Efficient Relaying Strategy Selection and Signal Combining using Error Estimation Codes

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***Abstract*—In this paper, we use recently developed error estimation coding (EEC) to devise an efficient relaying framework for a multi-relay network. EEC utilizes an added redundancy to form an estimate of the bit-error rate (BER) of data received over a noisy channel. Utilizing the BER estimate, we propose a relaying selection strategy that uses the BER estimate at any given relay to switch between Amplify-Forward (AF) and Detect-Forward (DF) cooperation. In addition, we propose a signal combining rule at the destination that weighs different copies of the same data using the corresponding BER estimates. For performance evaluations, we implement the proposed scheme on a USRP-based platform, and test its performance by conducting experiments in an indoor office environment. Our results validate the efficacy of the proposed strategy; the proposed scheme significantly outperforms standard equal gain combining-based AF and DF cooperation.**

I. Introduction

With a mushroom growth in the number of mobile hand-held devices over the past few decades, the demand for reliable high-rate data communications has also seen a steady incline. The biggest challenge in satisfying the increasing demand is the adverse nature of the wireless medium due to issues such as fading, shadowing, multi-path effects, bandwidth constraints, and cross-channel interference. Many of these issues can be overcome by employing multiple antennas, thus achieving spatial diversity and/or multiplexing gains. While it might be feasible to deploy multiple antennas at the base-stations, doing so at mobile devices might not be practical due to stringent size and cost constraints. An attractive alternate is cooperative communications [1], in which multiple nodes cooperate with each other to give the same diversity and multiplexing gains that are promised by multi-antenna systems.

The simplest form a cooperative communication network is a three-node relay network [2], consisting of a source, destination, and a dedicated relay. A popular relaying strategy is the so-called Detect-Forward (DF) cooperation, in which the relay makes decisions on the data bits being sent from the source, before forwarding the estimates to the destination. However, a disabling bottleneck in DF is the channel quality from the source to the relay. If the channel is degraded, the relay forwards estimates that are very erroneous, resulting in severe error propagation at the destination. A promising alternate in such situations is Amplify-Forward (AF), in which the relay only forwards to the destination the amplified version of the signal it receives. As a general rule of thumb, DF is the strategy of choice if the source to relay channel is good, otherwise AF is selected [3]. An extension to the three-node network is the multi-relay network [2]. Both DF and AF strategies developed for a three-node network can easily be extended to a multi-relay network as long as the multiple relays use orthogonal channels.

For both DF and AF strategies, the destination receives multiple copies of the same signal from two or more independent paths. The destination must combine these signals to minimize the probability of error. The optimal strategy that maximizes the signal-to-noise ratio is Maximal Ratio Combining (MRC). However, it requires the destination know the exact channel conditions on the source-relay, source-destination, and relay-destination links. The traditional method of acquiring this knowledge in packet-based communications is through pilot symbols, using which, the receivers estimate their respective channel coefficients. Since the destination needs to know source-to-relay channel conditions for all relays as well, the relays must inform the destination of these conditions by appending extra bits to their payload. Moreover, since the pilots are usually appended at the start of the packets, pilot-based estimates fail to capture changes in SNR along the entire length of the packet. Therefore, if the channel conditions vary abruptly during a packet's transmission (for example, because of collisions or high mobility), the pilot-based estimates will be very different from the actual SNR changes experienced by the packet. Now even if MRC is used with pilot-based estimates, the decisions will be sub-optimum. A simple alternate to MRC is the equal gain combining (EGC) rule which does not require knowledge of any channel conditions. However, EGC suffers from poor performance, especially when the conditions on the links vary widely from each other.

