On-demand Cooperation with Power Control: Protocol and Experimental Results

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Abstract—**In cooperative communications, wireless devices pool their resources to increase overall reliability. However, devices that would normally be idle spend energy to help neighbors. This altruism is a source of much debate on the efficacy of cooperative communications. In this work, we present the Power-controlled Distributed On-demand Cooperation (PDOC) protocol that employs cooperative relays in an energy efficient manner. PDOC provides significant reduction in energy usage at cooperative relays in two key regimes: when relays are close to destination nodes and when they are far away. In this work, we describe PDOC and evaluate the protocol with a real-time FPGA implementation and associated characterization.**

I. INTRODUCTION

Cooperative communications is a mechanism to exploit spatial diversity and harvest the resources of currently-idle nodes in a network for more reliable communication.

In effect, cooperative communication allows multiple wireless devices to pool their resources together to act as *virtual MIMO antennas*. From the perspective of a traffic sink (referred to as a *destination* in this work), multiple cooperative transmitters appear as a single multi-antenna wireless transmitter.

A key obstacle for cooperative communications is not technical, but rather motivational. It is unclear that users would allow their devices to spend battery power in assisting other users on the network. In the debate over cooperative altruism, cooperative communications can be given a much stronger bargaining position if there exist mechanisms for highly *energy efficient* cooperative relays.

In this work, we propose and evaluate Power-controlled Distributed On-demand Cooperation (PDOC). This cooperative MAC protocol shows substantial energy savings over the state-of-the-art while maintaining the same throughput performance. These energy savings stem from two key components: (i) PDOC lets cooperative relays disable transmissions if that transmission is not going to be successful anyway and (ii) PDOC lets cooperative relays transmit at less-than-maximum transmission power as long as the likelihood of success is not significantly perturbed.

To evaluate the merit of the proposed protocol, we construct a real-time implementation on the FPGA-based Rice University Wireless Open-Access Research Platform (WARP) [1].

Related Work:

In our prior work [2], we proposed a novel cooperative MAC protocol called Distributed On-demand Cooperation (DOC). Because cooperation requires two time slots (a relay listening phase and a relay transmission phase), DOC innovates over the state-of-the-art by only allowing cooperation in situations where MAC-level retransmissions would occur anyway. Devices employing the DOC protocol first attempt to communicate using direct communication much like the 802.11 DCF. In the event that the transmission fails, a cooperative retransmission occurs with simultaneous source and relay transmissions. This work serves as the basis for the proposed PDOC protocol.

Power-controlled relaying has seen a number of studies with an information theoretic focus [3, 4]. These studies show considerable performance gains for devices that employ power-control, but they rely on substantial amounts of channel state information to be available at all participating nodes. In our work, we focus on the protocol implications of delivering this channel state information to the relevant devices in the network.

A similar research area is the study of power control for Mobile Ad Hoc Networks (MANETs) [5–7]. In all of these works, power control is embedded into the MAC by hijacking the RTS/CTS mechanism established by the 802.11 DCF. Since power control requires feedback for the transmitter to know how much power to use, RTS/CTS handshakes are performed at maximum power and a lower power is selected for the DATA/ACK exchange. Perhaps most related to our work, the strategy proposed in [8] applies this RTS/CTS-based approach to cooperative relaying. In all commercial 802.11 devices, however, RTS/CTS behavior is disabled by default. This is due to the fact that the overhead required by using RTS/CTS handshakes in front of every data transmission is too large for normal use[1]. Since RTS/CTS are disabled, any form of power control would also be disabled by default. By contrast, our work requires no explicit handshake before attempting to transmit data. Our use of power control requires very little additional overhead.

Paper Outline:

In Section II, we offer information theoretic analysis that highlights two regimes where there can be energy savings for a cooperative MAC protocol. In Section III, we provide a detailed description of the PDOC protocol and highlight the mechanisms that allow it to save energy. In Section IV, we describe our FPGA implementation of PDOC and go on to describe its characterization in Section V. Concluding remarks are offered in Section VI.

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[1] RTS/CTS can still be enabled by users whose networks need it (e.g. extreme hidden terminal problems)

II. SYSTEM MODEL AND ANALYSIS

In this section, we provide an information theoretic basis for the study of energy efficient cooperative communications. Specifically, we highlight regimes where traditional cooperative communication protocols create energy waste. We then target these regimes in our protocol design in Section III.

