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Experimental Evaluation of DCOOP Protocol using USRP-RIO based testbed at 5.8GHz

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***Abstract*—Cooperative communication can attain lower error probability in wireless networks by exploiting the inherent broadcast nature and taking advantage of multi-path propagation. In order to leverage performance gains achieved by virtual multiple-input multiple-output (MIMO) systems, we design a novel cooperative protocol, Decode-to-Cooperate (DCOOP). We evaluate its performance on a testbed implemented on Universal Software Radio Peripheral Reconfigurable Input/Output (USRP-RIO) platform. The main challenge during the testbed deployment was to consider transmission under tightly synchronized nodes in a slow fading environment. Extensive experiments were performed to evaluate the performance of the testbed and the results show that it can operate at lower transmit power and increase the coverage area for a desired bit error rate (BER).**

***Index Terms*—Cooperative communications, Relay selection, USRP, Alamouti coding, Virtual MIMO, BER**

I. Introduction

Cooperative communication is an effective and efficient means of overcoming multi-path fading and interference in wireless communication. It takes advantage of the broadcast nature inherent to wireless channel, and thus, enables wireless nodes to cooperate for enhanced reception. Cooperative communication can be realized as a virtual multiple-input multiple-output (MIMO) system, enabling single-antenna devices to form a distributed antenna array system. Furthermore, dual-hop networks can achieve maximum diversity and spatial multiplexing gains by employing a cooperative virtual MIMO configuration [1,2].

Efficiency of cooperative protocols depends on relay selection, number of relays, and network geometry such as relay positioning and power allocation. In [3], the authors study relay selection and the diversity achieved by considering exact outage and capacity bounds. Similarly, diversity analysis of single and multiple-relay selection was investigated [4], to highlight the performance gain achieved by employing the later. Space-time block coding (STBC), not only offers larger diversity order than repetition-based algorithms, but can be effectively utilized for higher spectral efficiency [5]. Additionally, distributed Alamouti coding promises higher diversity order with lower error probability and could be employed as a virtual antenna scheme [6]. Recently, performance of single and multiple relay selection indicated marginal gain by selecting more than three relays for cooperative communication [7]. Decode-and-Forward (DF) strategy with best-relay (in terms of highest signal-to-noise (SNR)) alludes achieving maximum diversity order [8]. In terms of power allocation, error probability of DF strategy was evaluated for a cooperative single relay selection scheme with optimized power allocation [9].

Software Defined Radios (SDR's) are increasingly being used in the research community with a practical goal of evaluating the proposed protocols under realistic conditions. Selection relaying is investigated for performance improvement over direct transmission and it is observed that the cooperative testbed yields lower error probability [10]. Universal Software Defined Radio (USRP) with GNU radio platform is used to evaluate cooperative communication at 2.4GHz for Multi-relay synchronization using a timestamp methodology to attain significant improvement in performance when compared with direct transmission [11]. In [12], the authors combined Orthogonal Frequency-Division Multiplexing (OFDM) with STBC to enhance the performance using Amplify-and-Forward (AF) strategy at 2.4GHz. Most of the work mentioned above, and in particular considering DF based cooperative communication, are either not proposed for a particular wireless standard or theoretical [5] with certain assumptions that are used to over simplify certain avoidable factors and therefore, cannot be considered a fully functional real-world radio propagation model. Hence, design of a testbed, to incorporate cooperation into an existing wireless standard, is yet to be investigated. Moreover, considering other factors, such as low mobility and high density features of the emerging heterogeneous networks and the widely accepted IEEE 802.11 standard [13], the variant 802.11a, can serve as an ideal candidate due to its provision of higher data rates.

The objective can be set to verify the conjecture that incorporating cooperative communication can improve the performance of IEEE 802.11a, in terms of power consumption of nodes and/or extend its coverage area (as it is limited to coverage area when compared with the 802.11b variant). This led to the development of Decode-to-Cooperate (DCOOP) protocol and testbed implementation to study the performance of cooperative communication in contrast to non-cooperative communication.