In this paper, we devise an efficient cooperation framework for the multi-relay network using the recently developed error estimation codes (EEC) [4]. As opposed to error correction codes in which added redundancy is exploited to correct errors, EEC utilizes the redundancy to form an estimate of the packet bit-error rate (BER) with provable guarantees on the goodness of the estimate [4]. In contrast to pilot-based channel estimation, EEC provides an estimate of the BER by spreading the parity bits uniformly throughout the packet, thus incorporating the overall effect of conditions experienced by the packet as a whole. We propose to use a small amount of EEC redundancy to the source's packet transmissions; the EEC bits play a central role in the proposed cooperation framework. Besides the inherent advantages of EEC based estimation over other estimation strategies, the key features of our proposed cooperation framework and the contributions of our work are summarized below:

- Using the EEC framework, each relay forms a BER estimate for every packet from the source. Since DF is expected to perform well when the source-to-relay channel is good, we let the relays transmit using DF if the BER estimate is below a certain threshold. Otherwise, the relays employ AF.
- For each packet, the destination receives multiple copies; one copy directly from the source, and the others indirectly from the relays. For each copy, the destination forms a BER estimate using the EEC framework, utilizing which we propose an intelligent signal combining rule that performs close to the optimum MRC principle.
- An attractive feature of the proposed cooperation framework is that the network nodes are not required to coordinate with each other with respect to the choice between AF and DF. The forwarding decision at each relay depends solely on its local BER estimate. Moreover, the processing at the destination is also independent of whether the individual relays employ AF or DF. Therefore, all relaying decisions are made in a completely distributed fashion.
- We implement the proposed framework on a USRP-based platform, and test its performance by conducting experiments in an indoor office environment. Results generated using just 3% added EEC redundancy indicate that the proposed cooperation framework gives significant performance gains over standard AF and DF cooperation that utilizes EGC at the destination.

A. Related Work

The relay network has been widely studied in the research community (see [5], [6] and references therein). Besides theoretical studies, researchers have also focused on prototyping using software-defined radios. For instance, paper [7] presents an implementation of a real-time cooperative transceiver that employs AF and DF relaying, with a major focus on handling the carrier frequency offset correction and symbol-level synchronization of the cooperating nodes. Similarly, the authors in [8] presented a USRP-based implementation of single-relay as well as multiple-relay cooperation. In order to achieve timing synchronization between multiple distributed relays, the Verilog code in the USRP firmware was modified to maintain a hardware clock. In addition, external GPS based clocks were connected to the USRP nodes to avoid frequency drifts of the clock. In [9], DF cooperation was implemented in a three-node relay network using the USRP platform. The nodes were moved around during the transmissions to induce fading so as to verify the diversity gains associated with cooperation. Finally, a Texas Instruments DSP TMS320C6713 based DSP testbed was developed in [10] consisting of four nodes. The experimental setup consisted of a source, destination, and two relays in the middle. The work also proposed a relay selection strategy which chose only one of the two relays for cooperation, based on the strongest channel in terms of large-scale fading.

The remainder of the paper is organized as follows: We provide a brief background of EEC in Section II. In Section III, we provide a detailed description of the proposed relaying framework. In Section IV, we provide performance evaluations of the proposed relaying framework through simulations as well as using a test-bed based on software-defined radios, while we conclude the paper in Section V.

TABLE I. SUMMARY OF VALUES USED FOR EEC

Symbols	Values	Description
n	12000	# of data bits in a packet
k	360	# of EEC bits in a packet (i.e. $s \times l$)
s	90	# of EEC bits in one level
l	4	# of EEC bits levels
$\bar{p}$	0.25	maximum value of p incase of borderline cases
c_1,c_2	$0.25, 0.4$	algorithm constants

II. Overview of EEC

In this section, we give a brief background of how EEC is used for estimation of the BER; interested readers are referred to [4] for more details. A total of $k = 1 \times s$ EEC bits (called parity bits) are added to a packet of n data bits. The k extra bits are divided among $l = \log_2(n)$ different levels, where s is the total bits in each level. The value of s provides an insight into the estimation quality of p, which denotes the fraction of the flipped bits or equivalently the BER. Hence each packet contains a total of $n + k$ slots, where each slot signifies a single bit. An EEC bit at level i ($1 \leq i \leq l$) is simply obtained by performing binary addition on $2^i - 1$ randomly chosen bits among the n data bits. The k EEC bits are then distributed uniformly randomly between the n data bits to make a packet of $n + k$ bits. This randomization allows the EEC framework to operate on any arbitrarily correlated channel error patterns, and helps estimating the average BER experienced by the packet across its entire length.

