An Experimental Framework for the Evaluation of Cooperative Diversity

Glenn J. Bradford and J. Nicholas Laneman
Department of Electrical Engineering
University of Notre Dame
Notre Dame, Indiana 46556
Email: {gbradfor, jnl}@nd.edu

***Abstract*—Cooperative diversity is the result of relaying among nodes to achieve space diversity in multipath environments that offer limited time and frequency diversity. Although there is now substantial literature covering specification and analysis of cooperative communication strategies based upon models of wireless environments, there is much less work addressing experiments with real-world radio hardware and propagation channels. This work describes the construction of a three node, experimental testbed based upon a network of software-defined radios for development and verification of cooperative protocols. Several decode-and-forward relay protocols have been implemented and evaluated in terms of their diversity gains as measured from experimental curves of bit-error rate versus average signal-to-noise ratio. In contrast to the few other implementation efforts reported, the experimental setup maintains the relative node geometry while moving the network to induce fading, and the experimental results exhibit diversity benefits.**

I. INTRODUCTION

Cooperative diversity [1]–[3] is a way of combatting multipath fading by producing space diversity through relaying when node size in a network makes traditional spatial techniques impractical. Usually space diversity is achieved through the use of multiple antenna arrays, in which antennas must be separated by a distance on the order of the carrier wavelength to ensure transmissions from each antenna fade independently. Radio size and carrier frequency can often preclude this possibility for smaller devices, making relaying an attractive alternative for creating space diversity when other forms are not available. Systems with a diversity gain display a steeper slope in plots of their bit-error rate (BER) versus signal-to-noise ratio (SNR). In addition to diversity gains, cooperative systems can also provide path loss and shadowing benefits through their use of multi-hop transmission.

There are relatively few experimental evaluations of cooperative communications when compared with the large amount of theoretical literature on the topic. Cooperative diversity's blurring of the point-to-point communications link model [4] inherently suggests increased interaction between layers of the protocol stack and optimization across these layers. Decisions about how, when, and with whom to cooperate require information at and have implications for multiple layers. Experimental implementations of cooperative communication schemes thus provide a valuable opportunity to study the interaction between theoretical concepts and architectural choices. Each will be seen to have an influence on the other. Furthermore, experimentation makes it possible to validate assumptions made in theoretical modeling and identify regimes under which these assumptions break down.

The experimental decode-and-forward (DF) network shown in Fig. 1 is described and analyzed in the sequel. Due to cooperative diversity's potential for optimization across network protocol stack layers, the reconfigurable technology of software-defined radio (SDR) [5] is an ideal platform on which to experiment with cooperative protocols. SDR seeks to perform as much signal processing as possible in software or reconfigurable hardware to facilitate quick application development and dynamic system reconfiguration. These attributes provide valuable flexibility for the implementation of cooperative schemes.

The remainder of this paper is organized as follows. Section II will provide a brief overview of other implementation work done for cooperative schemes. Section III describes the design, implementation, and characterization of the experimental setup as well as the experimental procedure. Sections IV and V present simulation and experimental results of the DF relay network. Finally, Section VI draws some overall conclusions and highlights directions of future research.

II. RELATED WORKS

An early implementation of cooperative communications is found in [6], in which simple commodity hardware consisting of a microcontroller and radio unit were used to create cooperative relays. Performance is analyzed qualitatively through the transmission and display of weather information through the network. More quantitative performance measurements are undertaken in [7], in which an amplify-and-forward (AF) relay network is constructed based on an OFDM physical layer and distributed Alamouti transmit diversity scheme using WARP, an FPGA based SDR developed at Rice University [8]. Performance is measured in terms of the BER versus SNR behavior of the network, but the lack of node mobility precludes observation of diversity gains. Characterization of performance through BER versus SNR curves is a purely physical-layer analysis of performance and, as described later, can be challenging to obtain.

