Testing The Reliability And Flexibility Of Digitizers Adapting The Rf/if Signals Over Ip Applications Using A Testbed Platform

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TESTING THE RELIABILITY AND FLEXIBILITY OF DIGITIZERS ADAPTING THE
RF/IF SIGNALS OVER IP APPLICATIONS USING A
TESTBED PLATFORM.

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Dedication

I dedicate my work to God for the opportunity by completing another academic achievement

Also, to my loving family

My parents Jose Manuel Sandoval Barrón & Sandra Luz Maese Fernández

My brother Santiago Sandoval and Biby Sandoval

For the unconditional, love, support and effort that kept me focus

My friends whom always believed, inspired and motivated me
TESTING THE RELIABILITY AND FLEXIBILITY OF DIGITIZERS ADAPTING THE
RF/IF SIGNALS OVER IP APPLICATIONS USING
A TESTBED PLATFORM.

by

JOSE CARLOS SANDOVAL, B.S.E.E.

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Electrical and Computer Engineering
THE UNIVERSITY OF TEXAS AT EL PASO
December 2020
Acknowledgements

I would like to thank Dr. Virgilio Gonzalez of the Electrical and Computer Engineering Department at The University of Texas at El Paso for all advice and guidance through this process. Also, patience and tolerance that he has always shown during thesis meetings and project related activities. One research saying that will always be in my memory is “Does it work? What time does it stop working?” which gave me more knowledge and the ability to discover new methods.

Thank you is directed to my committee members Dr. Joel Quintana and Dr. Robert C Roberts for all the feedback provided and the help through this thesis research.

I would also like to express my gratitude to White Sands Missile Range. Specially to Pabel Corral and Duke Yasuda. Both are amazing persons full of knowledge and always supportive. In addition, I appreciate lending us the devices and all infrastructure needed to still work and developed a research thesis.

Special thanks to my research colleagues, Jose Antonio Castillo and Mirza Mohammad Maqbule Elahi for all the moments shared through this journey, all the projects together and the support to each other.

Moreover, I would like to thank the Electrical and Computer Engineering Department at the University of Texas at El Paso. Professors and staff whom always seem supportive and helpful guidance for academic steps towards completion of my Master’s degree.

In last, I would like to thank my friends and family for all the support and the motivation phrases through the entire cycle of my graduate life. My cousin Aldo Isaac Garcia who is a brother to me for always been there when needed. My mother whom always backed me up through my entire academic life, my father for all the wisdom and advises and my brother for all sincere advises
that help me focused to complete my thesis. I do not have words to express all my feelings, or even try to describe them.

The hardest test in my academic life is now completed. I am, deeply thankful for all help of classmates and friends during this cycle. Special thanks to Vianey Benitez for having the opportunity to help me and push me in my last semester. For these wonderful last months, I express my gratitude by continuing to be part of her life.

Thank you.
Abstract

As physical constraints can be challenging for Radio Frequency (RF) telemetry, a new solution has been exploited to support the demand for RF transmissions. As frequency spectrum gets crowded with more technologies, a solution to a reliable transmission is needed. Digitizers can mitigate many of the physical constraints in order to achieve a successful RF transmission. The method includes the conversion of the RF signals to be sent over IP networks, transmit and de-convert the signal. IP networks will mitigate many disadvantages over a regular signal transmission.

The authority in charge to allocate frequency bands is the Federal Communications Commission (FCC). FCC performs different Advanced Wireless Service (AWS) a term used to allocate the licensed bands to all users. For example, government, cellular companies, television, radio and much more. Numerous AWS have been performed to allocate new services or reallocate existing services due to high demand of the RF spectrum.

The digitizers are also able to preserve both frequency and timing characteristics, and then accurately reconstructing the original Telemetry signals to enable processing, recording or retransmission at another location. To characterize the digitizers, a Software Defined Radio (SDR) testbed with an external reference clock to analyze the impact of signal synchronization is used. Several experiments were done with different modulation schemes, destination IP, gain, packet size and others. Also, the utilization of a reference clock to perform testing will be added to compare result with the reference clock and in absence. The configurations of gain, bandwidth and frequency are also parameters of interest. In order to compare these results, diverse parameters were used to qualify and quantify the signal. In addition, the flexibility of SDR’s and digitizers provide, allow to test several scenarios. Furthermore, using the same concept for RF
over IP, experiments were also done with LTE signals to perform the same process and measure certain parameters.

To summarize, a set of RF over IP tests yielded results for comparison, mostly with the reference clock to make this layer as transparent as possible and characterize the limitations or other challenges that could be present with this solution.
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Chapter 1: Introduction

Physical limitations are a challenge for radio frequency transmission. Moreover, Telemetry (TM) signals have disadvantages, for example the degradation of signal over long distances. Not only degradation, but also, the noise due to other signals spectrum can affect the TM signal [1]. In addition, Radio Frequency (RF) spectrum is overcrowded due to high demand by several commercial users. As new technologies evolve and others emerge, RF spectrum is needed for internet of things or other services offered by commercial companies. Furthermore, different Advanced Wireless Services (AWS) auctions to deliver more reliability to the mobile users [2]. These auctions reallocate several mobile carries adjacent to TM signals. TM signals are being affected by these auctions; new solutions are explored to fit the needs of spectrum users. Mobile carriers’ modulation is Orthogonal Frequency Divide Multiplexing (OFDM) a very aggressive modulation compared to a TM signal modulation. OFDM modulation can cause degradation in TM signal [3]. RF over IP is an innovative solution that mitigates the physical constraints and enhance a successful transmission. The mitigation of the physical constraints for TM signal transmission will improve with RF over IP. Physical limitations are an immense disadvantage for many RF spectrum users, especially TM because of the modulation used for transmission. In addition, other RF spectrum users will create noise for the transmission. RF over IP will transmit in a different environment that will benefit and make a feasible transmission.

The Federal Communications Commission (FCC) is in charge of the control, distribution and supervision of the RF spectrum. Due to AWS auctions TM frequencies band have been reduced for commercial use. The bands of interest are the L-band (from 1-2GHz), S-band (from 2-4 GHz) and C-band (4-8 GHz) [4]. These bands are affected by the AWS auction with adjacent mobile carriers. As discussed in Interference Analysis and Mitigation of Telemetry and 4G LTE
systems in adjacent spectrum bands [3] there are certain limitations to transmit if signals TM and 4G LTE are adjacent. Due to OFDM modulation, 4G LTE does not have massive impact in the noise raise caused by TM signals. On the contrary, TM signal are affected severally by 4G LTE signals.

Digitizers are the devices used to create the conversion from RF to IP networks and perform the transmission. TM signal is digitally manipulated and transported in IP networks, repeating the process backwards to unconvert the signal. Capability of these devices include the preservation of frequency, configuration of bandwidth stream, and option for additional gain. Also, configuration of IP source and destination. In order, to test the digitizers a Software Defined Radio (SDR), testbed will emulate telemetry signals with diverse modulation schemes. SDR’s are controlled by a software called LabVIEW Communications, which generates a simulation of several signal transmission without affecting the RF spectrum. Different SDR’s have the capability and flexibility to test various scenarios including LTE signals. SDR’s will generate TM signal transmission with several changing parameters in order to have a deep analysis of the quality of signal after transmission. TM signal generated by the SDR will be sent to the digitizers to be converted and transmitted, after, signal is transmitted, thus it will be unconverted and received by another SDR, to prove that the digitizers could be added as a transparent layer of signal transmission.

RF over IP is an innovative solution for the extreme RF spectrum problem. RF spectrum has limited resources, also, RF spectrum demand has increased over the past few years. In consequence, as demand increases allocation for new users is needed and reallocation for existing users. Government agencies, such as, Department of Defense (DoD) has been a historical large user of RF spectrum. Due to AWS, parts of RF spectrum are sold forcing DoD to reallocate several
applications. DoD existing users are mostly legacy applications that still need to be supported. RF over IP technology is a possible solution that will support legacy applications using workarounds, such as, removing backhaul by moving the RF signal into a Data network.

To summarize, to perform a successful TM, signal transmission RF over IP technology could be added to the process to ensure reliability and flexibility of the system. Due to AWS auctions, need to different solutions is required from White Sands Missile Range (WSMR). RF over IP is a feasible mitigation technique interference to TM signals.
Chapter 2: Literature Review & Background Information

2.1 Telemetry History, Standards PCM/FM

In order to understand telemetry history, going back to 1950’s when telemetry was invented, many applications were implemented. According to Barculo the definition is “Telemetry is a technology that allows the remote measurement and reporting of information of interest to the system designer or operator. Telemetry typically refers to wireless communications, but can also refer to data transferred over other media, such as a telephone or computer network or via an optical link” [5].

Early telemetry was used in different fields of study. Biomedical is one important field in which telemetry has many applications. Telemetry has now become a vital constituent in the field of medical sciences to remote measurement of biological parameters. Biomedical telemetry provides a means for monitoring and studying human and animal physiologic functions from a remote site with wireless transmission for the goals of minimally disturbing normal activity or free restraint of target’s subject to allow ambulatory freedom. Signals derived from physiologic transducers have been encoded and formatted in many different ways in an effort to improve transmission reliability in air space and water and carrier signals have included radio, sound and light. [5]

In addition, there are several other fields of study for telemetry. For this research we focus on the telemetry that was applied in the topic of missiles and other fields that are relevant in signal transmission. Most of this telemetry systems were developed during cold war, around 1950. Telemetry intelligence (TEINT) (later to be called FISINT) was a critical source of performance information on foreign missiles and space vehicles while they were being developed and tested, as well as a source of telemetry from military aircraft during their development. TELINT could also provide much operational information on foreign satellites and space vehicles. The National Security Agency (NSA) became responsible for U.S. TELINT under a Department of Defense (DoD) directive in 1959 as part of NSA’s electronic intelligence (ELINT) responsibilities.
TELINT prior to 1959 was being conducted by all of the DoD military department, this is disputed by Smithsonian Air and Space Museum [6]

2.2 Antenna

This section is mainly to gain knowledge in how antennas work. Since, antennas play a big role in transmitting the signal, it is encouraged to understand how several antennas work. Antennas radiate power and that is how they distribute the signal. The main purpose of an antenna is to make a successful transmission over a media, either transmitting or receiving. According to Balanis, “An antenna radiation pattern or antenna pattern is defined as “a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization.” The radiation property of most concern is the two or three-dimensional spatial distribution of radiated energy as a function of the observer’s position along a path or surface of constant radius” [7]

There are several types of antennas that could be used for transmission. Depending of the purpose of the antenna the type could be defined. Also, some antennas perform better in different tasks than others. Antennas have different radiation patterns, “Various parts of a radiation pattern are referred to as lobes, which may be subclassified into major or main, minor, side, and back lobes” as noted in [7].

Several antennas have several radiation patterns, which vary their lobes. Antennas are a limiting factor in terms of a successful and reliable transmission, due to physical constraints and radiation pattern problems. As mentioned in Balanis “Minor lobes usually represent radiation in undesired directions, and they should be minimized. Side lobes are normally the largest of the minor lobes”. Antennas waste some of the power due to this radiation loss of power.
To conclude, antennas are a limiting factor due to loss of radiation power. On the other hand, antennas play a big role in transmission despite its constraints in nowadays transmissions. Antennas could perform a good transmission, but if users overcrowd the antenna there are limiting factors that compromise the transmission. Also, if there are other transmission, they could interfere or degrade the signal transmission since they are considered as noise.