For decoding purposes, all nodes in the cooperative network are assumed to have the same random seed to initialize their pseudo-random number generators. This ensures that they have the indices of the s parity bits for each level. The goal of EEC is to use the EEC bits to output an estimation $\hat{p}$ for p, with certain estimation quality. For each level i ($1 \leq i \leq l$), the algorithm computes the fraction, denoted by q_i, of the s parity bits that fail the check. If the value of q_i lies within the range (c_1, c_2), it estimates $\hat{p}$ to be $q_i/2^i$, where c_1 and c_2 are algorithm constants. The algorithm also takes into account borderline cases, i.e., in situations where $q_1 \geq c_1$, it outputs $\hat{p}=\bar{p}$ and for cases when $q_1 \leq c_1$, the algorithm outputs $\hat{p}=0$ and exits. In Table 1, we show the specific values that we have used for our EEC design in the cooperative network. In our specific model, we have incorporated a redundancy of 3%. For the algorithm constants as well as for the border cases, we have borrowed the values from [4] without making any changes.

III. Proposed Cooperation Framework

In this section, we present the details or our proposed cooperation framework. Since the framework is packet-based, we will first describe how the packets are constructed at the source. This will be followed by description of the processing at the relay and the destination.

A. Source

At the source, we randomly generate a set of 12000 data bits, which we use as a data payload for each packet.

For modulation, we use standard coherent quadrature phase-shift keying (QPSK), in which the payload is mapped to the constellation two bits at a time. For pulse shaping, we employ a root-raised cosine filter. The packet's payload is preceded by a header, which is composed of a 13-bit Barker sequence, and is deployed to facilitate packet synchronization at the relays as well as at the destination. For practical purposes, we require that the header bits be provided more error protection than the payload bits, as failing to detect the header results in loss of the entire packet. It is also important from the cooperation point of view, since in order for different copies of the same packet to be combined at the destination, it is important for the destination to be able to detect start of packets even if the effective channel is weak. We achieve a higher level of protection for the header by mapping each bit diagonally on the QPSK constellation, as shown in Fig. 1, thus achieving a higher Euclidean distance between adjacent constellation points. This can easily be accomplished by repeating each header bit once, and then using natural mapping for QPSK. In addition to the header, we also include packet-ID bits in the packet. For proper combining at the destination, it is also essential that the ID bits be recovered properly. Thus we provide the same level of protection to the ID bits as we do for the header bits.

The overall packet format is shown in Fig. 2. The 13-bit Barker sequence is repeated to form a 26-bit sequence. The packet ID is taken to be 18 bits long, which after repetition forms 36 bits, and is appended next to the header sequence. This is followed by the payload, which consists of 12000 random bits and 360 (redundancy of 3%) EEC bits that are placed randomly across the payload. The entire packet is mapped to QPSK constellation before being transmitted over the air.

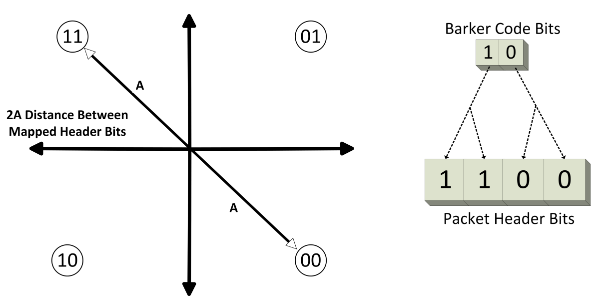

Fig. 1. Mapping of header bits on the QPSK constellation. The bits are repeated once, which results in the bits being effectively mapped to diagonal points on the constellation, thus providing greater error protection.

