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# Retransmission Strategies for Symmetric Relaying Using Superposition Modulation

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**Abstract**—In this paper, we study retransmission strategies for the symmetric relaying scenario when the number of retransmissions for a data packet is limited. We propose a retransmission scheme based on superposition modulation and give the exact packet drop probability expression for it when only one retransmission is allowed. We compare the performance of the proposed retransmission scheme with retransmission schemes based on classical decode-and-forward (DF) relaying and non-cooperative transmission. When only two retransmissions are allowed, the proposed scheme has a performance gain of 3 dB in SNR over the retransmission scheme based on classical DF relaying. Through simulations, we also study the effect of varying the superposition ratio for the retransmissions.

## I. INTRODUCTION

Cooperative diversity introduced in [1], [2] is a promising technique to provide spatial diversity in wireless systems. In a cooperative wireless system, users share their resources to forward each others data to the destination. Usually the cooperating users are geographically separated, and hence their transmit antennas can form a distributed antenna array and thereby provide transmit diversity. Several protocols have been developed in the literature for the operations at a relay. These are mainly classified into amplify-and-forward (AF) and decode-and-forward (DF) schemes [3]. A DF based cooperative transmission scheme based on superposition modulation has been proposed in [4] for the symmetric relaying scenario, where two peer nodes A and B both have data to send to a common destination D. See Fig. 1. In this scheme, each user forwards the other users' overheard data using superposition modulation. This method of user cooperation has shown to be more bandwidth efficient than classical DF relaying with the same receiver complexity. This idea has been extended to the code domain in [5] and resulted in further improvement in the performance, however this method requires carefully chosen codes and more complex iterative receivers. Because of its simplicity, we limit ourselves to the superposition in the modulation domain.

Fading in wireless channels results in the loss of data packets at the receiver. When a feedback channel from the receiver to the transmitter is available, automatic repeat request (ARQ) protocols are used in wireless networks to combat the effects of channel fading and thereby to provide reliable data transfer. One such ARQ mechanism is to append error detection bits to

the data packet and transmit it. After receiving the data packet, the receiver checks for errors in the received data. If there are errors, the receiver sends a negative-acknowledgment (NACK) signal on the feedback channel asking for a retransmission. If the packet is received without any errors, it sends an acknowledgment (ACK) signal to the transmitter. However, ARQ schemes suffer from reduction in throughput. In hybrid-ARQ (H-ARQ) schemes, throughput performance is improved by combining conventional ARQ mechanisms with forward error correction (FEC) schemes. More details about different types of H-ARQ schemes can be found in [6].

Conventional H-ARQ schemes can be easily extended to relaying systems. Several retransmission protocols exist in the literature for a single-relay network [7], [8] as well as for multi-relay networks [9]. In these protocols, depending on the availability of feedback at the relay(s), either only the source or both the source and the relay(s) can manage a retransmission. An upper bound on the block error rate of a cooperative DF relaying system with the general hop-by-hop H-ARQ transmission was derived in [10].

In this work, we discuss retransmission mechanisms for the symmetric relaying scenario when the maximum number of retransmissions ( $L$ ) for a data packet is fixed. We propose a retransmission scheme based on the superposition modulation of [4] and compare its performance with that of a non-cooperative retransmission scheme and a retransmission scheme based on classical DF relaying. In Section IV, we give a closed-form expression for the packet drop probability of the proposed scheme when only one retransmission is allowed. The simulation results in Section V show that the proposed retransmission scheme has significant performance gains over the retransmission scheme based on classical DF relaying.

## II. SYSTEM MODEL

In this section, we introduce the system model along with the three transmission methods considered in this paper. The symmetric relaying scenario is shown in Fig. 1, where two nodes A and B want to communicate with a common destination D. We consider only time-division half-duplex systems with nodes transmitting in orthogonal time slots. We assume that we are interested in decoding node A's data at D. We also assume that the duration of time slots is the same for both the users. Let  $s_{i_k}$  denote the  $k^{\text{th}}$  data packet of node  $i$ ,  $k \in \{1, 2, \dots\}$  and  $i \in \{A, B\}$ . Each data packet consists of a set of modulation symbols obtained from a fixed constellation  $\mathcal{S}$ . We assume that there are  $T$  channel uses

