Experimental Performance Analysis of Network Coding in Wireless Systems

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***Abstract*—Network coding (NC) holds great significance in the upcoming 5G paradigm because of the potential improvements it offers in terms of network throughput, energy efficiency and data security. However, the evidence for these potential advantages comes mainly from within a theoretical framework or is based on simulations; there is a paucity of empirical evidence. Secondly, few works have evaluated NC in terms of its impacts on both throughput and bit error rate (BER) simultaneously. The work outlined in this paper addresses both of the aforementioned issues. We implement both the NC and non-NC schemes for a communication system in the context of n-source multiple-input single-output (MISO) topologies on software-defined radios (SDRs). The performances of the two schemes have been compared in terms of BER, throughput and goodput or useful throughput. Our results show that the goodput improvement in NC when compared to non-NC is more pronounced at higher transmitter (Tx) gains and that below a certain Tx gain threshold, non-NC should be preferred over NC.**

***Keywords*—Network coding; BER; two-way relay channel; multiple-input single-output; USRP; GNU Radio**

I. Introduction

Network coding (NC) is considered to be one of the most significant enabling factors for the proposed fifth generation (5G) paradigm shift. As per the traditional scheme, all networked systems such as telephonic networks, public internet, peer-to-peer networks, sensor networks, etc., handle independent information streams separately, i.e., the intermediate nodes (relays) only forward the incoming data. However, the introduction of NC in the seminal paper by Ahlswede et al [1] proposed a significant departure from the traditional scheme. In network coding, the intermediate nodes in a network go beyond the simple amplify-and-forward mode of operation; instead, they combine the incoming data streams by applying some form of arbitrary coding operation and transmit this combination rather than the independent data streams. This simple but significant modification enables drastic improvements in network throughput, energy efficiency and data security [2].

The performance of network coded wireless systems varies with the topologies or coding methods employed. As seen in [3], straight-forward NC performed in a three-node file exchange network results in a throughput improvement of 33.3% as compared to the traditional scheduling scheme, while physical-layer network coding (PNC) utilizes the interference of electromagnetic waves to achieve a maximum throughput improvement of 50%. The star coding approach discussed in [4] provides efficient transmission by allowing a multiplicative improvement of a factor of 2.4 in the number of transmissions required to route the data from the sources to the destinations. As described in [5], NC can also help in improving the performance of device-to-device (D2D) networks, a technology proposed for future 5G systems.

Although a number of theoretical studies have elaborated upon the various advantages provided by NC [8-10], the practical implementations of NC are quite limited. In [6], a real-time implementation of PNC was performed using a universal software radio peripheral (USRP) software-defined radio (SDR) platform. The challenges involved in this implementation included the synchronization of transmission packets from the sources and catering for the latency between the USRP and the computer. An implementation of NC in a two-way relaying scenario is discussed in [7] and it describes a medium access control (MAC) protocol based on time division multiple access (TDMA) scheme. The protocol uses a modified packet structure that provides robust synchronization between the separate packets incoming at the relay. Moreover, to the best of authors' knowledge, NC has not been evaluated in terms of its effects on both throughput and BER. For example, the above-mentioned implementation in [7] only discusses the performance of NC in terms of throughput improvement. Similarly, some recent works that address various other aspects of NC are given in [11-13].

This paper details an experimental appraisal of NC in the context of multiple-input single-output (MISO) topologies with the aim of obtaining empirical evidence for the theoretically predicted advantages of NC. We perform a more holistic evaluation of NC in terms of goodput, which takes into account both throughput and BER, and, in the process, intend to discover any qualifications to the usefulness of NC schemes over non-NC schemes. Moreover, our paper also highlights how the improvements in throughput and energy efficiency due to NC vary with the number of sources in a MISO topology.

The rest of the paper is organized as follows. Section II describes the network topologies used and defines the parameters to evaluate the performance of NC in each topology. Theoretical analysis of each topology is done in Section III. Section IV explains the actual implementation and results of experimentation, while Section V concludes the paper.

