can be better understood in the sense that when OFDM is used there is a high requirement on linearity of power amplifiers which increases the cost of the terminal and drains off the battery of the terminal. High PAPR in case of OFDM drains the battery of the terminal. DFTS-OFDM is advantageous in the sense that it has less variations of instantaneous power of the transmitted signal. Thus, when this is used in the uplink of the communication scheme, the power efficiency of the transmitter can be increased which is very important. DFTS-OFDM poses a limitation on the uplink scheduling restrictions as contiguous frequency bands need to be allocated. Being a SC (Single Carrier) transmission scheme, it has less flexibility regarding adaptation to the variations in the channel. There is also a kind of restriction on the overall system capacity as compared to OFDM. The details of the two modulation schemes are discussed in detail in the upcoming sections.

An insight into the fact that which of the parameters of the power amplifiers are important to characterize has been gained. A method to measure them has also been found out. A lot of challenges were also faced while conducting the experiments. Interference between signals in the transmitting and receiving branch, amplification of noise, intercepting the path of the LTE signal from the device driver to the power amplifier being few of them. Several methods have been tried out to overcome these challenges. It is expected that investigating the power amplifier behavior as a function of output power and frequency allocation would help predict and draw conclusions when and under what circumstances OFDM and DFTS-OFDM must be scheduled.

1.1 Background

A lot of studies have been made about the power amplifier module in LTE phones. The input to these power amplifiers are generally signals with high peak to average power ratio. To have a better power efficiency it is required that the power amplifiers operate around its compression point which makes the output signals being distorted non-linearly. Understanding the characteristics of power amplifier, like 1 dB compression point, linearity, efficiency and devising a method to measure them has been performed here.

1.2 Hypothesis

The power amplifier operates in saturation mode. So, nonlinear distortions are expected in the output signals. In circumstances where low bandwidth is available for transmission of signals, envelope tracking mode can be useful. This would mean that the RF input to the power amplifier has the phase information and the DC signal to the power amplifier has the amplitude information.

However, when large bandwidth is available, the power amplifier is expected to behave in a linear mode. The input to that power amplifier has all the information. If the power amplifier behaves in this linear mode when bandwidth is low, it would have less efficiency than envelope tracking, and thus envelope tracking is feasible when the bandwidth is low.

The power amplifier in the user equipment operates in both modes: linear and saturated mode. In low power mode the power amplifier is expected to behave linearly. Envelope tracking modes is a linear mode where the supply voltage follows the envelope of the incoming signal. However, under relaxed conditions for example when the user equipment is transmitting at lower bandwidths, the power amplifier is expected to behave in saturated mode or power saving mode. Experimental set up has been designed and methods have been developed to measure certain characteristics of the power amplifier in the user equipment.

1.3 Purpose

The basic purpose is understanding the power amplifier characteristics and behavior. By analyzing certain characteristics of the power amplifier, it is expected to gain an insight into the preference of modulation schemes that must be scheduled in an uplink communication from the UE to the BS.

1.4 Delimitations

Surgical Intrusion into the pins of the front-end power amplifier module was one of the most difficult tasks. Identifying the trace and deciding the optimal way to inject a test signal to the RF IN pin of the power amplifier without damaging it was challenging. After that was done, the most difficult task was containing the leaking between the pins of the module and shielding them the most important concern. Creating a lossless path in the experimental set up, characterizing each of the components, limiting the noise floor were other challenges faced during the design of the experimental setup. Conducting experiments for characterizing the significant features of the power amplifier while maintaining the uplink over the air connection between the user equipment and base station was also a challenging task.

1.5 Objectives

The purpose of the thesis work has been to understand how a power amplifier and transmitter behave in an equipment in real operating conditions. Designing an experimental setup to measure different parameters of the user equipment and developing methods to do the same have also been an integral part of the work. The aim with this master’s thesis project is to also to find out which parameters related to the behavior of the Power Amplifier system in a User Equipment that are of importance to characterize.

CHAPTER 2

2 Theory

Some basic facts about LTE, user equipment, transmitter architectures, power amplifiers etc. have been discussed in this section.

2.1 LTE

The 3GPP (Third Generation Partnership Project) develops global standards for the mobile technologies. It was formed in 1998. It defines, approves and maintains a record of the functionalities, standards and specifications that are then converted into deliverables. The standards are structured as releases.

Generally, the latest release has the most advanced features. Most of the equipment have backward compatibility which means an equipment that is capable of delivering the functionalities of a higher release always works for a release that has been done earlier than that. The UE's are divided into different categories based on their uplink and downlink capabilities. In LTE, the UE category information is important for the bases station and the E-Node B's to communicate with the UE's knowing what capabilities the UE's have. With each release, new categories of user equipment are being released. This is presented below in the tabular format.[1]

Table 1: UE category vs release

Category	3GPP release
0	12
1	8
2	8
3	8
4	8
5	8
6	10
7	10
8	10
9	11
10	11
11	11
12	11
13	12
14	12

The LTE Cat 0 devices have UL and DL peak rate 1Mbps. Maximum UE transmit power is 23dBm. These devices support both full and half duplex mode. The basic advantage of these devices over the Cat 1 devices is the lower complexity of the modem. Cat 0 devices operate in power saving mode and are more preferred in cases of machine to machine communication. Since Cat 0 devices operate in power saving mode, they have better battery lives.

2.1.1 LTE TDD and FDD

LTE can use either method of duplexing: Frequency Division Duplexing or Time Division Duplexing. The basic difference between the two is that in FDD the uplink and the downlink frequencies are different where as in TDD the uplink and downlink frequencies are the same. The data is transmitted in different time slots for uplink and downlink in the same frequency band. The LTE bands operable in Sweden along with the channel bandwidths, uplink and downlink frequencies, duplexing mode and the band number are as below[2]:

Table 2: Different LTE bands with corresponding frequency range and modes

E UTRA BAND	f(in MHz)	Duplex Mode	Common Name	Uplink	Downlink	Channel Bandwidths
1	2100	FDD	IMT	1920-1980	2110-2170	5,10,15,20
3	1800	FDD	DCS	1710-1785	1805-1880	1.4,3,5,10,15,20
7	2600	FDD	IMT-E	2500-2570	2620-2690	5,10,15,20
20	800	FDD	EUDD	832-862	791-821	5,10,15,20
31	450	FDD		452.5-457.5	462.5-467.5	1.4,3,5
38	2600	TDD	IMT-E	2570-2620		5,10,15,20

2.1.2 LTE Resource Blocks

In LTE, the modulation scheme used is OFDMA. Basically, radio resources are allocated to users. This allocation of resource blocks is carried out by the eNodeB. One resource block is 0.5ms in time domain. The width of the resource block in frequency domain is 180kHz. In most cases, 12 subcarriers of 15kHz each make up a resource block.

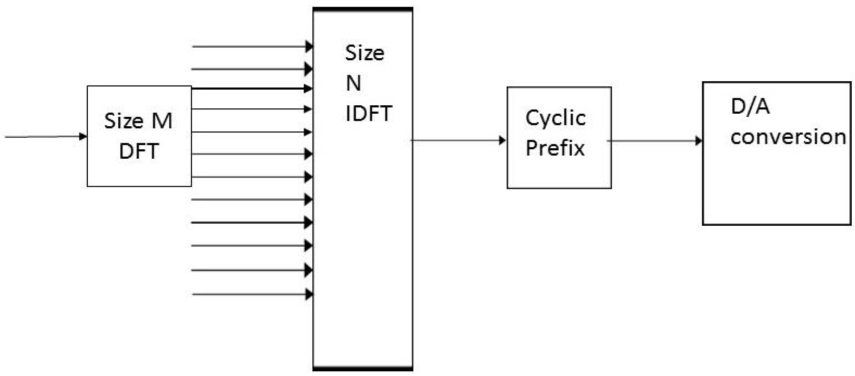
2.2 DFTS-OFDM

DFTS-OFDM can be thought of as pre-filtering or pre-coding being done to the data stream before OFDM modulation. This is used for LTE Uplink. There are advantages and disadvantages associated to it. This is a single carrier transmission scheme. So necessary measures have to be taken to counteract the disturbances caused due to frequency selectivity of the radio channel.

DFTS-OFDM is a transmission scheme that has the capability of having all the advantages or good properties like not much or little variations in instantaneous power of the transmitted signal, possibility of having a low complexity high quality equalization in frequency domain.

The basic block diagram of DFTS-OFDM is as below:

Figure 1: Block diagram for DFTS-OFDM



DFTS-OFDM means DFT spread OFDM. Data symbols first undergo M-size DFT. Then these symbols get modulated as a size-N inverse DFT. If N=M, then DFT and IDFT cancel each other. On the other hand, if M<N, remaining inputs are set to zero. Thus, at the output of the IDFT we have a signal that has the properties of a single carrier. Also, the resulting signal has low power variations and a bandwidth that depends on M. QAM symbols are first converted to frequency domain and then mapped to selected subcarriers at the input of the IDFT block.

Sub carriers are allocated to users and are called as resource blocks. The spacing between the sub carriers is 15kHz. One resource block has 12 subcarriers. So, one resource block occupies 12*15kHz=180kHz in the frequency domain and 0.5 milliseconds in time domain.

2.3 Scheduling in LTE

In LTE the time-frequency resources are shared among the terminals. The e-Node B, on the basis of some information as inputs to it decides which resources can be allocated to which terminals. The uplink and downlink schedulers are independent of each other. Scheduling in uplink is done per subframe level.

For uplink packet scheduling in LTE one thing is obvious:

1. Since the SC-FDMA is used, only adjacent or continuous resources to the same user can be granted in frequency.

Also, when resources are granted to users they are 180kHz each, so the complete bandwidth is allocated to each user. The e Node B allocates resource blocks to the user equipment every TTI (Transmission Time Interval) or 1 millisecond. The e-Node B estimates the uplink channel quality for each of the user equipment that is the channel quality for the channel as seen by the user equipment that are requesting for resources. Basically, channel sounding mechanism is used in the estimation of the channel. Each user equipment wanting to transmit some information first sends a sounding reference signal (SRS) to its corresponding e-Node B. The e-Node B then gets the channel state information (CSI) and sends it to the CSI manager for further processing. A channel conditions matrix is then created. Also, there must be way by which the UE can inform the e-Node B's about the amount of data that they have to send and their priority. The data is then categorized into different Radio Bearer Groups (RBG's) based on their priority level. The scheduler in the e Node B generally decides the payload for each user equipment but the user equipment also has the responsibility of selecting the RBG from which the data is taken.[3] On a broad level there are two types of scheduling algorithms that are considered: Channel Dependent Algorithm and Proportional Fairness algorithm.

As the name implies for channel dependent algorithm, the resources or more precisely the resource blocks are allocated based on quality of the channel. It basically considers the instantaneous channel rate for each user on each resource block at a particular time. The only disadvantage of this scheduling algorithms is that the high-quality channel get assigned the most resources and the low quality channel are assigned the least resources or even may not be assigned any resources at all. This could lead to starvation.

The proportional fairness algorithm takes care of the drawback of the channel dependent algorithm by taking care of the users with low quality channels also. Users with low quality channels at least get some resources instead of none. This is because channel conditions are considered over the entire lifetime and not just for an instant.

2.4 Power Amplifiers

Power Amplifiers in user equipment or mobile phones may be single band or multiple bands. This implies that the power amplifiers are expected to amplify signals that belong to a single band or multiple bands. In this particular experiment, a Broadcom power amplifier module has been chosen. It is a single band power amplifier meant for LTE Band 7. Although, recently the trend had been to integrate more bands into a power amplifier.

As we progress towards the next generation of communication standards, the basic improvement looked for is higher data rates. The biggest challenge is to keep the battery alive for a considerable amount of time while delivering higher data rates. This means to keep the power consumed from the battery of the phones is as less as possible is the key. It has been observed in studies that there is a direct correlation between data rates and peak to average power ratio. Peak to average power ratio in an OFDM symbol is basically the ratio of the peak power of a given sample of an OFDM transmit symbol to its average ratio. In a high-speed communication system, data to be transmitted is spread over large number of sub carriers which are then independently modulated. When each of these independent sub carriers reach their maximal value, the output envelope curve also goes up and becomes much more than the average power.

