Experimental Implementation of Cooperative Transmission Range Extension in Indoor Environments

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***Abstract*—This paper presents an experimental comparison between cooperative communication and single-input single-output (SISO) system, in terms of the corresponding ranges of signal reception in each case. Transmissions have been achieved using Universal Software Radio Peripheral (USRP) platform, with the signal processing and time synchronization occurring in the GNU Radio environment. The method has been implemented in a typical office environment, with cooperative transmission (CT) taking place over a multiple hop network, using the binary phase shift keying (BPSK) scheme. Presented herein are comparisons between SISO and cooperative networks with regards to ranges and bit error rate (BER) performance.**

***Index Terms*—Cooperative communication, GNU Radio, timing and synchronization, SDR, range, signal recombination, USRP, SISO, MISO**

I. Introduction

Cooperative communication is one of the fastest growing areas of research and is considered to be a key instrument for efficient spectrum use. The motivation behind user cooperation is resource sharing between multiple nodes in a given network. This sharing of power and computation with neighboring nodes can help conserve network resources. Moreover, this technique helps overcome multipath fading effects by employing diversity. The consequent signal-to-noise ratio (SNR) advantage from cooperative transmission (CT) can be used to extend the range of the transmissions and reduce the radiated power from individual transmitters [1]. This paper aims to investigate range extension in multi-hop cooperative communication networks, in an experimental setting.

Improved data rates and transmission range from SISO networks either require wider bandwidth or greater transmission power, neither of which proves to be economical especially in energy constrained applications such as wireless sensor networks (WSNs). It goes without saying that such limitations reduce the energy efficiency of these networks.

CT, in contrast, uses the concept of diversity to counter the effects of fading in the transmitted signals. It involves the transmission of multiple replicas of the original signal to the receiver, through uncorrelated fading channels which increases the probability that each replica will encounter independent channel responses. These uncorrelated faded signals are subsequently collected from diversity branches, and combined to give an improved performance of the communication system [2].

Despite the advantages of increased diversity and array gains, multi-relay cooperative networks demand synchronization in the reception and transmission of signals at the intermediate stage. It has been found that if timing errors are large enough, the setup would lose its efficacy in terms of diversity gain [3], resulting in performance degradation [4]. Such loss of synchronization may be countered by using certain metadata that can pass messages to signal processing blocks in GNU Radio. These 'stream tags' can control the time of transmission from USRPs and thus ensure that multiple radios transmit data in unison. This, in turn, allows for combination (or superposition) at the destination node.

The authors present herein an empirical proof of range extension using cooperative networks. Communication using SISO topology acts as a control experiment, against which the range of the multi-relay network will be compared. Each experiment consists of USRP test-bed nodes connected to general purpose personal computers that implement the modulation, demodulation and error rate determination in the GNU Radio environment. The paper includes flow graphs used for the method under investigation. The synchronization between multiple relay nodes has been achieved by employing stream tags in GNU Radio. The stream tags are used to implement a frequency division multiple access (FDMA) scheme for relay transmissions. At the destination node for CT, the replicas of the signals transmitted by multiple relays are then combined using equal gain combining (EGC). Finally, graphs for BER have been plotted for each scheme and analyzed.

II. Related Work

Considerable amount of work has been done to theoretically analyze cooperative multi-hop networks, e.g. [8]– [12]. There are several existing works that measure the performance of

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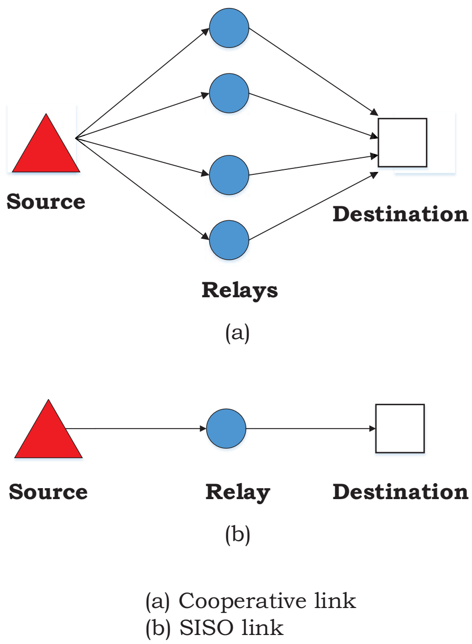


Fig. 1: Topologies tested

cooperative networks using USRP platforms, while keeping relay transmissions in sync. For instance, [1] aims to implement spatial diversity through multiple relaying nodes. The network thus designed utilizes schemes such as amplify-and-forward (AF) and decode-and-forward (DF). The performance of the resulting cooperative network is gauged by considering outage events and probabilities, which in turn determine the effect on the SNR. Using space diversity, however, incurs additional costs in the shape of greater hardware requirements. However, this paper implements both spatial and frequency diversity to determine range extension obtained by cooperative communication, with SISO networks used as control experiments.

