Implementation of Spatial Diversity and Spatial Multiplexing through MIMO in GNU Radio

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Abstract:

MIMO (Multiple-Input Multiple-output) is the current concept that is used in advanced wireless technology like 3G/4G cellular networks. MIMO makes antennas work smarter by enabling them to combine data streams arriving from different paths and at different times to effectively increase receiver signal-capture power. The main advantages of MIMO is to increase reliability of the link between transmitter and receiver and increase in throughput and capacity of the channel. These aspects of MIMO can be implemented through spatial diversity and spatial multiplexing techniques. Incorporating these ideas into GNU Radio will provide an opportunity to practically exploit the MIMO technology. My aim in the project here will be to design a MIMO module which can be included into the GNU Radio.

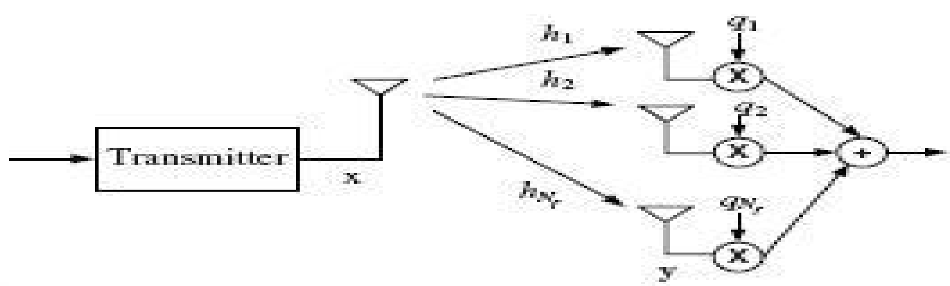
Background Information:

Currently I am pursuing my MS in wireless communication from IIIT Hyderabad, India. My area of research is in the area of Cognitive Cellular Network. My current GPA (first semester), is 9.67 (scale of 10). I completed my under graduation in Electronics and Telecommunication from IIIT Bhubaneswar, India with a GPA of 8.68 (scale of 10). Some of the courses I took in under graduation include Linear algebra, Analog and Digital communication, Adaptive signal processing, Radar communication , Mobile communication and Wireless Sensor Networks. I joined the MS program in fall of 2013 and have taken courses like 3G/4G cellular networks, Speech signal processing, Underwater signal processing , Wireless communication and Artificial neural network. My programming skills include C, C++, Shell Scripting, Matlab and Python. I started working on software defined radio when I joined the MS program. I am well versed with GNU Radio and have worked with USRP1 and USRP2. I have started making my own signal processing blocks in GNU Radio.

Concept behind MIMO:

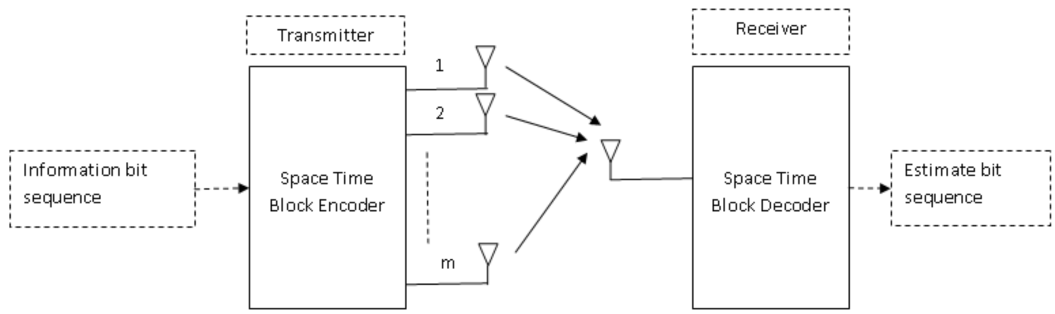
The explosion of number of subscribers to the available wireless technology have increased the expectations in service and capacity. For wireless technology, a novel solution for it is exploitation of multiple antenna system at both transmitter and receiver sides. Wireless systems with multiple antenna elements is known as Multiple Input Multiple output (MIMO) system. Use of multiple transmit and receive antennas in a wireless system helps in contributing in two aspects: Increasing reliability of the link and increasing capacity of the network ,i.e., the data rate[1,2,5]. The reliability of the link can be increased by the use of receive diversity. The network capacity is enhanced by use of MIMO systems employing techniques such as Space-Time Block Coding (STBC) and Spatial Multiplexing. Lets us briefly understand each of the concepts.

