Design and Implementation of Network Coding in NextGen systems

By

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Department of Electrical Engineering

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CERTIFICATE

It is certified that the contents and form of thesis entitled **"Design and Implementation of Network Coding in NextGen systems"** submitted by **Atif Salman Sheikh (NUST201305560BSEECS60413F), Shahzaib Qazi (NUST201305302BSEECS60413F) and S.M. Zain Zafar (NUST201306788BSEECS60413)** have been found satisfactory for the requirement of the degree.

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(Dr. Sajid Saleem)

DEDICATION

To Allah the Almighty

&

To my Parents and Faculty

ACKNOWLEDGEMENTS

We are deeply thankful to our advisor and co-advisor, Dr. Ali Hassan and Dr. Sajid Saleem for helping us throughout the course in accomplishing our final year project. Their guidance, support and motivation enabled us in achieving the objectives of the project.

We are also thankful to our committee members for their valuable feedback. Apart from them we are also thankful to Mr. Usman Haider (Lab engineer at Air University), Shahmeer Omar (Post Graduate student at Georgia Tech, USA) for their help at the crucial stages of the project and for guiding us through whatsapp meetings and sparing their valuable time for us.

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ABSTRACT

Network coding is a technique in which, instead of simply relaying the packets of information, the intermediate nodes of a network combine incoming input streams for transmission. These 'combinations' are subsequently decoded at the destination using algebraic methods.

We aim to implement the concept of Network Coding (NC) in three MISO topologies, using USRP Software-Defined Radio testbeds, and measure the performance of each topology against its non-NC counterpart using experimental results on Bit Error rates (BER), throughput and goodput.

Moreover, we aim to realize, whether network coding provides the theoretical advantage of throughput and energy efficiency and in which conditions it outperforms non-network coding operations.

Chapter 1

INTRODUCTION

Basic concept:

Network coding, as a field of study, is young. It was only in 2000 that the seminal paper by Ahlswede, Cai, Li, and Yeung, which is generally attributed with the "birth" of network coding, was published. As such, network coding, like many young fields, is characterized by some degree of confusion, of both excitement about its possibilities and skepticism about its potential. Clarifying this confusion is one of the principal aims of this book. Thus, we begin soberly, with a definition of network coding.

Traditional Routing Scheme:

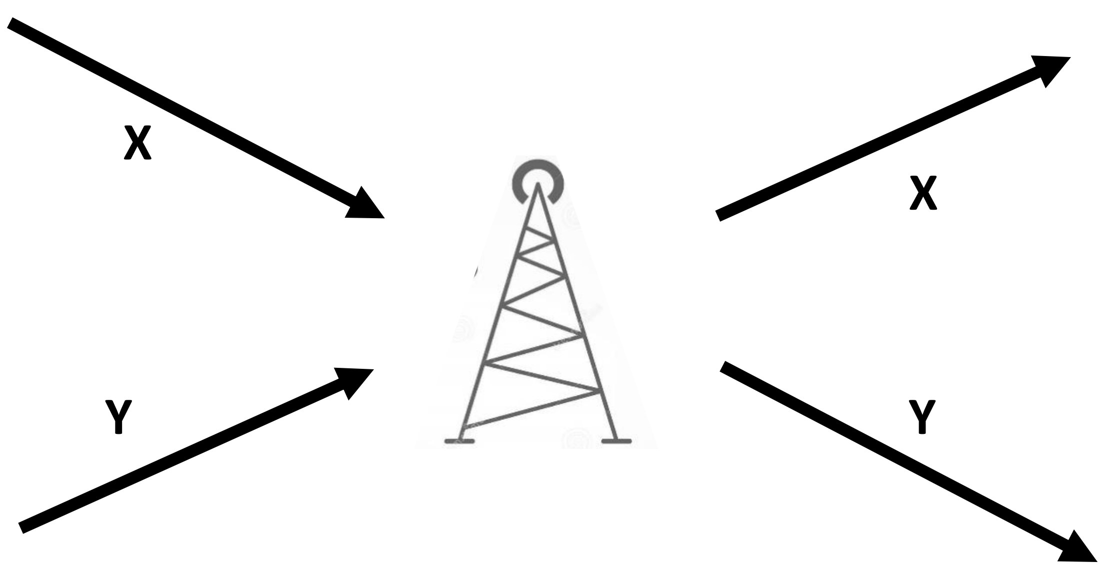


FIGURE 1: TRADITIONAL ROUTING SCHEME

Traditionally, the scheme used for forwarding data through the relay involved only decode and forward or amplify and forward mechanism, that is no complex processing was done on data reception and transmission.

Routing with Network Coding:

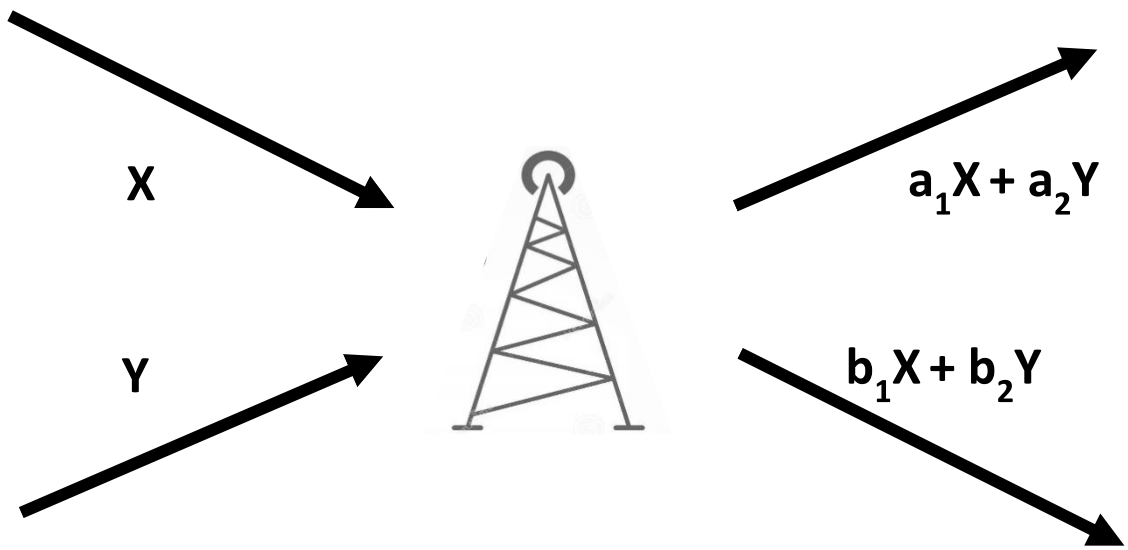


FIGURE 2: NETWORK CODED SCHEME

As the processing power became more and more cheap, there was a possibility of doing some processing to the receiving streams at nodes before forwarding them further. Network coding refers to this possibility, because it allows us to combine incoming streams of data by performing some algebraic manipulation to them.

Importance:

Network coding promises to offer benefits along very diverse dimensions of communication networks, such as throughput, wireless resources, security, complexity, and resilience to link failures.

Throughput:

The first demonstrated benefits of network coding were in terms of throughput when multicasting.

Figure 1.2 depicts a communication network represented as a directed graph where vertices correspond to terminals and edges correspond to channels. This example is commonly known in the network coding literature as the butterfly network. Assume that we have slotted time, and that through each channel we can send one bit per time slot. We have two sources S1 and S2, and two receivers R1 and R2. Each source produces one bit per time slot which we denote by x1 and x2, respectively (unit rate sources).

Now assume that both receivers want to simultaneously receive the information from both sources. That is, we are interested in multicasting. We then have a “contention” for the use of edge CE, arising from the fact that through this edge we can only send one bit per time slot. However, we would like to simultaneously send bit x1 to reach receiver

R2 and bit x2 to reach receiver R1.
Traditionally, information flow was treated like fluid through pipes, and independent information flows were kept separate. Applying this approach we would have to make a decision at edge CE: either use it to send bit x1, or use it to send bit x2. If for example we decide to send bit x1, then receiver R1 will only receive x1, while receiver R2 will receive both x1 and x2.
The simple but important observation made in the seminal work by Ahlswede et al. is that we can allow intermediate nodes in the network to process their incoming information streams, and not just forward them. In particular, node C can take bits x1 and x2 and xor them to create a third bit x3 = x1 + x2 which it can then send through edge CE (the xor operation corresponds to addition over the binary field). R1 receives {x1, x1 + x2}, and can solve this system of equations to retrieve x1 and x2. Similarly, R2 receives {x2, x1 + x2}, and can solve this system of equations to retrieve x1 and x2.

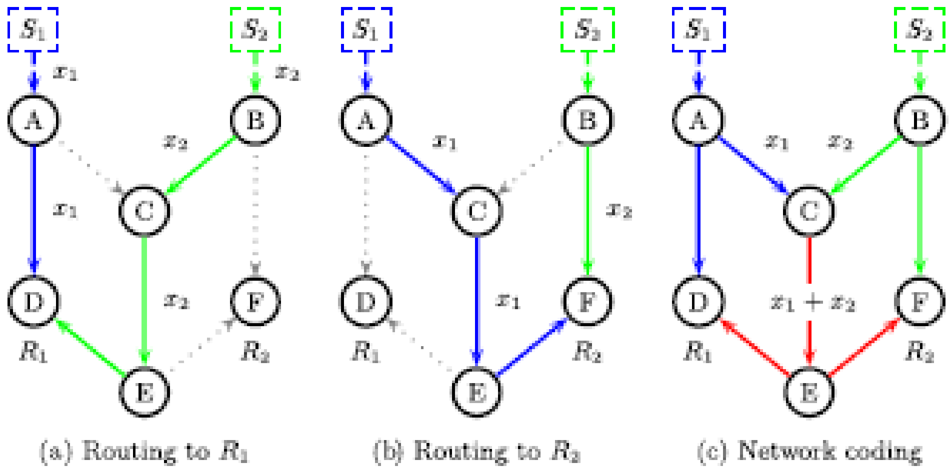


FIGURE 3: THROUGHPUT ADVANTAGE

Energy Efficiency:

Consider a wireless ad-hoc network, where devices A and C would like to exchange the binary files x1 and x2 using device B as a relay. We assume that time is slotted, and that a device can either transmit or receive a file during a timeslot (half-duplex communication). Figure 1.3 depicts on the left the standard approach: nodes A and C send their files to the relay B, who in turn forwards each file to the corresponding destination.

The network coding approach takes advantage of the natural capability of wireless channels for broadcasting to give benefits in terms of resource utilization, as illustrated in Fig. 4 In particular, node C receives both files x1 and x2, and bitwise xors them to create the file x1 + x2, which it then broadcasts to both receivers using a common transmission. Node A has x1 and can thus decode x2. Node C has x2 and can thus decode x1.

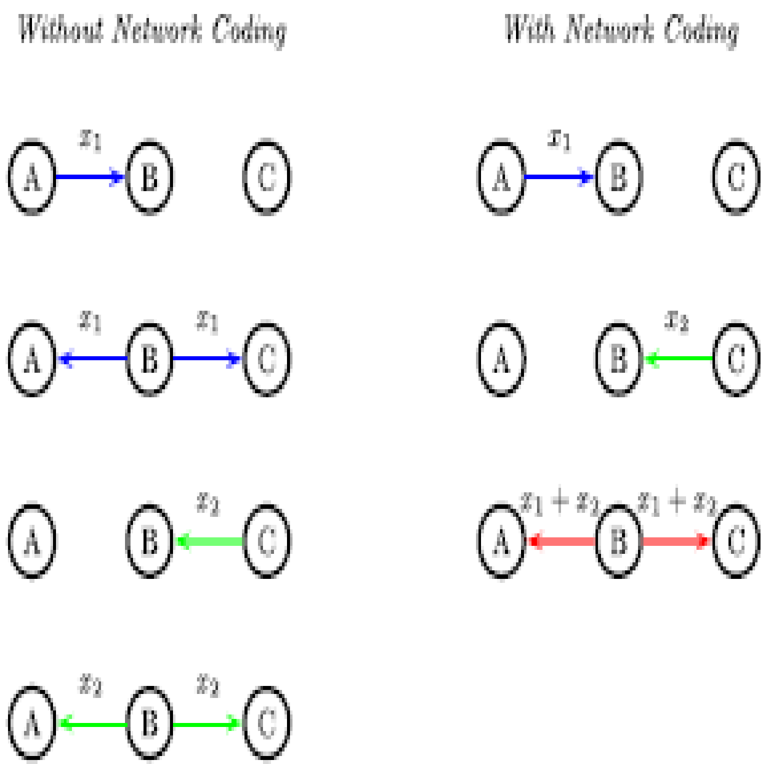


FIGURE 4: ENERGY EFFICIENCY ADVANTAGE

Security:

Consider node A that sends information to node D through two paths ABD and ACD in Figure 1.4. Assume that an adversary (Calvin) can wiretap a single path, and does not have access to the complementary path. If the independent symbols x1 and x2 are sent uncoded, Calvin can intercept one of them. If instead linear combinations (over some finite field) of the symbols are sent through the different routes, Calvin cannot decode any part of the data. If for example he retrieves x1 + x2, the probability of his guessing correctly x1 equals 50%, the same as random guessing.

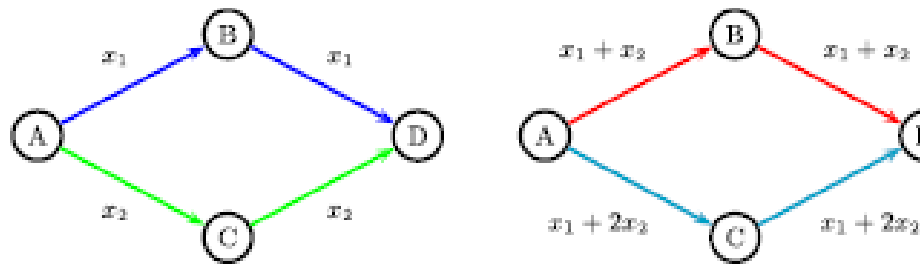


FIGURE 5: SECURITY ADVANTAGE

Project Goals :

1) ***Implementation of Network Coding in MISO topologies:***
   Network coding has been studied and researched in theory a lot, we aim to implement network coding on USRPs and realize it practically.

2) ***An experimental Evaluation in Terms of BER and throughput:***
   We aim to realize the advantages of energy efficiency and network throughput, discussed above.

3) ***To code or not to code:***
   Apart from realizing the advantages of network coding, we want to realize the practical implications of network coding, whether network coding is beneficial or not, and in what conditions it is suggested to be used.

Report organization:

The report is organized into following chapters

Chapter 2 explains the background knowledge and literature survey.