A timestamp methodology implemented using *hardware synchronization* is presented in [5]. The paper implements a wireless cooperative network in an indoor setting, with the test bed being based on GNU Radio and USRP platform and supporting both single and multi-relay topologies. Signal recombination is achieved using maximal ratio combining (MRC). This paper, in contrast, uses EGC for signal combining and attempts to achieve synchronization through GNU Radio. Additionally, [6] states the negative impacts of timing errors, caused by PC processing delays, on the signal received at the destination node and proceeds to rectify them by using time stamping. The resulting network is tested using a two hop and a ping pong experiment. BER for the experiments is determined by keeping nodes at fixed points and varying the transmit power.

III. The System Model

Fig. 1 shows the primary topologies used for the performance tests. They utilize the DF scheme, with BPSK modulation. The general form for BPSK follows the equation,

$$s_n(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi(1-n)), n = 0, 1 \qquad (1)$$

where E_b is the energy per bit, T_b refers to the bit duration and f_c is the frequency of the carrier wave. Additionally, the network is assumed to be homogeneous, with each node having identical capabilities.

The setup determines the bit error rates at the destination node for a given range of transmit powers. The tested networks include those with one, two, three and four relays at the first hop. Each arrangement has been tested at varying distances between the source and the destination. It has been ensured that the length of each individual hop is the same.

The network with a single relay represents a SISO topology. By extension, multiple relays at the intermediate level form a cooperative network.

IV. Implementation

Fig. 2 shows the sequence of the signal processing steps taking place in the proposed transmitter and relay designs. The subsequent sub-sections provide further insight into the working of the network.

A. Transmitter Operations

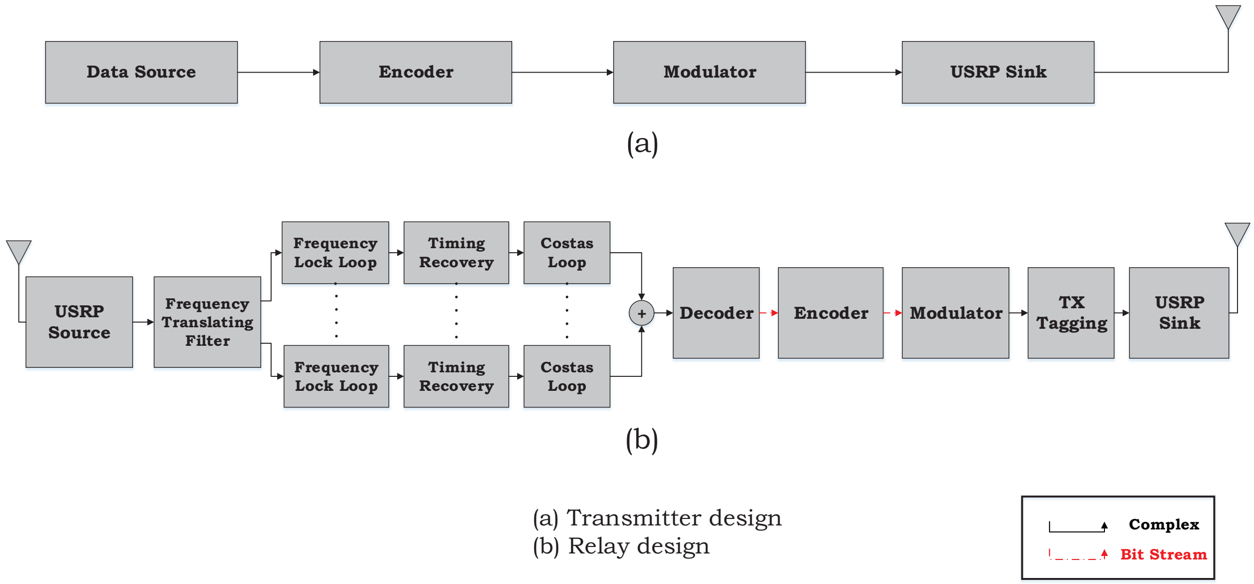
The data source feeds integer, character or float raw data into the system. The output from the signal source then enters the encoder, where it is converted into a packet of a specified payload length along with an access code. Our design uses a packet payload of 736 bits, with 64 bits allocated for the access code. Each packet is therefore 800 bits in length. Access codes are used to detect the start of packets. Following modulation, the complex signal reaches the USRP sink, the RF front end for transmitting radio signals.

