Evaluating the use of PXI modules in tests of a radio base station

WILLY WANG

Degree project in
Communication Systems
Second level, 30.0 HEC
Stockholm, Sweden

Evaluating the use of
PXI modules in tests of a radio base station

Willy Wang

2014-03-30

Master's Thesis

Examiner and academic adviser
Professor Gerald Q. Maguire Jr.

School of Information and Communication Technology (ICT)
KTH Royal Institute of Technology
Stockholm, Sweden

Abstract

This thesis project was carried out at the electromagnetic compatibility (EMC) department at Ericsson AB. One of the department's goals is to seek a possible replacement to the box test instruments by utilizing PCI extension for instrumentation (PXI) modules. The main objective of this project is to evaluate how different PXI modules work during testing of a radio base station (RBS), in terms of performance, test time, and cost. A downlink decoder was implemented in LabVIEW with an extension called MathScript and several software test solutions were examined to measure error vector magnitude (EVM), frequency error, and power, and to perform parallel measurements in a multiple radio access technology (multi-RAT) test configuration. Moreover, several uplink tests were performed to decide if PXI modules are a suitable substitute for the previous box based test instruments. The findings from this study show that PXI modules can replace the previous box based test instruments. However it was concluded that not all areas can be covered and not all discrete test instrument can (yet) be replaced. Future work should complete the downlink decoder implementation in the field programmable gate array (FPGA) level in order to further improve the performance further. Future work should also examine if it is possible to replace all of the discrete test instruments with PXI modules.

Keywords: *Vector signal transceiver (VST), multiple radio access technology (multi-RAT), PCI extension for instrumentation (PXI), LabVIEW, testing*

Sammanfattning

Detta examensarbete utfördes på elektromagnetisk kompatibilitet (EMC) avdelningen på Ericsson AB. Ett utav avdelningens mål är att hitta en möjlig ersättare till de tidigare boxbaserade testinstrumenten genom *PCI extension for instrumentation* (PXI) moduler. Huvudmålet i detta projekt är att utvärdera hur olika PXI-moduler fungerar i basstationstester med hänsyn till prestanda, testtid och kostnad. En avkodare i nerlänk har implementerats i LabVIEW med hjälp av MathScript och flera mjukvarutestlösningar har undersökts för att mäta *error vector magnitude* (EVM), frekvensfel och effekt, samt att utföra parallella mätningar i en multipel radioteknik (multi-RAT) testkonfiguration. Dessutom har flera upplänkstester utförts för att avgöra om PXI-moduler är en lämplig ersättare till de tidigare boxbaserade testinstrumenten. Resultaten från denna studie visar att PXI-moduler kan ersätta tidigare boxbaserade testinstrumenten, men dessa resultat visar även att inte alla områden kan täckas och inte alla diskreta testinstrument kan ersättas (ännu). Framtida arbete ska slutföra implementationen av avkodare i nerlänk i fältprogrammerbar grindmatris (FPGA)-nivå för att förbättra prestandan ytterligare. Framtida arbete bör även undersöka om det är möjligt att ersätta alla diskreta testinstrument med PXI-moduler.

Nyckelord: *Vektorsignal transceiver (VST), multipel radioteknik (multi-RAT), PCI extension for instrumentation (PXI), LabVIEW, testning*

Acknowledgements

First of all, I would like to express my deepest acknowledgements to everyone that has helped me in my thesis project. Without you, this master's thesis would have been an extreme struggle.

I would like to express my gratitude to **Professor Gerald Q. Maguire Jr.** for his advice and feedback that I have received for my report during this project. His invaluable guidance has assisted me through this work.

My gratitude for the EMC department at Ericsson AB must also be expressed, a special thanks to **Patrik Hellström** for allowing me to do this exciting thesis project, his precious pieces of advice and expertise within the subject has been highly appreciated.

I would also like to thank National Instruments and Agilent Technologies for lending me the test equipment for this thesis project. Notably, I would like to thank **Björn Beckman** (National Instruments) and **Andreas Tenggren** (Agilent Technologies) for providing me continuous support. I am also grateful for the courses in LabVIEW offered by National Instruments in the beginning of my thesis project.

Finally, I would like to thank my family and friends who have been supportive during the time I have been doing this thesis project.

Table of contents

List of Figures

List of Tables

List of acronyms and abbreviations

16 QAM	16-symbol Quadrature Amplitude Modulation
3GPP	Third Generation Partnership Project
64 QAM	64-symbol Quadrature Amplitude Modulation
ADC	Analog to Digital Converter
API	Application Programming Interface
ASIC	Application-Specific Integrated Circuit
BER	Bit Error Rate
BLER	Block Error Rate
BTS	Base Transceiver Station
CW	Continuous Wave
DAC	Digital to Analog Converter
DSP	Digital Signal Processing
E-UTRA	Evolved Universal Terrestrial Radio Access
EMC	Electromagnetic Compatibility
EVM	Error Vector Magnitude
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
GSM	Global System for Mobile
HDL	Hardware Description Language
I&V	Integration and Verification
IFFT	Inverse Fast Fourier Transform
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
NI	National Instruments
OFDMA	Orthogonal Frequency Division Multiple Access
PBCH	Physical Broadcast Channel
PCI	Peripheral Component Interconnect
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PXI	PCI eXtensions for Instrumentation
QPSK	Quadrature Phase Shift Keying
RAT	Radio Access Technology

RBS	Radio Base Station
RF	Radio Frequency
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCPI	Standard Commands for Programmable Instrumentation
TCP/IP	Transmission Control Protocol / Internet Protocol
TDD	Time Division Duplex
TS	Technical Specification
UAV	Unmanned Aerial Vehicles
UE	User Equipment
USRP	Universal Software Radio Peripheral
VHDL	VHSIC Hardware Description Language
VHSIC	Very High Speed Integrated Circuit
VI	Virtual Instrument
VISA	Virtual Instrument System Architecture
VSA	Vector Signal Analyzer
VSG	Vector Signal Generator
VST	Vector Signal Transceiver
WCDMA	Wideband Code Division Multiple Access

1 Introduction

This chapter gives a short introduction to the area, as well as a problem definition for this thesis project. This introduction is followed by a list of goals to be achieved in this study. The research methodology that has been selected for this thesis project is described and motivated. Finally, the chapter ends with a short description of the outline of this thesis.

1.1 General introduction to the area

In recent years, wireless networks have become part of people's daily activities in the form of cellular communication, mobile broadband, Wi-Fi, Bluetooth, and other wireless connectivity technologies. The demand for higher data rates has increased as the technologies have evolved. Long Term Evolution (LTE) technology is being developed and standardized by the third generation partnership project (3GPP). LTE aims to be a global standard for cellular communication services, by offering benefits to both consumers and network operators, via higher peak data rates, higher capacity, improved spectral efficiency, reduced latency, and reduced cost of services.

3GPP started to work on the evolution of the third generation mobile systems in 2004 [1]. The ideas for LTE were presented during an open workshop held for all interested organizations (which included mobile operators, manufacturers, and researchers). The participants in this workshop agreed that a feasibility study of new radio access technology (RAT) should take place. The main objective was to support higher data rates, reduce latency, and to adopt packet optimized technology.

LTE outperforms the previous mobile technologies in several aspects, for example it supports flexible channel bandwidths ranging from 1.4 MHz to 20 MHz. In addition, LTE also supports both frequency division duplex (FDD) and time division duplex (TDD), which means that operators can introduce LTE in both existing and new bands. However, LTE is considered one of the most complex RATs, which introduces new challenges in the design and testing of both network and user equipment (UE).

Smartphones are one of the most commonly purchased types of cellular communication equipment today. In addition to voice calls there is a trend of increasing user demands for data leading to an aggregate large amount of data traffic. This traffic comes from web browsing, video streaming, online gaming, and social networking. The total number of mobile subscriptions worldwide already (in 2013) exceeds 6.4 billion, Ericsson forecasts that mobile subscriptions will reach 9.1 billion by the end of 2018 [2]. The predicted growth in LTE capable subscriptions versus other RATs is shown in Figure 1-1. This expected growth in numbers of LTE subscribers and the expected growth in their data demands require higher data rates and higher capacity, therefore LTE is still evolving (leading to LTE-Advanced).
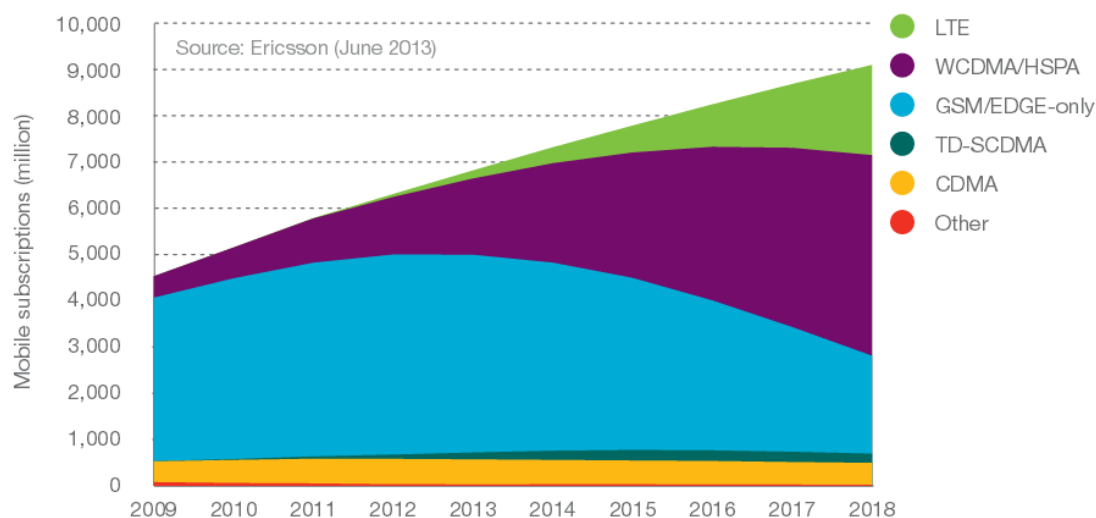

Figure 1-1: Mobile subscriptions forecast by technology, 2009-2018. [2] (Appears here with permission of Ericsson)

Engineers and scientists are constantly challenged to find new approaches to address the evolving radio frequency (RF) architectures. RF design challenges include troubleshooting, optimization, and design verification. One of the issues is to measure and verify the data content and RF structure of the downlink signal; as this is essential to ensure that an LTE radio base station (RBS) has been implemented according to the 3GPP's specifications. RBS is a terminology for a base transceiver station (BTS) within Ericsson. Hereafter, this paper will refer to a BTS as a RBS.

1.2 Problem definition

The RBS Node and Radio Integration and Verification (I&V) department at Ericsson is responsible for maintaining the high quality of the radio products for different RATs and developing base stations that meet the latest standards. Developing new base stations typically requires many tests and a number of test instruments. Using a test chamber to run a test system is both time-consuming and expensive (due to the costs of the test chamber itself and all of the test instruments); hence Ericsson wants to find a solution to reduce test times and total testing costs.

This master's thesis project is within the fields of wireless communication and digital signal analysis. The main objective of this thesis project is to evaluate the use of PCI extension for instrumentation (PXI) modules, such as National Instruments' (NI's) vector signal transceiver (VST), during I&V tests of a RBS. This includes decoding of the downlink modulated LTE signal, observing the data in LabVIEW, measuring error vector magnitude (EVM), frequency error, and power. Furthermore, parallel measurements in a multiple radio access technology (multi-RAT) setup will be performed for the combination of LTE and wideband code division multiple access (WCDMA) or global system for mobile (GSM). Finally, how to implement radio performance measurements will be examined in order to reduce the instrumentation needed for tests, reduce measurement time, and reduce total testing cost.

1.3 Goals and milestones

The main goal is to evaluate how PXI modules work in Ericsson's test environment in terms of performance, measurement time, and cost. To achieve this main goal the following milestones have been specified:

- Decode and analyze a downlink's modulated data using a single transceiver,

- Implement a number of radio performance measurements, and

- Perform parallel measurements in a multi-RAT environment, for instance perform simultaneous measurements of LTE and WCDMA.

If it is possible to enhance performance, shorten the measurement time, and lower the total testing cost, or performs measurements of multi-RAT equipment, then the instruments needed for testing can also be reduced, hence contributing to reducing the total cost of testing or enabling increased testing.

1.4 Limitations

The decoding will be limited to signals from one transmitter only. Transmitting on multiple transmitters and multiple input multiple output (MIMO) are not considered in this report, since this project focuses on downlink via a single antenna. Furthermore, implementations of electromagnetic compatibility (EMC) specific measurements in a field programmable gate array (FPGA) are not covered. Due to the scope of this thesis project, bit error rate (BER) measurement and block error rate (BLER) measurement implementation at the FPGA level are not covered in this thesis project. The limitations mentioned above are covered in another master's thesis project by *Viktor Arfwedson* from Uppsala University.

1.5 Research Methodology

This section presents the research approach of this thesis work. The choice of research method was decided prior to the data acquisition of this study, due to the fact that the problem definition and research directions were provided by Ericsson beforehand. After reading the description a quantitative

research approach was mainly chosen in this thesis project. The reasons why qualitative research methods were less used in the conduction of this study are mirrored in the problem definition. Another reason why a quantitative study is preferred is explained in the project focus; to be able to achieve the research goals through measuring data using a specific class of test instruments. Quantitative methods are able to generate more accurate results thus allowing the analysis of data and the drawing of conclusions in this thesis project. However, qualitative research approach cannot be entirely excluded, as this was a more convenient method used when collecting information for the literature study. Using a somewhat triangular research approach the ultimate aim is to accomplish the previously stated research goals.

Following Höst *et al.* [3] recommendations this report will be structured into three phases; literature study, experiment, and evaluation. The thesis project starts with a literature study to identify existing work in the area of study. Moreover, the literature study includes background material covering the main topics, such as: the VST and the LTE encoding process. Subsequently, this leads the project in a direction towards a quantitative data acquisition. In the next phase, an appropriate implementation approach was chosen based on the knowledge gained during previous phase, in other words an experiment is conducted to investigate the issues found during the literature study. Accordingly, the final phase consisted of an evaluation; given the results acquired from measurements and finally a conclusion is drawn as to whether or not PXI modules suits Ericsson's current test environment.

1.6 Structure of the thesis

Chapter 2 provides the reader with the basic background necessary to understand this thesis and presents a selection of work related to this project. Chapter 3 describes the methods used to achieve the goals in this project, including a description of the hardware used during the tests. Chapter 4 explains the implementation of the decoding process, as well as the parts of this process that will be implemented. Moreover, other test solutions from several different companies are presented. Chapter 5 presents the results obtained from the test cases and summarizes the knowledge gained during this thesis project. In addition, analysis of each test case is given along with a discussion. Chapter 6 summarizes the work; conclusions will be presented and reflected upon. Furthermore, all the work that has been considered but not yet been covered in this study will be discussed with the aim of inspiring future projects. Finally, a broad reflection on the thesis project is discussed.

2 Background

This chapter gives general background for the material presented in the rest of this thesis. A relevant selection of existing work will be presented, together with details of the equipment to be used in this thesis project. Some of the existing test equipment and test progress will be described at the end of this chapter.

2.1 Introduction to applications

In this section, a brief background is given about the NI VST, LabVIEW, and the FPGA in the VST. One of the important features of this new VST is the ability of users to program the FPGA.

