

Experimental Evaluation of Machine Learning based Wireless Communication Algorithms

Master Thesis

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Abstract

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Acronyms

AFW	Application Framework.
AWGN	Additive White Gaussian Noise.
BS	Base Station.
CRS	Cell Specific Reference Signal.
FPGA	Field Programmable Gate Array.
GSM	Global System for Mobile communication.
IEEE	Institute of Electrical and Electronics Engineers.
MIMO	Multiple Input Multiple Output.
OCXO	Oven Controlled Oscillator.
OFDM	Orthogonal Frequency Division Multiplexing.
PCIe	Peripheral Component Interconnect Express.
PDSCH	Physical Downlink Shared Channel.
PPS	Pulse Per Second.
PSS	Primary Synchronisation Signal.
SSS	Secondary Synchronisation Signal.
UE	User Equipment.

Introduction 1

System Model 2

As mentioned in Chapter 1, the goal of this thesis is to collect the measurement data from the MIMO setup. This collected experimental data will be applied to the machine learning model which has been developed in parallel with this thesis. In this chapter the relevant fundamentals of the LTE standard, which will be used as a basis for our channel estimation are described on a high level.

2.1 LTE

LTE stands of Long Term Evolution and is a successor standard to UMTS. LTE is a multicarrier approach for multiple access which uses Orthogonal Frequency-Division Multiple Access (OFDMA) in the physical layer. OFDM uses multiple carriers (known as sub carriers) spaced equally apart and can transmit independent data streams on each sub carrier [1].

Hence an LTE frame is commonly represented as a 2D time frequency grid, where the vertical axis represents the sub-carriers(Frequency) and the horizontal axis represents time. LTE also comes in 2 flavours Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). In this thesis the focus will be on FDD systems, which use seperate frequency bands, for uplink and for downlink data respectively. The advantage of an FDD system is that the uplink and downlink transmission can happen simultaneously.

LTE has a certain predefined signal symbol structure according to the standard [2]. In the following sections the frame structure and the different symbols in the LTE Frame shall be introduced.

2.2 LTE Waveform Processing

LTE stands of Long Term Evolution and is a successor standard to UMTS. LTE is a multicarrier approach for multiple access which uses Orthogonal Frequency-Division Multiple Access (OFDMA) in the physical layer. OFDM uses multiple carriers (known as sub carriers) spaced equally apart in frequency and can transmit independent data

streams on each sub carrier [1]. LTE also comes in 2 flavours Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). In this report the focus will be on FDD systems, which uses separate frequency bands for uplink and for downlink data so that the uplink and downlink data can be transmitted simultaneously.

LTE was chosen as a standard to use for the communication system given the integrated support of simulation environments like MATLAB and Simulink and that it is currently widespread in the telecommunications industry.

2.2.1 Transmission

A dual antenna transmitter using a USRP software defined radio as mentioned in 4.1 is used for the interface. A modified version of the LTE Application framework with MIMO 2x2 extension is used to log the data and run with different parameters. The transmitter USRP is connected to a Host PC using a 4-lane PCIe connection. This is necessary for the high data throughput exchanged between the host and the devices.

A LTE frame is commonly represented as a 2D time frequency grid, where the vertical axis represents the sub-carriers and the horizontal axis represents time.

LTE has a certain predefined signal symbol structure according to the standard [2]. In the following sections the frame structure and the symbols relevant to channel estimation shall be introduced.

2.2.1.1 LTE Frame

A single frame is 10ms long and consists of 10 smaller units called subframe, each 1ms long. A symbol is the smallest unit of time for an LTE system and one subframe has 14 such symbols each approximately 66.7us long. Scheduling is normally done on a subframe basis for both uplink and downlink communication.

LTE's time frequency grid contains many different signals each performing specific functionality like broadcasting, control channel information, data transfer, among other functions.

For the purpose of channel estimation, the most important signals are Primary Synchronisation Signal(PSS), Secondary Synchronisation Signal (SSS) and Cell Specific Reference Signal (CRS) which are described in detail in the subsequent sections.

2.2.1.2 Primary Synchronisation Signal (PSS)

OFDM is extremely time and frequency sensitive, hence it is very important to know the exact start of every frame. The PSS helps to achieve the synchronisation of

the frame by using a specific sequence called the Zadoff-Chu sequence [2]. The Zadoff-Chu sequence has the property of constant amplitude zero autocorrelation waveform (CAZAC sequences) that cyclically shifted versions of the waveform are orthogonal to each other. The sequence is described in Equation 2.1 where u can be 25, 29 or 34 depending on the cell ID. The PSS is broadcast twice every radio frame and the symbols are identical each time.

$$d_u(n) = \begin{cases} e^{-j \frac{\pi u n(n+1)}{63}} & n = 0, 1, \dots, 30 \\ e^{-j \frac{\pi u n(n+1)(n+2)}{63}} & n = 31, 32, \dots, 61 \end{cases} \quad (2.1)$$

2.2.1.3 Secondary Synchronisation Signal (SSS)

The SSS is a 62 bit pseudo random sequence [2]. It is broadcast twice in a frame once in subframe 0 and once in subframe 5, one symbol before the PSS. The 2 sequences of transmission in a frame are different so that the UE can identify which position in the frame the synchronisation happens.