B. Relay Operations

It is worth noting that since the relay node uses the DF scheme, it both receives and transmits signals. Therefore, the portion of the relay block diagram in Fig. 2 up till the decoder may be termed a receiver.

The receiver operates at a higher sampling rate allowing it to 'listen' for signals over a wider bandwidth. Moreover, the receiver is designed to receive BPSK modulated signals. The USRP source serves as the RF front end for receiving signals. It digitizes signals and transmits them to the PC via USB for processing. The frequency translating filter shifts each signal to the base-band, applies a low pass filter and decimates each stream such that the sampling rate for each stream matches with the transmission sampling rates.

The signal then proceeds to the frequency lock loop (FLL), where any carrier frequency offsets are eliminated. The timing recovery stage performs three operations. It ensures that symbols are sampled at the appropriate sampling points through a matched filtering operation using a root raised cosine (RRC) filter implemented in software. Additionally, it down samples the complex data stream from 4 samples per symbol to 1



(a) Transmitter design
(b) Relay design

Fig. 2: Transceiver Design

sample per symbol. Channel phase distortions are removed by the Costas Loop.

The signal replicas from each stream are then combined to achieve the advantages of frequency diversity. The network uses equal gain combining (EGC) for signal recombination. The signal-to-noise ratio (SNR) of the combined output thus obtained, γ_{EGC}, is given by,

$$\gamma_{EGC} = \frac{(\sum_{n=1}^{N_r} \sqrt{\gamma_n})^2}{N_r} \tag{2}$$

where N_r is the number of signal branches corresponding to the number of cooperating relays and γ_n is the SNR of the n^{th} branch.

Following combination, the packet extraction stage removes the access code, leaving behind the payload as the output. Transmit time synchronization is achieved by attaining a start of packet time using the 'stream tags' provided in the GNU Radio API and extrapolating this value using sample count and the sampling rate.

C. Timing and Synchronization

Cooperative networks, such as those used during the research work, involve a single source and destination node. Unlike SISO networks, however, the intermediate stage includes multiple radios (called *relay nodes*), each receiving a signal from a different spatial path. Research suggests that a high performance gain may be attained if the packets originating from the source node are transmitted from the these relays simultaneously [5]. Owing to the delays associated with PC scheduling and the subsequent data transfer from PC to USRP, however, it is improbable that the relays begin transmission at the same time. This loss in synchronization, in turn, results in destructive interference at the receiving nodes. It is worth noting that the primary role of the USRP is reception and amplification, followed by transmission. It does not perform signal processing; that is the function of the PC.

The synchronization scheme utilizes two different stream tags, each representing some unique information. These include

- rx–time: Generated once by the USRP Hardware Driver (UHD) block upon start of streaming.
- tx–time: The time-stamp that is compared with internal UHD clock for transmission.

The incoming messages are tagged once the signal reception begins (the *rx–time* tag). The resulting quantity has two components, indicating its integer and the fractional parts. A customized GNU Radio block reads this tag, extracts the timestamp and uses its value as a starting point for tagging in subsequent transmissions. The aforementioned block takes a single parameter, the delay, which should be greater than the random delays at each node.

The synchronization process may be divided into two stages. The samples are first tagged with timestamps, given by the formula,

$$\tau_{tx} = \frac{n}{R_{tx}} + d + \tau_{rx} \tag{3}$$

where τ_{tx} is the value of the tx time tag, n is the sample offset, R_{tx} is the transmitter sampling rate, d is a numerical value expected to be greater than the maximum delay of the PC and τ_{rx} is the value of the rx–time tag. This tagging stage is performed by the PC.

Next, these samples proceed to the USRP hardware, where they are stored in its buffer. Here, they wait for the local timer to reach the value specified by their corresponding

TABLE I: System Parameters

Parameter	Value
Modulation	BPSK
Source frequency	2.6 GHz
Relay frequencies	3.7992-3.8008 GHz
Bit rate	25 kbps
Samples per symbol	4

timestamps, following which the transmission begins. This scheme is implemented for all relay nodes and the delay is adjusted such that the transmitting node overcomes the random delays introduced by the PC, resulting in time-aligned transmissions.

