Cooperative Diversity Based on Code Superposition

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***Abstract*— This paper proposes a new approach to cooperative diversity based on the superposition of channel codes over a finite field. The scenario under consideration is one in which two "partners" – Node A and Node B – cooperate in transmitting information to a single destination; each partner transmits both locally-generated information and relayed information that originated at the other partner. A key observation is that Node B already knows Node A's relayed information (previously sent from Node B) and can exploit that knowledge when decoding Node A's local information. This leads to an encoding scheme in which each partner transmits the superposition of its local and relayed information, and the superimposed codeword is interpreted differently at the two receivers – i.e., at the other partner and at the destination node – based on their different *a priori* knowledge. It is shown via simulation that the proposed scheme provides substantial coding gain over other cooperative diversity techniques, including those based on time sharing and signal (Euclidean space) superposition.**

I. Introduction

Wireless data links are often error prone due to multipath fading. Diversity offers an effective countermeasure against channel fading by providing the receiver with multiple "looks" at the same information – different versions of the data transmitted with (ideally) independent channel gains [1, Chapter 14]. In a system employing *cooperative diversity*, this robustness is obtained by allowing a node to both transmit its own information *and* to serve as a relay for the data transmitted by the other node(s). Because information is transmitted multiple times – once from the originating node and then again from the relaying node(s) – diversity is effected [2]–[6].

Consider, for example, a system in which two source nodes are paired as "partners" for the transmission of their data to a common destination node; each partner transmits both its own *local information* as well as the *relayed information* it has received from its partner. In the cooperative diversity systems proposed up to now, some kind of mechanism is used to split the transmitter's resources between locally generated bits and relayed bits. For instance, the systems in [3]–[5] propose time division multiplexing in which each partner uses a portion of its time slot for local information and the rest for relayed information. In contrast, in [2] and [6], the superposition (in Euclidean space) of modulated signals is used to multiplex local and relayed bits in the context of direct sequence spread spectrum modulation and unequal error protected modulation, respectively.

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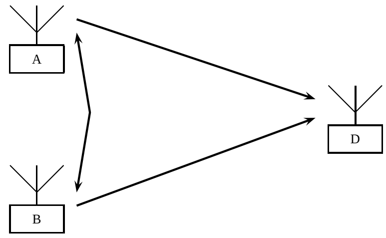

Fig. 1. In cooperative diversity, nodes A and B work in collaboration to deliver their packets to a common destination node D.

A key observation with respect to such a system is that the relayed information transmitted by one partner is already known to the other partner; after all, that is where the relayed information originated. From this perspective, the resources allocated to transmitting the relayed bits from one partner to the other are wasted; those resources would be better used for sending *local* information from one partner to the other. This leads to what we call the *cooperative dilemma:* by allocating resources to relay cooperation, the existing designs reduce the likelihood of *successful* cooperation by taking resources away from the vital partner-to-partner transmission of local information.

Based on this observation, we propose a new system design that makes efficient use of resources on both the partner-to-partner links and the partner-to-destination links. The main idea is for each partner to superimpose – for binary codes, to take the XOR of – the local codeword and the relayed codeword and then transmit the resulting superimposed codeword. The destination node decodes the received packet as a "nested" codeword with both information vectors as unknowns. The partner node, with its knowledge of the relayed codeword, views the XOR as a kind of "scrambling" and only needs to decode what it does not know after cancelling the relayed codeword from the received signal. In such an approach, no resources are used exclusively for the transmission of relayed information from one partner back to the other partner that originated the information. Consequently, significant performance gain is obtained by increasing the probability of successful collaboration.

The rest of this paper is organized as follows. The system model and an overview of existing designs are provided in Section II. The proposed transceiver structures are described in Section III. Code search and simulation results are presented in Section IV and conclusions are drawn in Section V.