2.2.1.4 Cell Specific Reference Signal (CRS)

As mentioned in Chapter 1 the channel needs to be estimated in order to reverse the channel propagation effects. With the help of CRS the channel can be estimated by placing equally spaced reference symbols along every 6 subcarriers starting from subcarrier 2 on symbols 1, 8, 15, etc... and every 6 subcarriers starting from subcarrier 5 on symbols 5, 12, 19, etc...[2]. The signals received by the UE and the channel effects are inferred based on amplitude damping and phase shift. Placing the signals in the above defined spacing gives the best coverage to interpolate over in time and frequency.

The signals to be placed on the grid are decided by the Equation 2.2 as shown below, with the parameters defined in Table 2.1 [2].

$$r_{l,n_s}(m) = \frac{1}{\sqrt{2}}(1 - 2 \cdot c(2m)) + j \frac{1}{\sqrt{2}}(1 - 2 \cdot c(2m+1)), \quad m = 0, 1, \dots, 2N_{RB}^{max,DL} - 1 \quad (2.2)$$

Parameter	Description
$c(m)$	Pseudo Random Sequence defined in [2]
$N_{RB}^{max,DL}$	Maximum number of Downlink resources blocks
n_s	Slot number in the frame
l	OFDM Symbol number in the frame

Table 2.1: Parameter definitions for evaluating CRS Symbols

2.2.1.5 Final Waveform

All the signals mentioned in Section 2.2.1.1 are generated in Labview using the LTE Application Framework Software and arranged in a 2D grid of frequency and time as shown below in Figure 2.1. The CRS are placed every 6 subcarriers in the frequency domain and every 3 or 4 time symbols apart, according to the position on the grid. Where as the PSS and SSS only repeat every 5 subframes.

Figure 2.1: Resource Block Grid for 2 sub frames

One of the disadvantages of using OFDM in the physical layer is the high peak to average power ratio (PAPR) of the signal. High PAPR translates to high fidelity requirements of power amplifiers on the transmitter side. It also induces non-linear distortions to the signal [1]. To ensure that the PAPR of the signal is as low as it can be, random QPSK symbols are transmitted on the unused slots instead of 0s.

2.2.2 Reception

For the LTE receiver processing a USRP captures in bursts and streams the data to a laptop connected via a USB interface. The signals are processed by a custom MATLAB application which performs the necessary steps to decode the LTE Frames, estimate the channel and display the information as a 3D surface. For the case of the demo the data was processed as soon as they were received from the USRP and the channel estimate was displayed in realtime. The data can alternatively be logged for offline postprocessing to get better granularity as intermittent processing delays dont appear.

Once enough samples have been captured (usually 2 or more Frames) the data can be processed in the following steps.

2.2.2.1 Carrier Offset Estimation and Correction

OFDM is extremely sensitive to frequency shifts in the received signal. In the case that the receiver or transmitter center frequency clock was not accurate enough, the frequency shift needs to be estimated and corrected. This is the very first step before processing the baseband waveform.

2.2.2.2 Frame synchronisation

As mentioned in Section 2.2.1.1 the synchronisation is a very important part of knowing where the LTE frame begins. This is done by correlating the received signal with the known Zadoff Chu Sequence and to look for the peak. Figure 2.2 shows an example correlation of a Zadoff Chu sequence and a received signal containing 307200 samples in total amounting to 2 frames of a 10MHz Bandwidth LTE signal. 4 peaks are to be expected here as there are 2 frames, each containing 2 PSS sequences.

Figure 2.2: PSS Correlation

2.2.2.3 Channel Estimation

Once the frame has been demodulated and the 2D OFDM grid has been obtained, the channel can be estimated based on the original pilot symbols structure known to the receiver, hence the phase and amplitude of the particular sub carrier can be obtained. A 2D Wiener filter is applied in both the time and frequency axis to interpolate the channel estimate. More explained in the Chapter 3.

2.2.3 Antenna

The analog time domain signal is transmitted from the USRP (Section 4.1) over the air using a Triband antenna. For the setup an omni directional Antenna from TODO capable of transmitting and receiving around frequencies of 144, 400 or 1200 MHz. The antenna radiation pattern is shown in Appendix ???. This antenna shown in Figure 2.3 was used as the transmit and the receive antenna for the demo setup.