2.1.1 Vector signal transceiver (VST)

Today most of the automated RF test systems use application software to communicate with the test instruments. Since RF applications are getting more and more complex with time, engineers and scientists are challenged to test an increasing amount of functionality without increasing test times and test costs. To reduce test time, improvements have been made in test algorithms; bus speeds have increased, and central processing unit speeds have been increased; nevertheless further improvements are required to match the increase in the complexity of RF test applications. [4]

Real-time instruments such as a vector signal analyzer (VSA) and a vector signal generator (VSG) are often used to measure BER, BLER, and EVM of known signals. In immunity tests, it is useful to have an objective set of metrics, for instance BER or BLER, rather than a subjective set of metrics such as waiting for a LED to stop blinking or manually observing distortions on a monitor. A VSA combines a real-time spectrum analyzer and a real-time oscilloscope. A VSG or a frequency generator generates analog or digital signals and is often used in testing and troubleshooting. For example, when calculating BER one could simply divide the total number of error bits received by the total number of bits received. An example of how to measure and compute BER is given in [5]. In this example a VSG generates a digitally modulated signal and the antenna sends it into the reverberation chamber. Afterwards a VSA is used to demodulate the received signal. To ensure that the digitally modulated signal is received without errors, the system is calibrated by connecting a VSA and a VSG. This same experimental configuration allows us to determine the magnitude and phase of the received signal and compare it with the transmitted signal. This example also shows that both the transmitter and receiver can be characterized if a suitably high data rate sampling is used in a signal generation system.

NI recently introduced a solution, called a vector signal transceiver (VST), to address the need for testing speed and flexibility. A VST is a small software defined RF system that includes both a VSA and a VSG. This system is packaged in an open industry standard, namely a PXI module. The VST has a user-programmable FPGA semiconductor chip embedded in it to provide software configured circuits for real time signal processing and control application purposes. This approach allows a VST to have great flexibility, enabling it to replace several RF test instruments. A comparison of the traditional approach and this new software-designed approach is shown in Figure 2-1.
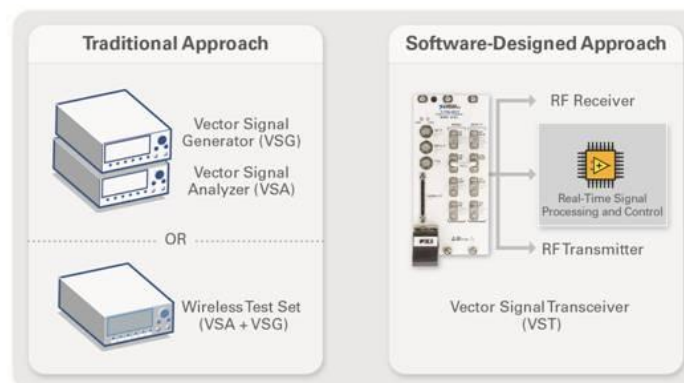

Figure 2-1: Comparison of traditional approaches (VSG and VSA) with the new software-designed approach (VST with FPGA). (Appears here with permission of National Instruments)

In radar system development it is important to be able to simulate a set of different signals that may affect the radar system. Several methods were investigated by *Tobias Hallberg* and *Robin Varis* in their bachelor's thesis [6] including the possibility of using a VST to run multiple simulations with respect to memory, speed, and reliability; two of these methods were implemented in LabVIEW, tested, and verified by *Richard Ferngren* and *Mikael Johansson* in their bachelor's thesis [7].

2.1.2 LabVIEW

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming environment developed by NI for data acquisition and measurement. The implementation of LabVIEW is done in terms of virtual instruments (VIs). A typical VI consists of two separate windows, a front panel and a block diagram as shown in Figure 2-2. The front panel window shows all indicators, such as digital values, graphs, bars, etc. It is also possible to add new controls and indicators to the front panel. The user can use a control on the front panel to adjust input values or can use buttons to switch from one mode to another. The block diagram contains all the logic and code to realize the application. The LabVIEW platform has also a lot of pre-defined VIs and a large toolbox. Using these VIs and the toolbox, an engineer or a scientist can implement a variety of applications in a relatively short time. [8]
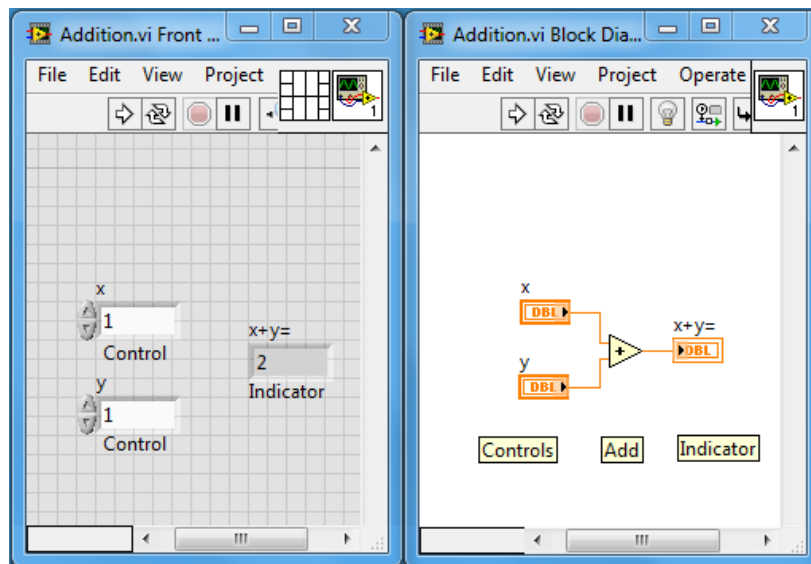
Figure 2-2: Front panel (left) and block diagram (right) windows of a simple addition VI.

A traditional electrical energy measuring system and a modern digital electrical energy measuring system are compared in [9]. In the modern approach data acquisition was done using LabVIEW with a digital signal processing (DSP) module. The LabVIEW approach uses less separate physical instrumentation than what would be needed in a normal DSP setting. Given the large number of predefined VIs and the LabVIEW toolbox the user does not need to use a DSP compiler nor manually load their code into a DSP engine, thus making the development of tests easier and less time consuming.

The MathScript RT Module is an extension to LabVIEW that adds a text based programming language. It is based on MATLAB and has more than 500 built-in functions. In addition, to address the signal processing, analysis, and mathematics tasks, MathScript uses m files and command line prompts. Users can also reuse scripts created in MATLAB by pointing to a search path in LabVIEW.

2.1.3 Field Programmable Gate Array (FPGA)

Performance and cost are key aspects engineers need to have in mind when designing new applications. For many years, industry has used application-specific integrated circuits (ASICs), due to their high performance and low production cost. However, it takes a very long time to develop a new ASIC and users cannot modify it after production. In contrast, an FPGA allows reduced production time and offers the ability to reprogram the FPGA even after a product has been shipped.

6

The first commercial FPGAs were introduced by Xilinx in the 1980s. This FPGA was a user-programmable semiconductor device and it consisted of many configurable logic gates and RAM blocks to do digital computations. The first FPGAs from Xilinx only had a few thousands logic blocks, while modern FPGAs have millions of logic blocks and in some cases include processor cores, DSP cores, etc. With this large amount of pieces added to the system, the FPGA becomes increasingly powerful and useful. Figure 2-3 shows the basic structure of an FPGA.
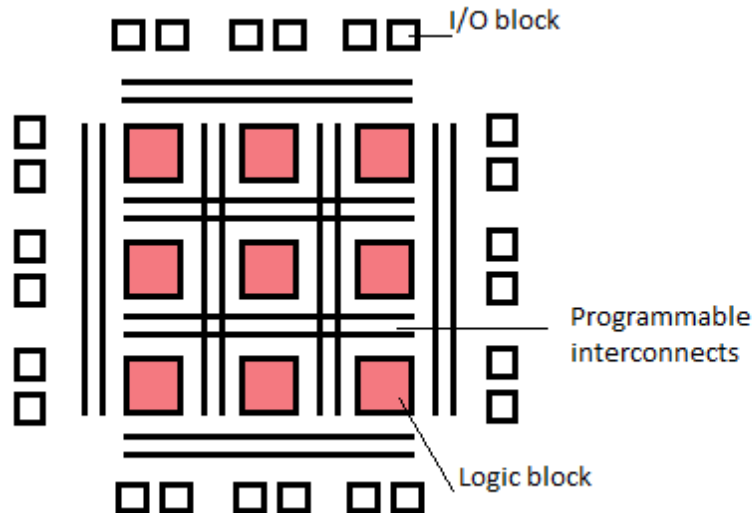
Figure 2-3: Basic structure of an FPGA

The FPGA is designed to allow users to program the device to realize a wide variety of functions. As the FPGA can be reprogrammed, it is even possible to time multiplex the FPGA to do different functions at different times, for example to perform certain functions and then later to perform a different set of functions. Lately, FPGAs are being used in RF test instruments to address the need for speed, flexibility, and reliability. Today the best parts of ASICs and processor-based systems have been combined into FPGAs. Users can test, verify, and customize their hardware without going through the long process of fabrication of a new chip. [3, 9]

Usually a hardware description language (HDL) is used when programming FPGAs. Newer FPGAs are also compatible with LabVIEW's built-in FPGA module. When LabVIEW compiles the code of a LabVIEW VI, it translates the graphical program into text-based HDL code, such as VHDL. Following this, a compiler converts this VHDL code into a bit file which is loaded to the FPGA chip to reconfigure the logic gates in order to realize the desired circuit.

System requirements change regularly over time, hence fabrication costs and assembly times can often be avoided by reprogramming the FPGA. According to Berkeley Design Technology, Inc., an FPGA can deliver more processing power per dollar than a DSP [11]. An FPGA can also be used to free up a computer by offloading computationally intensive processing to the FPGA. There are many benefits when using FPGAs, hence FPGAs applications are widely used, from aerospace and defense systems to medical applications and communication systems [12].

2.1.4 Encoding Process

In LTE, orthogonal frequency division multiple access (OFDMA) has been selected as the multiple access scheme for the downlink because of its robustness to multipath fading and interference. Multi carrier modulation is used to combat multipath interference at high data rates. The modulation is performed using many different subcarriers instead of a single carrier. Moreover, the modulators used for each of the carriers can be any type of single carrier modulators, for instance quadrature phase shift keying (QPSK), 16-symbol quadrature amplitude modulation (16 QAM), or 64 QAM.

OFDMA has a high peak to average power ratio, hence it requires a lot of power. Although, this is not an issue for the base station, it may be an issue for the battery powered UE. Therefore, single carrier frequency division multiple access (SC-FDMA) has been chosen for the uplink to achieve a low peak to average power ratio. SC-FDMA also exploits robustness to multipath fading and interference that OFDMA offers. [13]

The channel coding scheme includes error detection, segmentation, error correcting, rate matching, concatenation, and interleaving. This is based on 3GPP technical specification (TS) 36.212 [14].

The encoding process starts by attaching a short check value, called a cyclic redundancy check (CRC), to the transport block. The CRC is an error detection code used to ensure that data are correctly retrieved. The parity bits are generated from the entire transport block using a cyclic generator polynomial.

If the input bit sequence of the code block segmentation is larger than the maximum code block size of 6144 bits, segmentation of the input bit sequence is performed and an additional CRC sequence of 24 bits is added to each of the code blocks. Conversely, if the input bit sequence of code clock segmentation is less than 40 bits then filler bits are added to the beginning of the code block.

Channel coding handles the error correction in the transport channel. There are two types of channel coding schemes that can be applied to the control information and transport channel; tail biting convolutional coding and turbo coding. Turbo coding is usually used for the transport channel coding with a rate of 1/3. The coding rate represents the loss in capacity caused by redundancy and is defined by the ratio of input bits to the output bits. Figure 2-4 shows the structure of a rate 1/3 turbo encoder. The turbo encoder is a parallel concatenated convolutional code including two 8-state constituent encoders and one turbo code internal interleaver.
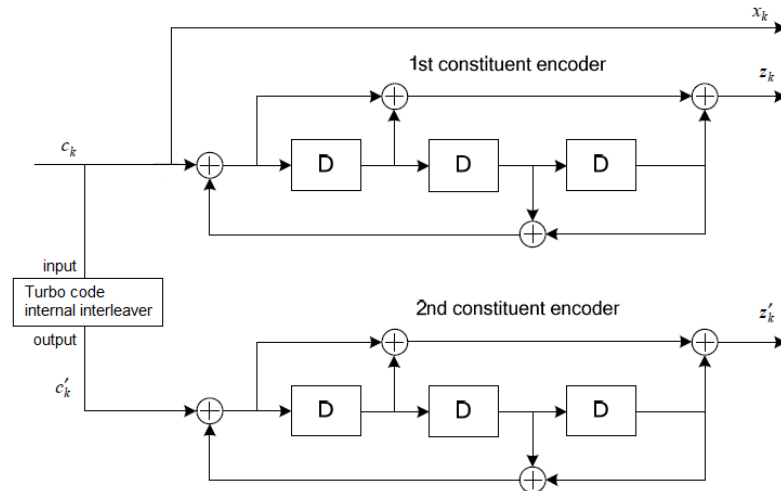
Figure 2-4: Structure of a 1/3 rate turbo encoder.

Rate matching for a turbo coded transport channel consists of interleaving the information bit streams into a collection of bits using a virtual circular buffer. Moreover, the code block concatenation concatenates the different code blocks from the rate matching outputs in a chronological order.

Scrambling of the code words ensures that the receiver can fully decode the code words and suppress interference. Every code word is scrambled according to:

$$\hat{b} = (b(i) + c(i))_{mod2}$$

where $c(i)$ is the scrambling sequence. This scrambling sequence is determined by the pseudo-random sequence generation after 1600 iterations to ensure a sufficiently random sequence. The pseudo-random sequences are defined by a Gold sequence of length 31 bits. The block of scrambled code words is equally distributed over all symbols using one of the modulation schemes; QPSK, 16 QAM, or 64 QAM. As a result, a block of complex-valued modulation symbols are ready to be mapped.

8

For transmission on single transmitter, the complex-valued modulation symbols $d^{(q)}(M_{symb} - 1)$, where the q is the code word and M_{symb} is the number of symbols per layer, are mapped into one layer. Layer mapping for a single transmitter is defined by:

$$x^{(0)}(i) = d^{(0)}(i)$$

The precoder takes the layer mapping $x(i)$ and maps into resources on the antenna port. Precoding for single transmitter is defined by:

$$y^{(p)}(i) = x^{(0)}(i)$$

where $p \in \{0,4,5,7,8\}$ is the number of the single antenna ports used for transmission.

If there are multiple antennas, then the layer mapping and precoding steps are performed in order to separate the symbols during transmission, otherwise these two steps are neglected. The case for multiple transmitters is described in detail in section 6.3.3.2 of 3GPP TS 36.211[15].

Since this project only focuses on a single transceiver, the complex-valued modulation symbols are directly mapped to resource elements.

A digital signal is typically converted to an analog signal before it is transmitted via an antenna. Subsequently, the received analog signal is converted back to a digital signal in order to receive the data that was to be communicated. At the transmitter side, as illustrated in Figure 2-5, a discrete signal $s[n]$ of binary digits is split into symbols which are processed in parallel. In the discussion that follows it is assumed that these symbols are mapped to subcarriers using the QPSK modulation scheme and an inverse fast Fourier transform (IFFT) is performed. The resulting signal $\hat{s}(t)$ is defined by:

$$\hat{s}(t) = \sum_{k=1}^{N} A\big(\cos\big(2\pi\Delta fkt + \phi(k)\big) + i\sin\big(2\pi\Delta fkt + \phi(k)\big)\big)$$

where N is the number of subcarriers, Δf is the subcarrier spacing, A is the amplitude of the signal, and the amplitude is assumed to be constant in the case of QPSK modulation.
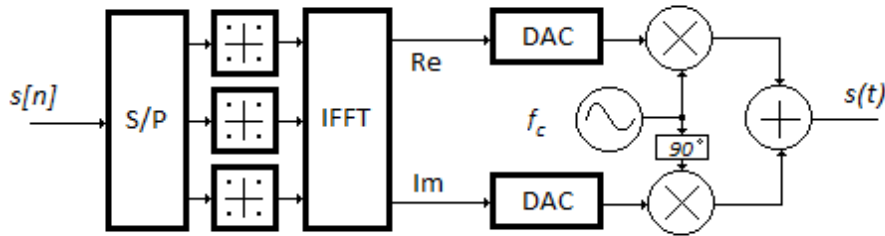
Figure 2-5: OFDMA system model in transmitter side.