Receive diversity deals with use of multiple antennas at the receiver to combat channel fading. It improves reliability of the link, which can be achieved by transmission and reception of several replicas of the same information through independent fading paths and hence reduces deep fading. The concept of replicas of the same information at the receiver is referred as receive diversity and the number of independent reception of same information at the receiver is defined as “diversity order” or “diversity gain”. The bit error rate (BER) is seen to decrease exponentially with the increasing “diversity order”[5,6]. In a typical receive diversity system, each receive antenna receives replicas of same information coming from the transmitter antennas. At the receiver , the weighted sum of the outputs of each receive antennas is computed in order to maximize the SNR. This method of combination of the receive antennas outputs is known as Maximal Ratio Combination and the receiver is known as Maximal Ratio Combiner (MRC). Receive diversity is a key idea in implementation of 3G/4G networks. As in 3G/4G systems, Gigahertz frequency range is used and hence the separation between antenna arrays becomes feasible to be implemented in a mobile handset (receiver). Summarily it can be said that implementation of receive diversity mitigates effect of channel fading and hence increasing the reliability of the link. Below is the block diagram of simple receive diversity employing one transmit antenna and multiple receive antennas[1].

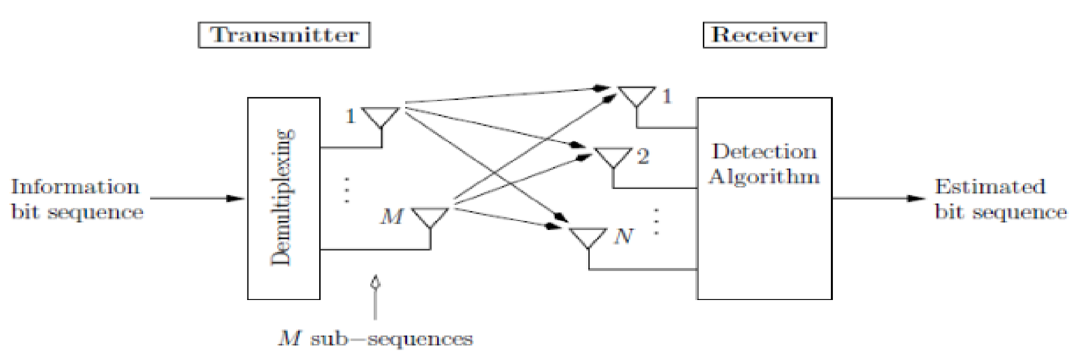


maximal ratio combing

MIMO systems employ different kind of techniques such as Space-Time Block Coding (STBC) and Spatial Multiplexing to increase the capacity of the network ,i.e, increasing the data rate. The simplest method used under STBC is Alamouti coding which does transmit diversity. Normal procedure for transmit diversity require channel state information (CSI) at the transmitter but using STBC, CSI will not be required at the transmitter. The simplest of the code is Alamouti Code[1,2,5] which can be used for 1X2 . At the receive, each of the symbol transmitted from the two transmit antennas are decoded with a diversity order of 2, hence increasing the data rate efficiently. If same symbol is transmitted from two antennas , it can increase the probability of correct reception of the symbol ,.i.e., avoid fading of symbol. Below is the block diagram of simple transmit diversity employing two transmitter antennas and one receive antenna employing Alamouti Code[1]:



Spatial multiplexing deals with transmitting independent streams across multiple antennas. The system involves multiple transmit and receive antennas. The general operation behind spatial multiplexing is to break the sequence of information bits into a certain set parallel of sub-streams. These sub- streams from each transmit antenna interfere in each of the multiple receive antennas. The receiver, then separate out the sub-streams, thereby establishing multiple parallel streams of data in the same channel. Assuming a rich multipath environment[5], the capacity of the system increases with the number of antennas while performing spatial multiplexing. The number of parallel data links established depends on the minimum between the number of transmitter antennas and the number of receiver antennas. To accomplish spatial multiplexing, I will be using one of the interference cancellation algorithm, e.g., linear zero-forcing (ZF)/ minimum-mean squared-error (MMSE) detector, maximum-likelihood (ML) detector, successive interference cancellation (SIC) detector (V-BLAST), to form parallel link for the streams between transmitter and receiver[1,5]. This technique reaches a closer bound to the available capacity of MIMO systems, since the spatial rate is equal to the number of parallel streams formed or the number of transmit antennas. Generally for spatial multiplexing, the number of receive antennas must be equal to or greater than number of transmit antenna. Below is the block diagram demonstrating MIMO system for spatial multiplexing[1]:

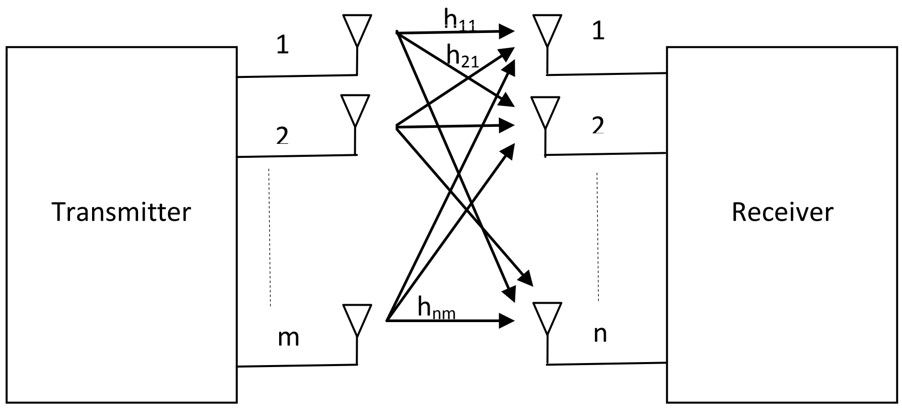


What is to be implemented in the Project?

In this project, an out of tree module for MIMO (gr-MIMO) will be designed. Almost every application of MIMO require channel state information (CSI) or the channel matrix , this parameter need to be estimated. For this I plan to design a block for precoding of the data stream at the transmitter which will add some preambles to the data packets. This preamble will be known at the receiver. At receiver by correlating these known set of preamble with the received preamble ,the channel state can be estimated. Hence correspondingly at receiver I will design a block for channel estimation.

$$\overline{h} = \begin{bmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nm} \end{bmatrix}$$

where $\overline{h}$ is the channel state matrix, **n** is number of receive antennas and **m** is number of transmit antennas. From the channel matrix $\overline{h}$, an element h_{ij} can be defined as channel response between transmit antenna **j** and receive antenna **i**. This can be graphically represented as:



The next step will be implementation of receive diversity in MIMO systems. For the receive diversity, same data streams will be transmitted from the transmit antennas and at the receiver, output of the receive antennas will be combined so as to maximize the SNR. At the receiver, I will be designing a block to compute the required weight vector which will be used to compute weighted sum of outputs of receive antennas to give the optimal results ,i.e, maximize SNR. The linear combination of output is given as :

$$y_T = \overline{w}^H \overline{y}$$

where the receive vector is given by $\overline{y} = [y_1\, y_2 \ldots y_k \ldots y_n]$. y_k is the receive symbol received at receive antenna k. The weight vector is given by $\overline{w}^H = [w_1^*\, w_2^* \,\ldots w_k \ldots\, w_n^*]$ such that $\overline{w}^H \overline{w} = 1$ and $\overline{w} = \frac{\overline{h}}{||h||}$. w_k multiplies with receive symbol y_k .

The third step will be to implementation of STBC which will enhance the data rate. The simplest STBC, Alamouti code will be used for the task. This will be done by designing a precoding block at the transmitter for Alamouti code. Correspondingly at the receiver I will design a decoder to decode the received signal from the single receive antenna. The Alamouti encoder gives the following:

$$\bar{x} = \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix}$$

where the rows gives symbols transmitted at different antennas, i.e, row 1 is transmitted from antenna 1 and row 2 transmitted from antenna 2. The columns gives symbols transmitted from successive time interval. This mean symbol $x_1$and symbol x_2 is transmitted from transmit antenna 1 and antenna 2 respectively at first time instant. Next the symbol $-x_2^*$and symbol x_1^* is transmitted from transmit antenna 1 and antenna 2 respectively at second time instant. At the receiver, the receive signal is given as:

$$\bar{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \text{channel noise}$$

where y_1 and y_2 are the receive symbols received at successive time intervals stacked together. h_1 is the channel response between transmit antenna 1 and receive antenna 1. Similarly $h_2$is the channel response between transmit antenna 1 and receive antenna 2.Now for detection of symbol x_1 with a diversity of order 2, the Alamouti decoder computes following

$$\widehat{x_1} = w_1^H \bar{y}$$

where $w_1 = \frac{1}{||\bar{h}||} \begin{bmatrix} h_1 \\ h_2^* \end{bmatrix}$. Similar results for symbol 2 can also be computed for $w_2 = \frac{1}{||\bar{h}||} \begin{bmatrix} h_2 \\ -h_1^* \end{bmatrix}$.

