Study and design of Multiple-Input Multiple-Output (MIMO) wireless communication systems

A Project Report

submitted by

Ritesh Rajesh Waykole (14EC156)

Karl Darryl Lewis (14EC123)

under the guidance of

Prof. U. Shripathi Acharya

in partial fulfilment of the requirements

for the award of the degree of

BACHELOR OF TECHNOLOGY

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA SURATHKAL, MANGALORE - 575025

17th April 2018

DECLARATION

by the B.Tech students

We hereby ***declare*** that the Project entitled **Study and design of Multiple-Input Multiple-Output (MIMO) wireless communication systems** which is being submitted to the ***National Institute of Technology Karnataka, Surathkal*** in partial fulfillment of the requirements for the award of the Degree of ***Bachelor of Technology*** is a ***bonafide report of the research work carried out by us***. The material contained in this thesis has not been submitted to any University or Institution for the award of any degree.

Ritesh Rajesh Waykole (14EC156)
Karl Darryl Lewis (14EC123)

Department of Electronics and Communication Engineering

Place: NITK - Surathkal

Date: 17th April 2018

CERTIFICATE

This is to *certify* that the Under Graduation Project work report titled **Study and design of Multiple-Input Multiple-Output (MIMO) wireless communication systems** submitted by

Ritesh Rajesh Waykole (14EC156)
Karl Darryl Lewis (14EC123)

as a record of the work carried out by them is accepted as a *U. G Project Work Report* submitted in partial fulfillment for the award of the degree **Bachelor of Technology in Electronics and Communication Engineering** in the department of Electronics and Communication Engineering at National Institute of Technology Karnataka, Surathkal during the academic year 2017-18.

Project Supervisor

Dr. U. Shripathi Acharya
Professor and Head,
Dept. of E and C Engineering,
NITK Surathkal

DUGC Chairman

Dr. U Sripati Acharya
Professor and Head,
Dept. of E and C Engineering,
NITK Surathkal

ACKNOWLEDGEMENTS

We take this opportunity to express our deepest gratitude and appreciation to all those who have helped us directly or indirectly towards the successful completion of this project.

First and foremost, we would like to express our sincere appreciation and gratitude to our esteemed guide Dr. U Sripati Acharya, Professor, Department of Electronics and Communication Engineering, NITK Surathkal for his insightful advice, encouragement, guidance, critique, and valuable suggestions throughout the course of our project work. Without his continued support, encouragement, and interest, this project would not have reached the stage it is at today.

Our sincere thanks to Mr. Raghavendra M.A.N.S., Ph.D candidate at the Department of Electonics and Communication Engineering, NITK Surathkal under Dr. U Sripati Acharya for his continuous motivation, support, technical aid, and guidance throughout this project.

We would like to take this opportunity to express our thanks towards the teaching and non-teaching staff in the Department of Electronics and Communication Engineering, NITK for their invaluable help and support in these four years of our study.

ABSTRACT

The goal of this project is to explore the field of communications systems with a focus on multiple-input multiple-output (MIMO) wireless systems with the help of several simulations and implementations in practical Rayleigh and Rician channels. We start with a basic single-input single-output system (SISO) simulation and move to multiple-input multiple-output system simulations. The MIMO systems clearly indicate an improvement in the performance of the system which can either be in terms of reliability or throughput. Several MIMO space time block codes (STBC's) were simulated and compared using BER performance to get an understanding of the importance of STBC's in a MIMO system. We proceeded towards implementation of a communication system using Software Defined Radio (SDR's), the USRP B210 along with GNU Radio. Starting with SISO, we face several challenges in the practical environment such as symbol timing mismatch, high channel fading, equalization and data frame synchronization. We have also been successful at implementing an Alamouti STBC encoder and decoder.

TABLE OF CONTENTS

CHAPTER 1
Introduction

1.1 Problem Definition

To study, simulate, and implement SISO and MIMO wireless communication systems on SDR in order to develop an understanding of the working of such communication systems in the physical layer.

1.2 Literature review

Most work on wireless communications until the early 1990s had focused on having an antenna array at only one end of the wireless link, usually at the receiver. Gerard J. Foschini and Michael J. Gans, Foschini and Emre Telatar showed that for the highly scattering environment great capacity gains can be made by using multiple antennas at both ends of the transmission channel. An alternative approach was to use multiple transmit antennas and only optionally multiple receive antennas. Vahid Tarokh, Nambi Seshadri and Robert Calderbank proposed these spacetime codes to achieve significant error rate improvements over single-antenna systems. Siavash Alamouti, and later Vahid Tarokh, Hamid Jafarkhani and Robert Calderbank to developed the first spacetime block-codes (STBCs). Space time codes involve the transmission of multiple redundant copies of data to compensate for fading and thermal noise in the hope that some of them may arrive at the receiver in a better state than others. In the case of space time block codes, the data stream to be transmitted is encoded in blocks, which are distributed among spaced antennas and across time. While it is necessary to have multiple transmit antennas, it is not necessary to have multiple receive antennas. Increasing the number of receive antennas improves performance. This process of receiving different copies of the data is known as diversity reception and was largely studied until Foschini's 1998 paper. Today the prototyping of all the wireless techniques is performed on software defined radios. Hence to understand the architecture and working of software defined radio, we had to refer to multiple papers [1,2,8,9,10,11,12]. Most of these papers although written on MIMO-OFDM systems, do contain a lot of information on the design of MIMO-only systems.

1.3 Motivation

A wireless communication systems performance is characterized by two primary parameters, the throughput and or reliability. As we move towards a 5th generation mobile communication system, the need for lower power, higher throughput, longer range and a more reliable link posses a challenge. Concepts in MIMO systems have been crucial in the development of the multiple wireless technologies of today, such as 4G LTE and 802.11ac/ad. We do see an improvement in performance due to the use of this technology.

1.4 Overview

To begin with, understanding of wireless communication systems and channel conditions is crucial to the simulation and implementation of the project. Knowing the effects that the channel inculcates on a transmitted signal are prerequisite to simulating and implementing a wireless communication system. A simple SISO system simulation was first performed to understand the effects of the channel. Then we moved to understanding transmit and receive diversity, and the improvement in the system performance due to the increase in diversity. A popular technique knows and Maximal Ratio Receive Combining (MRRC) was observed to be one of the best receive diversity technique. We have explored the working of space time block codes including the Alamouti technique, performed simulations in practical channel conditions and compared their performance with one another. Also different decoding strategies were simulated to get an understanding of optimal channel effect and noise cancellation with transmit and receive diversity. We have implemented a SISO wireless communication system using the B210 Software Defined Radio (SDR). The Alamouti 2x1 and 2x2 system designs were implemented and tested for functionality. All SDR designs were implemented on GNU radio. The implementation included designing the transmitter and the receiver on the GNU Radio platform. GNU Radio is an open source radio simulation software with SDR compatibility, and provides the freedom to implement data processing blocks using the user-friendly interface.

CHAPTER 2
Description

2.1 Diversity Schemes

Diversity scheme refers to a method that improves the reliability of a message signal sent using multiple communication channels with different parameters. Generally diversity encompasses a large number of concepts such as frequency, time, spacial, polarization and user diversity, but here we will limit ourselves to diversity related to MIMO, ie spatial diversity. In MIMO, we use transmit and receiver diversity schemes wherein multiple transmit and multiple receive antennas are used. We now introduce the basic diversity schemes below.

2.1.1 Maximal ratio receiver combing scheme

Abbreviated as MRRC, Maximal ratio receiver combing scheme is a type of a receiver combining scheme. A single transmit antenna is generally used, while multiple antennas receive the signal to collectively determine the symbol transmitted.

Assuming a symbol s is transmitted at the single tx antenna, the $i-th$ rx antenna would receive a signal

$$y_i = h_i s + z$$

where h_i is the channel state information between the tx and $i-th$ rx antenna and z is additive noise.