The signal splits into a real part and imaginary part, the cyclic prefix is added, and then converted from digital to analog using a digital to analog converter (DAC). Following this, the carrier frequency f_c and a phase shifted carrier frequency are multiplied with the real part and imaginary part to up convert the analog signal. Subsequently, the signals are merged before the result is transmitted over the channel. The resulting signal $s(t)$ is:

$$s(t) = Re\{\hat{s}(t)\}\sin(2\pi f_c t) + Im\{\hat{s}(t)\}\cos(2\pi f_c t)$$

$$= A\left(\sin(2\pi f_c t)\left[\sum_{k=1}^{N}\cos\big(2\pi\Delta fkt + \phi(k)\big)\right] + \cos(2\pi f_c t)\left[\sum_{k=1}^{N}\sin\big(2\pi\Delta fkt + \phi(k)\big)\right]\right)$$

At the receiver side, as illustrated in Figure 2-6, the received signal $r(t)$ is down converted by multiplying the signal with the carrier frequency f_c again. Next, an analog to digital converter (ADC), removes the cyclic prefix and a forward FFT is used to transform the signal back to the frequency

9

domain. Finally, a symbol detector is used to find the position of the parallel symbols and merge the symbols back into a single stream of binary digits ($\hat{s}[n]$). If the system works properly the received binary digits are equal to the transmitted binary digits.
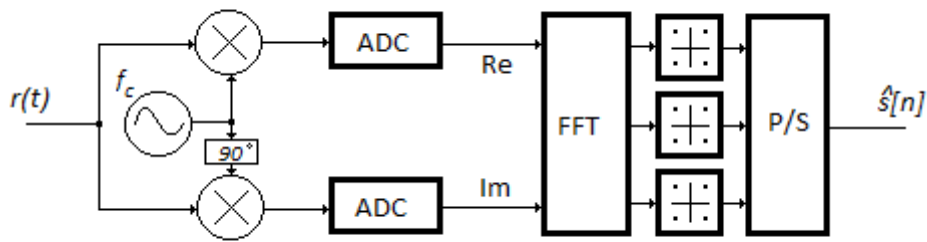
Figure 2-6: OFDMA system model in receiver side.

One of the key differences between LTE and other RATs appears in the physical layer. The physical layer for LTE supports the two multiple access schemes as mentioned earlier: OFDM and SC-FDMA. These multiple access schemes are designed to protect against the inter-symbol interference caused by multipath delay spread. The inter-symbol interference can be entirely eliminated if the delay spread is within a guard period and if the cyclic prefix is added to the guard period in the OFDM symbol, see Figure 2-7. According to the 3GPP TS 36.211 table 6.12-1 [15], the length of the cyclic prefix for the downlink is shown in Table 2-1.
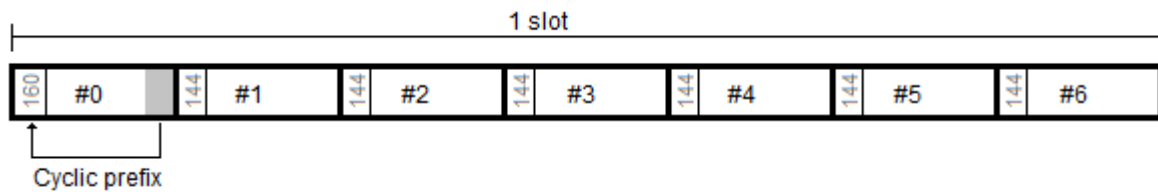
Figure 2-7: OFDM symbol structure

Table 2-1: OFDM cyclic prefix length for the downlink

Configuration		Cyclic prefix length $N_{CP,l}$
Normal cyclic prefix	$\Delta f = 15kHz$	160 $for\ l = 0$ 144 $for\ 1,2,\dots,6$
Extended cyclic prefix	$\Delta f = 15kHz$	512 $for\ 0,1,\dots,5$
	$\Delta f = 7.5kHz$	1024 $for\ 0,1,2$

There are 25 resource blocks in total in a LTE signal with a 5 MHz channel bandwidth. Each resource block consists of 12 subcarriers in the frequency domain and 7 OFDM or SC-FDMA symbols in the time domain. Seven symbols are equal to one slot and 20 slots forms a radio frame of 10 milliseconds. Additionally, the synchronization signals and physical channels are mapped to the 300×140 resource element structure in frequency versus time domain. Figure 2-8 illustrates an example of the downlink mapping in the first 11 slots, including primary and secondary synchronization signals in two slots.
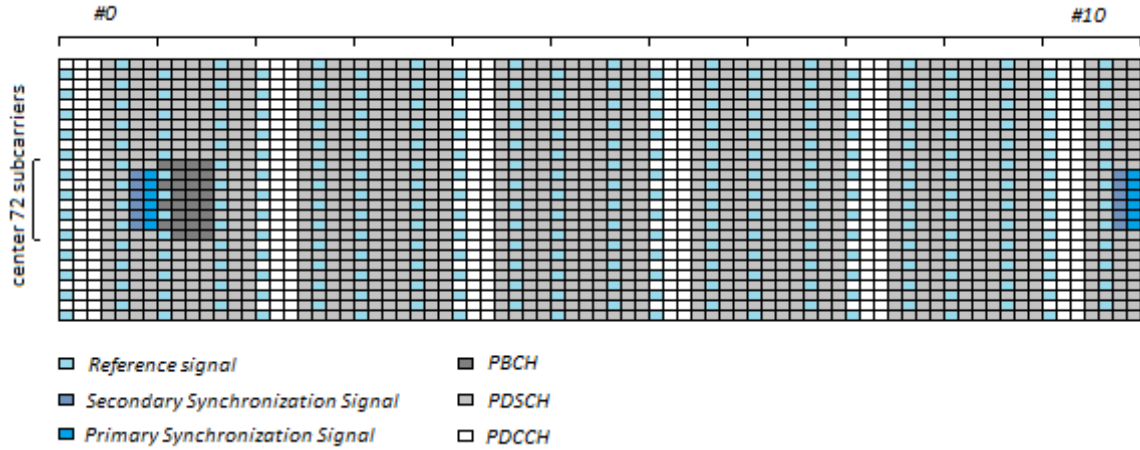
Figure 2-8: Example of the downlink mapping in the first 11 slots (not shown to scale)

In OFDM, the number of subcarriers and the transmission bandwidth can be determined independently. This enables six different transmission bandwidth configurations.

In a downlink radio frame, there are primary and secondary synchronizations signals, reference signals, Physical Downlink Shared Channel (PDSCH), Physical Broadcast Channel (PBCH), and Physical Downlink Control Channel (PDCCH). The UE is able to detect the primary and secondary synchronization signals, since they are transmitted twice every 10 milliseconds. The synchronization signals use only the central 62 of 72 subcarriers of a channel. This is done to enable the UE to use an efficient 64 symbol length FFT to perform a cell search procedure (details of the cell search procedure can be found in [16]). Figure 2-9 and Figure 2-10 show a plot of a constellation diagram including the synchronization signals. The subcarriers which the primary synchronization signal occupies, uses a frequency domain Zadoff-Chu sequence for modulation. The uth root Zadoff-Chu sequence is given by:

$$x_u(n) = e^{-j\frac{\pi u n(n+1)}{N}} \qquad , \qquad 0 \leq n \leq N-1$$

The sequence $d(n)$ used for the primary synchronization signal is generated according to 3GPP TS 36.211 [15]:

$$d_u(n) = \begin{cases} e^{-j\frac{\pi u n(n+1)}{63}} & n = 0,1,\dots,30 \\ e^{-j\frac{\pi u (n+1)(n+2)}{63}} & n = 31,32,\dots,61 \end{cases}$$

where the root index u corresponds to the cell identity $N_{ID}^{(2)}$ and it is given in Table 2-2.

Table 2-2: Root index for the primary synchronization signal.

Cell identity $N_{ID}^{(2)}$	Root index u
0	25
1	29
2	34
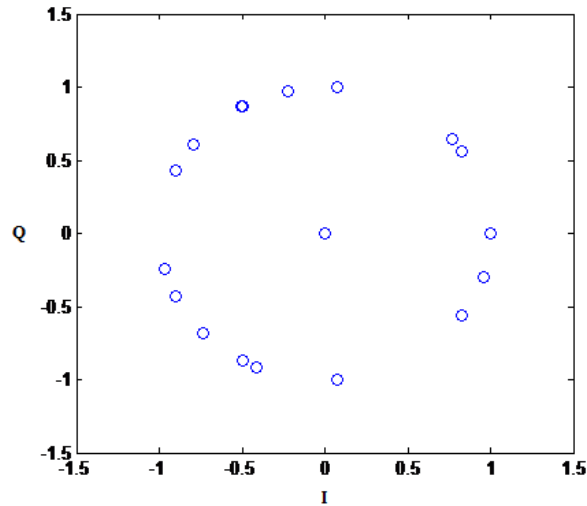
Figure 2-9: Primary synchronization signal in OFDM I/Q constellation diagram
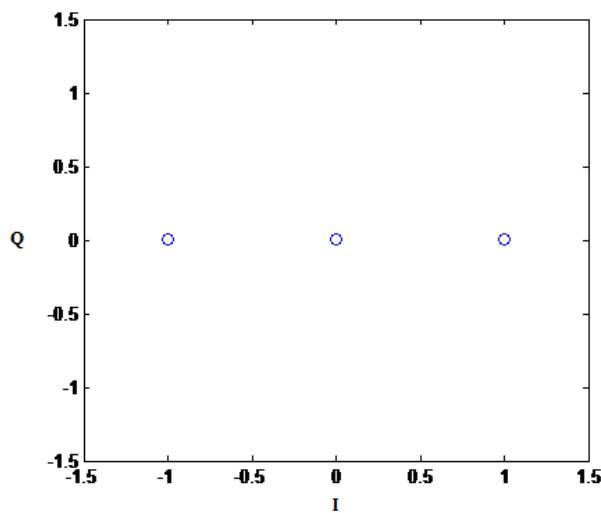
Figure 2-10: Secondary synchronization signal in OFDM I/Q constellation diagram

There are different kinds of reference signals; the cell-specific reference signal is one of them. The reference signals have known amplitudes and phases uniformly allocated in six subcarriers in the frequency domain and every two symbols per slot in the time domain. Because the received signal from a UE might contain amplitude-, phase-, and timing errors; using these references minimizes the probability of demodulation errors.

The PDSCH is a physical channel that transports the user data at high data rates and it is shared between many users in the time domain. This channel supports QPSK, 16 QAM, and 64 QAM modulation schemes and can be used with different multi-antenna techniques. PBCH is a physical channel that carries the broadcast channel, including cell-specific system identification and access control parameters. PBCH is transmitted in the center of the channel and it occupies 72 subcarriers over four symbols. PDCCH is a physical channel that carries channel allocation and control information. It is built by one or more control channel elements. Every control channel element corresponds to nine resource element groups. PBCH and PDCCH only support QPSK modulation scheme. [16, 17]

2.1.5 Signal quality measurement

This project includes signal quality measurement, such as error vector magnitude (EVM), frequency error, and power measurements.

12

The concept of an EVM is often mentioned when measuring the quality of digitally modulated signals. EVM expresses the difference between the measurements of a symbol's location (in the amplitude and phase domain) and the ideal symbol location. A constellation diagram is used to represent the demodulated signals, be they digital or analog, in terms of symbols. EVM measurements are usually performed using instruments which capture a signal over time and subsequently perform an FFT. This measurement is typically done with a real-time analyzer [18]. Figure 2-11 shows the received symbol, the error vector, and the location of an ideal symbol in a QPSK modulation and the EVM is expressed as:

$$EVM = 10 \log_{10} \left(\frac{|Error\ vector|}{Ideal\ symbol\ vector} \right) [dB]$$
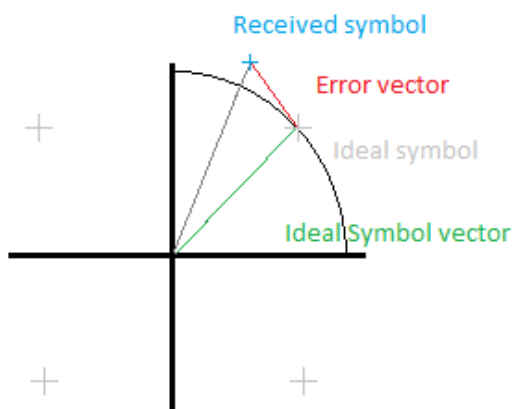
Figure 2-11: A received symbol, the error vector, and the location of an ideal symbol in a QPSK modulation. [19]

Frequency error is a measurement of the difference between the transmitted frequency and the assigned frequency. It is normally tested together with EVM test and computed as:

$$Frequency\ error = \frac{transmitted\ frequency}{assigned\ frequency}$$

Channel power is a measurement of the difference between the demodulated signal power and the reference signal power and calculated as:

$$Channel\ power = 10 \log_{10} \left(\frac{|Power\ of\ demodulated\ signal|}{Reference\ signal\ power} \right) [dB]$$

2.1.6 RBS and test systems

RBS deployment is expanding everywhere; in densely populated areas such as stadiums, shopping malls, train stations, and even in suburban and rural areas. Furthermore, different radio standards are evolving and some are being decommissioned; therefore each RBS is examined and tested to see that it meets the current standards that it is expected to support.

Ericsson's RBS 6000 series are the latest RBS releases that support multiple radio standards. This series has different solutions that are optimized to deliver high radio performance for improved cell planning. The RBS 6201 is the RBS cabinet used in this project. This single cabinet supports multiple standards. The radio shelves in the RBS 6201 cabinet can be equipped with virtually any combination of GSM, WCDMA, and LTE. This RBS consists of power supply units, two radio shelves for digital units and radio units, a cooling system, and transport network equipment (this connects the RBS into the radio access transport network). This RBS supports a broad selection of radio units and digital units encompassing all of the main frequency bands and combines multiple RF technologies. The RBS has an intelligent power system that provides power on demand; this conserves energy hence increasing UE battery lifetime. [20]

Many tests of the uplink require a frame trigger signal from the RBS. The frame trigger signal is a pulse used for testing purposes and appears at the beginning of an uplink frame. The VSG sets up a

continuous wave (CW) and waits for the frame trigger to activate the carrier signal. Therefore it is important to set a delay-time in a VSG after receiving a trigger pulse.

As of today, there are many test systems used for testing in different radio access networks. Testing and verifying new technology is necessary to reduce unexpected costs due to component failures, wireless interference, or incorrect installation. Therefore, test equipment is needed to perform different RF tests in order to ensure quality in the products. Some of the larger test equipment vendors are NI, Agilent Technologies, and Anritsu. All of them support both traditional discrete test instruments (each in its own box) and PXI solutions.

NI offers PXI solutions for cellular test systems which mainly focus on measuring transmission speed and EVM performance. These test systems are able to perform multi-RAT testing. Moreover, their test systems support 4×4 MIMO measurements and can execute 5-10 times faster than a traditional box based test system. The company also delivers toolkits for signal generation, analysis, visualization, and processing of modulation formats to keep up with the evolution and growing number of standards.