Open-source wireless card drivers are modified in [9] to allow for multi-hop transmission in 802.11 networks, though the fixed physical-layer hardware of the commercial wireless

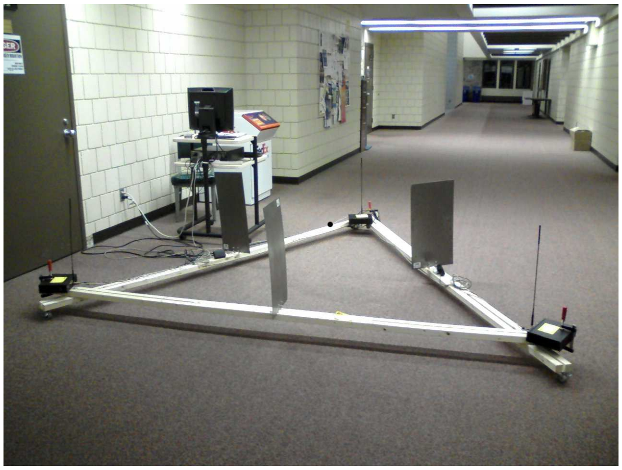

Fig. 1. Experimental setup for three node DF relaying schemes with USRPs in an equilateral triangle, controlling computer, and removable RF shields.

cards meant diversity combining at the receiver could not be implemented. Performance increases were thus restricted to purely path loss and shadowing gains. Here, performance is measured in terms of throughput, a metric associated with the link layer. Both physical and link layer performance quantifications have benefits and drawbacks and yield different insights. For instance, throughput is easier to obtain and more directly related to overall system performance than BER, but can obscure what is transpiring at the physical layer.

III. EXPERIMENTAL SETUP

The experimental network was comprised of a source, a relay, and a destination node communicating with each other using uncoded transmission. BER versus SNR, a physical-layer metric, was chosen as the performance metric for comparison between direct and cooperative transmission since it is the most common quantification of diversity in the literature. As we will see, use of this metric has implications for both experiment design and node architecture.

The relay fully detected the source's message before forwarding it on to the destination which, while not guaranteed to provide full diversity, is one of the simplest schemes possible. Two variations of this scheme were implemented. A simple DF scheme at the relay forwarded all packets it received, regardless of whether they contained errors, and a selective DF scheme only forwarded those packets it received without errors, determined through the use of an appended cyclic redundancy check (CRC). Error propagation in the simple scheme will be seen to cancel out any diversity gain in the network.

Radio nodes were composed of a Universal Software Radio Peripheral (USRP) [10] acting as an analog front-end to digitize signals with baseband processing done on a computer running GNU Radio [11], an open-source, software-defined radio package. The USRP has modular daughterboards that perform initial radio frequency (RF) filtering and frequency translation to an intermediate frequency (IF), allowing the USRP to operate in different frequency bands by swapping out of the daughterboards. A base motherboard has analog-to-digital converters and digital-to-analog converters for the digitization and reconstruction of signals. Additionally, there is an onboard FPGA for signal processing at IF and frequency translation to baseband. A USB interface allows the USRP to transfer and receive baseband samples from a host computer running GNU Radio.

GNU Radio runs on a general purpose processor and processes data in a streaming manner. Signal processing is performed in blocks implemented in C++ which are then tied together in a flow graph through the use of the Python programming language. This structure provides an efficient implementation of signal processing through compiled code while allowing for simpler application development based on interpreted code. Code for the experimental relay network drew heavily from functionality already implemented in GNU Radio.

A. Architectural Decisions

Because BER decreases with increasing SNR, the amount of data needed at higher SNR points to obtain BER estimates of similar accuracy increases. Larger amounts of data imply longer collection times for higher SNRs; hence, there was a motivation to keep the BER high. This desire to operate in the high BER regime led to the use of an uncoded system and, as further described in Sec. III-C, the desire that there not be a strong line-of-sight component. Metal shields, seen in Fig. 1, were placed between nodes to help attenuate any line-of-sight path.

Modulation in the experiment was differential binary phase shift keying (DBPSK), in which the information is carried on the change of phase of subsequent received symbols. This differential transmission simplifies receiver complexity as carrier recovery can be less accurate.

Transmissions from the source and relay were orthogonal in time. Although joint transmission of the source and relay promises large theoretical gains in the form of cooperative beamforming [12], distributed synchronization is a large implementation hurdle to overcome. This is a particular area of cooperative diversity research in which implementation work can prove particularly fruitful. Orthogonality could have been obtained in frequency, reducing decoding delay at the destination, however SDR dynamic range issues make this less desirable. One of the greatest flexibilities of SDR is the ability to digitize a large bandwidth of spectrum, but doing so can mean signals experience greater quantization noise effects than they otherwise would have if other inband signals had been filtered out. The variation in quantization noise resulting from orthogonalizing transmissions in frequency would have led to a disparity between the actual and expected instantaneous SNRs for a given internode distance, transmit power, and fading realization.