Figure 2.3: Wideband Omnidirectional Antenna used for transmitting and receiving the LTE Signals

Channel Estimation 3

LTE was chosen as the standard to use here as it is very mature and has readily available MATLAB/Labview based implementation. In the case of this thesis the aim is not to reinvent standard by redesigning pilot symbol placements. Instead existing standards were used in order to collect experimental data. This reduces design time and focusses more on the issue at hand which is channel estimation data of a MIMO Channel.

3.1 OFDM

LTE is based on OFDMA in the physical layer which is a multi carrier communication scheme [3]. As the name suggests OFDM uses orthogonal sub carriers from an orthonormal system to form the basis for independent data streams. For band limited transmission systems with finite access time per channel use the dimension of the parallel data stream is given by the equation 3.1 [4].

$$N = BT \quad (3.1)$$

Parameter	Description
N	Dimension of system
B	Signal Bandwidth
T	Channel access time

Table 3.1

The orthonormal basis function can be mathematically modelled as the equation 3.2 [4].

$$\begin{aligned} \psi_{b,q} &= p_{T_b}(t) \exp(j2\pi q \frac{t}{T}) \\ p_{T_b}(t) &= \begin{cases} 1; & t \in T_b \\ 0; & otherwise \end{cases} \end{aligned} \quad (3.2)$$

Parameter	Description
$\psi_{b,q}$	normalized orthogonal basis functions
b	channel access slot
q	sub carrier index
T	channel access time
T_b	$t bT \leq t < (b+1)T \subset \mathbb{R}$

Table 3.2: Parameter definitions for OFDM Definition

The transmitted data can hence be modelled as the following

$$x_b(t) = \sum_{q=0}^{N-1} \underbrace{X_{b,q}}_{\text{data}} \psi_{b,q}(t) \quad (3.3)$$

For a given ideal AWGN Channel, where there is no delay spread or multipath propogation, the corresponding received data is modelled as

$$y_b(t) = \sum_{q=0}^{N-1} x_b(t) \psi_{b,q}(t) + \eta_b(t) \quad (3.4)$$

where $\eta_b(t)$ is the additive noise

The demodulation is based on the same set of orthonormal basis vectors that as the receiver, hence we have

$$\hat{x}_{b,q} = \langle y, \psi_{b,q}(t) \rangle + \langle \eta_b, \psi_{b,q}(t) \rangle = x_{b,q}(t) + \eta_{b,q} \quad \forall q = 1, \dots, N$$

3.2 MIMO Channel Estimation

3.2.1 Maximum Ratio Combiner

3.2.2 Zero Forcing

3.2.3 MMSE

Potential Hardware Setups

4

Measurements of MIMO channel can be achieved in multiple methods. This chapter discusses some of the potential approaches which were tested and elaborates each of their advantages and disadvantages. A detailed final implementation is described in Chapter 5 where the setup configurations are discussed. The following are some possible realisation for a MIMO Setup.

4.1 Software Defined Radios USRP

USRP is a Software Defined Radio (SDR) designed by National Instruments that enables quick prototyping of different wireless applications. It is aimed at hobbyists, research labs, universities, etc... or anyone interested in evaluating custom algorithms. The SDR used in this masters thesis is a USRP2940, specifications of which are described in Table 4.1.

Model	USRP2940
Baseband Bandwidth	40MHz
RF-Operating Frequency	50MHz-2200MHz
FPGA	Kintex-7 410T
No of Transmitters	2
No of Receivers	2
Connectivity	MXIe, Ethernet
Oscillator	Internal Crystal
ADC/DAC	14 (For Rx)/16 (For Tx) bit
Frequency Accuracy	2.5 ppm
Maximum Power Output	20dBm
Maximum I/Q Sample Rate	200MHz

Table 4.1: USRP2940 SDR Product details

4.1.1 PCIe-8371

The USRP SDRs are PXIe communication based devices. They connect to a Host/PC using a 1/4/8 way PCIe slot. For this setup a 4 lane PCIe daughter card (*PCIe-8371*) was installed on the motherboard of the host PC to provide a dedicated PCIe communication port for the USRP.

4.1.2 Host

The host chosen to be used here is a Fujitsu Celcius M770 with the following specifications.

OS	Microsoft Windows 10 Education
Version	10.0.18363 Build 18363
OS Manufacturer	Microsoft Corporation
Systemname	TUEIMSV-PRAKT01
Manufacturer	FUJITSU
Systemmodel	CELSIUS M770
Systemtype	x64-based PC
System-SKU	S26361-Kxxx-Vyyy
Processor	Intel(R) Xeon(R) W-2123 CPU @ 3600 MHz 4 Cores, 8 logical Processors
BIOS-Version/-Date	FUJITSU // American Megatrends Inc. V5.0.0.13 R1.8.0 for D3498-A1x, 08.10.2019
SMBIOS-Version	3.2
BIOS-Modus	UEFI
BaseBoard-Manufacturer	FUJITSU
BaseBoard-Product	D3498-A1
BaseBoard-Version	S26361-D3498-A1
Platform Type	Workstation
Installed Physical Memory	16,0 GB
Total Physical Memory	15,6 GB

Table 4.2: Fujitsu Celcius M770 Configuration

4.2 MIMO Application Framework (MIMO AFW)

MIMO Application Framework (MIMO AFW) is a Software developed by National Instruments, that offers a comprehensive plug and play MIMO setup. This setup requires a host of additional hardware which are required for the functioning of the MIMO AFW [5]. When setup with all the required Hardware MIMO AFW can support a Multi-user system with a maximum of 128 Antennas on the Base Station (BS) side and upto 12 Antennas on the User Equipment (UE) side.