The VST (PXIe 5644) includes an RF generator and analyzer in a small 3 slot PXI express module. This module was designed to perform variety tests of cellular and wireless standards, such as IEEE 802.11ac and LTE. Practical tests on IEEE 802.11ac using a VST have measured an EVM less than 0.5 percent for a 256 QAM signal. Moreover, the VST has a user-programmable FPGA integrated for real time signal processing. [21]

The VSA (PXIe 5665) can be used as both a spectrum analyzer and signal analyzer to measure signals over a wide frequency range, ranging from 20 Hz to 14 GHz. It is designed to support a broad selection of communication standards using analysis toolkits from NI or third-parties. All measurements are software defined and the system can at any point simply be reconfigured using standard toolkits. For example, the NI Modulation toolkit can be used to perform modulation analysis. [22]

A typical test system from NI consists of an embedded controller and a VST in a PXI chassis and a set of applications for signal generation and analysis measurements [23]. NI has provided many companies with different system solutions to reduce the number of test instruments, measurement times, and cost for testing. ST-Ericsson[1], a semiconductor developer for smartphones and tablets, normally runs about 800,000 measurements for a single set of tests. Using products from NI ST-Ericsson has reduced both costs and measurement times by replacing the classical box instruments with a PXI platform and LabVIEW [25].

Agilent Technologies offers applications for base station and UE transmitter test for GSM, WCDMA, and LTE [26]. Their applications enable measurements in time, frequency, and modulation domains. A set of evolved universal terrestrial radio access (E-UTRA) test models (E-TMs) presets based on 3GPP TS 36.141 are available for conformance testing in LTE, and similar the test models are available for the other two RATs. For example, their 89600 VSA software is capable of performing signal modulation analysis. This includes LTE modulation analysis in both FDD and TDD.

The VSA (M9391A PXIe) and the VSG (M9381A PXIe) are modular solutions designed to cooperate with each other. They support fast and high quality measurements in frequency coverage from 1 MHz to 6 GHz meant for RF test environments. [25, 26]

The *N5182A MXG* VSG is a non-modular instrument used for uplink tests. This instrument supports up to 6 GHz bandwidth and are able to generate signals according to most of the cellular standards. This VSG can be controlled using both a display and buttons on the front panel or remote access through a general purpose interface bus (GPIB) or a local area network (LAN). [29]

Anritsu has designed LTE test solutions to help ensure both performance and quality of LTE devices and network equipment. They have VSAs and VSGs for LTE uplink and downlink analysis, as well as realistic LTE signal generation. [17]

---

[1] A joint venture of Ericsson and STMicroelectronics split up in August 2013 [24].

The LTE test bed used in this thesis project includes an application server, RBS, UE, and a host. The connection between an application server and UE is via TCP/IP over Ethernet. The structure of a RBS and an UE are nearly identical from a hardware perspective; the only difference is the RF output power in the antenna systems. A Global Positioning System (GPS) receiver is used to synchronize the RBS and the UE [30] by sending one pulse per second to the RBS and a 10 MHz reference frequency to the test instrument. The idea of using a GPS receiver is to enhance the accuracy of time synchronizations. This synchronization is especially desirable for the test that needs long runs (alternatives to the GPS receiver are described in [31]). The test bed for this project is shown in Figure 2-12. In this figure DU stands for digital unit and RU stands for radio unit. The box labelled GPS is a GPS receiver.
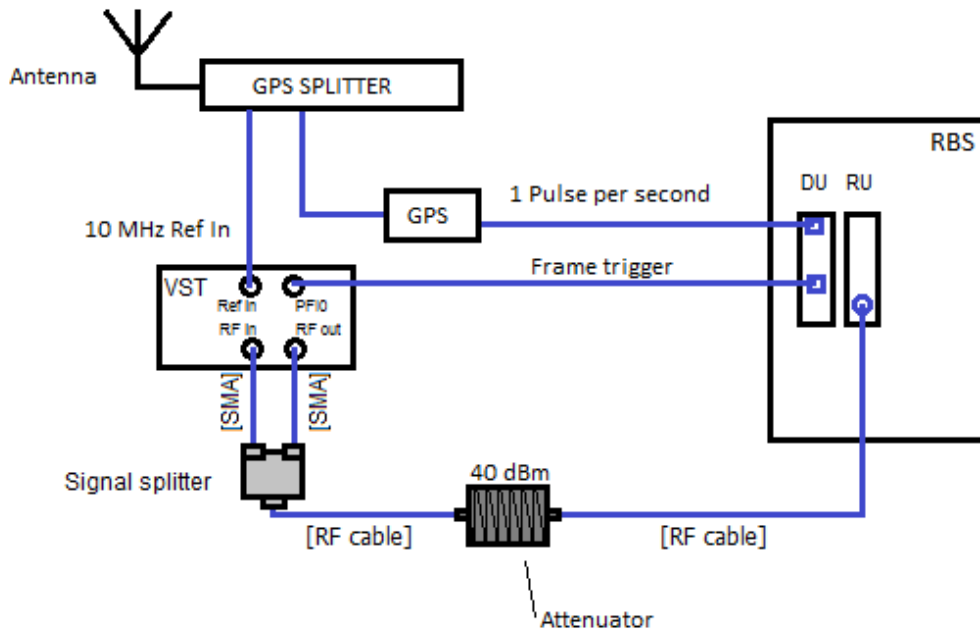
Figure 2-12: Diagram showing how the test instruments are connected during tests.

The EMC department uses one test instrument per radio standard, which means several test instruments are included in multi-RAT measurements. This project will examine multi-RAT solutions in different vendor's softwares and test solutions. If this is possible, then the number of test equipment can be reduced.

2.2 Related Works

To familiarize the reader with what has already been done and to provide some additional context for the work described in this thesis, a selection of related work was chosen. These related works are summarized in this section. The selections were limited to the fields of aerospace and defense, medical applications, and communications systems as these are the field that are most relevant to the work that was expected to be part of this thesis project.

2.2.1 Radar system on aircraft

As mentioned in section 2.1.1, radar system development includes measurement and verification. Testing radar systems on an aircraft is the ultimate way to evaluate their performance, unfortunately such testing are also very expensive. In addition, the test results acquired by different aircrafts are not repeatable. Thus, testing requires many different flights in order to draw a statistical conclusion; however in practice this would be cost prohibitive. As a result virtual flight testing is a better method to evaluate a radar system for potential deployment on aircraft, as this method of testing greatly reduces the cost of testing. Agilent Technologies and Analytical Graphics Inc. have combined their respective strengths to tackle difficult radar modeling and verification issues. [32]

Agilent Technologies' SystemVue is an electronic-system-level design program, widely used when designing radar and communications systems. This software is designed to support implementers of RF, DSP, and FPGA/ASIC solutions. During a virtual test, the software simulates the radar system by doing waveform generation, DSP processing, RF processing, and radar post-processing. The Systems Tool Kit by Analytical Graphics Inc. simulates flight scenarios and signal path characteristics.

2.2.2 Unmanned Aerial Vehicles

Unmanned-Aerial-Vehicles (UAVs) are widely used both by the military and civilians. In a military context an UAV may be used in suppression of enemy air defense, air-to-ground targeting, avoiding dangerous zones, or gathering intelligence. In a civilian context an UAV may be used for weather forecasting, farm field seeding, or border surveillance. All of these tasks require real-time path planning. Regardless of the area of use, most UAVs require a human to navigate. Genetic algorithm solutions with and without FPGA for UAVs were investigated in [33]. The FPGA not only suits the implementation of a real-time path planner, but operates 10,000 times faster than the software running on a Pentium 4 processor.

2.2.3 Image Processing in Medical Applications

FPGAs can be used for image processing in medical applications. Real-time volume rendering is the focus in [24], where Xing, Liu, and Zhao used an FPGA to accelerate volume rendering. Their real-time application is using a block-based algorithm to scan the volume data and independently rendering each block data in parallel. This speeds up the execution times and reduces total memory usage, resulting in an efficient real-time application.

2.2.4 Telemedicine via TCP/IP

Instead of transporting a patient to another clinic for diagnosis, telemedicine transmits diagnostic data from a local clinic to an expert physician. Based on the digital image the expert physician can give advice to the local physician. Combining LabVIEW with TCP/IP is discussed in [35]. Data is reliably transmitted using TCP/IP and the security of this data is ensured using a high encryption level.

2.2.5 Communication System at High Speed

LTE is capable of delivering high data rates despite high speed motion of the devices. Ericsson did a flight test to measure the impact of the Doppler effect, handover performance, and video stream stability [36]. The test was done together with Saab Aeronautics, flying at an altitude of 300 meters above ground and a speed of 700 kilometers per hour, a laptop with a LTE dongle could receive a peak data rate of 19 megabits per second via the downlink. As the Doppler effect limits the user to having stable internet connectivity while moving at a high speed in a straight line from a RBS, the aircraft had to lower its speed to 600 kilometers per hour to maintain stability. Handover without any visible disturbances was achieved at a speed of 500 kilometers per hour.

2.2.6 The Universal Software Radio Peripheral

The Universal software radio peripheral (USRP) products are hosted on computers as software radios, prototyping wireless RF and communication systems. The USRP products were initially developed and sold by Ettus Research and now also sold by NI. The main idea of this approach is to turn radio hardware problems into software problems. The design of an USRP covers a wide range of frequencies and with appropriate daughter cards it transmits and receives a wide variation of signals, which enables quick implementation and execution of new radio protocols. A second generation USRP (USRP2) includes a FPGA chip, gigabit Ethernet interface, USB interface, ADC, DAC, and SD card reader.

The FPGA chip is the most important part in this system. It performs all high bandwidth calculations and optimizes the data rate, making it capable of transferring data over an USB 2.0 interface. A broadcast FM receiver is one of the simple examples of using a USRP.[37]

NI has released its own USRP products, which are paired with LabVIEW and widely used both in research and education. All these products have a tunable center frequency with a range covering FM radios, GPS, GSM, GNSS, and Wi-Fi in higher frequency ranges. [38]

A SC-FDMA transceiver communicating between two nodes running on USRP2 was investigated and implemented in a study by Jorgensen *et al*. [39]. Since SC-FDMA is the air interface selected for LTE, the implementation uses the Physical Uplink Shared Channel (PUSCH) slot structure and QPSK, 16 QAM, and 64 QAM modulations are supported. Furthermore, a theoretical additive white Gaussian noise (AWGN) channel model was derived to compare with experimental results. Jorgensen *et al*. compared the performance of their implementation to the theoretical model in terms of BER.

Synchronization was an important part of their experiment. Jorgensen *et al.* used a one pulse per second reference signal instead of frame level synchronization, because downlink reference signals are required to obtain synchronization in the uplink and no downlink signals were available during their implementation. Tests have shown that the one pulse per second reference signal was accurate to within an order of 20 samples when a 10 MHz reference clock was shared (i.e., they were synchronized to within 2 microseconds).

3 Method

This chapter explains the methods used to conduct this study focusing on achieving the specified goals. As stated in section 1.3 the main goal is to evaluate how PXI modules work in Ericsson's test environment in terms of performance, measurement time, and cost. A number of tests were performed to evaluate this, with several additional tests to provide more accurate results. The PXI modules may replace the traditional test instruments in at least some of the current testing areas. There is still a need to investigate if the test results are truthful. Different departments have different requirements for their test instruments. The test results should tell them if the PXI systems are appropriate substitutes for their existing test instruments. The number of tests conducted in this thesis project was limited due to the purposely wide selection of tests and the amount of time available with both the test instruments and the time available for this thesis project. Each test requires some code or software to generate or analyze a signal and to acquire measurement results.

The programming language that was chosen for this project was LabVIEW. This choice had several reasons, including the fact that most of the PXI modules were compatible with LabVIEW. This was true because PXI is an open standard developed by NI. Moreover, the PXI modules that were used also have their own application programming interface (API) for LabVIEW. Another advantage is that NI provides toolkits for a variety of different cellular communication and modulation analysis. In addition, the MathScript RT Module extends the programming options with a text based command line environment.

A decoder had to be implemented in LabVIEW in order to verify the VST and perform downlink tests. This included performance measurements based upon an EVM measurement, frequency error calculation, channel power measurement, and time measurement. The verification of the decoder was done in two parts. During the implementation, verifications were performed on a recorded signal to enable the device to receive the same input every time the test was run. This was followed by real-time measurements on a RBS. The decoding process is based on the encoding process, described in section 2.1.5. This implementation also investigated if MathScript could be used and if there was any difference in performance (with respect to testing time).

The VST and other PXI modules were also verified by comparing the test solutions from several different vendors. The different functions offered by the test solutions were examined and tested. In particular, conformance measurements and multi-RAT measurements were the focus of these tests. Since measuring in multi-RAT in existing test instruments require one instrument per RAT. The number of test instruments can be reduced if the VST is able to operate in multi-RAT.

During the evaluation process, it was important to identify whether or not the PXI systems are suitable for use in Ericsson's test environment. The result of this project has led to a suggestion that Ericsson use the PXI systems as their test systems. Moreover, the companies behind the PXI systems and test solutions will receive evaluation feedback through this thesis.

In addition to the EMC department, other departments at Ericsson have been examined and a number of test cases were developed to determine if the PXI systems and the test solution would be practical in their respective test areas. One of the methods chosen in this study was to verify if the PXI modules function correctly in Ericsson's test environment. Test cases were based on receiver characteristics and these tests were the base station reference sensitivity test and base station in-band blocking test. Each of these tests will be described in detail in a subsequent section.

3.1 Base station reference sensitivity test

The base station reference sensitivity test is to find the reference sensitivity by varying the output power level of a signal generator and measuring the throughput of the reference measurement channel, which is the RBS in this case. The reference sensitivity level is where the throughput is ≥95% of the maximum throughput. The requirements of this test are defined as a function of operating band, channel bandwidth, and modulation type. For channel bandwidths of 5 MHz or higher, the typical power level according to 3GPP TS 36.104 for reference sensitivity tests is -101.5 dBm [40], but Ericsson has their own testing requirements that differ from these general levels. This test will be performing using the VST (PXIe 5644) and the VSG (M9381A).

3.2 Base station in-band blocking test

The base station in-band blocking test measures the ability of the receiver to receive a desired signal in its allocated channel with an unwanted interferer nearby. The interferer is often a 1.4 MHz, 3 MHz, or 5 MHz E-UTRA signal for in-band blocking tests. The maximum mean power allowed by 3GPP TS 36.104 is -43 dBm [40], but each tester may have their own requirements that differ from the general levels.

The in-band blocking test can be performed using two or more signal generators. Usually only two signal generators are used, one as a main carrier and another as the interferer. This test measures the BER at the carrier as the output power incrementally increases at the interferer. The noise level from the interference will eventually exceed the desired signal throughput at the carrier.

3.3 Other receiver tests

Other receiver tests were considered, but have not been included in this study due to insufficient resources. These tests are adjacent channel selectivity and intermodulation. This section briefly explain each of the tests and the minimum requirements can be found in [40].

Adjacent Channel selectivity test measures the receiver ability to receive a wanted signal at assigned channel bandwidth with an adjacent interfering signal. This test is basically the same as blocking test except they have different requirements on power level and interferer type.

Intermodulation test measures the ability of a receiver to handle two interfering signals very close to the wanted signal. One of the interferer is a CW signal with an offset frequency based on the channel bandwidth. The other interferer is a modulated E-UTRA signal with offset frequency twice as the CW signal.

3.4 Summary of receiver tests to be made

The reference sensitivity test and in-band blocking test are receiver tests and hence both require a signal generator to generate the uplink signal. Therefore, it is necessary to implement signal generation code for each of the desired signal generators.