Hardware on hand allowed for operation in the 400-500 MHz band. This band is sufficient for inducing multipath fading, but it is hardly ideal, as coherence distance, the distance a node must travel to observe an independent channel realization, is inversely proportional to carrier frequency. A common approximation of coherence distance is one quarter of the carrier wavelength, which for the frequency band used gives a coherence distance of 0.17 m. For comparison, the approximate coherence distance in the 2.4 GHz band is 3 cm. Using a higher carrier frequency would have meant less mobility was necessary to collect the same amount of independently faded data, a positive for experimentation.

B. *BER Measurement*

To plot an experimental BER curve, the average SNR for a given topology of the network must be known. This average SNR is a function of the transmit power, the distance between two given nodes, and the noise floor. Estimating SNR for a given channel realization is not helpful, as this includes the variation in instantaneous SNR from multipath fading. This difficulty can be overcome by choosing to fix either the distance between nodes or the transmit power, while varying the other quantity. For simplicity, distance was fixed. To see the benefits of diversity, performance needs to be averaged over multiple channel gain realizations, requiring the nodes be moved within their environment.

The requirement that the nodes move in their environment yet stay fixed relative to one another led to an experimental setup, Fig. 1, in the form of an equilateral triangle with a radio node connected at each vertex. Wheels on the bottom of the setup allowed for easy movement to obtain multiple channel realizations. The equal distances between nodes ensured that any gain observed was the result of a diversity gain rather than a path loss gain; however, because power was not normalized, the diversity scheme enjoyed an advantage over direct transmission due to the additional power from the relay's transmission. Most importantly, the nodes could be moved in their environment to induce multipath fading while keeping the geometry of the network fixed to collect data at a fixed average SNR value.

In a sense, the equal distances between nodes is a pessimistic scenario. As mentioned earlier, partner selection is an important aspect of any cooperative scheme. The source-relay channel dominates performance in DF schemes because detection at the relay is done without the benefit of diversity. In a larger cooperative network where a source has multiple potential partners with which it can cooperate, the source would most likely pick a relay that gave a strong interuser channel. Thus if diversity benefits can be demonstrated in our setup, it is likely they exist for a large number of possible network topologies.

During data collection, the source and relay synchronously varied their transmit powers between three different values. Data was transmitted in packets whose transmission duration was much smaller than the coherence time of the channels, i.e., the time between which channel uses experience independent multipath gains. While packets were being transmitted, the setup was moved quickly enough to ensure each packet on a link experienced an independent fading realization. Because BER decreases with increasing SNR, the higher transmit powers required more data be collected in order to obtain a BER estimate of similar accuracy. The GNU Radio baseband processing was done on a single central computer to simplify data collection and analysis. Doing so made it easier to determine the number of errors in a received packet by comparing it with the original. Additionally, time orthogonality of the source and relay transmissions could be guaranteed.

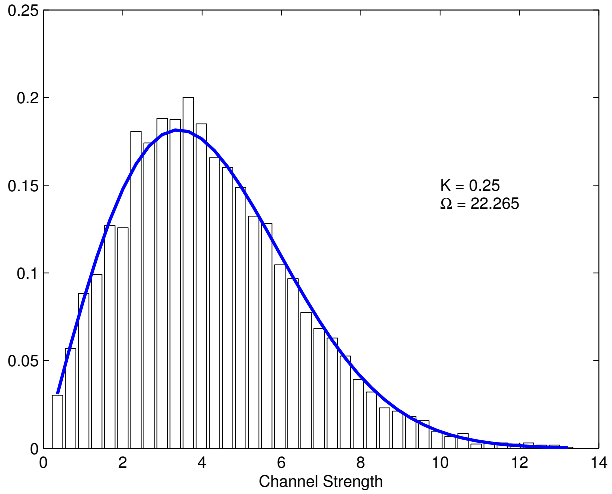

Fig. 2. Histogram of channel strength and its approximate distribution for experimental environment with RF shields in place.

C. *Setup Characterization*

Control of transmit power on the USRP is coarse and no means of automatic calibration are provided. This results in varying performance from one USRP to the next. Although precise SNR knowledge is not necessary for the plotting of BER curves, the relative increase in SNR between data points should be accurate in order to reproduce the desired graph geometry. In order to manually calibrate the transmit power of the USRPs, each USRP was attached directly to a spectrum analyzer. The transmit power was then measured while the USRP sent a signal identical to that used for transmission in the relay experiment. Two USRPs with similar transmit powers were chosen for the source and relay nodes, the two transmitting nodes in the experiment.