***Contributions**:* We believe the methodology we use for protocols design and testbed construction will provide suggestions to incorporate cooperative mechanism into existing as well as the design of future wireless systems. We have the following contributions in this paper:

- We develop a cooperative protocol and implement a testbed framework based on USRP, which includes a physical layer implementation.

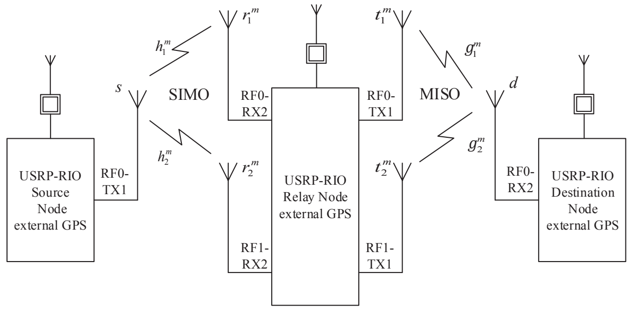


Fig. 1: DCOOP testbed as virtual antenna SIMO-MISO array.

- We conducted extensive experiments to reveal the system performance of cooperative communication with our platform. The result shows significant gain of cooperative transmission compared with direct transmission.

***Organization of the paper**:* The remaining of this paper is organized as follows: in Section II, we present the rationale behind the cooperative protocol. In Section III, system design for testbed implementation and related design challenges are discussed. Measurement results and analysis is given in Section IV, and finally Section V, presents the conclusion and considerations for future work.

II. Cooperative Protocol

The cooperative protocol is inspired by our previous work [14] and the testbed aims to meet IEEE 802.11a specification. Firstly, we have a source *s* transmitting sequentially, and the destination *d* seeks help from nearby relay node(s) *r*, when it is unable to decode directly from the source. In turn, relay(s) successfully decoding the transmission from source, show willingness to cooperate and after going through the process of selection, transmit using distributed Alamouti coding [5], over a dual-hop network, as shown in Fig. 1. We adopt time-division multiple access (TDMA) method in our design and consider coherence time [15], to consider a slow fading environment. Furthermore, we have a data transmission phase (consisting of two time slots) and a control phase (four time slots to implement relay selection) as shown in Fig. 2. The relay selection process is based on a handshake between relays and destination. The outset of the control phase occurs with a Negative-Acknowledgment (NACK) from the destination. Then the listening relay(s) send relay ID and the average SNR (ASNR) for the information symbols received in two time slots, indicating that they have decoded and are willing to cooperate. The destination calculates SNR from the relay, in addition to the received information form the relay and broadcast the indices of the selected relay(s). A relay is selected based on the ASNR gain at the relay (i.e., source-to-relay link) and the destination (i.e., relay-to-destination links). Now, after the control phase the selected relay operate as transmitting relay to transmit the decoded information to the destination. During the subsequent transmission phase, the source chooses to transmit new symbols or retransmit the

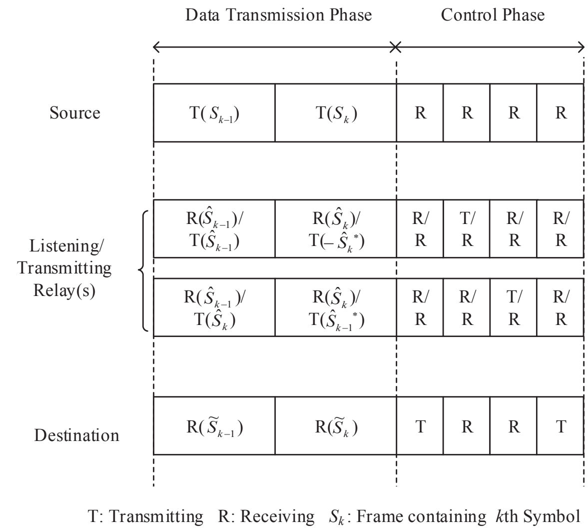


Fig. 2: Timing diagram illustrating data transmission and control phases.

old symbols (if the transmission from relay falls below a desired SNR level for decoding). This process of alternate transmission and control phase continues until the source has transmitted all the frames.