A list of different Hardware parts needed to run this MIMO AFW is listed in Table 4.3. There are many different MIMO configurations possible and the hardware requirements of each of these configurations are mentioned in Table 4.4. A high level system overview of the main features of MIMO AFW is as follows

- Multi-User MIMO transmission between one Base Station (BS) with up to 128 Antennas and up to 12 single antenna Mobile Stations (MS)
- Single-user MIMO transmission between one BS with up to 128 antennas and one MS with up to 12 antennas
- Modulation Schemes from QPSK to 256 QAM
- Automatic gain control (AGC) at the BS and MS
- FPGA based real time signal processing such as modulation, over-the-air synchronization, MIMO equalization and MIMO precoding
- Scalable number of antennas (multi-antenna MS: between 2 and 12; BS: between 2 and 128). Interfaces and configuration adapt automatically
- Fully reconfigurable LTE like radio frame structure
- Bi Directional TDD and FDD functionality transmission of 20MHz bandwidth
- FPGA based real time signal processing such as modulation, over-the-air synchronization, MIMO equalization and MIMO precoding

Part Number	Description
USRP-2940	SDR
PXle-7976	FPGA Module for FlexRIO
CDA-2990	Clock Distribution Device
CPS-8910	Switch Device for PCI Express
PXle-6674T	Synchronization Module
PXle-1085	Chassis
PXle-8135	Controller

Table 4.3: Additional Hardware for required for MIMO AFW to function

	128-antenna BS 8 subsystems	64-antenna BS 4 subsystems	32-antenna BS 2 subsystems	16-antenna BS 1 subsystems	8-antenna BS 1 subsystems
USRP-29xx SDR Reconfigurable Device	64	32	16	8	6
PXle-1085 Chassis (18-Slot, 24 GB/sSystem Bandwidth (BW))	1	1	1	1	1
PXle-8135 Controller	1	1	1	1	1
PXle-7976 FPGA Module for FlexRIO	5	3	2	2	2
PXle-6674T Synchronization	1	1	1	1	1
CDA-2990 Clock Distribution Device	8	5	3	1	1
CPS-8910 Switch Device for PCI Express	8	4	2	1	1

Table 4.4: MIMO Configurations and HW requirements

4.2 MIMO Application Framework (MIMO AFW)

4.2.1 USRP 2940

As mentioned in Section 4.1, this is the backbone of the architecture. The Software defined radio (USRP2940) is used as an air interface for over the air transmission. There are host of other options that can be used here instead of the USRP2940. Table 4.5 lists the alternatives with an overview of the functionality of each of the parts.

4.2.2 PXIe-7976

MIMO has very demanding operations that are quite compute intensive such as precoding, equalization as well as channel estimation in the frequency domain. In addition to the aforementioned processing tasks this FPGA card also perform the *bit processing*. This PXIe communication based FPGA card contains a Xilinx Kintex-7 FPGA and moves data in and out using an 8 lane PCIe slot.

4.2.3 CDA-2990

This device also known as the Octoclock is a clock distribution accessory. It can either receive an input reference clock and distribute the clock to 8 other devices synchronously along with a PPS (Pulse Per Second). The CDA-2990 also contains an input for a GNSS Antenna which uses the GNSS signal to generate a PPS signal. In the absense of a GNSS Antenna the device generates its own internal clock based on an internal oven controlled oscillator (OCXO).

4.2.4 CPS-8910

The CPS-8910 is a 8 way PCIe data aggregator and has 2 upstream ports. With the 8 downstream ports it can aggregate large amounts of data from a maximum of 8 USRPs and send them out to a PC/Controller via the 2 other upstream ports. This is essential for Massive MIMO applications.

4.2.5 PXIe-1085

National instruments is a company that manufactures devices intended for different industries and end applications. Hence they follow a modular approach to their designs. The PXIe-1085 is an 18 slot chassis, which can be populated by many different daughter cards suitable to the customers needs. Out of the 18 slots 16 are hybrid that can be populated with various add ones, and one slot is reserved for a timing and synchronisation slot as described in section 4.2.6 and the other reserved for a

PXI-controller which is define in section 4.2.7. The chassis is capable of supporting a throughput of upto 24GBps.

