# Demonstration and Implementation of Energy Efficiency in Cooperative Networks

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***Abstract*—This paper presents a comparison between cooperative networks with full relay participation and limited participation (LP), in terms of the energy used by the entire network and the bit error rate (BER) of the received signal. The Universal Software Radio Peripheral (USRP) platform was used to perform the transmissions while signal processing, combination and time synchronization was performed on the GNU Radio Companion (GRC). The experiments were performed in an indoor office environment with cooperative transmission (CT) taking place over a single hop network, using binary phase shift keying (BPSK) as the modulation scheme. It has been demonstrated that relay selection provides better energy efficiency for a required quality of service (QoS).**

***Index Terms*—BER, Cooperative Communication, Energy Efficiency, Gnu Radio Companion, MISO, Software Defined Radio, Synchronization, USRP**

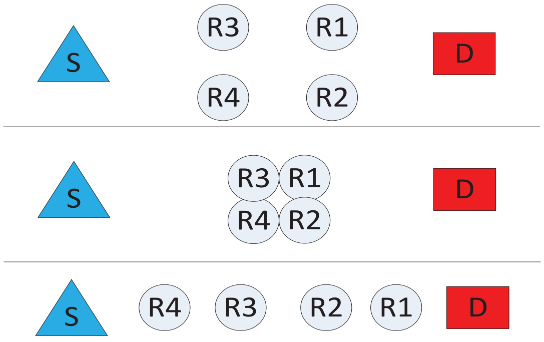

Fig. 1: The network topologies. Top: 2-D, Center: Co-located, Bottom: 1-D

## I. INTRODUCTION

A fast growing area of research, cooperative transmission (CT) makes use of the broadcast nature of wireless channels to improve the quality of transmissions. This is accomplished by using multiple relays, which transmit the same signal over different paths providing a spatial diversity gain at the receiver, which effectively counter acts the adverse effects of multipath fading [1]. The subsequent increase in signal-to-noise ratio (SNR) makes it possible to extend the range of transmission and increase the data rates while reducing individual transmit power [2]. CT is one of the candidates for multihop networks where large number of nodes deploy cooperation at each hop. Multi-hop CT networks have shown advantages in terms of range extension [3], energy efficiency [4] and MAC free broadcasting.

Various theoretical aspects of CT have been thoroughly studied, for example in [5]- [10]. CT has been implemented on several experimental testbeds as in [11] and [12]. In [11], the authors have implemented a cooperative network in an indoor environment using GNU Radio and USRP hardware on a single and multi-hop networks with a hardware time synchronization technique and maximal ratio combining (MRC) as opposed to equal gain combining (EGC), which we have used in this paper. In [12], the authors present an implementation of a cooperative network where wired synchronization is not necessary. Instead they have achieved synchronization by using time stamps.The performance of cooperative networks in terms of BER has also been studied.

Theoretical aspects of energy efficiency in CT has been discussed in [13] and [15]. In [13], the authors have presented the analytical results of how a certain QoS for a transmission may be maintained while decreasing the number of nodes that participate at each level of a multi-hop network. The current paper aims to present empirical evidence of such a phenomenon in a typical indoor environment.

The authors herein present an implementation of CT to achieve energy efficiency. A comparison between complete cooperative networks (CCN) and limited participation (LP) networks is made. By CCN, we imply that all the intermediate relay nodes participate to transmit the data to the destination. However in an LP network, a subset of the nodes participate to deliver the information to the destination. We show that in some cases LP networks out perform fully cooperative networks with respect to energy efficiency. The experiments have been performed using USRPs, each connected to a high end personal computer (PC) on which signal modulation, demodulation and processing has been done. Relay synchronization has been achieved via relay transmit time synchronization through time-stamps. BER has been plotted for both networks at various transmit powers and it has been shown that the number of nodes required to achieve a certain