A. Decode-to-Cooperate (DCOOP)

The source *s* transmits two information bearing symbols S_{k-1} and S_k during the initial data transmission phase in two time slots. The symbols received at the listening antennas r_1^m and r_2^m of the m-th relay, each having their own channel coefficients h_1^m and h_2^m are,

$$\left.\begin{aligned}\hat{S}^m_{1(k-1)} &= S_{(k-1)}h_1^m\sqrt{P_1}+n^m_{1(k-1)}\\ \hat{S}^m_{1(k)} &= S_{(k)}h_1^m\sqrt{P_1}+n^m_{1(k)}\end{aligned}\right\} r_1^m$$
$$\left.\begin{aligned}\hat{S}^m_{2(k-1)} &= S_{(k-1)}h_2^m\sqrt{P_1}+n^m_{2(k-1)}\\ \hat{S}^m_{2(k)} &= S_{(k)}h_2^m\sqrt{P_1}+n^m_{2(k)}\end{aligned}\right\} r_2^m \quad (1)$$

respectively. Where we have, $\forall\ k \in\ n^m_{1(k)} \sim \mathcal{N}(0,\sigma^2)$ and $n^m_{2(k)} \sim \mathcal{N}(0,\sigma^2)$, as normally distributed additive white Gaussian noise samples with zero mean and variance σ^2. P_1 refers to the transmission power at the source and h^m denotes a quasi-static Rayleigh fading channel from $s \to r^m$, having a circularly symmetric complex Gaussian envelop with variance δ^2_{sm}. The received signal at the destination using distributed Alamouti STBC is given as,

$$\left.\begin{aligned}\hat{\hat{S}}_{(k-1)} &= \hat{S}^m_{1(k-1)}g_1^m\sqrt{P_2}+\hat{S}^m_{2(k)}g_2^m\sqrt{P_2}+n^{md}_{(k-1)}\\ \hat{\hat{S}}_{(k)} &= -\hat{S}^{m^*}_{1(k)}g_1^m\sqrt{P_2}+\hat{S}^{m^*}_{2(k-1)}g_2^m\sqrt{P_2}+n^{md}_{(k)}\end{aligned}\right\} \quad (2)$$

where we have, $\forall\ k \in\ n^{md}_{(k)} \sim \mathcal{N}(0,\sigma^2)$ as normally distributed additive white Gaussian noise samples with zero mean and variance σ^2, from the selected relay(s) to destination. P_2 refers to the transmission power at the relay node and g_m denotes a quasi-static Rayleigh fading channel from

$r^m \to d$, having a circularly symmetric complex Gaussian envelop with variance δ^2_{md}. Finally, the destination combines the information bearing symbols as,

$$\left.\begin{aligned} \tilde{S}_{(k-1)} &= \frac{\hat{\hat{S}}_{(k-1)} g_1^{m^*} + \hat{\hat{S}}^*_{(k)} g_2^m}{|g_1^m|^2 + |g_2^m|^2} \\ \tilde{S}_{(k)} &= \frac{\hat{\hat{S}}_{(k-1)} g_2^{m^*} - \hat{\hat{S}}^*_{(k)} g_1^m}{|g_1^m|^2 + |g_2^m|^2} \end{aligned}\right\} \tag{3}$$