The next step will be to implement spatial multiplexing. The 'stream to streams' (used as de multiplexer) will be used at transmitter to divide the data streams into multiple parallel sub-streams. Also multiple users can be assigned to different transmit antennas to form a multi user multiplexing scheme. At the receiver I will be using a MMSE receiver (or V-BLAST) to decode the individual data streams at every receive antenna to establish independent parallel data links. The decoded data streams are combined into a single stream using 'streams to stream'(used as multiplexer). All the applications will be using the channel state matrix estimated for the decoding procedure .The MMSE receiver output is given as:

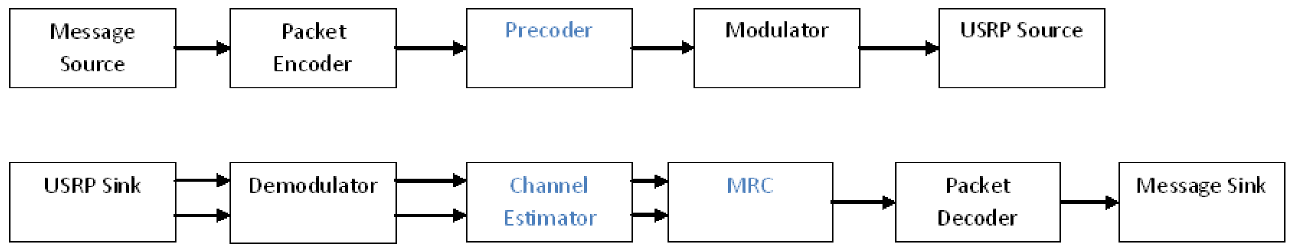
$$\hat{\bar{x}} = P_d (P_d \bar{h}^H \bar{h} + \sigma_n^2 I)^{-1} \bar{h}^H \bar{y}$$

where $\hat{\bar{x}}$ is the estimated transmit vector such that transmit vector is given as $\bar{x} = [x_1\ x_2 \dots x_l \dots x_m]^T$. x_l is the transmit symbol transmitted from transmit antenna l. P_d is the transmit symbol power which is assumed to be known at the receiver. $\bar{y}$ is the receive vector where $\bar{y} = [y_1\ y_2 \dots y_k \dots y_n]$. $y_k$is the receive symbol received at receive antenna k.

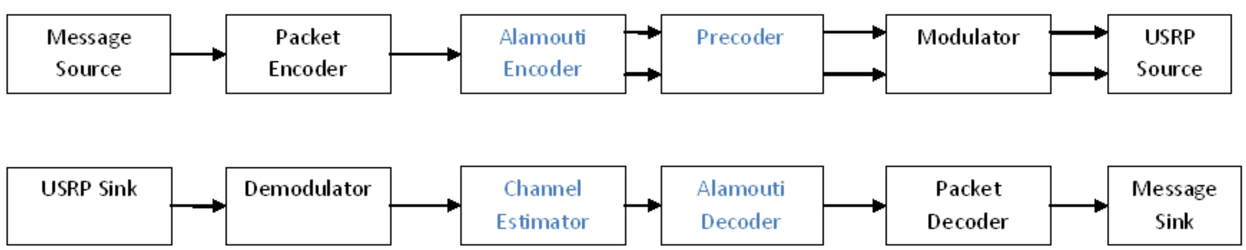
Deliverables:

- *Block for adding preamble in packets for channel estimation (At transmitter):* Add preambles to the data packets.

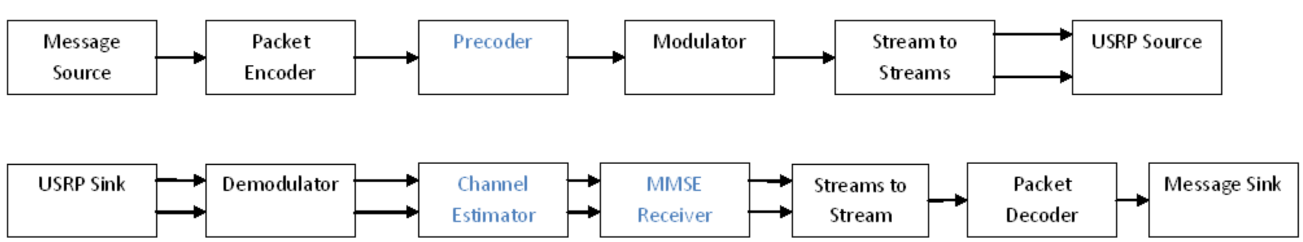
- *Block for channel estimation (At receiver):* Estimate channel response by correlating known preamble with the received preamble from the transmitter.
- *Block for maximum ratio combination (At receiver):* Calculate weight vector which will give optimum weighted sum of outputs of receive antennas.