II. Cooperative Diversity and the Cooperative Dilemma

The scenario addressed in this paper is depicted in Figure 1. Two source nodes A and B work in cooperation to deliver

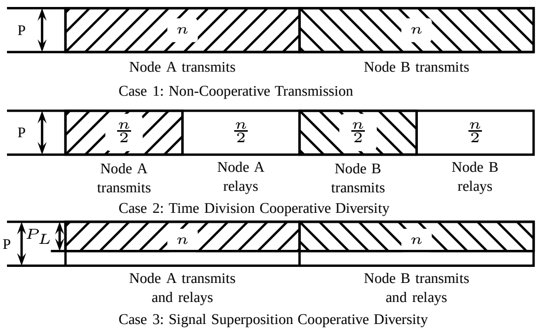

Fig. 2. The frame structures of several designs and the resources used to protect the link between Node A and Node B.

TABLE I
NOTATION SUMMARY

	Time t first half	Time t second half
Transmission	$A \rightarrow B, D$	$B \rightarrow A, D$
Codeword	$C^A(t)$	$C^B(t)$
Own Information	$i_L^A(t)$	$i_L^B(t)$
Relayed Information	$i_R^A(t) = \pi\big(i_L^B(t-1)\big)$	$i_R^B(t) = \pi\big(i_L^A(t)\big)$

their packets of k bits each to a common destination node D. We refer to nodes A and B as each other's partner. During time slot t, Node A transmits in the first half slot, while Node B transmits in the second half slot. Each source node receives the frame sent by its partner node and attempts to decode its partner's information. If the decoding is successful, then some of this information – the part that originated at the partner – will be relayed in a future transmission to provide the destination D with spatial diversity. If a source node fails to decode its partner's information, and therefore does not have information to relay, then that source node will operate in a non-cooperative mode.

By symmetry, we can focus on packets that originate at Node A. There can be no diversity at the destination node if the packets originating at Node A are not received correctly at Node B; this illustrates the importance of $P_{A,B}$, the packet error rate for the link between A and B. Since the diversity order determines the slope of the error curves [1, Chapter 14], it is desirable to have a small $P_{A,B}$ to increase the likelihood of Node A being assisted by its partner node.

The frame structures of three different cooperative diversity designs are shown in Figure 2. The shaded portions of the figure represent the resources dedicated to the transmission of local information from one partner to the other. It is assumed each source node generates k bits of local data per time slot and the channel resources available during a half-slot are n transmitted bits with a transmit power of P.

- In the non-cooperative configuration, nodes A and B transmit their own information in turn during each slot. If the source nodes want to decode each other's information in this case, the information bits may be protected by a rate k/n code with full power – the best level of protection a node can offer its partner.
- In a time division based cooperative scheme [3]–[5], each source node uses part of its transmission time to act as a relay for its partner. A node's relayed information, originally generated at the partner node, is of no use to the partner node. Hence, for example, when B tries to obtain A's information, it only needs to demodulate and decode the half of A's frame that contains A's locally generated bits. Because A must transmit $2k$ bits – k local and k relayed – the channel code must be of rate $2k/n$ and full power may be used during transmission.
- In a cooperative scheme based on signal superposition [2], [6], the modulated signal for a relayed codeword is added to the modulated signal for the locally generated codeword. The partner node, with knowledge of the relayed bits, can subtract the portion of the signal due to the relayed codeword from the received signal and decode the locally generated information bits. Since part of the power has been used to modulate the relayed codeword, which is later subtracted at the partner node, each source node decodes its partner's information based on a rate k/n code but with only partial power P_L.

The above analysis indicates that, in the existing cooperative diversity schemes, the transmission of a source node's local information to its partner is carried out with diminished resources – either a higher code rate or less power – compared to the non-cooperative approach. Since higher code rates and lower power imply a higher probability of error, the packet error rate $P_{A,B}$ between A and B necessarily increases when resources are allocated for relay cooperation under the existing designs. Because $P_{A,B}$ is, effectively, the probability that Node B will not be able to supply diversity about Node A's local information to the destination, we have this apparent conundrum: the extent to which a user dedicates resources to cooperation reduces the probability that the cooperation is successful.