These symbols are then decoded using a Maximum Likelihood (ML) decision rule [16]. The transmitting antennas (t_1^m, t_2^m) of the relay, flush the accumulated interference after transmitting the decoded symbols. Furthermore, interference cancellation [17,18] is used at the listening antennas (r_1^m, r_1^m) of the relay, to decode the information symbols from source. They receive successive symbols from the source and interference as the previously decoded symbols from the transmitting antennas of the relay, simultaneously. After decoding the interference, it is then subtracted from the previously decoded symbols to obtain the desired symbols, if $\delta^2_{m_t m_r} \gg \delta^2_{s m_r}$ (i.e., the channel gain between the transmitting and listening antennas is greater as compared to source and listening antennas) or discards the transmission from transmitting relay as noise if $\delta^2_{m_t m_r} \ll \delta^2_{s m_r}$, before eventually flushing the accumulated interference and start fresh when the source transmits the next symbols sequentially. In this work, we only consider the performance evaluation of the protocol for testbed implementation. For interested reader theoretical performance analysis in terms of optimum power allocation and optimum relay position is given in [19].

III. Implementation

The measurement campaign was carried out at Queensland University of Technology (Gardens Point Campus, S-Block, Level-6) at 5.865GHz (ISM band). The walls and pillars of this level are made of reinforced concrete (approx. 30cm thick) and having clear glass single glazed windows, soft-partitions and glass doors (approx. 1.5cm thick) as shown in Fig. 3. We have three software-defined radio nodes, with RF-frontend implemented in Universal Software Radio Peripheral board (USRP-2953R) [20], and the cooperative module implemented in LabVIEW. USRP-2953R is a radio peripheral capable of operating at 1.2GHz to 6GHz supporting upto 40MHz bandwidth and also contains a Global Positioning System Disciplined Oscillator (GPSDO) for synchronization purpose. We are using omnidirectional VERT2450 dual-band antennas (operating under $2.4-2.5$ and $4.9-5.9$GHz) and the baseband digital signal out of USRP-2953R motherboard is sent via cabled PCI-Express connectivity kit to the host computer for physical layer signal processing. We implement the testbed with a single MIMO enabled relay node (as seen in Fig. 1) to avoid unnecessary implementation complexity, and this can essentially serve as a combination of two near-by relays.

A. System Design

DCOOP is designed to support dual-hop communication by employing a fixed short-preamble, such that, the frame detection is only triggered at the first hop (i.e., at the relays).

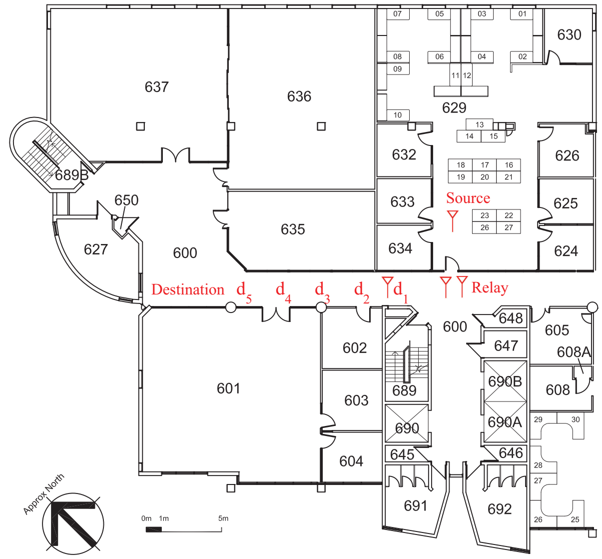


Fig. 3: Floor plan and location of source, relay and destination.