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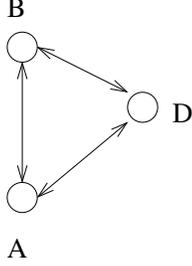


Figure 1. Symmetric relaying scenario.

per transmission and that we transmit one modulated symbol per channel use. Without loss of generality, for simplicity, we assume that the modulated symbols have unit energy. We consider a block fading channel in which the channel gains are constant during one transmission and change independently between the (re)transmissions. Let  $h_{ij}^t$  denote channel gain from  $i \rightarrow j$ ,  $i \in \{A, B\}$  and  $j \in \{B, D\}$  during time slot  $t$ . We assume that these channel gains are independent and Rayleigh fading with perfect channel state information (CSI) available at the corresponding receivers. We assume that  $\mathbb{E}|h_{ij}^t|^2 = \lambda_{ij}$ ,  $\forall t$ . We also assume that the nodes A and B can transmit with average powers  $P_A$  and  $P_B$  respectively. Now we describe the transmission schemes considered in this paper, illustrated in Fig. 2.

#### A. Non-cooperative Transmission

In a non-cooperative transmission, at time slot  $2k - 1$ , node A transmits its packet  $s_{A_k}$ , and in time slot  $2k$  node B transmits its data packet  $s_{B_k}$ .

#### B. Classical DF Relay Transmission

In a conventional DF relay transmission, during the first half of time slot  $2k - 1$ , node A transmits its data packet  $s_{A_k}$  and at the same time node B tries to decode  $s_{A_k}$ . If the decoding at node B is successful, it relays  $s_{A'_k}$  (can be re-encoded) during the remaining half of the time slot. During time slot  $2k$ , the procedure is repeated for the packet  $s_{B_k}$ .

#### C. Superposition Modulated Cooperative Transmission

In the superposition modulation based cooperation [4], along with its own data, each node forwards the data overheard from other node in the previous time slot using superposition modulation. The amount of superposition is varied by the superposition ratio  $\gamma^2$ , which is the fraction of the total transmit power allocated for the partner's data. During time slot  $2k - 1$ , node A transmits its own packet  $s_{A_k}$  superimposed with node B's packet  $s_{B'_{k-1}}$  which it has received during the previous time slot. The received signals at nodes D and B during time slot  $2k - 1$  can be written as:

$$\begin{aligned} y_{D2k-1} &= \sqrt{P_A} h_{AD}^{2k-1} \left( \sqrt{1 - \gamma^2} s_{A_k} + \gamma s_{B'_{k-1}} \right) + w_{D2k-1} \\ y_{B2k-1} &= \sqrt{P_A} h_{AB}^{2k-1} \left( \sqrt{1 - \gamma^2} s_{A_k} + \gamma s_{B'_{k-1}} \right) + w_{B2k-1} \end{aligned} \quad (1)$$

where  $w_{D2k-1}$ ,  $w_{B2k-1}$  denote the additive noise at nodes D and B during time slot  $2k - 1$ . Node B decodes  $s_{A_k}$  using

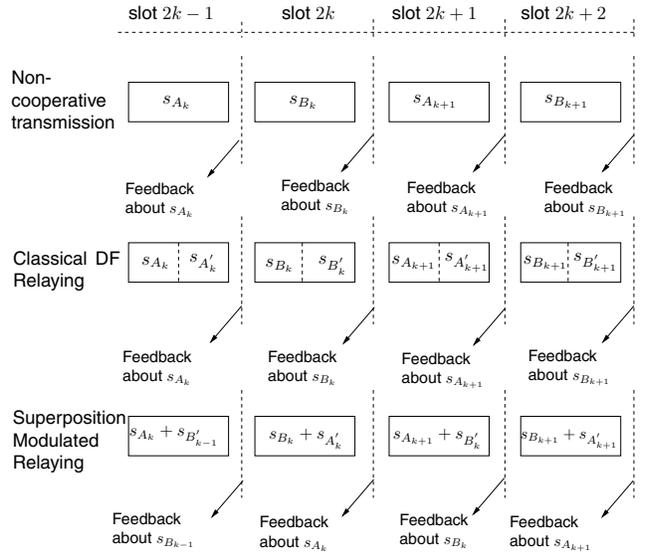


Figure 2. The three transmission methods considered for the symmetric relaying scenario.