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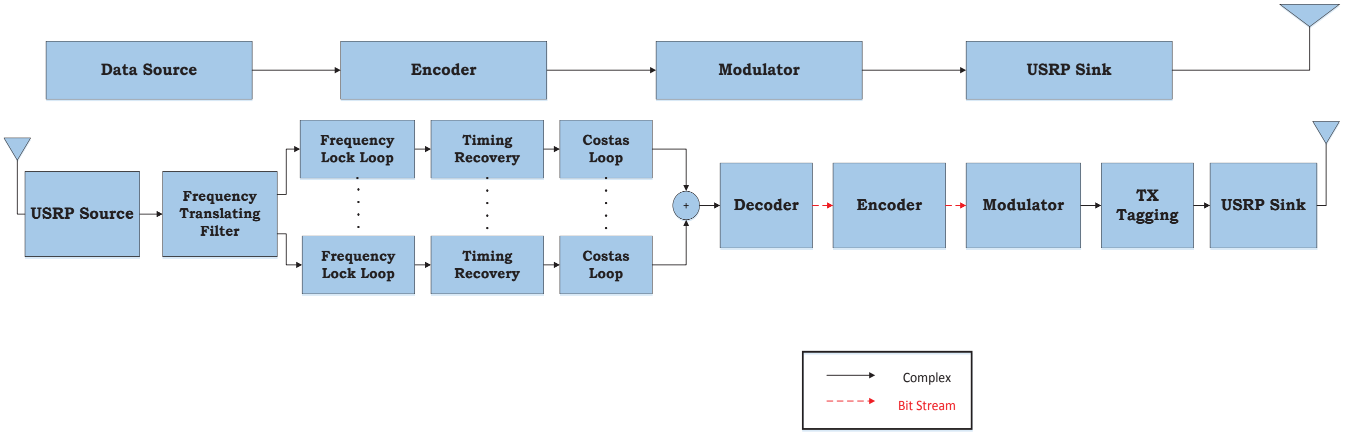

Fig. 2: The block diagram of the transmitter and receiver operations. Top: Transmitter, Bottom: Relay

BER varies according to the transmit power, network topology and BER to be achieved. The paper shows that for different network topologies energy efficiency may be achieved by using an LP network for a certain range of BER values after which the CCN becomes more energy efficient. This cross over point depends on the network topology.

The rest of the paper is organized as follows: Section II describes the system model along with the topologies to be tested, forwarding techniques and the testing methodology. Section III discusses the implementation of a cooperative network using GNU Radio and the USRP hardware. Section IV discusses the details of the experimental setup used while performing the tests and discusses the results of the experiments performed. Finally, Section V states the conclusions drawn from the results.

## II. SYSTEM MODEL

We consider different CT topologies, as shown in Fig. 1. Each topology is comprised of four relay nodes (R1-R4), a source node S, and a destination node, D. The first topology is a two dimensional (2-D) strip network as the relay nodes are arranged in a 2-D manner. The source transmits the message to all four relays, which then forward it to the destination node after employing cooperation. We use decode-and-forward (DF) strategy to transmit the data while the receiver employs EGC to combine the received replicas. The second topology is a one dimensional (1-D) linear network as the relay nodes are placed in a straight line. The transmission phenomenon remains the same. Finally the third topology has the relays within close proximity of each other. This topology is the co-located one where nodes form a cluster to transmit data. It may be noticed that in all three topologies the distance between S and D is kept constant. However since the path loss varies in all three topologies, hence the effects of CT will not be the same and different topologies would lead to different levels of energy efficiency, which is the main motivation behind this study.

Frequency division multiplexing (FDM) has been implemented such that each relay node transmits its message to the destination using a distinct carrier frequency. There is a sufficient guard band between each carrier frequency to prevent transmission from different relays interfering with each other. The destination node is able to select channels and tune to the transmissions of each of the relay. One such link forms a single-input-single-output (SISO) system. Once the receiver has received messages from all the participating nodes, it combines them using EGC. The produced waveform is the result of CT or a multiple-input single-output (MISO) operation. For an LP network, only a subset of the nodes transmit their messages, while in CCN all nodes participate. For each topology, the BER of CCN and LP at the destination node is measured for various values of transmit power. The error rates are then compared to draw conclusions on the efficiency of CCN and LP networks for the three topologies.

## III. IMPLEMENTATION

### A. Transmitter Operations

We begin discussing the system implementation by describing the transmitter flowgraph first. As seen in Fig. 2, the transmitter flowgraph, which runs on the GNU Radio companion, consists of a data source, encoder and finally a USRP sink. The data source forwards the data to be transmitted to the encoder. The encoder forms packets of 100 bytes to be transmitted, by combining 92 bytes from the data source and adding an 8 byte access code at the start of the data. This access code marks the beginning of a new packet and is essential for the operation of the receiver. The encoded packets are then sent to the modulator block which, as stated previously, generates BPSK modulated signal as

$$s_n(t) = Acos(2\pi f_c t + \pi(1-n)), n = 0, 1, \qquad (1)$$

where $f_c$ is the carrier frequency, $A$ is the symbol amplitude, and $n$ is the bit to be encoded. The signal is then directed to the USRP sink.

