Technische Universität München

Experimental Evaluation of Machine Learning based Wireless Communication Algorithms

Master Thesis

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Abstract

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Acronyms

AFW Application Framework.

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.

PCIe Peripheral Component Interconnect Express.

PDSCH Physical Downlink Shared Channel.

PSS Primary Synchronisation Signal.

SSS Secondary Synchronisation Signal.

UE User Entity.

Introduction 1

2 System Model

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 transmittion 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 seperate 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 relavent 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 funtionality like broadcasting, control channel information, data transfer, among other functions.

For the puprpose of channel estmation, 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.

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

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 propogation 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].

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

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 senstive 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

3 Channel Estimation

3.1 OFDM

3.2 MIMO Channel Estimation

3.2.1 Simple

3.2.2 Zero Forcing

3.2.3 MMSE

4 Potential Hardware Setups

Measurements of MIMO channel can be achieved in multiple methods. This chapter discusses some of the potential approaches which were implemented and elaborates each of their advantages and disadvantages.

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 hobbists, research labs, universities, etc... or anyone interested in evaluating custom algorithms. The SDR used in this masters thesis is a USRP294, 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

4.2 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 [3]. When setup with all the required Hardware MIMO AFW can support a maximum of 128 Antennas on the Base Station (BS) side and upto 12 Antennas on the

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

Table 4.2: Additional Hardware for required for MIMO AFW to function

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 4.3 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

4.2.4 CPS-8910

4.2.5 PXIe-6674T

4.2.6 PXIe-1085

4.2.7 PXIe-8135

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 4.3: 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 set up a LTE setup. This setup requires a host of additional hardware which are required for the functioning of the LTE AFW.

5 Experimantal Setup

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 reliabily 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 continously 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.

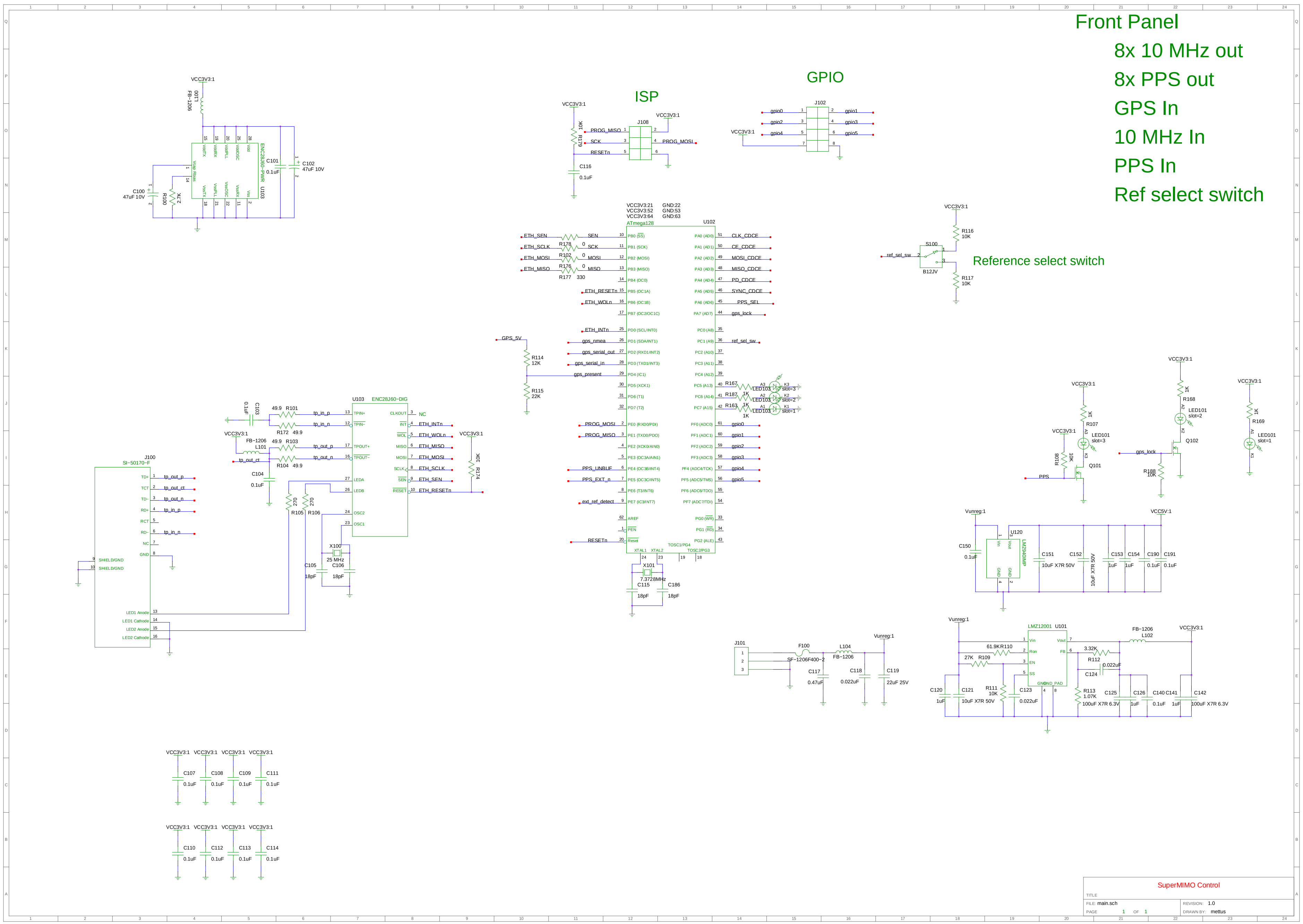
Shown below in Figure **??** is a legend of what is seen as a part of the demo video and the subsequent figures that follow this. The first figure on top shows position of the object w.r.t the Radar transceiver. The 2nd figure displays the 2D channel estimate in both the time axis as well as the frequency 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 infered from Figure **??** and Figure **??** where the channel returns to normal.