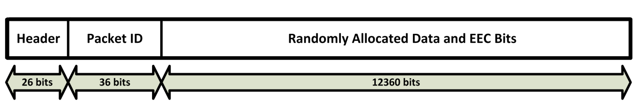

Fig. 2. Packet format used in the relaying framework.

B. Relaying Strategy Selection

Each relay employs a traditional QPSK receiver, consisting of standard root-raised cosine matched filter, frame synchronization, frequency and phase offset compensation, and timing synchronization blocks [11]. Using the demodulated data, we use EEC decoding to estimate the BER of each received packet. If the quality of the received packet is good, we use DF, since employing AF in this case could result in amplification of the noise along the source-relay link. In particular, relay utilizes DF if the BER estimated through EEC decoding is less than a threshold β. For DF cooperation, the relays re-form the packet using the packet format indicated in Fig. 2. On the other hand, if the estimated BER falls above the threshold β, we employ AF cooperation at the relays. In particular, demodulated outputs corresponding to the payload bits are modulated again and concatenated with the modulated version of the header and the packet ID before being forwarded to the destination. The use of AF in such a situation is also intuitive since using DF could result in error propagation at the destination. We point out that this type of AF that we employ is different than the cheap/dumb AF prevalent in the research literature; a dumb AF relaying is purely an analog approach in which the received analog signal is simply amplified and re-transmitted. In contrast, we use an AF strategy in which packet detection is performed before relaying. This introduces efficiency in the sense that the relay does not always perform cooperation; it does so only in the case of successful detection of the packet header. Note that the relay could have made other decisions if it had access to global CSI. However, the proposed approach is based solely on the local CSI, and is therefore much more practical. Finally, we point out that each relay makes an independent decision as to the type of relaying to use. In addition, each relay is assumed to transmit to the destination in a mutually orthogonal slot.

C. Signal Combining at the Destination

In any cooperative topology, multiple signal copies are received at the destination as a result of transmission in different slots. In our case, the destination receives data in multiple orthogonal time slots. In the first time slot, the destination receives data from the source, and during the next few slots, it receives data being sent from each one of the relay. For all received signals, the destination uses standard QPSK receiver to recover the packet IDs for each detected packet. A question that arises is how to combine the signals corresponding to the same packet received over multiple independent paths. In principle, one could employ MRC to minimize the BER. However, for both AF and DF, that requires the destination to know the exact channel conditions of all source-to-relay and relay-to-destination links. A simple alternate that does not require this channel knowledge is equal gain combining (EGC) [12], in which the signals are given equal weight in the combination. In particular, if Y_{SD} is the signal received from the source, and Y^i_{RD} is the signal received from relay i, the combination is given by

$$Y = \frac{1}{K+1}\left(Y_{SD} + \sum_{i=1}^{K} Y^i_{RD}\right), \quad (1)$$

where K is the number of relaying nodes. The test statistic Y is then used for forming decision on the payload bits. Whereas, EGC is attractive from the point of view of its simplicity, it suffers greatly in situations where there is a significant difference in SNRs along different relay channels. In that case, a single relay channel in deep fade can result in lots of errors and hence mitigate the good SNRs along the remaining channels. As a solution, we propose a combining rule which makes use of the BER estimates at the destination, and call

