# Experimental Evaluation of Machine Learning based Wireless Communication Algorithms

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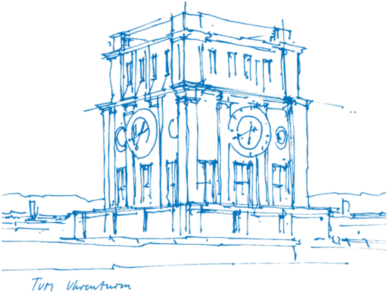
07. Sep 2020



# Introduction

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- For massive MIMO $\Rightarrow$ No. of Antennas $\propto$ Pilot overhead

- Current reseach for potential solutions include
  - Model based channel estimation
  - Machine learning based algorithms to find the channel

# Summary of Thesis

- Setup a MIMO Test Jig

[1] Jonas Maas. “Invertible Neural Networks for MIMO Detection”. BA thesis. Technical University of Munich, 2020.

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# Summary of Thesis

- Setup a MIMO Test Jig
- Collect real world experimental Tx-Rx data from the MIMO Setup
- Use the data to train a Inverted Neural Network [1] as shown below

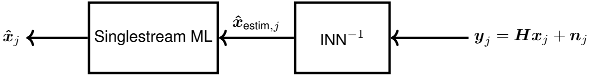


Figure: ML Model for learning the network

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# Summary of Thesis

- Software Defined Radio - USRP
- Possible Options for a MIMO Setup
- LTE Fundamentals
- Chosen Experimental Setup
- Results
- Conclusions and future work

# Software Defined Radio - USRP

| | |
|---|---|
| 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: USRP2940 SDR Product details

# Software Defined Radio - USRP

Figure: Insides of USRP2940

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   - ✓ supports upto 128 Antennas on the BS
   - ✗ Expensive! $>$€100.000 for a minimum working setup
   - ✗ Needs many additional HW components

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3. LTE Application Framework
   - ✓ Only 2 USRPs and a Host are required
   - ✗ Limited to 2x2 MIMO setup

# Option 1 - Standalone USRP

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$$y(t) = cos(\omega t) + j * sin(\omega t)$$

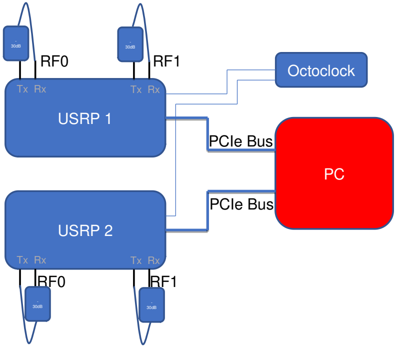


Figure: Setup of the USRPs in loopback Configuration

# Option 1 - Standalone USRP

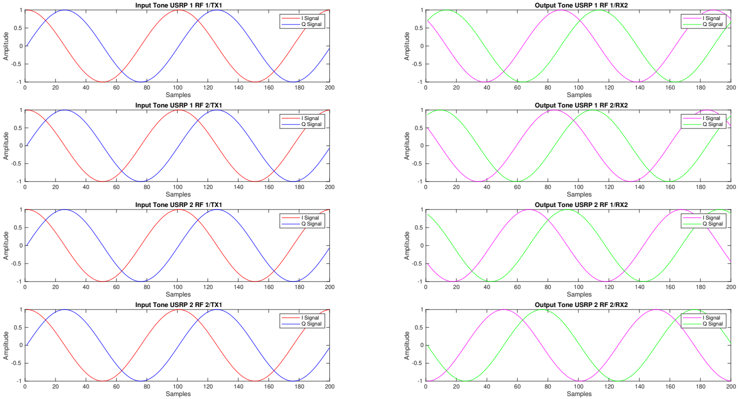


Figure: The left waveforms are the TX waveforms and the right waveforms are the RX waveforms. It can be seen that the received IQ waveforms are unsynchronised and clearly have a phase shift