Chapter 3 discusses the network topologies we used.

Chapter 4 explains the system design and grc flowgraphs.

Chapter 5 focuses on implementation, results and discusses them.

Chapter 6 & 7 gives the conclusion and references

Chapter 2

LITERATURE REVIEW

Relevant work by researchers:

Network coding is a technique that focuses on the optimization of wireless data flow and is believed to be one of the factors necessary in bringing a paradigm shift that will make the future 5G mobile networks a reality. In traditional wireless systems, the intermediate nodes used simple store-and-forward method to route the data to its destination. The technique of network coding has now broken this tradition of simple routing by introducing the concept that the data is transmitted from an intermediate node after combination of two or more distinct streams of data that share a common destination. Thus, the transmission from intermediate nodes depends upon more than a single stream of input data. Network coding was proposed in [1] and described as a method that would help in increasing the throughput of wireless broadcast systems by reducing useful packet transmissions. Combination of data prevents eavesdroppers to tap and obtain the data at a node where coding is applied, thus making security an inherent advantage of network coding. Both of these advantages have also been described in [2]. The throughput and transmission efficient performance of network coded wireless systems varies with the topologies or coding methods employed. As we see [3], straight-forward network coding performed in a three-node wireless linear network saves one time slot as compared to four in traditional scheduling scheme, while physical-layer network coding (PNC) saves two out of four time slots by using interference of electromagnetic waves as a means to save timeslots, allowing a maximum throughput improvement of 50%. The star coding approach discussed in [4] provides efficient transmission by allowing a multiplicative improvement of factor 2.4 in number of transmissions required to route data from sources to destinations.

While there have been a number of theories related to throughput and performance advantages provided by network coding, to best of authors' knowledge the practical implementations are quite limited. In [5], first real-time implementation of PNC is done using a USRP software-defined radio platform. Challenges like achieving synchronization of transmission packets from sources and to cater for the latency between scheduling at USRP and computer are also discussed here. Network coding in two-way relaying is also implemented on USRP in [6], which focuses on designing a MAC protocol based on TDMA scheme using a modified packet structure that provides robust synchronization between the separate packets incoming at the relay.

Uniqueness of the proposed solution

When any proposed method is practically performed, there are a number of known or unknown factors that may result in a performance that is not as good as proposed. So it remains a question whether network coding works as well as described in theories. Our paper is based on the experimentation of network coding on some Multiple Input Single Output (MISO) topologies. By performing practical implementation of network coding, we try to demonstrate how this technique allows the proposed topologies to be more energy efficient and how much increase in throughput is actually achieved using the respective topologies. Unlike previous researches, the main aim of this paper is not only focused towards the bright side of network coding. On the basis of our experiments and their results, we figure out the conditions required for the three network coded systems (described later) to provide a better quality of service (QoS) than the corresponding non-network coded system and the conditions when a system without network coding may perform better than network coded systems. Moreover, the paper also highlights the difference between performances of these three different network coding topologies.

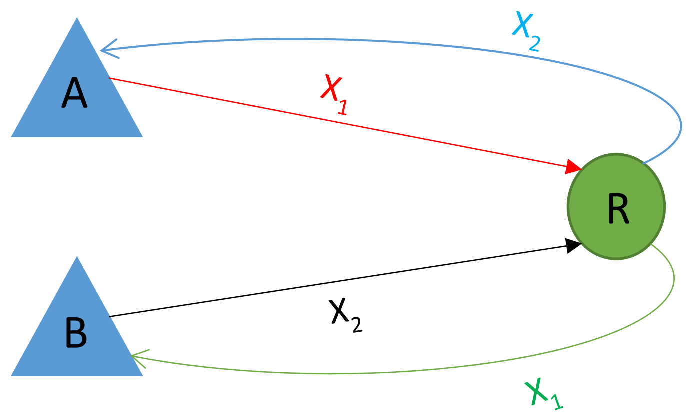
Chapter 3

NETWORK TOPOLOGIES

Two-way relay coding (TWRC):

We started our investigation with a simple textbook implementation of the Network Coding (NC) scheme of communication on a two-way relay channel (TWRC), where two terminal nodes exchange packets of information via a relay node, and compared its performance to the non-NC scheme.

However, there were two major simplifications in the TWRC model. Firstly, the terminal nodes already had half the information and just needed the other half. Secondly, the relay only needed to construct one unique code from the two incoming input streams for successful data recovery at the terminal nodes; and this was achieved using a simple XOR operation. However, the XOR operation would not have been sufficient if two or more unique codes had to be constructed at the relay.



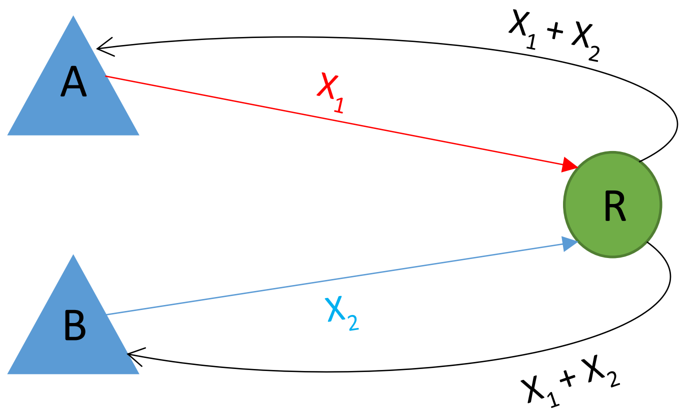
Timeslot 1 → A broadcasts X_1 at frequency f_1

Timeslot 2 → R broadcasts X_1 at frequency f_2

Timeslot 3 → B broadcasts X_2 at frequency f_1

Timeslot 4 → R broadcasts X_2 at frequency f_2

FIGURE 6: NON-NETWORK CODED SCHEME FOR TWRC



Timeslot 1 → A broadcasts X_1 at frequency f_1

Timeslot 2 → B broadcasts X_2 at frequency f_1

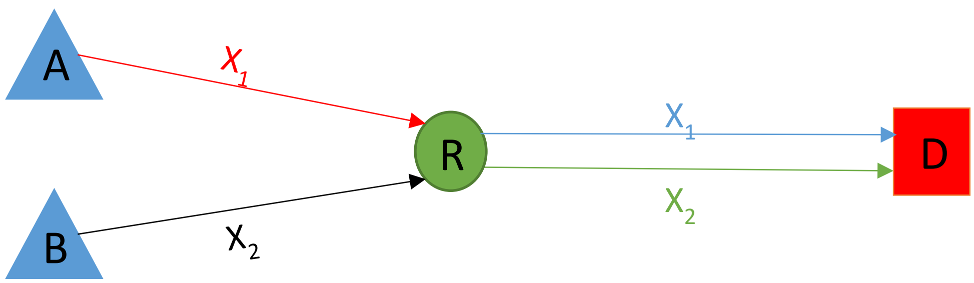
Timeslot 3 → R broadcasts $X_1 + X_2$ at frequency f_2

FIGURE 7: NETWORK CODED SCHEME FOR TWRC

Therefore, we broadened the scope of our experiments to include *n*-source MISO topologies where the relay constructs and broadcasts *n* linearly independent algebraic combinations of source packets S_1, S_2 …S_n. The destination node subsequently solves the system of *n* equations to obtain the *n* source packets.

All of the topologies mentioned above had symmetric channels and, with the exception of the simplex destination nodes in the MISO topologies, all nodes were full-duplex enabled.

2-source MISO:



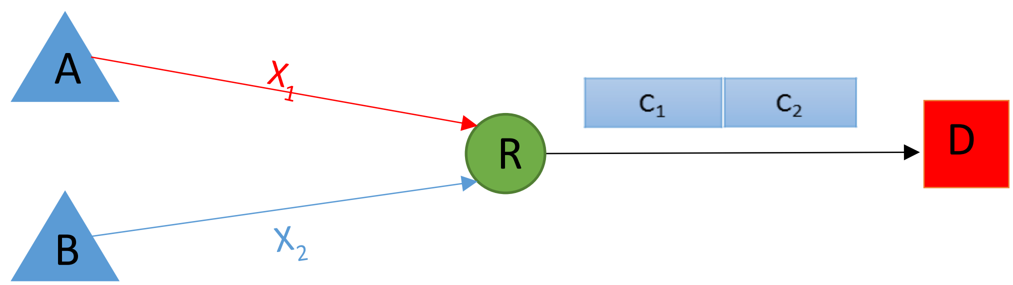
Timeslot 1 → A broadcasts X_1 at frequency f_1

Timeslot 2 → R broadcasts X_1 at frequency f_2

Timeslot 3 → B broadcasts X_2 at frequency f_1

Timeslot 4 → R broadcasts X_2 at frequency f_2

FIGURE 8: NON-NETWORK CODED SCHEME FOR 2-SOURCE MISO



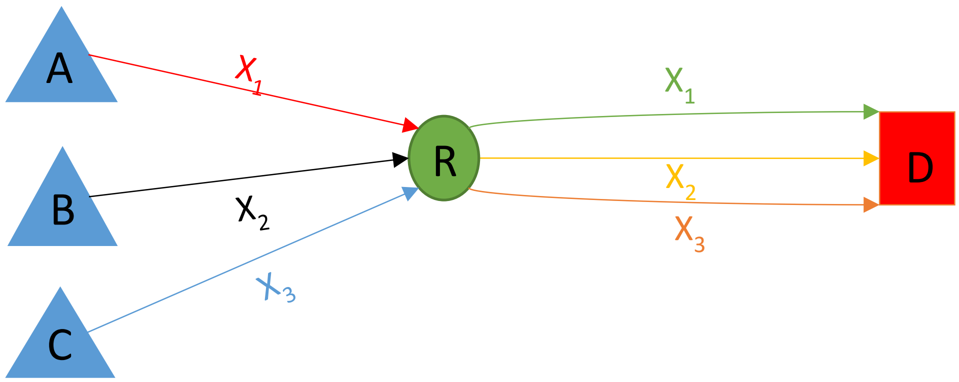
Timeslot 1 → A broadcasts X_1

Timeslot 2 → B broadcasts X_2

Timeslot 3 → R broadcasts C_1 & C_2

FIGURE 9:NETWORK CODED SCHEME FOR 2-SOURCE MISO

3-source MISO:



Timeslot 1 → A broadcasts X_1 at frequency f_1

Timeslot 2 → R broadcasts X_1 at frequency f_2

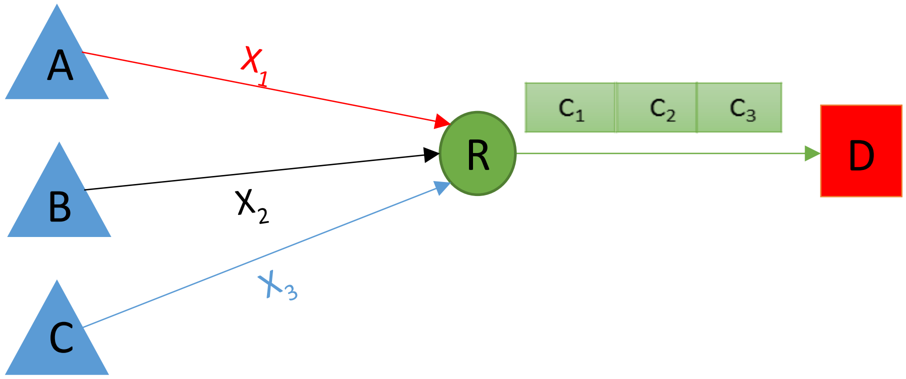
Timeslot 3 → B broadcasts X_2 at frequency f_1

Timeslot 4 → R broadcasts X_2 at frequency f_2

Timeslot 5 → C broadcasts X_3 at frequency f_1

Timeslot 6 → R broadcasts X_3 at frequency f_2

FIGURE 10: NON-NETWORK CODED SCHEME FOR 3-SOURCE MISO



Timeslot 1 → A broadcasts X_1 at frequency f_1

Timeslot 2 → B broadcasts X_2 at frequency f_1

Timeslot 3 → C broadcasts X_3 at frequency f_1

Timeslot 4 → C broadcasts C_1, C_2 & C_3 at frequencies f_1, f_2 & f_3

FIGURE 11: NETWORK CODED SCHEME FOR 3-SOURCE MISO

Performance evaluation parameters:

The following parameters have been employed to evaluate the performance of NC in the various topologies:-

1.) ***Throughput***

The number of bits received as part of the payload (i.e. the remainder of the data packet after overheads have been removed) per unit time.

2.) ***Bit Error Rate, BER***

The ratio of incorrect bits to the total number of bits received as part of the payload.

3.) ***Goodput****:*

The number of correct bits received as part of the payload per unit time. So, goodput can be computed from the following formula:

$$Goodput = BER \times Throughput$$

Theoretical Analysis:

This section outlines, from a theoretical standpoint, the expected performance of the NC scheme vis-à-vis the non-NC scheme in each of the topologies.

a) TWRC Topology:

Under the non-NC scheme, the terminal nodes exchange the packets X_1 and X_2 over the course of four timeslots/transmissions whereas, under the NC scheme, the exchange is completed in three timeslots or transmissions. This is because the relay R, instead of broadcasting X_1 and X_2 separately over two timeslots, broadcasts their XORed combination in just one timeslot. The terminal nodes recover their respective unknown packets by XORing their native packets with this combined broadcast. Assuming that all transmissions have the same duration and all antennas have the same TX gain, the saving of one timeslot or transmission translates into a throughput improvement of $33^1/_3$ percent. It also results in an energy saving of 25%, as the energy expended is directly proportional to the number of transmissions. However, we cannot assert with similar certainty whether the goodput, which has a direct relation with throughput and an inverse relation with BER, will mirror the throughput improvement. Table I, gives the analysis of potential throughput improvement and energy efficiency of all three topologies

TABLE I. Theoretical Analysis

		Two-source MISO	**Three-source MISO**	***n*-source MISO**
Non-NC	Timeslots	4	6	$2n$
	Throughput	$\frac{2}{4} = 0.5$	$\frac{3}{6} = 0.5$	$\frac{n}{2n} = 0.5$
	Transmissions	4	6	$2n$
NC	Timeslots	3	4	$n + 1$
	Throughput	$\frac{2}{3}$	$\frac{3}{4}$	$\frac{n}{n+1}$
	Transmissions	3	4	$n + 1$
	% Increase in Throughput	$33\frac{1}{3}\%$	50%	$\frac{n-1}{n+1} \times 100\%$
	Potential % decrease in energy expenditure	25%	$33\frac{1}{3}\%$	$\frac{n-1}{2n} \times 100\%$
	Potential % Increase in TX gain	$33\frac{1}{3}\%$	50%	$\frac{n-1}{n+1} \times 100\%$
	Potential Increase in TX gain (dB)	1.25	1.76	$10\log\left(\frac{2n}{n+1}\right)$

SYSTEM DESIGN AND FLOWGRAPHS

Transmitter Design:

Fig. 9 shows the transmission of data at the transmitting end of the USRP. Description below explains the working of blocks.