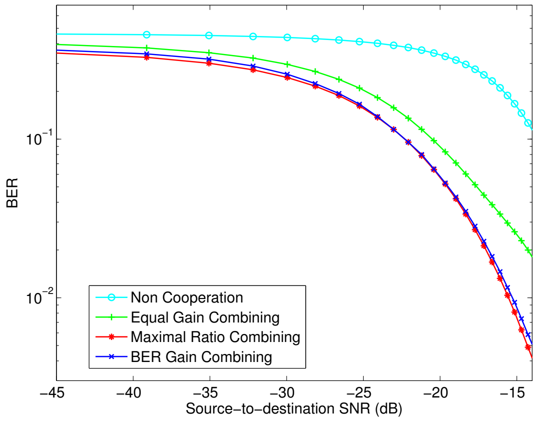

Fig. 3. BER versus the average SNR on the source-to-destination link. The average SNRs on the source-to-relay, and relay-to-destination links are 18 dB higher than that on the source-to-destination link.

it the BER-based-gain combining (BGC) rule. The proposed combination rule is given as

$$Y = \left[(p_{SD})^{-1} + \sum_{i=1}^{K} \left(p_{RD}^{i}\right)^{-1} \right]^{-1} \times \left[(p_{SD})^{-1} Y_{SD} + \sum_{k=1}^{K} \left(p_{RD}^{i}\right)^{-1} Y_{RD}^{i} \right], \quad (2)$$

where p_{SD} and p_{RD}^{i} are the BER estimates of the copies received from the source and the relay i, respectively. The biggest advantage of BGC[1] over MRC is that it does not need explicit knowledge of any channel conditions. The channel conditions on the source-destination link are implicity estimated through p_{SD}, whereas the conditions on the compound links from source-to-relay-to-destination are estimated with the help of p_{RD}. At the same time, it promises a much better performance than EGC (as will be presented in the next section), since it takes into account the varying quality of the received signals. In short, the rule tries to mimic the performance gains of MRC with a simplicity that is comparable to EGC. Another salient feature of BGC is that it is independent of whether the relays adopt AF or DF for cooperation. In fact, the entire framework does not require any of the nodes to coordinate with each other with respect to the selection of the relaying strategy.

IV. Experimental Evaluations using Software-Defined Radios

In this section, we present the performance results of our proposed cooperation framework. We first simulate the framework assuming Rayleigh fading models and verify the associated benefits. We then implement the strategy using a test-bed based on software-defined radios and exhibits the scheme's effectiveness by testing it in an indoor office environment.

A. Simulations

To test the validity of our scheme, we performed simulations based on the Monte-Carlo method for a simple three-node network consisting of a single relay node. To create an environment similar to the experimental conditions with our test-bed, we modeled each one of the three links as suffering from independent Rayleigh fading. Packet payload along with the EEC bits were modulated onto QPSK before transmitting over the simulation channel. The signals received at the destination were combined using the rule specified in (2). At the relay, we switched between AF and DF based on a threshold β that was optimized after multiple experimental runs. The resulting BER versus the average SNR on the source-to-destination link is shown in Fig. 3, when the other two links are assumed to significantly stronger than the direct link. While it is evident that cooperation proves to be extremely beneficial, EGC gives us sub-optimum results, especially because of the great mismatch in channel conditions. Meanwhile, our BGC rule approaches BER values that are very close to the optimum MRC rule. The reason why it does not exactly coincide is because of the inherent imperfections in the BER estimates obtained through EEC. In short, the simulation results verify that out strategy can be extremely beneficial, even without requiring information about the exact channel parameters.

B. Experimental Results using Software-defined Radios

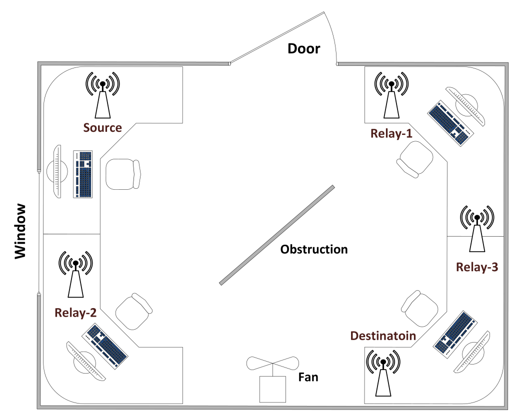

Fig. 4. Floor-map of the experimental topology.