4 Implementation

This chapter describes the implementation of decoding for the downlink as well as solutions for modulation analysis and uplink signal generation. In section 4.1, the downlink decoding implementation done in this study will be explained. In section 4.2, the different suppliers' test solutions are introduced.

4.1 Downlink decoding implementation

The focus of this decoder is the LTE 5 MHz downlink signal. Hence the sampling frequency is 7.68 MHz according to 3GPP standards. For this study, it is sufficient to measure only one cell and in this implementation the cell ID was chosen to be 1. Furthermore, all of the other tests described later in this thesis will have the same settings unless stated otherwise.

Before implementing the downlink decoder, different instruments were investigated to record a sample of the signal sent from a RBS. All recordings were successfully conducted using a signal analysis PXI module. NI's soft front panel based on NI-RFSA drivers was used for their VST (PXIe 5644) and VSA (PXIe 5665), and 89600 VSA software was used for the Agilent Technologies' VSA (M9381A). The raw data collected from the different software were more or less the same.

An LTE signal of 22 milliseconds length was recorded as a verification signal for the implementation. This recording covers slightly more than two radio frames, which is sufficient to catch the synchronization signal. Theoretically, one radio frame has a length of 10 milliseconds and consists of 10 sub frames with 2 slots in each. In this case the signal has 168960 points of I and Q data, where "I" is the in-phase component of the waveform and "Q" is the quadrature component of the waveform. The signal is converted to complex form by identifying the real part and the imaginary part.

The decoder in OFDM starts by initializing the relevant parameters, such as bandwidth, cell ID, test model, sampling frequency, and a file path to the signal (only used for testing when developing the implementation). Figure 4-1 shows the block diagram of the downlink decoder VI during development in LabVIEW.
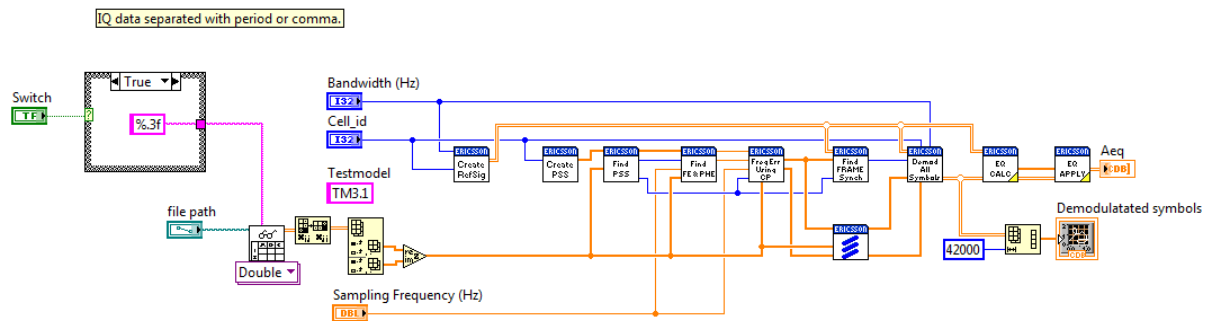
Figure 4-1: Block diagram of downlink decoder VI (signal from file)

This implementation process is the inverse of the process described in section 2.1.4, it starts by creating the reference signal and synchronization signals. First, a rough synchronization is found by cross correlation and then a finer synchronization is found using the primary synchronization signals. In addition, frame synchronization is acquired from the secondary synchronization signal. Figure 4-2 shows the demodulated signal with frequency error and phase error.
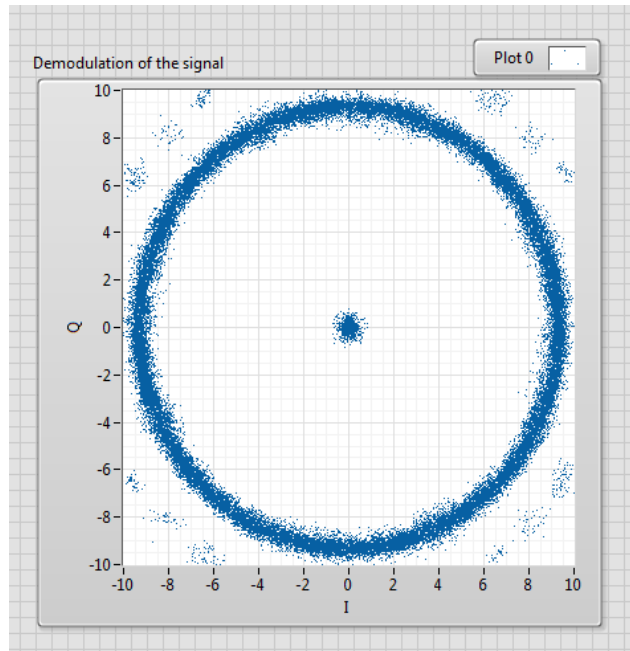
Figure 4-2: Signal with frequency error and phase error including the reference signal and synchronization signals.

Subsequently, frequency error and phase error are found and adjusted for by multiplying the signal $s(t)$ with $e^{-i(2\pi f_{erro\ r}t+\phi_{error})}$. Resulting in:

$$s(t)e^{-i(2\pi f_{erro\ r}t+\phi_{error})} = A(\cos(2\pi f_{sc}t + \phi(t)) + i\sin(2\pi f_{sc}t + \phi(t)))e^{-i(2\pi f_{erro\ r}t+\phi_{error})}$$

$$= Ae^{-i(2\pi(f_{sc}+f_{error})t+(\phi+\phi_{error}))}$$

where f_{sc} is the subcarrier frequency (the above is only for one subcarrier).

The remaining frequency error and phase error can be found, as shown in Figure 4-3. Any residual frequency error and phase error have to be found and adjusted for again. Figure 4-4 shows the frequency error and phase error have been removed from the signal.
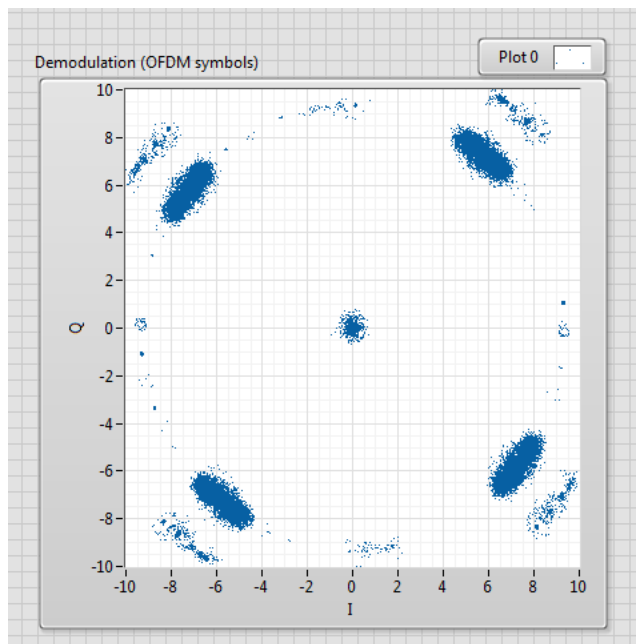
Figure 4-3: Frequency and phase adjusted signal including the reference signal and synchronization signals.
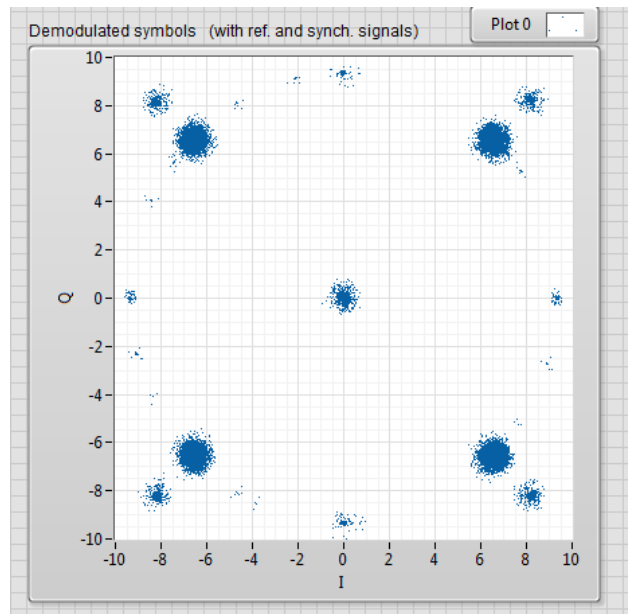
Figure 4-4: Demodulated signal including the reference signal and synchronization signals.

In order to differentiate the sent signal from the reference signal and synchronization signals, one frame of each physical channel is mapped to the resource element structure. The signal symbols are mapped to PDSCH, hence plotting this will result the demodulated signal. Figure 4-5 shows the completely demodulated (QPSK) test signal.
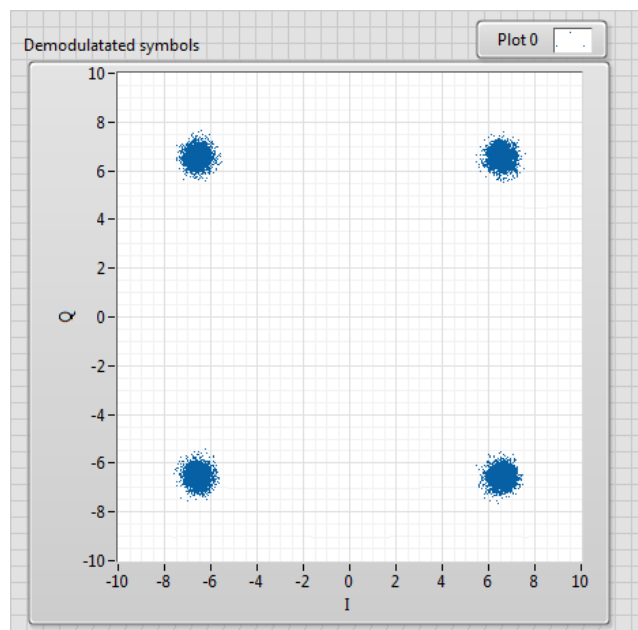
Figure 4-5: Demodulated QPSK signal (reference signal and synchronization signals removed)

Descrambling is done in the same way as scrambling, as was described in section 2.1.4. Hence applying the same scrambling code with the same pseudo-random sequence will lead to the same block of code words as before it was scrambled. Table 4-1 shows an example of scrambling, where c denotes the scrambling code, b denotes bits to be scrambled, and $\hat{b}$ and $\tilde{b}$ denote the scrambled bits.

Table 4-1: Example of scrambling

$\hat{b}(i)$ = $(b(i) + c(i))_{mod2}$	
$\tilde{b}(i)$ = $(\hat{b}(i) + c(i))_{mod2}$	

$c(i) = 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 1\ 0\ 0\ 0\ 1$
$b(i) = 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 0$
$\hat{b}(i) = 0\ 1\ 0\ 0\ 0\ 1\ 0\ 1\ 0\ 1\ 1\ 1\ 1$
$\tilde{b}(i) = 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 0$

The rest of the decoding was not implemented in LabVIEW, however it could be implemented in the reverse order of what was described in the encoding process.

It is possible to use a test model as an input parameter to measure EVM and power in different physical channels. Apparently, the signal sent from the RBS was only meant for test model 1.1 (described in Appendix A), which does not include these measurements. Power measurement and EVM measurement were not implemented for test model 1.1 according to 3GPP specifications; however these measurements can be implemented according to section 2.1.5. Moreover, signal quality measurement according to 3GPP specifications worked perfectly on a signal meant for test model 3.3.

4.2 Solutions in modulation analysis

This section describes alternate solutions for modulation analysis. The purpose is to identify other test solutions (from different vendors) and see if they are able to perform modulation analysis, conformance measurements, and multi-RAT measurements. Moreover, this project investigated if it was possible to create our own or recreate an analysis and generation application in LabVIEW using the available programming drivers from the respective vendor. Section 4.2.1 discusses test solution from Gefle Testteknik, section 4.2.2 discusses test solutions from Agilent Technologies, and finally section 4.2.3 discusses test solutions from NI.

4.2.1 Gefle Testteknik

Gefle Testteknik is a supplier of test system solutions and is an alliance partner of NI. The company has recently developed a set of software for modulation analysis and signal generation for GSM, WCDMA, and LTE. The software is called RBS toolkit and was investigated as a solution for modulation analysis of LTE and WCDMA during this thesis project.

Their LTE Downlink Acquisition and Generation software implements both analysis and generation in the same window. It has many possibilities, for instance generating a test signal and analyzing it through a loopback cable (RF out to RF in), or by generating an uplink signal to the RBS. This software is based on several toolkits from NI, which extends the programming options in LabVIEW, the hardware and software requirements can be found in Appendix B. The LTE Downlink Acquisition and Generation software has functions to perform measurements of LTE signals according to the 3GPP specifications. Additionally, the acquisition part performs continuous measurements while the application runs.

WCDMA acquisition and signal generation are in separate programs. The generation part is rather simple, yet it has many useful functions. For example, it is able to configure center frequency, average power, external attenuation, trigger setting, reference setting, and type of signal. The analysis part performs a single run and measures adjacent channel power, modulation measurements, code domain power, spectrum emission mask, channel power, and occupied bandwidth.

Multi-RAT measurements are not included in their RBS toolkit, however it is possible to add a feature to analyze multiple radio standards. This is not a software issue; but rather a hardware issue where the possibility depends on the frequencies and bandwidths on the analyzer. Gefle Testteknik has shown a demonstration that is able to measure in GSM, WCDMA, and LTE simultaneously.

4.2.2 Agilent Technologies

A number of software solutions from Agilent Technologies are presented in this section.

The X-Series Measurement Application for Modular Instruments enables the VSA to deliver faster RF conformance measurements. All of the applications are based on the 3GPP specifications. This application includes a unique resource manager that directly shares the PXI VSA driver, which also enables simultaneously rapid spectrum measurements and rapid modulation measurement. It also supports multiple cellular and wireless standards (for example WLAN, GSM, WCDMA, and LTE). Switching between different standards is done rather fast thanks to their resource manager. [41]

LTE FDD and TDD is one of the measurement applications for their modular instruments. These modes enable RF transmitter measurements on RBS and UE in time, frequency, and modulation domains. Furthermore, the tester can simply perform RF conformance tests for all LTE bandwidths by recalling E-TM presets according to 3GPP TS 36.141 (see also Appendix A). There are functions to test beyond the physical layer and to verify the channel coding by accessing de-mapped, de-interleaved, de-scrambled, de-ratematched, and decoded data. [26]

Agilent Command Expert is a free program that the user can use to send commands to an instrument. The software also includes command documentation and syntax checking. It works with instruments that support Standard Commands for Programmable Instrumentation (SCPI[2]) or IVI-COM drivers. [42]

SCPI is a common interface language between computers and test instruments. The command syntax is text based and it supports any computer test language and the test application environments, such as LabVIEW and MATLAB. [43]

The 89600 VSA software has functions to measure signal quality; including vector analysis and modulation analysis. This application can be controlled using menus and dialog boxes in the software window or via the VSA programming APIs, such as .NET and SCPI.

This software is also able to measure multiple radio standards simultaneously, for example GSM, WCDMA, and LTE (as shown in Figure 4-6). This requires a VSA with a wide frequency range it cover all of the carriers at once. Agilent Technologies' VSA can analyze multiple signals, as long as they are within a bandwidth of 160 MHz. Although, it is possible to measure signals in different frequencies, it requires multiple VSAs connected to the software.

Figure 4-6: Spectrum of multiple radio standards in a 15.5 MHz range centered at 1.8575 GHz using the 89600 VSA software.

---

[2] The Standard Commands for Programmable Instrumentation (SCPI) Consortium has been incorporated into the IVI Foundation (see http://www.ivifoundation.org/scpi/).