In this work, we employ an information theoretic outage model to describe link performance in the presence of fading. Formally, let

$$P_{out} \;= Pr\{\log\left(1 + \mathsf{SNR}\cdot|h^2|\right) < R\} \tag{1}$$

represent the probability that a transmission of rate R fails to be decoded. We use this expression to describe packet loss rate in the absence of any interference. In [2], the DOC protocol innovated over the state-of-the-art by ensuring that cooperation only occurs when direct transmission fails. Let the labels S, R, D represent source, relay, and destination respectively. DOC only attempts to cooperate when

$$\log\left(1 + \mathsf{SNR}_{\mathsf{SD}}\cdot|h_{\mathsf{SD}}|^2\right) < R \tag{2}$$

$$\log\left(1 + \frac{T_{\mathsf{S}}L_{\mathsf{SD}}}{N_0}|h_{\mathsf{SD}}|^2\right) < R, \tag{3}$$

where T_{S} represents the transmission power of the source in watts, L_{SD} represents the pathloss between source and destination as a unitless linear scale factor, and N_0 represents the power of a thermal noise floor at the receiver. Assuming a Rayleigh fading channel, $H_{\mathsf{SD}} = |h_{\mathsf{SD}}|^2$ is drawn as an exponential random variable with unit parameter. However, this density describes all possible channel conditions between source and destination. Since cooperation only occurs on a subset of these conditions, we can manipulate Equation 3 in order to redefine the density on H_{SD} as an exponential that is clipped to finite support. Formally, the probability density function for H_{SD} given relay transmission under the DOC protocol is

$$f_{H_{\mathsf{SD}}}(x) = \begin{cases} \dfrac{\exp(-x)}{1-\exp\left(\frac{-(N_0(2^{R_{\mathsf{SD}}}-1)}{T_{\mathsf{S}}L_{\mathsf{SD}}}\right)} & x \in [0, \frac{(N_0(2^{R_{\mathsf{SD}}}-1)}{T_{\mathsf{S}}L_{\mathsf{SD}}}] \\ 0 & \text{otherwise} \end{cases}$$

Borrowing from [9], the rate of a link using decode-and-forward cooperative signaling is

$$R = \log\left(1 + \mathsf{SNR}_{\mathsf{SD}}|h_{\mathsf{SD}}|^2 + \mathsf{SNR}_{\mathsf{RD}}|h_{\mathsf{RD}}|^2\right) \tag{4}$$

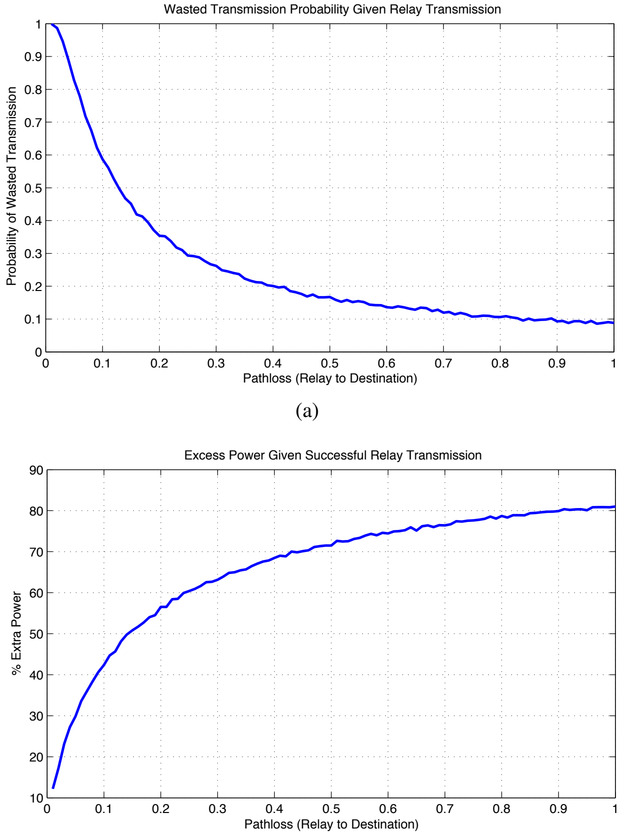
$$R = \log\left(1 + \frac{T_{\mathsf{S}}L_{\mathsf{SD}}}{N_0}|h_{\mathsf{SD}}|^2 + \frac{T_{\mathsf{R}}L_{\mathsf{RD}}}{N_0}|h_{\mathsf{RD}}|^2\right), \tag{5}$$