2.3 Software Defined Radio (SDR)

A Software Defined Radio (SDR) is a radio communication system in which its hardware it is replaced by software components. SDR Forum defines as a “Radio in which some or all of the physical layer functions are Software Defined” [8]. Several devices are used for the experiments throughout history measuring several parameters to qualify and quantify signal transmission, one of them is the SDR. SDR’s not only can transmit and receive a signal, also, they can qualify and quantify a signal with the right: tools to be measured. According to “SDR usually is compared to a radio PC, which can host different air interface applications and the major focus is on the access system. However, it is necessary to broaden the scope and to include all layers for optimizing network resources and improving user satisfaction. The traditional SDR concept introduces flexible terminal reconfiguration by replacing radios completely implemented in hardware by those that are configurable or even programmable in software to a large extent. These concepts include reconfiguration of the antenna, the radio transceiver and the baseband” [9].

SDR’s will facilitate the communication and provide reliability to the signal transmission. In addition, SDR could replicate real scenarios with the right: parameters to be inputted. Now, National Instruments (NI) Universal Software Radio Peripheral (USRP) are the SDR used for RF applications [10]. Also, USRP’s are a feasible device and will be used for experiments in this thesis. Figure 2.3.1 shows a system level diagram of the NI USRP-2920. NI USRP-2920 will be used to generate Telemetry (TM) signal.
Furthermore, Figure 2.3.2 shows the system level diagram from an NI USRP-2954 that will be used to generate the 4G LTE signal for other experiments. This is a more complex SDR because it includes the input for a GPS antenna, also, frequency capability is higher than the NI USRP-2920.
To conclude, SDR’s play a big role in the experiments for several applications. Since, legacy technology through latest technology as 4G LTE. In addition, for the set of experiments to be presented, it is fundamental to have SDR’s to replicate the scenarios and give a detailed understanding. SDR’s facilitate the scenarios and experiments to describe the behavior of signal transmissions.

2.4 Other Techniques

Several techniques have been researched in order to optimize transmission. Specially as RF Spectrum is overcrowded, different techniques are explored. Several techniques in order to mitigate interferences between adjacent frequency bands. Previous techniques involve the same testbed using SDR’s to simulate several environments to provide knowledge.

The first technique is to set boundaries or rules to transmit within a safe range of other frequency bands. Gonzalez proposed in “Interference analysis and mitigation of Telemetry (TM) and 4G Long-Term Evolution (LTE) systems in adjacent spectrum bands” research that “focus of this document is to explore what solutions there are to adjacent interfering bands. This to be able to operate normally without any hindrance from external systems; meaning that the wireless systems from WSMR are to not interfere with the 4G LTE Uplink and Downlink bands, and vice-versa” [3]. In order, to have a reliable transmission research, safe frequency will not be affected by other adjacent frequency bands. Gonzalez’s technique involves a testbed that was created in order to simulate several signal transmissions. Understand how these signals could interfere with each other and qualify and quantify the transmission.

Another technique that has been researched is the “Interference mitigation of adjacent radio frequency signals on a flexible software-defined radio testbed platform” which proposes a digital filtering in order to mitigate the interferences between adjacent frequency bands. According to Elahi, “Digital filtering technique is a very effective application in mitigating interference between adjacent spectrum users. It rejects the adjacent interfering signal by reducing its signal power. This
can be achieved in the laboratory by designing filters with the desired rejection levels on a flexible testbed” [11].

2.5 Radio Frequency (RF) over Internet Protocols (IP)

One feasible mitigation technique to transmit RF signals is RF over IP networks. RF over IP will help to decongest the RF Spectrum. RF over IP could mitigate the physical problems that regular transmissions could be affecting and degrade the signal. Telemetry (TM) have several physical constraints when performing a long transmission. According to Chengyu, “By digitizing the signal, Radio Frequency over IP (RFoIP) reduces the signal degradation of the RF signal during long-distance transmission and reduces the effect from noise” [12]. RFoIP is innovative solution that has been exploited for the last years. As cited by Chengyu, “In order to meet the compatibility between networks, RFoIP technology is an effective solution. RFoIP is a technology that converts RF signal generated by an RF-based device into digital signal and implements transmission of the RF signal using IP network” [12]. Many companies have developed devices to convert the legacy systems RF signals to IP packets. These devices are called Digitizers, capable of converting and de-conveting the signal in order to perform a transmission over the IP network.

RT Logic, a Kratos company, developed a digitizer in order to fulfill customers necessities. Digitizers have complexity to ensure a successful transmission. In addition, other technologies are added to have control over the transmission and perform a feasible reconstruction of the RF signal. Also, digitizers include the ability to manage the IP for the interface and the source and destination IP. RFoIP, an innovative solution could be described as RT logic cites “This technology extends the transport of analog RF or intermediate frequency (IF) data to IP-based networks, e.g., the Internet. Using specialized techniques packetized IF can move digitized spectrum deterministically anywhere over an IP network, and reconstruct it at the destination so it can be processed by either digital or analog equipment. The specialized techniques achieve this with minimal added latency and no lost data all while being agnostic to the spectral content being transported. Since IP network
protocols provide neither deterministic data transport nor minimal latency, the implementation of packetized IF requires several innovations to achieve these objectives” [13]. Understanding the process for the digitizers when performing conversion and transmission is easier if it is explained step by step. Furthermore, a reference clock is added to synchronize the digitizers. Figure 2.5.1 shows how RF signal is converted to IP packets and de-converted back to RF signal.

![Figure 2.5.1 Packetized IF decouples transport and processing from receive/transmit Source adapted from: [13]](image)

In conclusion, RFoIP is a feasible technology that could mitigate physical constraints of TM signal transmission. In addition, SDR’s are included on the testbed generating the TM signal, which will be converted, transmitted, de-converted by the digitizers. Finally, TM signal will be received by the second SDR which will qualify and quantify the signal received. To summarize, RFoIP is a feasible technology to mitigate disadvantages of RF signal transmission over the air.

**2.6 RF Spectrum**

According to National Telecommunications and Information Administration (NTIA), the RF spectrum ranges from 3 kHz up to 300 kHz [4]. RF Spectrum is controlled by the FCC, but, supervise and ensure everything complies by the FCC Enforcement Bureau (FCCEB). This
department will check that all RF spectrum companies do not go beyond or below of the frequency allocated for its services. If any company will infringe the rules established it could result in fines applied by the FCCEB [14].

As the demand for newer technology increases, the users of the RF spectrum increase as well. Now, Internet of Things (IoT) will increase even more the demand for RF spectrum space. IoT refers to several technologies, for example, smart home security systems, autonomous cars, autonomous farming equipment and more. Any smart device will require connection, RF spectrum will be overcrowded. In addition, users are using many smart devices and all require a separate connection. In order to fulfill this demands readjustments to the RF spectrum are in progress, Advanced Wireless Services (AWS) auctions are taking place to reallocate certain frequency bands.

2.7 MODULATION TECHNIQUES

The process to transmit data is called modulation. Data needs to be transformed into a signal which later will be demodulated and converted back to data. There are several modulation techniques. They are divided into analog and digital modulations. For example, analog modulations are the common radio signals, Amplitude Modulation (AM) and Frequency Modulation (FM). AM and FM are the radio stations that can be listened in a car. Now, digital modulations are more complex. According to Sklar, “Digital modulation is the process by which digital symbols are transformed in waveforms that are compatible with the characteristics of the channel” [15]. Three basic digital modulations are:

- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)
ASK is the first basic Digital modulation. ASK will vary the amplitude of the signal in order to transmit different data. Fuqin cites that “In ASK, the modulator puts out a burst of carrier for every symbol 1, and no signal for every symbol 0” [16]. Figure 2.7.1 shows ASK representation of the analytic, waveform and vector representation. In the waveform, we can appreciate the representation of the symbol 1 then a symbol 0 and at the end again a symbol 1. In order to represent the two symbols, it is necessary to change the amplitude. This example could be also called On and Off keying (OOK) since there is no amplitude at the time symbol 0 is sent [16].

![ASK Analytic, Waveform and Vector representation](source)

Figure 2.7.1 ASK Analytic, Waveform and Vector representation Source adapted from: [15]

FSK is the second basic digital Modulation. FSK will vary the frequency in order to send symbols 1 and 0. Different frequency had to be denoted in order to know which will be for symbol 0 and symbol 1. According to Dharma, “Frequency shift keying (FSK) is used for modulating a digital signal over two carriers by using a different frequency for a “1” or a “0” the carriers is known as the frequency shift” [17]. The difference between Figure 2.7.2 shows first the frequency signal for the symbol 1, then the frequency signal for symbol 0. In addition, message signals to represent what symbols are being sent, finally, the FSK signal with both frequency symbols representing the message.
PSK is the final basic modulation. According to Dharma, “In digital transmission, the phase of the carrier is discretely varied with respect to a reference phase and according to the data being transmitted. PSK is a method of transmitting and receiving digital signals in which the phase of a transmitted signal is varied to convey information. For example, when encoding, the phase shift could be 0° for encoding a “0” and 180° for encoding a “1,” thus making the representations for “0” and “1” apart by a total of 180°. This kind of PSK is also called binary phase shift keying (BPSK) since 1 bit is transmitted in a single modulation symbol” [17]. Figure 2.7.3 shows the waveform signal of PSK.
Now, using the same concept of PSK several derivations could be used in order to send more symbols. Quadrature Phase Shift Keying (QPSK) is created in order to send more symbols. Dharma cites, “Quadrature phase shift keying (QPSK) takes the concept of PSK a step further as it assumes that the number of phase shifts is not limited to only two states. The transmitted carrier can undergo any number of phase changes. This is indeed the case in quadrature phase shift keying. With QPSK, the carrier undergoes four changes in phase and can thus represent four binary bit patterns of data, effectively doubling the bandwidth of the carrier. The following are the phase shifts with the four different combinations of input bits. Figure 2.7.4 shows the comparison of BPSK and QPSK in the constellation diagram.

![Constellation diagram of (a) BPSK and (b) QPSK](image)

Figure 2.7.4 Constellation diagram of (a) BPSK and (b) QPSK. Source adapted from: [17]

Moreover, Quadrature Amplitude Modulation (QAM) is another modulation to research. “The majority of the passband modulation schemes we have studied in previous chapters are constant envelope schemes. The constant envelope property of these schemes is especially important to systems with power amplifiers which must operate in the nonlinear region of the input-output characteristic for maximum power efficiency, like the satellite transponders. For some other communication systems, constant envelope may not be a crucial requirement, whereas bandwidth efficiency is more important. QAM is a class of nonconstant envelope schemes that can achieve higher bandwidth efficiency than M-PSK with the same average signal power. QAM is widely used in modems designed for telephone channels” [16]. In addition, Dharma describes as “simply a combination of AM and PSK, in which two carriers out of phase by 90° are amplitude modulated” [17]. Also, there are several QAM variations. For example, “16QAM involves
splitting the signal into 12 different phases and 3 different amplitudes for a total of 16 different possible values, each encoding 4 bits” [17]. Figure 2.7.5 shows the constellation diagram of 16QAM, also bit combination distributed along the constellation.