4.2.6 PXIe-6674T

The PXIe-6674T generates and routes clocks and trigger signals (PPS Signals) between PXI devices or chassis. This timing and synchronisation card not only generates an accurate clock but can also shift levels of an input signal according to the user's settings. Although the octoclock distributes the clock, it is generated, synchronised and level shifted by the PXIe-6674T.

4.2.7 PXIe-8135

The PXIe-8135 is a PXI Controller needed to handle the different slot daughter cards installed in the *PXIe-1085* (section 4.2.5). Its a Intel Core i7 based embedded controller for PXI express systems. The controller also has a variety of ports to support the 10/100/1000BASE-TX Gigabit Ethernet, 2 SuperSpeed USB ports and four Hi-Speed USB ports, as well as an integrated hard drive, serial port, and other peripheral I/O.

4.2.8 Implementation Advantages and Disadvantages

The advantages of using MIMO AFW is that it reduces time to prototype as the functionality is readily available in the form of Hardware and Software, it is also a scalable model providing a solution with up to 128 BS antennas and 12 MS antennas. But given the amount of hardware required to have a minimum viable product, it is quite an expensive undertaking (over €100.000) and is hence cost preventative. Apart from that there is also the time cost to setup the instrument and check it functionality which is not to be neglected.

Model	RF-Frequency Range	RF-Frontend Bandwidth	FPGA	Inputs	Outputs	Communication	GPS Osillator
USRP-2940	5 MHz - 2.2 GHz	40 MHz	Kintex-7 410T	2	2	MXIe Ethernet	No
USRP-2940	50 MHz – 2.2 GHz	120 MHz	Kintex-7 410T	2	2	MXIe Ethernet	No
USRP-2942	400 MHz - 4.4 GHz	40 MHz	Kintex-7 410T	2	2	MXIe Ethernet	No
USRP-2942	400 MHz - 4.4 GHz	120 MHz	Kintex-7 410T	2	2	MXIe Ethernet	No
USRP-2943	1.2 GHz - 6 GHz	40 MHz	Kintex-7 410T	2	2	MXIe Ethernet	No
USRP-2943	1.2 GHz – 6 GHz	120 MHz	Kintex-7 410T	2	2	MXIe Ethernet	No
USRP-2944	10 MHz - 6 GHz	160 MHz	Kintex-7 410T	2	2	MXIe Ethernet	No
USRP-2945	10 MHz - 6 GHz	80 MHz	Kintex-7 410T	4	0	MXIe Ethernet	No
USRP-2950	50 MHz - 2.2 GHz	40 MHz	Kintex-7 410T	2	2	MXIe Ethernet	Yes
USRP-2950	50 MHz - 2.2 GHz	120 MHz	Kintex-7 410T	2	2	MXIe Ethernet	Yes
USRP-2952	400 MHz - 4.4 GHz	40 MHz	Kintex-7 410T	2	2	MXIe Ethernet	Yes
USRP-2952	400 MHz - 4.4 GHz	120 MHz	Kintex-7 410T	2	2	MXIe Ethernet	Yes
USRP-2953	1.2 GHz - 6 GHz	40 MHz	Kintex-7 410T	2	2	MXIe Ethernet	Yes
USRP-2953	1.2 GHz - 6 GHz	120 MHz	Kintex-7 410T	2	2	MXIe Ethernet	Yes
USRP-2954	10 MHz - 6 GHz	160 MHz	Kintex-7 410T	2	2	MXIe Ethernet	Yes
USRP-2955	10 MHz - 6 GHz	80 MHz	Kintex-7 410T	4	0	MXIe Ethernet	Yes

Table 4.5: List of alternative Software defined radios offered by National Instruments

4.3 LTE Application Framework

LTE Application Framework is a Software that National Instruments designed and offers to provides us a *Downlink Only* 2x2 LTE setup. This setup does not require the additional hardware which are required for the functioning of the MIMO AFW.

4.3.1 Hardware Requirements

This setup is quite a simplified version of the MIMO AFW and only requires a pair of USRPs (4.1), a pair of the PCIe daughter cards(4.1.1) and a host PC(4.1.2). One USRP acts as a eNodeB with 2 antennas (Base Station) and the other USRP acts as a UE with 2 antennas.

4.3.2 Software Requirements

The LTE AFW Software template that NI provides in its example libraries only has a LTE SISO implementation. But an internal development version of a 2x2 MIMO Extension was issued to TUM for the sake of expediting the experimental setup since MIMO AFW was not a financial viable option. However the NI internal development version of the code was meant to be run on a version 2.1 of Labview Communication Suite which is not supported on Windows 10. Hence the project had to be ported to the latest version of Labview Communications Suite (now called Labview NXG). Details of the software project are described in Chapter 5

4.3.3 Implementation Advantages and Disadvantages

The advantages of using LTE AFW is that it works with minimum hardware, albeit with a limited capability of providing only a 2x2 MIMO system. Unlike MIMO AFW which is capable of bidirectional MIMO communications, LTE AFW can only perform unidirectional communications, namely from the eNodeB(Base station) to the UE. However given all the time and budget constraints, LTE AFW was chosen as the preferred solution. The architecture of the software and the modifications are explained in the following chapter.