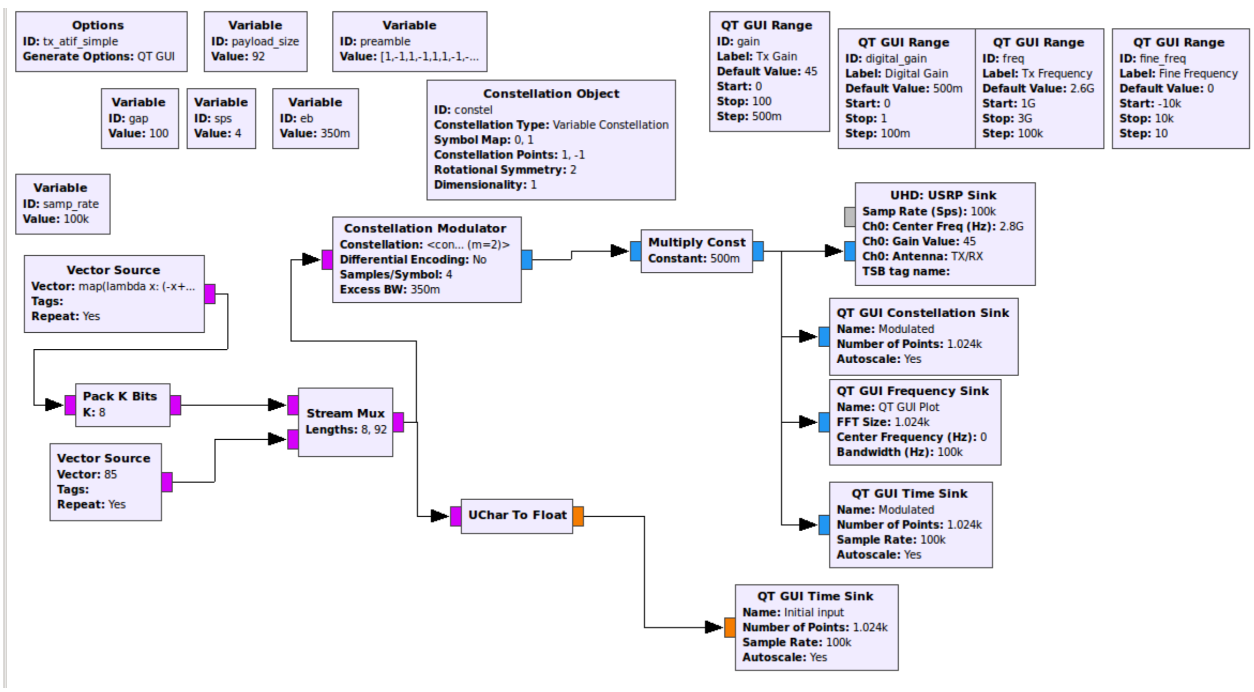


FIGURE 12: TRANSMITTER FLOW GRAPH

Preamble:

A preamble is a signal used at start of the packets used to synchronize transmission timing between two or more systems. A 64-bit access code is used as preamble in our work, which not only synchronizes timing, but is also used to detect starting bit of the useful packet.

Payload:

A payload is the part of a packet in a network communication which contains the required meaningful data that is intended to be transmitted within a network. We are using a payload of 736 bits in a single packet, i.e. 736 useful data is being transmitted in a single packet. The payload does not include the overhead data (preamble+header) required to get the packet to its destination.

Constellation Modulator:

Constellation Modulator block is used with a Constellation Object which helps in defining the complete modulation. We can set the constellation points as well as how the symbols are mapped to those points. The constellation object allows us to determine how the symbols are coded and if we want to use Gray coding or not. The modulator block can then use this modulation scheme with or without differential encoding. The constellation modulator expects packed bytes, so we have a random source generator providing bytes with values 0 - 255.

Coding Scheme Design:

After transmitting it to the relay, it receives it, decodes the data and then performs the network coding operation.

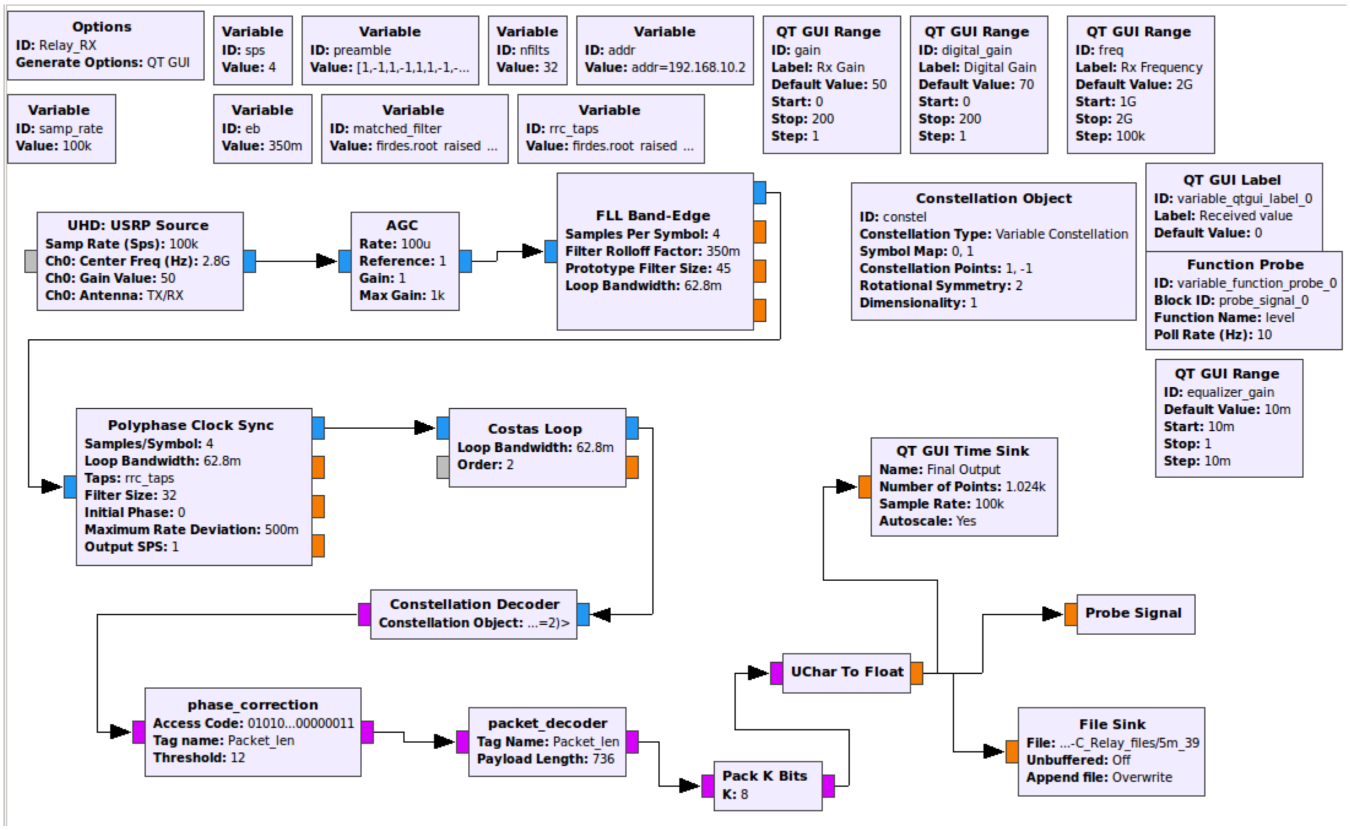


FIGURE 13: RELAY RECEIVER

Two-way Relay coding (TWRC):

After receiving the data, relay performs the coding operation.

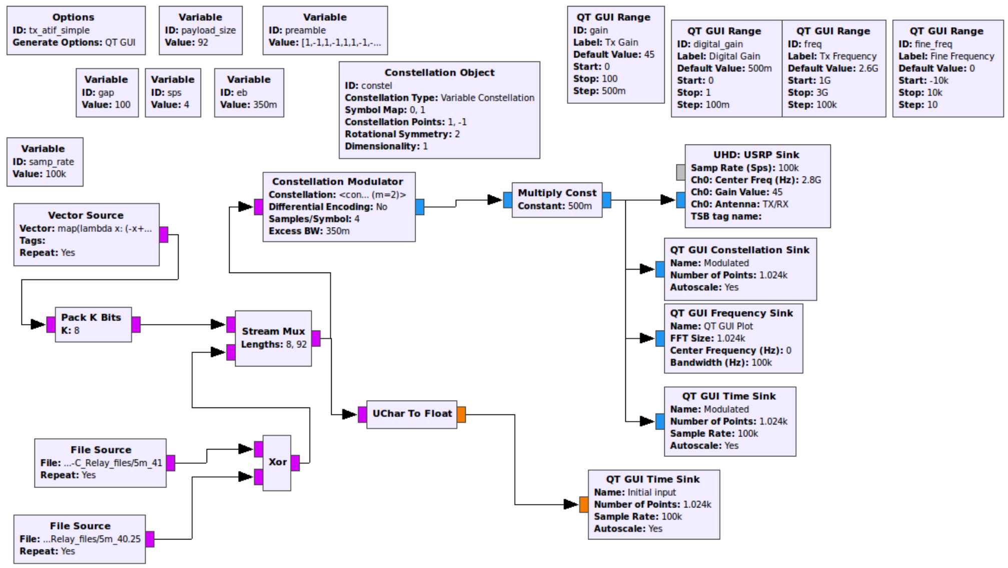


FIGURE 14: XOR CODING AT RELAY

Two-Source MISO Topology:

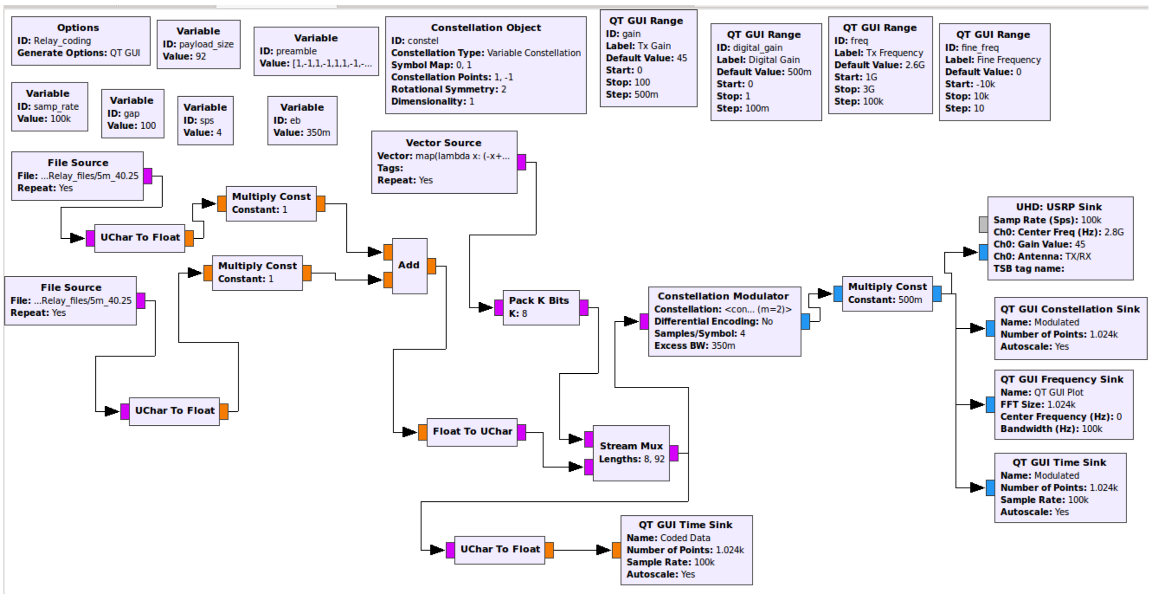


FIGURE 15: ALGEBRAIC CODING AT RELAY FOR TWO SOURCES

Three-Source MISO Topology:

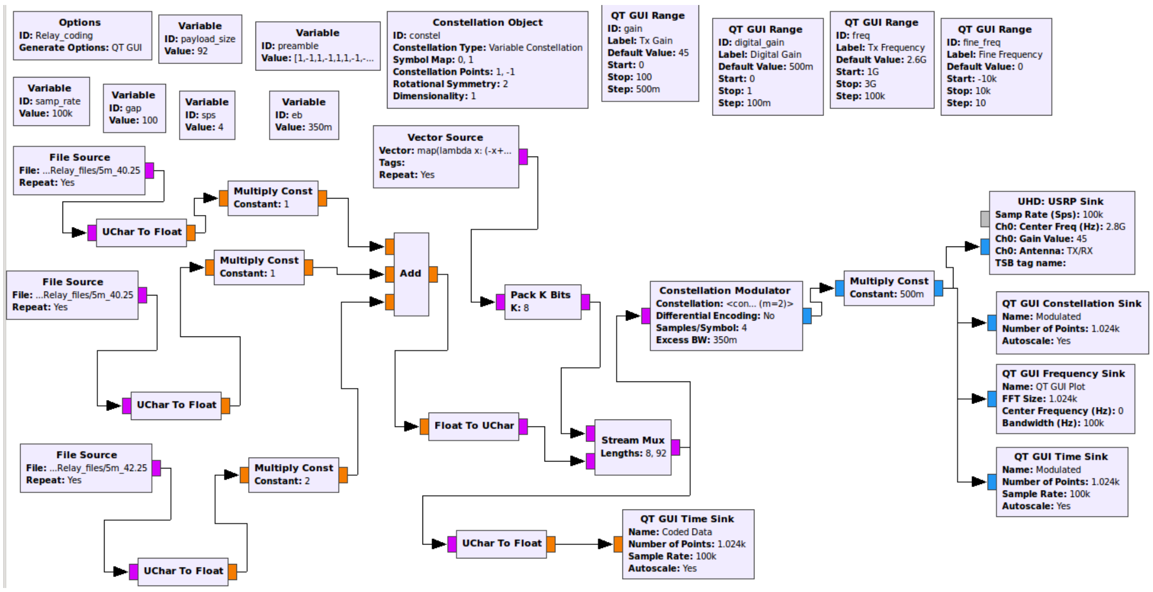


FIGURE 16: ALGEBRAIC CODING AT RELAY

Receiver Design:

After relay transmits the code, destination receives it, before performing the decoding operation.