Power Amplifiers can have various modes of operation ranging from class A to class F. A brief summary of their performance parameters in different modes are listed below[4]:

Table 3: Power amplifier characteristics

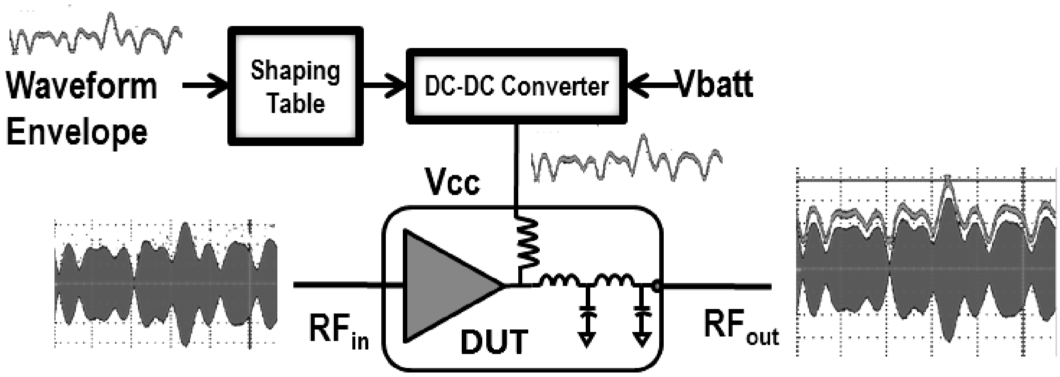
Class	Maximum Efficiency	Normalized Output Power	Constant Envelope	Comments
A	50%	0.125	no	highest linearity, low efficiency
B	78.5%	0.125	no	better efficiency, less linearity
C	100%	Very close to 0	no	low linearity, low output power
D	100%	0.16	yes	high output power, fast switches
E	100%	0.098	yes	low normalized power
F	100%	0.16	yes	Better than E

In most of the cases the power amplifiers that operate in linear mode, in user equipment's or mobile handsets operate in class F. This is because a class F load gives us all the characteristics in a power amplifier that are looked for, when it is implemented in a user equipment. Some of it may be like having low intermodulation products and producing more linear power for a given efficiency. When using power amplifiers care must be taken so that the saturated output power is set high enough that it does not clip the peaks of the waveforms. This in turn results in more power being consumed from battery because the average power is set much below the saturated power.

Thus, in most of the upcoming power amplifier modules, envelope tracking is employed in most of the cases because the power amplifier performs more efficiently in this mode. This saves battery life and that is what is desirable.

An envelope tracking power amplifier is normally implemented in the following manner[5]:

Figure 2: Envelope Tracking power amplifier module



It is mostly the DC-DC converter that generally limits the efficiency of the ET amplifier system. It has been seen in studies that despite this limitation of DC-DC converters limiting their efficiency, the ET systems still deliver 10% improvement in efficiency. This ET- PA envelope tracking modulator is normally used with a digital pre-distortion hardware and calibration software in order to obtain linearity performance data for the complete RF frontend.

In simple terms, a power amplifier can be said to operate in an envelope tracking mode when the following is observed:

1. When the RF transmit signal, amplitude is below a certain level, the collector voltage remains the same.
2. When the RF transmit signal, amplitude is above a certain level, the collector voltage follows the envelope of the RF signal.

When comparing a power amplifier that operates in normal mode and in envelope tracking mode, studies have proven that the efficiency of the system is improved by roughly 10% in case of both voice and data mode.

2.4.1 Modulation Techniques

There are many modulation techniques that the power amplifier in the DUT could be using. Some of them are supply voltage modulation, load modulation and RF pulse width modulation. As per the specification of the power amplifier front end module, it behaves in two power modes- linear mode and saturated mode.

In cases where supply voltage modulation is used, the challenges could be that when the supply voltage is below a certain value the power amplifier does not amplify the signal. When the power amplifier does supply voltage modulation it means that the gain of the power amplifier is also in some way or the other dependent on supply voltage. There are also polar architectures for power amplifiers. In that case the phase information and the amplitude information are carried into the power amplifier differently. This also uses envelope modulation for the amplitude information. However, there could be some challenges linked to this, for e.g. bandwidth expansion or timing misalignment.

Studies have shown that though many different architectures of power amplifiers could be used, for highest efficiency supply voltage modulation should be used so that unnecessary switching could be avoided.

2.5 Transmitter Architecture

In user equipment, there is normally a transceiver that can transmit and receive signals. User equipment normally can send and receive signals that are a part of different frequency bands. The user equipment or the device under test is also one of the types. There are then power amplifiers that are supposed to amplify signals belonging to one band or many bands depending on their type. The power amplifiers that can amplify signals belonging to more than one frequency band is called a multiband power amplifier. The power amplifier whose behavior is investigated in the thesis work is a single band power amplifier supposed to amplify Band 7. The structure of the transmitter in the DUT has been discussed in detail in the following section.

CHAPTER 3

3 Experimental Set-Up

Designing the experimental set up has been a challenging task. Choosing the DUT, gathering basic knowledge about its components and their functionality have been done in a systematic way.

3.1 Choosing the DUT

A list of available mobile phones was prepared. The cellular phone with the latest LTE category and max uplink speed was selected. For this experiment, the Xiaomi Mi 5 was selected. The modem speed was HSPA 42.2/5.76 Mbps, LTE Cat12 600/150 Mbps. The higher modem speed in Category 12 is basically possible because of the carrier aggregation. Carrier aggregation serves to increase the bandwidth and the data rate. This is possible because multiple component carriers can be used. Another important factor for selecting DUT was that we had technical documentation on the Mi5 that had been found on the internet.

3.2 Power Amplifier in User Equipment

The role of power amplifier in a UE is to provide enough signal power that the signal c propagates to the intended destination (the base station in this case). Higher efficiency of a power amplifier means better power management which in turn means better battery life of the user equipment. In LTE UE most of the RF power amplifiers operate in envelope tracking mode.

The power amplifier that has been investigated in this is a Band 7 power amplifier manufactured by Broadcom. The datasheet for the power amplifier reads that the power amplifier operates in two power modes – quiescent current control for high power mode and low power mode. This is evident in the efficiency plot for the power amplifier.

It is assumed that the power amplifier behaves in two modes: linear Envelope tracking mode and the saturated mode. The power amplifier, when operating in linear envelope tracking mode is expected to be highly linear. Envelope tracking is used when the PA is operating in linear mode When operating in saturated mode, the signals get clipped which gives rise to non-linearity. This introduces intermodulation which has to be compensated for on the RF input signal. This is the tricky part when using polar modulation.

3.2.1 1dB Compression Point

For most power amplifiers the ratio of output to input power in Watts or the difference between output and input power in dB remains the same till the input is up to a certain level. This is the gain of a power amplifier. When the output power is plotted against the input power, the resulting plot is a straight linear meaning that the gain is linear up to a certain point and the gain gets compressed because the power amplifier goes into saturation. The input power at which the output power is 1dB less than the expected output power had the power amplifier been linear is called 1dB compression point.

Gain=Output/Input (in Watts or Milliwatts)

Gain=Output-Input (in dB)

So, this is basically the input signal level where the output signal is compressed by 1dB. This usually occurs when the input power goes above a certain limit. It could be useful to know this so that the input level of the power amplifier could be kept from going above this limit in cases where distortions are undesirable.

3.2.2Third Order Intermodulation Products

When a power amplifier module has an input signal, it is ideally expected to give an amplified version of the input as its output. However, in a real scenario, harmonics of the input signals are also mixed. This is mostly because of the non-linearity of real systems. In addition to these, non-linearities also increase as the PA goes into saturation. If the signals are too close to each other and if the bandwidth of signals not too narrow, these intermodulation signals come up and create interference.

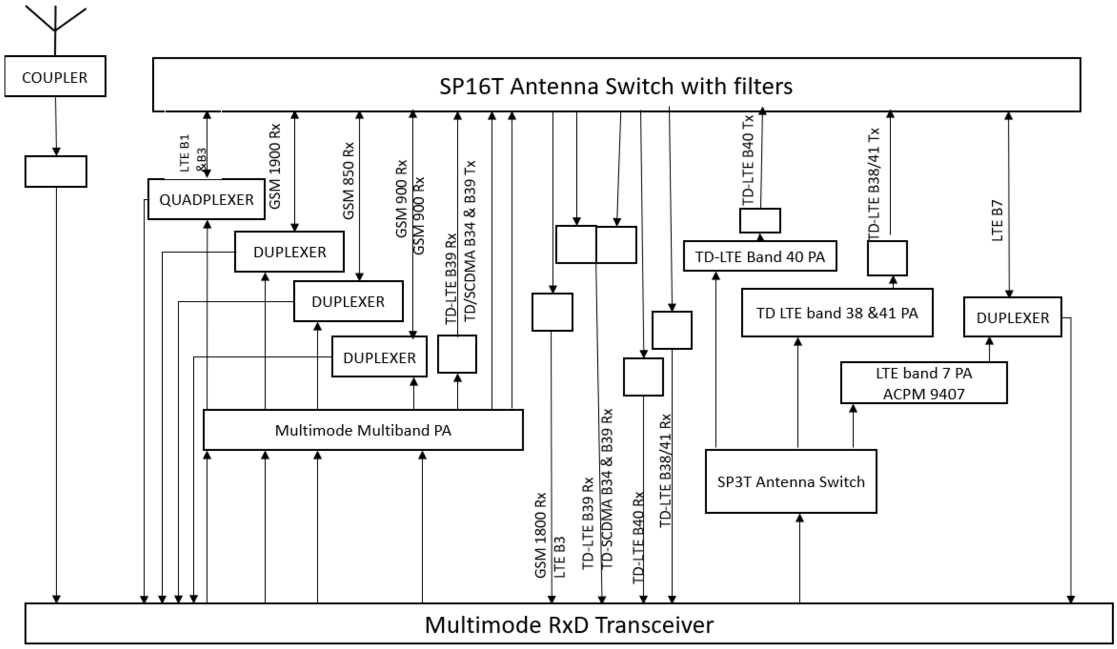
The intermodulation products are a result of non-linearities of power amplifiers. When a linear amplifier is injected with two tones at its input, the output is only an amplified version of the input two tones. But if the power amplifier is non-linear, harmonics of the input signal will also appear at the output pf the power amplifier. In addition to second and third harmonics of the input tones, different combinations of first and second order harmonics will also be produced at the output of the power amplifier. For e.g. a non-linear power amplifier being injected with 2 tones with frequencies f1 and f2, will have outputs at f1, f2, f1 + f2, f1-f2, 2f1, 2f2, 2f1-f2, 2f2-f1, 3f1, 3f2 etc. This intermodulation could cause different problems in transmitters and receivers. In a transmitter it could cause problems like interference with signals from adjacent channels.

This has also been studied and an experimental set up is designed to see how this power amplifier module behaves when two tones are injected to the power amplifier module input for fraction of seconds.

3.3 Transmitter in User Equipment

The structure of a transceiver of the DUT is studied. The main antenna of the transceiver is connected to a coupler. After the coupler is an antenna switch with an integrated MIPI controller. The antenna switches in case of the state-of-the-art equipment is a single pole 16 through switch. The main advantages of using such a switch is that they have good isolation properties and low insertion loss. These properties make it an ideal choice when receiving and transmitting multiple bands in a user equipment. It also has very good intermodulation distortion performance, which also means that it can transmit and receive at frequency bands closes to each other without having much interference. The antenna switch is connected to multiple duplexer and quadplexers that are basically filters supposed to isolate the transmit and receive signals. The main purpose of these is that communication is facilitated in both directions over one path. The implementation of duplexers and quadplexes make it possible so the signals can be transmitted and received a single main antenna. They are basically switches that operate based on the type of signals they handle. When the state-of-the-art equipment receives signals, they pass through these duplexers and then reach the multimode transceiver. In the other case when the state-of-the-art equipment is in a transmit mode, the signals after passing through the multimode transceiver pass through an antenna switch (a single pole 3 throw) switch which routes them to the power amplifier of the corresponding bands. The transmit signals after being amplified at the corresponding power amplifiers are filtered before they are transmitted through the main antenna after passing through the antenna switch and coupler. This means that the transmit path has a bit more complexity than the receive path. A simple block diagram of the transmitter in the user equipment has been shown below[6].

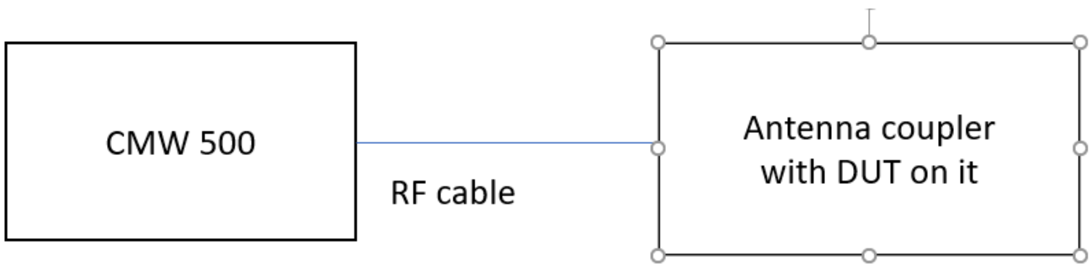
Figure 3: Transmitter in User Equipment



3.4 CMW 500

The CMW 500 is a wideband radio communication tester which can generate as well as measure signals. For the experiment and to be able to measure during live connection, CMW500 acts as the base station. LTE signals are transmitted from the UE to the base station. The block diagram below shows how the DUT is connected to the CMW500. CMW is connect to an antenna coupler with an RF cable.