![Figure 2.7.5 Rectangular constellation Diagram of 16QAM. Source adapted from: [17].](image)

In last, one of the latest and most reliable modulations is the Orthogonal Frequency Divide Multiplexing (OFDM). According to Fuqin, “Recently multicarrier modulations (MCM) are getting more and more attention and are used in many applications because of their many advantages. One obvious advantage is that transmitting N data symbols on N carriers simultaneously reduces the symbol rate to one N-th of the original symbol rate of the serial data, or increases the symbol duration by N times. Thus, the effect of inversible interference due to time dispersion of the channel will be reduced and equalization in the receiver will be easier or even unnecessary. The multiple carriers in MCM are called subcarriers. The frequency band occupied by the signal carried by a subcarrier is called a sub-band. To separate the signals of sub-bands at receiver, the earliest method, which is borrowed from ‘‘frequency division multiplexing (FDM),’’
is to space the subcarrier center frequencies far apart so that the spectra of \( N \) sub-bands are virtually nonoverlapped, and \( N \) bandpass filters are used in the receiver to separate the sub-bands. This method requires each bandpass filter to have a very sharp frequency response” [16]. Figure 2.7.6 shows the comparison of a single carrier of OFDM modulation and multiple carries of OFDM modulation.

![Figure 2.7.5 Frequency Spectrum of an OFDM signal. Source adapted from: [17].](image)

In conclusion, there are different modulation techniques that are able to transmit data. Each modulation has its advantages and disadvantages. Depending on the needs for the transmission a modulation technique could fit best. OFDM modulation is one of the latest modulations. OFDM can transmit several data. Also, OFDM modulation provides reliability to the user’s due to the aggressive modulation. To finalize, basic and complex modulations are described in order to provide knowledge and understand the process of transmission.
2.8 4G LTE

One of the latest technologies that proven to ensure a successful transmission is 4G LTE technology. Cellular companies are the most common technology to transmit and receive data. 4G LTE was the replacement of 3G technology and came with new features for the user’s including flexibility and reliability. According to Dalhman and others, “The 4G LTE technology was from the beginning developed for packet-data support and has no support for circuit-switched voice, unlike the 3G where HSPA was an “add-on” to provide high-performance packet data on top of an existing technology. Mobile broadband services were the focus, with tough requirements on high data rates, low latency, and high capacity. Spectrum flexibility and maximum commonality between FDD and TDD solutions were other important requirements” [18].

4G LTE was designed to unify the technologies developed by several companies. “One significant aspect of LTE is the worldwide acceptance of a single technology, unlike previous generations for which there has been several competing technologies” [18]. In addition, Figure 2.8.1 shows a path from early technologies developed by several companies merging to 4G LTE and unify technologies in order to accelerate progress and also taking a path to the future 5G technology [18].

Figure 2.8.1 History of wireless technology. Source: Adapted from [18]
4G LTE technology uses two frequencies in order to separate the uplink and the downlink bands. Figure 2.8.2 shows how the uplink frequency band and downlink frequency band are separated by a gap, also, Figure shows that 4G LTE is a full duplex communication.

![Figure 2.8.2 Frequency Bands. Source adapted from: [19]](image)

Furthermore, Rumney cites, “OFDM is the modulation scheme chosen for the LTE downlink. It is a digital multicarrier scheme that uses a large number of closely spaced subcarriers to carry data and control information. Each individual subcarrier is modulated at a low symbol rate with a conventional modulation format such as QAM. The combination of the many low-rate subcarriers provides overall data rates similar to conventional single-carrier modulations schemes using the same bandwidth” [19]. In addition, “The high peak-to-average ratio (PAPR) associated with OFDM led 3GPP to look for an alternative modulation scheme for the LTE uplink. SC-FDMA was chosen since it combines the low PAPR techniques of single carrier transmission systems such as GSM and CDMA with the multipath resistance and flexible frequency allocation of OFDMA” [19].

In conclusion, 4G LTE is one of the latest technologies to be used by all companies. Legacy systems are affected by this technology due to its modulation as mentioned in [3]. On the other hand, 4G LTE could be used for a successful transmission. Legacy systems, such as, telemetry could be converted in to IP networks and later be transmitted 4G LTE, since it is wireless IP network. This technique will be also explored in order to achieve another possible solution.
Chapter 3: Methodology

In order to perform a deep analysis on Radio Frequency over Internet Protocols (RFoIP) several experiment scenarios need to be designed. Testbed platform could be configured in many ways delivering enough flexibility to perform a feasible testing. The testbed is composed of three main devices, which are, SDR from NI called Universal Software Radio Peripheral, NI Reference clock and the RT Logic Digitizer. Many parameters will vary for these three devices depending on the testing set up. To qualify and quantify results there are other parameters that could interpret a good or bad signal transmission, and likewise will explain and deliver knowledge of signal transmission results.

3.1 Frequency Bands of Interest

The experiments focused on specific bands, which were the bands of interest. The frequency bands of interest were the L-band, S-band, and C-band, and the experiment consisted in comparing each case of the bands. Table 1 shows the frequency bands of interest.

Table 3.1.1 L-Band, S-Band and C-Band frequency bands of interest.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range (MHz)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Lower: 1435 – 1525</td>
<td>Mobile and Telemetry</td>
</tr>
<tr>
<td></td>
<td>Upper: 1710 – 1990</td>
<td>Telemetry: 1780 – 1850 MHz</td>
</tr>
<tr>
<td>S</td>
<td>Lower: 2200 – 2290</td>
<td>Telemetry</td>
</tr>
<tr>
<td></td>
<td>Upper: 2360 – 2395</td>
<td>Telemetry</td>
</tr>
<tr>
<td>C</td>
<td>Lower: 4400 – 4940</td>
<td>Telemetry</td>
</tr>
<tr>
<td></td>
<td>Mid: 5090 – 5150</td>
<td>Telemetry</td>
</tr>
</tbody>
</table>

The interested bands for testing reliability are the L-band, S-band and C-band. Figure 3.1.1 shows L-band frequency allocation, Figure 3.1.2 shows the S-band, another band of interest for the testbed experiments, and in addition, Figure 3.1.3 shows C-band the last frequency band of interest.
Figure 3.1.1 L-band frequency allocation [4]

Figure 3.1.2 S-band frequency allocation [4]
3.2 Numerical Parameters

In order to quantify the signal, there are several parameters that needed to be considered. The testbed was set to have parameters in the USRP and the digitizer. There, were many parameters defined in both devices. Some parameters were repeated in order to achieve a synchronization between both testbed platforms.

**Numerical Parameters for USRP’s:**

- Antenna Gain
  - G/t
- Bandwidth (BW) of the Transmitted Signal
- Center Frequency (fc)
- Data Rate
- BER or BLER (in LTE systems)
  - Typically required to be $\leq 10^{-6}$
• I/Q Rate*
• Modulation Scheme
• Noise Floor
  o Calculated by a Spectrum Analyzer
• RX Power
  o RX Sensitivity Level (detection threshold)
• SNR
• TX Power

**Numerical Parameters for Digitizers:**

• A/D Bits
• Center Frequency (fc)
• Destination IP
• Digitizer Utilization
• Gain Mode
  o Automatic or Manual
    o Current/Min Gain
• Max Packet size
• Min Delay
• Output Enabled
• Packet Protection
• Stream Bandwidth
• Stream Offset
• System Bandwidth (BW)

* This Parameters are fixed.
3.3 Visual Parameters

In addition, visual parameters would support qualify the signal transmission. These parameters were essential to demonstrate performance of testbed, since numerical parameters are tied with visual parameters. Indeed, these parameters explained and provided a greater sense of signal transmission results.

There were four key visual parameters that will give more detail of the signal quality. The visual parameters were:

- Constellation Diagram

![Figure 3.1 BPSK constellation diagram with a rotation of 90 degrees](image1)

- Eye Diagram

![Figure 3.2 ASK Eye Diagram representation for illustration purposes.](image2)
• Spectrum Graph (Display SNR)

![Spectrum Graph](image)

Figure 3.3 Power Spectrum Density representation for illustration purposes.

Visual parameters qualify the signal transmission and can allow for classification of the signal by observing visual contemplation of how the signal is performing. In addition, visual parameters identify Power of signal, SNR and much more. Several parameters were used in order to obtain a complete and thorough experiment for the testbed. To conclude, the testbed had many different parameters which provides a more detailed analysis of the signal transmission. Furthermore, signal should be classified by the experiment results, and help define rules or procedures to follow for a better signal transmission.

3.4 Experiment Description

Experiments consisted of sending a signal directly from TX SDR to the RX SDR, which is the ideal case of signal transmission. Now, compare this signal transmission to the following set ups:

• SDR-SDR (ideal case)
• SDR TM-Digitizer-Digitizer-SDR TM (No clock)
• SDR TM -Digitizer-Digitizer-SDR TM (Clock)
• SDR LTE-Digitizer-Digitizer- SDR LTE (No Clock)
• SDR LTE-Digitizer-Digitizer- SDR LTE (Clock)

A signal is sent from TX SDR, converted from RF to IP by a digitizer, de-converted back from IP to a RF signal by another digitizer, and finally received by the RX SDR. This signal conversion and transmission could add some noise to the signal, by quantifying and qualifying this signal through the use of numerical and visual parameters to determine and classify the transmission. Figure 3.4.1 shows the testbed implementation of telemetry with clock connections. Figure 3.4.2 shows the testbed implementation of LTE with clock connections. Illustration 1 shows the physical layout of the testbed with SDRs for telemetry representation and digitizers. Illustration 2 shows the physical layout of the testbed with SDRs for LTE representation and digitizers for LTE transmission including splitters/combiners. Illustration 3 shows the complete physical testbed including telemetry SDRs, LTE SDRs, splitters/combiners and digitizers.

Figure 3.4.1 Telemetry testbed implementation.
Figure 3.4.2 LTE testbed implementation.

Illustration 1. Physical Telemetry Testbed design with front (left) and back (right:) views without spectrum analyzer.
Illustration 2. Physical LTE Testbed design with digitizers and LTE SDR’s.

Illustration 3. Complete physical testbed including telemetry and LTE SDR’s. In addition, Digitizers at bottom.
3.5 TESTBED ADJUSTMENT AND CALIBRATION

In order to calibrate the testbed, it is necessary to measure initial power sent by TX SDR with a spectrum analyzer to quantify the real power sent. In addition, the power levels measured by the RX SDR were compared. These measurements included the digitizer power level, since parameters of power were also manipulated on these devices. Several scenarios of testing have to be measured, such as Telemetry and LTE platforms being tested with and without Digitizers.

First, telemetry platform was measured with and without the 30dB attenuator, and also, with and without two gain parameters. Figure 3.5.1 shows a TM signal with no attenuator and no gain measured by FieldFox RF analyzer N9914A at 2 GHz with a channel power at -25.11dBm. In addition, to measure the real effect of the 30 dB attenuator. Figure 3.5.2 shows a TM signal with attenuator and no gain measured by FieldFox RF analyzer N9914A at 2GHZ with channel power of -55.45 dBm. In conclusion, there is an accurate attenuation of 30 dB.

Figure 3.5.1 Telemetry signal measured by Fieldfox handheld RF Analyzer N9914A without attenuator and no gain.
Figure 3.5.2 Telemetry signal measured by Fieldfox handheld RF Analyzer N9914A with attenuator and no gain.