a maximum a posteriori (MAP) detector as described in [4]. Assuming successful decoding of  $s_{A_k}$ , node B transmits  $s_{A'_k}$  using the superposition modulation along with its data packet  $s_{B_k}$  in time slot  $2k$ . The received signals at nodes D and A during the time slot  $2k$  can be written as:

$$\begin{aligned} y_{D2k} &= \sqrt{P_B} h_{BD}^{2k} \left( \sqrt{1 - \gamma^2} s_{B_k} + \gamma s_{A'_k} \right) + w_{D2k} \\ y_{A2k} &= \sqrt{P_B} h_{AB}^{2k} \left( \sqrt{1 - \gamma^2} s_{B_k} + \gamma s_{A'_k} \right) + w_{A2k} \end{aligned} \quad (2)$$

where  $w_{D2k}$ ,  $w_{A2k}$  denote the additive noise at nodes D and A during time slot  $2k$ . The destination node recovers  $s_{A_k}$  corresponding to node A using a MAP detector by operating on the information received during the two successive slots  $2k - 1$  and  $2k$  [4]. We assume that the noise samples per channel use at nodes A, B and D are i.i.d.  $\mathcal{CN}(0, N_0)$ .

### III. RETRANSMISSION SCHEMES

In this section, we present the retransmission scheme based on superposition modulation for the symmetric relaying scenario. Before that, we briefly describe a retransmission scheme for the non-cooperative transmission as well as a retransmission scheme based on DF relaying. We chose these base retransmission schemes from [7] and adopted them for the symmetric relaying scenario. We consider a type-II H-ARQ scheme with chase combining, i.e., all the retransmissions carry the same information and the receiver performs maximal-ratio-combining (MRC) to decode the data packet. We assume that the ACK/NACK signals sent by D are received both by node A and node B and that the feedback channel is instantaneous and error-free. The source node (A in the present case) maintains a retransmission index counter  $l$  and increments it for each new retransmission. When  $l$  is greater than  $L$ , it drops the current packet and moves to the next one.

In a non-cooperative retransmission protocol, node A retransmits the erroneously received packet in its allocated slots (odd time slots in Fig. 2) until it receives an ACK signal or