The MRRC combining scheme states that the received estimate would be

$$\bar{s} = \frac{\sum_{i=1}^{n} h_i^* y_i}{\sum_{i=1}^{n} |h_i^2|}$$

2.1.2 Alamouti Scheme

This scheme introduces transmit diversity into the system by using two transmit antennas, and N_r receive antennas. The channel state information for the channel between tx antenna i and rx antenna j is represented as h_{ij}. We transmit the symbol s_1 and s_2 from tx antenna 1 and 2 respectively in the time slot 1, and $-s_2^*$ and s_1^* from tx antenna 1 and 2 respectively in the time slot 2. This block is generally represented as

$$\begin{vmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{vmatrix}$$

At the receiver, $r_j(k)$ denotes signal received by $j-th$ antenna in the $k-th$ time slot. Thus we can generalize,

$$r_j(1) = h_{1j}(s_1) + h_{2j}(s_2) + z$$

$$r_j(2) = h_{1j}(-s_2^*) + h_{2j}(s_1^*) + z$$

Now, the combiner is designed such that we can extract the two symbol estimates $\bar{s_1}$ and $\bar{s_2}$ using the following equations,

$$\bar{s_1} = h_{1j}^* r_j(1) + h_{2j} r_j^*(2)$$

$$\bar{s_2} = h_{2j}^* r_j(1) - h_{1j} r_j^*(2)$$

2.2 Decoding Strategies

2.2.1 Zero Forcing Equalizer (ZF)

We know that the received signal can be represented in a matrix form as $Y = HX + N$. Now one of the ways to obtain the matrix X is given by the ZF equalizing method. In essence we try to obtain an inverse of H such that we can calculate X.

$$Y = HX + N$$

Now we find a matrix W such that

$$WH = I$$

The zero forcing linear detector is given by

$$W = (H^H H)^{-1} H^H$$

This matrix is also known as the pseudo inverse matrix of H.

2.2.2 Minimum Mean Squared Error equalizer

Another way to decode X is using the MMSE equalizer. This is similar to the ZF method. For $Y = HX + N$ we minimize the following

$$E[(WY - X)(WY - X)^H]$$

Now solving this we get,

$$W = (H^H H + N_0 I)^{-1} H^H$$

From the above equation we notice that when the noise term is zero, MMSE effectively becomes ZF.

2.2.3 Maximum Likelihood Decoding

The ML decoding is the optimal decoding method. The method basically involves choosing the constellation symbol with minimum distance from the received symbol. The symbol $\hat{x}$ that minimizes the following function is chosen

$$J = |Y - H\hat{x}|^2$$

2.2.4 Successive Interference Cancellation Technique (SIC)

In this method, either of the estimated signal $\hat{x_1}$ or is $\hat{x_2}$ subtracted from the received signals y_1 and y_2. The selection of which estimate to subtract is random here.

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} y_1 - h_{1,2}\hat{x_2} \\ y_2 - h_{2,2}\hat{x_2} \end{bmatrix} = \begin{bmatrix} h_{1,1}\hat{x_1} + n_1 \\ h_{2,1}\hat{x_1} + n_1 \end{bmatrix}$$

This can then be written as

$$R = Hx_1 + N$$

Thus the equalized symbol is

$$\hat{x} = \frac{H^H R}{H^H H}$$

2.2.5 SIC with optimal ordering

Now an optimization of the above method is called SIC with optimal ordering. In this the power P_{x_1} and P_{x_2} is taken at both the receive antennas.

$$P_{x_1} = |h_{1,1}|^2 + |h_{2,1}|^2$$

$$P_{x_2} = |h_{1,2}|^2 + |h_{2,2}|^2$$

Now if $P_{x_1} > P_{x_2}$ the receiver decides to remove the effect of x_1 from y_1 and y_2 and estimate x_2. If $P_{x_1} < P_{x_2}$ the opposite happens.

2.2.6 VBLAST

Most discussed techniques tend to focus on improving the error performance in the wireless communication system. On the other hand there are a few techniques to improve spectral efficiency of communication, thus improving data rates for the same spectrum. One such technique we shall discuss in vertical BLAST (Bell Laboratories Layered Space- Time) or V-BLAST. Below we have a diagram depicting the VBLAST setup

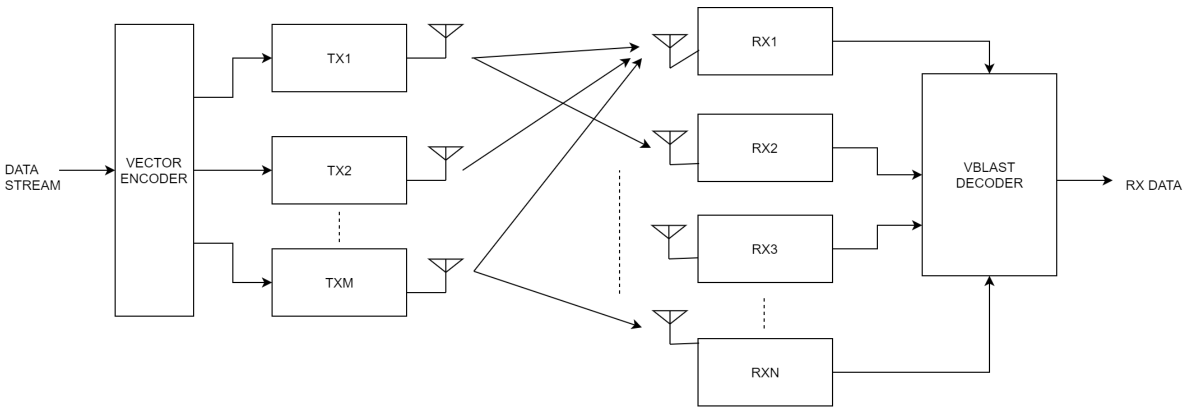


Figure 2.1: VBLAST scheme

The vector encoder encodes the incoming data stream to $a_1, a_2, a_3 ... a_n$ into vectors corresponding to the number of transmit antennas as $a = [a_1, a_2, a_3, ..a_{ntx}]^T$. The decoding strategy of VBLAST is a combination of the above mentioned methods. The figure below depicts the flow of data in VBLAST.

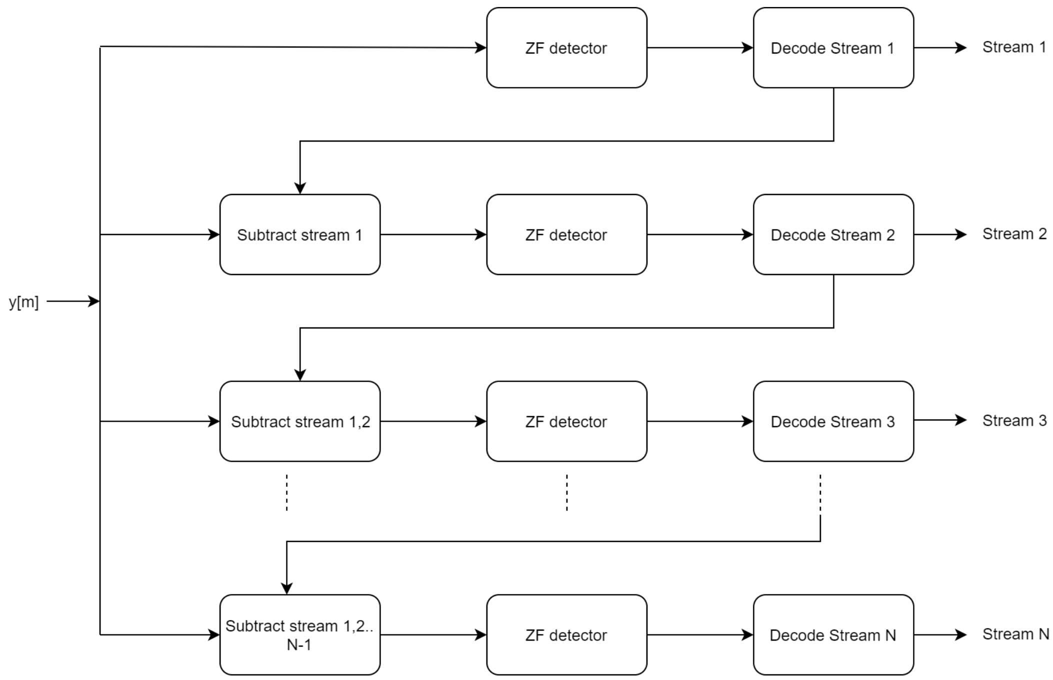


Figure 2.2: VBLAST Decoder

2.3 STBC Construction

A good STBC is determined by two main criteria, the Rank and Determinant criteria. The rank criteria states that for a code word matrix C, a matrix B is defined as the difference between the actual code matrix and received code matrix

$$B = C - \bar{C}$$

Another matrix A as,

$$A = B(B^*)^T$$

This matrix A must be of full rank for all possible combinations of C and $\bar{C}$.
The determinant criterion states that the minimum valued determinant of matrix A must be maximized for all combinations of C.

CHAPTER 3
Implementation on GNU Radio

3.1 Software Defined Radio

Software defined radio (SDR) is a concept in which components usually implemented in hardware (such as filters, detectors, modulators, demodulators etc) are implemented in software. Below we the basic architecture of a software defined radio.