### B. Receiver Operation

Reception of the transmissions from all the relays requires the receiver to operate at a greater sample rate so as to sample the appropriate bandwidth, which consists of the carrier frequencies from all the relays. An appropriate center frequency is chosen at the receiving antenna, which is in range of the relay carrier frequencies. The relay flowgraph is arranged as in Fig. 2(bottom), which is essentially a combination of the transmitter and receiver flowgraph. After the USRP source, the frequency translating filter is used as a channelizer. This block is a combination of frequency translator, low pass filter (LPF) and a decimator. By shifting the signal along to the frequency axis from central carrier frequency to one of the relay carrier frequencies, applying a LPF to filter out the unwanted transmissions and decimating the transmitted signal of a specific relay may be sifted out effectively. It may be noted that the use of the frequency translating filter is not required at any node receiving one hop away from the transmitting source, as at this point the only node transmitting is the source itself at a single carrier frequency.

Once the signal of a specific relay has been selected, frequency, timing and phase recovery must be performed to obtain a clean signal at the baseband, which may then be decoded. To this end, the output of the translating filter is fed first to the frequency lock loop (FLL) block. The FLL block locks on to the relay carrier frequency and removes any carrier frequency offsets using a band edge filter. The output of this block is fed to the timing recovery block, which uses polyphase filter banks as described in [14]. This technique attempts to minimize the inter symbol interference (ISI) and therefore maximize the SNR. It also ensures correct sampling of the baseband signal and acts as a matched filter as well. Finally the Costas loop block is used to detect any phase offset in the baseband stream and correct the stream accordingly. These three processes are performed for each received relay signal as well as the destination node. Once the signal has passed through the recovery phase, it may be demodulated and decoded to get the SISO bit stream or it may be combined with the output of the other receiver branches via EGC. This combined stream may be demodulated and decoded to get the CT bitstream. The demodulator used is a constellation demodulator, which converts the received BPSK symbols to bits. This bit stream is then searched for the access code, which was inserted at the start of the packet by the transmitter flow graph. The decoder calculates the Hamming distance between the known access code and the incoming bitstream and makes a decision when the bitstream matches a sufficient number of bits to the access code based on a user provided threshold. The decoder then extracts the payload from this packet and outputs the received data.

### C. Timing Synchronization

When implementing CT, all relays must be synchronized and transmit simultaneous to achieve a high performance gain at the destination [11]. As the signal processing of the received transmission is done on a PC and the delays due to scheduling on the PC and the transfer of data to the PC from the USRP for each relay are very unlikely to be the same it is highly unlikely that all the relays will start their transmissions at the same time. This loss of synchronization causes destructive interference at the destination node resulting in poor performance of the network.

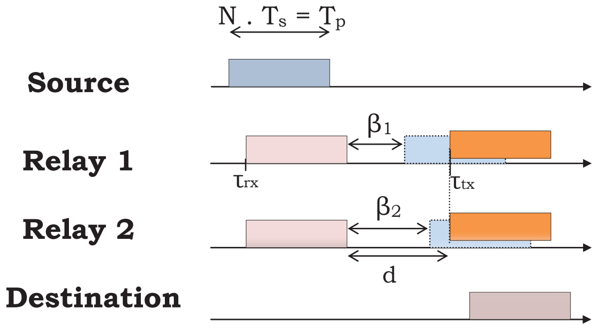

Fig. 3: Packet Timing

A synchronization system, similar to the one implemented by [12], utilizing two tags has been implemented in the network presented herein. Each tag carries information essential to the synchronization of the relays. The tags used are as follows

- 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 rx-time tag is placed at the start of each reception, which has an integer and a fractional part. A customized GNU-Radio block is used to extract a time-stamp value from this block, which is used as a starting point for tagging subsequent transmission. The block is given a parameter, which is the delay to be enforced before the relay starts transmitting. This delay must be greater than the random delays at each relay node. The custom block uses this delay to tag the received samples as follows

$$\tau_{tx} = n/R_{tx} + d + \tau_{rx} \tag{2}$$

where $\tau_{tx}$ is the value of the tx-time tag, $n$ is the sample offset, $R_{tx}$ is the transmitter sampling rate, $d$ is the value of the aforementioned delay, which is expected to be greater than the maximum delay due to the PC and $\tau_{rx}$ is the value of the rx-time tag. Once the tags have been added by the PC, the tags are sent to the USRP hardware and stored there on a buffer. The USRP waits until the value of its local timer reaches that specified by the tx-time tag and then begins transmission. This block is implemented on each node and the value of the delay is adjusted until all relays begin transmission simultaneously.