- *Block for Alamouti encoding (At transmitter):* Encodes the data symbols to implement Alamouti STBC.
- *Block for Alamouti decoding (At receiver):* Decode the Alamouti code transmitted from transmitter and detect the two symbol transmitted from two transmit antennas.



- *Block for MMSE (or V-BLAST) for implementing spatial multiplexing (At receiver):* Decodes individual sub stream of data transmitted from transmitter as parallel sub-streams of data from multiple transmit antenna. These sub-streams of data is received by multiple receive antennas.



Tentative Timeline :

I will be available from April 21 to August 22 as my institute will be having summer vacation and GSoC will be my only commitment during this period. Though I will be visiting my family during initial 10 days and for around 5 days in month of July but I will not let it affect the flow of project and continue with the plan I have from myself.

April 21 to May 18:
Interact with the mentor. Discuss with him the ideas and consolidate the plan to execute the project. Complete revision of MIMO process and concepts related to the project.

May 19 to May 26:
Theoretical survey for practical implementation of channel estimation techniques to design block for channel estimation.

May 27 to June 15:
Implementation of channel estimation block to derive channel state matrix. This procedure is very important for all the further MIMO implementation.

June 16 to June 30:
Designing the blocks for implementation of Maximum Ratio Combiner(MRC).

July 1 to July 6:
Consolidate ideas on Alamouti code in context of implementing transmit diversity to enhance data rate.

July 7 to July 20:
Designing the Alamouti encoder and decoder.
(If enough time will be available after implementing Alamouti code for 1X2 systems, I will extend the idea for 1X3 MIMO system.)

July 21 to July 28:
Analysis of designing procedures for MMSE receiver (or V-BLAST) for the implementation of spatial multiplexing.

July 29 to August 15:
Design of receiver block (MMSE or V-BLAST) to accomplish spatial multiplexing.

August 15 to August 22:
Final documentation, finishing touches, reviews from the mentor and community.

What are the benefits of the project?

MIMO is the next big thing in the implementation of cellular networks, specially 3G/4G telephone networks[3,4,5]. From a perspective of a communication engineer, learning the functionality of MIMO by implementing it, will help in understanding the concept from a practical point of view. GNU Radio is an excellent platform to design any technology of the wireless communication. The basic MIMO module, if included in the GNU Radio, will assist in implementing the two of basic key aspects of MIMO: Enhancing link reliability and data rate. This will help in designing various advanced wireless technology through GNU Radio. MIMO is the future of advanced wireless technology and using the platform of openSource, there will also be scope for improvement of the module as time progress for inclusion of new developments in the field of MIMO.

Why choosing this topic?

My current work is on cognitive cellular network and my future goal is to do PhD in this area. MIMO is a principal concept in 3G/4G cellular network which contribute in increasing the efficiency of the cellular system. Hence to succeed in this area, practical understanding of implementation of the MIMO is very important. And GNU Radio is a perfect platform which gives an opportunity to work in MIMO in a real world scenario. From the high school days, I had a zeal towards programming and I never missed any coding contest. The GSoC will not only provide me the opportunity to try out my skill in coding but also the experience here will assist me in a long term in my research work. This is also an perfect platform to contribute the community of GNU Radio. Also I have all the pre requisite knowledge related to wireless communication and MIMO technology. My institute is one of the few in India which is working on software defined radio from last few years. The present work in the lab is "Implementation of cognitive concept in cellular network". The work done in the lab provide me a strong motivation to contribute something meaningful in the area. Also I wish to be an active contributor to GNU Radio community, after GSoC. I realize the potential GNU Radio processes and will be GNU Radio for my future research work. I will be sharing all my experience, I gain, with the community.

URL to work done in SDR:

http://www.youtube.com/channel/UCStYdbRK-d64_hohDMvIogQ/videos (Done along with my colleague)

Hardware Available:

1.USRP1 and USRP2.
2.SBX, RFX and XCVR daughter boards.
3.Vert2450 , Vert900 and Directional antennas.
4. (Ordered placed and will be there by April end) N series USRP , octoclock, WBX daughter boards and switches.

References:

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3. Bauch, G.; Alexiou, A., "MIMO technologies for the wireless future," *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on* , vol., no., pp.1,6, 15-18 Sept. 2008
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