We consider IEEE 802.11a standard and a 24 bit long, PHY Layer Convergence Procedure (PLCP) preamble. This choice of preamble length is long enough to account for least square (LS) channel estimation. Next, we consider a single OFDM symbol transmitted per PLCP Protocol Data Unit (PPDU) frame with $N_D = 96$ data bits per OFDM symbol, as shown in Fig. 4. This allows us to compare frame transmission time in contrast to channel coherence time T_c. We anticipate the channel to remain constant till the initial two frames from the source are received at the destination (i.e., $k = 8$), and define this expected time for multiple frames transmission as total transmission time T_t. Table I summarizes coherence time and total transmission time, with node mobility v and consider the mandatory data rates as defined in the IEEE 802.11a OFDM PHY i.e., $1.5, 3,$ and 6Mbps for quarter-clocked 5MHz channel bandwidth, $3, 6,$ and 12Mbps for half-clocked 10MHz and $6, 12,$ and 24Mbps for 20MHz. For pedestrian walking at 1m/s (or 3.6km/hr), T_c is approximately twenty folds greater than T_t for the lowest data rate of 1.5Mbps with $N_D = 96$ bits and reduces to ten folds of T_t with $N_D = 48$ bits, which in theory is emblematic of a slow fading environment. In this work, we only consider $N_D = 96$ bits and fixed node transmission, however, from Table I, it is quite evident that increasing speed upto 3m/s (or 10.8km/hr) still maintains a slow fading environment.

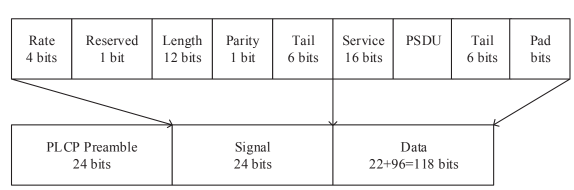


Fig. 4: IEEE 802.11a PPDU Frame Format for DCOOP.

Table I: Coherence and total Transmission time for QPSK based Modulation

v [m/s]	$T_c[\mu s]$	$T_t[\mu s]$				
		1.5Mbps	3Mbps	6Mbps	12Mbps	24Mbps
1	21636.8					
2	10818.4	885.33 with $N_D = 96$	442.66 with $N_D = 96$	221.33 with $N_D = 96$	110.66 with $N_D = 96$	55.3333 with $N_D = 96$
3	7212.6					
4	5409.2	1770.66 with $N_D = 48$	885.33 with $N_D = 48$	442.66 with $N_D = 48$	221.33 with $N_D = 48$	110.666 with $N_D = 48$
5	4327.3					

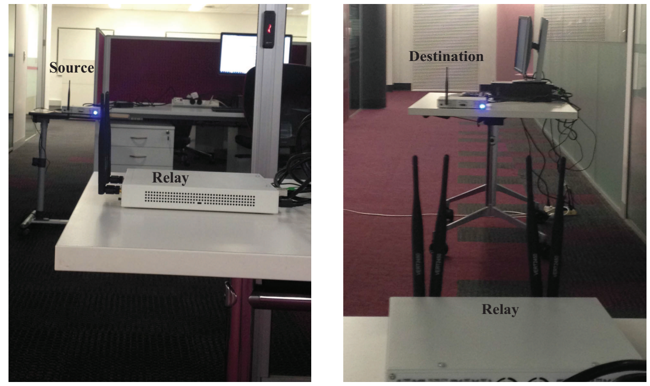
B. Design Challenge

To implement the testbed as described in the previous sections, we have two key challenges,

- To distinguish the start of a new frame for synchronization. This is required to synchronize the transmission between source-to-relay and relay-to-destination.
- To design the nodes such that they transmit and receive in a TDMA manner as in Fig. 2.