In addition to using the software mentioned above, it is also possible to control the VSA or VSG instruments through the corresponding API for LabVIEW.

4.2.3 NI Modulation Toolkit

The NI Modulation Toolkit handles modulated signal processing for LabVIEW. This toolkit extends the programming possibilities with functions for signal generation, analysis visualization, and the processing of different modulation formats. This includes digital and analog modulation and demodulation, modulation analysis, and channel coding. According to NI this toolkit increases the speed of application development for research, design, characterization, validation, and test communications systems. [44]

NI has developed soft front panels to easily analyze and generate signals with their VSA and VSG hardware. NI-RFSA soft front panel monitors and analyzes RF signals using the VSA. NI-RFSG soft front panel can be used to generate modulated RF signals or continuous waveform (CW) using the VSG. In addition, it is possible to start multiple instances if using multiple instruments in a chassis. This enables generation and acquisition of many RF signals at once. Both NI-RFSA and NI-RFSG are built on instrument drivers for the VSA and VSG, and also are compatible with the VST.

5 Test and Analysis

Section 5.1 presents the tests performed during the project. Each test is followed by an analysis of the test methods and the results. In section 5.2, problems and challenges concerning the other parts of the project are discussed.

5.1 Test Cases

The implementation described in section 4.1 was integrated into modified LabVIEW example code for the VST. This code is located in the embedded controller in the PXI chassis and it performs real-time decoding of the downlink signal from the RBS. The VI consists of four loops in parallel, where each of them decodes the signal either directly from the RBS or from recorded samples placed in a queue. Figure 5-1 shows the block diagram of the downlink decoder VI in the embedded controller and Figure 5-2 shows the corresponding front panel.
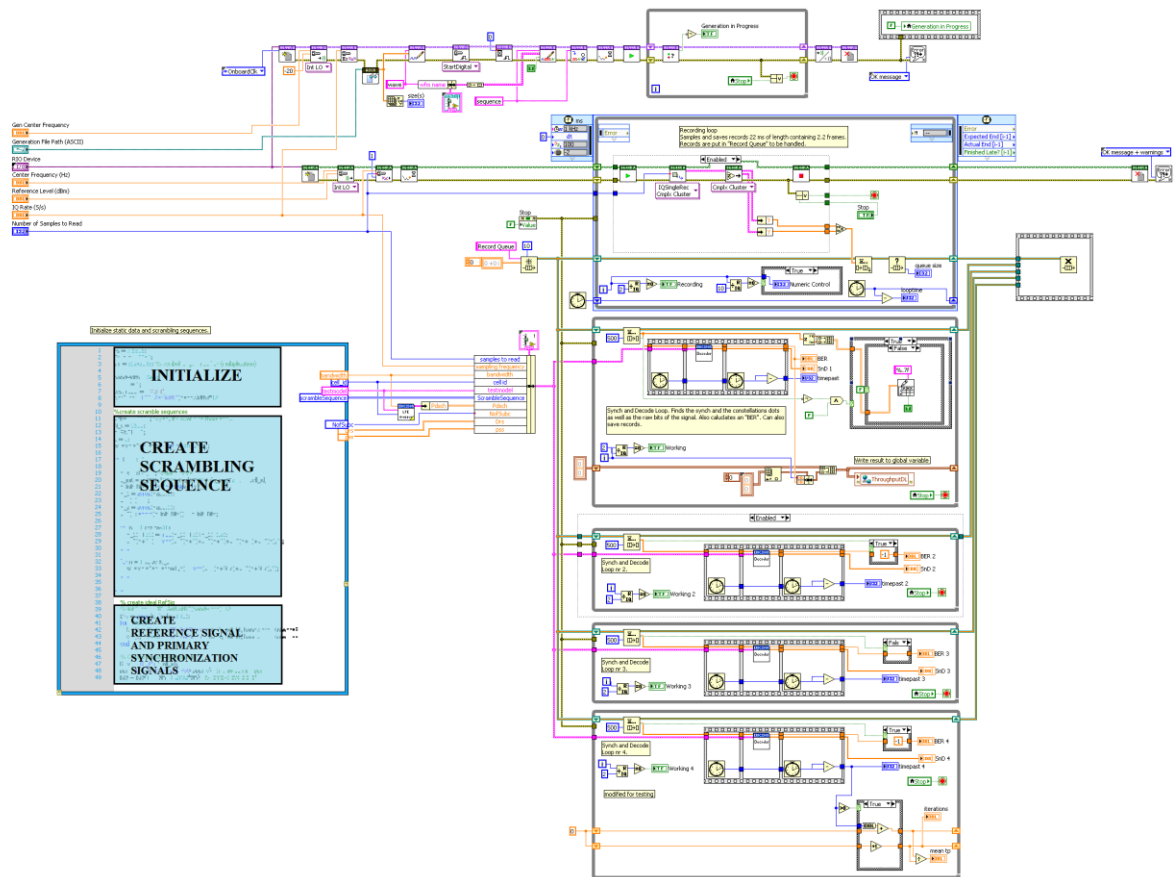

Figure 5-1: Block diagram of downlink decoder VI (performs real-time measurement of signal from the RBS)
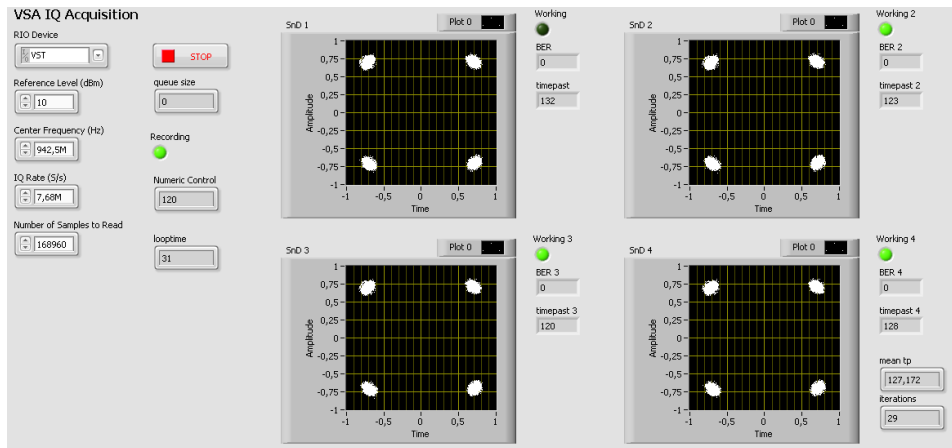
Figure 5-2: Front panel of the downlink decoder VI (performs real-time measurement of signal from the RBS)

The execution time of LabVIEW code and MATLAB code were compared in a test. Practical tests have shown that combining these two types of codes yields shorter execution time of measurements on a single radio frame. Using only text based command line in MathScript nodes took around 700 milliseconds to measure a single radio frame of 10 millisecond duration. Figure 5-1 shows the execution time for these two types of codes combined and optimized. This test only measured the difference in time efficiency between these two programming languages.

Table 5-1: Execution time of one frame using different configurations in the code

Code	Execution time (ms)
Mostly LabVIEW	225.5
Mostly MATLAB	87.1

Why use LabVIEW when MATLAB code (in MathScript) executed faster?

It is convenient to have a good overview of the application in LabVIEW code, while still being able to read and write code in MATLAB. However, LabVIEW is not able to handle large arrays and matrices (i.e. 140×300) as fast as MATLAB. Nevertheless, MATLAB also has its weaknesses, hence leading to situations where LabVIEW would be the preferred language. The interaction between these two programming languages gives some opportunities to enhance the performance with respect to the execution time.

The reference sensitivity test was performed to verify if the PXI modules are able to perform the same test as the box instruments. The measurement was done in band 8 and according to [40] the maximum total power level shall not exceed -101.5 dBm. However, a lower level can be set by the tester and the specific power level used can vary depending on the tester's requirements. The test procedure starts by generating a signal on the uplink and adjusting the reference power level to observe the throughput characteristic (for range between 90% and 99%). The goal is to find the power level that gives a steady throughput of 95%. This is to ensure 100% throughput after adding an extra margin of power.

The signal generation code was implemented in LabVIEW for the two PXI modules respectively. Each implementation has used the available instrument API for LabVIEW.

The signal generation code for M9381A was based upon a modification of some example code for this VSG. The example code itself is based upon the M938x instrument drivers, which is the same as Agilent Technologies' own developed soft front panel for the VSG. This signal generation code begins by creating a SCPI resource string to set up a communication link between PXI modules and the

controller. The string is determined by *PXI[bus]::device::function::INSTR* and Table 5-2 shows the VISA[3] addresses for respective PXI module in a default configured PXI chassis. [45]

<div align="center">

Table 5-2: Resource address for the VSG (M9381A)

</div>

Module Name	M9311A PXIe Modulator	M9310A PXIe Source Output	M9301A PXIe Synthesizer	M9300A PXIe Reference
Slot number	2	4	5	6
VISA address	PXI8::0::0::INSTR;	PXI11::0::0::INSTR;	PXI12::0::0::INSTR;	PXI13::0::0::INSTR;

The string (*PXI8::0::0::INSTR;PXI11::0::0::INSTR;PXI12::0::0::INSTR;PXI13::0::0::INSTR*) refers to the VSG (M9381A). (Note that the values are different depending how the PXI chassis is configured).

The signal generation code for the PXIe 5644 was also based upon a modification of some example code for this VST. This implementation initializes by setting up an appropriate I/O device, such as the VST.

The ability to choose an external reference and external frame trigger are included in both of these codes. An external 10 MHz reference is acquired from a GPS receiver and an external frame trigger signal is obtained from the DU (as was shown in Figure 2-12). In addition, a power level controller was added to be able to change the power level in the middle of a run, without resetting the application. This power level controller is placed in an event structure in LabVIEW; hence the program waits for a power level change and then executing the change.

The signal is generated from a file pointed out in the code. The file includes a waveform of a LTE signal with a 5 MHz channel bandwidth meant for signal generation of the uplink. Figure 5-3 and Figure 5-4 show front panel and block diagram of the signal generation VI for the VSG (M9381A). Figure 5-5 and Figure 5-6 show front panel and block diagram of the signal generation VI for the VST.

<div align="center">
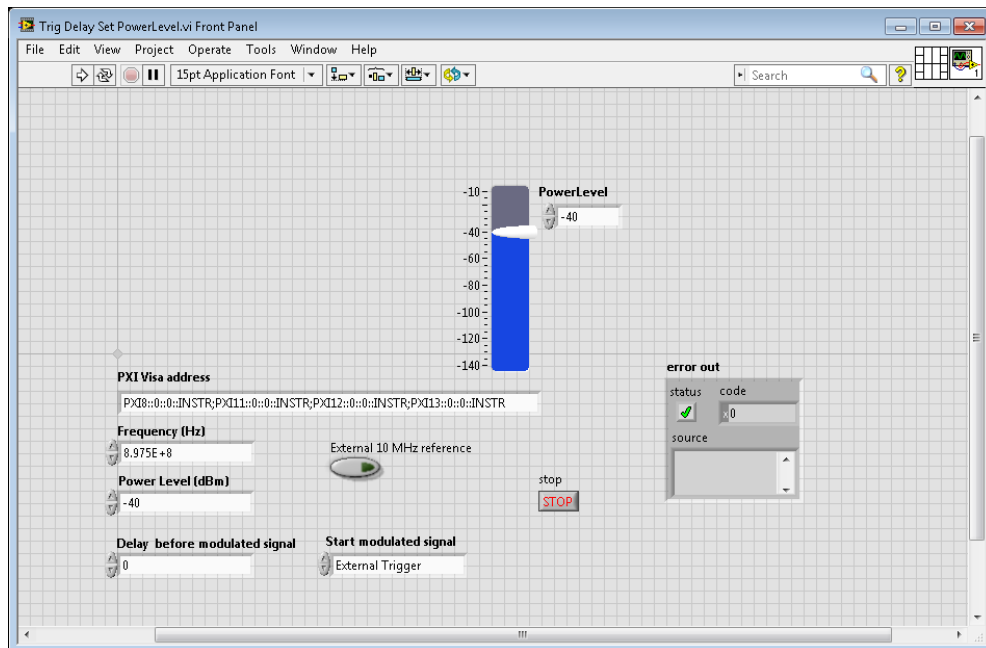
Figure 5-3: Front panel of the signal generation VI for the VSG (M9381A)

</div>

---

[3] VISA stands for Virtual Instrument System Architecture.
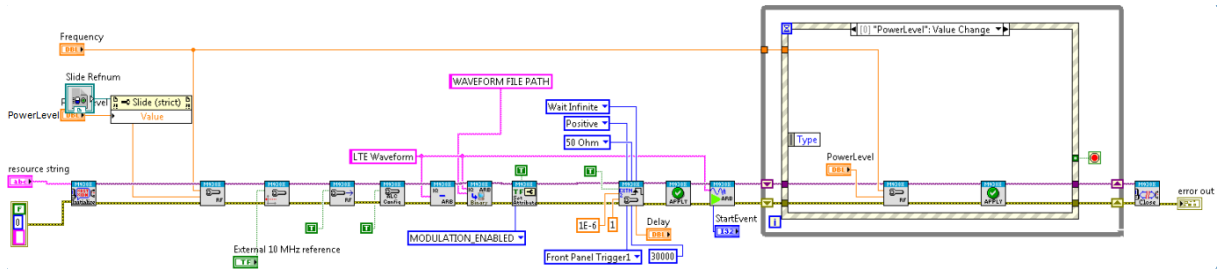
Figure 5-4: Block diagram of the generation VI for the VSG (M9381A)
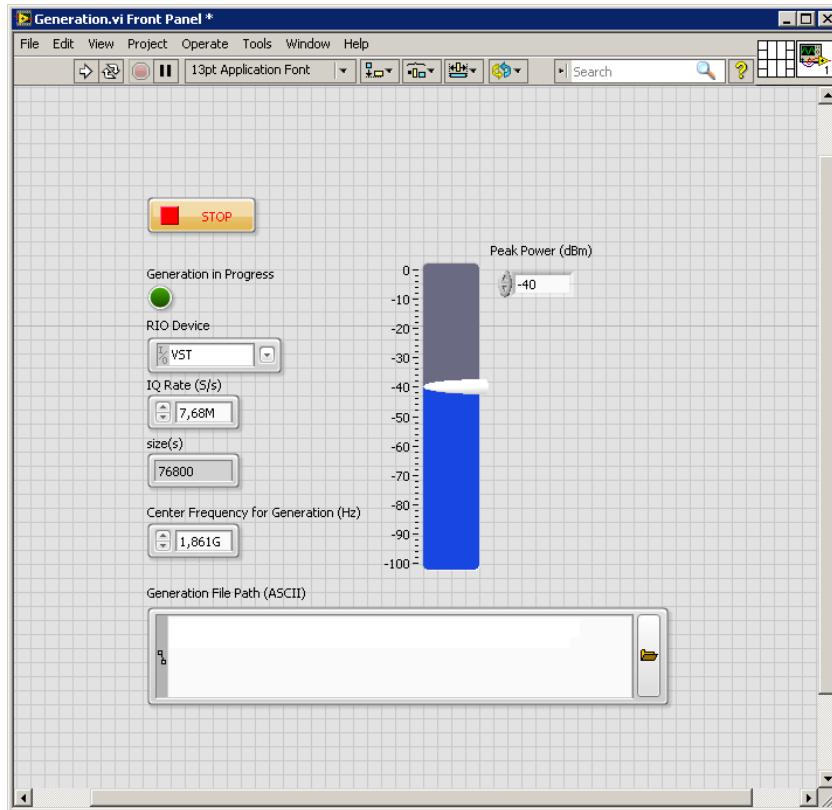
Figure 5-5: Front panel of the generation VI for the VST
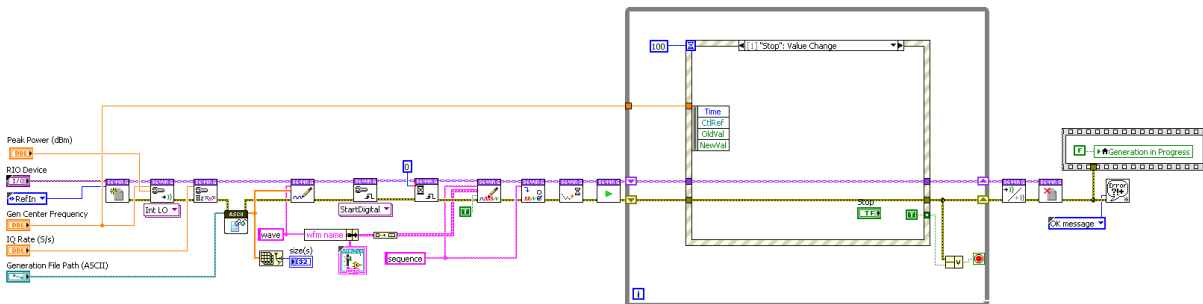
Figure 5-6: Block diagram of the generation VI for the VST

The tests were initialized by generating a signal with relatively high power level (-45dBm) and progressively reducing the power level while measuring the throughput at the RBS. The measurement at the RBS starts by collecting radio frames for a given period of time. This is followed by CRC calculation on the collected radio frames to determine the throughput. The first test used a VSG (M9381A) as the signal generator and Table 5-3 shows the results.