II. Network Topologies

To investigate the performance of NC, an implementation of a communication system based on two-way relay channel

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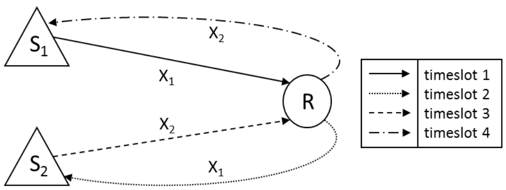
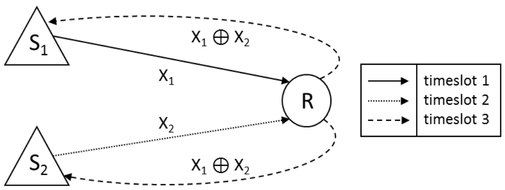
(TWRC) is performed, where two terminal nodes exchange packets of information via a relay node. We compare the performance of this system to the non-NC scheme. The timeslot-wise breakdowns of both the schemes are illustrated in Fig. 1.

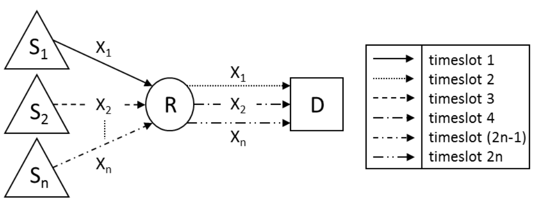


(a) System without NC

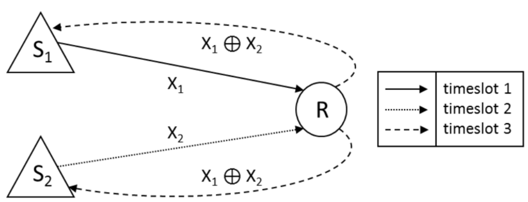


(b) System with NC

Fig. 1: Two-way relay channel



(a) System without NC



(b) System with NC

Fig. 2: Multiple-input single-output Topologies

We also broaden the scope of our experiments to include 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 a system of n equations to obtain the data of n source packets. Fig. 2 illustrates the non-NC and NC schemes for MISO topologies. They are also discussed in detail in next section.

All of the topologies mentioned above have symmetric channels and, with the exception of the simplex destination nodes in the MISO topologies, all nodes are half-duplex enabled. In further sections of the paper, TWRC is referred to as T_1 and two-source MISO and three-source MISO topologies are referred as T_2 and T_3, respectively.

III. Theoretical Analysis

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

A. TWRC Topology

As Fig. 1 shows, one time slot can be saved using NC scheme over non-NC scheme. This is because of combination and recovery of packets using XOR operation. Assuming all transmissions have the same duration, the saving of one timeslot or transmission translates into a throughput improvement of 33.3% for one packet exchange. Furthermore, if all the antennas have the same transmit power, there is also an energy saving of 25%, as the energy consumed is directly proportional to the number of transmissions.

Although a net gain of throughput can be seen in NC, 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. This is because the BER at the terminal nodes for the T_1-NC scheme is expected to be worse than that for the non-NC scheme. To illustrate this point, Table I presents an error analysis of the two schemes, assuming symmetric channels with common transmit power, Y, where Z is BER induced in a single channel. The higher terminal cumulative BER results due to XOR operation at relay, which compounds the errors of two incoming streams.

Moreover, the percentage increase in goodput is the same as that in throughput (i.e. 33.3%) only in a perfectly error-free channel. As the errors increase, the percentage increase in goodput diminishes rapidly and reaches zero at the *NC-usefulness-threshold* (UT_{NC}) value, which is the upper limit of channel BER for goodput advantage of NC system. Table II presents a numerical illustration of the above.

TABLE I: Error analysis at TX power, Y

T_1-NC		non-NC	
Channel	Cumulative BER	Channel	Cumulative BER
S_1-to-R	Z	S_1-to-R	Z
S_2-to-R	Z	S_2-to-R	Z
R-to-S_1/S_2	$2Z$+Z=$3Z$	R-to-S_1	Z+Z=$2Z$
–	–	R-to-S_2	Z+Z=$2Z$

TABLE II: Increase in goodput (GP) vs channel BER, Z

Z	0	0.03	0.06	0.09	0.12	0.15	0.16
GP increase (%)	33.3	29.1	24.2	18.7	12.3	4.8	0

Lastly, there is the possibility of improving the UT_{NC} by foregoing the previously mentioned energy saving in the NC scheme to transmit data at a transmit power greater than that in the non-NC scheme. For example, in the case of the TWRC topology, the energy saving of 25% in NC can be traded off for an increase of 33.3% or 1.25 dB in transmit power. While keeping the total energy consumption same, this would lower the terminal cumulative BER for the NC scheme, which would hence maintain a better goodput than the non-NC scheme over a greater range of channel BER or transmit powers.