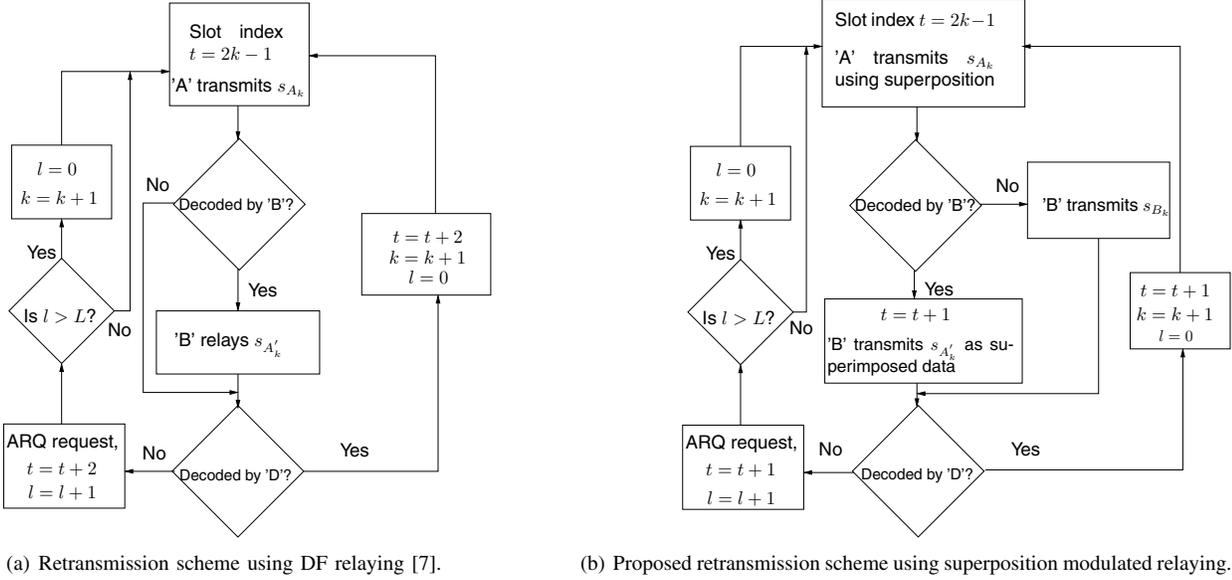


Figure 3. Flowcharts for the retransmission schemes based on DF relaying and superposition modulation based relaying.

it reaches the maximum retransmissions limit. Note that node B does not contribute to the retransmission mechanism here. Fig. 3(a) shows the flowchart of a retransmission scheme based on DF relaying. After getting the NACK signal from node D for its packet  $s_{A_k}$  transmitted during the slot  $2k - 1$ , node A retransmits it during the first half of the odd time slots and node B also relays  $s_{A'_k}$  during the other half of the odd time slots. In this scheme, both node A and node B retransmit the data packet of node A which was in error.

#### A. Proposed Retransmission Scheme

Fig. 3(b) summarizes the proposed retransmission scheme using the superposition modulation based relaying. If the packet  $s_{A_k}$  is in error, node A will retransmit the same packet during the odd time slots and superimpose node B's data that it received during the previous slot. During the even time slots, node B will transmit its own packet (new packet or a retransmitted packet) as well as node A's packet  $s_{A'_k}$  using superposition modulation. This procedure is continued until  $s_{A_k}$  is successfully decoded by node D or  $l$  reaches its limit. The proposed retransmission scheme with superposition relaying has the same complexity as that of the retransmission scheme based on DF relaying. In the retransmission schemes based on DF relaying and superposition modulated relaying which use node B for relaying, we assume that the source node sends a new packet flag bit with each data packet to enable node B to distinguish between a new packet or a retransmitted packet. Based on this information, node B will try to decode the retransmitted packet from node A only if it was not successfully decoded during the previous (re)transmissions.

#### IV. PACKET DROP PROBABILITY ANALYSIS

In this section, we give the packet drop probability ( $P_{\text{drop}}^L$ ) expressions for the proposed scheme after the first transmission and when only one retransmission is allowed. In

the analysis, we assume repetition coding during the relay operation. We omit the proofs because of space constraints. We use outage events to characterize whether node D sends a NACK/ACK signal after a transmission. A transmission link with received signal-to-noise-ratio (SNR)  $\beta$  and a target spectral efficiency of  $\eta$  bits per channel use (bpcu) is in outage if the instantaneous spectral efficiency<sup>1</sup> given by  $I \triangleq \log_2(1 + \beta)$  is smaller than  $\eta$ , and the probability of outage event can be written as:

$$P_{\text{out}} \triangleq \Pr(I < \eta) \quad (3)$$

Let  $I_{xy}$  denote the spectral efficiency along the path  $x \rightarrow y$  during the first transmission and let  $I_{MRC}(xy^l)$  denote the spectral efficiency at node  $y$  after the MRC as a function of  $xy^l$ , i.e., the average mutual information it received along path  $x \rightarrow y$  in the  $l^{\text{th}}$  retransmission. Note that  $l = 0$  corresponds to the first transmission,  $I_{MRC}(xy^0) = I_{xy}$ . When considering the links  $A \rightarrow D$  and  $B \rightarrow D$ , we assume that the transmitters perform "dirty paper" coding, treating the superimposed data stream as known interference [11]. Under this assumption, as an example, we write  $I_{AD} = \log_2(1 + P_A(1 - \gamma^2)\alpha_{AD})$ , where  $\alpha_{AD} = \frac{|h_{AD}|^2}{N_0}$ . Without loss of generality, in the further analysis we assume that  $N_0 = 1$  and hence  $f_{\alpha_{ij}}(t) = \frac{1}{\lambda_{ij}} \exp\left(-\frac{t}{\lambda_{ij}}\right)$ ,  $t \geq 0$ .