Table 5-3: Results of reference sensitivity test with a M9381A.

Power level (dBm)	Throughput (%)	Stable
-45	100.0	Yes
-49	100.0	Yes
-51	100.0	Yes
-53	~99.9	Yes
-55	~99.5	Yes
-57	~98.8	Yes
-58	~98.7	Yes
-59	~95.0	No

Figure 5-7 shows throughput percentage over time for a -59 dBm power level set at the signal generator. It was challenging to determine an exact throughput percentage, since the throughput characteristic is highly unstable around 95%. Figure 5-8 shows a graph of the throughput characteristic versus power level. Hence, adding the power lost in the attenuator and cables results in a reference power level of -102.5 dBm.
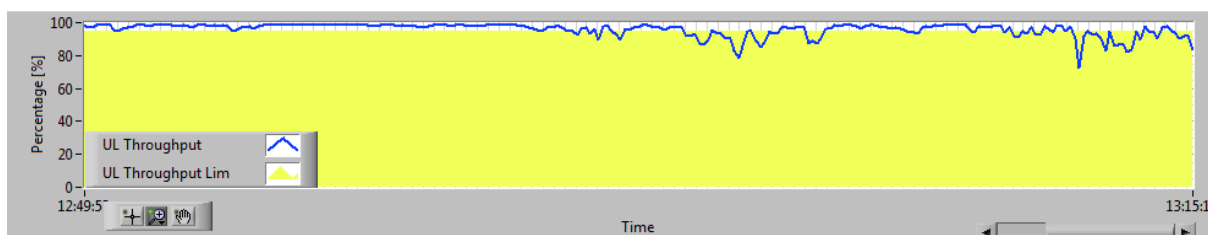
Figure 5-7: Throughput percentage over time for -59 dBm power level.
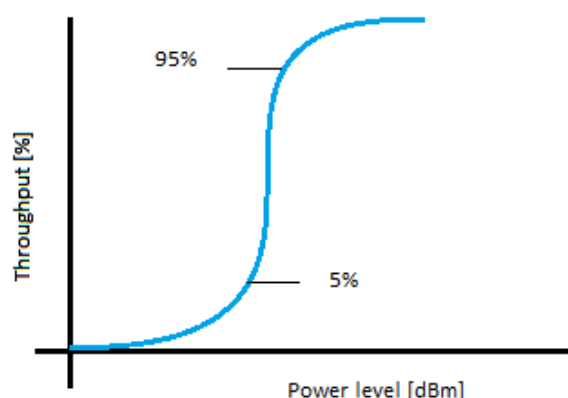
Figure 5-8: Throughput versus power level characteristic

A second test was made and the results are presented in Table 5-4. The signal was generated by the VST (PXIe 5644) and a total reference power level of -104.6 dBm was obtained.

Table 5-4: Results of reference sensitivity test with a VST (PXIe 5644).

| Power level (dBm)	Throughput (%)	Stable
-45	100.0	Yes
-47	100.0	Yes
-48	96.6	Yes
-50	~99.0	Yes
-53	~97.7	Yes
-54	~96.0	Yes
-55	~95.0	No

There may be some uncertainty in the results, because the throughput was always slightly better in the beginning of the measurements, but become worse over time at the same power level. It is possible that the problem lies in the external reference synchronization signal. Although, this hypothesis was not verified with further tests, however future work should investigate the use of an external reference signal.

The in-band blocking test was performed. This test included two signal generators, one as carrier and the other as interferer. The purpose was to compare the PXI instrument (i.e. signal generation part of the NI's VST) with a box instrument (i.e. VSG from Agilent Technologies, called the N5182A MXG, this VSG is described in more detailed in [29]). These signal generators acted as an interferer and the BER measurement was performed on another MXG that transmitted a WCDMA carrier signal at 893.5 MHz in band 0 for both cases. Figure 5-9 shows the frequency spectrum of the test setting.
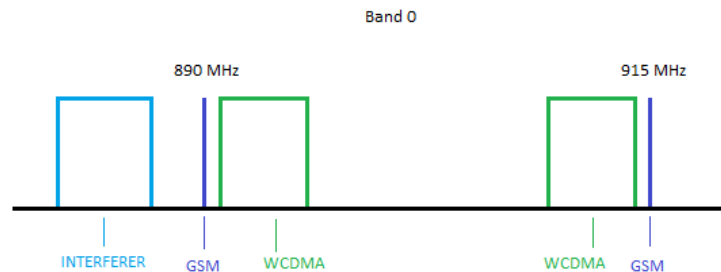
Figure 5-9: Spectrum of band 0 (890 MHz – 915 MHz) with WCDMA carrier and an interferer near band edge

The total power level is limited to -43 dBm in accordance with the 3GPP specification [40] on a wide area base station. With an antenna loss of 4.5 dBm the remaining total power was -38.5 dBm power from the signal generator.

The VST and its associated cables were calibrated with a power meter before measurement. Consequently the results show a total loss of 7.8dBm because a modulated signal tends to have a much lower output power. During the test, the output power from the generators was decreased or increased stepwise until the BER fell below 0.001, i.e., 0.1%. The VST uses the same generation code that was implemented for base station receiver sensitivity test as shown in Figure 5-5 and Figure 5-6.

In the first test, the interferer transmitted a 5 MHz LTE signal at 871 MHz. The BER was measured at the carrier. The test results in Table 5-5 indicate that the VST performs around 4 dBm better than the MXG.

Power [dBm]	BER (with VST)	BER (with MXG)
-15.55	0	0.001
-13.55	0	>0.001
-11.55	0.007	

In the second test, the interferer was transmitted at 887.5 MHz (worst case), which is the closest distance a 5 MHz channel allocation interferer can transmit in without increasing the power of the WCDMA signal. The results in Table 5-6 differ quite much from the first test. That is because the noise caused by the interferers in the first test was fairly low. The BER measurement did not pick up any interference until the power was very high. In order to measure the adjacent channel power from the interferer, the interferer has to transmit closer to the band edge.

Table 5-6: Results of the second blocking test.

Power [dBm]	BER (with VST)	BER (with MXG)
-17.55	No Throughput	No Throughput
-20.55	No Throughput	No Throughput
-22.55	No Throughput	0.3652
-23.55	No Throughput	0.0069
-29.55	0.1349	0
-31.55	0.0229	0
-33.55	0.0223	0
-35.55	0.0029	0
-37.55	0.000004	0

Although, it is possible to increase the performance with an external local oscillator attached. For example using a Phase Matrix USB signal generator with QuickSyn technology as an external local oscillator to the signal generation part in the VST could lower the phase noise. This should be part of future work.

5.2 Discussion

Many challenges have occurred during this project. These challenges will be discussed in this section.

The downlink decoder implementation has combined two programming languages in order to increase the performance and shorten the execution time. Combining these languages also gives the user a better overview and complete track understanding of what is being done. As a novice in LabVIEW (but with lots of experience with MATLAB), it was more comfortable to have assisting code in MATLAB. The code can also be optimized to take advantage of LabVIEW and MATLAB for their respective strengths. However, users have to buy licenses for the MathScript RT Module; but these costs are relatively low compared to the cost of the VST.

The uplink tests required generation of signal data from file, external frame trigger to activate the carrier signal, and external reference to synchronize. Agilent Technologies' VSG soft front panel could read .ascii or .txt formats (which are the desired formats of the file), however it could not apply any external triggers. The Command Expert had triggers functions in its library and could use an external trigger including the trigger delay, instead it could not read the desired file formats. Only binary

format (.bin) and waveform format (.wfm) were accepted by this software. Finally different LabVIEW example codes have the external trigger functions, still the desired file formats could not be loaded. To solve this, the signal input file was converted to .bin format beforehand to suit this implementation, however it would also be possible to use one's own implementation (for example convert the file after loading). Using LabVIEW not only solved the external trigger and text file issues, it also extended the possibility to add endless number of features. The different software configurations that include an external trigger and the desired file format are shown in Table 5-7.

Table 5-7: Different software configurations that include external trigger and desired file format.

Software	External trigger	Text file
VSG soft front panel		×
Command Expert	×	
Modified LabVIEW example	×	×

6 Conclusions and future work

This chapter summarizes the conclusion of this master's thesis project and also suggestions some future work. Section 6.1 provides the conclusion of this thesis. This is followed by section 6.2, which discusses future steps that could be done in a follow up study to this thesis project. Suggestions for new areas to study will be presented. Finally, section 6.3 discusses reflections on the economic, social, environmental, and ethical aspects of this thesis project.

6.1 Conclusions

To conclude this thesis, part of the implementation was successfully done, many alternate solutions were investigated, and a few tests were conducted. These tests all showed that PXI modules are able to replace the box instruments, (at least in some areas of use).

The PXI modules managed to perform every test conducted in this thesis project. Unfortunately, this may still not fulfill every department's internal requirements, and because of this the PXI test instruments cannot replace the old test systems in all departments. Hence, this testing will need to be supplemented by using extra instruments to achieve better qualified test results. The VST was shown to be able to be used to decode a downlink signal and perform reference sensitivity tests in the EMC department. Using PXI modules with LabVIEW implementation instead of box instruments is suggested by the study's results; however, the final decision rests with the appropriate personnel within Ericsson.

Using both graphical programming and a text based command line environment in LabVIEW (with MathScript) enhanced the performance of the decoder. Both programming languages have their own strengths and weaknesses. Using only one of the languages, the application tends to run slower than expected, but combining these two showed an improved result.

Moreover, the available toolkits could have been used to implement the decoding part; this would have decreased the time needed for development. Taking advantage of the available toolkits and instrument drivers for LabVIEW would have greatly decreased the development time when implementing the decoder. However, implementing the downlink decoder from scratch based on the 3GPP TSs, increased my knowledge of how the decoder and modulation actually works, step by step.

The purpose of performing the test cases was to find out if PXI modules were able to make measurements required by these tests. Due to the limitations of time and resources, only two tests were performed. If more tests were conducted, additional areas of use could be covered and a stronger conclusion could be drawn. With sufficient additional test it might be possible to generalize the results.

6.2 Future work

This section presents the work that could be in a follow up study to this thesis project.

Some parts of the downlink decoder were meant to be implemented on the FPGA level, which would increase the performance due to the powerful FPGA. These parts include de-segmentation, channel decoding, and de-rate matching. Unfortunately, these have not been implemented due to limited time. Therefore, future work should examine the implementation of the rest of the downlink decoder in the FPGA and use the available instrument drivers and toolkits for LabVIEW, for example using the *NI Modulation Toolkit* and the *NI Spectral Measurements Toolkit*.

The results of the in-band blocking test for the VST, in section 5.1, showed that the power level was very near the minimum requirement set by the 3GPP. The PXI test instrument might need additional instruments to improve the results and widen the margin to the minimum requirements. The phase noise can be improved by attaching an external local oscillator, for example a Phase Matrix USB 10 MHz or 20 MHz signal generator. Future work should investigate methods to cancel phase noise in these tests and conduct similar tests with additional support instruments.

During the base station reference sensitivity test, the test results indicated unstableness of the signal the longer it has been up and running. The reason has not been found and the problem was

presumably in the external reference. Future work should investigate this and apply different synchronization clocks as external reference signals.

The implementation framework of the downlink decoder only works with a 5 MHz channel bandwidth; the other five LTE bandwidths have not been explored. No consideration was given to the fact that there was a need to analyze the tests when using different LTE bandwidths. Future work should investigate this implementation further and modify the code to function in all bandwidths. This could be done by adding six different cases, where each case is a function of, for example, sampling frequency rate, FFT size, and cyclic prefix length.

6.3 Required reflections

This section presents some reflections on this thesis work, where different aspects are considered.

This project has focused on the test equipment for communication technology in a development phase, which means it does not have any direct impact on the society. Indirectly, these instruments can be used to enhance the ability of mobile devices to communicate with each other; this could allow people to stream data at higher rates and use their communication devices for various purposes.

The final implementation will make an **economical** contribution as it offers high performance tests in shorter test time and requires fewer test instruments. Using only one PXI module to analyze in multi-RAT has larger scale benefits not only to Ericsson AB but it also lowers the general cost of testing and hence of manufacturing, yielding either higher profit margins or lower costs for Ericsson's customers.

The fact that less equipment has to be used to conduct measurements in multi-RAT and at a faster rate means that this research has positive **environmental** impact because it also uses less electricity. Having this in mind and taking advantages of the reprogrammable FPGA chip within the VST in the final implementation also requires fewer test instruments to be manufactured. Hence it opens the doors to other future research that takes advantage of the optimizations in this thesis project.

One of the **ethical** aspects considered in this thesis project is to not reveal any confidential information from Ericsson AB, therefore the general values and requirements have been taken from the 3GPP specifications instead of using internal requirements. Other ethical consequences to society lay far beyond the scope of this report.

References

[1] 3GPP, 'UTRA-UTRAN Long Term Evolution (LTE) and 3GPP System Architecture
     Evolution (SAE)'. 2006 [Online]. Available:
     ftp://ftp.3gpp.org/Inbox/2008_web_files/LTA_Paper.pdf

[2] Ericsson, 'Ericsson Mobility Report', 2013 [Online]. Available:
     http://www.ericsson.com/res/docs/2013/ericsson-mobility-report-june-2013.pdf

[3] M. Höst, B. Regnell, and P. Runeson, *Att genomföra examensarbete*. Lund:
     Studentlitteratur, 2006.