where all variables are defined similarly to before[2]. Solving for the relay transmit power T_{R} in Equation 5,

$$T_{\mathsf{R}} = \frac{N_0\left(2^R - \frac{T_{\mathsf{S}}L_{\mathsf{SD}}}{N_0}|h_{\mathsf{SD}}|^2 - 1\right)}{L_{\mathsf{RD}}|h_{\mathsf{RD}}|^2}. \tag{6}$$

Depending on the instantaneous channel realizations between source/destination and relay/destination, T_{R} can take on a range of values. When very small, this expression tells us that the relay need not transmit at large power in order to ensure that it assists the source on that particular packet. When very large, the converse is true: the relay would require an extraordinarily large amount of transmission power in order to be beneficial.

Suppose T_{S} represents the maximum possible transmission power that each radio can produce. For all cases of $T_{\mathsf{R}} > T_{\mathsf{S}}$, it is impossible for cooperation to assist without violating this constraint. As such, a relay transmitting at maximum power in these regimes produces *wasted* transmissions that only serve to draw power from the relay, meanwhile providing no cooperative benefit. Calculating $Pr\{T_{\mathsf{R}} > T_{\mathsf{S}}\}$ in closed-form is highly involved due to the simultaneous interplay of a clipped exponential random variable along with a standard exponential random variable, so we turn to simulation of these expressions to evaluate this probability. Figure 1(a) shows the likelihood of wasted transmissions as a function of L_{RD}. When there is a significant distance between relay and destination (i.e. small L_{RD}) there is a large chance that the power required by the relay exceeds the maximum power constraint. Thus, the DOC relay transmits in these regimes even though it simply cannot



(a)

(b)

Fig. 1. There are two regimes of waste for the relay: far from the destination and close to the destination. An energy efficient protocol should be able to find maximal savings in these regimes.

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[2] It is worth noting that the $|h_{\mathsf{RD}}|^2$ channel power is modeled as a standard exponential random variable, whereas $|h_{\mathsf{SD}}|^2$ follows the density of the clipped exponential defined earlier.

help.

In Figure 1(b), we plot the following metric:

$$\frac{E[T_{\mathsf{S}} - T_{\mathsf{R}}]}{T_{\mathsf{S}}} \;\forall\; T_{\mathsf{R}} \le T_{\mathsf{S}}. \tag{7}$$

This metric captures all the cases where relay transmission would help and then evaluates how much excess power a full power transmission at the relay draws as compared to the minimum that would be needed. Figure 1(b) shows that as the relay gets close to the destination (i.e. large L_{RD}), the DOC relay spends upwards of 80% more power than would be strictly required in order to have reliable communication.

From this analysis we find two guiding protocol design goals:

- When a relay cannot help, it should avoid wasted transmissions and simply not transmit.
- When a relay can help, it it should only transmit with *just enough* power to ensure the reliable delivery of the packet and no more.

We use these findings to motivate the structure of our proposed protocol in Section III.

III. THE PDOC PROTOCOL

In this section, we describe the Power-controlled DOC protocol (PDOC). The protocol exhibits two key features that are in line with the observations made in Section II:

- PDOC only transmits when doing so results in a successfully delivered packet.
- PDOC will also only transmit at a power level that is only just sufficient for successful decoding.

PDOC is able to make these determinations by exploiting feedback from the destination node in the event of packet losses.

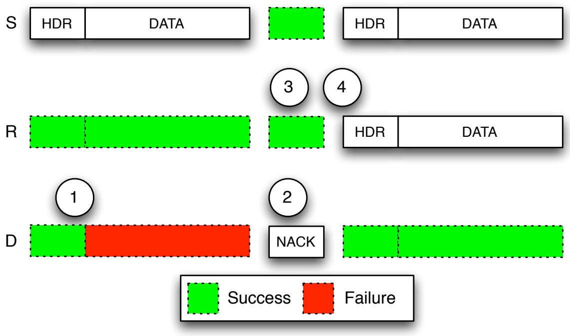

Fig. 2. Protocol timeline.