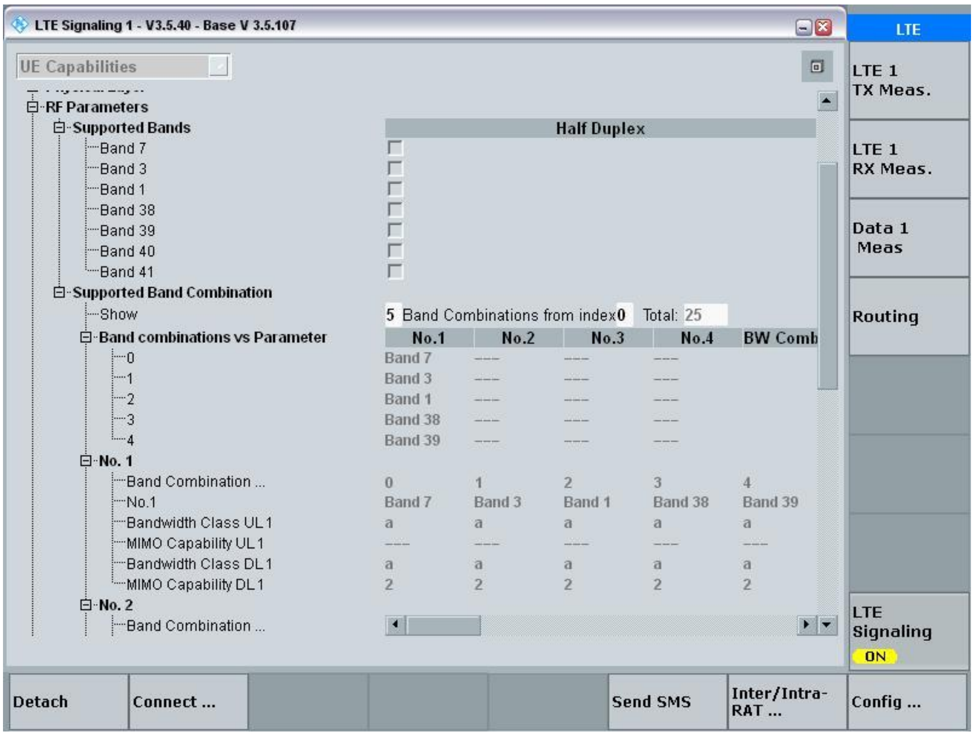
Figure 4: Block diagram of CMW 500 and antenna coupler



The capabilities of the user equipment like the bands it supports, the CA (Carrier Aggregation) combinations it supports etc. can be found out from the CMW500. CA means many LTE carries each with a maximum bandwidth of 20MHz can be transmitted in parallel to or from the same UE. Band 7 LTE signal is generated in this experiment. The duplex mode is FDD. The RS EPRE is -85dBm/15kHz by default and is set to -75dBm/15kHz for the experiments conducted. The calculation of attenuation between the CMW connector and the antenna of the DUT is very important to ensure that the measurements performed are accurate. This has been explained in detail in the upcoming sections.

For this case, it was seen that the DUT (Xiaomi Mi 5) could support some of the combinations of the bands. Also, after the DUT is connected to CMW500, a lot of information known as UE measurement reports can be found out from the CMW500. A screenshot of the CMW500 displaying the capabilities of Xiaomi Mi 5 is shown below:

Figure 5: Screenshot of the screen of CMW500



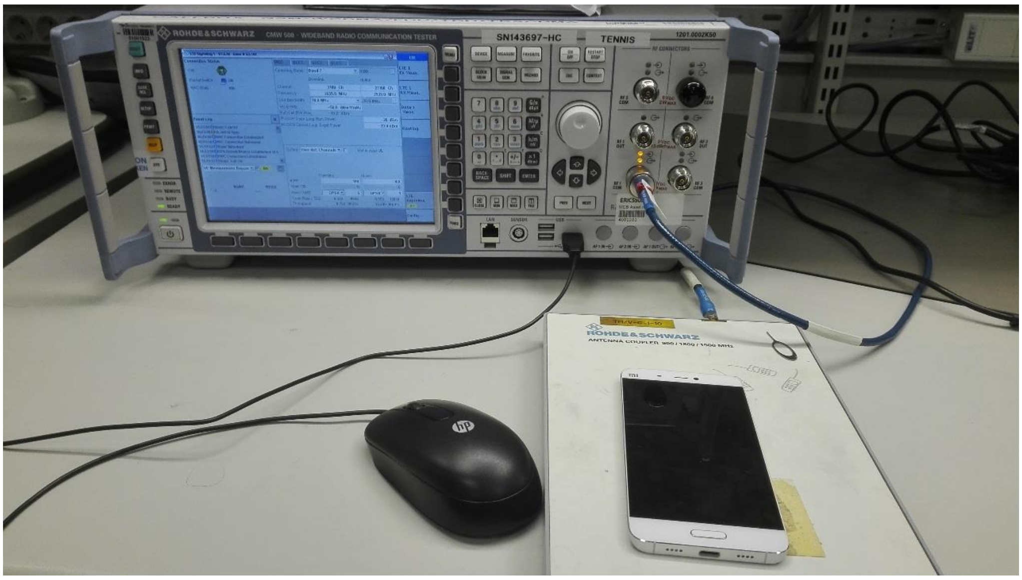
3.4.1 Connecting the DUT and CMW

A data path first needs to be created between the DUT and the CMW500. An access point is set up in the DUT. The name and APN of the access point is named the same. Thus, a data transfer path is created between the DUT and CMW500. The CMW 500 is also operated in a data application mode rather than the default test mode. Also, in the CMW, one of the short keys is chosen as data application measurement. So, this means in addition to RX and TX measurements, the data measurement reports could be seen in one go. Below is a detailed explanation of how to set up the connection or say the data path between the DUT and the CMW where the DUT transmits signals to the CMW500

3.4.2 Setting up a CMW500 to send data

The experimental set up is as follows:

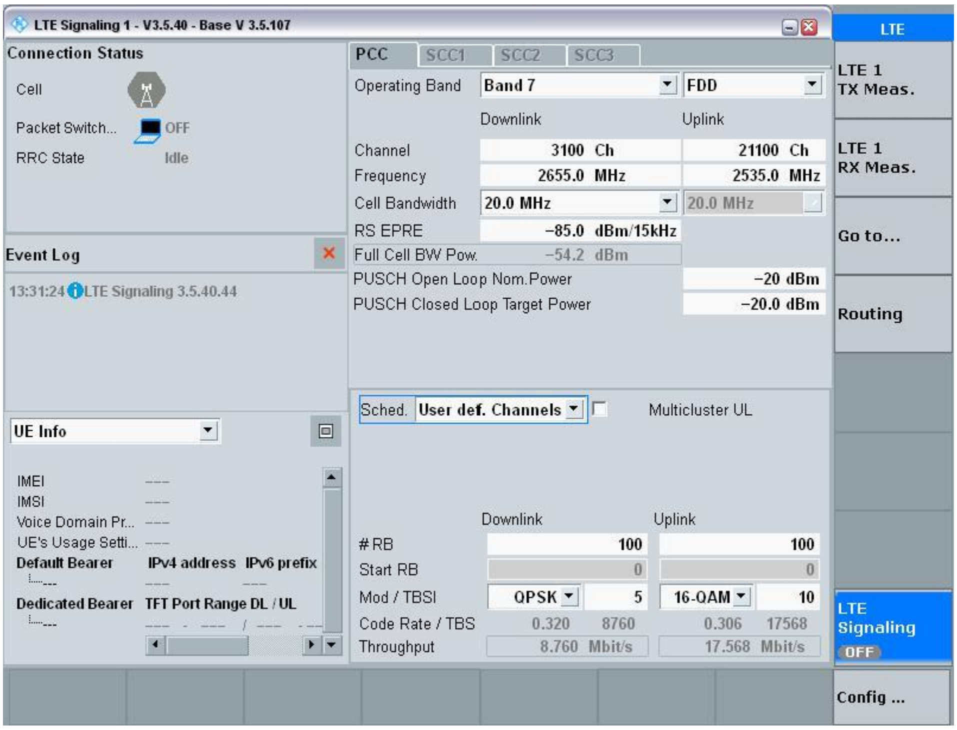
Figure 6: A picture of CMW500 and UE with wired connection



The CMW500 is connected to power supply. The RF1 COM connector of the CMW500 is connected to the antenna coupler on which the device under test is placed.

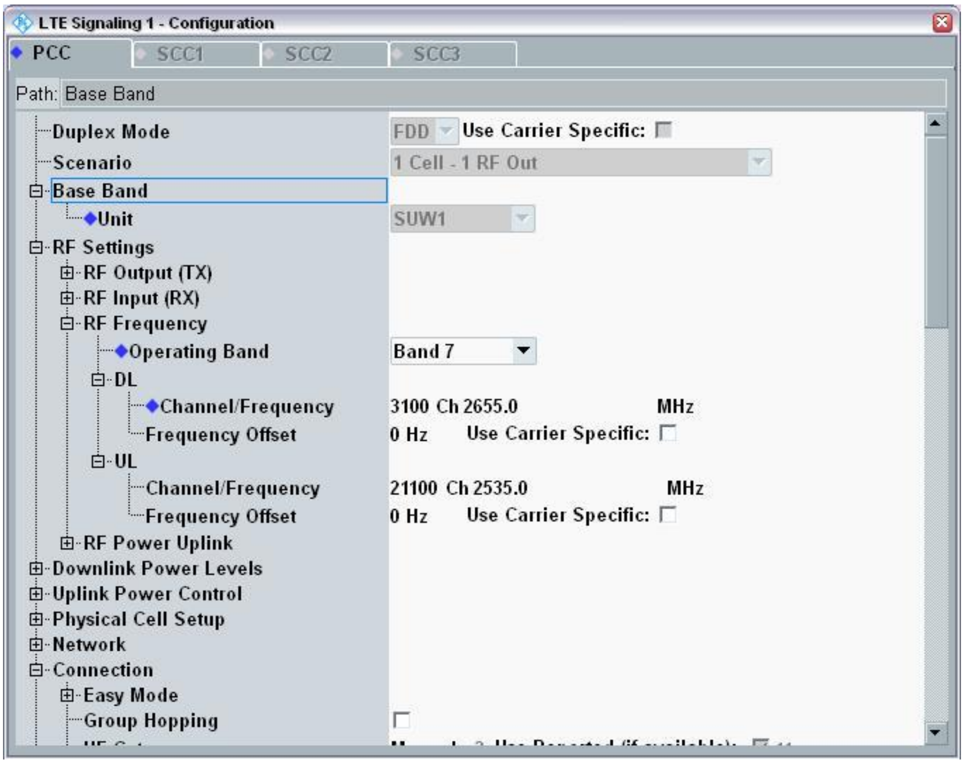
The instrument is powered up. It takes some time for the instrument to load all the settings. Once the settings are loaded, the next step is going to the signal generator function of the CMW500.Out of many options of the generator or the signaling controller LTE Signaling 1 is selected. The window looks something like this:

Figure 7: Screesnshot of the screen of CMW500 with all parameters set and displaying the connection status



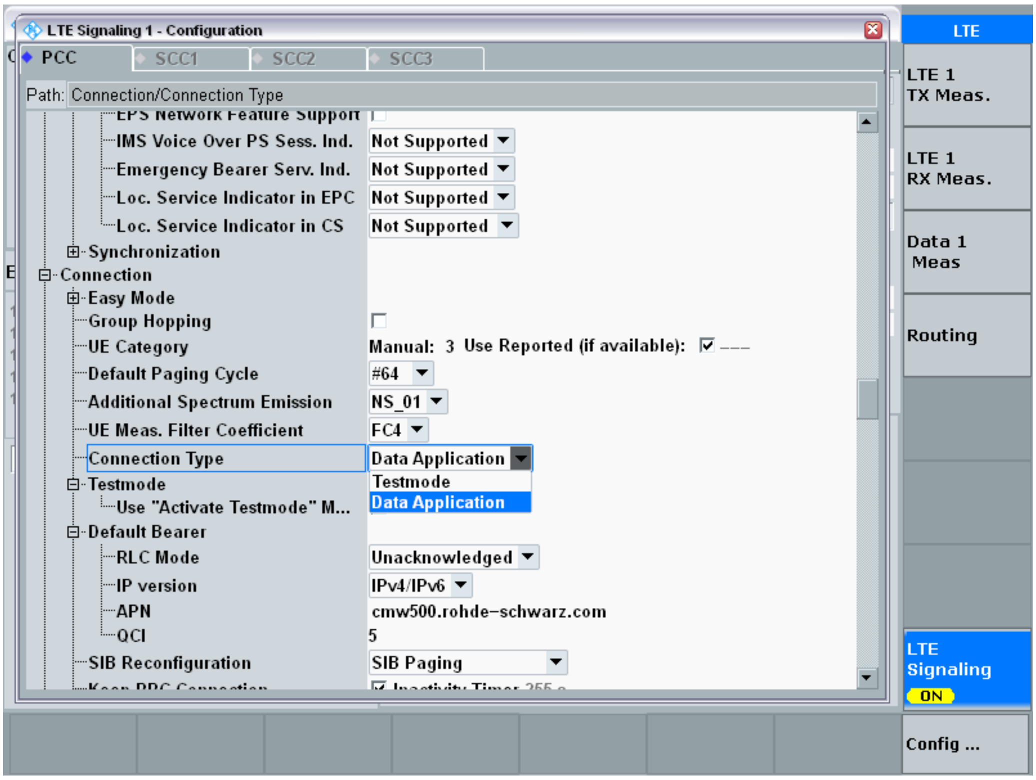
Some of the default parameters are to be changed. For scheduling, the channels are changed from radio measurement channels to user defined channels. Also, modulation is changed to 16 QAM and the corresponding TBSI is changed to 21. Then the configuration tab is clicked, and the following window appears.