#### A. Derivation of $P_{\text{drop}}^0$

When there are no retransmissions ( $L = 0$ ) allowed, the packet drop probability can be written as:

$$P_{\text{drop}}^0 = \Pr(I_{AB} < R) \Pr(I_{AD} < R) + \Pr(I_{AB} > R) \Pr(I_{MRC}(AD^0, BD^0) < R) \quad (4)$$

where  $R$  is the target spectral efficiency in bpcu. If  $N_I$  is the number of information bits, then  $R = \frac{N_I}{T}$  bpcu. We can

<sup>1</sup>Assuming an infinite block length and a Gaussian code book.

$$P_{\text{drop}}^0 = \begin{cases} [1 - \exp(X_{AD})][1 - \exp(X_{AB})] + \exp(X_{AB}) \times \\ \left[1 - \exp(X_{BD}) - \frac{\exp(X_{AD})}{\delta} (1 - \exp(X_{BD}\delta))\right], & \text{if } \rho \neq 1 \\ [1 - \exp(X_{AD})][1 - \exp(X_{AB})] + \exp(X_{AB}) \times \\ [1 - \exp(X_{BD}) + X_{BD} \exp(X_{AD})], & \text{if } \rho = 1 \end{cases} \quad (5)$$

$$P_{\text{drop}}^1 = \begin{cases} \left\{ [1 - \exp(X_{AD})(1 - X_{AD})][1 - \exp(X_{AB})(1 - X_{AB})] - \right. \\ X_{AB} \exp(X_{AB}) \left[1 - \exp(X_{BD}) + \frac{\exp(X_{AD})(X_{AD}-1)}{\delta} (1 - \exp(X_{BD}\delta))\right] + \\ \rho \exp(X_{AD}) \left(\exp(X_{BD}\delta) \left(\frac{X_{BD}}{\delta} - \frac{1}{\delta^2}\right) + \frac{1}{\delta^2}\right) \left. \right\} + \\ \exp(X_{AB}) \left[1 - \exp(X_{BD})(1 - X_{BD}) + \exp(X_{AD})(X_{AD}-1) \times \right. \\ \left. \left(\exp(X_{BD}\delta) \left(\frac{X_{BD}}{\delta} - \frac{1}{\delta^2}\right) + \frac{1}{\delta^2}\right) + \right. \\ \left. \rho \exp(X_{AD}) \left(\exp(X_{BD}\delta) \left(-\frac{X_{BD}^2}{\delta} + \frac{2X_{BD}}{\delta^2} - \frac{2}{\delta^3}\right) + \frac{2}{\delta^3}\right) \right], & \text{if } \rho \neq 1 \\ [1 - \exp(X_{AD})(1 - X_{AD})][1 - \exp(X_{AB})(1 - X_{AB})] - \\ X_{AB} \exp(X_{AB}) \left[1 - \exp(X_{BD}) - \exp(X_{AD})(X_{AD}-1)X_{BD} + \frac{\exp(X_{AD})X_{AD}X_{BD}}{2}\right] + \\ \exp(X_{AB}) \left[1 - \exp(X_{BD})(1 - X_{BD}) + \right. \\ \left. \exp(X_{AD})(X_{AD}-1) \frac{X_{BD}^2}{2} - \frac{\exp(X_{AD})X_{AD}X_{BD}^2}{3} \right], & \text{if } \rho = 1 \end{cases} \quad (8)$$

simplify (4) to arrive at (5) shown on top of this page, in which  $X_{AB} = \frac{1-2^R}{P_A(1-\gamma^2)\lambda_{AB}}$ ,  $X_{BD} = \frac{1-2^R}{P_B\gamma^2\lambda_{BD}}$ ,  $X_{AD} = \frac{1-2^R}{P_A(1-\gamma^2)\lambda_{AD}}$  and  $\delta = 1 - \rho$  with  $\rho = \frac{P_B\gamma^2\lambda_{BD}}{P_A(1-\gamma^2)\lambda_{AD}}$ . By using a series expansion, it can be shown that

$$P_{\text{drop}}^0 = X_{AD}X_{AB} + \frac{1}{2}X_{AD}X_{BD} + O\left(\frac{1}{P^3}\right) \quad (6)$$

From (6), we see that the superposition modulated relaying scheme has a diversity order of 2.