Fig. 3 provides a pictorial representation to the process explained above. Here, β_1 and β_2 refer to random delays in packet transmission. In addition, T_p is the deterministic duration of the source packet, N is the number of samples in the source packet and T_s is the sampling period after down-sampling. τ_{tx}, τ_{rx} and d are the quantities discussed previously in this sub-section. It may be seen that d, mentioned in (3), is greater than both β_1 and β_2.

V. Performance Evaluation

A. Experimental Setup

The arrangements for the tests are shown in Figs. 4-5. The proposed topology has been tested on USRP B200 nodes, which have an RF coverage from 700 MHz to 6 GHz. The setup uses VERT2450 antennas with 3 dBi gains. Each reading has been obtained after 5 minutes of continuous source transmission. This duration results in the reception of approximately 7.5 million bits at the destination. The relay nodes were connected to separate PCs, each of which were executing GNU Radio Companion (GRC) flow-graphs independently.

The first phase of testing involved increasing the source-destination distance from 4m to 6m in fixed steps for a given number of relays. The transmit power of the source was then progressively increased and the BER at the destination node noted. Particular care was taken to ensure that the total transmit power at each hop and the net power transmission for the entire network were constant. As previously stated, the source-relay and relay-destination distances were kept equal. As a further precaution, the distances between the relays for 3-relay and 4-relay cooperative networks were also kept the same. The recorded values of the BER were then plotted to ascertain the underlying trend.

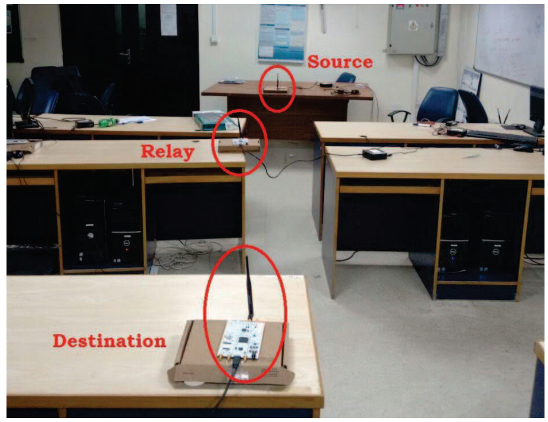


Fig. 4: Test setup for SISO link.

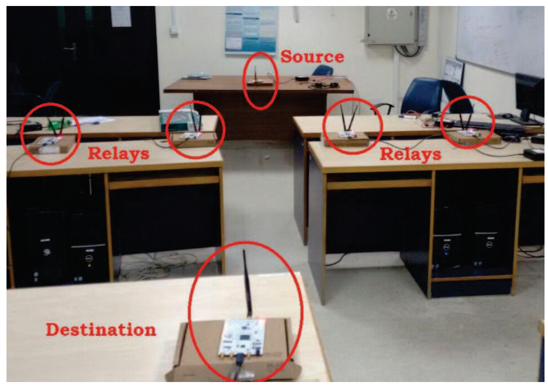


Fig. 5: Test setup for cooperative network.

The primary objective of these experiments was to determine whether cooperative communication provides improved performance, in terms of BER, for a given source-destination distance compared to a SISO topology in a typical office environment. Moreover, the effect of increasing the number of relays on the performance metrics of a cooperative network was also verified.

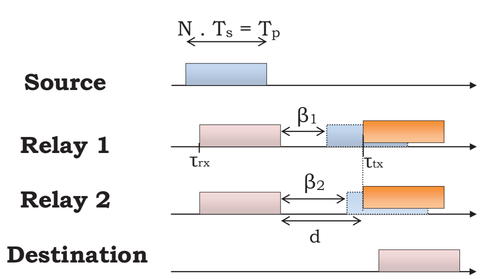


Fig. 3: Packet timing.

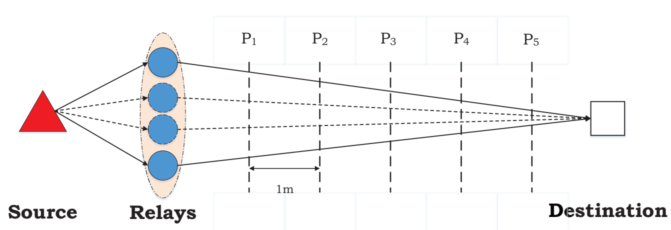


Fig. 6: Topology for determining optimum node placement.