# Option 1 - Standalone USRP

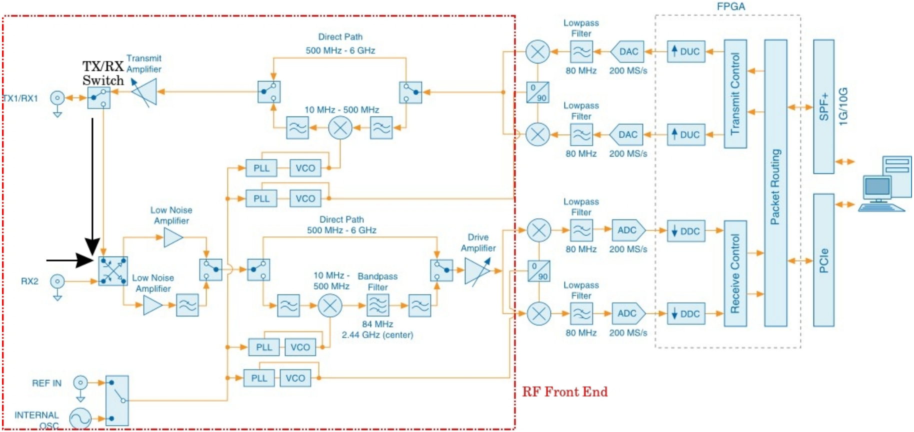


Figure: USRP 2940 Internal Components

# Option 2 - MIMO Application Framework

- Multi-User MIMO **Single 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
- Scalable number of antennas (multi-antenna MS: between 2 and 12; BS: between 2 and 128).
- Modulation Schemes - QPSK to 256 QAM
- Automatic gain control (AGC) at the BS and MS

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- Modulation Schemes - 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
  - MIMO precoding
- Fully reconfigurable LTE like radio frame structure
- Bi Directional TDD and FDD functionality transmission of 20MHz bandwidth

# Option 2 - MIMO Application Framework

| 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: 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 |
| PXIe-1085 Chassis (18-Slot, 24 GB/sSystem Bandwidth (BW)) | 1 | 1 | 1 | 1 | 1 |
| PXIe-8135 Controller | 1 | 1 | 1 | 1 | 1 |
| PXIe-7976 FPGA Module for FlexRIO | 5 | 3 | 2 | 2 | 2 |
| PXIe-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: MIMO Configurations and HW requirements

# Option 2 - MIMO Application Framework

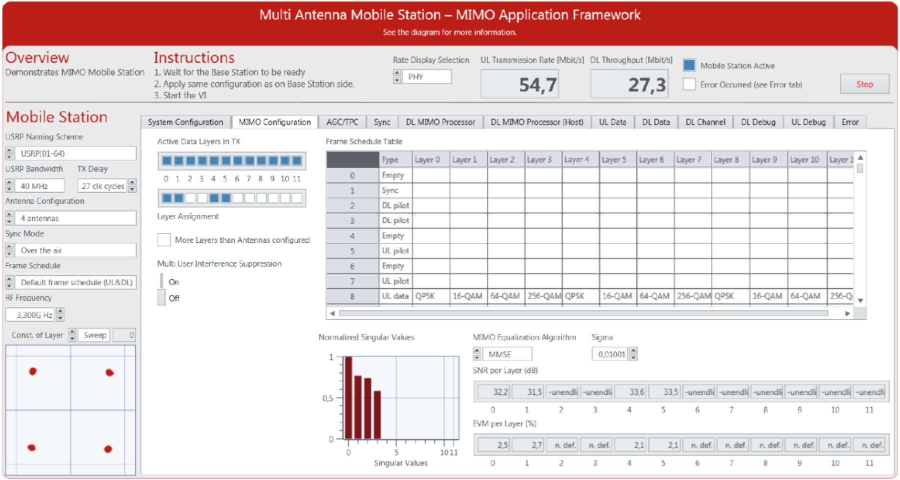


Figure: MIMO AFW

# Option 3 - LTE Application Framework MIMO Extension

- Based on a LTE Application Framework, an LTE Release 10 implementation
- Developed by NI to demonstrate a functioning 2x2 MIMO System
- Provides a **Downlink ONLY** 2x2 LTE Setup
- Upto 64 QAM modulation
- FPGA based realtime signal processing
- 3 different Equalisation algorithms
  - Matched Filter
  - Zero Forcing
  - MMSE

# LTE Fundamentals

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- Frame based communication scheme of 10ms per Frame

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  - Primary Synchronisation Signal (PSS) -**QPSK**
  - Secondary Synchronisation Signal (SSS) - **BPSK**
  - Cell Specific Reference Signal (CRS) - **QPSK**

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# LTE Fundamentals

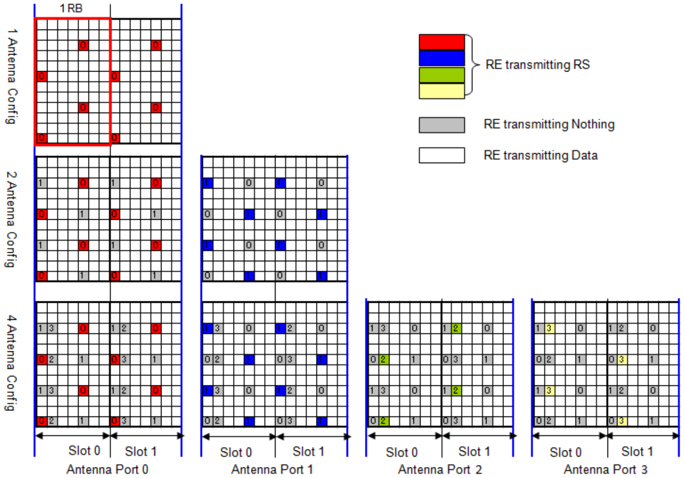
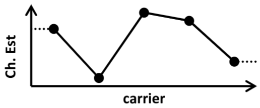