Experimental Setup 5

5.1 LTE Application Framework

5.2 Application Example

Results 6

Over the course of the internship many different parameters had to be determined and set up for the final demo. This chapters documents the results of all the experiments performed as well as the final demo of the working setup.

6.1 Transmit Power Measurements

A Rohde and Schwarz FSQ 8GHz spectrum analyser was used to capture the spurious emission at the output of the Spectrum analyser. The spectrum analyser had the following settings for this test.

Parameter	Value
RBW	20kHz
VBW	50kHz
SWP Time	50ms

Table 6.1: Spectrum analyser settings for the transmit power tests

An unmodulated test signal containing 2 sine tones each at 0.5 MHz and 1MHz was sent from the USRP transmitter with the measurement setup as shown below in the Figure ???. The 25W 20dB attenuator from spinner (Pt No: 36234) was used to protect the input of the spectrum analyser from high power.

The results in Figure ?? and Table 6.3 show that any gain setting above 60 results in out of band emissions. Hence the maximum setting was chosen, which did not introduce any out of band emissions, namely Tx Gain setting of 60 which corresponds to -25dBm.

Tx Gain Setting USRP	Attenuator (dBm)	Tx Power Measured (dBm)	Tx Power Actual (dBm)	Distortion observed
35	20	-70.18	-50.18	No
40	20	-64.95	-44.95	No
45	20	-60.01	-40.01	No
50	20	-54.9	-34.9	No
55	20	-50.05	-30.05	No
60	20	-44.99	-24.99	No
65	20	-39.96	-19.96	Yes
70	20	-34.77	-14.77	Yes
75	20	-29.9	-9.9	Yes
80	20	-24.9	-4.9	Yes

Table 6.2: Distortion Values

6.2 Path Loss Measurements

The measurements were performed in the Nokia car park entrance as shown below in Figure ???. The free space path loss experiments were performed by setting the transmit power to -25dBm and measuring the received power at Line of Sight(LoS) locations which were 4,6,8 and 10m apart.

Range (m)	Tx Pwr (dBm)	Antenna Gain (dBi)	Calculated Path Loss(dBm)	Expected Rx Pwr(dBm)	Measured (dBm)	Delta (dBm)
4	-25	4.0	49.0	-66.0	-69.8	-3.8
6	-25	4.0	53.0	-70.0	-74.5	-4.5
8	-25	4.0	55.8	-72.8	-75.8	-3.0
10	-25	4.0	58.0	-75.0	-77.3	-2.3

Mean	-3.4
------	------

Table 6.3: Path Loss Measurements

6.3 Transmit and Receive Loopback

This test was performed to test and identify the transmitter and receiver system response without the air interface. The system should ideally return a flat response across all the subcarriers with a magnitude of 0dBm. But due to cable and insertion losses the response is lower than 0dBm. Figure ?? shows the mean value of the magnitude in dB over the frequency is -2.36dBm which corresponds approximately to the loss figure obtained from Section 6.2. The other losses could be attributed to insertion losses when the antenna is plugged in on both ends.

For this experiment the transmit power was -25dBm with the center frequency 2.6GHz and the LTE Frame described in Section 2.2.1.1 was transmitted. The transmitter was connected to the receiver with the help of a 1.5m long 50 Ω coaxial cable.

6.4 Radar Calibration

An object was placed in the horizontal axis of the radar sensor at a distance of 10m from the radar sensor. Markings were laid out on the road as shown in the figure ?? and the reading was compared to the data processed by the radar sensor which was 10.1m still within the accuracy of the radar sensor.

6.5 Hardware Performance

6.5.1 USRP Sampling Rate

The USRP Software defined radio is very convenient for prototyping. There are although some drawbacks with using the drivers in MATLAB. Experiments with the full LTE bandwidth of 20MHz resulted in consistently dropped frames and consequently led to unreliable channel estimation data. On further investigation it was found that the MATLAB drivers were single threaded and could not allocate sufficient buffers in the kernel to support the higher sampling rates of 15.36MSps and 30.72MSps. Therefore a 7.68MSps was chosen which corresponds to a 5MHz LTE bandwidth as this worked the most reliably with the current available hardware. Alternatives to MATLAB to USRP interface is described in Section ??.

6.5.2 Max Frame Rate for Demo

Real time processing of channel estimation is an especially demanding operation for a general purpose compute platform. The performance was better on a more powerful

intel i7 compared to an intel i5 processor.