Fig. 3 helps visualize the tagging and transmit synchronization process. A packet with a deterministic duration $T_p$ containing $N$ samples is sent by the source. $T_s$ is the sampling period of the source after downsampling. The figure shows $\tau_{rx}$ tag inserted at both relays. The relays have a random delay of $\beta_1$ and $\beta_2$ respectively while $d$ is the aforementioned delay, which is greater than $\beta_1$ and $\beta_2$ and is used to synchronize

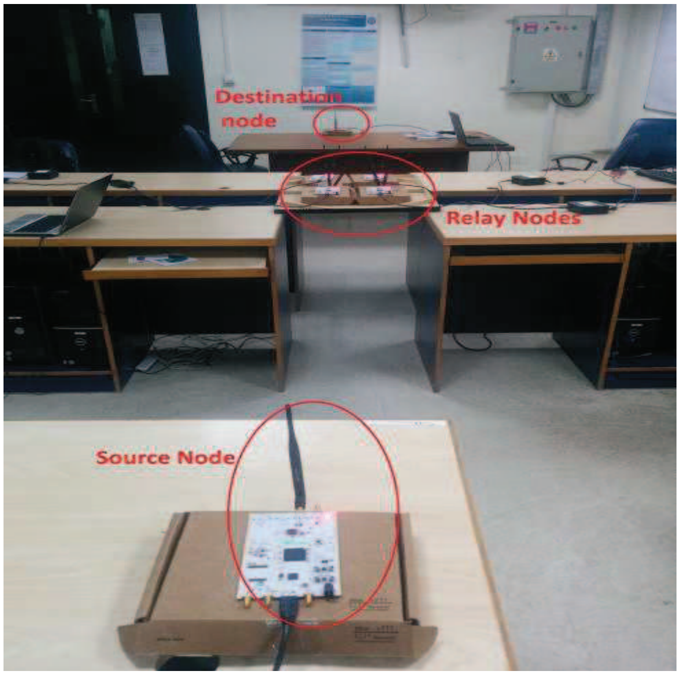

Fig. 4: Experimental setup of the co-located topology in an office environment

the transmit times of the relay by inserting $\tau_{tx}$ according to the previously mentioned equation.

## IV. PERFORMANCE EVALUATION

### A. Experimental Setup

The proposed topologies are tested on USRP B200 nodes, which have an RF coverage from 700 MHz-6 GHz. The setup uses VERT2450 antennas with 3 dBi gains. The co-located topology to be tested is shown in Fig. 4 at NUST in an indoor office environment. The other topologies shown in Fig. 1 were also tested with the same apparatus and in the same environment. The total distance between the source and destination in all three topologies is 5.5m. For the 2-D topology forward relay nodes (R1,R2) have a horizontal distance of 2.25m from the receiver node, while the back layer of the relay nodes (R3,R4) have a horizontal distance of 3.25m from the receiver node. The node closest to the source in the 1-D topology is 1.25 m away from the source. All subsequent nodes are 1 m from this node (R2-R4). Finally in the co-located topology all four nodes are in close proximity to each other and are at a distance of 2.75m from the source and the destination. For the purpose of the experiment, we define an LP network in which only the two nodes closest to the destination (R1,R2) relay the message from the source to the destination. On the other hand, the topology where all the relays participate in the transmission is termed as CCN topology. A final test where no relays were involved and only the source transmitted its message to the destination was also performed. This was the direct link (DL) topology. The source and destination were 5.5m apart. To compare the results of this test to the tests that involved relays, the power of the source was increased.