To lend further credibility to the proposed framework, we implement and test it on test-bed based on software-defined radios. In particular, we use USRP-1 devices [13] connected to windows-based personal computers, with all baseband processing being done in Matlab. Although MATLAB-Simulink does not provide official support for USRP-1 devices, we were able to configure our hardware using the Simulink-UHD libraries provided by KIT [14]. We first conducted experiments on a three-node network in an indoor lab environment, the floor map of which is shown in Fig. 4, along with the positions of the source, relay (represented by Relay-1 in the figure), and the destination nodes. The source to destination link was disrupted by the placement of few metal obstacles as well as a revolving metallic fan. For performance evaluations, we transmitted a total of 100 packets from the source. After applying the selection strategy at the relay, and the BGC rule at the destination, we obtained the overall BER averaged over the 100 packets. In Fig. 5, we show the variation of the overall BER as a function of the threshold β being employed for relaying strategy selection. We note that the proposed hybrid scheme that switches between AF and DF reduces to pure DF

[1]Note that the BGC rule is in fact MRC if the BER estimates are exact, and if the channels are assumed to suffer from Rayleigh fading.

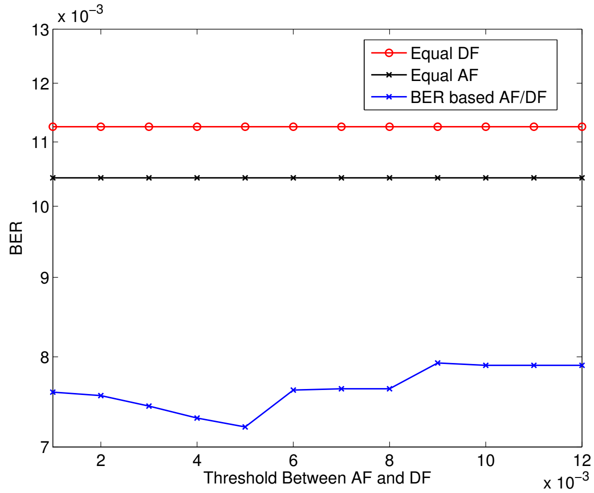

Fig. 5. Variation of overall BER versus the threshold β.

when $\beta = 1$, and reduces to pure AF when $\beta = 0$. Searching over the thresholds over the experimental data, we find that the optimal β that minimizes the overall BER is approximately equal to 5×10^{-3}. From Fig. 5, we observe that the proposed relaying framework with optimized β performs much better than both EGC-based AF and DF.

Next, we perform experiments using three relaying nodes, with the positions of each one of the five nodes shown on the floormap in Fig. 4. The relays were positioned strategically, so that there were both line-of-sight and non-line-of-sight links. Applying the relaying strategy selection at each one of the individual relaying nodes, and the BGC rule at the destination to combine different copies of the same packet, we obtain the optimized results in Fig. 6 for the case of one, two, and three relaying nodes. In comparison with EGC-based AF and DF, we observe that the proposed scheme achieves a lower BER. In addition, one observes that utilizing more relays results in further improvement in performance.

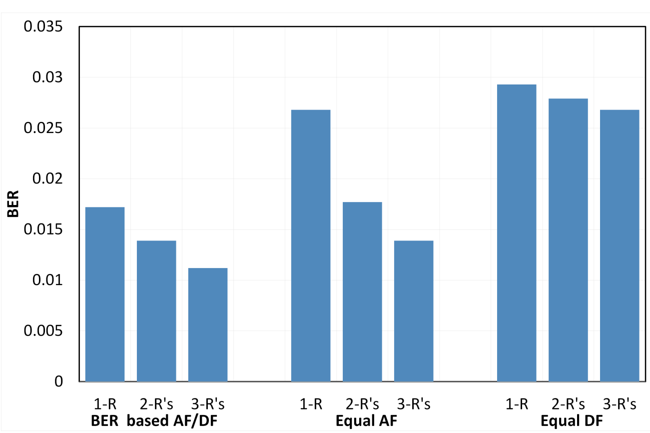

Fig. 6. Experimental results with multiple relaying nodes.