It was also found that the USRP drivers worked more reliably on a linux platform than on a windows platform i.e: for a given USRP sampling rate the frame drops were seldom observed on the linux platform. Table 6.4 is a comparison of a standalone channel estimation application running on MATLAB on 2 devices and the approximate frame rates that could be achieved. The frame rate performance does degrade upon running other compute intensive programs simultaneously.

	OS	Update Rate Frames/s
Nokia Laptop	Windows 10	1-2
Personal Laptop	Linux	8-10

Table 6.4: Comparison on different operating systems

6.6 Demo

The demo took place in the carpark entrance of the Nokia Munich site in St.Martin Straße as shown in Figure ???. The setup for the final demo is shown in the Figure ??? below. The LTE frame was transmitted by a laptop running on a Linux OS continuously transmitting LTE frames. The laptop across the street was connected to the USRP, which receives and decodes the LTE frames. The radar sensor is also attached to this computer to get the range and angle data. The laptops were placed approximately 15m apart on opposite sides of the carpark entry ramp.

Shown below in Figure ??? is a legend of what is seen as a part of the demo video and the subsequent figures that follow this. The first figure on top shows position of the object w.r.t the Radar transceiver. The 2nd figure displays the 2D channel estimate in both the time axis as well as the frequency axis (subcarriers). The third figure below the 2D grid shows the trend of the first, middle and the last subcarrier namely 1,150 and 300 subcarriers. The magnitude for both the plots is in dBm and the x axis on the figure at the bottom represents the symbols captured. This is 20 Symbols per frame, this is the compressed information picking only every 7th symbol in the frame of 140 symbols.

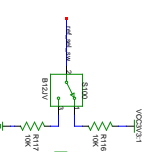
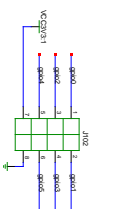
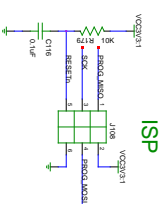
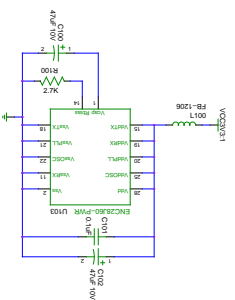
Figures ??? - ??? show the screen captures of an object passing through the LoS channel. The Figures ??, ?? and ?? show the state of the channel before, during and after the object has passed. The object passed by around 9m and this is shown in Figure ???. The channel trend shows that the channel is severely attenuated when the

object obstructs the channel. This can also be inferred from Figure ?? and Figure ?? where the channel returns to normal.

The full video of the demo can be viewed here [?].

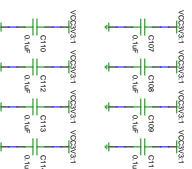
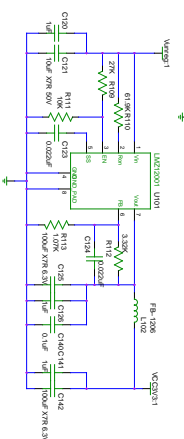
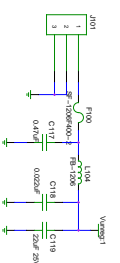
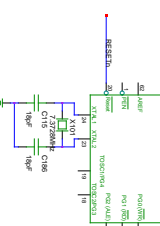
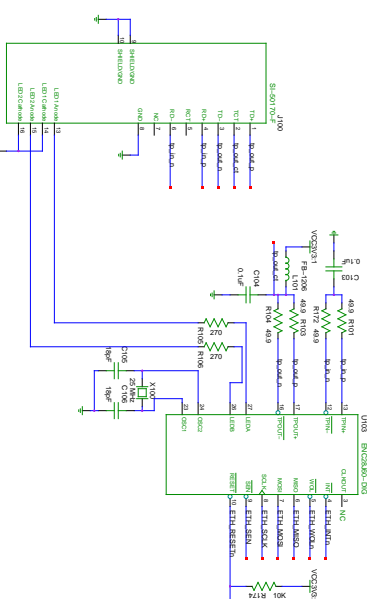
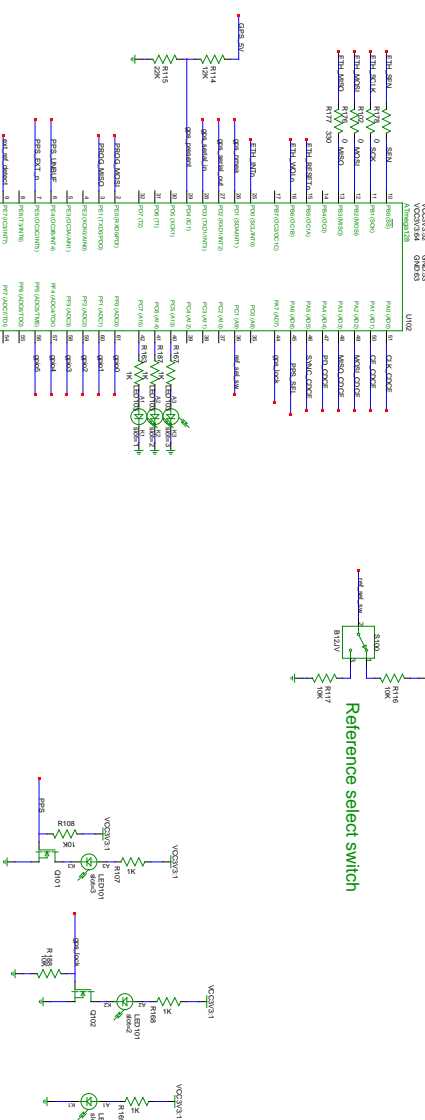
Conclusion and Outlook 7