B. MISO Topologies

It can be seen that TWRC itself can be taken as a two-source MISO topology. Therefore, the analysis presented above for the TWRC topology can be easily extended to the MISO topologies. Table III presents some key performance characteristics and their variation with the number of sources. As the table shows, the maximum possible percentage increase in throughput and transmit power is 100%, whereas the maximum possible energy savings are 50%.

IV. Implementation and Results

This section discusses the hardware and software used for experiments, setup for each experiment and the results obtained after performing the respective experiment.

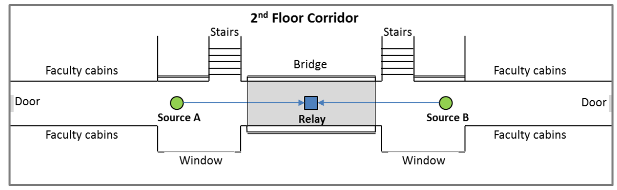
A. Experimental Setup

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 through built-in as well as custom programmed blocks. The antennae used at each radio are VERT2450 having a gain of 3.3dBi.

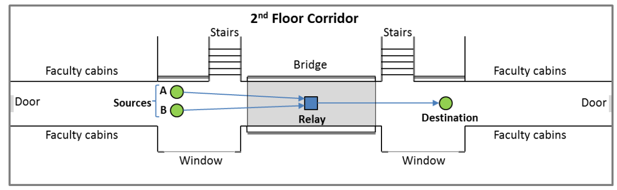
For all experiments, the channels are indoor, line-of-sight (LoS) with a distance of 5m between each transmitter-relay and relay-receiver pair, and the modulation technique employed is binary phase shift keying (BPSK). The setup for testing all three topologies is shown in Fig. 3 whereas Fig. 4 shows the actual environment for each setup. The environment is selected such that the source-relay and relay-destination channels at each experiment apparently behave symmetrical. For each topology, we perform experiments using both non-NC and NC schemes.

The time scheduling and synchronisation of the data transmissions from sources to relay is achieved using the TDMA-based MAC protocol, proposed in [7]. It is a master-slave protocol which uses some overhead bits (header) as control signals. These control signals achieve time scheduling, as required by the three topologies discussed earlier, in receiving data from multiple sources to relay and subsequent transmission after employing NC at relay. Buffers are used at the relay to store received packets before constructing codes from them. While in [7], the proposed protocol only focuses on NC in T_1, we have implemented the similar protocol in T_2 and T_3 topologies to achieve TDMA at transmission only. Frequency division multiplexing (FDM) is used at the relay for both T_2 and T_3 topologies to aid transmission of coded data to the destination in a single time slot.

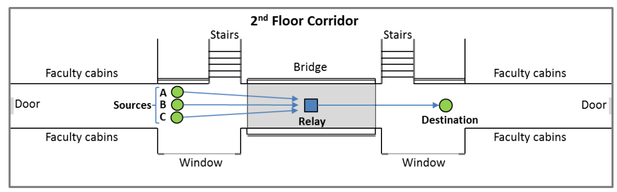
All experiments are conducted for the T_1, T_2 and T_3 topologies. For the BER experiments, two million bits have been transmitted from each source to the destination via the relay. For the non-NC scheme, values of BER have been recorded at the destination node over a transmit power range of -51.5dBm to -41.5dBm.



(a) T_1 topology

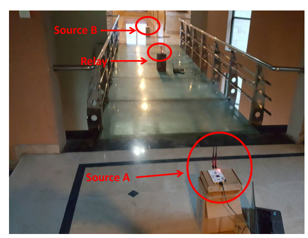


(b) T_2 topology



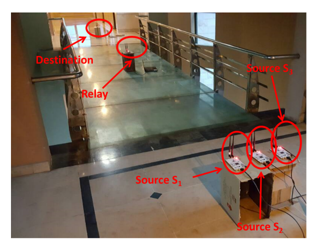
(c) T_3 topology

Fig. 3: System topologies tested



(a) T_1 topology

(b) T_2 topology



(c) T_3 topology

Fig. 4: Experimental setup

However, as discussed in the previous section, the transmit power, under the NC scheme, can be increased by a specific amount at the expense of the energy saving that accompanies the reduction in the number of transmissions. Therefore, as is shown in Table III, the transmit power of each node is increased by 33% or 1.25dBm in the NC scheme for both T_1 and T_2 topologies and BER readings are taken over a transmit power range of -50.25 dBm to -40.25dBm. Similarly, the transmit power of each node is increased by 50% or 1.76dBm