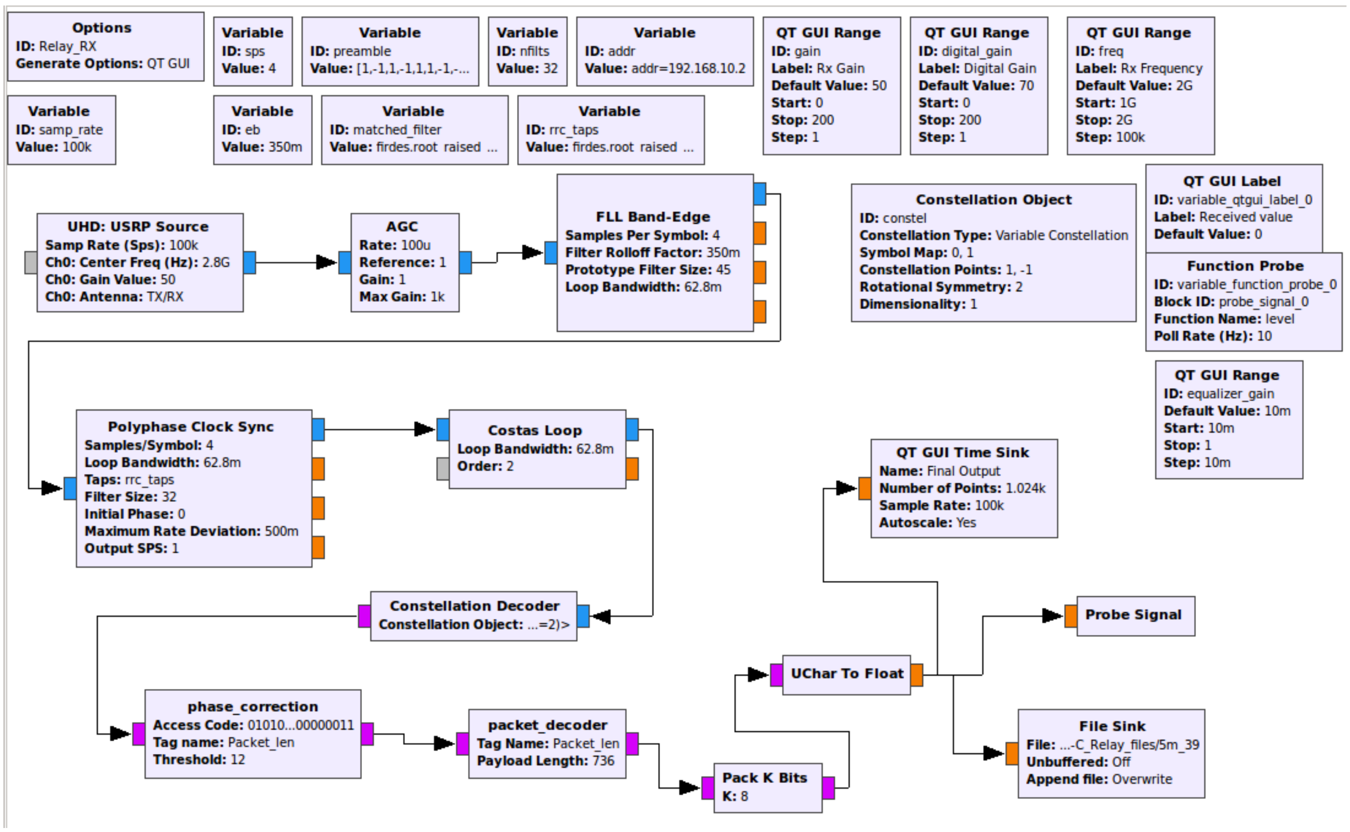


FIGURE 17: RECEIVING AT THE DESTINATION

FLL band edge:

The frequency lock loop derives a band-edge filter that covers the upper and lower bandwidths of a digitally-modulated signal. The bandwidth range is determined by the excess bandwidth (e.g., rolloff factor) of the modulated signal. The placement in frequency of the band-edges is determined by the oversampling ratio (number of samples per symbol) and the excess bandwidth. The size of the filters should be fairly large so as to average over a number of symbols.

PolyPhase Clock Sync:

The PolyPhase Clock Sync block is used to find the best time to sample the incoming signals, which will maximize the SNR of each sample as well as reduce affects of inter symbol interference (ISI). This block takes in values for number of filter taps, loop bandwidth and expected samples per symbol (sps). Sps should match with the transmission side sps, to avoid timing offset.

Constellation Decoder:

Constellation demodulator is used to to convert the modulated signals back to the unpacked bytes at receiver side on the basis of the modulation technique selected (e.g. BPSK, QPSK) and the corresponding mapped symbols for each set of bits.

Costas Loop:

The Costas loop locks the signal to its center frequency and downconverts it to baseband. When order=2, it is used for BPSK where the real part of the output signal is the baseband BPSK signal and the imaginary part is the error signal. When order=4, it can be used for QPSK where both I and Q (real and imaginary) are outputted. When order=8, it is used for 8PSK.

Packet Decoder:

This is a custom block, which is to detect start of payload, i.e. meaningful data, by using a tag that has been added before this block, and to remove the overhead bits from the packet, such that only payload is the output of this block.

Decoding Scheme Design:

Destination, after receiving the data at the destination it performs the decoding operation.

Two-way Relay coding (TWRC):

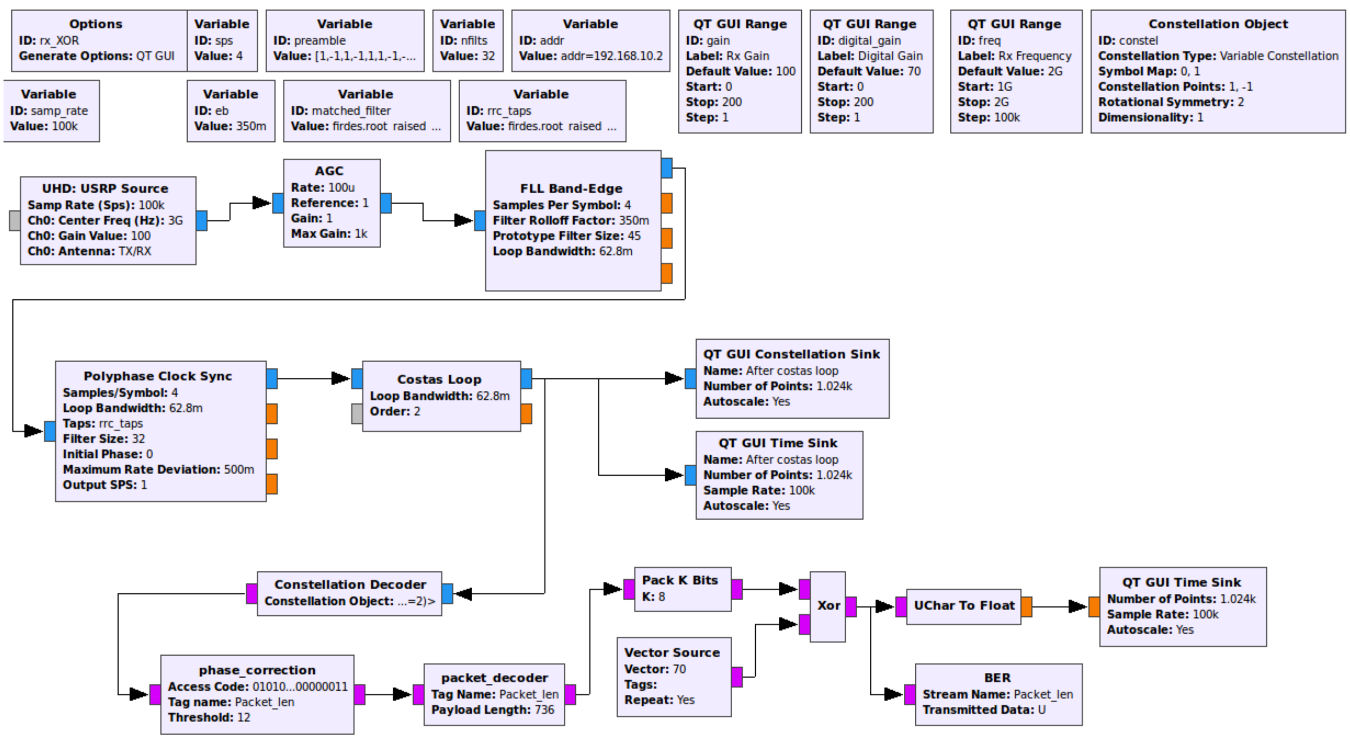


FIGURE 18: XOR DECODING AT THE DESTINATION

Two-Source MISO Topology:

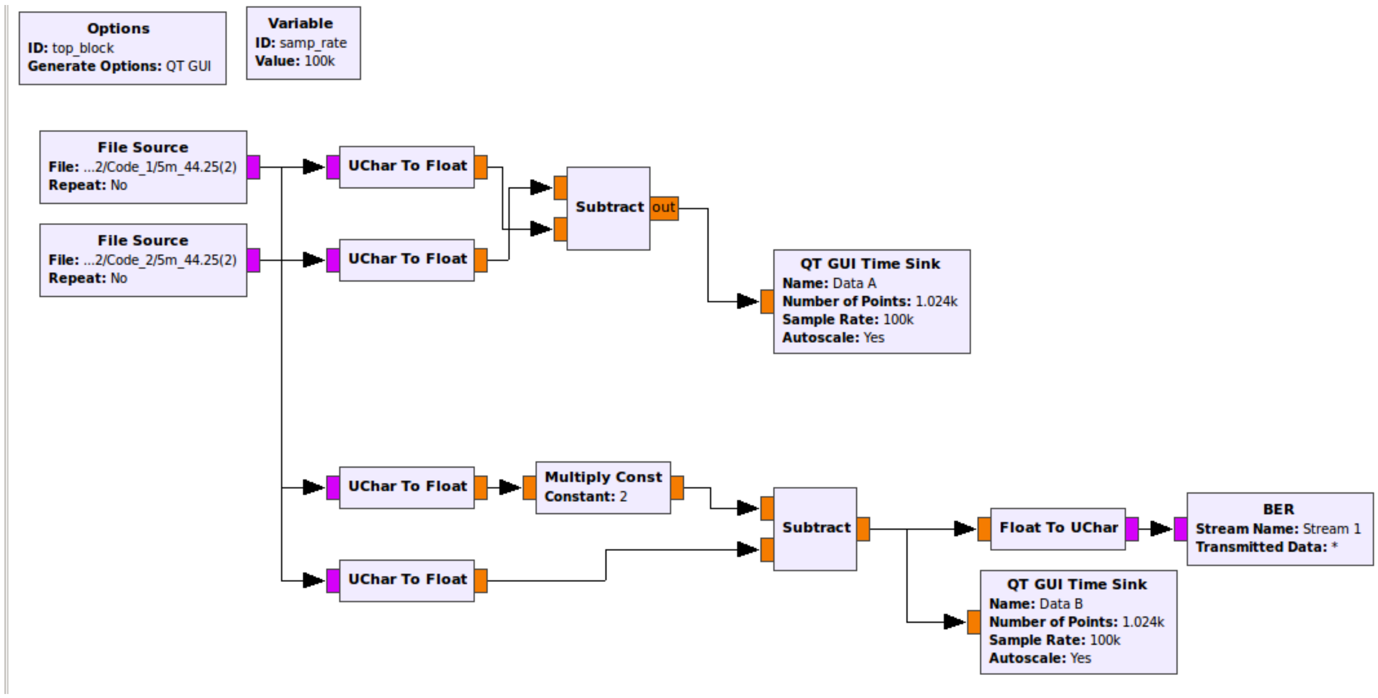


FIGURE 19: 2-SOURCE DECODING AT THE DESTINATION

Three-Source MISO Topology:

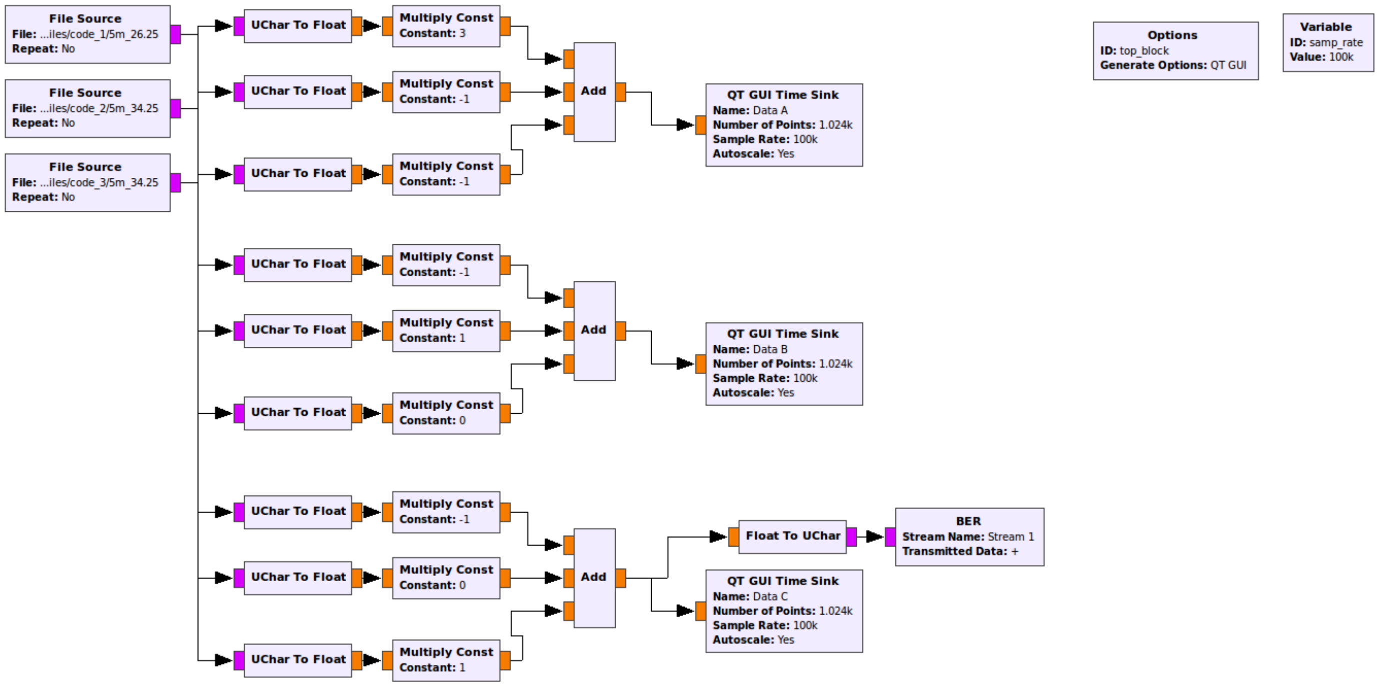
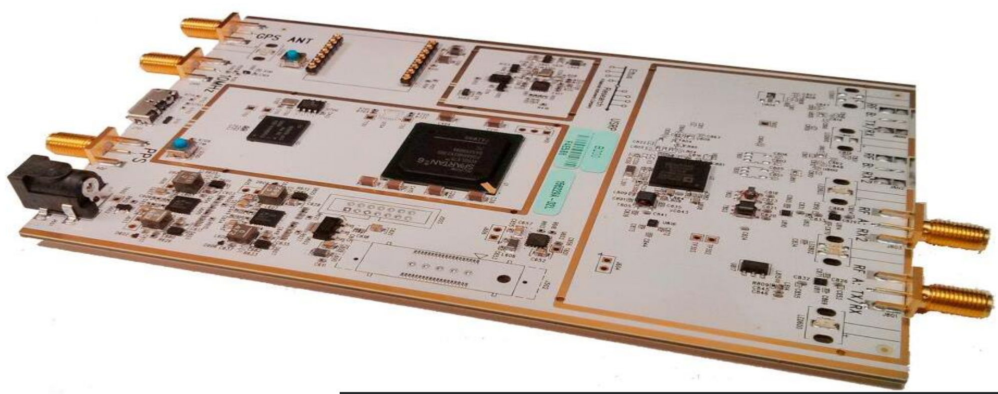
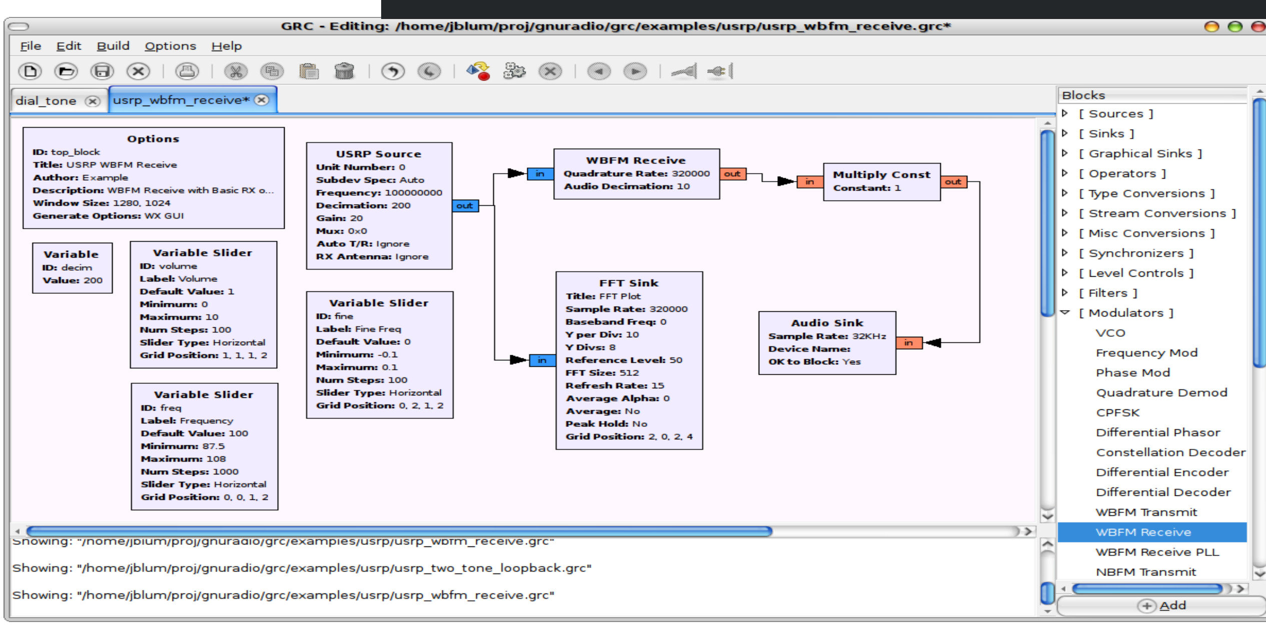


FIGURE 20: 3-SOURCE DECODING AT THE DESTINATION

IMPLEMENTATION

Tools used:





Getting started:

Before starting our project, it was important for us to familiarize ourselves with the software and hardware we used for the project. So we used the tutorials in [7] to learn the basic concepts. We then implemented following basic example communication systems to further enhance our understanding

- Basic Transmitter-Receiver
- Basic Relay
- FDM

Master- Slave scheduling scheme:

Here, we will explain the protocol for two-way relay coding network, which will develop the understanding for other topologies too. Packet which we used for our transmission is shown in Fig. 9 below

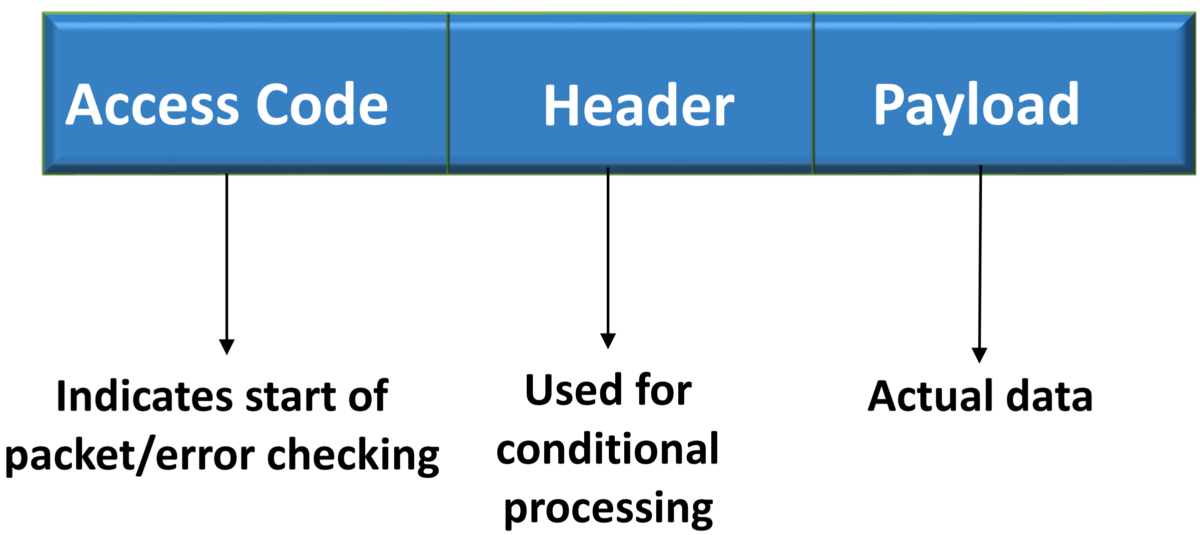


FIGURE 21: : PACKET DESCRIPTION

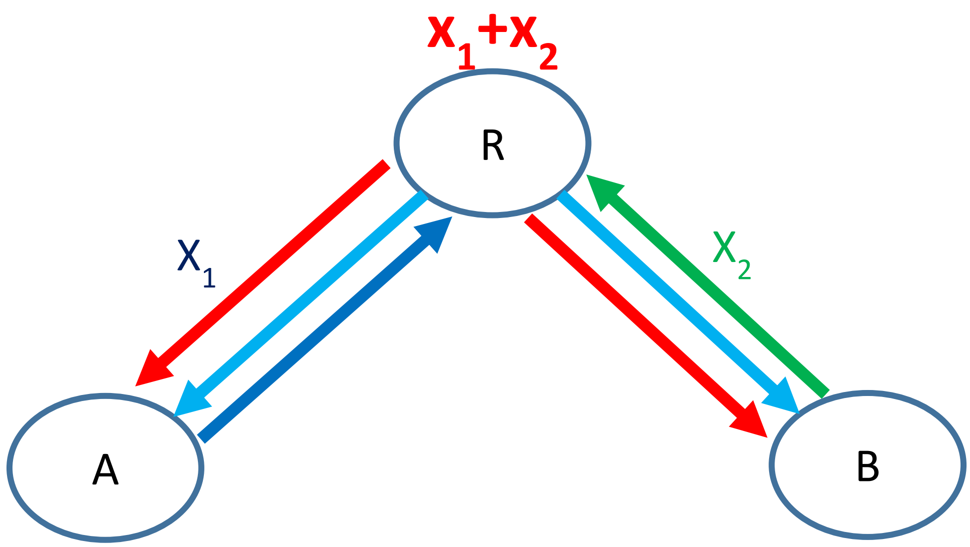


FIGURE 22: : MASTER-SLAVE SCHEDULING

Figure above explains the complete protocol for TWRC, which is illustrated in points below.

- Tx_start signal sent to A
- Packet A sent to relay R
- Tx_stop signal sent to A
- Tx_start signal sent to B
- Packet B sent to relay R
- Tx_stop signal sent to B
- Data coded in R
- Coded data sent to A & B

Time scheduling and synchronization:

The time scheduling and synchronization of the data transmissions from sources to relay was achieved using the Time Division Multiple Access (TDMA) scheme based Medium

Access (MAC) protocol, proposed in [6]. It is a master-slave protocol which uses some overhead bits (header) as control signals. These control signals ensure time scheduling, as required by the three topologies discussed earlier, in receiving data from multiple sources to relay and subsequent transmission after employing Network Coding at relay. Buffers are used at relay to store received packets before creating codes from them. While in [6] he proposed protocol only focuses on Network Coding in Two-way decode-and-forward Relaying Network, we have implemented the similar protocol on the two-source-one-destination and three-source-one-destination relaying schemes to achieve TDMA at transmission only. Frequency Division Multiplexing (FDM) was used at the relay for to aid transmission of coded data to the destination in single time slot.

Experimental Setup:

All the experiments are performed using USRP B200, Software Defined Radios by Ettus Research. These radios are able to transmit and receive signals in the Radio Frequency (RF) range of 70MHz to 6GHz. The transmitters, receivers and relays used in the experiments are implemented on these radios and designed using GNU Radio Companion, an open-source software development toolkit used to perform signal processing using built-in as well as custom programmed blocks, and to design software defined radios or simulation environment. The antennae used at each radio were VERT2450 having a gain of 3.3dBi.

For all experiments, the channels were Line-of-Sight (LoS) with a distance of 5m between each transmitter-relay and relay-receiver pair, and the modulation technique employed was Binary Phase Shift Keying (BPSK).

These LoS channels were selected such that the source-relay and relay-destination channels at each experiment were almost symmetrical and thus both channels affect the transmission in the same way. For each topology mentioned earlier, we performed experiments for both Non-Network Coding and Network Coding models.

All experiments conducted for the three topologies discussed earlier were performed for the transmission of 2 million bits from each source. For each experiment, Bit Error Rate (BER) was calculated at the destination nodes using custom GRC block. Values of BER were taken for the gain range of -51.5dBm to -41.5dBm for each setup that did not employ network coding at relay. When network coding was applied in each topology, the gain is increased by a specific amount before taking BER readings, such that the total energy of the system remains same in both cases.

For both two-way relay and two-source-one-destination models, as discussed in the previous section, network coding system decreases the number of transmissions to three, as opposed to four in non-networking coding system. So to keep the system energy constant, the transmission power of each node was increased by 33% or 1.25dBm. The gain range for BER readings was thus taken from -50.25 dBm to -40.25dBm. On the other hand, the three-source-one-destination network coding system decreases the number of transmissions to three, as opposed to six in non-networking coding system., thus transmission power of each node was increased by 50% or 1.76dBm. So the BER readings were taken for the range of -49.74dBm to -39.74dBm for this model. All readings were taken with step of 2dBm, and recorded after performing three transmissions at the same gain and then taking average.

For throughput readings, each experiment was repeated such that the total time taken for the data flow from source to destination was kept constant for the non-Network Coding and Network Coding models. For every experiment without Network Coding, we let the destination nodes receive data for 60 seconds and count the number of bits received during this time at the receiving end using custom GRC block. To keep the total time of data flow from source to destination constant, the receiving time for network coding models was increased. For two-way relay and two-source-one-destination network coding models, we made a 33% increase in the transmission time, i.e. 80 seconds. Similarly for three-source-one-destination model, 50% increase in transmission time was done, so data was received for 90 seconds. Total bits received were calculated in both cases which gives an experimental result of the throughput in each case. Subsequently, we calculated the goodput for each throughput readings, from the formula discussed above.

Fig. 11, Fig. 12 and Fig. 13 below shows the experimental setup for each topology.