To guarantee correct decoding, frame initiation or preambles of any two transmitted frames need to be identified. Our testbed tends to exploit spatial diversity, by employing concurrent transmissions from spatially co-located antennas. For concurrent transmission, signal from one path should be combined with the other path's signal. It can only be done when preamble is known at all the nodes, as only after the signals are correlated with a known preamble, the start of the frame can be identified. The destination receives multiple signals at the same time, it cannot separate them individually. Instead, it receives a superposition of the two signals after path fading. Furthermore, as the distance between two nodes is only several meters, the delay differentiation from relay to the destination can be reasonably ignored. In order to achieve tight synchronization between all the nodes, we can use either an external clock source (common to all the nodes) or by utilizing the inbuilt GPS capability of USRP-2953R. The use of GPS was favourable for the experimental apparatus to avoid unnecessary connections between nodes. For this, all the nodes were allowed to start randomly and once locked to the GPS, the pre-lock transmission was discarded. Use of OFDM based distributed Alamouti transmission along with a shorter preamble [21], allowed suppressing the timing and frequency offsets. As a result, we achieve synchronization by employing a MIMO enabled relay for indoor environment.

To deal with the second design challenge, we scale down the onboard clock (125MHz) of the USRP-2953R, to our transmission bandwidth of 20MHz and define the frame duration as well as the frame decoding and generation delay. Based on the fixed frame length (of 166bits from Fig. 4), we calculate the frame duration (e.g., 27.66μs for 6Mbps) and add a realistic hardware based delay (of 100μs), when the frame is received at the relay and regenerated to be sent to the destination [11]. Although, this increases T_t (in Table I), however, does not compromise slow fading conditions for the testbed (e.g., 1021.33μs for 6Mbps). So, the source transmits two frames and then waits for four frame slots to transmit the next two frames and continues until all frames are sent. The relay node after receiving the initial two frames (slots $1-2$) from the source, receives a NACK (slot 3) from the destination and transmits one control frame from interface RF0/TX1 (slot 4) and another from interface RF1/TX1 (slot 5). These control frames sent by the relay includes a two bit-long ASNR (signalled as "00" $\leq$ 6dB, "01" for $6-12$dB, "10" for $13-18$dB and "11" for ≥ 19dB based on QPSK and can be modified for higher order modulation) along with an identification marker of equal length for the interface information. The destination now ranks the relay interfaces and broadcasts the indices (slot 6). When aggregating the transmission phase and the control phase, we have a cycle of 6 frame slots. Hence, we achieve a synchronous TDMA transmission for the cooperative testbed implementation.



(a) Source and relay node (b) Relay and destination node

Fig. 5: Experimental setup for DCOOP.

IV. Experimental Results

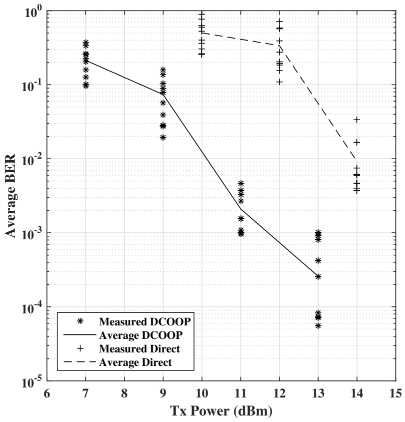
In this section, we present the experimental apparatus, related parameters and study the physical layer performance of the testbed in terms of bit error rate (BER). The experiments were carried out in an indoor room-corridor scenario as in Fig. 5 and the measurement parameters are listed in Table II.

Table II: Measurement Parameters

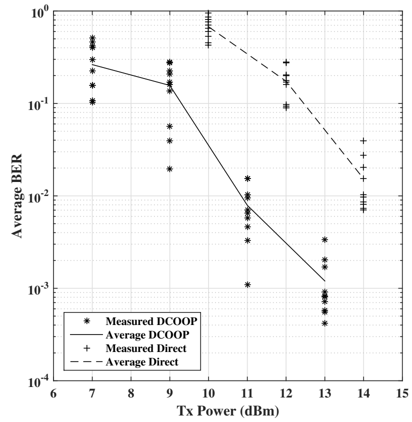
Carrier Frequency [GHz]	5.865
Bandwidth [MHz]	20
Data Rate [Mbps]	24, 12, 6
OFDM Symbol Duration [μs]	4, 8, 16
Preamble [μs]	1, 2, 4
Antenna Height [m]	0.8
Modulation	QPSK

For DCOOP, source and relay nodes are fixed at a distance approximately 5m apart, and the distance between relay and destination varies (Fig. 3). To compare the performance of DCOOP, we also considered direct transmission by replacing the relay with the source node and receive a re-transmitted frame at the destination, to have fairness in comparison with minimal changes to the testbed. To calculate BER, we transmit 100 frames and record 10 readings for each transmission and average the recorded values to attain average BER. This average is taken to generalize and compare the performance of DCOOP and direct transmission under realistic environment.