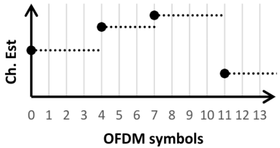

Figure: Cell Reference Signal layout for multi antenna configurations of 1,2 and 4 antenna systems in LTE

# Experimental Setup - FPGA

# Experimental Setup - CRS Data Transmission



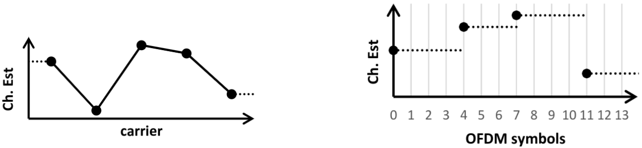

(a) Channel Estimation Interpolation over Frequency




(b) Channel Estimation Zero order hold over time

Figure: Illustration of channel estimation interpolation over time and frequency

# Experimental Setup - CRS Data Transmission




(a) Channel Estimation Interpolation over Frequency

(b) Channel Estimation Zero order hold over time

Figure: Illustration of channel estimation interpolation over time and frequency

- The RF Front end phase offset correction is applied to all the subcarriers and time symbols
- Fixed transmit pattern as defined by standard

# Experimental Setup - Wideband Noise Calculation

# Demo

# Results - Data Loss

```
Microsoft Windows [Version 10.0.18363.1016]
(c) 2019 Microsoft Corporation. Alle Rechte vorbehalten.

C:\Users\ge69mog>cd Downloads\iperf-2.0.9-win64\iperf-2.0.9-win64

C:\Users\ge69mog\Downloads\iperf-2.0.9-win64\iperf-2.0.9-win64>iperf.exe -s -u
-B 127.0.0.1 -i 1 -p 60000
------------------------------------------------------------
Server listening on UDP port 60000
Binding to local address 127.0.0.1
Receiving 1470 byte datagrams
UDP buffer size:  208 KByte (default)
------------------------------------------------------------
[  3] local 127.0.0.1 port 60000 connected with 127.0.0.1 port 49721
[ ID] Interval       Transfer     Bandwidth        Jitter   Lost/Total Datagrams
[  3]  0.0- 1.0 sec   996 KBytes  8.16 Mbits/sec   2.017 ms  166/  860 (19%)
[  3] 0.00-1.00 sec  50 datagrams received out-of-order
[  3]  1.0- 2.0 sec   904 KBytes  7.41 Mbits/sec   2.426 ms  227/  857 (26%)
[  3] 1.00-2.00 sec  70 datagrams received out-of-order
[  3]  2.0- 3.0 sec   902 KBytes  7.39 Mbits/sec   2.148 ms  219/  847 (26%)
[  3] 2.00-3.00 sec  61 datagrams received out-of-order
[  3]  3.0- 4.0 sec   916 KBytes  7.50 Mbits/sec   1.904 ms  222/  860 (26%)
[  3] 3.00-4.00 sec  69 datagrams received out-of-order
[  3]  4.0- 5.0 sec   871 KBytes  7.14 Mbits/sec   4.137 ms  206/  813 (25%)
[  3] 4.00-5.00 sec  56 datagrams received out-of-order
[  3]  5.0- 6.0 sec   953 KBytes  7.81 Mbits/sec   4.710 ms  226/  890 (25%)
[  3] 5.00-6.00 sec  86 datagrams received out-of-order
[  3]  6.0- 7.0 sec   828 KBytes  6.79 Mbits/sec   2.786 ms  253/  830 (30%)
[  3] 6.00-7.00 sec  84 datagrams received out-of-order
[  3]  7.0- 8.0 sec   843 KBytes  6.90 Mbits/sec   4.467 ms  250/  837 (30%)
[  3] 7.00-8.00 sec  90 datagrams received out-of-order
[  3]  8.0- 9.0 sec   970 KBytes  7.95 Mbits/sec   1.648 ms  200/  876 (23%)
[  3] 8.00-9.00 sec  61 datagrams received out-of-order
[  3]  0.0-10.0 sec  8.86 MBytes  7.43 Mbits/sec   2.888 ms 2183/ 8505 (26%)
[  3] 0.00-10.00 sec  689 datagrams received out-of-order
```