Figure 8: Screenshot of the screen of CMW500 displaying the operating band chosen



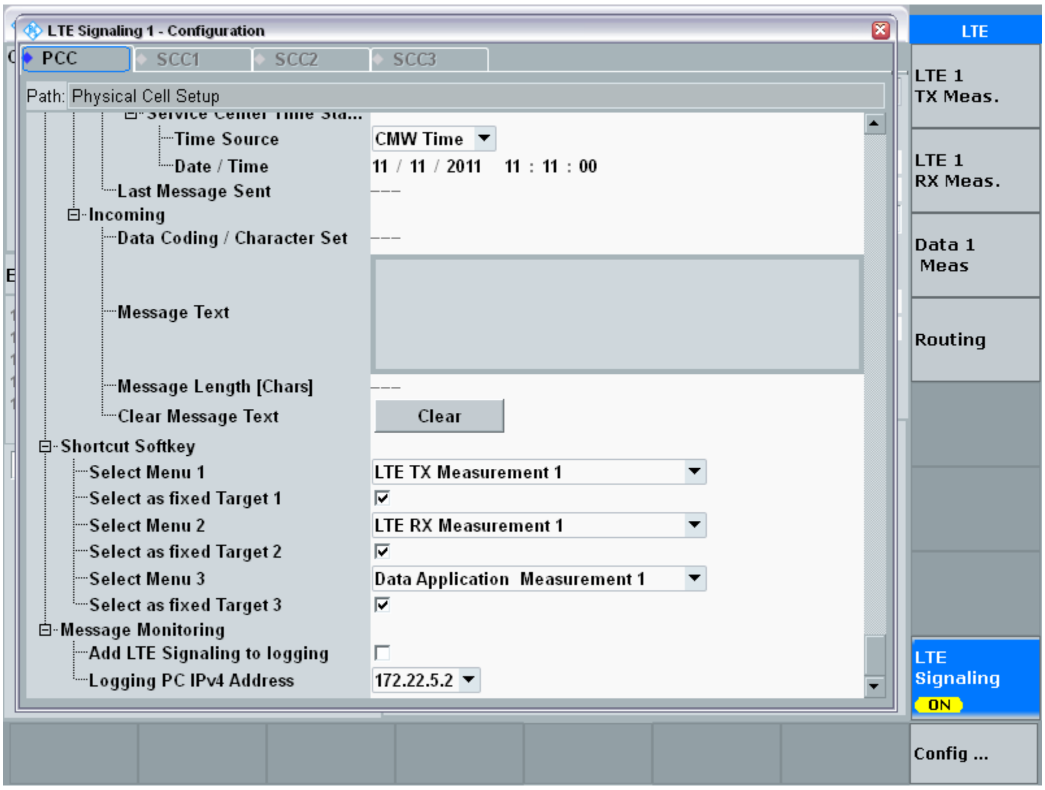
Then in the connection option of the tree, the connection type is changed from test mode to data application.

Figure 9:Screenshot of the screen of CMW500 displaying other important parameters set



Also, the data application measurement is selected as one of the soft keys so that parameters related to those can be viewed once the connection is set up.

Figure10:Screenshot of the screen of CMW500 displaying the measurement modes



The LTE signaling is then switched on and the phone is connected to the CMW500 which emulates the base station. All the UE Info, UR Measurement Report and UE Capabilities can be viewed in the tab below event log.

Access Point Name is also configured in the phone. The following path is followed:

Settings> SIM cards and mobile networks>Default Service Provider Name>Access Point Names>New APN. Then APN and name is set to CMW.

Figure 11: Screenshot of the screen of DUT with access points being set in Iperf app

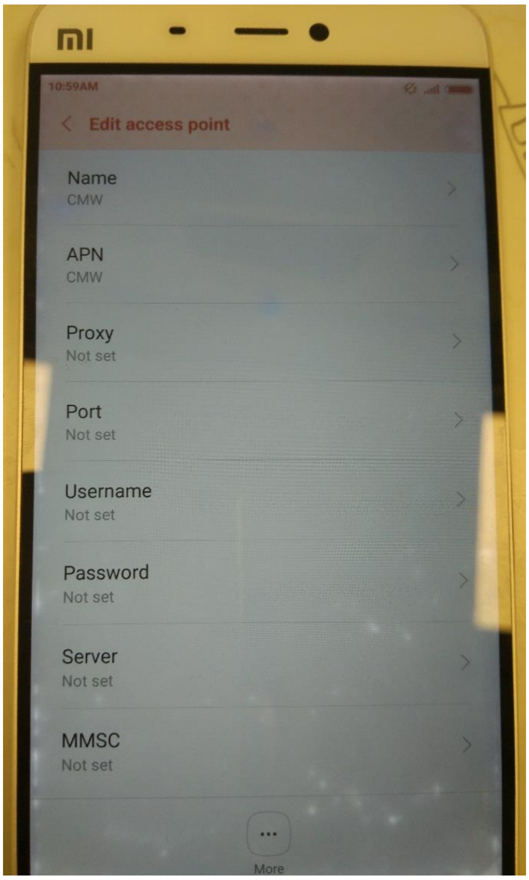
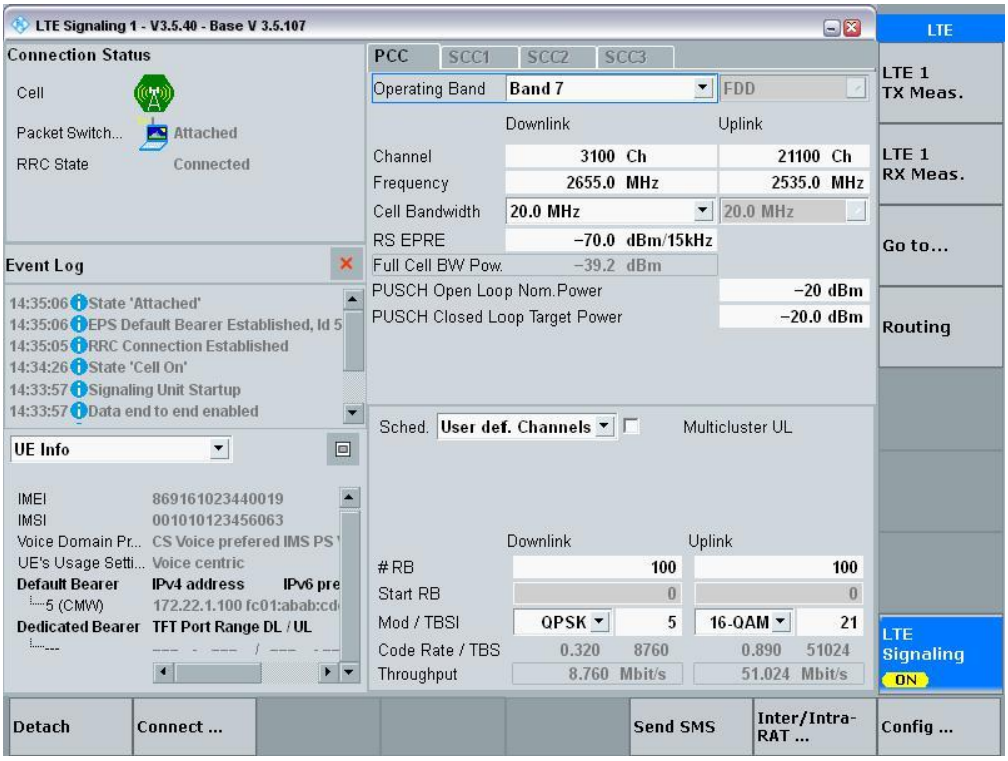


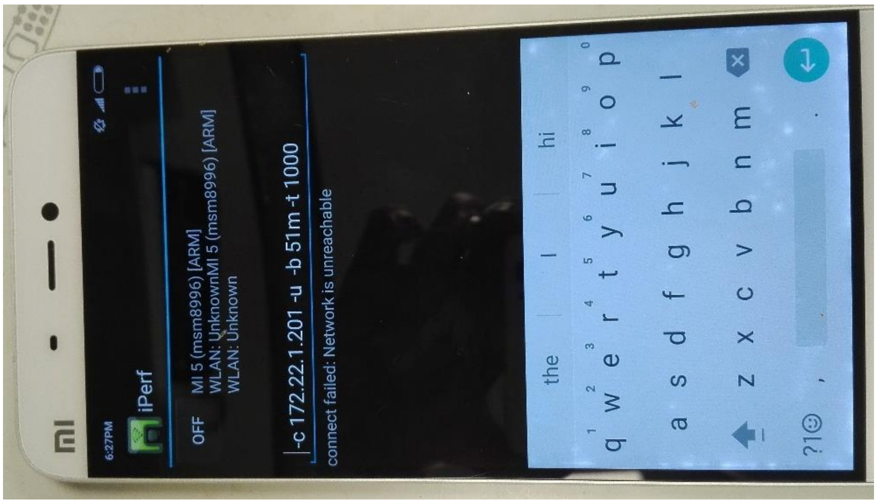
Figure 12: Screenshot of the screen of CMW500 where it can be seen that the LTE connection had been successful between the CMW500 and the DUT



IMEI, IMSI And IP address of the phone can be found out from this. If the option is changed to UE measurement report, then the signal strength as received by the DUT can be found. In the primary component carrier (PCC) tab, the RS EPRE value is set to -70dBm/15kHz. In the UE Measurement report tab the RSRP value is found out to be -96 to -95dBm.

Iperf app is downloaded from Google play store to the phone. Iperf is an application in google play store that can be used to test and measure performance of a network. The following command is given.

Figure 13:Screenshot of the screen of DUT showing configuration details in iPerf app



The connection between the CMW500 and the DUT is checked to be stable.The iPerf tab is switched on the CMW500 and on the DUT also. The throughput tab is also switched on.

For the iPerf tab, its configuration is modified slightly. The CMW acts as the server and the DUT as client.So, the client is sending data to the server. The protocol is changed to UDP and window size to 208kbytes.The following can then be seen:

Figure 14: Screenshot of the screen of CMW500 showing uplink connection details

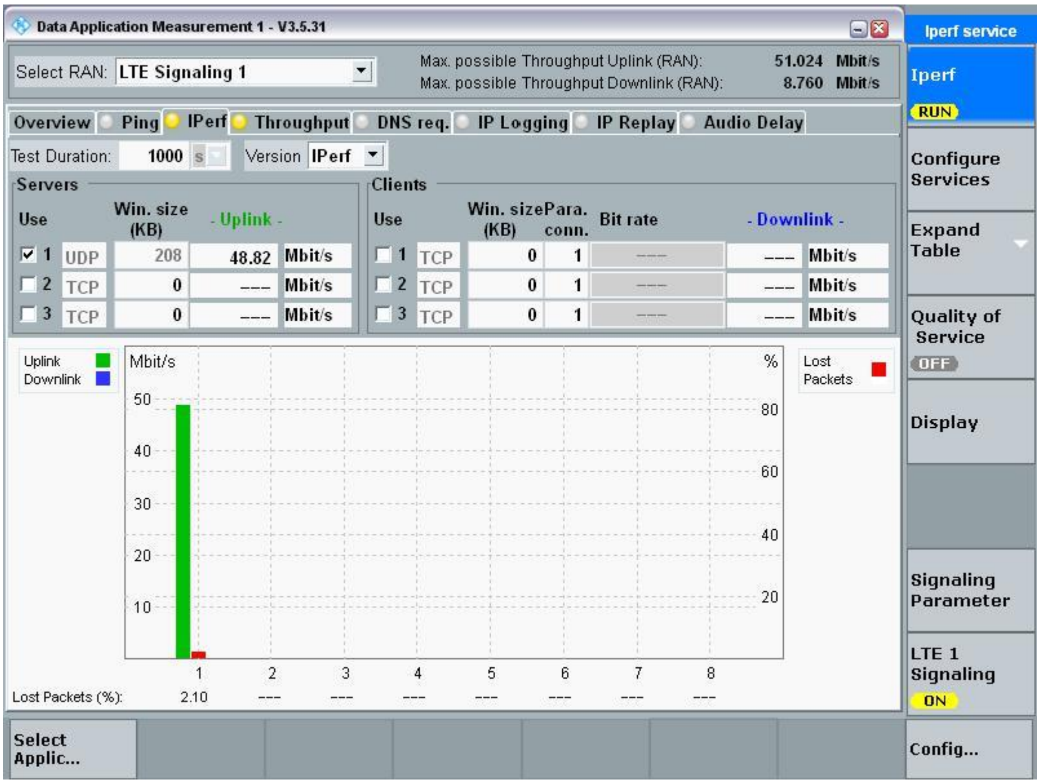
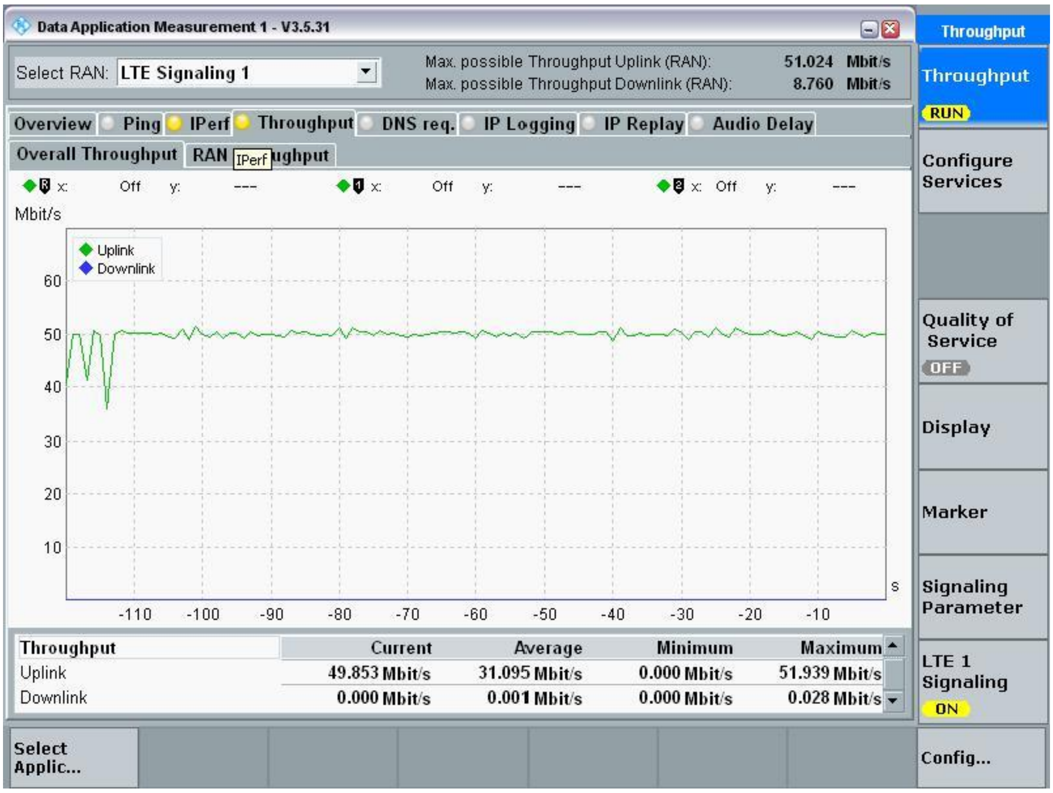


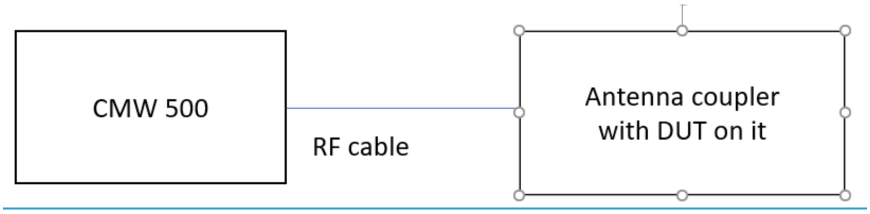
Figure 15: Screenshot of the screen of CMW500 displaying throughput when connected to the DUT



3.4.3 Attenuation Calculation

The aim is to perform reliable measurements. To achieve this, it is very important that attenuation between the connectors of the CMW and the DUT (Xiaomi Mi 5) are determined as accurately as possible and then compensated for. The methodology for determining the uplink and downlink attenuation is described below. A basic block diagram of the CMW 500, DUT and the antenna coupler is shown below:

Figure 16: Block diagram of CMW500 connected to Antenna coupler



The uplink attenuation is the loss that occurred when the signal emitted from the DUT is received by the CMW500. The difference between the power levels of the emitted signal from DUT and received signal at the CMW500 is the uplink attenuation that is compensated for. The loss encountered when signal is emitted by CMW 500 and received by DUT is downlink attenuation.

Downlink Attenuation:

Downlink implies connection from CMW500 to the UE. The values of importance for this calculation are RS EPRE and RSRP. As soon as the DUT is connected to the CMW, the measurement report shows the RSRP values. The mean of these RSRP values is taken and can be recorded as mean RSRP values for our reference. The difference of this value and the RS EPRE value gives the downlink external attenuation.

Downlink External attenuation = RS EPRE – mean RSRP

With the experimental setup, when the CMW is connected to the antenna connector of the DUT which implies a wired connection, the values for RS EPRE and mean RSRP were -70dBm/15kHz and -72dBm respectively. Thus, the downlink attenuation in that case come to be -72-(-70)=2dB.

When the DUT and the CMW are connected over the air the downlink attenuation comes to be around 25dB.

Uplink Attenuation:

To determine the uplink attenuation it is required that the DUT is transmiiting with known power. The maximum power that the UE is allowed to transmit can be controlled by setting the Maximum Allowed Power P Max with the CMW. The maximum power that the DUT can transmit was found to be 23dBm. In order to ensure a stable connection, it is good to choose the value of Maximum Allowed Power P Max much less than the maximum power that the DUT can transmit. The connection between the CMW 500 and the TX measurement report shows the TX Power. The difference between the Maximum Allowed Power P Max and the TX Power gives the uplink attenuation.

Uplink External Attenuation = Maximum Allowed Power P Max – TX Power

After this has been entered in the RX Input external attenuation, the TX Power is found to be very close to the Maximum Allowed Power P Max. In this, the Maximum Allowed Power P Max is set to 10dBm which is much below the maximum power that the UE can transmit. The TX power is now measured to be around 7.2dBm. The uplink external attenuation is calculated to be 10-7.2=2.8dBm. So the uplink external attenuation is calculated to be 2.8dBm. After the attenuation is set to this value, the TX power comes out to be very close to 10dBm.

Setting up the CMW:

The CMW acts as the base station and there are various parameters to choose from. The parameters have been set as follows:

Table 4: Table of parameters set in CMW for the experiments

Parameters	Values
Operating Band	Band 7
Cell Bandwidth	20MHz
Mod/TBSI for UL	16QAM/21
Downlink External Attenuation	2dB
Uplink External Attenuation	2.8dB

CHAPTER 4

4 External Equipment used

Experimental set up are designed to measure the three basic characteristics of power amplifiers:

1. 1dB compression point measurement
2. Third Order Modulation Products
3. Efficiency and Current measurements

Equipment with specific functionalities have been used in the experiments.

4.1 RF Switch

This is a solid-state PIN diode switch.

Figure 17: Picture of the diode switch P9402C

Key sight P9402C is used. It's fast switching time and good port to port isolation makes it an obvious choice for this experiment. Its insertion loss is also very low. It is needed to have the LTE connection up and running while injecting the test signal

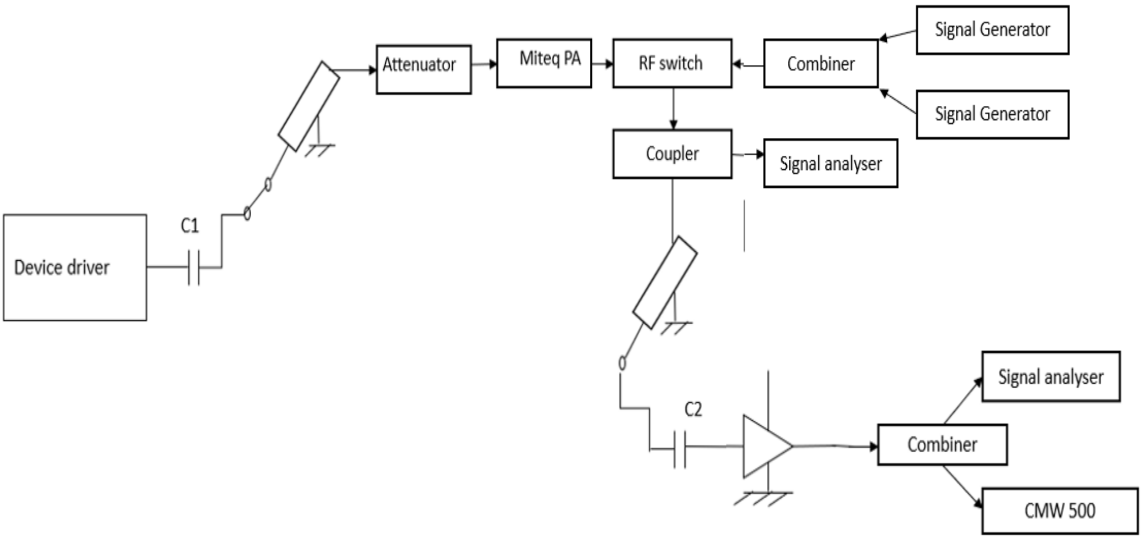
The Pin works on Control logic. There are 2 input pins and one output pin. For control Logic 0 the path from RFIN to RFCOM, will be a low pass path while for control logic 1 the path will be high pass. Also, the switching time is quite fast and the isolation is high. This makes the switch an ideal choice for this experiment. Also, the pin has ground, Vcc and -Vcc for bias points, and CTRL1 and CTRL 2 for the two control signals[7]. The experimental set up for two tone injection is described below so that the need for other equipment like the amplifier and attenuator can be understood.

The idea is to inject two tone for some time (in the order of milli seconds) without losing the LTE connection. One of the RF inputs is the two tone and the other input is the IQ signal from the modulator. It is an excellent switch as it has very fast switching time of the order of few nanoseconds.

The experimental set up is as follows:

Device driver output soldered to coaxial cable ---coaxial cable to attenuator---amplifier ---- RF Switch (output from 1 amplifier)

Figure 18: Block diagram of experimental set-up



The objective is that the power amplifier is fed with the RF input of a desired level. For the intermodulation distortion the path from output of device driver to input of power amplifier is broken. The input to the power amplifier is now controlled by the above-mentioned switch. The output from the device driver is fed into an attenuator first and then an amplifier which is finally fed into one of the inputs of the RF switch. The other input of the RF switch comes from the signal generators after the combiner so that two tones are generated. The output of the switch is fed to a coupler and then to the input of the power amplifier. The order for amplifier and attenuator is such so as to have as minimum noise figure as possible.

4.2 Power Amplifier (MITEQ)

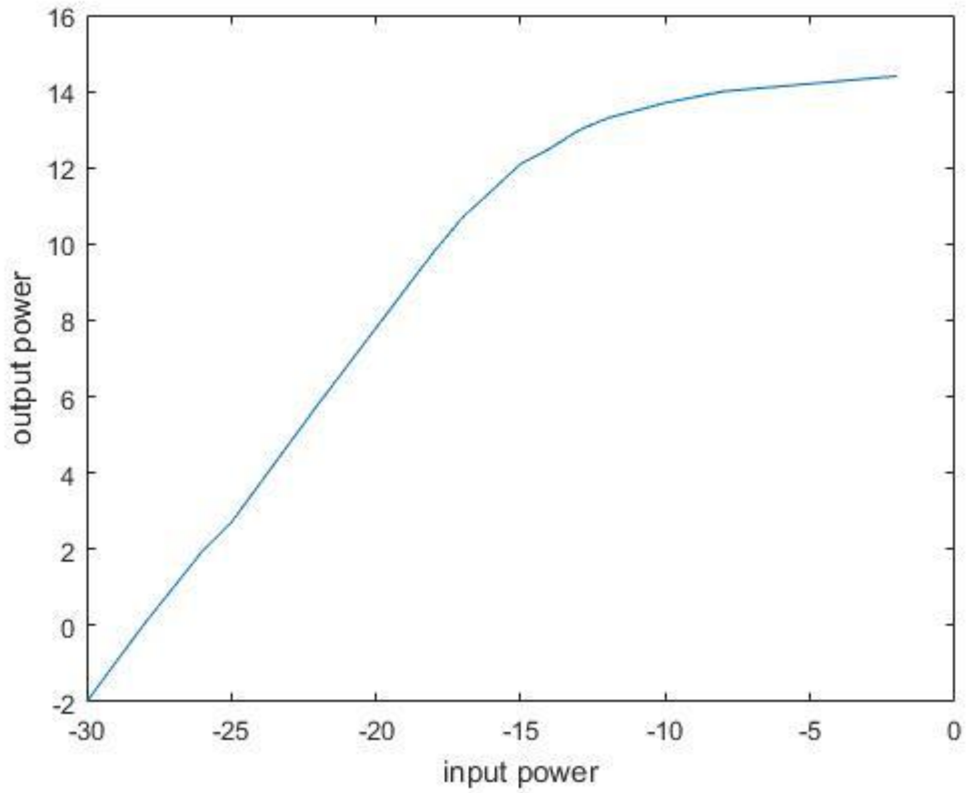
The amplification of the power amplifier is measured to be around 24-27dBm. The gain of the amplifier was -27.75dBm.