FIGURE 23: TWRC TOPOLOGY

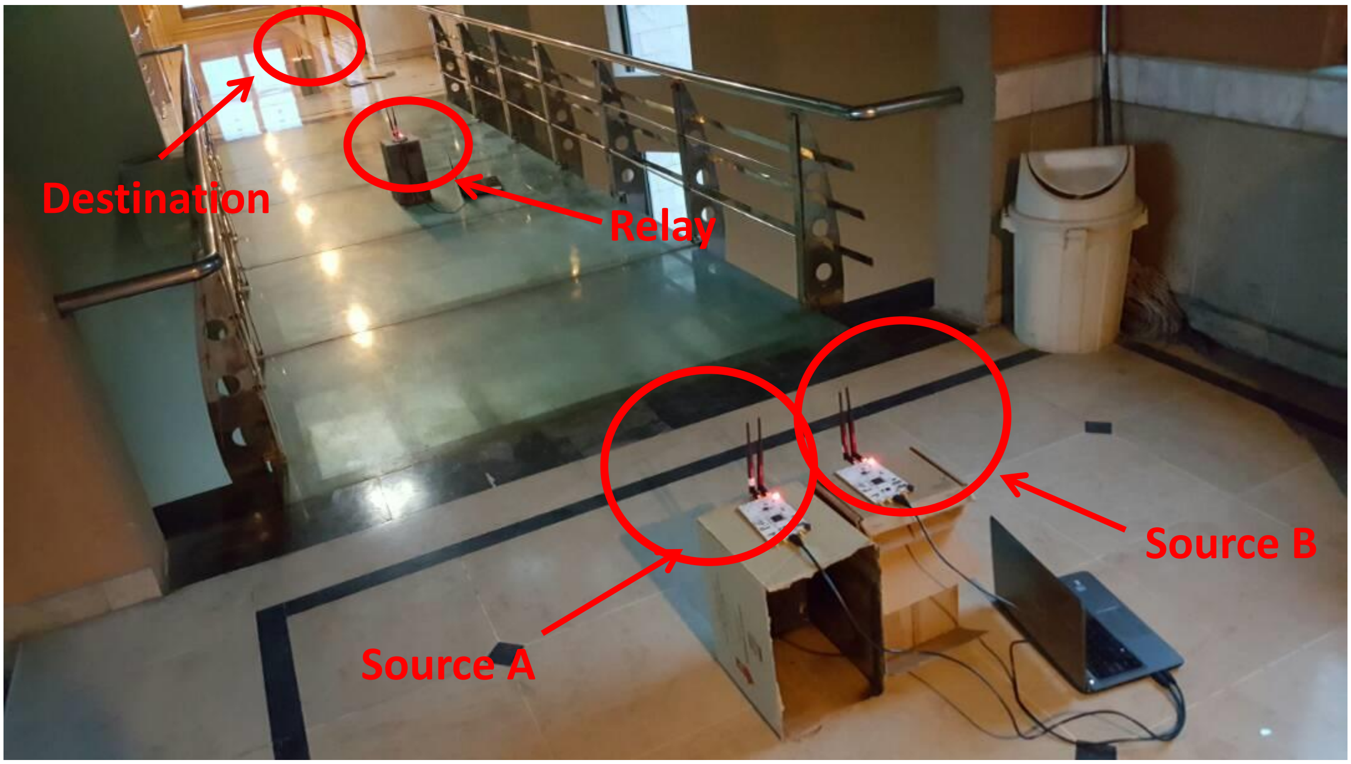


FIGURE 24: 2-SOURCE MISO TOPOLOGY

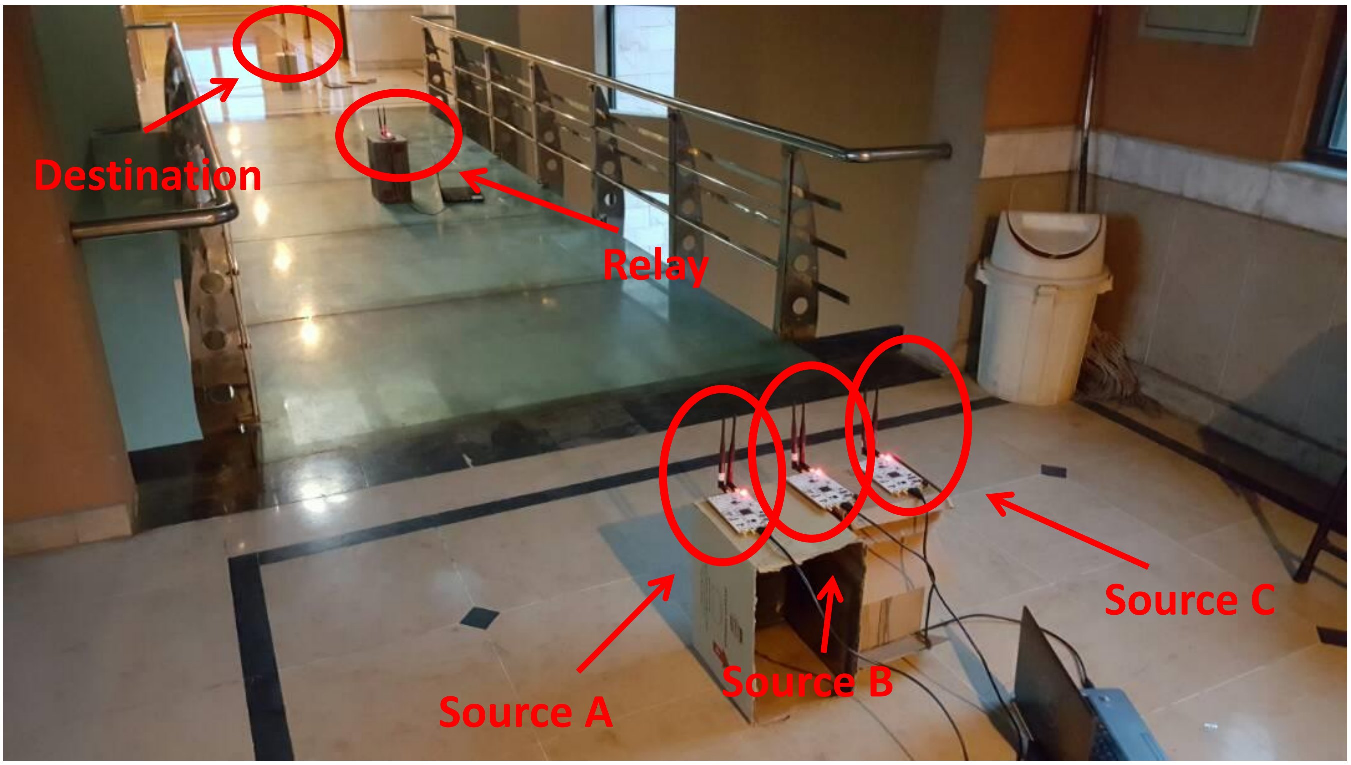


FIGURE 25: 3-SOURCE TOPOLOGY

Fig. 14, Fig. 15 and Fig. 16 shows schematic setups of each topology, showing the symmetricity of the channel.

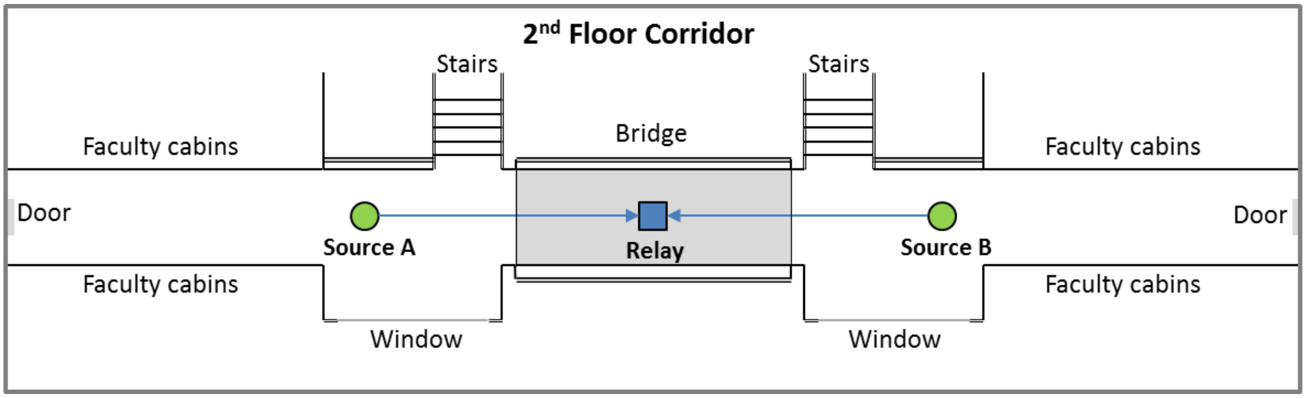


FIGURE 26: TWRC TOPOLOGY

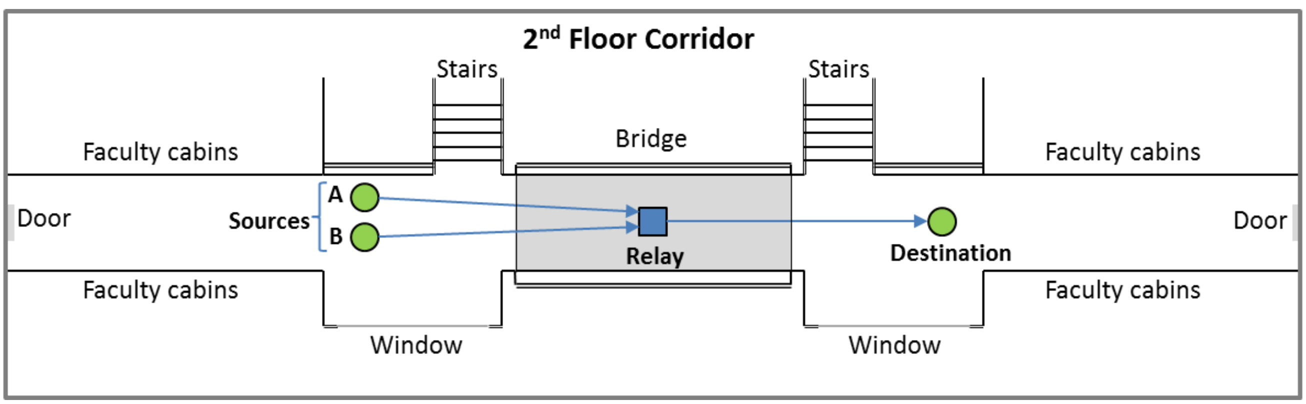


FIGURE 27: 2-SOURCE TOPOLOGY

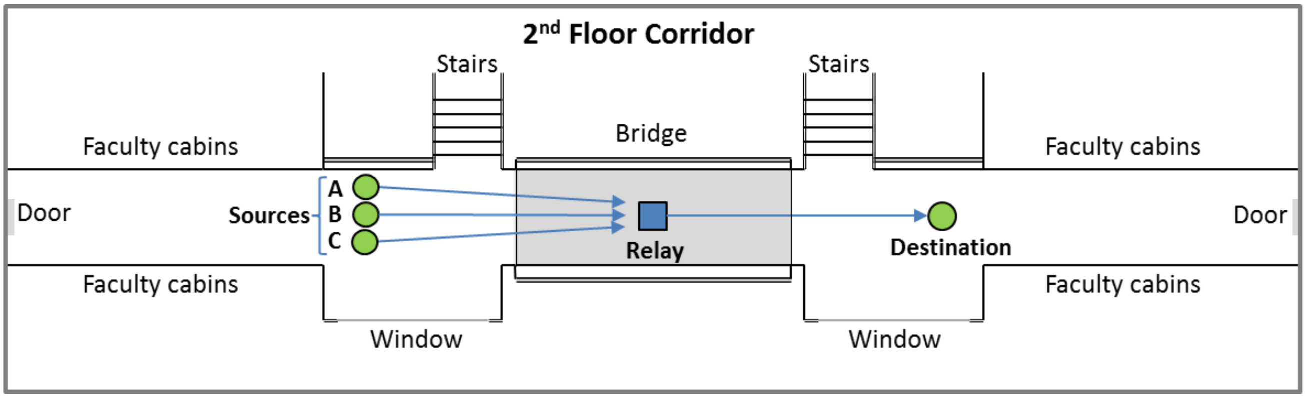


FIGURE 28: 3-SOURCE TOPOLOGY

Results and Discussion:

Fig 17-21 depicts the relationship between the transmit power at each node and the corresponding BERs of the data decoded at the destination for non-NC and NC schemes for each topology stated in previous sections.

Single experiment was conducted for the data received on the destination for the non-NC schemes of all the topologies. Fig. 17 compares the BERs of the data received at the destination for non-NC scheme from source A and source B, for the 2-source topologies and from source C for the 3-source topology. Although seemingly identical channels were used to transmit the data from each source to destination, and one must anticipate completely replicable curves. However, difference in antenna gains of the USRPs and time varying effects of channel accounts for the differences in the BER curves of the data from each source.

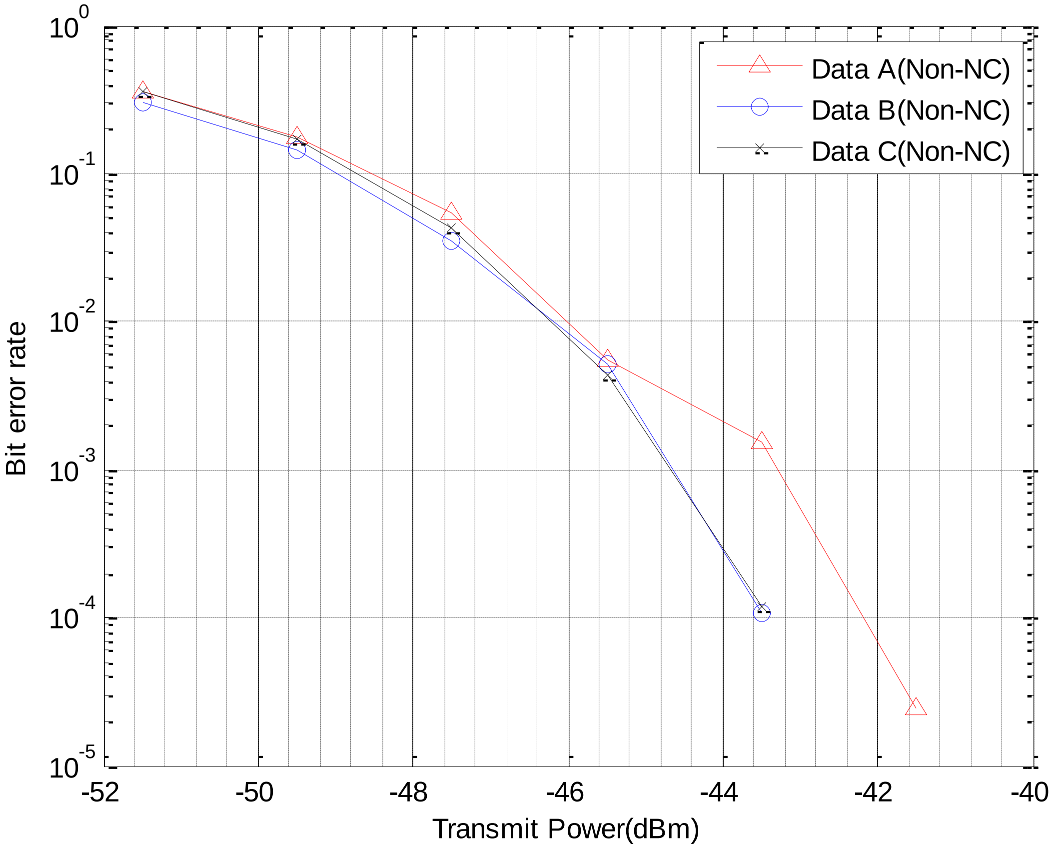


FIGURE 29: : NON-NC SCHEME TOPOLOGIES

Fig. 18 and Fig. 19 shows the transmit powers and the corresponding BERs at the destination for the data from each source for non-NC and NC schemes for the 2 source-XOR-coded topology, 2-source-algebraic-coded topology and 3-source-algebraic-coded topology respectively. For the 2 source-XOR-coded topology and 2-source-algebraic-coded topology, it can be observed that when NC scheme is employed each data decoded at the destination has a lower BER when compared with its respective non-NC scheme. Although combining the two streams at relay in network coding combines their errors too and one must anticipate a higher BER. However, as previously stated, keeping the total power of the system constant 2-source NC scheme allows us to increase the transmit power of each node by 33%, hence, negating the effect of accumulation of error and thus lowering the BER. The results further depict that as transmitting power increases the difference in BERs of the NC and non-NC schemes becomes greater. We notice that percentage difference in BER was 12% at 41.5dBm, which increased to 90% at the transmit power of -45.5 dBm. This is primarily due to the fact that 33% increase in transmit power of each node at higher transmitting powers has greater effect on BER compared to lower transmit powers. Furthermore, incoming streams combining at higher transmit powers are prone to less error as compared to the streams coming at lower transmit powers. For the 3-source-algebraic-coded topology, as shown in Fig. 3, it can be noticed that BERs at the destination for NC scheme is not always lower than that of Non-NC scheme. At lower gains, non-NC seems to outperform NC, as stated previously, at lower transmit powers effect of increase in transmit power is not enhanced in the decrease in BER. Although NC allowed us to increase the transmit power by 50%, but in this topology, data from three sources are combined at the relay and hence increasing the possibility of error due to coding of data. However, general trend can be observed that greater advantage of NC can be realized on the system when transmissions are carried out at a higher transmit powers.