We had started work on the Wireless Access Research Platform (WARP v3) board by Mango Communications but due to lack of support and compatibility issues at the physical layer we had to discontinue working on these boards. Hence we have completed all our work on the Ettus Research B210 SDR board.

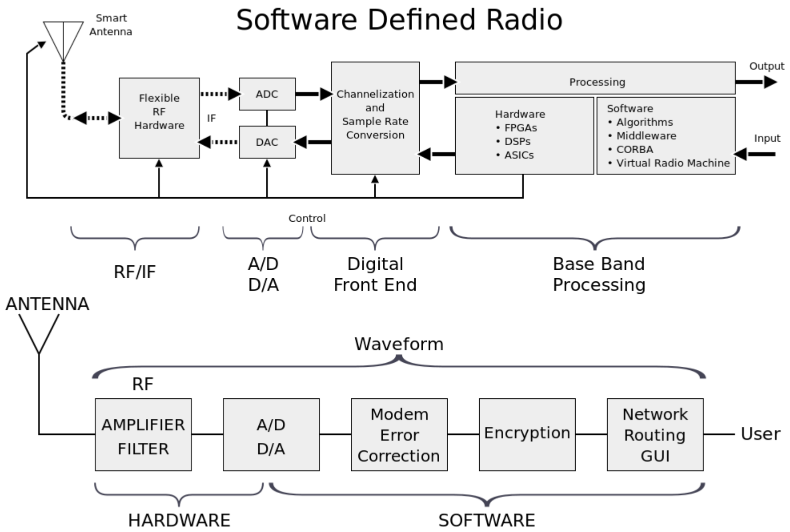


Figure 3.1: Software Defined Radio block diagram

3.1.1 GNU radio

The software end of our setup is an open source software called GNU Radio, supported by the USRP B210 platform.

We use the the GNU Radio Companion (GRC) which has a GUI interface to simulate and implement physical layer designs. The basic steps involved in using GNU Radio are to create a flow graph, generate the Python code corresponding to the flow graph, and finally execute the code.

Flow Graphs

In a GRC flow graph, block input and output ports are connected together to create a logical stream of data from a source to a sink. Every flow graph must have at least one source and one sink. When connecting blocks to create a flow graph blocks with matching port data types have to be connected.

Block Types

- Source : This type of block is an output only block as it produces samples and has no inputs.
- Sink : This type of block is an input only block as it receives samples and has no outputs.
- Interpolating/Decimating : These blocks have an input and output with different samples rates depending upon the oversampling/undersampling factor chosen.
- Variable : This block is used to define a universal variable in the flowgraph.
- Sync : This block has the same output data rate as input data rate.
- Hierarchial : This is an abstraction of an independent flowgraph that can be used as a single block in other designs.
- General : This type of block can have any ratio of input rate to output rate.

3.1.2 SISO Transmitter

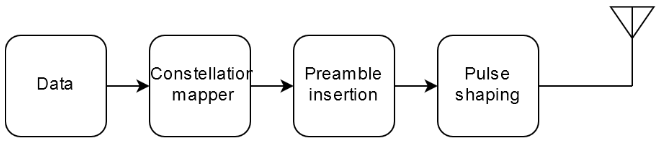
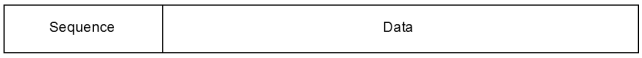


Figure 3.2: SISO Transmitter

- The file containing data to be transmitted is read using the **File Source** block.
- In order to use a modulation scheme, the information bits must be repacked in the symbol capacites. The **Repack Bits** block was used to repack 8-bits into m-bits. It converts the incoming byte to unpacked bytes, for eg. a byte of data is split into 4 sets of 2 bits so that each set can be transmitted using QPSK (2 bits per symbol).
- The **Chunks to Symbols** block maps the unpacked bytes of data into QPSK constellation symbols which are of complex type.
- A Unique Codeword was inserted periodically between the symbols to be transmitted to achieve symbol level synchronization at the receiver. Barker codes were used to synchronize data frames but the correlation with data was observed to be comparable to that with itself.

- We chose the the following complex Unique Codeword : -1-1j, -1-1j, -1-1j, -1-1j, -1+1j, 1+1j, -1+1j, -1-1j, -1-1j, -1-1j, -1-1j. This codeword gave us good autocorrelation peaks and poor cross correlation with rest of the frame. **Vector Insert** block was used to perform the function.



Tx frame

- **Polyphase Arbitrary Resampler** with root raised cosine filter coefficients followed by a **Low pass filter** was used for interpolated pulse shaping.
- The **UHD: USRP sink** block was used to pass the processed data to the hardware for transmission.

3.1.3 SISO Receiver

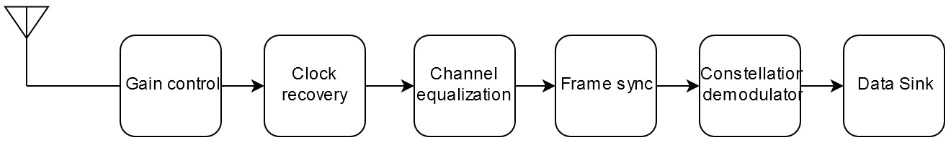


Figure 3.3: SISO Receiver

- The **UHD : USRP source** block is used to obtain the received I/Q values.
- The **Automatic Gain Control (AGC)** block was used to automatically control the sample energy of the received data stream to the amount specified in the reference setting.
- The **Polyphase Clock Sync** block was used to perform timing recovery.
- Frame synchronization is performed using the custom made hierarchial **Corr, Sync and Ch. Estimate block**. The block also performs simple channel estimation for the purpose of equalization.
- The data was then extracted from the synchronization frame using the **Keep M in N block**.
- The synchronized data is then decoded using **Constellation decoder**. The block then converts the constellation symbols into data bits and outputs them in unpacked byte format. The **Repack Bits** block is then used to convert the unpacked bytes into packed bytes.
- The **File Sink** block is then used to write the demodulated data into the output file.

3.1.4 MIMO Transceiver

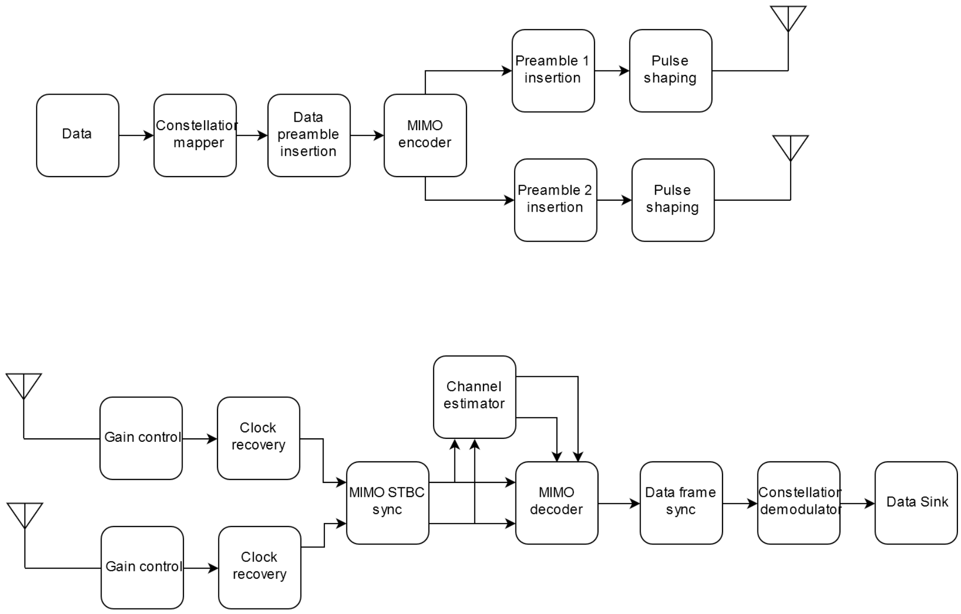


Figure 3.4: MIMO Transceiver

The flow of data in a MIMO system is similar to that of a SISO system except for the STBC sync and encoder/decoder.

- MIMO STBC synchronization is performed so that the receiver is able to clearly identify the starting point of the STBC from symbol data received.