TABLE III: A comparison of various performance related parameters of MISO topologies

		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 transmit power	$33\frac{1}{3}\%$	50%	$\frac{n-1}{n+1} \times 100\%$
	Potential increase in transmit power (dB)	1.25	1.76	$10log(\frac{2n}{n+1})$

in the NC scheme for T_3 topology and BER readings are taken over a transmit power range of -49.74dBm to -39.74dBm.

For the throughput experiments, the total transmission time of complete data flow from the source to the destination is kept constant for the non-NC and NC schemes in each topology. Under the non-NC scheme, a single channel transmission is performed for 60 seconds. As there is a 33% reduction in the total number of time-slots under the NC scheme for the T_1 and T_2 topologies, each channel transmission time is increased by 33%, or 20 seconds. Similarly, each channel transmission time is increased by 50%, or 30 seconds under the NC scheme for the T_3 topology. Thus the ratio of the total bits received to the total transmission time in each case provides a measure of the throughput. These readings are not repeated over a range of transmit powers as throughput primarily depends on the transmission time in this case. Subsequently, the goodput values were calculated using the BER and throughput results.

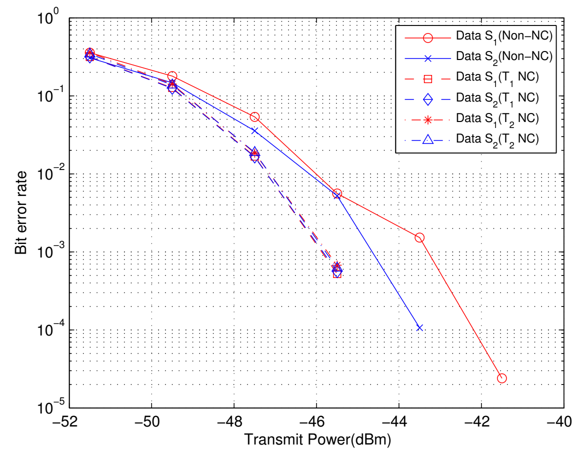


Fig. 5: Performance of T_1 and T_2 with and without NC

B. Results and Discussion

Figs. 5-7 depict the relationship between the transmit power and the corresponding BER at the destination for non-NC and NC schemes for each topology stated in the previous sections.

Fig. 5 and Fig. 6 show the transmit powers and the corresponding BER at the destination for non-NC and NC schemes for the T_1, T_2 and T_3 topology, respectively. The slight disparity in some channels is due to the unaccounted differences in antenna gains of the USRPs and the time-varying nature of the channel. When two streams are combined at the relay, their errors are compounded. However, the increased transmit power compensates for this, resulting in a terminal BER lower than that of the corresponding non-NC scheme. The results further depict that as transmit power increases, the difference in BER of the NC and non-NC schemes becomes larger. We notice that the percentage difference in the BER is 12% at 41.5dBm, and increases to 90% at -45.5 dBm. This is primarily due to the exponential relationship between BER and transmit power.

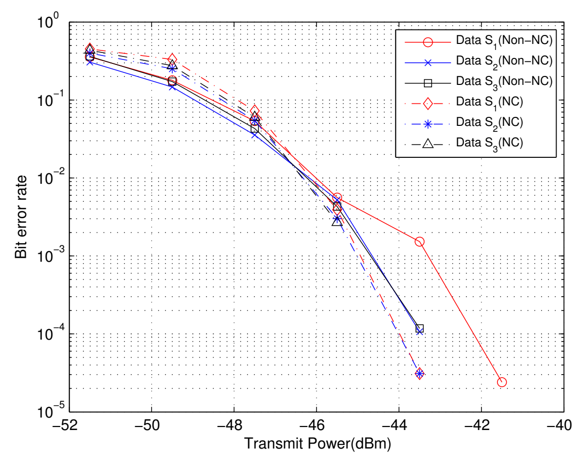


Fig. 6: Performance of T_3 with and without NC

For the T_3 topology, as shown in Fig. 6, BER at the destination for NC scheme is not always lower than that of non-NC scheme. At lower transmit powers, non-NC outperforms NC. This is becausethe compounding effect of errors is greater. However, it can be observed that the advantage of NC is more marked at higher transmit powers.