Table 5 : Observations regarding input and output characteristics of Miteq Power Amplifier

Sl no.	Input	Output	Gain
1	-30	-2	28
2	-28	-0.05	27.95
3	-26	1.95	27.95
4	-25	2.7	27.7
5	-22	5.8	27.8
6	-20	7.8	27.8
7	-18	9.8	27.8
8	-17	10.7	27.7
9	-16	11.4	27.4
10	-15	12.1	27.1
11	-14	12.5	26.5
12	-13	12.98	25.98
13	-12	13.3	25.3
14	-10	13.7	23.7
15	-8	14	22
16	-5	14.2	19.2
17	-2	14.4	16.4

So, the input and output characteristics when plotted look like this:

Figure 19 : Input power versus output power of Miteq PA



Thus, the gain of the amplifier is calculated as -27.7dB.

4.3 Coupler

The RF power coupler is used such that the output from the switch can be sent to the input of the power amplifier. The couple has an input, a port coupled to input and the output. The difference in power between the input and the coupled port was found to be 10.3dB. The difference between in power between the output and input ports was found to be around 1.6dB. The coupler is used so that the output from the coupled port could be used to view the input to the power amplifier.

So, for example if we have a signal from the coupled port and it measures to be 5dBm, then the input to the power amplifier is given by the expression

Input to power amplifier = Output at coupled port – 8.7dB

4.4 Attenuator

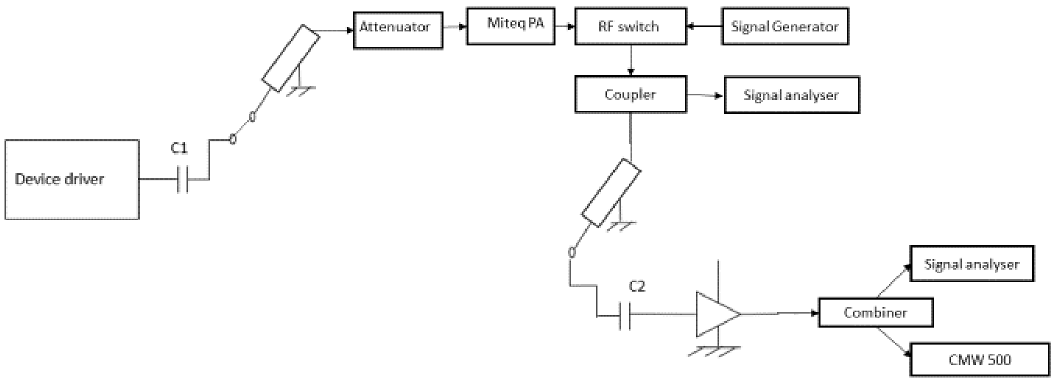
The attenuator was also characterized, and it was found that the attenuation was 1.4dB more than what was set in the attenuator. The attenuator was given a certain input and the output was measured. The values of attenuation could be adjusted by a rotating knob. So, the values of the input and output and the corresponding attenuation values are like this:

Table 6: Observations regarding attenuation measured and attenuation set in the attenuator

Sl no.	Attenuation set on the attenuator	Attenuation measured
1	10	11.4
2	11	12.4
3	12	13.4
4	13	14.4
5	14	15.4
6	15	16.4
7	16	17.4
8	17	18.4
9	18	19.4
10	19	20.4
11	20	21.4
12	21	22.4
13	22	23.4
14	23	24.4

Adjusting the value of the attenuator to get a 0dB loss in the block diagram shown below:

Figure 20: Block diagram of the experimental set-up to calculate gain and attenuation along the intercepted path



The experimental set-up has the attenuator just before the amplifier for a lower value of noise figure. The attenuator, being a variable one, was set to a value such that the in out to the power amplifier is same as the output from the driver. This means characterizing the components in between the device driver and the input to the power amplifier and adjusting the value of the attenuator accordingly such that the path is a no loss no gain path. The path from the device driver to the power amplifier has the attenuator, power amplifier, RF switch, coupler and signal analyzer in between them. This is done to ensure that the experimental arrangement does not attenuate the signals so much that the signal level is less than the minimum signal level to establish the connection. The attenuation of the amplifier is assumed to be x. The characteristics of all the equipment are measured and recorded.

Table 7: Gain and loss characteristics of instruments used in experiments

Sl no.	Equipment	Gain	Loss
1	Attenuator		x+1.4
2	Amplifier	27	
3	RF Switch		2.3
4	Coupler		1.6

Equating total loss with total gain, the value of x is calculated as 21.7. So the attenuator is set to the value 22.

CHAPTER 5

5 Experiments, measurements and analysis

5.1 Linearity measurements

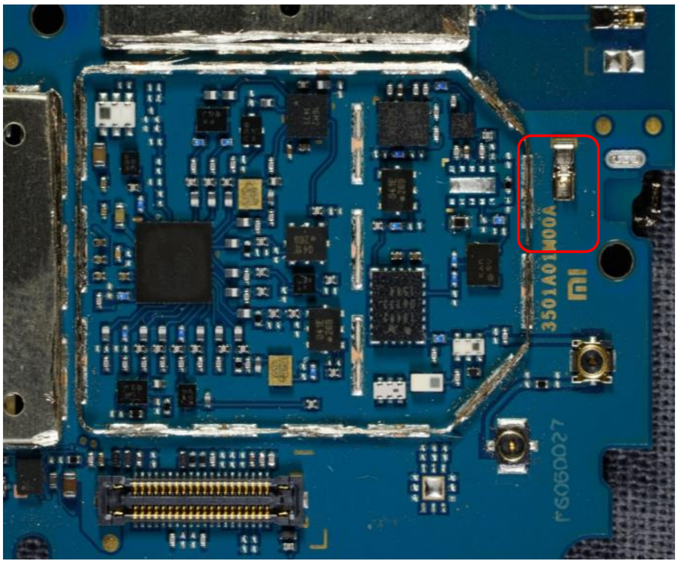
The idea behind the experimental set up is that while the LTE connection is up, a signal with known power level is injected into the RF input of the power amplifier. The power level of this signal is varied and the signal at the output of the power amplifier is measured accordingly.

Linearity of a power amplifier is an important characteristic that is desirable in any system using amplitude modulation schemes. In simple terms linearity of a PA means that it should be able to amplify the input signal without introducing distortions. However, the disadvantage associated with linear power amplifiers is that the energy consumption is much higher. Thus, experimental setup has been designed and measurements have been recorded to get an idea of the compression point and 3rd order intermodulation products.

This experimental setup with little modification could be used to measure the 3rd order intermodulation products and look at the intermodulation products being generated. The power of the two tones is varied. In the output it is seen that along with the two injected tones some intermodulation products are also generated. The intermodulation products have been introduced because of the non-linearity of the power amplifier. All measurements are performed in the LTE Band 7(2500-2570 MHz).

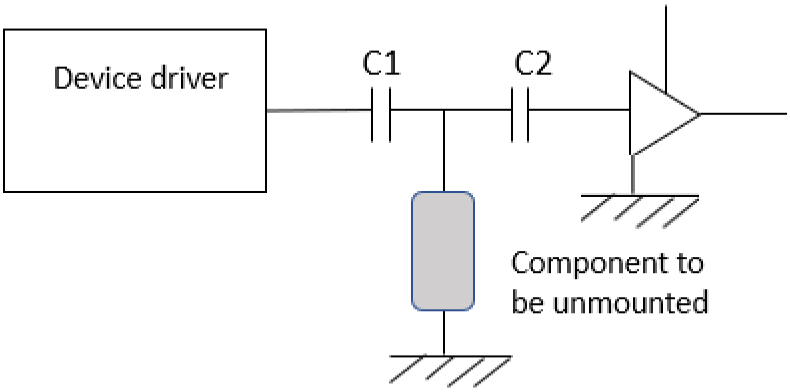
The pictures below show the phone was surgically modified.

Figure 21: A picture of the power amplifier front end module



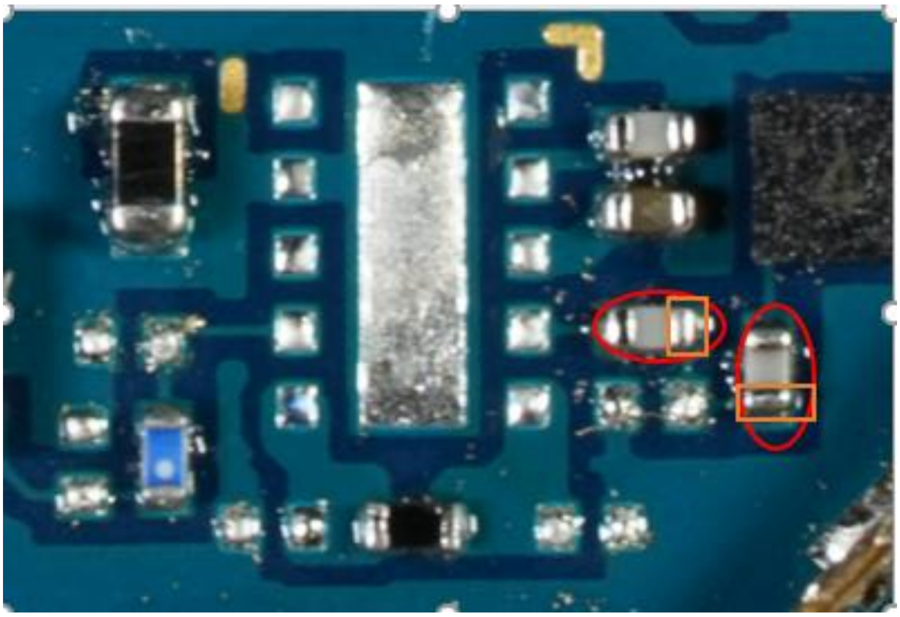
A simple block diagram looks like this:

Figure 22:Block diagram depicting surgical intrusion of the power amplifier front end module



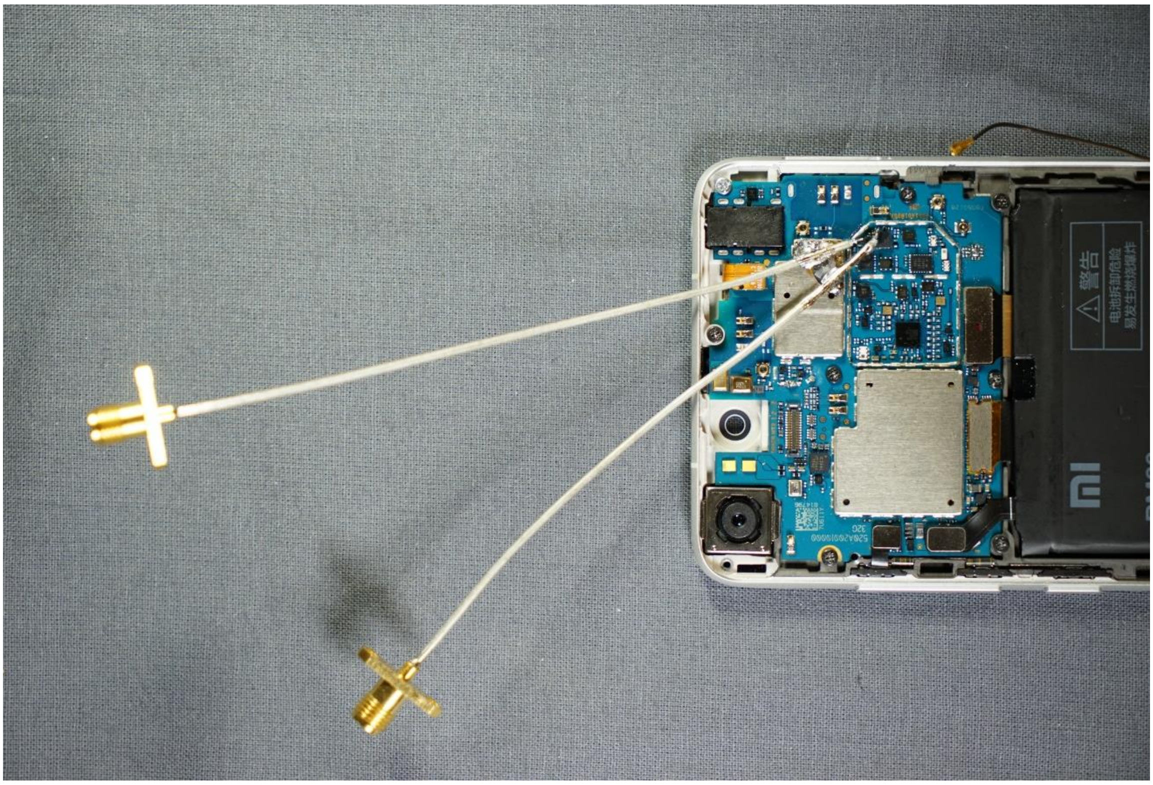
The power amplifier module whose behavior is to be investigated is marked in red and called ACPM-9407. It has 10 pins and the pin configuration can be found out from the website (*https://html.alldatasheet.com/html-pdf/936205/BOARDCOM/ACPM-9407-TR1/390/1/ACPM-9407-TR1.html*) easily. The brief description of the power amplifier module reads that the power amplifier operates in two power modes: high and low. This is somewhat in coherence to what is experienced when the UE is asked to transmit different values of power to connect to the base station.