[4] National Instruments, 'What Is a Vector Signal Transceiver (VST)?' [Online].
     Available: http://www.ni.com/white-paper/14027/en. [Accessed: 26-Aug-2013]

[5] S. J. Floris, K. A. Remley, and C. L. Holloway, 'Bit Error Rate Measurements in
     Reverberation Chambers Using Real-Time Vector Receivers', *IEEE Antennas and
     Wireless Propagation Letters*, vol. 9, pp. 619–622, 2010. DOI:
     10.1109/LAWP.2010.2053513

[6] Tobias Hallberg and Robin Varis, 'Radarstimuli med Vector Signal Transceiver, del A',
     Kandidate, Chalmers University of Technology, Göteborg, 2013 [Online]. Available:
     http://studentarbeten.chalmers.se/publication/179318-radarstimuli-med-vector-signal-
     transceiver-del-a. [Accessed: 06-Sep-2013]

[7] Richard Ferngren and Mikael Johansson, 'Radarstimuli med Vector Signal Transceiver,
     del B', Kandidate, Chalmers University of Technology, Göteborg, 2013 [Online].
     Available: http://studentarbeten.chalmers.se/publication/179316-radarstimuli-med-
     vector-signal-transceiver-del-b. [Accessed: 06-Sep-2013]

[8] National Instruments, 'NI LabVIEW - Improving the Productivity of Engineers and
     Scientists'. [Online]. Available: http://sine.ni.com/np/app/main/p/docid/nav-
     104/lang/sv/. [Accessed: 26-Aug-2013]

[9] Jing Li, Yihan Yang, Wenbin Yu, and Guoqing Zhang, 'Digital electric energy meter
     individually measuring electric energy of fundamental wave and harmonic wave based
     on LabVIEW DSP module', presented at the China International Conference on
     Electricity Distribution - CICED, 2008, pp. 1–5 [Online]. DOI:
     10.1109/CICED.2008.5211765

[10] National Instruments, 'FPGA Fundamentals', 03-May-2012. [Online]. Available:
     http://www.ni.com/white-paper/6983/en. [Accessed: 26-Aug-2013]

[11] BDTI, 'The Evolving Role of FPGA in DSP Applications', 28-Mar-2007. [Online].
     Available: http://www.bdti.com/MyBDTI/pubs/fpga_article.pdf. [Accessed: 26-Aug-
     2013]

[12] Xilinx, 'What is a FPGA?' [Online]. Available: http://www.xilinx.com/fpga/index.htm.
     [Accessed: 26-Aug-2013]

[13] E. Dahlman, S. Parkvall, and J. Skold, *4G LTE/LTE-Advanced for mobile broadband*.
     Oxford; Burlington, MA: Academic Press, 2011 [Online]. Available:
     http://www.engineeringvillage.com/controller/servlet/OpenURL?genre=book&isbn=978
     0123854896. [Accessed: 27-Sep-2013]

[14] European Telecommunications Standards Institute, 'LTE; Evolved Universal Terrestrial
     Radio Access (E-UTRA); Multiplexing and channel coding (3GPP TS 36.212 version
     11.4.0 Release 11)'. 2014 [Online]. Available:
     http://www.etsi.org/deliver/etsi_ts/136200_136299/136212/11.04.00_60/ts_136212v110
     400p.pdf

[15] European Telecommunications Standards Institute, 'LTE; Evolved Universal Terrestrial
     Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version
     11.4.0 Release 11)', Sophia Antipolis Cedex, France, 2013 [Online]. Available:

http://www.etsi.org/deliver/etsi_ts/136200_136299/136211/11.04.00_60/ts_136211v110
400p.pdf

[16] *LTE and the evolution to 4G wireless: design and measurement challenges*, Second edition. Chichester, West Sussex, United Kingdom: John Wiley & Sons, 2013.

[17] Anritsu Company, 'LTE Resource Guide'. 2009 [Online]. Available: http://web.cecs.pdx.edu/~fli/class/LTE_Reource_Guide.pdf. [Accessed: 18-Mar-2014]

[18] Michael D. McKinley, Kate A. Remley, Maciej Myslinski, J. Stevenson Kenney, Dominique Schreurs, and Bart Nauwekaers, 'EVM Calculation for Broadband Modulated Signals', *64th ARFTG Conference, Orlando*, pp. 45–52, Dec. 2004.

[19] National Instruments, 'Modulation Error Ratio (MER) and Error Vector Magnitude (EVM)'. [Online]. Available: http://www.ni.com/white-paper/3652/en/. [Accessed: 03-Sep-2013]

[20] Ericsson, 'Product description for RBS 6201'. 24-Mar-2010 [Online]. Available: https://lafibre.info/images/4g/201004_ericsson_rbs6201_lte1800.pdf

[21] National Instruments, 'NI PXIe-5644R/5645R - Data Sheet'. [Online]. Available: http://sine.ni.com/ds/app/doc/p/id/ds-422/lang/sv. [Accessed: 26-Aug-2013]

[22] National Instruments, 'NI PXIe-5665 - Data Sheet', 2011. [Online]. Available: http://sine.ni.com/ds/app/doc/p/id/ds-321/lang/sv

[23] National Instruments, 'NI Cellular Test System'. [Online]. Available: http://sine.ni.com/nips/cds/view/p/lang/sv/nid/211028. [Accessed: 08-Oct-2013]

[24] Ericsson, 'Ericsson and STMicroelectronics complete transaction to split up ST-Ericsson', 05-Aug-2013. [Online]. Available: http://www.ericsson.com/thecompany/press/releases/2013/08/1721084

[25] Sylvain Bertrand - ST-Ericsson, 'ST-Ericsson Reduces Semiconductor Test Time 10X Using LabVIEW and NI PXI RF Instruments - Solutions - National Instruments'. [Online]. Available: http://sine.ni.com/cs/app/doc/p/id/cs-14361. [Accessed: 09-Oct-2013]

[26] Agilent Technologies, 'M9080A & M9082A LTE FDD/TDD - Technical Overview'. 2013 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5991-3010EN.pdf. [Accessed: 08-Oct-2013]

[27] Agilent Technologies, 'Agilent M9391A PXIe Vector Signal Analyzer - Data Sheet'. 2014 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5991-2603EN.pdf

[28] Agilent Technologies, 'Agilent M9381A PXIe Vector Signal Generator - Data Sheet'. 2014 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5991-0279EN.pdf

[29] Agilent Technologies, 'N5182A MXG Vector Signal Generator, up to 6 GHz'. [Online]. Available: http://www.home.agilent.com/en/pd-797248-pn-N5182A/mxg-rf-vector-signal-generator. [Accessed: 18-Mar-2014]

[30] Bernt Johansson and Tomas Sundin, 'LTE test bed'. Ericsson, 2007 [Online]. Available: http://www.ericsson.com/ericsson/corpinfo/publications/review/2007_01/files/2_lte_web.pdf

[31] Elham Khorami, 'Providing accurate time information to a radio base station via a GPS receiver emulator', Master's thesis, KTH Royal Institute of Technology, School of Information and Communication Technology, Communication Systems, Stockholm, Sweden, 2013 [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-118070. [Accessed: 14-Feb-2014]

[32] Agilent Technologies, 'Virtual Flight Testing of Radar System Performance Using SystemVue and STK'. 2012 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5991-1254EN.pdf

[33] F. C. J. Allaire, M. Tarbouchi, G. Labonté, and G. Fusina, 'FPGA Implementation of Genetic Algorithm for UAV Real-Time Path Planning', *Journal of Intelligent and*

Robotic Systems, vol. 54, no. 1–3, pp. 495–510, Jul. 2008. DOI: 10.1007/s10846-008-9276-8

[34] J. Xing, S. Liu, and W. Zhao, 'FPGA-accelerated real-time volume rendering for 3D medical image', presented at the 3rd International Conference on Biomedical Engineering and Informatics (BMEI), Yantai, 2010, pp. 273–276 [Online]. DOI: 10.1109/BMEI.2010.5639475

[35] Himanshu Shekhar, J.Sam Jeba Kumar, V.Ashok, and Dr. A.Vimala Juliet, 'Applied Medical Informatics Using LabVIEW', *International Journal on Computer Science and Engineering*, vol. 2, no. 2, pp. 198–203, 2010.

[36] Ericsson, 'Ericsson tests LTE in extreme conditions'. [Online]. Available: http://www.ericsson.com/news/121101-ericsson-tests-lte-in-extreme-conditions_244159017_c. [Accessed: 08-Oct-2013]

[37] Eric Blossom, 'Exploring GNU Radio'. [Online]. Available: http://gnu.cs.pu.edu.tw/software/gnuradio/doc/exploring-gnuradio.html#usrp-block-diagram-fig. [Accessed: 13-Nov-2013]

[38] National Instruments, 'NI USRP-29xx Datasheet', 2013. [Online]. Available: http://sine.ni.com/ds/app/doc/p/id/ds-355/lang/sv

[39] P. B. Jorgensen, T. L. Hansen, T. B. Sorensen, and G. Berardinelli, 'Implementation of LTE SC-FDMA on the USRP2 software defined radio platform', 2011, pp. 34–39 [Online]. DOI: 10.1109/Swe-CTW.2011.6082485

[40] European Telecommunications Standards Institute, 'LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (3GPP TS 36.104 version 11.6.0 Release 11)', Sophia Antipolis Cedex, France, 2013 [Online]. Available: http://www.etsi.org/deliver/etsi_ts/136100_136199/136104/11.06.00_60/ts_136104v110600p.pdf

[41] Agilent Technologies, 'Agilent M90XA X-Series Measurement Applications for Modular Instruments - Startup Guide'. 2013 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/M9000-90001.pdf

[42] Agilent Technologies, 'Agilent Command Expert - Data Sheet'. 2014 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5990-9362EN.pdf

[43] IVI Foundation, 'SCPI'. [Online]. Available: http://www.ivifoundation.org/scpi/. [Accessed: 06-Feb-2014]

[44] National Instruments, 'Tools for Digital and Analog Modulation/Demodulation Communications Analysis'. 2008 [Online]. Available: http://www.ni.com/pdf/products/us/032753305101.pdf

[45] Agilent Technologies, 'Agilent M9391A PXIe Vector Signal Analyzer and M9381A PXIe Vector Signal Generator: Programming Guide for Creating IVI-COM Console Applications'. 28-Oct-2013 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/M9300-90080.pdf

[46] European Telecommunications Standards Institute, 'LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) conformance testing (3GPP TS 36.141 version 11.6.1 Release 11)', Sophia Antipolis Cedex, France, 2013 [Online]. Available: http://www.etsi.org/deliver/etsi_ts/136100_136199/136141/11.06.01_60/ts_136141v110601p.pdf

[47] Gefle Testteknik, 'GTT LTE Toolkit', 2014. [Online]. Available: http://testteknik.se/content/gtt-lte-toolkit. [Accessed: 20-Mar-2014]

[48] Gefle Testteknik, 'GTT GSM/WCDMA Toolkit', 2014. [Online]. Available: http://testteknik.se/content/gtt-gsmwcdma-toolkit. [Accessed: 20-Mar-2014]

[49] Agilent Technologies, '89600 VSA Software - Configuration Guide'. 2013 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5990-6386EN.pdf

[50] Agilent Technologies, 'Accelerate PXI VSA Measurements with X-Series Measurement Applications for Modular Instruments - Product Brochure'. 2014 [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5991-2604EN.pdf

Appendix A.   Test Model

3GPP has defined several different E-UTRA test models (E-TM) for different physical channel tests. [46]

A.1 Test Model 1.1

This test model is intended for tests of

- Base station output power

- Unwanted emissions

    o   Occupied bandwidth

    o   Adjacent channel leakage power ratio

    o   Operating band unwanted emissions

    o   Transmitter spurious emissions

- Transmitter intermodulation

- RS absolute accuracy

A.2 Test Model 1.2

This test model is intended for tests of

Unwanted emissions

- Adjacent channel leakage power ratio

- Operating band unwanted emissions

A.3 Test Model 2

This test model is intended for tests of

Total power dynamic range (lower OFDM symbol power limit at min power)

- EVM of single 64 QAM PRB allocation (at min power)
- Frequency error (at min power)

A.4 Test Model 3.1

This test model is intended for tests of

- Output power dynamics
    o   Total power dynamic range (upper OFDM symbol power limit at max power with all 64 QAM PRB allocated)
- Transmitted signal quality
    o   Frequency error
    o   EVM for 64 QAM modulation (at max power)

A.5 Test Model 3.2

This test model is intended for tests of

Transmitted signal quality

- Frequency Error
- EVM for 16 QAM modulation

A.6 Test Model 3.3

This test model is intended for test on

Transmitted signal quality

- Frequency error
- EVM for QPSK modulation

Appendix B.   Options from Gefle Testteknik

This section presents the options from Gefle Testteknik as well as hardware and software requirements for the RBS Toolkit developed by them. This RBS Toolkit includes two separate softwares: **LTE RBS Toolkit** and **GSM/WCDMA RBS Toolkit**. However, the hardware and software requirements are the same for these toolkits. Appendix Table B-1 shows the requirements and license required for the softwares. [47, 48]

Appendix Table B-1: Hardware and software requirements for the RBS Toolkit (including license requirement)

Hardware requirements	
NI PXIe-1083 chassis (or similar)	
NI PXIe-8135 Controller (or similar)	
NI PXIe-5644R or NI PXIe-5645R VST	
Software requirements	**License req.**
Windows 7 (32- or 64 bit).	×
NI LabVIEW Full development system 2012 (32-bit) SP1 (or later).	×
NI Spectral Measurements Toolkit 2.6.3 (or later).	×
NI Modulation Toolkit 4.3.3 (or later).	×
NI-RFSA 2.7 (or later).	
NI-RFSG 1.9 (or later).	
NI PXIe-5644R/5645R Instrument Design Libraries 2012.1 (or later).	
NI LTE Toolkit 2.1.1 (or later).	×

Appendix C.   Options from Agilent Technologies

This section presents different options for 89600 VSA software and X-Series Measurement Applications for Modular Instruments. Only options for cellular communications are considered here, options for other wireless connectivity can be found in [49, 50].

Options for 89600 VSA software

The options for the software have two types of license; transportable and floating license. Transportable licenses are located in a PC or instrument and it can be transferred to another PC or instrument at any time. Floating licenses are located in a server and can be accessed by multiple users. Number of licenses determines the maximum number of users accessing the software at the same time. The available options for this software are shown in Appendix Table C-1.

Appendix Table C-1: Options for 89600 VSA software

Standard	Description
LTE FDD modulation analysis	Modulation analysis of LTE FDD signals (Release 8/9).
LTE TDD modulation analysis	Modulation analysis of LTE TDD signals (Release 8/9).
LTE-Advanced FDD modulation analysis	Modulation analysis of LTE-Advanced FDD signals (Release 10). Requires LTE FDD modulation analysis.
LTE-Advanced TDD modulation analysis	Modulation analysis of LTE-Advanced TDD signals (Release 10). Requires LTE TDD modulation analysis.
cdma2000®/1xEV-DV modulation analysis	Modulation analysis of cdma2000 and 1xEV-DV signals
W-CDMA/HSPA+ modulation analysis	Modulation analysis of WCDMA and HSPA+ signals
1xEV-DO modulation analysis	Modulation analysis of 1xEV-DO signals
TD-SCDMA/HSPA modulation analysis	Modulation analysis of TD-SCDMA and HSPA signals

Options for X-Series Measurement Applications for Modular Instruments

The X-Series Measurement Applications for Modular Instruments are available for use with VSA (M9391A) or later. The available options for this software are the same as for the 89600 VSA software, except this software does not offer any floating license. The available options for this software are shown in Appendix Table C-2.

Appendix Table C-2: Options for X-Series Measurement Applications for Modular Instruments

Standard	Description
GSM / EDGE / EVO	Modulation analysis of GSM, EDGE, and EVO signals
cdma2000 & cdmaOne	Modulation analysis of cdma2000 and cdmaOne signals
WCDMA & HSPA+	Modulation analysis of WCDMA and HSPA+ signals
1xEV-DO	Modulation analysis of 1xEV-DO signals
TD-SCDMA / HSPA	Modulation analysis of TD-SCDMA and HSPA signals
LTE / LTE-A FDD	Modulation analysis of LTE FDD and LTE-Advanced FDD signals
LTE / LTE-A TDD	Modulation analysis of LTE TDD and LTE-Advanced TDD signals