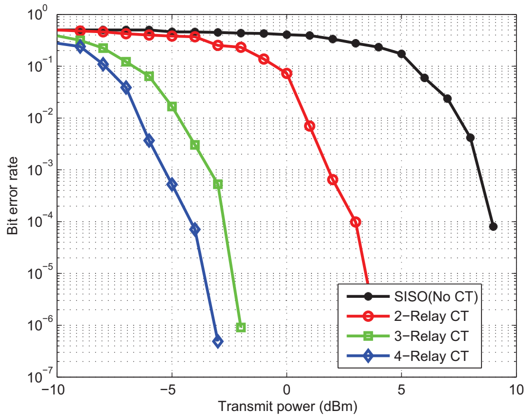


Fig. 7: BER results for SISO and CT topologies at a source-destination distance of 6m

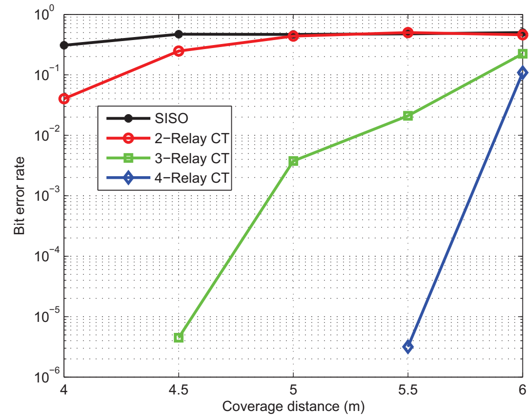


Fig. 9: BER versus source-destination distance plot, with a source power of -8 dBm.

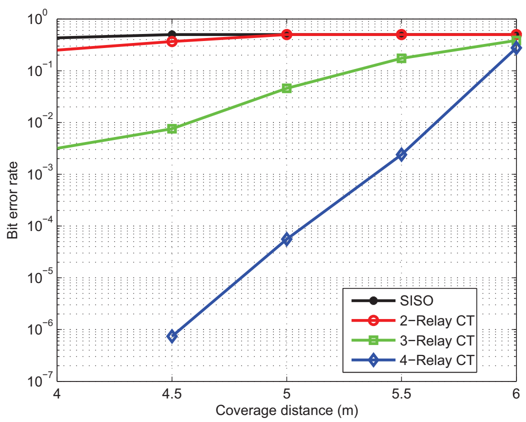


Fig. 8: BER versus source-destination distance plot, with a source power of -10 dBm

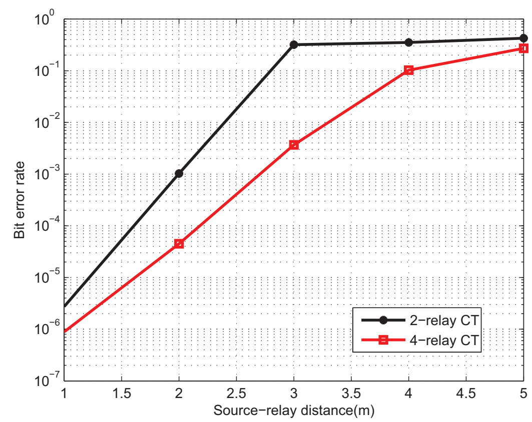


Fig. 10: BER versus source-relay distance plot.

B. Performance Analysis

Fig. 7 demonstrates the relationship between the transmit power and the corresponding BER for the topologies discussed earlier. The curves for the CT-based networks at low transmit powers show that the relays receive corrupted bits from the source. Hence the system performance is degraded with a high BER in this region since the relays forward a noisy version of the message signal to the destination. At high transmit powers, however, the bit error rate is reduced by employing cooperation. This trend represents that at high transmit powers, diversity gain starts to play its role and the BER of the system improves as compared to conventional SISO link.

It should be noted that the total power consumption in all four topologies is kept constant. The results further depict a progressive decrease in the BER for increasing number of relays, at the same transmit power. This trend is most clearly seen in the curves for 2-relay and 4-relay links. For instance, at -3 dBm, the BER for the 4-relay network is approximately 10^{-6} times the 2-relay network. This is due to the increased diversity gain at the destination.