Nevertheless, to measure the real gain of the NI USRP 2920 in the telemetry platform. Figure 3.5.3 shows a telemetry signal with no attenuator and a gain of 12 dB measured by the FieldFox RF analyzer N9914A. Comparing Figure 3.5.1 measurement and Figure 3.5.3 there is a real gain of 11.75 dB. Furthermore, Figure 3.5.4 shows a telemetry signal with attenuator and a gain of 12 dB measured by the FieldFox RF analyzer N9914A. Comparing Figure 3.5.2 measurement with Figure 3.5.4 measurement there is a real gain of -11.72 dB. In conclusion there is a real gain of 11.72-11.75 dB from the NI USRP 2920.
Figure 3.5.3 Telemetry signal measured by Fieldfox handheld RF Analyzer N9914A without attenuator and 12dB gain.

Figure 3.5.4 Telemetry signal measured by Fieldfox handheld RF Analyzer N9914A with attenuator and 12dB gain.
In second, LTE EnB signal will be measured by the FieldFox RF analyzer. LTE EnB could work as a stand-alone signal, but LTE UE is a slave of LTE EnB it is necessary to mix the signals through a splitter/combiner. Splitter/combiner will generate a loss in power. Splitter combiners is a Mini-circuits ZNPD1-63HP-S. According to Mini-circuits datasheet in the frequency bands of interest loss in dB ranges from 6.59 to 6.78 [20]. Table 2 shows the loss in dB corresponding to each frequency range. It is necessary to measure the real loss through each stage of the signal transmission [20].

Table 3.5. Typical performance data of splitter/combiner.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Total loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s-1</td>
</tr>
<tr>
<td>1500</td>
<td>6.59</td>
</tr>
<tr>
<td>2000</td>
<td>6.63</td>
</tr>
<tr>
<td>2500</td>
<td>6.77</td>
</tr>
</tbody>
</table>

Moreover, Figure 3.5.5 shows an LTE EnB measurement with no attenuator and no gain measured by the FieldFox RF analyzer N9914A with a channel power of -18.65 dBm. Figure 3.5.6 shows an LTE EnB measurement with no attenuator and 20dBm gain. FieldFox RF analyzer N9914A shows a 0.01 dBm. Comparing the two Figures there is a difference of -18.66 dBm.
Figure 3.5.5 LTE EnB signal measured by FieldFox RF analyzer N9914A without attenuator and no gain.

Figure 3.5.6 LTE EnB signal measured by FieldFox RF analyzer N9914A without attenuator and 20 dBm power.
In addition, Figure 3.5.7 shows an LTE EnB signal measured by FieldFox RF analyzer N9914A with attenuator and no gain with a channel power of -49.30 dBm. Also, Figure 3.5.8 shows an LTE EnB signal measured by FieldFox RF analyzer N9914A with attenuator and 20 dBm power with channel power of -29.46 dBm. In comparison, Figures 3.5.7 and 3.5.8 show a difference of -19.84 dBm.

Figure 3.5.7 LTE EnB signal measured by FieldFox RF analyzer N9914A with attenuator and no gain.
Nevertheless, Figure 3.5.9 shows an LTE EnB signal measured by FieldFox RF analyzer N9914A with attenuator after the first splitter/combiner ZNPD1-63HP-S with no gain with a channel power of -56.92 dBm. Figure 3.5.10 shows an LTE EnB signal measured by FieldFox RF analyzer N9914A with attenuator after the first splitter/combiner ZNPD1-63HP-S with 20dBm gain with a channel power of -37.64 dBm. Figure 3.5.10 shows a difference of -19.28 dBm over Figure 3.5.9.
Figure 3.5.9 LTE EnB signal measure by FieldFox RF analyzer N9914A with attenuator after first splitter/combiner ZNPD1-63HP-S and no gain.

Figure 3.5.10 LTE EnB signal measure by FieldFox RF analyzer N9914A with attenuator after first splitter/combiner ZNPD1-63HP-S and 20 dBm power.
In last, Figure 3.5.11 shows an LTE EnB signal measured by FieldFox RF analyzer N9914A with attenuator after the second splitter/combiner ZNPD1-63HP-S with no gain with a channel power of -61.51 dBm. Figure 3.5.12 shows an LTE EnB signal measured by FieldFox RF analyzer N9914A with attenuator after the second splitter/combiner ZNPD1-63HP-S with 20dBm gain with a channel power of -43.32 dBm. Figure 3.5.11 shows a difference of -19.19 dBm over Figure 3.5.12.

![Figure 3.5.11 LTE EnB signal measure by FieldFox RF analyzer N9914A with attenuator after second splitter/combiner ZNPD1-63HP-S and no gain.](image-url)
In conclusion, there is consistency on the loss of power of each component according to the specifications. In addition, the real gain of the NI USRP 2954 is consistent with the measurements performed by the FieldFox RF analyzer N9914A.

In fourth, LTE UE will be measured by the FieldFox RF analyzer repeating the same process as the LTE EnB. LTE UE is a slave of the LTE EnB; therefore, LTE EnB needs to be active in order to have a successful LTE UE transmission. LTE UE only be measured after the second splitter/combiner since other scenarios in LTE EnB show a consistency in the measurements previously performed by FieldFox RF analyzer N9914A. Figure 3.5.13 shows LTE UE signal measured by FieldFox RF analyzer N9914A after second splitter/combiner with 20 dBm gain with a channel power of -52.61 dBm. Figure 3.5.14 shows LTE UE signal measured by
FieldFox RF analyzer N9914A after second splitter/combiner with no gain with a channel power of -65.24dBm.

Figure 3.5.13 LTE UE signal measured by FieldFox RF analyzer N9914A after second splitter/combiner at 20dBm gain.

Figure 3.5.14 LTE UE signal measured by FieldFox RF analyzer N9914A after second splitter/combiner with no gain.
In conclusion, LTE UE will need a gain of 20dBm in order to perform correctly. Another approach will be to remove the 30 dB attenuator to perform an LTE UE signal transmission with no gain at the TX.

In last, digitizers are included in each testbed setup, because there a gain manipulation by the device that could vary some parameters at the qualification and quantification of the signal transmission. Telemetry platform will be tested with no gain and a 12dB gain. Figure 3.5.15 shows a telemetry signal after the attenuator and digitizer with no gain. Figure 3.5.16 shows a telemetry signal after the attenuator and digitizer with 12 dB gain. Comparing Figure 3.5.15 and 3.5.16 we see a difference of 11.91 dB.

Figure 3.5.15 Telemetry signal measured by Fieldfox handheld RF Analyzer N9914A with attenuator after digitizer and no gain.
In addition, Figure 3.5.4 shows a channel power of -43.73 and Figure 3.5.16 shows a channel power of -52.81. Digitizer adds 9.08 dB into the channel power. In conclusion, there is some channel power loss during the digitizer transmission. Channel power loss could affect signal transmission if the signal does not have enough gain to transmit.

Now, LTE EnB will be measured after the second splitter/combiner in order to compare the last scenario of the LTE EnB. Figure 3.5.17 shows an LTE EnB with attenuator after the second splitter/combiner with no gain. Figure 3.5.18 shows an LTE EnB with attenuator after the second splitter/combiner with 20 dBm power.

Figure 3.5.17 shows a channel power of -65.66 dBm. LTE EnB could be able to transmit but the SNR is minimum. On the other hand, Figure 3.5.18 20 dBm power is enough to have a high SNR with a channel power of -54.99 dBm. In conclusion, digitizer represents a power loss in LTE EnB signal. Figure 3.5.17 compared with Figure 3.5.11 shows a difference of -4.15 dBm. Figure 3.5.12 and Figure 3.5.18 show a difference of -11.67 dBm.
Figure 3.5.17 LTE EnB signal measured by Fieldfox handheld RF Analyzer N9914A with attenuator after digitizer and no gain.

Figure 3.5.18 LTE EnB signal measured by Fieldfox handheld RF Analyzer N9914A with attenuator after digitizer and 20 dBm power.
In last, LTE UE will be measured after the digitizer, which is placed after the second splitter/combiner, following the same procedure as the previous measurements. Figure 3.5.19 shows an LTE UE after digitizer at frequency 2GHz with no gain. Figure 3.5.20 shows an LTE UE after digitizer at frequency 2 GHz with 20 dBm power.

Figure 3.5.19 LTE UE signal measured by Fieldfox handheld RF Analyzer N9914A with attenuator after digitizer and no gain.
In conclusion, LTE UE suffers some power loss due to digitizers. Figure 3.5.19 has a loss in SNR and it is possible that signal transmission could not be performed as expected. Figure 3.5.20 shows enough SNR to perform a good signal transmission. Figure 3.5.19 compared to Figure 3.5.14 shows a difference of -0.83 dBm. On the contrary, Figure 3.5.20 compared to Figure 3.5.13 shows a difference of -7.78 dBm. To summarize, digitizer presents a power loss in the LTE UE signal.
Chapter 4: Results

After several experiments the qualitative and quantitative parameters, such as, eye diagram, constellation, power spectrum, throughput and more were collected. Also, the use of a reference clock will be tested in each scenario to prove if it is necessary. In order, to compare the experiments results, ideal cases have been tested first to set the baseline parameters.

4.1 Baseline Parameters

First, telemetry platform ideal cases are recorded with the following parameters.

- Carrier frequency: 1.8 GHz, 2 GHz and 2.2 GHz
- Modulation: QPSK, 8-PSK and OQPSK
- Gain: 12 dB
- Include a 30 dB attenuator

The generated figures show the quality of the testbed for the telemetry signal transmission. Figure 4.1.1 shows a telemetry QPSK signal at a frequency of 1.8 GHz and a gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

![Image](image.png)

Figure 4.1.1 telemetry QPSK signal, frequency 1.8 GHz, and gain 12 dB. From left to right: constellation diagram, power spectrum, and eye diagram.
Figure 4.1.2 shows a telemetry 8-PSK signal at a frequency of 1.8 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

Figure 4.1.2 telemetry 8-PSK signal, frequency 1.8 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.1.3 shows a telemetry OQPSK signal at a frequency of 1.8 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

Figure 4.1.3 telemetry OQPSK signal, frequency 1.8 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.
In conclusion, there is no change of qualitative results between frequencies. In addition, a clean constellation diagram is displayed. Power spectrum has a high SNR and an open eye diagram in each scenario. For more experiments including other frequencies please go to Appendix A.

Second, testbed LTE platform will include the following parameters:

- Carrier frequency: 1.8 GHz and 2.2 GHz
- Modulation Coding Scheme (MCS): QPSK, 16-QAM and 64-QAM (different rates)
- TX power: 20dBm
- Include a 30 dB attenuator

For this experiment, the LTE EnB signal transmission is tested as a stand-alone without traveling through the two splitter/combiner, reflecting no channel power loss that splitter/combiners could cause. Figure 4.1.10 shows an EnB to UE signal transmission with an MCS 0 QPSK MCS at a frequency of 1.8 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also includes, PDSCH constellation, throughput and data rate.

Figure 4.1.10 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.1.11 shows an EnB to UE signal transmission with a MCS 12 16-QAM rate at a frequency of 1.8 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, PDSCH constellation, throughput and data rate.

Figure 4.1.11 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.1.12 shows an EnB to UE signal transmission with an MCS 17 64-QAM at a frequency of 1.8 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, PDSCH constellation, throughput and data rate.
Figure 4.1.12 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.1.13 shows an EnB to UE signal transmission with an MCS 28 64-QAM rate at a frequency of 1.8 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, PDSCH constellation, throughput and data rate.

Figure 4.1.13 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
In conclusion, there is no change in qualitative or quantitative result between carrier frequencies and MCS. Also, we have a high SNR in both power spectrums, clean PDSCH constellation, good throughput depending on the MCS and excellent data rate in each scenario. Other frequencies experiments can be found in Appendix A.