Figure 2 illustrates a timeline of events that occur with the PDOC protocol. The figure shows a failed direct packet exchange followed by a successful cooperative packet exchange. The numbered circles correspond to particular points in time where PDOC behaves differently than the traditional DOC protocol. These events correspond to:

1) The destination estimates the channel $T_{\mathsf{S}}L_{\mathsf{SD}}|h_{\mathsf{SD}}|^2$ when receiving the packet. This estimation occurs anyway in any coherent communication system with channel-state-information-at-the-receiver (CSIR). Rather than throw away the estimate after using it to attempt to detect and decode the packet, PDOC receivers save the value into memory.
2) In DOC, a failure event in decoding the payload of the source's transmission causes the destination to generate a negative acknowledgment (NACK) and broadcasts it to both the source and relay. PDOC enhances this behavior by including the $T_{\mathsf{S}}L_{\mathsf{SD}}|h_{\mathsf{SD}}|^2$ estimate inside the NACK packet. While this extra information increases the overhead in the protocol over DOC, it is very likely this additional overhead can be negligible. For example, in our WARP implementation of PDOC in Section IV, received signal strength (RSSI) is a 10-bit value. The only overhead PDOC incurs over DOC is the inclusion of this 10-bit value in the NACK packet. If this is too much, a further quantized version of the value could be included instead at the cost of accuracy in the estimate of $T_{\mathsf{S}}L_{\mathsf{SD}}|h_{\mathsf{SD}}|^2$.
3) Upon receiving the NACK, the relay directly estimates the channel $T_{\mathsf{S}}L_{\mathsf{RD}}|h_{\mathsf{RD}}|^2$. Additionally, it reads $T_{\mathsf{S}}L_{\mathsf{SD}}|h_{\mathsf{SD}}|^2$ out of the NACK itself, giving it access to both the SD and RD channels[3].
4) Finally, the relay decides whether or not to transmit and at what power level. This determination is made as a function of the SD and RD channel values.

The relay determines whether or not its transmission would be helpful by calculating

$$X_{\mathsf{DEC}} = \left[\frac{T_{\mathsf{S}}L_{\mathsf{SD}}|h_{\mathsf{SD}}|^2 + T_{\mathsf{S}}L_{\mathsf{RD}}|h_{\mathsf{RD}}|^2}{N_0} \ge Th\right], \tag{8}$$

where $[\cdot]$ is the Iverson bracket and Th is an *a priori* known threshold calibrated to the performance of the physical layer. $X_{\mathsf{DEC}} = 1$ if the relay's transmission will allow the destination to decode the source's message and $X_{\mathsf{DEC}} = 0$ otherwise[4].

Given that transmission can be helpful, the PDOC protocol can determine a scale factor on its transmission power such that $X_{\mathsf{DEC}} = 1$ is *still* ensured.

$$T_{\mathsf{excess}} = \min\left(1, \frac{ThN_0 - T_{\mathsf{S}}L_{\mathsf{SD}}|h_{\mathsf{SD}}|^2}{T_{\mathsf{S}}L_{\mathsf{RD}}|h_{\mathsf{RD}}|^2}\right). \tag{9}$$

Note that $T_{\mathsf{excess}} \in [0, 1]$ represents how much less T_{R} can be than the maximum transmission power T_{S} while still allowing decoding. Thus, the transmission power the relay chooses is simply $T_{\mathsf{R}} = T_{\mathsf{S}} \cdot T_{\mathsf{excess}}$.

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[3] This expression assumes that the destination would transmit the NACK at full power. Since the source transmits the data at full power as well, $T_{\mathsf{S}} = T_{\mathsf{D}}$.

[4] In its current form, PDOC assumes no interference from the rest of the network. We believe this can be extended to more general settings by allowing the destination to measure the ambient interference levels during the SIFS interval prior to sending the NACK. This interference measurement can be sent to the relay in the NACK so it can be considered in the function determining relay transmission power.