Figure 23: Magnified picture of the power amplifier front end module



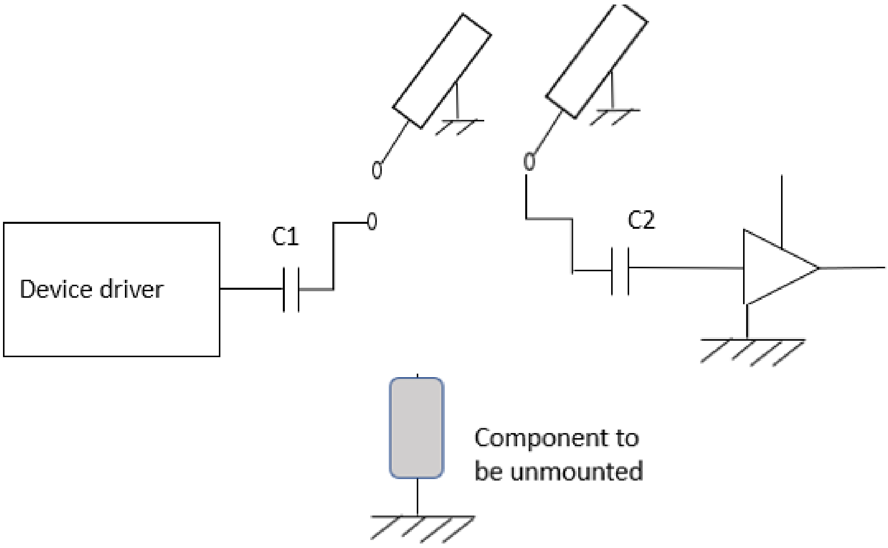
The surgical intrusion is described here. The two indicated capacitors are mounted standing upright on the PCB with the ends marked with □ are detached from the PCB and kept floating in air, and the other ends soldered to their original positions. If possible, measure the capacitance value of the two capacitors. Semi-rigid coaxial cables (diameter approx. 1.2 mm) are connected to floating ends of the capacitors in air. The inner conductor of the coaxial cable is connected to the floating end of the capacitor. The outer conductor of the coaxial cable is soldered with one of the nearest shield cans for grounding as shown in the figure below.

Figure 24: A picture of the power amplifier front end module after surgical intrusion



A block diagram of the surgical intrusion is as follows:

Figure 25: Block diagram of the experimental set-up depicting the intrusion



All measurements in the following sections have been carried out in the wired scenario.

When over the air experiments were conducted in similar scenario, the power loss was very high around 30dBs. There are lot of uncertainties in measuring parameters over the air. For e.g. The measurements are seen to be very dependent on the position of the phone on the antenna coupler.

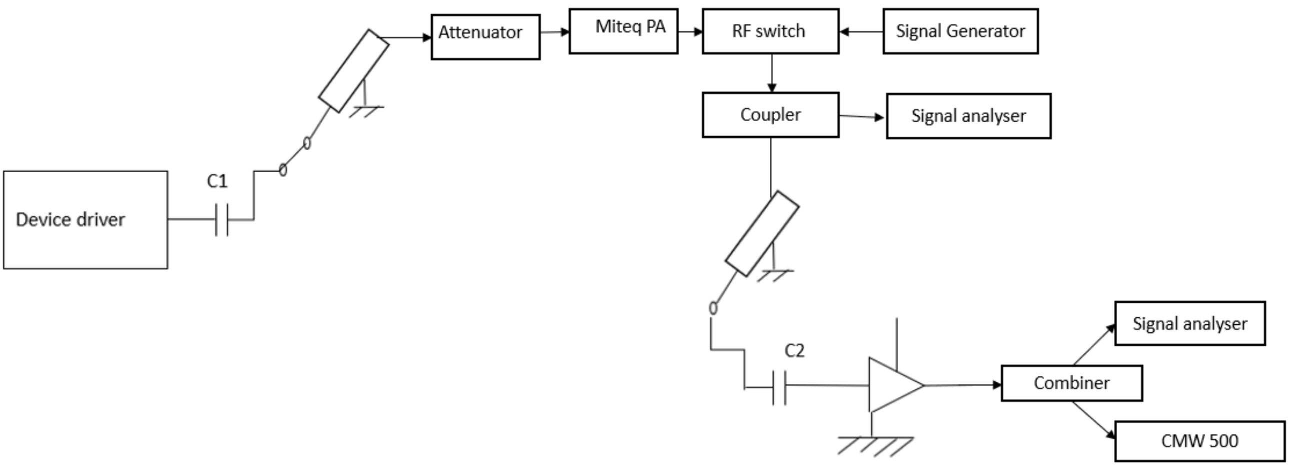
5.1.1 Compression point

The input to the power amplifier from the output of the device driver is modified in a manner that desired input could be provided. This means that a switch is used which can control the input to the power amplifier. The RF switch works on control logic. A pulse generator is used to provide the control signal to the RF Switch. The control signals are such that out of every 100ms, the LTE signal is interrupted for 20 ms. For measuring linearity, a signal or more precisely a single tone generated by a signal generator is injected. The frequency of the single used is 2.535GHz.

The experimental set up looks something like this:

So, the linearity measurements are as follows:

Figure 26: Block diagram of the experimental set up for measuring linearity of the power amplifier module



The experiments readings are as follows:

Table 8: Observations regarding the input and output characteristics of power amplifier and signal generator and signal analyzer readings

SG readings	PA input	SA readings	PA output
-25	-28.9	-10.62	- 0.62
-24	-27.9	-9.69	0.31
-23	-26.9	-8.71	1.29
-22	-25.9	-7.74	2.26
-21	-24.9	-6.79	3.21
-20	-23.9	-5.76	4.24
-19	-22.9	-4.80	5.20
-18	-21.9	-3.8	6.2
-17	-20.9	-2.82	7.18
-16	-19.9	-1.81	8.19
-15	-18.9	-0.88	9.12
-14	-17.9	0	10
-13	-16.9	0.97	10.97
-12	-15.9	1.83	11.83
-11	-14.9	2.75	12.75
-10	-13.9	3.63	13.63
-9	-12.9	4.63	14.63
-8	-11.9	5.45	15.45
-7	-10.9	6.24	16.24
-6	-9.9	6.9	16.9
-5	-8.9	7.50	17.50
-4	-7.9	7.92	17.92
-3	-6.9	8.30	18.30
-2	-5.9	8.65	18.65
-1	-4.9	8.97	18.97
0	-3.9	9.11	19.11
1	-2.9	9.32	19.32
2	-1.9	9.45	19.45
3	-0.9	9.55	19.55
4	0.1	9.66	19.66
5	-28.9	-10.62	- 0.62
6	-27.9	-9.69	0.31
7	-26.9	-8.71	1.29
8	-25.9	-7.74	2.26
9	-24.9	-6.79	3.21

Calculations:

The signal generated by the signal generator passes through the RF switch and the coupler before entering as input for the power amplifier module. The input to the power amplifier is the signal generator signal attenuated by losses in the coupler and RF switch. As mentioned above loss due to coupler is 1.6 dB and that due to RF switch is 2.3 dB So, total loss due to both is 3.9dB.

PA Input (in dBm) = Signal Generator Readings (in dBm) – Losses in coupler and RF switch(in dB)

= Signal Generator readings (in dBm) -- 3.9 dB

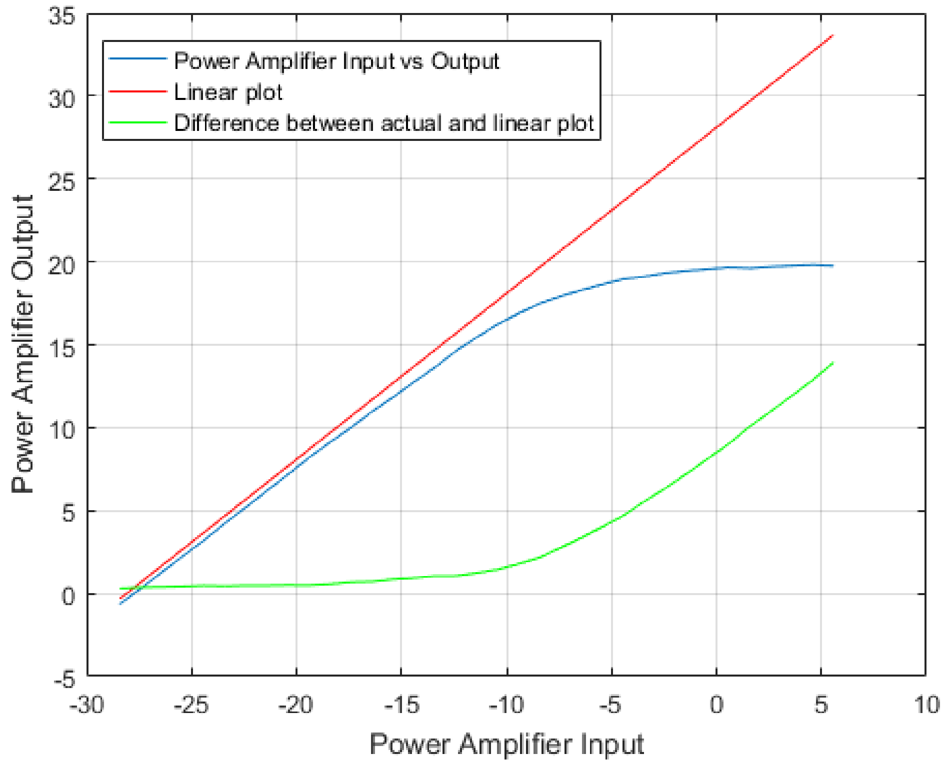
The Signal Analyzers reading is indicative of the PA output. The value indicative of the PA output after being attenuated at the antenna and the combiner is read at the signal Analyzer.

PA Output (in dBm) = Signal analyzer Readings (in dBm) + Losses in antenna and combiner (in dB)

Loss in antenna and combiner is measured to be around 10 dB So, in this way the output of the power amplifier is calculated.

The linearity graph is

Figure 27: Linearity plot of the power amplifier module



The compression point appears to be around -10dBm for Power Amplifier Input and the corresponding Power Amplifier output is 17dBm. Though the maximum power that the UE can transmit is 23dBm, the power amplifier is expected to be linear below linear -10dBm. This was done when the UE was asked to transmit power of 10dbm.

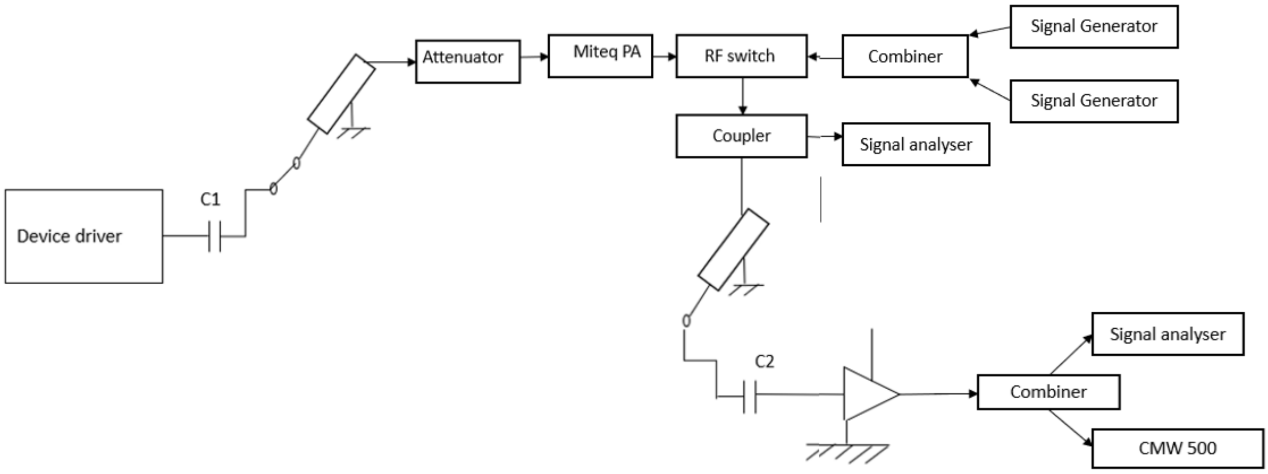
The compression point is not directly pointing to a linear power range. The required linear power range is dependent on other parameters such as spectrum broadening and EVR (error vector magnitude). However, the compression point must be above the linear output power level.