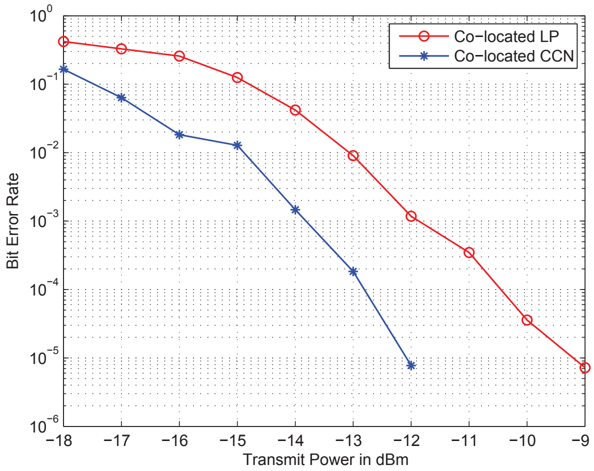

Fig. 5: Results for co-located topology

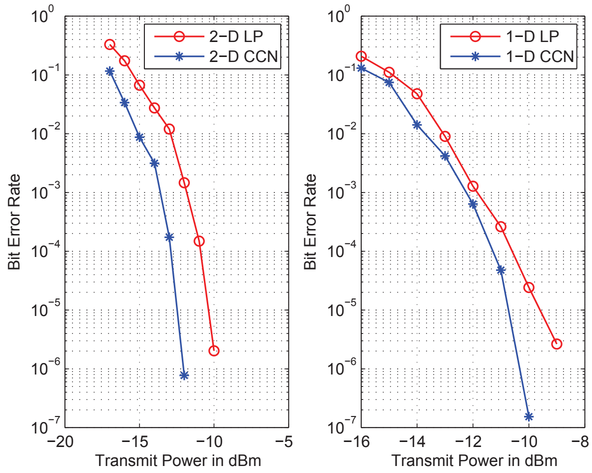

Fig. 6: Results for 2-D topology(left) and 1-D topology (right)

For the experiment, ten values of BER at the destination node for both CCN and LP networks were recorded for each value of transmit power(at the source and the relays) and then averaged to get the final value. Each test transmission was 5 minutes long to ensure that enough bits were transmitted to obtain high precision BER values. BPSK modulation was used at 2.6 GHz for the source transmission, 3.992- 3.8008 GHz for the relay transmissions, a bit rate of 25 kbps and 4 samples per symbol.

### B. Experimental Results

First a comparison between the CCN and LP networks is performed for the co-located network. In Fig. 5, the values of BER of CCN and LP transmissions for the co-located topologies are plotted against the transmit power in dBm. Note that the transmit power on the x-axis is the power of one node. For instance, -10 dBm implies that the source and all relays operate at -10 dBm each. We can see that at lower values of transmit power, the curves are approximately parallel before falling off at higher transmit powers, indicating the advantage of diversity. It may also be noted that the CCN topology requires less transmit powers at individual nodes as compared to the LP network. For example, for a BER of $10^{-3}$ a CCN network requires -13.82 dBm power at the source and the relay nodes individually while the LP network requires -11.87 dBm at all transmitting nodes to achieve the same BER. For all values of transmit power the BER curve for the LP network remains above that of the CCN indicating that CCN requires less power at each node.

Similarly the BER curves for the 2-D network and the 1-D network are shown in Fig. 6. We can draw conclusions for these networks similar to those for the co-located topology about the transmit power required for a CCN and an LP network, i.e., the transmit power required to achieve a given BER/QoS is more for an LP network. However, this does not inform us about the energy efficiency of the overall network as the values of transmit powers are for single nodes and don't reflect the total power used by the network.

To find the energy efficiency of the complete network, the energy used by the entire network is calculated for given values of BER. This may be done by finding the transmit powers for a specific BER in each network, converting these values to milliwatts and then multiplying them with the total number of transmitting nodes in a network. There are 5 nodes transmitting in a CCN (S, R1-R4) and 3 nodes transmitting in the LP network (S,R1,R2). Table I shows the calculated total power for each system to obtain four selected values of BER. The table also shows the power required for the DL topology to achieve the same QoS values.

TABLE I: Power used by each network topology in mW

| **BER** | **2-D CCN** | **2-D LP** | **1-D CCN** | **1-D LP** | **Colocated CCN** | **Colocated LP** | **DL** |
|---|---|---|---|---|---|---|---|
| $\mathbf{10^{-2}}$ | 0.1542 | 0.1532 | 0.2128 | 0.1480 | 0.1622 | 0.1480 | 4.6569 |
| $\mathbf{10^{-3}}$ | 0.2178 | 0.1964 | 0.2985 | 0.1959 | 0.2075 | 0.1950 | 6.9647 |
| $\mathbf{10^{-4}}$ | 0.2564 | 0.2433 | 0.3715 | 0.2613 | 0.2618 | 0.2705 | 10 |
| $\mathbf{10^{-5}}$ | 0.2831 | 0.2755 | 0.4226 | 0.3286 | 0.3097 | 0.3598 | 11.9674 |