Next, LTE UE TX experiment as an ideal case is presented in different frequency scenarios. In addition, LTE UE is a dependent signal of LTE EnB, therefore, LTE EnB signal must be transmitting to establish an LTE UE TX transmission. LTE EnB TX will remain with any of the ideal cases in order for LTE UE TX to perform several experiments. Figure 4.1.18 shows LTE UE TX and LTE EnB RX with an MCS 0 QPSK at a frequency 1.8GHz and 20 dBm power. This includes power spectrum of the UE TX and EnB RX power spectrum. Also, Block Error Rate (BLER), PUSCH Throughput and Reported Downlink (DL) BLER. Figure 4.1.19 shows LTE UE TX and LTE EnB RX with an MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes power spectrum of the UE TX and EnB RX power spectrum. Also includes, Block Error Rate (BLER), PUSCH Throughput and Reported Downlink (DL) BLER.
Figure 4.1.18 LTE UE TX and LTE EnB RX, frequency 1.8 GHz and 20 dBm power. From left to right: UE TX power spectrum, EnB RX power spectrum, BLER, PUSCH Throughput and Reported DL BLER.

Figure 4.1.19 LTE UE TX and LTE EnB RX, frequency 2.2 GHz and 20 dBm power. From left to right: UE TX power spectrum, EnB RX power spectrum, BLER, PUSCH Throughput and Reported DL BLER.
In conclusion, there is no change in qualitative or quantitative parameters. Power spectrum in LTE UE TX and LTE EnB RX show high SNR. BLER over time show zero errors and PUSCH throughput is at 0.31 Mbps, which corresponded to the MCS 0 QPSK modulation. In addition, the reported DL BLER is zero. To conclude, there is no difference in results from both frequencies.

4.2 Telemetry over IP

The first experiment scenario is TMoIP. TMoIP will be tested with and without a reference clock, in order, to determine if a reference clock is necessary to perform a signal transmission through IP. Several parameters will be adjusted to qualify the behavior of telemetry signals over the network. Parameters to qualify telemetry signal transmission are constellation diagram, power spectrum (SNR) and eye diagram. In addition, digitizers will perform in an automatic mode, if necessary, digitizer parameters will be adjusted manually to ensure a good telemetry signal transmission.

4.2.1 No clock

The first scenario experiment is to test without a reference clock. Testing TMoIP will require to vary several parameters. Parameters to be adjusted are:

- Carrier frequency: 1.8 GHz, 2 GHz and 2.2 GHz
- Modulation: QPSK, 8-PSK and OQPSK
- Gain: 0 dB and 12 dB
- Include a 30 dB attenuator

In addition, digitizers will operate in an automatic mode. Important parameters to be consider are the following:

- Stream Bandwidth: 2 MHz
- Center Frequency: frequency to be tested
- A/D bits: 12-bits
- System Bandwidth: 10 MHz (lowest)
• Gain mode: automatic
• Max Packet size: 1500 bytes
• Data source: network using a programmed buffer
• Attenuation: 0 dB

Figure 4.2.1.1 shows a QPSK telemetry signal at a frequency of 1.8 GHz and gain of 12 dB. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.1.2 shows an 8-PSK telemetry signal at a frequency of 1.8 GHz and gain of 12 dB. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.1.3 shows an OQPSK telemetry signal at a frequency of 1.8 GHz and gain of 12 dB. This includes constellation diagram, power spectrum and eye diagram.
In conclusion, there was no change on qualitative parameters between frequencies or gain. Compared to baseline parameters, there is a more jittery constellation diagram in all experiments. In addition, the power spectrum has a 10 dB difference from baseline parameters and eye diagram changes the aperture. More experiments in other frequencies are found in Appendix A.

4.2.2 Clock

The second scenario experiment is to test with a reference clock. Testing TMoIP will require variation of several parameters. Parameters to be adjusted are:

- Carrier frequency: 1.8 GHz, 2 GHz and 2.2 GHz
- Modulation: QPSK, 8-PSK and OQPSK
- Gain: 12 dB
- Include a 30 dB attenuator

In addition, digitizers will operate in an automatic mode. Important parameters to consider are the following:

- Stream Bandwidth: 2 MHz
- Center Frequency: frequency to be tested
- A/D bits: 12-bits
- System Bandwidth: 10 MHz (lowest)
- Gain mode: automatic
- Max Packet size: 1500 bytes
- Data source: network using a programmed delay
- Attenuation or Serial Path Gain (SPG): 0 dB

Figure 4.2.2.1 shows a QPSK telemetry signal at frequency 1.8 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.1 telemetry QPSK signal, frequency 1.8 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.2 shows an 8-PSK telemetry signal at frequency 1.8 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.2 telemetry 8-PSK signal, frequency 1.8 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

---

1 Programmed delay is set to 10 milliseconds.
Figure 4.2.2.3 shows an OQPSK telemetry signal at frequency 1.8 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

![Figure 4.2.2.3 telemetry OQPSK signal, frequency 1.8 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.](image)

In conclusion, there is no change between frequencies in qualitative results, constellation diagram is jittery and power spectrum shows a good SNR. Reference clock improved the aperture of the eye diagram. More experiments in other frequencies are found in Appendix A.

### 4.3 LTE OVER IP

The next scenario is to test LTE platform over the digitizers. In order to test LTE over IP there are several scenarios to be included. The following scenarios are:

- LTE EnB stand-alone
- LTE EnB through the system with LTE UE
- LTE UE

These three scenarios will vary different parameters in the LTE platform and digitizers in order to acquire a successful transmission. Digitizer will be tested with and without reference clock to realize if it is essential to be used. If necessary, digitizer parameters will be adjusted manually, again, to acquire a good signal transmission.

#### 4.3.1 No clock

First, experiments in LTE platform will be without the use of a reference clock. LTE scenarios will be varying in the following parameters:
• Carrier frequency: 1.8 GHz and 2.2 GHz.
• Modulation Coding Scheme (MCS): QPSK, 16-QAM and 64-QAM.
• Power: 0 dBm and 20 dBm.
• Include a 30 dB attenuator.

Furthermore, digitizers are operating in automatic mode. Some parameters to consider for the following scenarios are:

• Stream Bandwidth: 20 MHz
• Center Frequency: frequency to be tested
• A/D bits: 12-bits
• System Bandwidth: 22 MHz
• Gain mode: automatic
• Max Packet size: 1500 bytes
• Data source: network using a programmed delay
• Attenuation or serial path gain (SPG): 0 dB

**LTE EnB stand-alone**

For these sets of experiments, LTE EnB will only be used as a stand-alone and without the use of a reference clock. Also, there is no loss in the path due to the two splitter/combiners used in the full system. Moreover, other parameters will be modified in order to describe the behavior of the LTE EnB signal transmission in order to qualify and quantify this signal transmission. Figure 4.3.1.1 shows a MCS 0 QPSK LTE EnB signal at a frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the LTE EnB TX and LTE UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

---

2 Programmed delay is set to 10 milliseconds
Figure 4.3.1.1 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.2 shows MCS 0 QPSK LTE EnB signal at a frequency of 1.8 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.1.2 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.1.3 shows MCS 12 16QAM LTE EnB signal and frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.1.3 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and no gain. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.4 shows MCS 12 16QAM LTE EnB signal and a frequency of 1.8 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.1.4 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.1.5 shows MCS 17 64QAM LTE EnB signal and a frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.1.5 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.6 shows MCS 17 64QAM LTE EnB signal at a frequency of 1.8 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.1.6 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.1.7 shows MCS 28 64QAM LTE EnB signal at a frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

In last, Figure 4.3.1.8 shows MCS 28 64QAM LTE EnB signal at a frequency of 1.8 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.
To conclude, other experiments were performed varying the carrier frequency providing the same results as previous frequency. LTE EnB stand-alone performs a good signal transmission. There are some differences between power parameters. PDSCH constellation looks jittery in experiments performed with 0 dBm power. On the other hand, experiments with 20 dBm power have a clean PDSCH constellation.
Next, experiments scenarios will be performed using full system. These experiments involve signal transmission traveling through the attenuators, two splitter/combiner and digitizer. In addition, experiments are performed without the use of a reference clock. LTE EnB TX is the platform that is traveling through the digitizers. For this section LTE EnB TX and RX or Downlink (DL) are qualified and quantify in the same platform. In addition, LTE UE TX and RX or Uplink (UL) are qualified and quantified equal to LTE EnB. LTE UE will remain with same parameters only varying power according to LTE DL. Figure 4.3.1.9 shows LTE Downlink with MCS 0 QPSK at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.10 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

![Figure 4.3.1.9 QPSK LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.](image-url)
Figure 4.3.1.10 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.11 shows LTE Downlink with MCS 0 QPSK at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.12 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.11 QPSK LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.1.12 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Now LTE DL will increase to a more complex MCS. LTE UL will remain with the same MCS. Figure 4.3.1.13 shows LTE Downlink with MCS 12 16QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.14 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.13 16QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.1.14 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.15 shows LTE Downlink with MCS 12 16QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.16 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.15 16QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.1.16 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.17 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.18 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.17 64QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.1.18 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.19 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.20 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.19 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.1.20 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.21 shows LTE Downlink with MCS 28 64QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.22 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.21 64QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.1.22 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.23 shows LTE Downlink with MCS 28 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.24 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.23 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Last experiment scenario is to test when does the system will stop working with 0 dBm power and no reference clock. Figure 4.3.1.25 shows LTE Downlink with MCS 23 64QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.26 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.25 64QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.1.26 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right:
LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

To conclude, other carrier frequencies delivered same results as frequency 1.8 GHz. Additionally, power improves the quality of the signal specially in higher MCS’s. Also, experiments performed with 0 dBm power had a jittery PDSCH constellation. Highest MCS 28 64QAM will require 20 dBm in order to perform a signal transmission. Furthermore, LTE EnB system stops working at MCS 23 64QAM. LTE EnB TX through entire system requires a good power in order to be transmitted through digitizers. LTE EnB RX maintained a low BLER at zero, regardless of gain modifications. All experiments were performed without the use of a reference clock.

**LTE UE**

Lastly, LTE UL will be digitized in order to qualify and quantify signal transmission. LTE DL will now be fixed at a certain MCS. Following experiments will be performed without the use of a reference clock. Frequency and power parameters will vary in order to describe behavior of signal transmission under different scenarios.
Figure 4.3.1.27 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.28 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.27 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.1.28 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.1.29 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.30 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.1.29 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.1.30 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Several adjustments in the LTE platform were made, such as frequency, power, MCS and others with no success to transmit. In addition, digitizers were adjusted manually with no success also. This is due to a synchronization problem. Since, there is no reference clock in these experiments, program buffer will not deliver the correct delay. To summarize LTE UE needs a reference clock in order to be transmitted over IP networks.

4.3.2 Clock

Next, experiments in LTE platform will be with the use of a reference clock. LTE scenarios will be varying the following parameters:

- Carrier frequency: 1.8 GHz and 2.2 GHz.
- Modulation Coding Scheme (MCS): QPSK, 16-QAM and 64-QAM.
- TX Power: 0 dBm and 20 dBm.
- Include a 30 dB attenuator.