IV. FPGA IMPLEMENTATION

To evaluate the merit of the proposed PDOC protocol, we have chosen to implement the entire protocol in real-time on the Rice University Wireless Open-Access Research Platform (WARP) [1]. Our implementation is based on our prior implementations of a cooperative decode-and-forward physical layer [10, 11] and the DOC cooperative medium-access control layer [2]. Given this foundational work for our experiment, in this section we choose to focus solely on one particular challenge associated with the implementation of PDOC. In Equations 8 and 9, relay transmission power is directly computed from the formal definition of an information theoretic outage event in Equation 3. This computation is straightforward thanks to an infinite-length block code that can *guarantee* the success or failure of a transmission for any given relay transmission power. In practice, any finite length code cannot make this guarantee. Instead of directly calculating the required relay transmission power like in Equations 8 and 9, we experimentally determine the mapping between relay power and successful decoding probability for *our* physical layer implementation.

In this experiment, we use the Azimuth ACE400WB emulator [12] to control the source-to-destination (SD) and relay-to-destination (RD) channel qualities. We then artificially trigger node transmissions and measure three outputs from the network: (i) the SD link power (RSSI) of a source-only transmission at the destination, (ii) the RD RSSI of a destination-only NACK transmission at the relay, and (iii) the packet error rate (PER) of a cooperative $\mathsf{S+R}$ transmission as a function of the first two measurements.

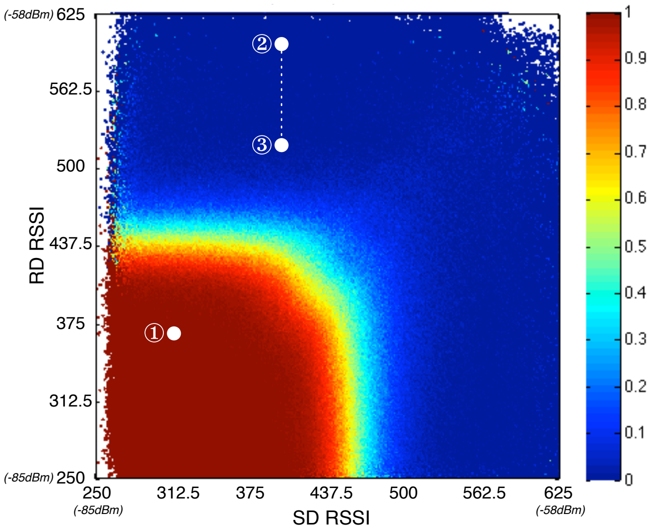


Fig. 3. Packet error rate of cooperative transmission.

Figure 3 shows the packet error rate of our cooperative physical layer as a function of the SD and RD channel qualities[5]. The regions in red correspond to cooperative transmissions that are nearly guaranteed to ultimately fail despite the presence of the relay. Regions in blue, however, show scenarios where cooperative transmissions are very likely to succeed.

A useful interpretation of this figure is that random fading in the network amounts to a random dart throw in this RSSI space[6]. As an example, if this dart happens to land at the point labelled ①, the relay knows that *even at maximum transmission power*, the cooperative packet is still very likely to fail. Therefore, the relay simply avoids transmission. However, if the random fading dart happens to land at the point ②, then the relay knows it can scale back its transmission power such that the final operating point will be point ③ without much harm to the error rate. Given this behavior, a function can be crafted that maps whether the relay will transmit and at what power it will do so as a function of the observed SD and RD RSSI values.

Along with the protocol mechanisms described in Section III, a critical difference between the implementation of DOC and the new PDOC protocol is the presence of the function derived from the data in Figure 3. We hardcode this function into a lookup table in the relay so that, given the SD and RD RSSI values gleaned from the NACK feedback, the relay can calculate the appropriate power level for transmission (or whether to transmit at all).