5.1.2 3rd order Intermodulation Products Distortion measurements

For measuring the intermodulation distortion, two tones are used. The frequency of the two tones used are 2.5345GHz and 2. 5355GHz.The LTE Band 7 is from 2.5GHz to 2.57GHz

The experimental set up for intermodulation products measurement looks something like this:

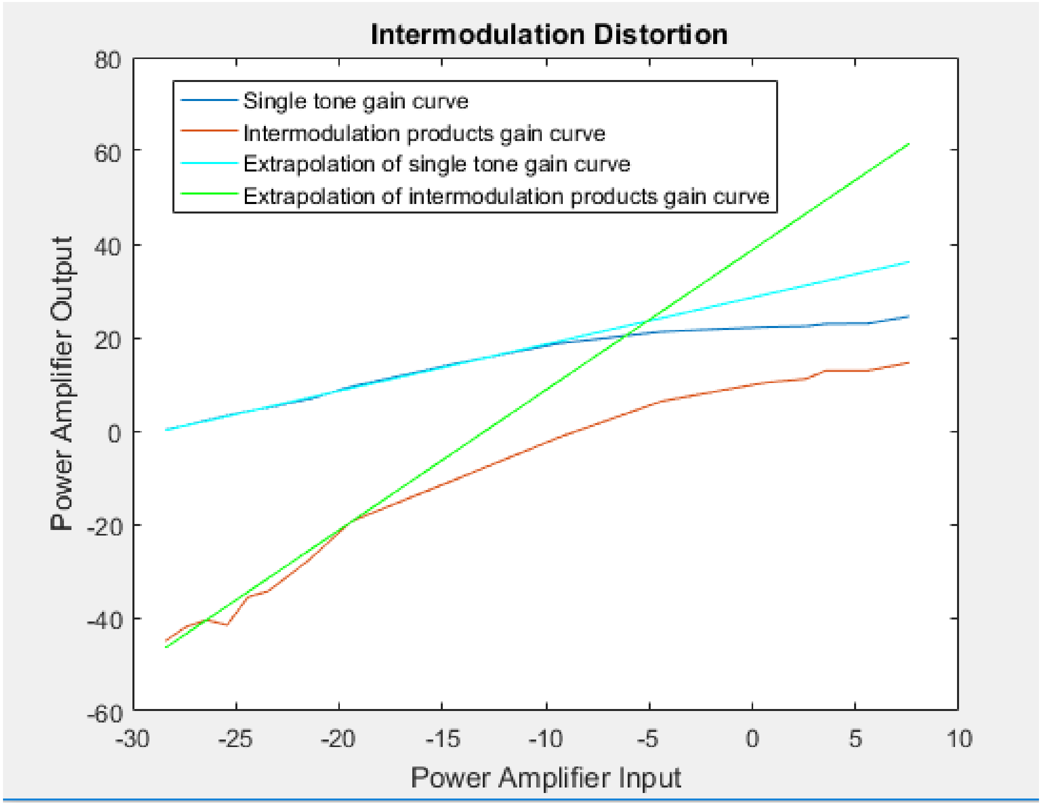
Figure 28: Block diagram depicting the experimental set to measure 3rd order intermodulation products distortion



The calculations are almost similar as in case of linearity measurements except that while calculating the loss in the path of input to the power amplifier an extra component that is a combiner is added to it.

The graph for the above experiment looks like this:

Figure 29: Intermodulation distortion plot



From the graph above it is noted that the 3dB order intercept point for the power amplifier is found to be around -5dBm for power amplifier input. The power amplifier output is found to be around 18dBm.

After the setup is done the following is observed:

1. The power level of the injected signal at the input of the power amplifier is varied to record measurements at different power levels. The minimum power level at which the output of the RF PA could be clearly seen and measured was -25dBm. When the power level of the injected signal is reduced below -25dBm, the output is lost in the noise floor. In other words, it could be said that the power level of the noise floor and the output of the injected tone is the same as each other, which results in inability in measuring when the input injected signal level of the power amplifier is below -25dBm.

This could be explained in the following manner. The signal and the noise floor are a few dB above the thermal noise. When they pass through the external attenuator, connected before the RF switch, everything gets attenuated. So, the signal gets attenuated and so does the noise. But, noise cannot go below the thermal noise. So, after the attenuator the signal to noise ratio becomes worse than it was in the beginning. Thus, it means that the signal gets corrupted and what we see doesn't make much sense. The noise increases both in the receiver and the transmitter path.

Using a filter might be a solution to limit the signals in the RX band interfering with the signals in the transmit band.

2. Also, lot of components have been introduced in between the device driver and the power amplifier, thus introducing a delay in between the phase modulation and the amplitude modulation which might be critical for integrity of the signals.

It is observed that the amplifier behaves linearly in low power conditions but in high power conditions it probably switches to envelope tracking mode. When the UE is asked for higher power transmission, the power management system of the phone behaves differently and transmits a much lower power. This becomes much clearer when the efficiency measurements are looked at.

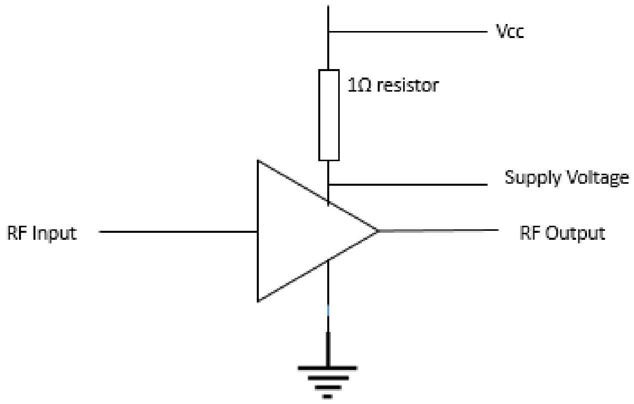
5.2 Efficiency Measurements

The efficiency of the power amplifier is measured as the ratio of output RF power to supply power. So, arrangements are made to perform these experiments. The schematics of the UE is available online. The supply voltage to the power amplifier is measured. Arrangements are made to connect a 1-ohm resistor with the objective of measuring current across it through its voltage drop. The value of current be given as the same as the voltage drop across the resistor because the resistor is a 1-ohm resistor. The product of Vcc and the current through the resistor gives the value of the input power to the amplifier.

Introducing the resistor does not affect the supply voltage because it has been introduced before the voltage regulating circuit. The schematics is easily available online. It has been studied and the unity resistor has been introduced such that it does not affect the input supply voltage to the power amplifier.

The circuit diagram for the efficiency measurement experimental setup looks something like this:

Figure 30: Power amplifier with unity resistor



The table with the measured values of current and voltage looks something like this:

Table 9: Observations for power measurements of the power amplifier module

TX power in CMW	Power measured by RF power meter	Supply Voltage Vcc	Current across 1 ohm resistor
21.17	14.41	2.132	0.267
20.2	13.4	1.975	0.252
19.04	12.43	1.846	0.238
18.02	11.45	1.732	0.223
16.96	10.44	1.631	0.208
15.95	9.42	1.5145	0.192
14.95	8.44	1.442	0.1778
13.87	7.44	1.378	0.164
12.86	6.4	1.285	0.1496
11.9	5.38	2.845	0.1316
10.95	4.40	2.778	0.124
10.01	3.39	2.712	0.117
9.04	2.41	2.592	0.112
7.96	1.41	2.461	0.1073
6.86	0.38	2.3385	0.10334
5.81	-0.64	2.245	0.10026
4.86	-1.61	2.184	0.098
3.85	-2.53	2.062	0.095
2.96	-3.48	1.971	0.0943
2.0	-4.46	1.97	0.0933
0.99	-5.47	1.849	0.09196

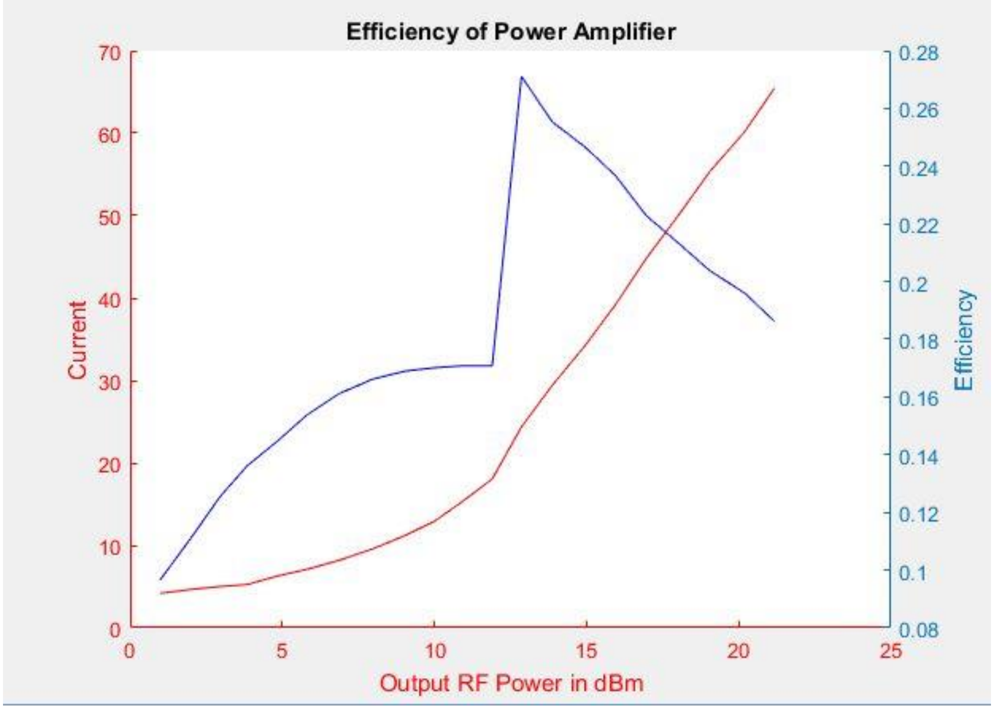
The output RF power is measured by an RF power meter. The ratio of output RF power to input power gives us a measure of efficiency of the power amplifier.

Calculations:

The efficiency of the power amplifier is measured as the ratio of output RF power from the power amplifier to the input DC power to the power amplifier. The output power of the power amplifier is measured by a RF power meter.

For measurement of the input DC power to the power amplifier, the power management module of the user equipment is surgically intruded. The schematics of the power amplifier module were used for reference. A resistor of value 1 ohm is connected in series between the points Vcc and the input to the power amplifier. The other end is grounded as shown in the diagram. The voltage drop across the resistor is measured. This is equal to the current across the resistor since it is a unity resistor. The voltage supply to the power amplifier is measured by measuring the voltage difference between the input to the power amplifier and the ground. The product of this voltage difference and current across the unity resistor gives us the input power to the power amplifier. The ratio of RF output power and this gives us the value of efficiency of the power amplifier.

Figure 31: Plot for efficient of the power amplifier



The efficiency curve shows that the power amplifier behaves in two mode operation. This is coherent with the power amplifier specifications given for the particular power amplifier front end module of the user equipment. From the graph it is seen that the maximum efficiency that the power amplifier can achieve is found to be around 27 %. The highest efficiency is when the output power is 13dBm. The graph shows that up to 12dBm the power amplifier module behaves in a particular manner and after that it switches into another mode where the efficiency starts increasing sharply and then starts to drop after reaching its maximum value which in this case is 27%.

CHAPTER 6

6 Conclusions and Future Work

Experiments have been designed and measurements have been performed on the power amplifier module, which is one of the largest power consumers in a user equipment. The goal has been to understand the behavior with the latest standards and advanced architectures to save power. A test setup has been designed where data throughput has been pushed to its maximum speed. In addition to it, the TX path has been successfully intercepted with a test signal while keeping the connection with the CMW 500.

The most important point that has been kept in mind is that the user equipment is connected to the base station via LTE signals while performing experiments. This means that during the experiments the test signals were inserted into the power amplifiers while it was connected to the CMW 500 that was emulating the base station. Then, response of the power amplifier was measured.

The power amplifier behaves in two modes: a low power mode with constant supply power and a high-power mode where envelope tracking sets in and the supply voltage varies. When the power amplifiers operate in a high-power mode it is difficult to get expected results with the setup because of the varying supply voltage. Thus, the behaviour of the power amplifier is difficult to control.

As per the specification of the power amplifier, it is compatible with MIPI RFFE. This means that the power amplifier mode is controlled digitally. While doing experiments, there was no control over what mode the power amplifier was in. Thus, it was difficult to characterize the behaviour of the power amplifier. This means that there is a need to understand the communication between the power amplifier and the processing unit which in turn decides the mode in which the power amplifier operates.

Thus the results obtained during the experiments were difficult to use because of the behaviour of the system or precisely the different operating modes of the system.

In future, it will be good to understand the communication protocol between the processing unit and the power amplifier. Also, studies could be made to understand how to handle envelope tracking. Maybe, applying an external supply voltage to the power amplifier could be a good option. Experiments performed after these studies are made could help us understand the best way for communication between user equipment and the base station in uplink.

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