V. Conclusion and Future Work

We have presented an efficient cooperation framework for multi-relay networks using error estimation codes. The relaying framework uses the EEC-based BER estimates to perform relaying strategy selection, as well as to develop a signal combining scheme at the destination. A key feature of the proposed framework is that it does not require any coordination between the network nodes with respect to the selection of the relaying strategy. We evaluate the performance of our scheme through simulations as well as testing it on a USRP-1 based platform, and show that it outperforms traditional AF and DF that employ EGC at the destination. In future, we plan to expand the framework using error correction codes and multi-user networks. We also plan to test the scheme on a Wi-fi based test-bed, where the traffic nature is bursty and see its efficiency in cases of packet collisions.

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References

[1] A. Sendonaris, E. Erkip, and B. Aazhang,“User cooperation diversity – Parts I & II,” *IEEE Transactions on Communications,* vol. 51, pp. 19271948, Nov. 2003.

[2] M. Valenti and B. Zhao, “Distributed turbo coded diversity for the relay channel,” *IEE Electronics Letters*, vol. 39, pp. 786-787, May 2003.

[3] A. Høst-Madsen and J. Zhang, “Capacity bounds and power allocation for the wireless relay channel,” *IEEE Trans. Inform. Theory*, vol. 51, pp. 2020–2040, June 2005.

[4] Binbin Chen, Ziling Zhou, Yuda Zhao, Haifeng Yu, “Efficient Error Estimating Coding: Feasibility and Applications,” *Proceedings of ACM SIGCOMM*, Sept. 2010.

[5] M. Uppal, G. Yue, X. Wang, and Z. Xiong, “A rateless coded protocol for half-duplex wireless relay channels,” *IEEE Transactions on Signal Processing*, Jan. 2011.

[6] C. La Palombara, V. Tralli, B. Masini, and A. Conti, “Relay-assisted diversity communications,” *IEEE Transactions on Vehicular Techology,*, Jan 2013.

[7] P. Murhpy and A. Sabharwal, ”Design, implementation, and characterization of a cooperative communication system,” *IEEE Transactions on Vehicular Technology*, July 2011.

[8] J. Zhang, J. Jia, Q. Zhang, and E. Lo, “Implementation and evaluation of cooperative communication schemes in software-defined radio testbed,” in *Proc. IEEE INFOCOM*, March 2010.

[9] G. Bradford and J. Laneman, ‘An experimental framework for evaluating cooperative diversity,” in *Proc. CISS*, March, 2009.

[10] P. Zetterberg, C. Mavrokefalidis, A. Lalos and E. Matigakis, “Experimental investigation of cooperative schemes on a real-time DSP-based testbed,” *EURASIP Journal on Wireless Communications and Networking - Special Issue on Cooperative Communications in Wireless Networks*, Feb. 2009.

[11] Michael Rice, “Digital Communications - A Discrete-Time Approach,” Prentice Hall, April. 2008.

[12] Salama S.Ikki and Mohamed H. “Performance of Cooperative Diversity Using Equal Gain Combining(EGC) over Nakagami-m Fading Channels,” *IEEE Transaction on Wireless Communications*, Feb. 2009.

[13] USRP-1, “Ettus-Research Product Details,” Internet https://www.ettus.com/product/details/USRPPKG, 2013. [Sep. 15, 2013]

[14] Michael Schwall and Sebastian Koslowski, “KIT – University of the State of Baden-Wuerttemberg and National Research Center of the Helmholtz Association,” Internet http://www.cel.kit.edu/english/simulink-uhd.php, 2012. [Sep. 1, 2013]