Schematic Octoclock A

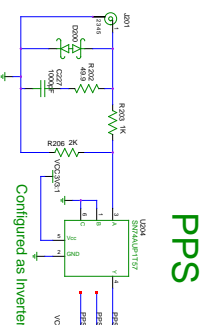
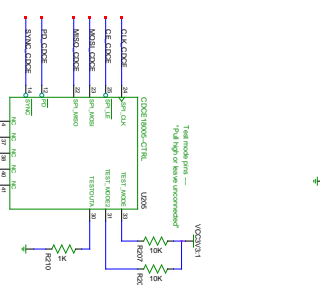
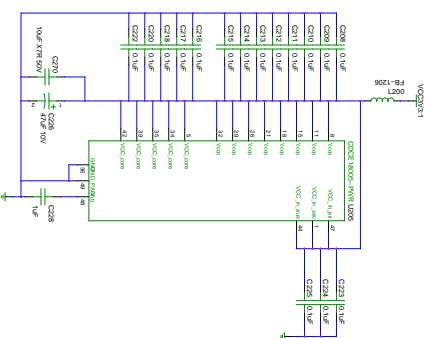
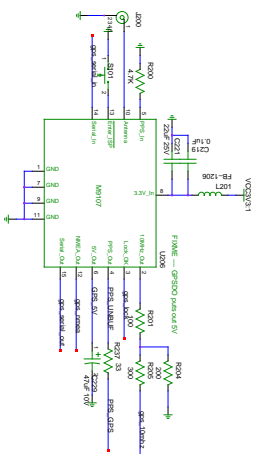
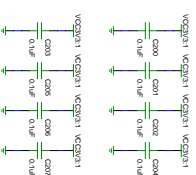


Front Panel

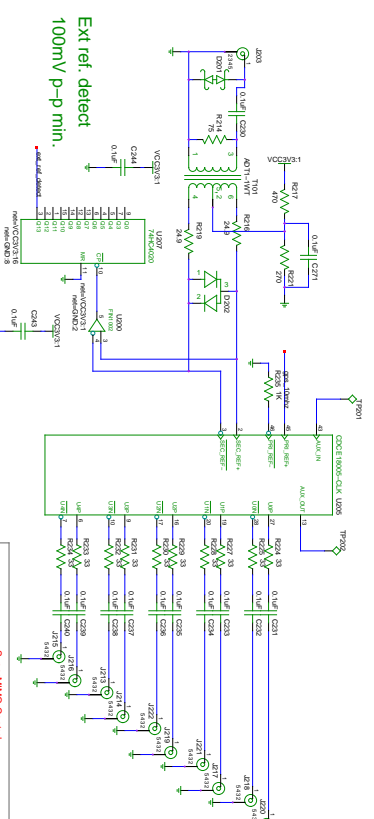
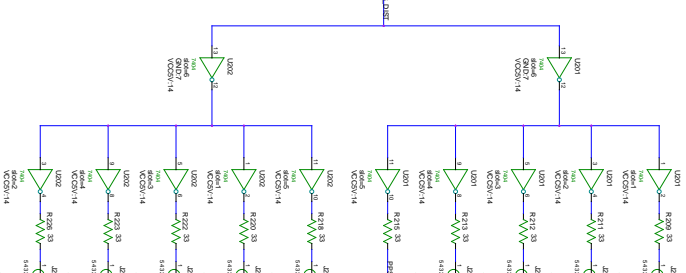
- 8x 10 MHz out
- 8x PPS out
- GPS In
- 10 MHz In
- PPS In
- Ref select switch



Front Panel
8x 10 MHz out
8x PPS out
RS232 out
GPS In
10 MHz In
PPS In



PPS
Configured as Inverter



Ext ref. detect
100mV p-p min.

SuperMINI Control

TITLE	
Rev	1.0
Rev	1.0
Rev	1.0

Troubleshooting B

B.1 Boot Order

B.2 Synchronisation of the USRPs

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