Furthermore, digitizers are operating in automatic mode. Some parameters to consider for the following scenarios are:

- Stream Bandwidth: 20 MHz
- Center Frequency: frequency to be tested
- A/D bits: 12-bits
- System Bandwidth: 22 MHz
- Gain mode: Automatic
- Max Packet size: 1500 bytes
- Data source: network using a programmed delay\(^3\)
- Attenuation or serial path gain (SPG): 0 dB

\(^3\) Programmed delay is set to 10 milliseconds
**LTE EnB stand-alone**

First experiment is to test LTE EnB stand-alone with a reference clock. Figure 4.3.2.1 shows MCS 0 QPSK LTE EnB signal at a frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.1 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.2 shows MCS 0 QPSK LTE EnB signal at a frequency of 1.8 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.
Figure 4.3.2.2 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.3 shows MCS 12 16QAM LTE EnB signal and a frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.3 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.4 shows MCS 12 16QAM LTE EnB signal and a frequency of 1.8 GHz with 20dBm gain. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.4 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.5 shows MCS 17 64QAM LTE EnB signal and a frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.5 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.6 shows MCS 17 64QAM LTE EnB signal and a frequency of 1.8 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.6 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.7 shows MCS 28 64QAM LTE EnB signal and a frequency of 1.8 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.7 LTE EnB TX to LTE UE RX, frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.8 shows MCS 28 64QAM LTE EnB signal and a frequency of 1.8 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

In conclusion, LTE EnB as a stand-alone will perform a good signal transmission. There was no difference on qualitative or quantitate measurements between carrier frequencies. In addition, there is some jittery in PDSCH constellation that occurred with the adjustment of the power parameter in each pair of experiments performed.

**LTE EnB through the system with LTE UE**

Moreover, experiments scenarios will be performed using full system. These experiments involve signal transmission traveling through the attenuators, two splitter/combiner and digitizer. In addition, experiments are performed with the use of a reference clock. LTE EnB TX is the platform that is traveling through the digitizers. For this section LTE EnB TX and RX or Downlink (DL) are qualified and quantify in the same platform. In addition, LTE UE TX and RX or Uplink (UL) are qualified and quantified equal to LTE EnB. LTE UE will remain with same parameters only varying gain according to LTE DL.
Figure 4.3.2.9 shows LTE Downlink with MCS 0 QPSK at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.10 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.9 QPSK LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.10 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.11 shows LTE Downlink with MCS 0 QPSK at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.12 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.11 QPSK LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.12 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Now LTE DL will increase to a more complex MCS. LTE UL will remain with the same MCS. Figure 4.3.2.13 shows LTE Downlink with MCS 12 16QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.14 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.13 16QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.14 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.15 shows LTE Downlink with MCS 12 16QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.16 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.15 16QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.16 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.17 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.18 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.17 64QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.18 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.19 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.20 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.19 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.20 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.21 shows LTE Downlink with MCS 28 64QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.22 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.21 64QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.22 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.23 shows LTE Downlink with MCS 28 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.24 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.23 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.3.2.24 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Last experiment scenario is to test when does the system will stop working with 0 dBm power and no reference clock. Figure 4.3.1.25 shows LTE Downlink with MCS 24 64QAM at a frequency 1.8 GHz and 0 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.26 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

![LTE Downlink with MCS 24 64QAM at 1.8 GHz and 0 dBm power](image)

Figure 4.3.2.25 64QAM LTE DL at frequency 1.8 GHz and 0 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER

![LTE Uplink with MCS 0 QPSK at 2.2 GHz and 20 dBm power](image)

Figure 4.3.2.26 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
To conclude, other carrier frequencies delivered same results as frequency 1.8 GHz. Additionally, power improves the quality of the signal specially in higher MCS’s. Also, experiments performed with 0 dBm power had a jittery PDSCH constellation. Highest MCS 28 64QAM will require 20 dBm in order to perform a signal transmission. Furthermore, LTE EnB system stops working at MCS 24 64QAM. LTE EnB TX through entire system requires a good power in order to be transmitted through digitizers. LTE EnB RX maintained a low BLER at zero, regardless of gain modifications. All experiments were performed with the use of a reference clock. **LTE UE**

Lastly, LTE UL will be digitized in order to qualify and quantify signal transmission. LTE DL will now be fixed at a certain MCS. Following experiments will be performed with the use of a reference clock. Frequency and gain parameters will vary in order to describe behavior of signal transmission under different scenarios.

Figure 4.3.2.27 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.28 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.28 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.29 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.1.30 shows LTE Uplink with MCS 0 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.29 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.2.30 QPSK LTE UL at frequency 2.2 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.31 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.32 shows LTE Uplink with MCS 9 QPSK at a frequency 2.2 GHz and 0 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.31 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
Figure 4.3.2.32 QPSK LTE UL at frequency 2.2 GHz and 0 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.33 shows LTE Downlink with MCS 17 64QAM at a frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.3.2.34 shows LTE Uplink with MCS 9 QPSK at a frequency 2.2 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.33 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.
In conclusion, other carrier frequencies were tested delivering same results as frequency 1.8 GHz. LTE UE performs a good signal transmission regardless of gain. Highest MCS tested was MCS 9 QPSK. To conclude, LTE UE must have a reference clock in order to perform a good signal transmission.

### 4.4 Application Scenarios

Last section of experiment scenarios is to test how good a digitizer could work under particular conditions and parameters. Special scenarios will vary parameters in the LTE platform and on the digitizer. Each scenario will have unique conditions to ensure digitizers can work under the specifications denoted.

First scenario will test the capabilities of digitizers to transmit an LTE EnB signal with a power of -60 dBm. According to digitizer specifications RF input ranges from -60dBm to 0dBm. For this scenario LTE EnB is used as a stand-alone signal. In order to calibrate channel power to the desired real power, it must be measured by FieldFox RF analyzer N9914A before transmission can be tested. Calibration purposes included the addition of two 30dB attenuators at the LTE EnB
TX and a power of 20 dBm in the LTE platform. Figure 4.4.1 shows measurement of channel power of LTE EnB at 2.2 GHz.

Figure 4.4.1 LTE EnB signal measured by FieldFox RF analyzer N9914A calibrated to -60 dBm.

Furthermore, following experiment scenarios are to achieve signal transmission according to specifications. In addition, if signal transmission is achieved, determine the highest MCS that could be transmitted with the lowest gain. LTE EnB parameters are set to the following:

- Carrier frequency: 2.2 GHz.
- Modulation Coding Scheme (MCS): QPSK, 16-QAM and 64-QAM (different rates).
- TX power: 20 dBm.
- Include two 30 dB attenuators.
- Reference clock required.
Furthermore, digitizers are operating in automatic mode. Some parameters to consider for the following scenarios are:

- **Stream Bandwidth**: 20 MHz
- **Center Frequency**: 2.2 GHz
- **A/D bits**: 12-bits
- **System Bandwidth**: 22 MHz
- **Gain mode**: Automatic
- **Max Packet size**: 1500 bytes
- **Data source**: network using a programmed delay
- **Attenuation or serial path gain (SPG)**: 0 dB

Figure 4.4.2 shows LTE EnB stand-alone platform with MCS 0 QPSK, frequency 2.2 GHz and real power of -60 dBm.

Figure 4.4.2 LTE EnB TX to LTE UE RX, frequency 2.2 GHz. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

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4 Programmed delay is set to 10 milliseconds
Next, Figure 4.4.3 shows LTE EnB stand-alone platform with MCS 12 16QAM, frequency 2.2 GHz and real power of -60 dBm.

Moreover, Figure 4.4.4 shows the highest modulation to be achieved by a real power of -60 dBm. Figure 4.4.4 shows LTE EnB stand-alone platform with MCS 27 64QAM, frequency 2.2 GHz and real gain of -60 dBm.

Figure 4.4.3 LTE EnB TX to LTE UE RX, frequency 2.2 GHz. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.4.4 LTE EnB TX to LTE UE RX, frequency 2.2 GHz. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
In last, Figure 4.4.5 shows an LTE EnB stand-alone platform with MCS 28 64QAM, frequency 2.2 GHz and real power of -60 dBm. This last scenario is a failed scenario for the digitizer RF input condition.

![LTE EnB TX to LTE UE RX](image)

**Figure 4.4.5 LTE EnB TX to LTE UE RX, frequency 2.2 GHz.** From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

In conclusion, first application scenario tests the capability of the RF input to be transmitted at a channel power of -60 dBm. Digitizer is able to transmit up to MCS 27 64QAM showing a throughput of 59.26 Mbps. Digitizers are limited to transmit MCS 28 64QAM showing a throughput of .41 Mbps.

Second application scenario is to test the limits to send an LTE EnB signal with the least amount of A/D bits. LTE EnB stand-alone system will be used for this application scenario. This application scenario could be applied if there are some network constraints. The parameters for LTE EnB are the ideal, while digitizers will vary parameters to the lowest conditions. LTE EnB parameters are:

- Carrier frequency: 2.2 GHz.
- Modulation Coding Scheme (MCS): QPSK, 16-QAM and 64-QAM.
- TX Power: 20 dBm.
- Reference clock required.

Furthermore, digitizers are operating in automatic mode. Some parameters to consider for the following scenarios are:

- Stream Bandwidth: 20 MHz
- Center Frequency: 2.2 GHz
- A/D bits: 4-bits or 6-bits
- System Bandwidth: 22 MHz
- Gain mode: Min
- Max Packet size: 1500 bytes
- Data source: network using a programmed delay
- Attenuation or serial path gain (SPG): 0 dB

Figure 4.4.6 shows an LTE EnB stand-alone platform with MCS 0 QPSK, frequency 2.2 GHz and ideal power conditions. Digitizer is set to minimum gain and A/D bits set to 4-bits.

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Figure 4.4.6 LTE EnB TX to LTE UE RX, ideal conditions and 4-bits. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

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5 Programmed delay is set to 10 milliseconds
Figure 4.4.7 shows an LTE EnB stand-alone platform with MCS 12 16QAM, frequency 2.2 GHz and ideal power conditions. Digitizer is set to minimum gain and A/D bits set to 4-bits.

Figure 4.4.7 LTE EnB TX to LTE UE RX, ideal conditions and 4-bits. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.4.8 shows an LTE EnB stand-alone platform with MCS 22 64QAM, frequency 2.2 GHz and ideal power conditions. Digitizer is set to minimum gain and A/D bits set to 4-bits.

Figure 4.4.8 LTE EnB TX to LTE UE RX, ideal conditions and 4-bits. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.4.9 shows an LTE EnB stand-alone platform with MCS 23 64QAM, frequency 2.2 GHz and ideal power conditions. Digitizer is set to minimum gain and A/D bits set to 4-bits. This experiment scenario is a failed test, throughput decreases to at least half.

In last, to transmit the highest modulation with the lowest conditions of digitizers required to set A/D to 6-bits. Figure 4.4.10 shows an LTE EnB stand-alone platform with MCS 28 64QAM, frequency 2.2 GHz and ideal gain conditions.

Figure 4.4.10 LTE EnB TX to LTE UE RX, ideal conditions and 6-bits. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
In conclusion, digitizers could operate using the minimum gain. Highest modulation to transmit with A/D 4-bits is MCS 22 64QAM. In addition, the minimum required to transmit MCS 28 64QAM is A/D 6-bits.

Next application scenario is to send both signals through the digitizer. Digitizer will be connected in the middle of each splitter/combiner. Also, frequency is modified to be adjacent to each other following recommendations of Interference analysis and mitigation of telemetry and 4G LTE systems in adjacent spectrum bands [3]. This application scenario will require the use of the full duplex LTE system. Moreover, LTE parameters are the following:

- Carrier frequency: 1.8 GHz and 1.82 GHz.
- Modulation Coding Scheme (MCS): QPSK and 64-QAM.
- TX power: 20 dBm.
- Reference clock required.