MIMO stream 1	Sequence 1	Null sequence	STBC symbol data
MIMO stream 2	Null sequence	Sequence 2	STBC symbol data

MIMO transmission frame

- We have used the Alamouti scheme in all our MIMO SDR simulations and lab trials. The custom designed Alamouti encoder, Alamouti 2x1 and 2x2 decoder blocks were used to implement the scheme.

3.2 Designs

The following design is our design for simulation of a SISO system with pulse shaping, gain control, timing recovery, and frame synchronization.

3.2.1 SISO design

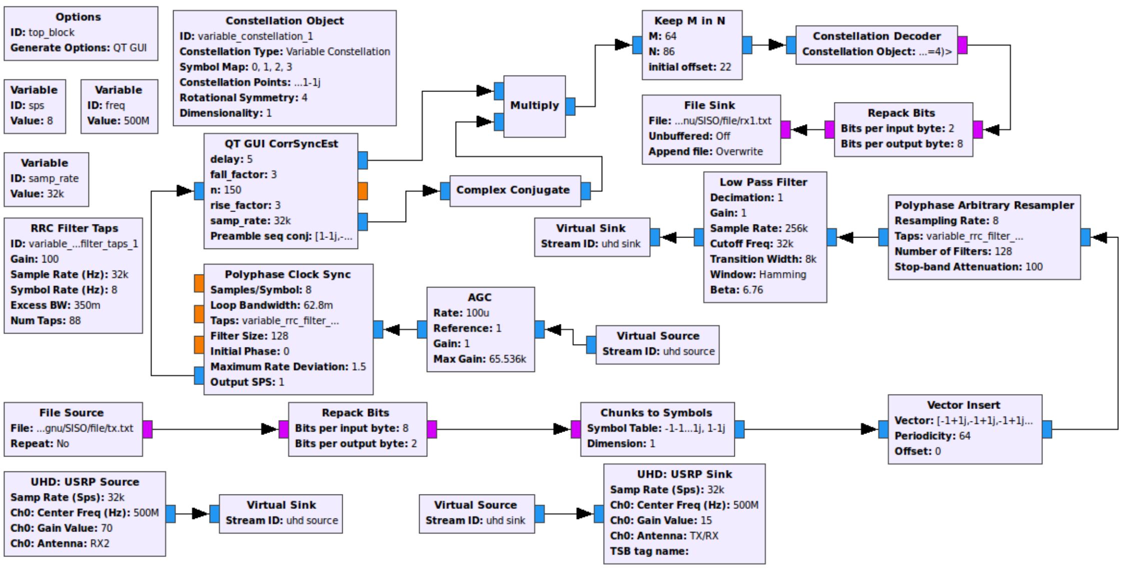


Figure 3.5: SISO implementation in GNU Radio Companion

3.2.2 MISO/MIMO simulation design

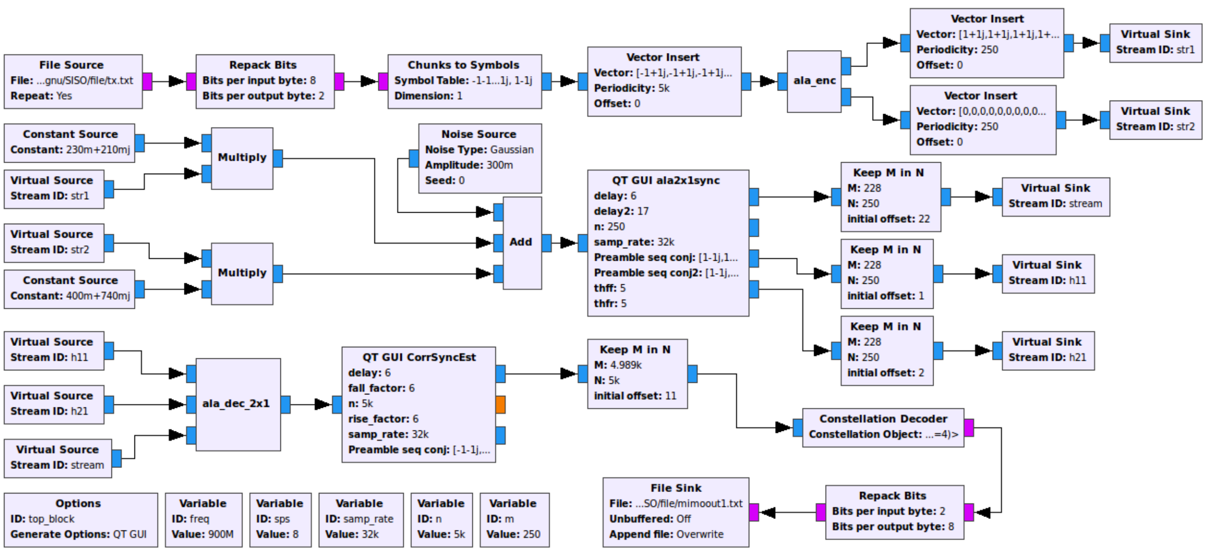


Figure 3.6: MISO implementation in GNU Radio Companion

Similarly we have used a 2x2 MIMO synchronization block in place of the 2x1 and a 2x2 Alamouti decoder in place of the 2x1 Alamouti decoder. Our simulations have given almost perfect results with these designs, with results shown in figure 4.11.