If the received wireless signal has a strong line-of-sight component, the advantage of a diversity scheme over direct transmission can be greatly reduced [13], [14]. Although this strong line-of-sight component is beneficial to the performance of the communication system, it makes experimentally detecting the presence of diversity more difficult. One must look at higher SNRs to see the benefits of diversity, requiring more data and thus longer experimental runs. To obtain a characterization of the channel, one node in the experimental setup with shielding was configured to transmit a pure tone at the carrier frequency while another recorded the magnitude

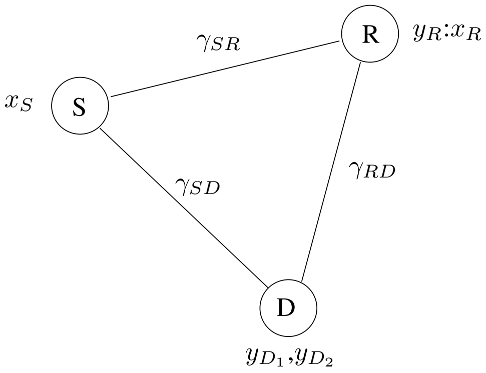

Fig. 3. Relay Network Model.

of the received signal. The experimental setup was moved as in the BER experiment. Fig. 2 plots a histogram of the data along with a Rician probability distribution, often used to model fading with a line-of-sight component, with parameters computed from the data using a moment-based estimator [15]. The K parameter of the Rician distribution, whose size is proportional to the strength of the line-of-sight component, was estimated from the data to be 0.25, which is quite small, suggesting there is no dominant line-of-sight path.

IV. SIMULATION

Theoretical results and simulations already exist in the literature for cooperative diversity with differential transmission, for example [16], [17], but are reproduced here for comparison with experimental results. The experimental relay network was simulated using the discrete-time, baseband mathematical model depicted in Fig. 3. Here, x_S and x_R are the transmitted symbols of the source and relay, respectively, and are drawn from the alphabet $\mathcal{X} = \{-1, 1\}$ since binary modulation is used. As in the experimental setup, transmissions of the source and relay occur in non-interfering orthogonal channels. Frequency non-selective, block fading is assumed along with additive white Gaussian noise (AWGN), resulting in input-output relationships for the three channels of the form

$$\begin{aligned} y_R &= \gamma_{SR} x_S + z_R \\ y_{D_1} &= \gamma_{SD} x_S + z_{D_1} \\ y_{D_2} &= \gamma_{RD} x_R + z_{D_2} \end{aligned}$$

where y_R and y_{D_1} are the reception of the source's transmitted symbol at the relay and destination, respectively, and y_{D_2} is the reception of the relay's transmitted symbol at the destination. Because the Rician parameter K was estimated in the experimental setup to be very close to zero, it was assumed the links were affected by Rayleigh fading. Hence, $\gamma_{SD}, \gamma_{SR}, \gamma_{RD} \sim \mathcal{CN}(0, 1)$ are the channel gains for the source-relay, source-destination, and relay-destination links. The thermal noise has power N_0, giving noise terms $z_R, z_{D_1}, z_{D_2} \sim \mathcal{CN}(0, N_0)$ at the relay, the destination while receiving the source's transmission, and the destination while receiving the relay's transmission, respectively.

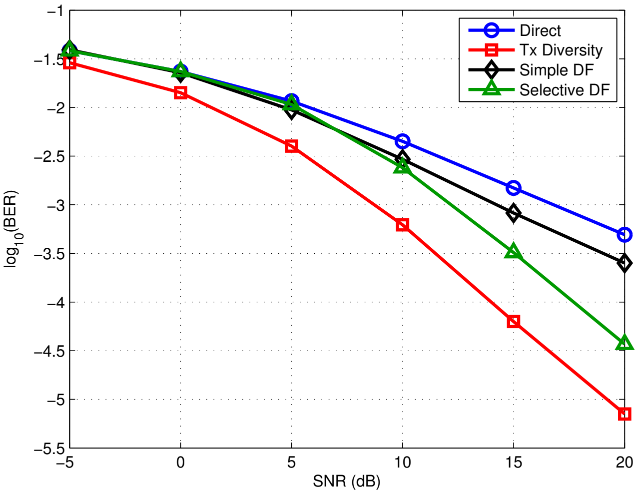

Fig. 4. Simulation of BER versus SNR for Experimental Setup.