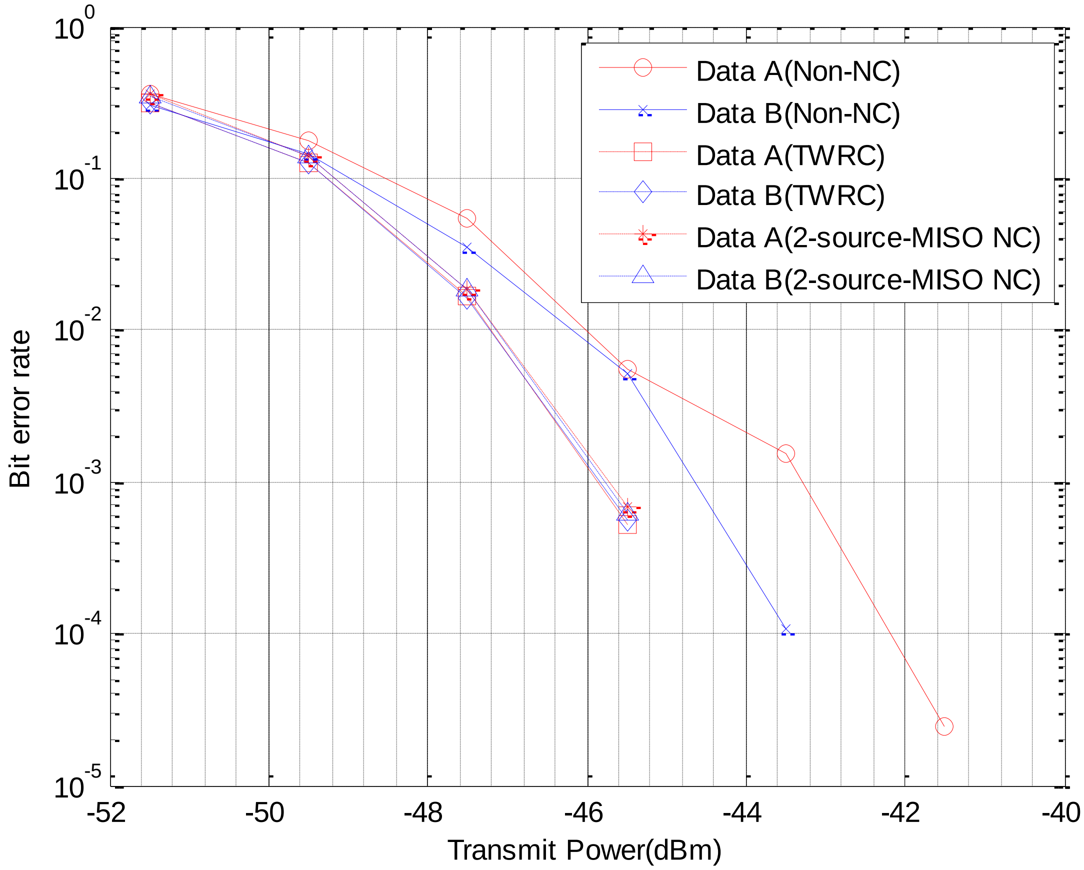


FIGURE 30: NON-NC & NC SCHEMES FOR 2-SOURCE TOPOLOGIES

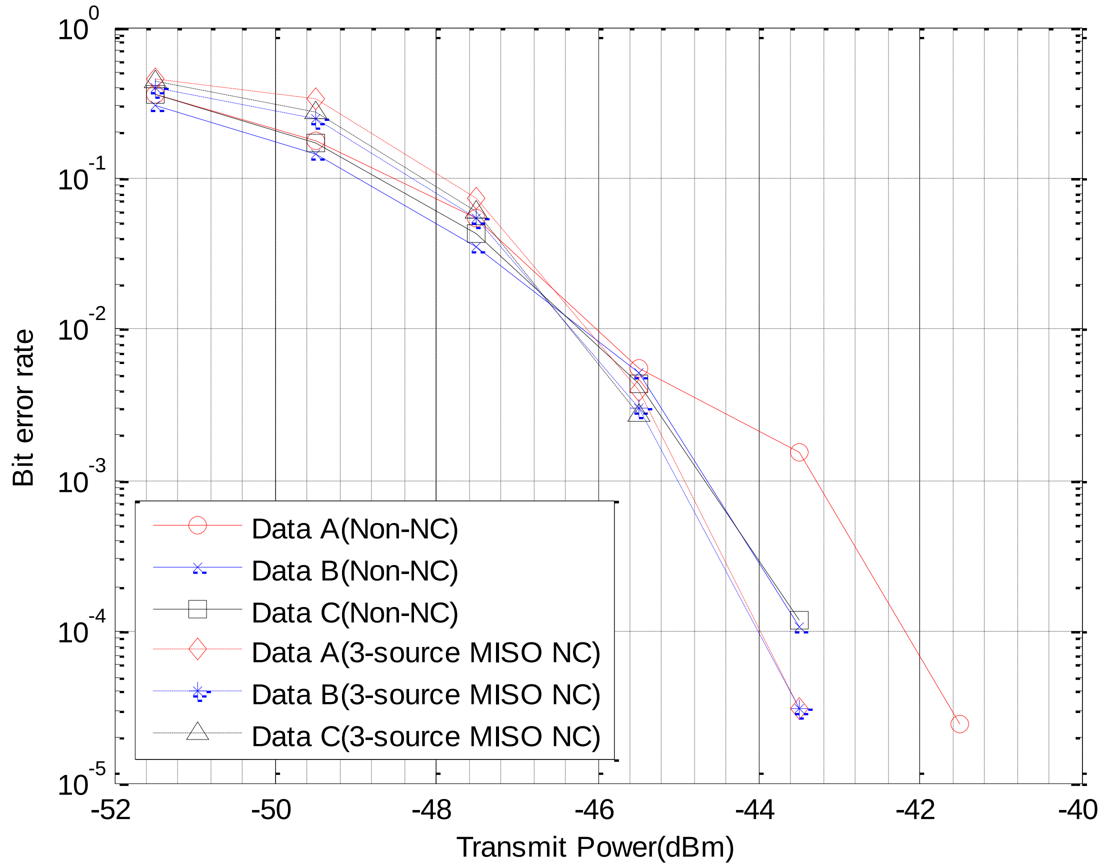


FIGURE 31: NON-NC & NC SCHEMES FOR 3-SOURCE TOPOLOGY

Fig. 20 plots the transmit power and corresponding BER curves at the destination for the network-coded scheme of each topology. An observation can be made that 3-source topology has overall greater BER than 2-source topologies at each gain, accounting for increased error due to combining of more number of data streams at relay. Another important observation, which is further illustrated in the bar graph in Fig. 21 is that BER curve of 2-source-algebraic-coded topology is slightly greater than the 2 source-XOR-coded topology.

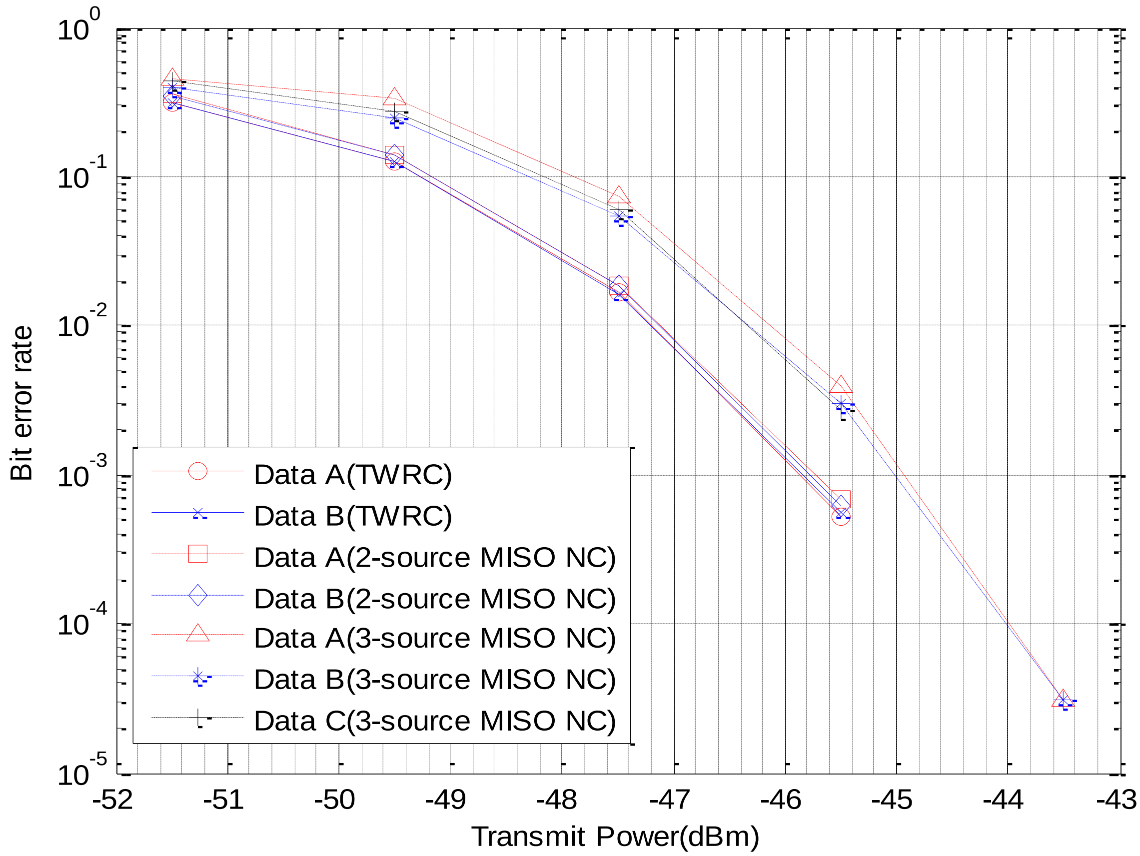


FIGURE 32: NC SCHEMES FOR ALL TOPOLOGIES

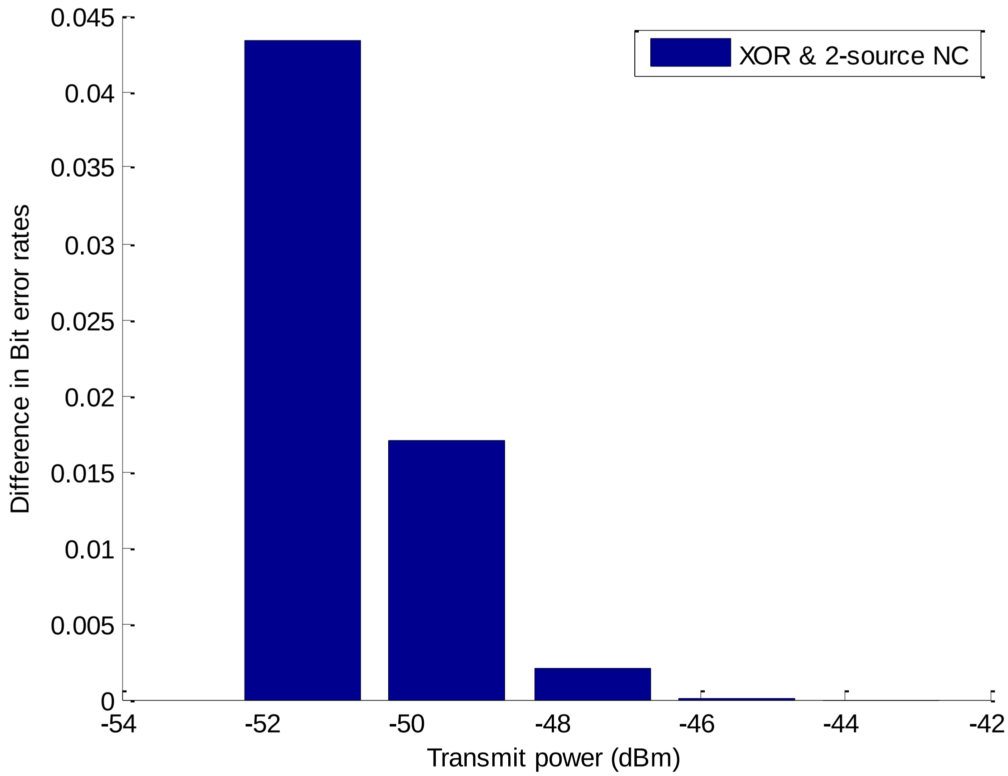


FIGURE 33: DIFFERENCE BETWEEN 2-SOURCE TOPOLOGIES

The second part of our testing was based on calculating the throughput and the corresponding goodput for each topology and realizing the advantage of NC scheme due to decrease in time slots. Fig. 22 shows goodput of the Source A's data decoded at the destination for the non-NC and NC scheme for each topology, as the transmitting power is varied. It can be noticed that for all transmitting powers, NC scheme for each topology has a greater goodput than the non-NC scheme. This is due to the fact that NC scheme saves certain number of time slots (depending on the topology). As stated in previous section, keeping the total transmission time of the system constant, NC scheme allows us to increase the time of transmission by 33% for the 2-sources topology and 50% for 3-source topology. As expected, 2-source-XOR-coded topology has a greater or an equal goodput compared to 2-source-algebraic-coded topology. This result further emphasizes the BER comparisons of two topologies done above. A surprising observation, that at higher transmitting powers 3-source-NC topology has a greater goodput than 2-source-NC topologies. This means that increase in total number of bits due to greater transmission time for the 3-source-NC scheme topology compared to 2-source-NC scheme topology has compensated for the errors. This makes an important result for us, if we combine the results of BER and goodput, at higher transmitting powers 3-source-NC topology performs better than 2-source topologies.