Fig. 8 depicts the plot for the BER against the coverage distance, while limiting the total transmit power to -10 dBm, where the coverage distance represents the end-to-end distance between the source and the destination. It can be noticed that there is a monotonic increase in the BER when the source-

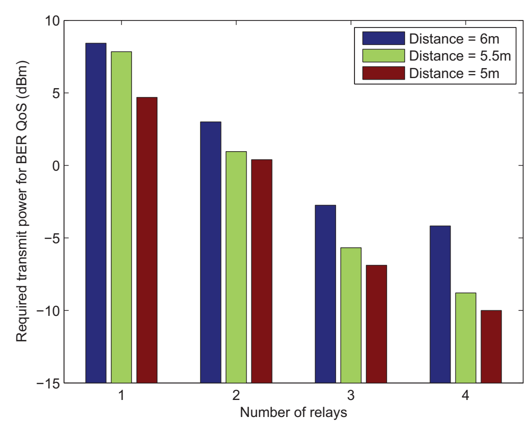


Fig. 11: Range comparison between SISO and CT networks for obtaining a QoS BER of 10^{-4}.

destination distance increases, however the slope of each curve varies.

In order to achieve a source-destination distance of 5m, a SISO topology offers the lowest quality of service (QoS) in terms of BER. We notice that if the QoS is high, which is typically the case in sensor networks, we require cooperation to reach larger distances. For instance, for the case under discussion, if we require a QoS of 10^{-4} BER for the same distance of 5m, then only the 4-relay topology provides the required QoS. Similarly, for achieving a BER of 10^{-2}, the 4-relay case provides 23.9% range extension compared to a 3-relay topology. Hence it is clear that CT provides a considerable improvement in an indoor environment.

If we increase the transmit power to -8 dBm, then Fig. 9 shows the improved performance of the same system. At a BER of 10^{-2}, the performance of the 4-relay topology, in terms of range extension, is improved by 9.26% as compared to the 3-relay topology, which is less than that in the previous figure.

A commonality in Figs. 8-9 is that the BER starts to converge at greater source-destination distances (that is, at low SNRs). As this appeared to be due to the SISO link at the first hop, a third topology, shown in Fig. 6, was tested.

The second phase of testing involved the 2-relay and 4-relay cooperative networks only. The source-relay distance in each case was steadily increased from 1m to 5m, while keeping the destination node fixed. Fig. 6 displays the layout of this topology, where labels P_1 to P_5 represent the 5 locations of the relays at which the tests were conducted. As before, BER readings were recorded after 5 minutes of continuous source transmission. The resulting curves were used to determine the optimum placement of the relays in 2-relay and 4-relay cooperative links.

Fig. 10 demonstrates that the BER for the 2-relay cooperative network rises at a greater rate than that for the 4-relay link. It can be seen that as the source-relay distance increases, the difference in BER of the two cases is reduced. In fact, at 5m, the BERs of the two networks are very similar as the relays either fail to decode the signal or transmit an erroneous version of the signal. This plot therefore exhibits the importance of optimum node geometry, in addition to the number of relays, in a cooperative network. Furthermore, the graph also shows the improved range capabilities of the cooperative network as the second hop (which employs cooperation) has an increased range than the first hop (which is a SISO link). This factor will have a lesser bearing on the overall system performance if a multi-hop cooperative network with a hop count greater than 2 is implemented, which is left as future work.

The bar graph in Fig. 11 is a comparison of the transmit power required to achieve a QoS of BER 10^{-4}, for an increasing number of relays at the intermediate level. As expected, the greatest transmit power in each set of results is that for a coverage distance of 6m. Proceeding from a SISO link to a 2-relay cooperative network reduces the required transmit power at this distance by nearly 3.6 times. Subsequent cooperative topologies witness a similar decrease in the required transmit powers. On a concluding note, the transmit power for the SISO network to achieve the QoS at 5m is approximately 9 dB greater than that for the 4-relay network at 6m. This shows that a cooperative network provides an added advantage of range extension.

VI. Conclusion

In this paper, a series of tests were conducted to determine the range of signal reception for cooperative networks in an office environment, using GNU Radio and USRP software defined radios. SISO-based communication and multiple relay cooperation were tested for comparison. The results showed that the latter produces a greater range for signal reception than the former.

As a future extension to this work, we will investigate the range extension of an opportunistic network such as in [7], which is a multi-hop network as opposed to a dual-hop network in this paper. We also aim to investigate various other combining schemes at the relay nodes such as maximal-ratio combining (MRC). In addition, we intend to test cooperative networks in outdoor environments and to empirically estimate channel responses.

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