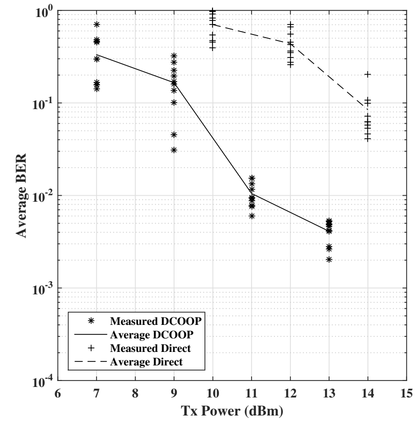
In Fig. 6, we study the performance of the testbed by evaluating average BER for different transmit power (Tx



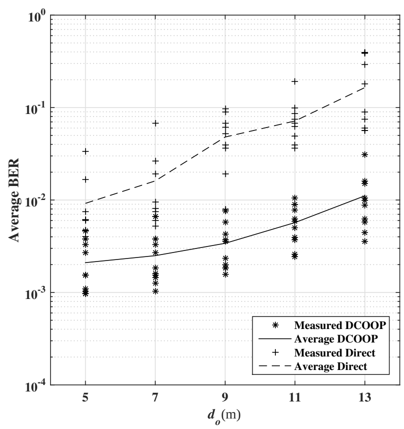
(a) Data Rate 6Mbps



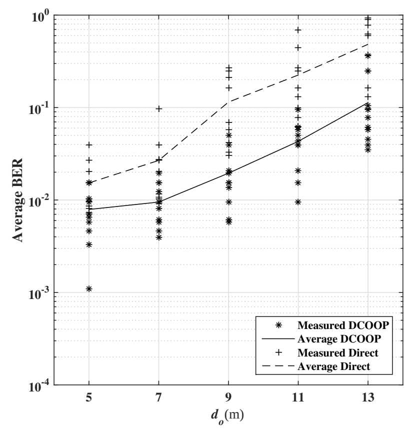
(b) Data Rate 12Mbps



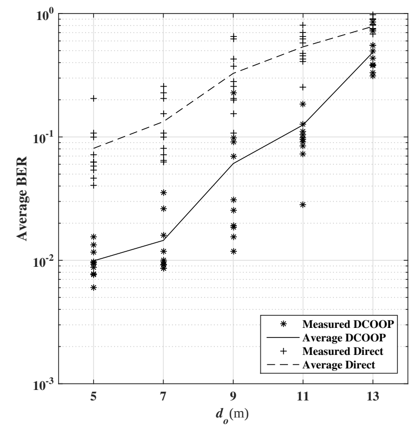
(c) Data Rate 24Mbps



(d) Data Rate 6Mbps



(e) Data Rate 12Mbps



(f) Data Rate 24Mbps

Fig. 6: Performace evaluation of DCOOP and Direct transmission based on Tx Power and d_o.