### B. Derivation of $P_{\text{drop}}^1$

When only one retransmission ( $L = 1$ ) is allowed, the packet drop probability can be expressed as:

$$P_{\text{drop}}^1 = \Pr(I_{MRC}(AB^0, AB^1) < R) \Pr(I_{MRC}(AD^0, AD^1) < R) + \\ \Pr(I_{AB} < R, I_{MRC}(AB^0, AB^1) > R) \times \\ \Pr(I_{MRC}(AD^0, AD^1, BD^1) < R) + \\ \Pr(I_{AB} > R) \Pr(I_{MRC}(AD^0, AD^1, BD^0, BD^1) < R) \quad (7)$$

By simplifying (7), we arrive at the expression shown in (8) on top of this page. We can show that using a series expansion,  $P_{\text{drop}}^1$  can be written as:

$$P_{\text{drop}}^1 = \frac{1}{4}X_{AD}^2X_{AB}^2 + \frac{1}{6}X_{AB}X_{AD}^2X_{BD} + \frac{1}{24}X_{BD}^2X_{AD}^2 + O\left(\frac{1}{P^5}\right) \quad (9)$$

From (9), we see that with one additional retransmission, a diversity order of 4 can be achieved with the proposed superposition modulation based retransmission scheme.

## V. SIMULATION RESULTS

In this section, first we compare the analytical packet drop probability expressions given in Section IV with empirical results. Fig. 4 shows the comparison of analytical and

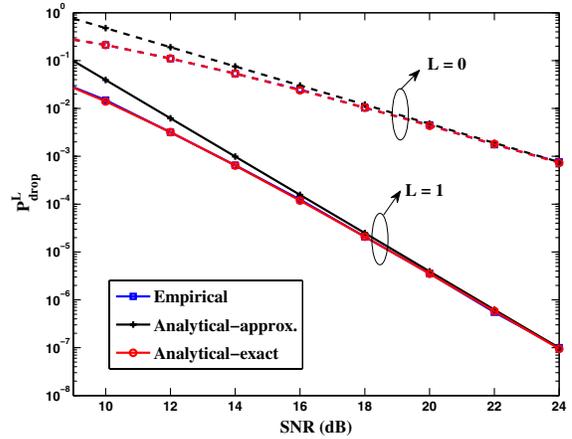


Figure 4. Analytical and empirical performance comparison of the packet drop probability for the superposition modulated relaying. Parameters for the simulation are  $R = 2$  bpcu,  $\lambda_{AD} = \lambda_{BD} = \lambda_{AB}$ ,  $P_A = P_B = 0$  dB and  $\gamma^2 = 0.15$ . Empirical curves are obtained by generating the random channel gains and numerically computing the probabilities using (4) and (7). For analytical-exact curves, we used the expressions in (5) and (8) to compute the packet drop probability. Analytical-approx. curves are high-SNR approximations obtained by neglecting  $O\left(\frac{1}{P^3}\right)$  and  $O\left(\frac{1}{P^5}\right)$  terms in (6) and (9) respectively.

empirical results for  $P_{\text{drop}}^L$ . We have used  $R = 2$  bpcu,  $\lambda_{AD} = \lambda_{BD} = \lambda_{AB}$ ,  $P_A = P_B = 0$  dB in the simulation. As in [4], superposition ratio  $\gamma^2$  was set to 0.15 (it may not be optimal in the outage probability sense). From the figure, we see that the analytical result matches closely with the empirical result and the approximation result is also tight for SNR values higher than 15 dB.

Fig. 5 shows a comparison of  $P_{\text{drop}}^L$  for different values of  $L$ . We used a (1000, 3, 6) LDPC code (with block length 1000 and rate  $r = 1/2$ ) for the simulation. BPSK modulation was used for the non-cooperative transmission and the transmis-