3.2.3 Custom block design

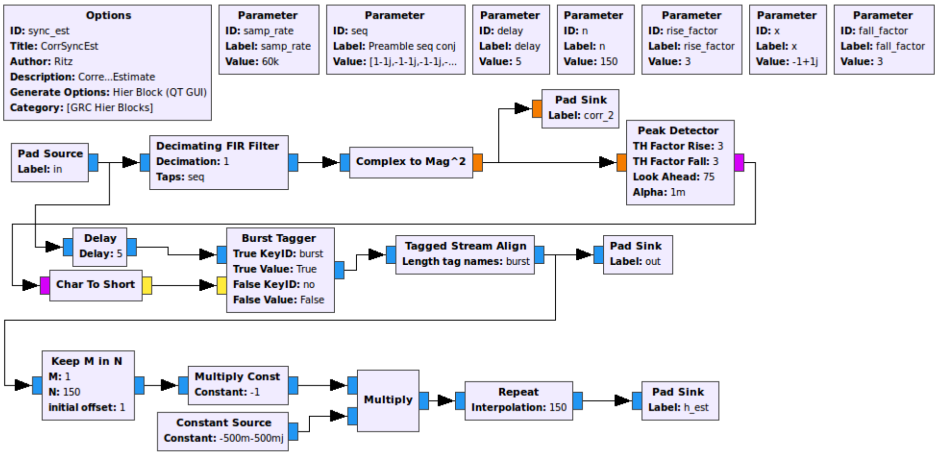


Figure 3.7: Data frame synchronization

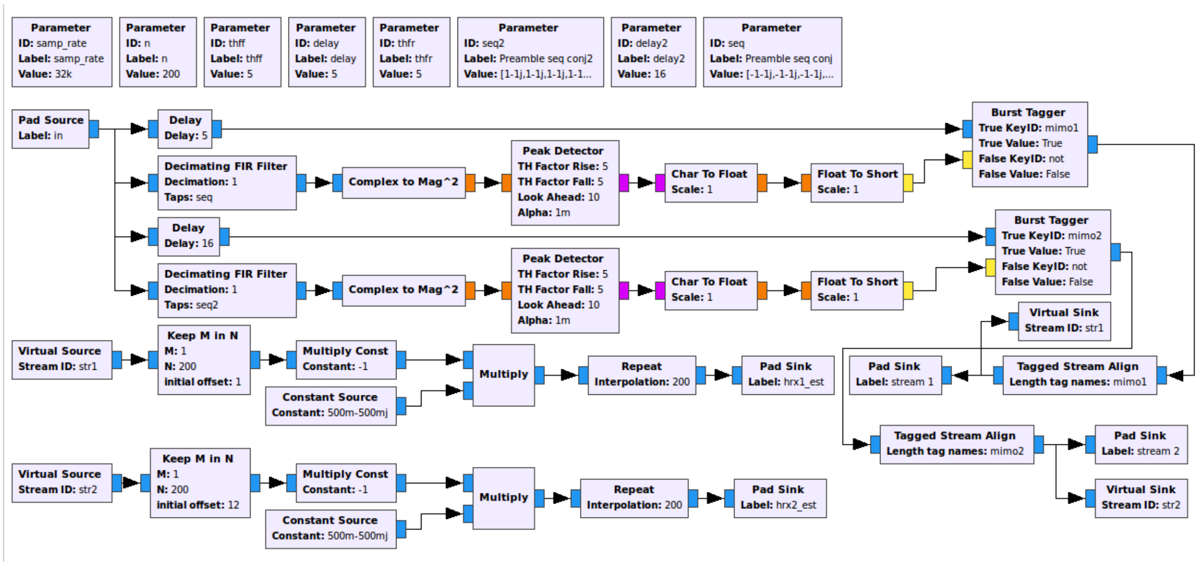


Figure 3.8: MIMO frame synchronization

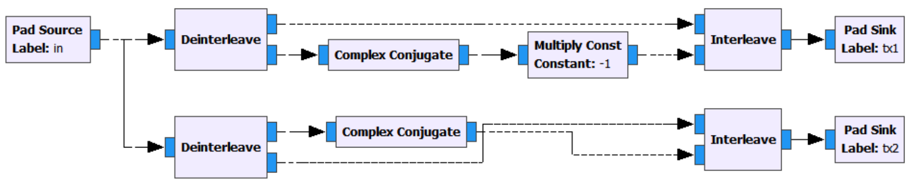


Figure 3.9: Alamouti encoder design

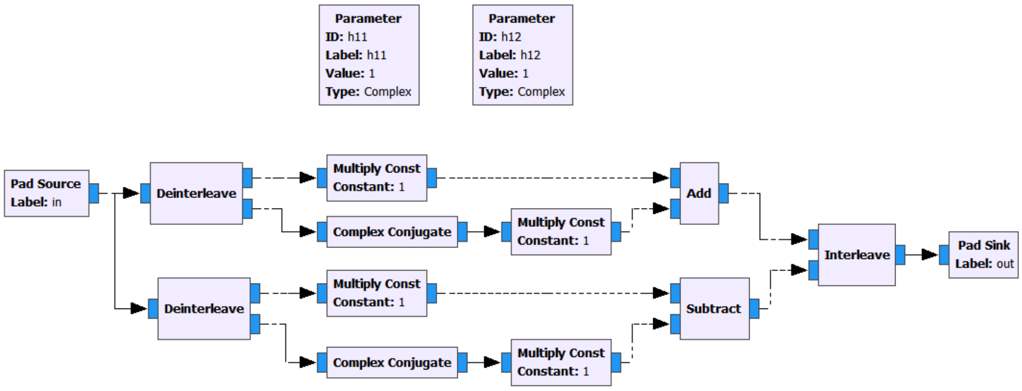


Figure 3.10: Alamouti 2x1 decoder

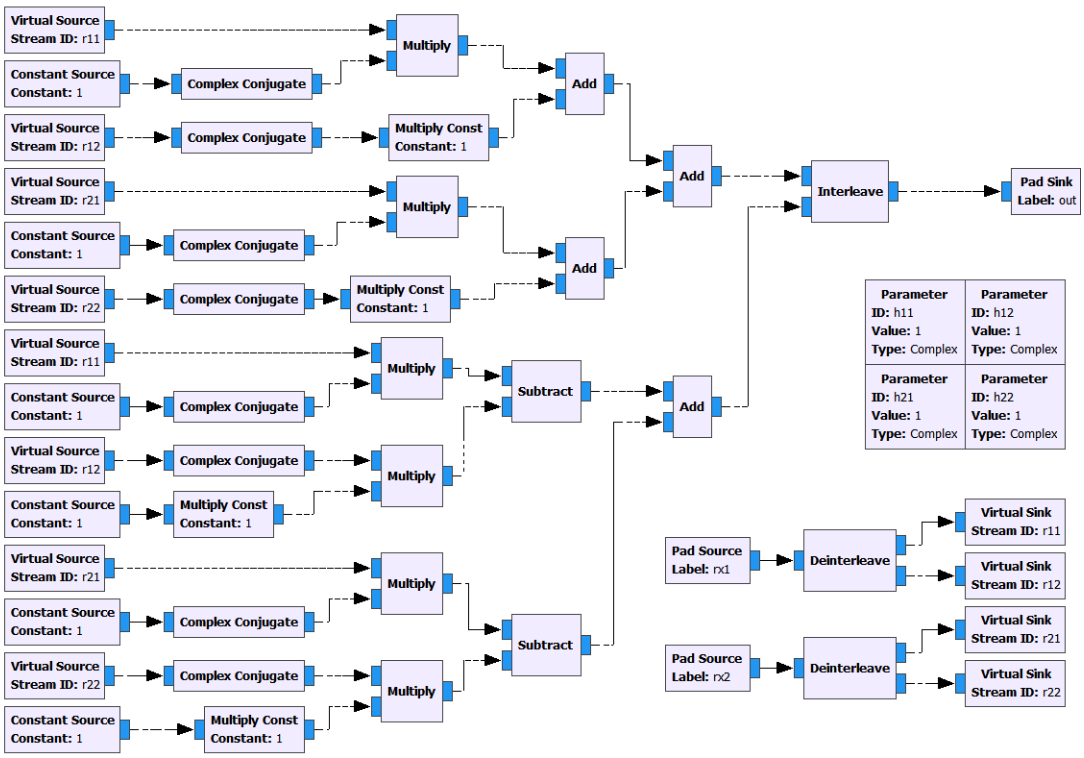


Figure 3.11: Alamouti 2x2 decoder

CHAPTER 4
Conclusions

4.1 Analysis

4.1.1 Simulation results

Fading Channels

We have begun our simulations by simulating the fading channels. In order to account for the sudden changes in the signal due to multipath effects, a Rayleigh or Rician channel model can be used. The Rayleigh channel model is useful in describing small scale fading effects in the absence of a dominant Line of Sight component, whereas, the Rician model describes the fading process in the presence of a dominant LoS component. We go for the Rayleigh model.

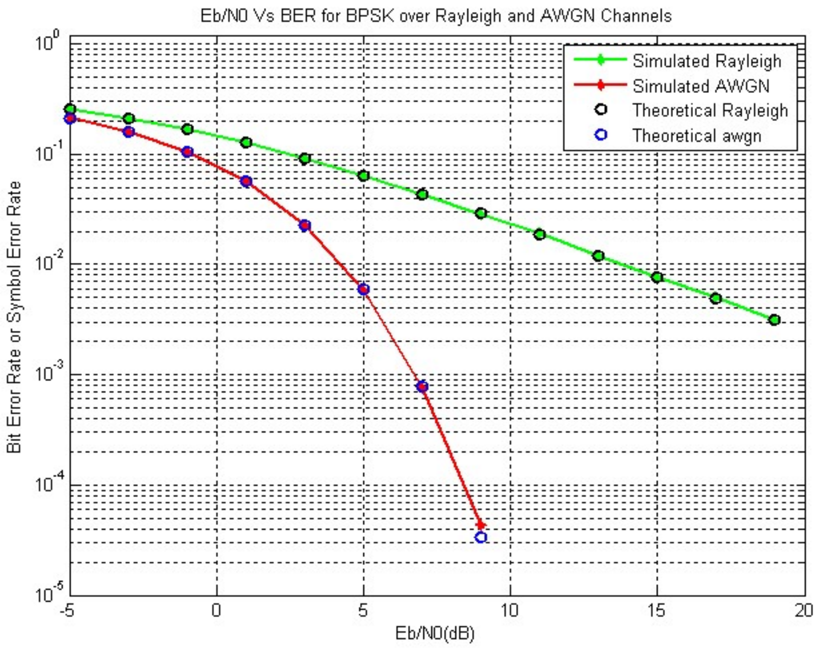


Figure 4.1: Performance of BPSK system over AWGN vs Rayleigh channel

The theoretical BER of a BPSK signal in AWGN channel is given as,

$$P = \frac{1}{2} erfc(\sqrt{\frac{E}{N}})$$

The theoretical Symbol Error Rate of a QPSK signal in AWGN channel is given as,

$$P = erfc(\sqrt{\frac{E}{2N}})$$

The theoretical BER of a BPSK signal in Rayleigh channel is given as,

$$P = \frac{1}{2}(1 - \sqrt{\frac{\frac{E}{N}}{\frac{E}{N}+1}})$$

We notice that the a communication system has better performance in the AWGN channel, but in practice we generally observe Rayleigh channel behaviour, impeding performance significantly over the AWGN case. The fundamental goal of the antenna diversity techniques is to convert a wireless fading channel into a stable AWGN like channel without significant instantaneous fading, thereby steepening the BER versus SNR curve and hence improving the reliability of the communication system. It is observed that the performance of a BPSK modulated system over a Rayleigh channel is about 15dB worse than that over an ideal AWGN channel at a BER of 0.01.