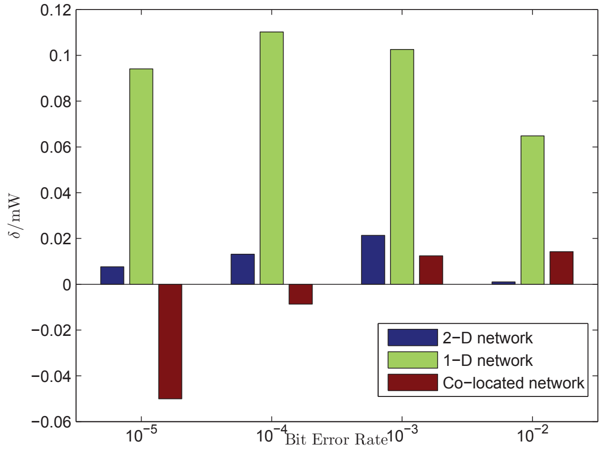

Fig. 7: The difference in the consumed power, $\delta$, for different topologies vs BER

In Table I, we can see that the DL topology is the most inefficient of all topologies. The power required to achieve the same QoS in the DL topology is many times greater than that of CCN and LP networks. For example, to achieve a QoS of $10^{-3}$, the DL network required 6.9647 mW while the highest power requirement amongst the relaying network topologies was 0.2985 mW for the 1-D CCN topology. This means that the DL network required a lot more energy as compared to the 1-D CCN topology. Therefore, we can easily conclude that the non-cooperative DL topology performs worst as compared to any CT topology.

Next we see that the CCN is not always the most power efficient one. For example, for the co-located topology, the CCN uses 0.162 mW in total to obtain a QoS/BER of $10^{-2}$ while the LP variation uses 0.146 mW to obtain the same QoS, hence saving $9.8\%$ energy. This shows that it is not always efficient to use the CCN, even though the transmit power at each node for an LP network is greater than the transmit power for CCN. To further investigate this finding, we define $\delta$ as

$$\delta = P_{CCN} - P_{LP}, \tag{3}$$

where $P_{CCN}$ is the total power consumed by the CCN to achieve a certain QoS/BER and $P_{LP}$ is the power consumed by the LP network with the same topology to achieve the same BER. A positive $\delta$ indicates that LP network is more energy efficient than CCN and vice versa. Fig. 7 shows how $\delta$ varies for different topologies and for different BER values. From this graph, we may see that the CCN and LP variant of each topology are energy efficient for different values of BER. Generally, we see that the power saved by the LP network increases up to a certain point after which the CCN becomes more efficient. This cross over point is seen in Fig. 7 for the co-located topology, while the other two topologies show the trend where the power saved by LP rises to a maximum value and then starts to fall as the required BER decreases. In all cases, as the required BER decreases and the total power required by the system increases, LP starts to lose its advantage over CCN. This is due to the fact that the first hop link between the source and the relays becomes strong enough such that when all relays contribute, they provide full diversity as compared to when only a few contribute.

We can see that for different topologies, the BER varies where the CCN becomes more energy efficient than LP. This has to do with the fact that the first hop (source to relays) acts as a bottle-neck for proper cooperation to occur. For example, the cross over point occurs quickly in the co-located topology as all the relays are located at the same position. Therefore, their links to the source become stronger at the same source transmit power and the relays 'activate' simultaneously, providing greater diversity at the receiver. In the case of 2-D and 1-D networks, since the node placement varies, all relays form strong links with the source at different powers and thus full diversity will be achieved. In 1-D specifically, where the farthest relay is over 4 m from the source, it would take a high transmit power for this relay to positively contribute to the cooperative network. Thus, its cross over point may occur at a higher value of transmit power and BER.

## V. CONCLUSION

This paper has demonstrated experimentally how cooperative networks may be made energy efficient by using either full or limited relay participation, depending on the required QoS and network topology. The experiments were tested on USRP platform whereas the signal processing module was designed in GNU radio companion. The study identified that the first source to relay link acts as a limiting factor for different topologies to achieve energy efficiency in full cooperation. It was also shown that limiting relay participation in cooperative networks achieves energy efficiency while still achieving the required QoS. Future work includes experiments using multiple hops or an increased number of nodes per hop and eventually testing the simultaneous coverage and energy efficiency for an opportunistic large array (OLA) network.

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