V. PROTOCOL EVALUATION

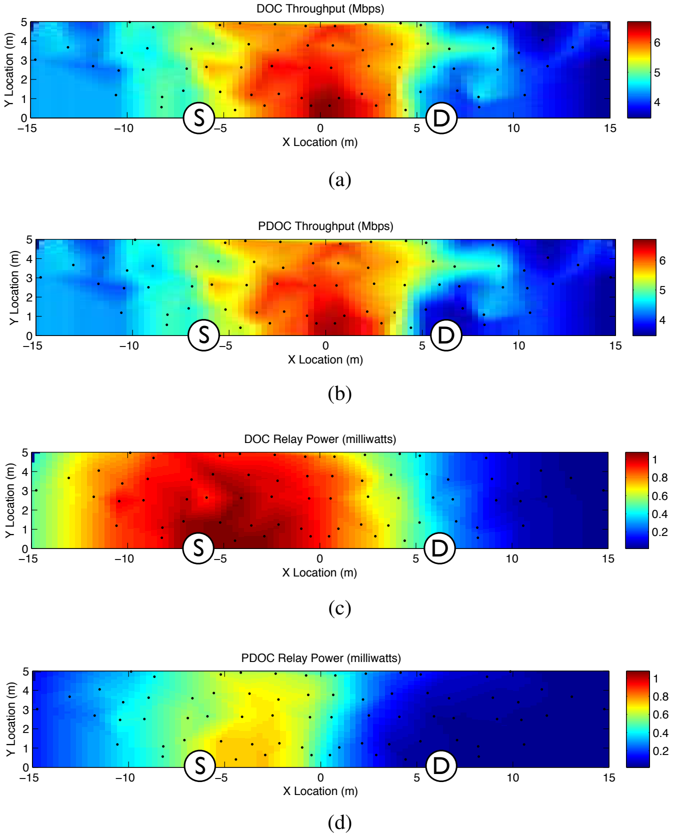
To evaluate and characterize the performance of the full PDOC implementation we use the channel emulator to effectively mimic a 2D topology with fixed source and destination locations by controlling the output attenuation on each path. The emulator itself controls the small-scale Rayleigh fading applied to each link. We then sweep the relay along points in the 2D space and linearly interpolate the results.

Figure 4(a) shows that the throughput performance of our real-time DOC implementation. When the relay is in the region between the source and destination, the throughput gains can are quite significant (from just over 3Mbps to nearly 7Mbps). Figure 4(b) shows the throughput performance from the new PDOC implementation. The proposed protocol is able to achieve the same performance as the original DOC protocol, which means that energy savings do not come at the cost of any lost performance.

Figure 4(c) shows the average amount of power that the DOC relay spends transmitting while Figure 4(d) shows the same information for the PDOC implementation using the same color scale. There are significant power savings at every point in the topology. Furthermore, two key regimes for savings are apparent:

[5] For this experiment, we use a variant of our physical layer that employes no channel coding. The same characterization can be applied to the different code rates thereby allowing PDOC to coexist with automatic rate adaptation schemes.

[6] This experiment uses our emulator with a single channel tap and is therefore frequency flat. In frequency selective channels, PDOC may be extended by exchanging RSSI to a per-subcarrier power measurement.



(a)

(b)

(c)

(d)

Fig. 4. The PDOC protocol successfully saves energy in regimes both close to and far away from the destination.

- **Far-from-Destination Relay:** When the relay is far from the destination (e.g. the relay is to the left of the source in Figure 4), there are many occurrences of channel fades that lead to a scenario in which cooperative transmission still fails. PDOC recognizes these conditions and appropriately disables relay action to save significant amounts of energy without adversely affecting performance.
- **Close-to-Destination Relay:** When the relay is close to the destination, there are many occurrences of channel fades in which the relay need only transmit at a small fraction of maximum transmission power to still be successful.

These two observations perfectly line up with our predictions from Figures 1(a) and 1(b).

VI. CONCLUSIONS

Cooperative communications is destined to play a large role in upcoming wireless standards. In this work, we have presented a protocol that can substantially reduce the energy usage of cooperative relays. The implications of energy usage at the relay are vast. In this work, we have cast energy savings as a benefit to battery life in mobile cooperative relays. In addition to this fact, one might also consider the network-capacity implications of energy efficient cooperative communications. In wireless communications, all transmissions are inherently broadcast. Even if the *traffic* is unicast, the physical transmission mechanism radiates energy in many directions. If a cooperative relay places less energy on the air, the spatial footprint of a cooperative flow will be reduced. This potentially could allow higher spatial reuse in multi-flow networks where surrounding flows treat relay transmissions as interference.

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