# Results - CRS Data Transmission

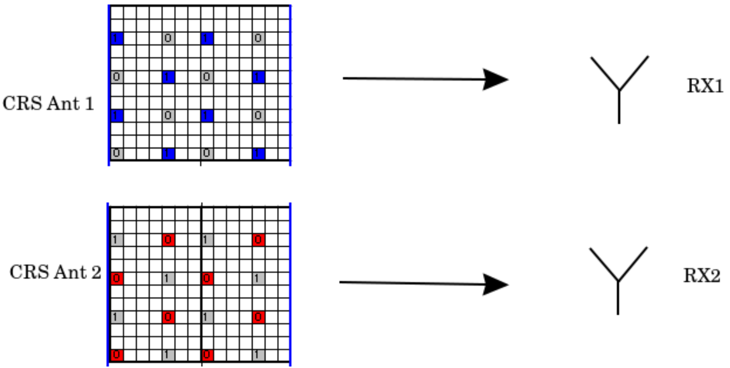
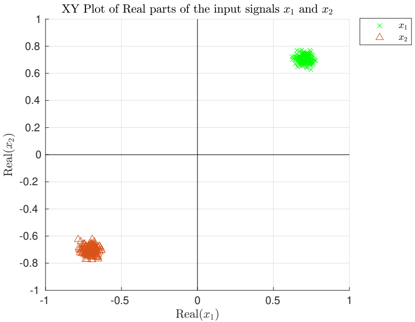


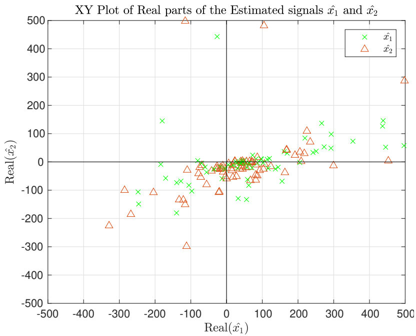

Figure: Illustration of the CRS signals and channel estimation coefficients used as the ($x$,$y$) pair

- A sequence of 8342 time symbols for the 200 CRS carriers were recorded
- Final matrix size of $200 \times 8342$

# Results - INN Detection




(a) XY plot of the real parts of the input signals $x_1$ and $x_2$ with noise




(b) XY plot of the real parts of the INN Estimated signals $\hat{x_1}$ and $\hat{x_2}$

Figure: Detection accuracy of **22%** from the INN

# Conclusion

# References I

# A Slide with a different header

Some text, possibly **bold** or highlighted.

- Bullet points
- Second point
  - Sub-bullet

# A Slide with a different header

Some text, possibly **bold** or highlighted.

- Bullet points
- Second point
  - Sub-bullet

1. First
2. Second
3. Third

# Frame with highlight boxes and alternative header

## Important Result[1]

The following holds:[2]

$$E = mc^2$$

[1] This is a footnote in a block title.
[2] This is a footnote in a block body.

# Frame with highlight boxes and alternative header

## Important Result[1]

The following holds:[2]

$$E = mc^2$$

$$\Downarrow$$

Can also be used without a title. Three color types are available: block (blue), alertblock (red), and exampleblock (green). Spacing may need some manual adjustment if formulas are included at the top or bottom of blocks.

[1] This is a footnote in a block title.
[2] This is a footnote in a block body.

- We consider some simple formulas, e.g. $\max(0,1) = 1$
- Complicated formula: $h_J(y) = \sum_{K \subset N} \int_{\mathbb{R}} g_K(x,y) f_J(x) dx$
- This looks slightly weired since math fonts are smaller than text fonts.

However, this does not really affect equations.

$$h_J(y) = \sum_{K \subset N} \int_{\mathbb{R}} g_K(x,y) f_J(x) dx$$

No title on this frame.[2]

### Example Block

Spacing around blocks is minimal (if option frameblock is used). Extra spaces, e.g. `vskip` or `vspace`, should be used.

Text below block.

[2] Smith et al., 2100: “Title of a paper that will be written in the future”, *IEEE Trans Inf. Theory*

# TUM Colors

In diagrams and plots only use the following colors:

- Black, White
- Yellow, RGB 255/180/000
- Orange, RGB 255/128/000
- Red, RGB 229/052/024
- Dark Red, RGB 202/033/063
- Blue, RGB 000/153/255
- Light Blue, RGB 065/190/255
- Green, RGB 145/172/107
- Light Green, RGB 181/202/130

# Final Slide

Add some vertical space.

Increase spacing between bullet points:

- More information can be found in the beamer user guide
- Use `pdflatex` to compile the source
- Have fun creating your slides!