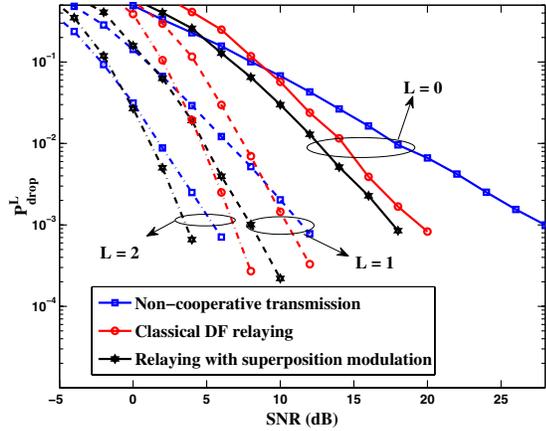


Figure 5. Packet drop probability comparison of various schemes for different values of  $L$ . We used a (1000, 3, 6) LDPC code with a 24 bit CRC code for error detection. Same value of  $\gamma^2$  was used for all the transmissions.

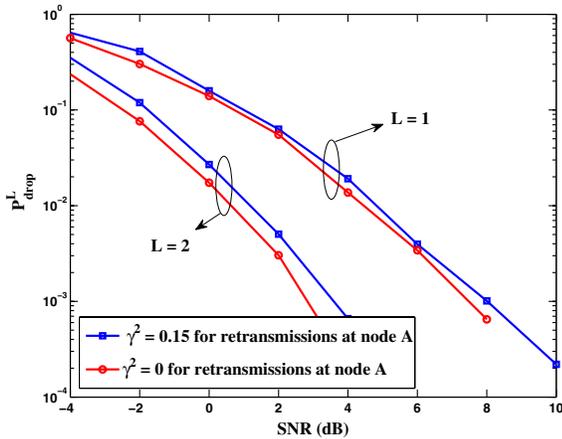


Figure 6. Packet drop probability comparison with  $\gamma^2 = 0$  and with  $\gamma^2 = 0.15$  at node A during retransmissions. Simulation parameters are similar to the ones in Fig. 5.

sion using superposition modulation, and 4-PAM modulation was used for the DF relaying scheme. The information bits were appended with a 24 bit CRC code for error detection. Repetition coding was used at the relay for DF operation. We set the superposition ratio value to  $\gamma^2 = 0.15$  and used the same value of  $\gamma^2$  for all the retransmissions. For  $L = 0$  and at a packet drop probability of  $10^{-3}$ , relaying with superposition modulation has a performance gain of 1.8 dB compared to the classical DF relaying. This result is in agreement with the results in [4]. When  $L = 1$  and 2, the performance difference between relaying with superposition modulation and DF relaying is 2.5 dB and 3 dB respectively. Another important observation is that, with  $L = 2$  and at a packet drop probability of  $10^{-3}$ , the non-cooperative retransmission scheme is performing better than the retransmission with DF relaying. This is due to the fact that the target spectral efficiency of the DF based scheme is double that of non-cooperative scheme and that the diversity advantage for DF based scheme is coming into picture only for packet drop probability values smaller than  $10^{-4}$ .

Next we present a simulation result for the case in which node A transmits its own packet without superimposing the partners data during the retransmission. The motivation for this simulation is that, in case the receiver can send additional feedback about the reliability of the previous transmissions, the transmitter can adjust its superposition ratio during the retransmissions. Fig. 6 shows the performance comparison of the packet drop probability, for the case when node A does not superimpose node B's data during the retransmissions compared to the case in which node A superimposes node B's data during retransmissions. We see that, when  $L = 2$ , making  $\gamma^2 = 0$  for retransmissions can only provide a marginal gain of 0.5 dB at a packet drop probability of  $10^{-3}$ . This suggests that with the proposed retransmission scheme, even during retransmissions, node A can still cooperate with node B without significant degradation in its performance.

## VI. CONCLUSIONS AND DISCUSSION

The proposed retransmission scheme based on the superposition modulation based relaying of [4] can provide gains over a non-cooperative retransmission scheme even in cases where a retransmission scheme based on DF relaying has inferior performance compared to a non-cooperative retransmission scheme. With the proposed method for the symmetric relaying scenario, nodes can still cooperate with each other even when their packets are received in error, without significantly losing performance. Based on closed-form expressions for the packet drop probability (see Section IV), one can numerically optimize the superposition ratio  $\gamma^2$  in [4]. A similar theoretical performance analysis for incremental redundancy based HARQ schemes remains for future work.

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