Power) and by varying distance (d_o). We control Tx Power by adjusting the antenna gain parameter and use a power meter to measure it. In Fig. 6a, 6b, 6c, we consider different data rates ($6, 12$, and 24Mbps) to evaluate the performance when all the nodes are equi-distance (approximately 5m) from each other. For fairness in comparison, we consider total transmit power for direct transmission and distribute this power equally between the source and the relay for DCOOP (e.g., if the source employs 10dBm for direct transmission, it is equivalent to 7dBm for DCOOP at source and relay node and similarly for other power levels). Here, we have two key observations, firstly, DCOOP outperforms direct transmission for all data rates considered and secondly, the least BER is recorded for the lowest data rate. Furthermore, in Table III, we notice that for 6Mbps and Tx Power of 11dBm for DCOOP, the average BER is 2.12×10^{-3}, lower than the average BER of 9.27×10^{-3} for direct transmission with Tx Power 14dBm. Similarly, improved BER is achieved by the testbed for all power levels, when compared with direct transmission. This improvement in performance can be used to transmit at a lower power level to conserve energy and achieve a desired BER for the testbed.

Next, in Fig. 6d, 6e, 6f, we have constant Tx Power for both DCOOP (11dBm) and direct transmission (14dBm), and then study the affect on BER by changing the distance of the destination node ($d_1 = 5$m, $d_2 = 7$m, $d_3 = 9$m, $d_4 = 11$m, $d_5 = 13$m). In general, moving the destination further away, leads to degraded performance for both DCOOP and direct transmission. With increasing data rates, the average BER shows a steep increase when d_o reaches 9m for both DCOOP and direct transmission. This dual-slope log distance path loss model was experimentally verified in [22] for direct communication. Our experimental findings are not only in agreement for direct transmission but also suggest that it is applicable on cooperative transmission (i.e., DCOOP testbed).

Table III: Average BER based on transmit power

Tx P[dBm]	6Mbps		12Mbps		24Mbps	
	DCOOP	Direct	DCOOP	Direct	DCOOP	Direct
7	2.13E-1	–	2.63E-1	–	3.32E-1	–
9	7.37E-2	–	1.56E-1	–	1.65E-1	–
10	–	5.01E-1	–	6.75E-1	–	7.01E-1
11	2.12E-3	–	7.92E-3	–	1.05E-2	–
12	–	3.3E-1	–	1.74E-1	–	0.43E-1
13	2.58E-4	–	1.25E-3	–	4.12E-3	–
14	–	9.27E-3	–	1.53E-2	–	8.45E-2

In Table IV, we calculate the average BER, and provide detailed performance improvement of the testbed as compared to direct transmission. It can be seen that for a given data rate of 6Mbps, direct transmission achieves an average BER of 1.61×10^{-2}, when the source is 7m apart from the destination. In comparison, we observe increase in coverage area with almost similar error rate (1.11×10^{-2}) for DCOOP transmission, with the destination 13m away from the relay. This enhancement in performance can be observed for higher data rates as well. Hence, in conclusion, our testbed is not only capable of operating at low power level but can also be considered to improve the coverage area.

Table IV: Average BER based on distance between relay and destination (DCOOP), source and destination (Direct)

d_o[m]	6Mbps		12Mbps		24Mbps	
	DCOOP	Direct	DCOOP	Direct	DCOOP	Direct
5	2.12E-3	9.27E-3	7.92E-3	1.53E-2	1.05E-2	8.45E-2
7	2.51E-3	1.61E-2	9.58E-3	2.68E-2	1.45E-2	1.33E-1
9	3.46E-3	4.80E-2	1.95E-2	1.14E-1	6.08E-2	3.27E-1
11	5.73E-3	7.16E-2	4.31E-2	2.25E-1	1.25E-1	5.37E-1
13	1.11E-2	1.64E-1	1.13E-2	4.83E-1	4.85E-1	7.87E-1

V. Conclusion

In this work, we have developed a novel cooperative protocol and studied its performance by implementing it on a testbed based on IEEE 802.11a standard. Empirical results for indoor measurements suggests that, DCOOP can effectively enhance the performance of existing wireless standards. It can also be considered for the design of future wireless communication networks, especially high density environments subjected to direct communication constraint. Future work will focus on evaluating performance of the testbed by considering node mobility.

Acknowledgements

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