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

7 Conclusion and Outlook

Schematic Octoclock A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8x PPS out
GPS In
10 MHz In
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ENC28J60-PWR
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SI-50170-F
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REVISION: 1.0
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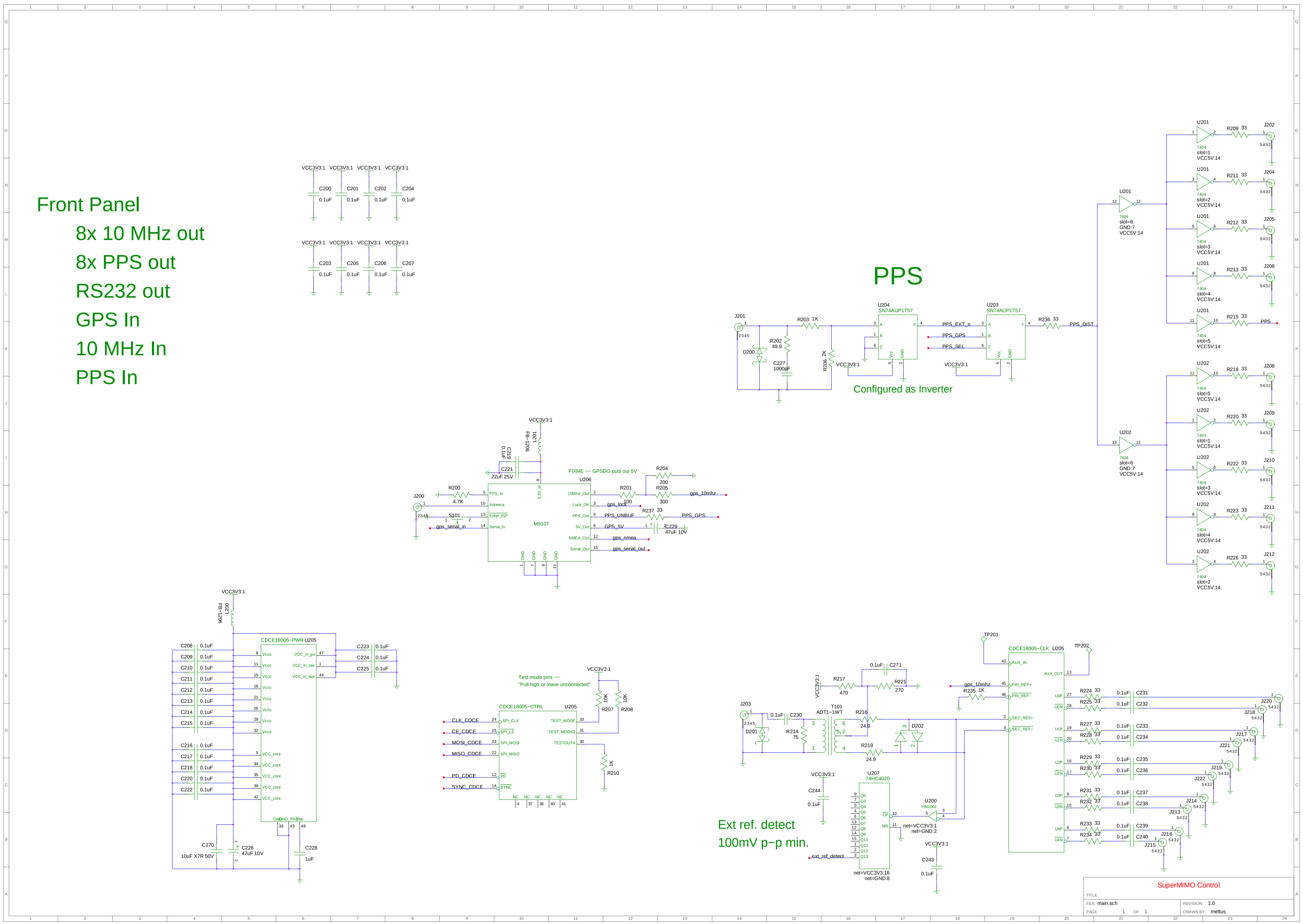
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8x 10 MHz out
8x PPS out
RS232 out
GPS In
10 MHz In
PPS In
PPS
Configured as Inverter
FIXME -- GPSDO puts out 5V
Test mode pins --
"Pull high or leave unconnected"
Ext ref. detect
100mV p-p min.
CDCE18005-PWR U205
CDCE18005-CTRL U205
CDCE18005-CLK U205
M9107 U206
SN74AUP1T57 U204
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74HC4020 U207
ADT1-1WT T101
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Troubleshooting B

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