Maximal Ratio Receiver Combining (MRRC)

From our simulations we notice that MRRC performance improves as diversity order is increased; aligning with expectations. Simulation has been performed in a Rayleigh channel.

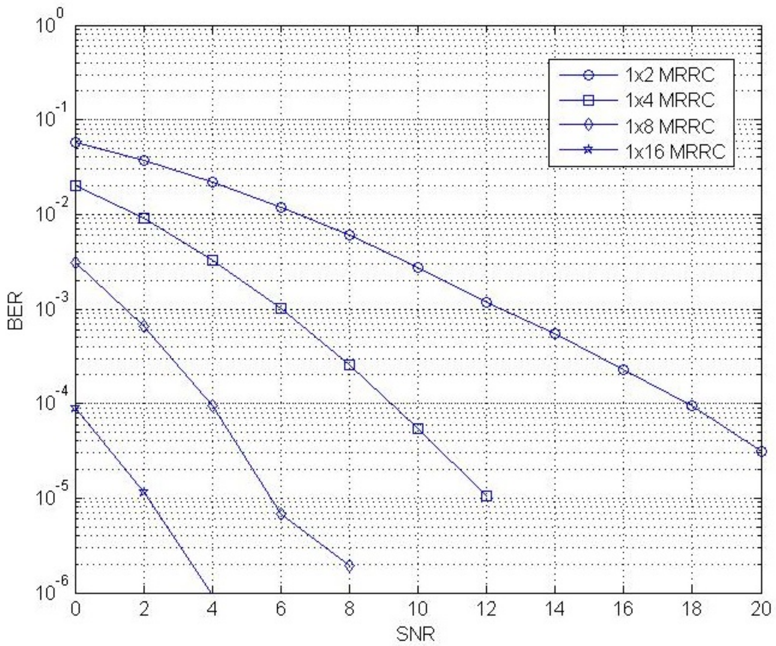


Figure 4.2: MRRC scheme for different diversity orders

It is observed that as the diversity order is increased, the reliability of the communication system improves. The MRRC 1X4 system gives about 4.3dB improvement over the MRRC 1X2 system at a BER of 0.01. The MRRC 1X8 system gives about 4.5dB improvement over the MRRC

1X4 system at a BER of 0.0001. The MRRC 1X16 system gives about 4dB improvement over the MRRC 1X8 system at a BER of 0.0001.

MRRC vs Alamouti vs Real STBC

We have also compared the performance of basic 2x1 Alamouti, 1x2 MRRC and a real 3x4 STBC (QPSK modulation used for all).

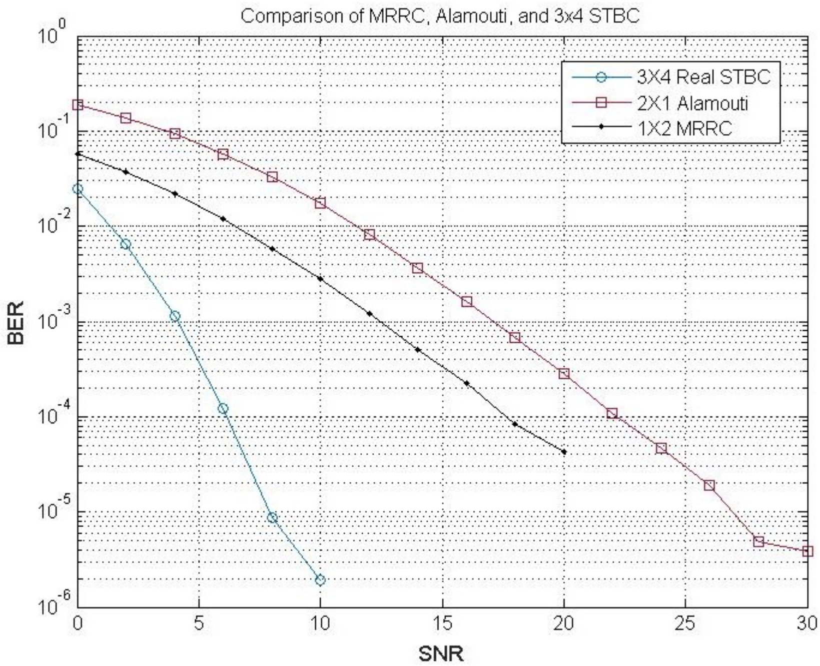


Figure 4.3: 1X2 MRRC vs 2X1 Alamouti vs 3X4 real STBC comparison

It is observed that the 1X2 MRRC scheme shows a 5dB improvement over the 2X1 Alamouti Scheme at a BER of 0.001. The 3X4 real STBC shows 7.5 dB improvement over the 2X1 Alamouti scheme at a BER of 0.001.

We now demonstrate how different decoding and equalization techniques at the receiver improve the performance of the communication system. In order to compare the effects of various techniques we use a 2X2 system as a benchmark.

Decoding strategies

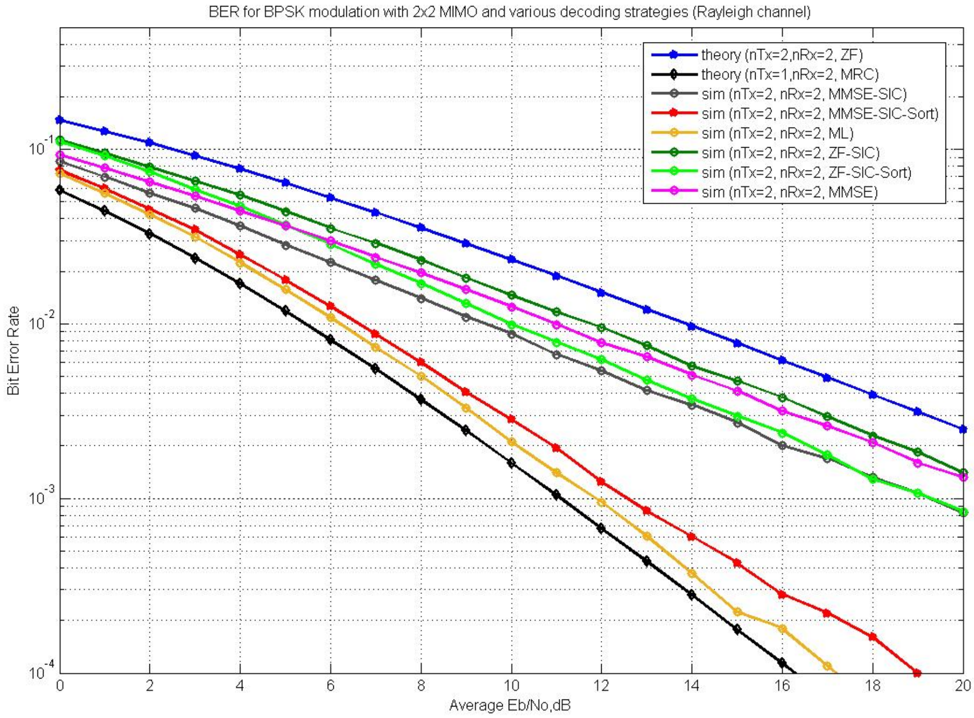


Figure 4.4: Comparison of various decoding strategies

The Zero Forcing equalizer is not the best possible way to equalize the received symbol. The zero forcing equalizer helps us to achieve the data rate gain, but cannot take advantage of diversity gain. We might not be able to achieve the two fold data rate improvement in all channel conditions. It may be possible that the channels are highly correlated and hence we might not be able to solve for the two unknown transmitted symbols. Compared to ZF, addition of SIC results in about 2.2dB of improvement for BER of 0.001. The improvement is due to decoding of the information using noise estimated from estimation of the previous symbol. Compared to the Zero Forcing equalizer, it can be seen that the Minimum Mean Square Error (MMSE) equalizer results in around 3dB of improvement at a BER of 0.001. Compared to MMSE-SIC, adding optimal ordering to it results in about 5dB improvement at a BER of 0.001. Maximum Likelihood (ML) decoding gives us the best performance among all other strategies. We use Rayleigh flat fading multi-path channel with BPSK modulation. The results for 2x2 MIMO with ML equalization achieves a performance close to the 1x2 MRRC case with MRRC being better by about 1dB. If we use a higher order constellation such as 64QAM, computing Maximum Likelihood equalization becomes very complex. To handle this problem other techniques such as Sphere Decoding could be used.