Differential encoding for BPSK means that the transmitted symbol at time index n is formed from the previously transmitted symbol $x[n-1]$ and the current data symbol $s[n]$ by

$$x[n] = x[n-1]s[n].$$

At the receiver, the differential encoding is undone for a given receive symbol y by forming the statistic

$$r[n] = y[n](y[n-1])^*.$$

Simulations were performed for direct transmission as well as simple DF, selective DF, and transmit diversity. Direct transmission is limited to the use of r_{D_1} when estimating the source's data symbol, while the latter three form a statistic

$$r = r_{D_1} + r_{D_2},$$

through the use of equal gain diversity combining, for detecting the source's symbol. In both simple DF and selective DF, the relay fully detected the source's symbol before forwarding it on to the destination; however, in selective DF the symbol was only forwarded if it was correctly detected. Transmit diversity provides an upper bound on the performance of DF algorithms as it assumes that the relay always detects the source's symbol correctly.

The results of the simulation are provided in Fig. 4. The BER of both direct transmission and transmit diversity decay with the expected slopes of one and two orders of magnitude per decade of increase in SNR, respectively. Transmit diversity obtains the full diversity order possible in the system. The simple DF scheme does not provide any diversity benefit over direct transmission, as error propagation from the relay is negating any gain that may be occurring. However, if selective DF relaying is employed, the error propagation from the relay is reduced and a diversity gain recovered.

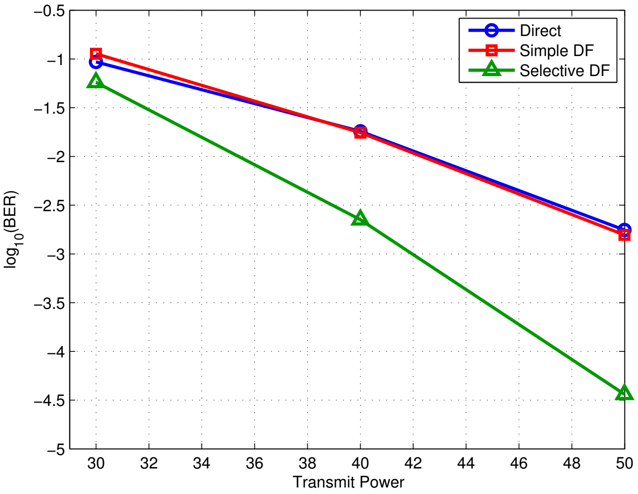

Fig. 5. BER versus transmit power for direct, simple DF, and selective DF schemes.

V. Experimental Results

Fig. 5 provides the experimental BER versus SNR plots for direct, simple DF, and selective DF transmission. It should be noted that BER is plotted against a scaling parameter in the code controlling transmit power rather than SNR. Although this parameter is neither the true transmit power nor SNR, the spacing between the points was checked during calibration to ensure the the slope of the BER curves would be preserved. The simple DF scheme provided no discernible diversity gain. Both it and direct transmission decay by one order of magnitude per decade increase in transmit power. The lack of diversity in the simple DF scheme is not surprising, as error propagation from the relay can eliminate a diversity gain. If the interuser source-relay channel had better average SNR, error propagation may not have dominated the diversity gain.

By selectively relaying only those transmissions received without error, the error propagation was reduced and some diversity gain recovered, exhibited in the steeper slope of the selective DF scheme's graph. Both DF schemes, however, are operating with approximately twice the power of the direct scheme. This disparity can be accounted for by shifting the direct transmission graph to the left by 3 dB, but the steeper slope of the selective DF graph ensures that this relaying scheme will still outperform direct transmission at sufficiently large transmit powers. Overall, the experimental results for the setup match nicely with the theoretical predictions provided by the simulation. This similarity is not surprising due to the fact that the characterization of the communications channel in Sec. III-C closely resembled the probabilistic model used in the literature for multipath fading.

VI. Conclusions and Future Work

An experimental framework for the evaluation of the spatial diversity benefits of cooperative diversity techniques was described. This framework was used to analyze a DF relay network which led to the experimental observation of a diversity gain when the relay forwarded selectively. Directions of future research include the integration of error coding, implementation of other relaying strategies such as amplify-and-forward and compress-and-forward, and the development of cross layer protocol architectures. Accurate SNR estimates during experimentation, experiments in outdoor channel environments, and the development of portable experiments are also areas of intended future work.

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