Fig. 7 plots the transmit power and corresponding BER at the destination for the NC scheme of each topology. An observation can be made that T_3 has overall larger BER than T_1 and T_2 at all transmit powers, while BER of T_2 is slightly greater than T_1. Thus, it can be observed that BER rises with increase in the number of input streams.

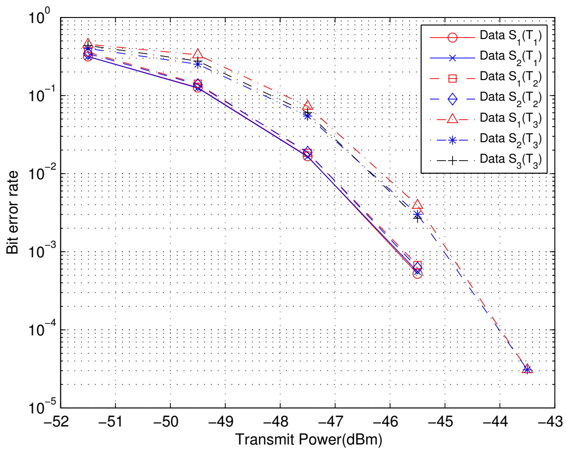


Fig. 7: Performance of all topologies employing NC

In the second part of our testing, we calculated the throughput and the corresponding goodput for each topology. Fig. 8 shows goodput for S_1 data decoded at the destination for the non-NC and NC scheme for each topology, as the transmit power is varied. It can be noticed that for the entire range of transmit powers in these experiments, 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 T_1 and T_2 topologies and 50% for T_3 topology. As expected, T_1 has a greater or an equal goodput compared to T_2. This result further emphasizes the BER comparisons of the two topologies mentioned above. A surprising observation, is that at higher transmit powers T_3 has a larger goodput than T_1 and T_2 topologies. This implies that an increase in the total number of bits due to greater transmission time for the T_3-NC scheme compared to T_1-NC and T_2-NC schemes has compensated for the compounding effect of errors.

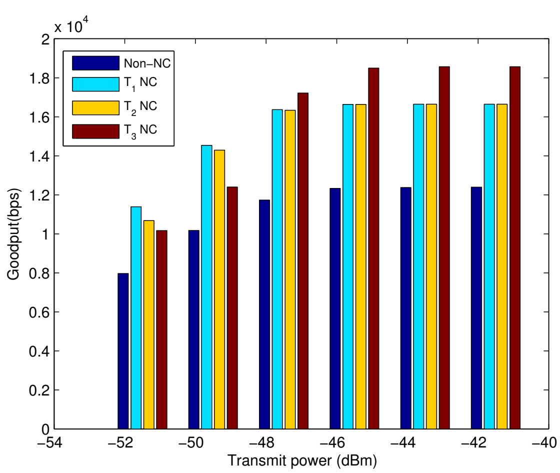


Fig. 8: Goodput for all topologies

We realize that there is a trade-off between number of sources, transmit power and goodput. Using three-source MISO (T_3) instead of two-source MISO (T_2) means that fewer relays would be required to cater to all the sources in a wireless network - thus lowering the infrastructure cost. On the other hand, NC in T_3 provides a better goodput than its T_2 counterpart only at higher transmit powers which entail greater energy consumption. At lower transmit powers, NC in T_2 provides a better goodput than NC in T_3 and needless to say the energy consumption is also lesser.

V. Conclusion

This paper empirically evaluated the theoretically predicted advantages of NC and investigated the conditions under which NC performs better than non-NC in terms of goodput. The results showed that the goodput improvement due to NC is more noticeable at higher TX gains; and that there exists a certain TX gain threshold below which the non-NC scheme of communication results in a better goodput than NC. The paper also experimentally demonstrated the trade-offs between energy consumption, QoS and infrastructure cost as the number of sources is varied in a MISO topology.

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