Furthermore, digitizers are operating in automatic mode. Some parameters to consider for the following scenarios are:

- Stream Bandwidth: 40 MHz
- Center Frequency: 1.81 GHz
- A/D bits: 10-bits (Max due to digitizer physical constraints)
- System Bandwidth: 54 MHz
- Gain mode: Automatic
- Max Packet size: 1500 bytes
- Data source: network using a programmed delay
- Attenuation or serial path gain (SPG): 0 dB

LTE platform and digitizers will be using full capabilities in order to perform the highest MCS possible for the system. Digitizers will be transmitting both signals combined by the first splitter/combiner and delivered to both systems by second splitter/combiner.

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6 Programmed delay is set to 10 milliseconds
Figure 4.4.11 shows LTE Downlink with MCS 28 64QAM at frequency 1.8 GHz and 20 dBm power. This includes EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER. Figure 4.4.12 shows LTE Uplink with MCS 9 QPSK at a frequency 1.82 GHz and 20 dBm power. This includes LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.4.11 64QAM LTE DL at frequency 1.8 GHz and 20 dBm power. From left to right: EnB TX power spectrum, EnB RX power spectrum, BLER, PUSCH throughput and reported DL BLER.

Figure 4.4.12 QPSK LTE UL frequency 1.82 GHz and 20 dBm power. From left to right: LTE UE TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

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In conclusion, digitizers are capable to transmit a full duplex LTE system in Downlink and Uplink. Digitizers were used in full capability according to specifications. Also, LTE system platform had ideal case scenarios in order to transmit this application scenario.

Last application scenario is to test a video transmission through the digitizers using the LTE system platform. This scenario is a real application to be able to send a video transmission through the signal transmission established. In order to perform a transmission, VLC media program is needed to send and play the video.

Figure 4.4.13 shows the LTE DL with a fragment of video been played. LTE DL at a frequency of 1.8 GHz, power of 20 dBm and MCS 17 64QAM. Figure 4.4.14 shows LTE UL with a fragment of video been played. Also, there is some changes in the data-rate graph showing user data been utilized. Frequency is 2.2GHz, power of 20dBm and MCS 0.
In conclusion, digitizer is able to send a video through the LTE system. This last application scenario performs a real signal transmission. To conclude, digitizers perform as the specifications are proven.
Chapter 5: Analysis and Conclusions

Final section includes analysis on experiments of TMoIP and LTE over IP transmission. Certain behaviors and recommendations in order to perform a good signal transmission with different adjustment of parameters and observation. All scenarios will be compared to the baseline parameters to perform a qualitative and quantitative analysis. Due to digitizer physical constraints and specifications C-band was not able to be tested.

TMoIP

In first, TMoIP is tested with and without a reference clock. Behavior of signal transmission description is provided in the following sections. In order to achieve a good signal transmission. Experiments scenarios were focused on the L-band and S-band for TM bands given. This section will qualify signal transmission with three main visual parameters. Constellation graph, Power spectrum (SNR) and Eye diagram.

TMoIP signal transmission changed certain parameters. In addition, adjusted parameters are in the telemetry platform. Digitizers were set to automatic in the following scenarios. Telemetry parameters adjusted are the following:

- Carrier frequency: 1.8GHz, 2.0 GHz and 2.2 GHz.
- Gain: 0 dB and 12 dB.
- Modulation: QPSK, 8-PSK and OQPSK
- Reference clock

In first, frequency presented equal results between carrier frequencies. In addition, gain presented same results. Moreover, modulation scheme presented several changes. Next, each scenario will be compared to baseline parameters. Furthermore, the use of a reference clock is not essential for telemetry transmission. Both, experiment scenarios presented equal qualitative results.
QPSK

QPSK modulation presented a small jittery constellation graph compared to baseline parameters. Eye diagram aperture was reduced by 10%. To summarize, QPSK modulation was transmitted delivering some qualitative differences, but a proper signal transmission.

8-PSK

8-PSK modulation presented jittery in constellation graph. Power spectrum suffers no change compared to baseline parameters. On the contrary, eye diagram suffers a decrease in apertures. Main aperture is reduced by 33%, a considerable loss.

OQPSK

OQPSK modulation presents high jittery in the constellation diagram. OQPSK signal transmitted over IP is not able to show difference in each symbol concentration. Eye diagram presents a reduced in aperture.

In conclusion, lower modulation schemes show a proper signal transmission. High order modulation schemes present jittery constellations and a considerable reduced in eye diagram aperture. Further analysis could be performed in order to quantify the signal transmission.

LTE OVER IP

In second LTE over IP had several scenarios to test. In addition, LTE over IP was tested with and without the use of a reference clock. Experiments scenarios are focused on the L-band and S-band. For qualification and quantification purposes there are several parameters to describe the behavior of the signal.

LTE over IP tested several scenarios for EnB and UE. Following scenarios are:

- LTE EnB stand-alone
- LTE EnB through the system with LTE UE
- LTE UE
Nevertheless, other parameters are adjusted in order to describe the signal behavior. Digitizer parameters will remain to be set in automatic. LTE platform parameters to be adjusted are:

- Carrier frequency: 1.8 GHz and 2.2 GHz.
- Modulation Coding Scheme (MCS): QPSK, 16-QAM and 64-QAM.
- TX power: 0 dBm and 20 dBm.
- Reference clock

Frequency is a parameter that show consistent results across the multiple frequencies. Gain presented some changes on signal behavior on the different scenarios. The use of a reference clock is essential in some scenarios. Experiment results are compared to the baseline parameters.

**LTE EnB stand-alone**

First scenario, is LTE EnB stand-alone with and without a reference clock. There was consistency in results across parameters. LTE over IP as stand-alone performs a good signal transmission. MCS variation performs equally compared to baseline parameters with or without reference clock. Quantitative results show no changed compared to the baseline parameters. Qualitative measurements show only some jittery in PDSCH constellation due to gain adjustment in each pair of experiments.

In conclusion, LTE EnB as a stand-alone will perform a good signal transmission. There was no difference in the use of the reference clock for this matter of experiment scenarios.

**LTE EnB through the system**

Second scenario, is to test LTE DL through the system using the splitter/combiners. LTE DL and LTE UL is used as a full duplex communication. LTE DL will be sent through IP networks while LTE UL will remain as a regular RF transmission. After several experiment scenarios there are many channel power losses through the attenuators and the splitter/combiners.
First set of experiments are without the use of a reference clock. There was no difference in results across frequencies, delivering equal results. Gain parameter is a factor through due to channel power losses. 0 dBm power parameters show a jittery PDSCH constellation. On the contrary, 20 dBm power perform a good signal transmission and clean PDSCH constellation. In last, highest MCS 28 64QAM requires a 20 dBm power in order to be transmitted.

Second set of experiments are performed with the use of a reference clock. Second set of experiments demonstrate the same results as previous results. Showing consistency of results across multiple frequencies. Again, 0 dBm power experiment results present a jittery PDSCH constellation. Highest MCS 28 64QAM will require 20 dBm in order to perform a signal transmission. Furthermore, LTE eNB through the system stop working with 0 dBm power and different MCS with and without the use of a reference clock. Without the use of a reference clock and 0 dBm power highest MCS achieved is MCS 22 64QAM. On the other hand, with the use of a reference clock highest MCS achieved is MCS 23 64QAM.

In last, both scenarios LTE EnB RX maintained a low BLER at zero, regardless of gain modifications. Meaning that LTE UL worked across the entire sets of experiment scenarios.

**LTE UE**

Lastly, LTE UL platform will be sent over to IP. Since, LTE UL is a slave of the LTE DL, LTE DL must remain active. LTE DL remained with a fixed MCS, gain and frequency. Moreover, experiment scenarios will be performed with and without the use of a reference clock.

First experiment scenarios were performed without the use of a reference clock. After several adjustments in LTE UL with no success of transmission. In addition, several adjustments in the digitizers were performed with no success. This is due to a synchronization problem between the LTE DL and the LTE UL.

Second experiments scenarios were performed with the use of a reference clock. To conclude, other carrier frequencies were tested delivering equal results. Highest MCS tested was
MCS 9. To summarize LTE UL must have a reference clock in order to perform a signal transmission through the digitizers.

**Application Scenarios**

In last, application scenarios are focused on particular cases that could be presented. These application scenarios will vary parameters in LTE platform and digitizer to accomplish the desired environment for signal transmission. Each scenario will have unique conditions to ensure digitizers can perform a signal transmission as denoted in the specifications.

First scenario is to perform a signal transmission with a channel power of -60 dBm. Parameters included a calibration through FieldFox RF analyzer N9914A. Along with, digitizer automatic parameters. In conclusion, digitizer is able to transmit up to MCS 27 64QAM showing a throughput of 59.26 Mbps highest MCS to be transmitted. Digitizers are limited to transmit MCS 28 64QAM showing a throughput of .41 Mbps

Second scenario is to perform signal transmission with the lowest digitizer conditions. Second application scenario is tested due to ethernet constraints. LTE platform had ideal conditions, while digitizer had lowest conditions. In conclusion, digitizers could operate using the minimum gain. Highest modulation to transmit with A\D 4-bits is MCS 22 64QAM. In addition, the minimum required to transmit MCS 28 64QAM is A\D 6-bits.

Third scenario is to perform both signal transmission through the digitizer. Third scenario demonstrates the capability of digitizers to send enough bandwidth. In conclusion, digitizers are capable to transmit a full duplex LTE system with highest modulations in Downlink and Uplink. Digitizers were used in full capability according to specifications.

Last scenario is to perform a video transmission in LTE platform through the digitizers. Last scenario, demonstrates a real application that could be given to the digitizers. Besides, this application scenario proves that digitizer perform as expected with specifications denoted.
To conclude, table 5.1 shows recommendations for each type of transmission. Table includes, signal type and configurations for both SDR’s and digitizers. In addition, some parameters are required, recommended and the minimum required.