4.1.2 Experiments on B210 SDR

We have analyzed the data at the output of critical blocks in terms of constellation points. The experiments were conducted in indoor lab environment which can be modeled as a Rician fading channel. The first round of experiments dealt with the implementation of a SISO communication system on a single B210 board. The message sent was a 2.9kB text file of alphabets. The file was read and mapped onto constellation points and transmitted over a wireless channel. The transmission was carried out at various frequencies in the 0.5-2 Ghz range. The best performance was observed at 900 Mhz.

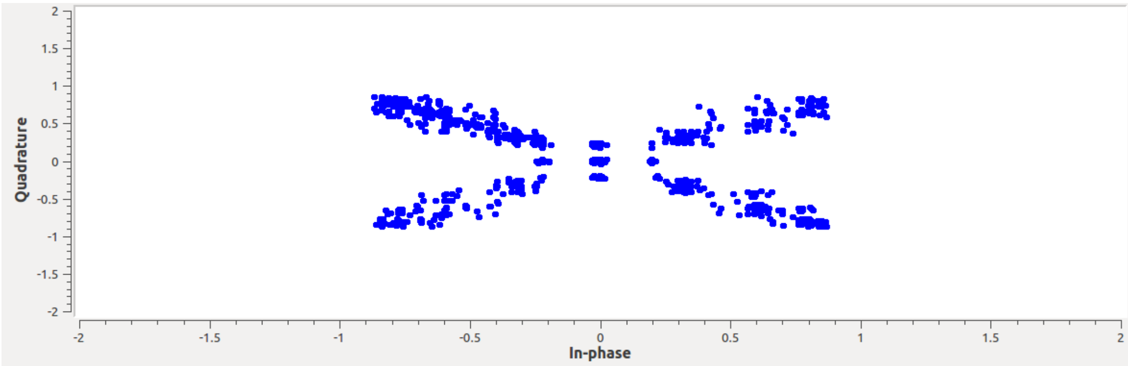


Figure 4.5: Transmitted constellation

The above constellation tends to have multiple samples of varying amplitude for the same data point due to the low-pass filter used after oversampling (2x-8x) the transmission symbols.

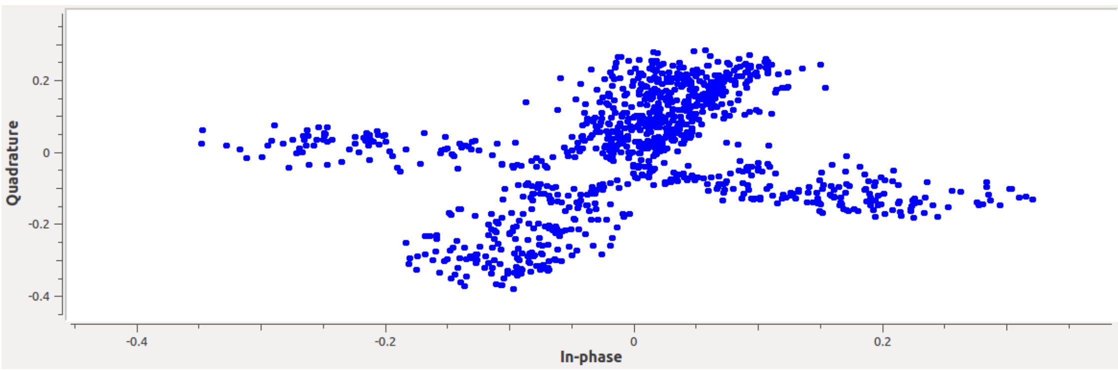


Figure 4.6: Received constellation

We can notice that the received constellation has been amplitude and phase shifted by the channel. Another peculiar inference made was that at each run of the program, the received constellation was differently affected preventing us from using static channel state information for the next execution although our setup was in a laboratory environment.

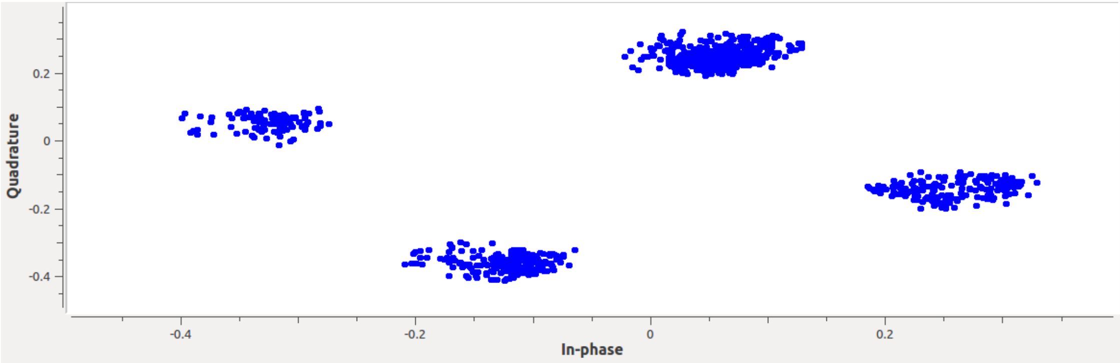


Figure 4.7: After timing recovery

We see that the symbols after timing recovery appear as a clear and not so noisy constellation.

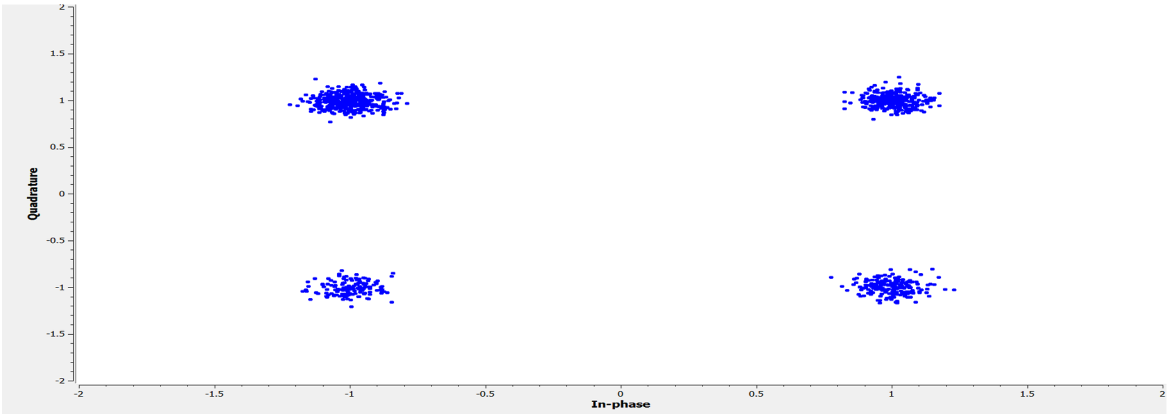


Figure 4.8: After equalization

We see that the symbols after equalization appear as a 4-QAM constellation.

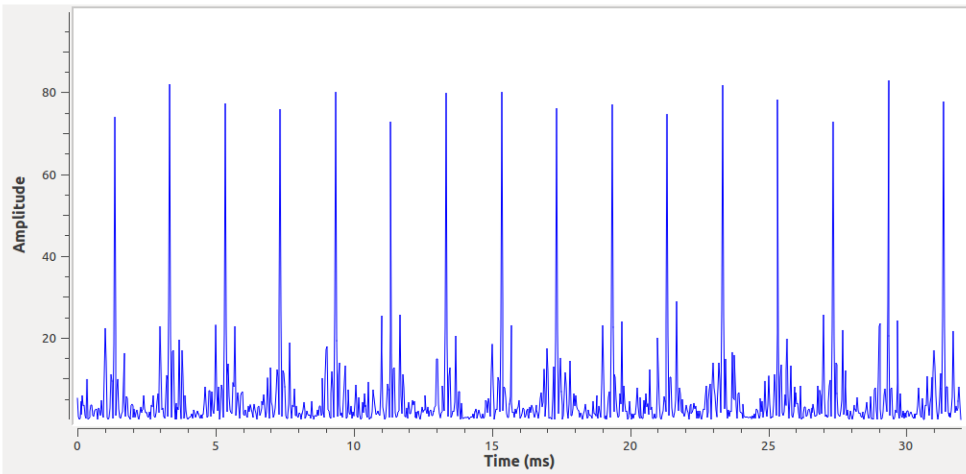


Figure 4.9: Data frame correlation peaks

The frame synchronized and decoded data appears to have errors such as (best case) over SISO SDR transmission:

```
abcdefghijklmnopqrstuvwxyz29
abcdUÕ_ejklmnopqrsUuvwxyz29
```