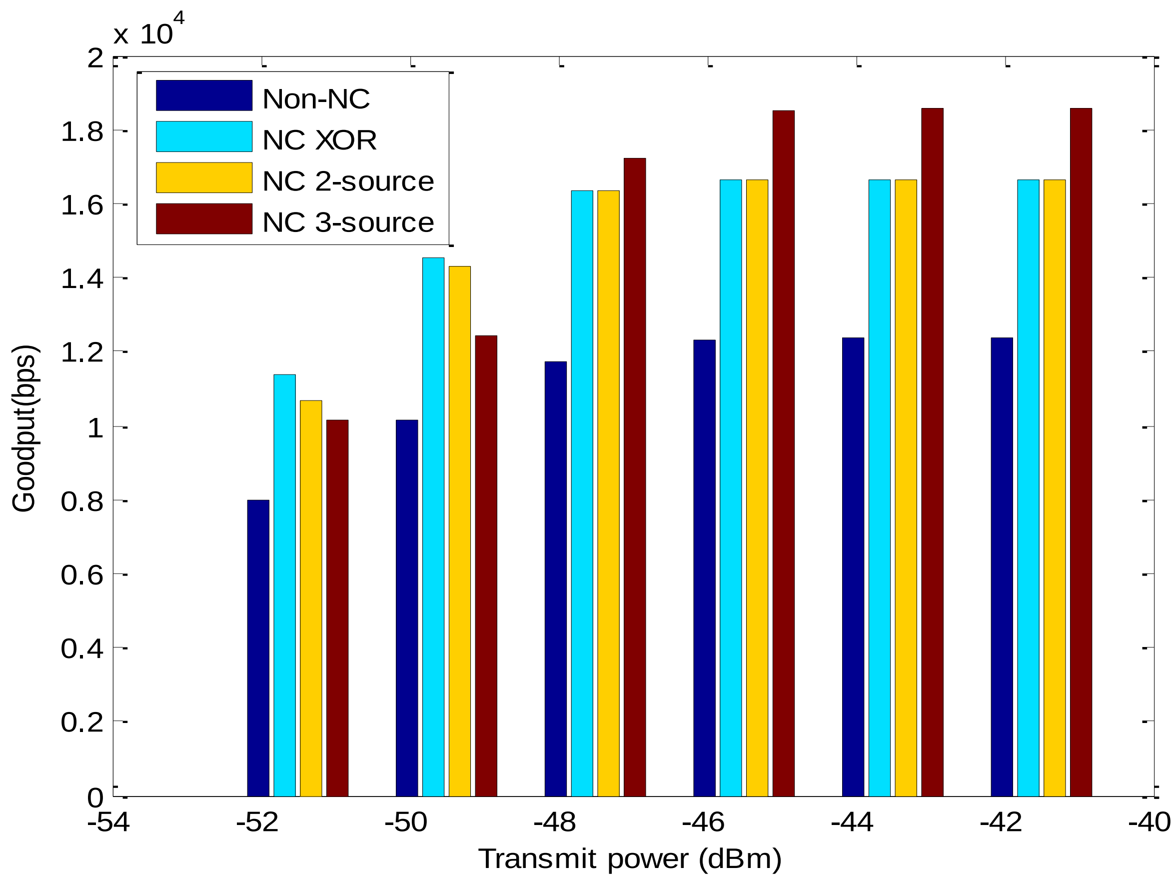


FIGURE 34: GOODPUT FOR ALL TOPOLOGIES

We realize that there is a trade-off between number of sources, transmitting powers and goodput being achieved at the destination. This can be further elaborated with an example of wireless sensor networks. If we are operating at lower transmitting powers, and we combine the data from every three sensors at the relay, less number of relay nodes would be required, as opposed to combining the data from two sensors. Less number of relay nodes and less transmitting powers would ensure less infrastructure and energy efficient network but the user will have to compromise on the goodput, or the Quality of Service (QOS). On the other hand, if we are operating at higher transmitting powers, and are using three source topology instead of 2-source topology, we are lessening the infrastructure deployment of relays and are also achieving a better quality of service at the destination but the system will not be energy efficient.

Simulation Results:

To verify our results, we conducted simulations. Fig. 23, Fig. 24 and Fig. 25 shows the simulation results.

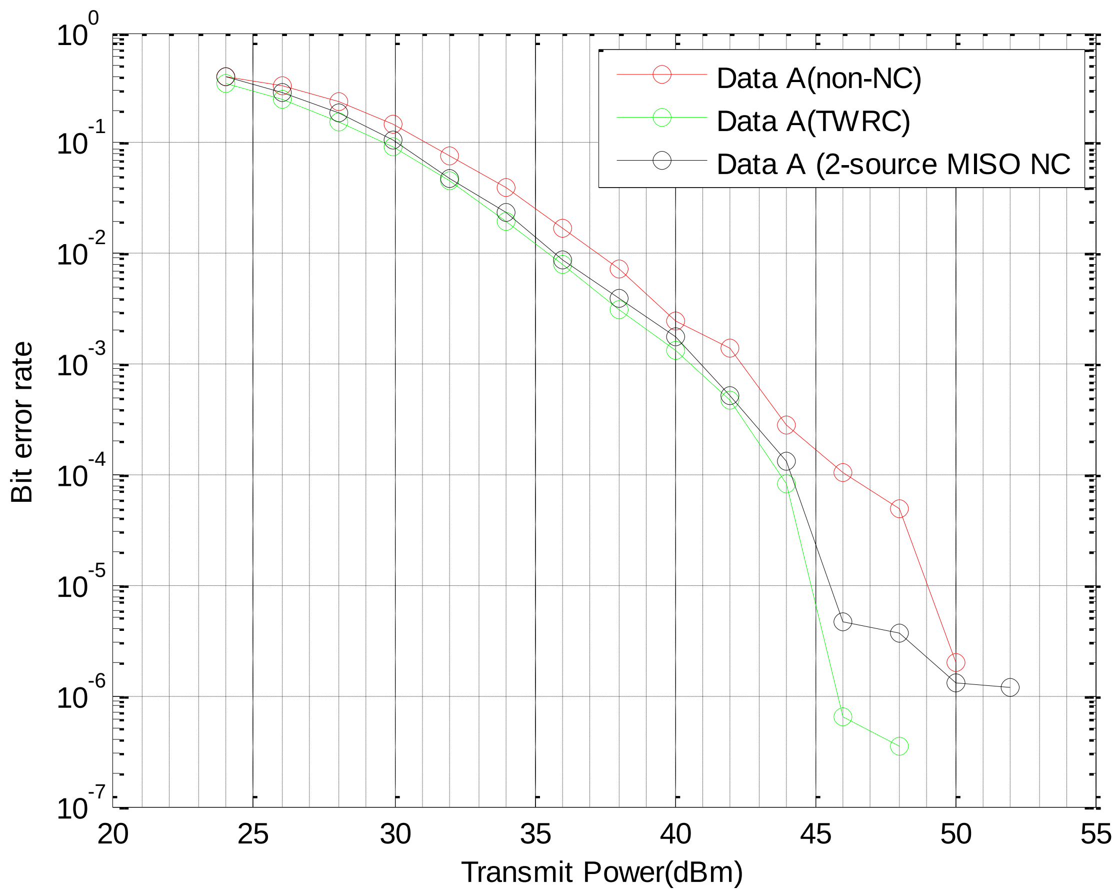


FIGURE 35: NON-NC & NC SCHEMES FOR 2-SOURCE TOPOLOGIES

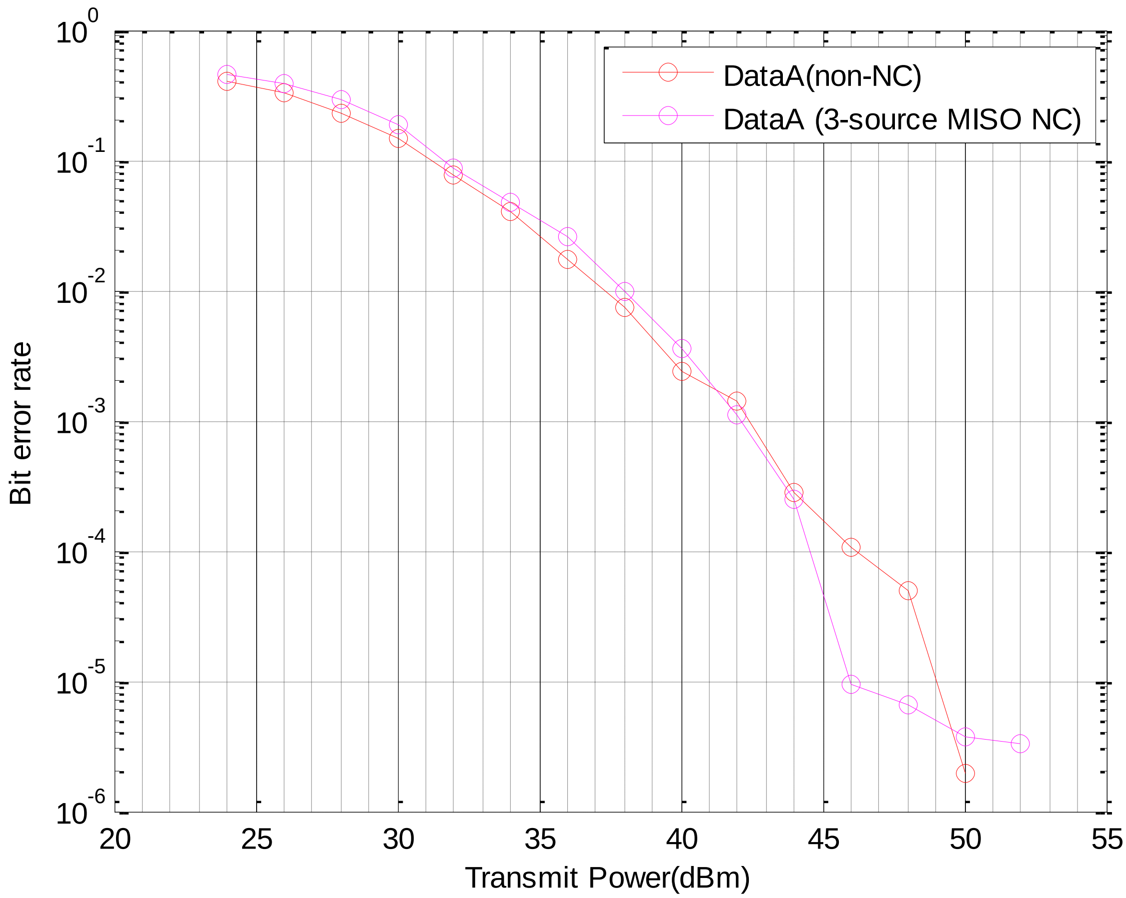


Figure 36: Non-NC & NC schemes for 3-source topology

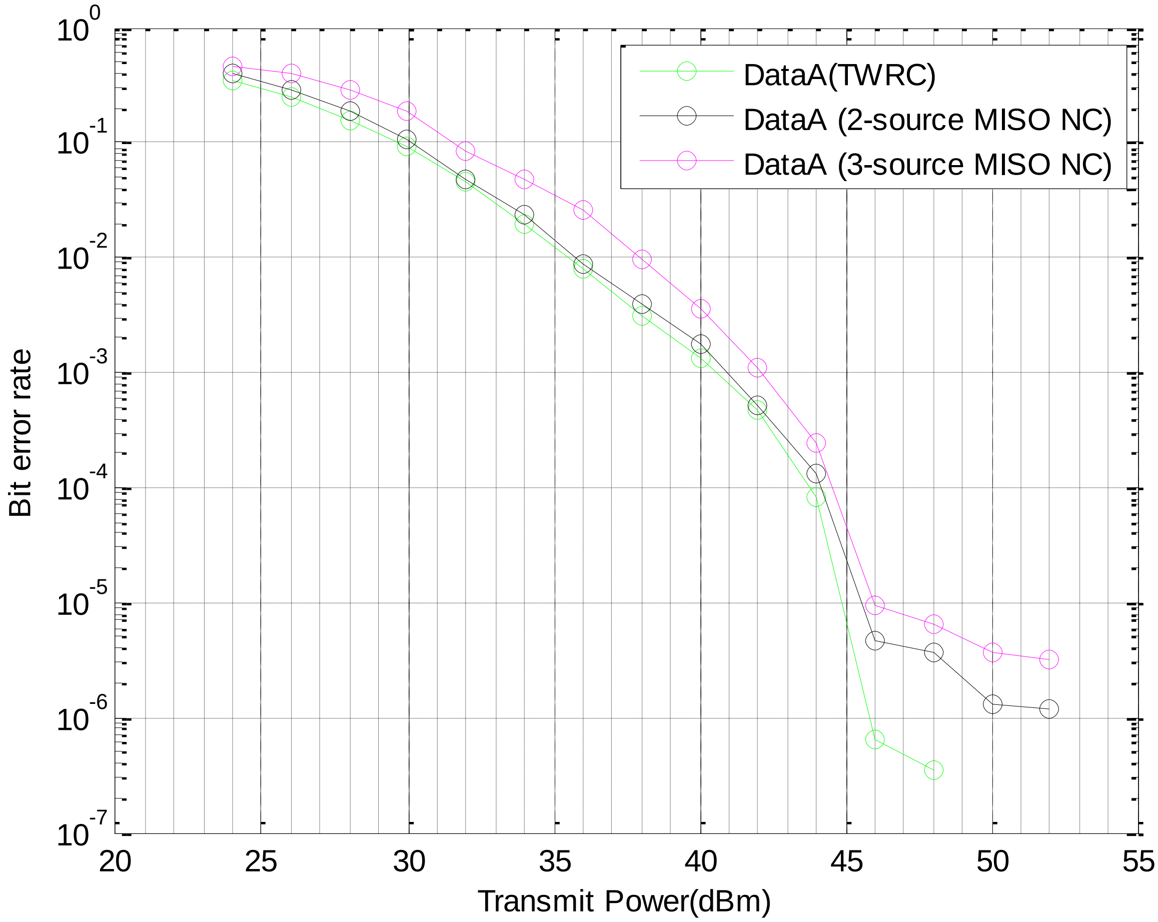


FIGURE 37: NC SCHEMES FOR ALL TOPOLOGIES

CONCLUSION

So, in conclusion, network coding is an idea whose time has come. And as we have already discussed, it is finding important applications in many diverse areas and it is one of the major enabling factors for 5G paradigm shift.

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