Table 5.1 Recommended configurations for successful transmission

<table>
<thead>
<tr>
<th>Transmission Type</th>
<th>Signal Type</th>
<th>Modulation</th>
<th>Gain or Power level</th>
<th>System BW</th>
<th>Stream BW</th>
<th>RF Input min</th>
<th>A/D bits Min</th>
<th>Gain mode</th>
<th>Reference clock</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>QPSK</td>
<td>12 dB recommended</td>
<td>10 MHz</td>
<td>2 MHz</td>
<td>-60 dBm</td>
<td>4-bits</td>
<td>Automatic</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>TM</td>
<td>OQPSK</td>
<td>12 dB recommended</td>
<td>10 MHz</td>
<td>2 MHz</td>
<td>-60 dBm</td>
<td>4-bits</td>
<td>Automatic</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>TM</td>
<td>8-PSK</td>
<td>12 dB recommended</td>
<td>10 MHz</td>
<td>2 MHz</td>
<td>-60 dBm</td>
<td>4-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LTE EnB stand-alone</td>
<td>LTE EnB</td>
<td>MCS 1 - MCS 28</td>
<td>0 dBm minimum</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>4-bits</td>
<td>Automatic</td>
<td>No</td>
</tr>
<tr>
<td>LTE EnB Through the system</td>
<td>LTE EnB</td>
<td>MCS 1 - MCS 23</td>
<td>0 dBm minimum</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>4-bits</td>
<td>Automatic</td>
<td>No</td>
</tr>
<tr>
<td>LTE EnB</td>
<td>MCS 24</td>
<td>0 dBm minimum</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>4-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LTE EnB</td>
<td>MCS 27</td>
<td>0 dBm minimum</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>4-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LTE EnB</td>
<td>MCS 28</td>
<td>20 dBm required</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>6-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LTE UE</td>
<td>LTE UE</td>
<td>MCS 1</td>
<td>0 dBm</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>12-bits</td>
<td>Automatic</td>
<td>Yes</td>
</tr>
<tr>
<td>LTE UE</td>
<td>MCS 9</td>
<td>0 dBm</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>12-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LTE UE</td>
<td>MCS 1 - MCS 9</td>
<td>20 dBm required</td>
<td>54 MHz</td>
<td>40 MHz</td>
<td>-60 dBm</td>
<td>10-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LTE UE</td>
<td>MCS 1 - MCS 28</td>
<td>20 dBm required</td>
<td>54 MHz</td>
<td>40 MHz</td>
<td>-60 dBm</td>
<td>10-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Video stream UE</td>
<td>MCS 9</td>
<td>20 dBm required</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>12-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Video stream EnB</td>
<td>MCS 17</td>
<td>20 dBm required</td>
<td>22 MHz</td>
<td>20 MHz</td>
<td>-60 dBm</td>
<td>12-bits</td>
<td>Automatic</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 6: Final conclusions and Future work.

This section will summarize rules and recommendations for each scenario. In addition, main points that should be considered according to each scenario are denoted as follows.

TMOIP

- Lower modulation schemes are properly transmitted.
- Qualitative parameters show better results with lower modulation schemes.
- Gain was not a parameter to affect the signal transmission.
- Carrier frequency was not a parameter to affect signal transmission.
- The use of a reference clock is not essential for telemetry transmission.
  - Has small impact with lower data-rate tested at 500k symbols/second.
- High order modulation schemes present jittery constellations and noticeable reduced in eye diagram aperture. Recommend to have a clock in those schemes.

LTE OVER IP

LTE EnB stand-alone

- LTE EnB will perform a good signal transmission.
- LTE EnB performed good signal transmission without the use of a reference clock.
- Gain is not a parameter to consider due to small channel power loss.
- Frequency was not a parameter to affect the signal transmission.

LTE EnB through the system

- LTE EnB will perform a good signal transmission.
- LTE EnB performed good signal transmission with and without the use of a reference clock with certain constraints.
  - No clock MCS 23 64QAM and 0 dBm.
  - Clock MCS 24 64QAM and 0 dBm.
- Gain is a parameter to be consider due multiple channel power losses.
Ensure that the input power to the digitizer satisfy the minimum level of -60dBm.

- 0 dBm TX power in SDR scenarios show a jittery PDSCH constellation
- Highest MCS 28 64 QAM will require 20 dBm in order to perform a signal transmission.
- Carrier frequency was not a parameter to affect the signal transmission.
  - Within digitizer limits (2.5GHz).

**LTE UE**

- Carrier frequency was not a parameter to affect the signal transmission.
- Reference power tested at 0 dBm is not a parameter to be consider.
  - LTE UE will automatically set to LTE EnB control.
- The use of a reference clock is essential to perform a signal transmission.
- Highest MCS to be transmitted was MCS 9 QPSK.

**APPLICATION SCENARIOS**

**Lowest RF input power**

- Digitizer is able to transmit up to MCS 27 64QAM showing a throughput of 59.26 Mbps highest MCS to be transmitted.
- Digitizers are limited to transmit MCS 28 64QAM showing a throughput of .41 Mbps
- MCS 27 is supported, MCS 28 is not supported.

**Lowest digitizer conditions**

- Highest modulation to transmit with A\D 4-bits is MCS 22 64QAM.
- The minimum required to transmit MCS 28 64QAM is A\D 6-bits.
**Full Duplex LTE system transmitted**

- Digitizer is able to transmit full duplex LTE system.
- Requires a stream bandwidth of 40 MHz
- System bandwidth must be 54 MHz
- Digitizers are capable to transmit a full duplex LTE system.

**Video transmission**

- Demonstrates a real application.
- Video is able to be transmitted.
- Performance specifications are proven.
- Digitizers are capable to transmit an LTE video Downlink direction.

**Future work**

Future work will be to perform further analysis in TMoIP. Not only to qualify the parameters, but also, quantify parameters. For example, Bit-error-rate (BER) or other parameters to quantify errors during signal transmission.

Second, digitizer physical constraints are not able to test higher frequencies, such as, C-band. Analysis on C-band could be performed with another digitizer that fit the necessity.

Third, these results are based only on RT logic digitizer. There are other companies with several variation of digitizers. Future work could include the comparison to other digitizers.

The 5G concept is now been deployed into different parts of the world. As frequency spectrum is getting crowded the necessity of other alternatives is urgent. Future work could include 5G technology over IP networks.
References


Appendix A

This section includes information on testbed adjustment and calibration. These experiments are part of Chapter 4: Results.

A1.1 Baseline Parameters

These are other parameters for telemetry platform. Figure 4.1.4 shows a telemetry QPSK signal at a frequency of 2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

Figure 4.1.4 telemetry QPSK signal, frequency 2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.1.5 shows a telemetry 8-PSK signal at a frequency of 2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

Figure 4.1.5 telemetry 8-PSK signal, frequency 2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.
Figure 4.1.6 shows a telemetry OQPSK signal at a frequency of 2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

Figure 4.1.6 telemetry OQPSK signal, frequency 2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.1.7 shows a telemetry QPSK signal at a frequency of 2.2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

Figure 4.1.7 telemetry QPSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.1.8 shows a telemetry 8-PSK signal at a frequency of 2.2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.
Figure 4.1.8 telemetry 8-PSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.1.9 shows a telemetry 8-PSK signal at a frequency of 2.2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum (SNR) and eye diagram.

Figure 4.1.9 telemetry OQPSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.
Figure 4.1.14 shows an EnB to UE signal transmission with an QPSK MCS at a 0.12 rate at a frequency of 2.2 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.1.15 shows an EnB to UE signal transmission with a 16-QAM MCS at a 0.42 rate at a frequency of 2.2 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.
Figure 4.1.15 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.1.16 shows an EnB to UE signal transmission with a 64-QAM MCS at a 0.43 rate at a frequency of 2.2 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.1.16 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.1.17 shows an EnB to UE signal transmission with a 64-QAM MCS at a 0.93 rate at a frequency of 2.2 GHz and 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.1.17 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.1.17 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

A1.2 TMoIP

No clock

Frequency is 2 GHz and other parameters will remain as before. Figure 4.2.1.4 shows a QPSK telemetry signal at a frequency of 2GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.1.4 telemetry QPSK signal, frequency 2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.
Figure 4.2.1.5 shows an 8-PSK telemetry signal at a frequency 2GHz and gain of 12 dB. This includes constellation diagram, power spectrum and eye diagram.

In last, for the frequency of 2 GHz. Figure 4.2.1.6 shows a OQPSK telemetry signal at a frequency of 2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Last experiment scenario is frequency at 2.2 GHz. All other parameters will remain as before. Figure 4.2.1.7 shows a QPSK telemetry signal at a frequency of 2.2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum and eye diagram.
Figure 4.2.1.7 telemetry QPSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.2.1.8 shows an 8-PSK telemetry signal at a frequency of 2.2 GHz and gain of 12 dB. This includes constellation diagram, power spectrum and eye diagram.
Finally, Figure 4.2.1.9 shows an OQPSK telemetry signal at a frequency of 2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

![Figure 4.2.1.9 telemetry OQPSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram](image)

Clock

Next, these are other experiments using a reference clock at 2 GHz frequency. Figure 4.2.2.4 shows a QPSK telemetry signal at frequency 2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

![Figure 4.2.2.4 telemetry QPSK signal, frequency 2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram](image)
Figure 4.2.2.5 shows an 8-PSK telemetry signal at frequency 2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.5 telemetry 8-PSK signal, frequency 2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

In last, Figure 4.2.2.6 shows an OQPSK telemetry signal at frequency 2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.6 telemetry OQPSK signal, frequency 2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.
To conclude, experiments for the frequency at 2.2 GHz. Figure 4.2.2.7 shows a QPSK telemetry signal at frequency 2.2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.7 telemetry QPSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.8 shows an 8-PSK telemetry signal at frequency 2.2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

Figure 4.2.2.8 telemetry 8-PSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.
Lastly, Figure 4.2.2.9 shows an OQPSK telemetry signal at frequency 2.2 GHz and 12 dB gain. This includes constellation diagram, power spectrum and eye diagram.

![Telemetry OQPSK Signal](image)

**Figure 4.2.2.9 telescym OQPSK signal, frequency 2.2 GHz and gain 12dB. From left to right: constellation diagram, power spectrum and eye diagram.**

### A1.3 LTE OVER IP CLOCK

**LTE stand-alone**

Now, frequency will change to 2.2 GHz all other parameters will remain as before. Figure 4.3.2.9 shows QPSK LTE EnB signal at a frequency of 2.2 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

![LTE EnB TX to LTE UE RX](image)

**Figure 4.3.2.9 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.**
Figure 4.3.2.10 shows QPSK LTE EnB signal at a frequency of 2.2 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.10 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.11 shows 16QAM LTE EnB signal at a rate of 0.42 and a frequency of 2.2 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.11 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.12 shows 16QAM LTE EnB signal at a rate of 0.42 and a frequency of 2.2 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

![Figure 4.3.2.12 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.](image-url)
Figure 4.3.2.13 shows 64QAM LTE EnB signal at a rate of 0.43 and a frequency of 2.2 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.13 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 0 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.14 shows 64QAM LTE EnB signal at a rate of 0.43 and a frequency of 2.2 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.14 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.
Figure 4.3.2.15 shows 64QAM LTE EnB signal at a rate of 0.93 and a frequency of 2.2 GHz with 0 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.15 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

Figure 4.3.2.16 shows 64QAM LTE EnB signal at a rate of 0.93 and a frequency of 2.2 GHz with 20 dBm power. This includes power spectrum of the EnB TX and UE RX power spectrum. Also, includes PDSCH constellation, throughput and data rate.

Figure 4.3.2.16 LTE EnB TX to LTE UE RX, frequency 2.2 GHz and 20 dBm power. From left to right: EnB TX power spectrum, UE RX power spectrum, PDSCH constellation, throughput and data rate.

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Vita

Jose Carlos Sandoval was born on August 8, 1993. First child of Jose Manuel Sandoval Barron and Sandra Luz Maese Fernandez. Both parents of Mexican nationality. Enrolled as an undergraduate student at the University of Texas at El Paso (UTEP) in 2012. Pursuing a Bachelor’s degree in Electrical Engineering. During bachelor’s degree he worked 4 years for the Technology Support Center at UTEP library in the role of Information Technology (IT) assistant. He obtained his Bachelor of science in Electrical Engineering with Cum Laude honors on May 2016.

In Fall 2018, he began his graduate studies at UTEP to pursue a Master’s degree in Electrical Engineering. Worked as a Teacher Assistant for Electronics I and later as a Research Assistant under supervision of Dr. Virgilio Gonzalez assisting on a White Sands Missile Range Project. Published a research paper for the International Telemetry Conference (ITC) 2019 which was the beginning of the research thesis.

Thesis typed by Jose Carlos Sandoval.