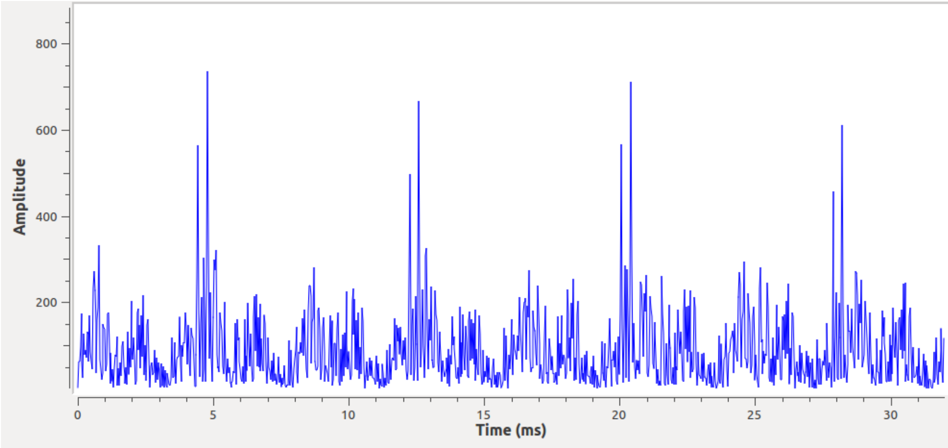


Figure 4.10: MIMO Frame Correlation peaks

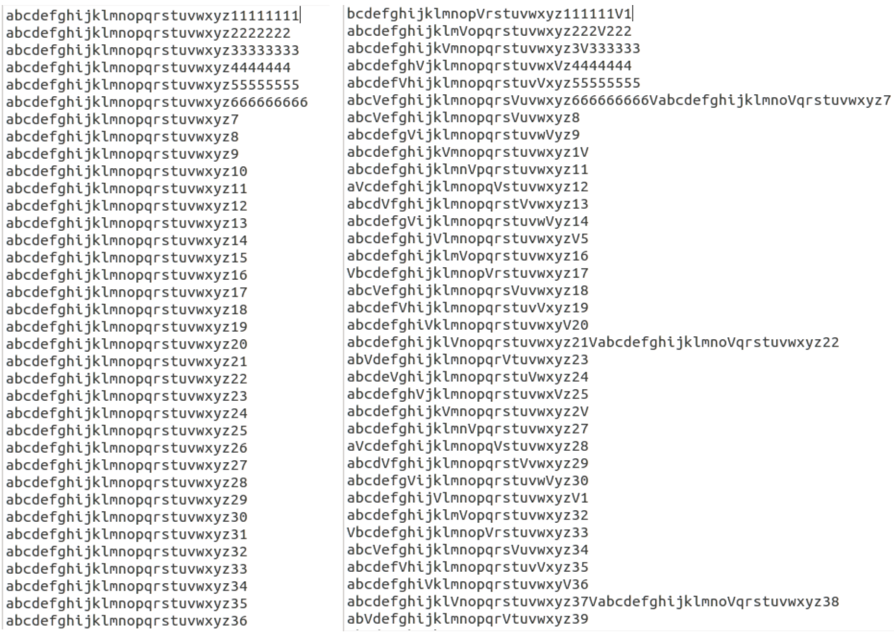


Figure 4.11: MIMO simulation transmitted vs received

4.2 Summary

The deterministic free space path loss model using antenna parameters, wavelength and distance from the transmitter was not sufficient to characterize a channel. This model did not take into account the effects of fading in practical channels. In order to account for the changes in the signal due to multipath effects, a Rayleigh/Rician channel model was used. The Rayleigh channel model is useful in describing small scale fading effects in the absence of a dominant Line of Sight component, whereas, the Rician model describes the fading process in the presence of a dominant LoS component. The performance of a SISO system over a practical Rayleigh channel is significantly poorer compares to its performance over an AWGN channel. In an effort to reduce the probability of the signal undergoing deep fades in a Rayleigh channel we try to get around the problem by using multiple antennas. This approach is based on the fact that the probability of the signal being depleted along each of the paths is lower compared to the SISO case. Various diversity techniques involving transmit diversity, receive diversity or both were compared. The BER vs SNR characteristic improved with higher diversity order. Communication systems utilizing different decoding strategies were compared. The various equalization strategies used are Zero Forcing (ZF), Minimum mean squared error (MMSE) and Maximum Likelihood (ML) decoding. The above decoding techniques are improved using Successive Interference Cancellation (SIC). The performance is further improved by employing the Optimal Ordering technique. However, the ML approach out performs all the above approaches.

Most of our work was based in the physical layer, that is, sending bits of data from one antenna to another. This process involved quite a few steps ranging from encoding of data, repacking of bits, managing byte operations, mapping data into symbols, sending data over a wireless channel and effective reception. Symbol synchronization and nulling out channel disturbances are the key areas where we continue to face a lot of challenges. Symbol timing synchronization issues were handled to a certain extent by using the Polyphase Clock Sync block[4] and data frame synchronization issues were solved using a custom designed correlation, sync and estimation block. Simple channel estimation was performed within the correlation and syncronization block, and the estimate was used to equalize the synchronized signal. Due to limitations of the software to execute data flow loops we were unable to implement adaptive equalization using GNU Radio.

The MIMO frame sync, data frame synchronization, Alamouti 2x1 and 2x2 decoder, Alamouti encoder, channel estimation and equalization (sub)blocks were verified to be working within practical simulation runs with data recovered with an accuracy of 99% or above. Due to SDR performance challenges the system was unable to receive a signal clear and powerful enough for error free decoding in majority of the trial runs. However at times of good performance, we have been able to obtain the results as shown above in the Analysis section.

REFERENCES

[1] "Multiple-input multiple-output wavelet packet modulation based software-defined radio transceiver design", by Michael R. Cribbs, Naval Postgraduate School.

[2] "Implementation of Two Physical Layer Security Techniques in an OTA system" by Kevin Ryland, Marc Lichtman, T. Charles Clancy, Vol 2 No 1 (2017): Proceedings of the 7th GNU Radio Conference

[3] S. M. Alamouti, A simple transmit diversity technique for wireless communications, IEEE J. Select. Areas Commun., vol. 16, pp. 14511458, Oct. 1998.

[4] IEEE journal on selected areas in communications, VOL. 19, NO. 12, DECEMBER 2001 Multirate Digital Filters for Symbol Timing Synchronization in Software Defined Radios Fredric J. Harris , Senior Member, IEEE, and Michael Rice, Senior Member, IEEE

[5] S. M. Alamouti, A simple transmit diversity technique for wireless communications, IEEE J. Select. Areas Commun., vol. 16, pp. 14511458, Oct. 1998.

[6] V. T. Tarokh, S. M. Alamouti, and P. Poon, New detection schemes for transmit diversity with no channel estimation, in Proc. IEEE Int. Conf. Universal Pers. Commun. (ICUPC 98), vol. 2, Oct. 1998, pp. 917920.

[7] V. Tarokh, H. Jafarkhani, A.R. Calderbank, Space Time Block Coding from Orthogonal Designs, IEEE Trans. Inform. Theory, July 1999.

[8] Ebrahimi, Mojtaba & Aidin Bassam, Seyed & Helaoui, Mohamed & Ghannouchi, F.M.. (2010). Packet Detection, Frequency Synchronization, and Channel Estimation/Equalization of Reconfigurable OFDM-Based Receivers for SDR Applications. 87-93.

[9] An Experimental Study on Channel Estimation and Synchronization to Reduce Error Rate in OFDM Using GNU Radio C Anjanaa, S Sundaresana, Tessy Zachariaa, R Gandhirajb, K P Somana

[10] B. Bougard, A. Bourdoux, F. Naessens, M. Glassee, V. Derudder and L. Van der Perre, "Energy-efficient software-defined radio solutions for MIMO-based broadband communication," 2007 15th European Signal Processing Conference, Poznan, 2007, pp. 1141-1145

[11] E. G. Larsson and J. Li, ”Preamble design for multiple-antenna OFDM-based WLANs with null subcarriers,” in IEEE Signal Processing Letters, vol. 8, no. 11, pp. 285-288, Nov. 2001

[12] Martelli, Francesca & Kocian, Alexander & Santi, Paolo & Gardellin, Vanessa. (2014). MIMO-OFDM spatial multiplexing technique implementation for GNU radio. SRIF 2014 - Proceedings of the ACM SIGCOMM 2014 Workshop on Software Radio Implementation Forum.

[13] https://wiki.gnuradio.org/index.php/GuidedTutorials

[14] https://gnuradio.org/doc/doxygen/index.html (GNU Radio Manual and API reference)