We refer to this as the *cooperative dilemma*. This dilemma is explained by the fact that a source node must deliver its own packet and a relayed packet to the destination node, but only its own packet is required at the partner node. When transmission time and/or power are divided, the portion of those resources allocated to the relayed information is wasted from the perspective of the partner node. In the next section, we solve this cooperative dilemma with a new system design that allows the partner node and the destination node to carry out the decoding operation at different *effective code rates*.

III. NEW SYSTEM DESIGN

The notation used in characterizing the new system design is summarized in Table I. Let $i_L^A(t)$ denote the local information vector originating at Node A for transmission during time slot t, and let $i_R^A(t)$ denote the relayed information vector transmitted by Node A during the same time slot. Similarly, for Node B we define $i_L^B(t)$ and $i_R^B(t)$. We assume each source node can determine whether it has successfully decoded the local information vector transmitted by its partner; this can be done either by using a CRC or by employing a soft-decision decoder and using the soft outputs to assess the reliability of the decoded information.

Let $C^A(t)$ and $C^B(t)$ denote the n-bit codeword sent by nodes A and B, respectively, during time slot t. The code

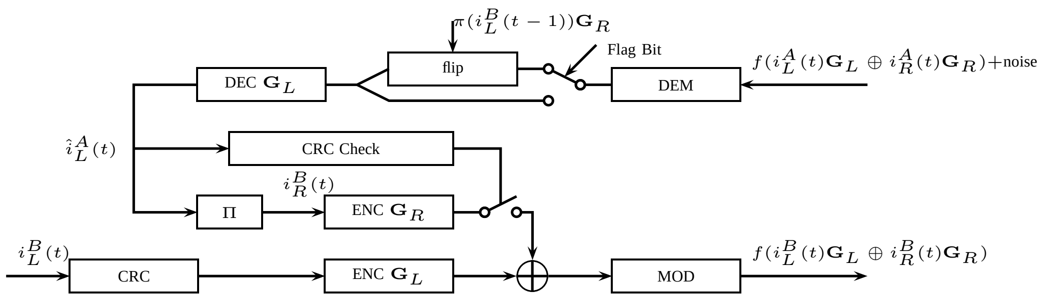

Fig. 3. The transceiver structure at Node B. Soft decoding is assumed and $f(\cdot)$ is the modulation function. The transceiver at Node A is analogous.

generator matrix for the locally generated information bits is $\mathbf{G}_L$ and for the relayed bits is $\mathbf{G}_R$; both codes have rate k/n. Invoking symmetry, we now provide a detailed description of the encoding operation at Node A and the decoding operation at Node B,

A. The Encoder at the Source Nodes

During time slot t, Node A must convey its local information vector $i_L^A(t)$ while relaying Node B's information $i_L^B(t-1)$ – assuming it has decoded $i_L^B(t-1)$ correctly.

If Node A has decoded $i_L^B(t-1)$ successfully, it first interleaves $i_L^B(t-1)$ to generate the relay information, i.e.,

$$i_R^A(t) = \pi(i_L^B(t-1)), \tag{1}$$

and the transmitted codeword is the XOR of the codeword containing Node A's local information and the codeword containing Node B's relayed bits

$$C^A(t) = i_L^A(t)\mathbf{G}_L \oplus i_R^A(t)\mathbf{G}_R = [i_L^A(t)\ i_R^A(t)] \begin{bmatrix} \mathbf{G}_L \\ \mathbf{G}_R \end{bmatrix}. \tag{2}$$

The interleaving in (1) facilitates iterative decoding at the destination node; it guarantees that the destination's decoder for Node B provides extrinsic information to its decoder for Node A that is independent of the other information available to the Node A decoder. Also note that the XOR of two codewords is equivalent to encoding the information vectors $i_L^A(t)$ and $i_R^A(t)$ using a "nested" code with generator matrix $\mathbf{G} \triangleq \begin{bmatrix} \mathbf{G}_L \\ \mathbf{G}_R \end{bmatrix}$, as indicated in (2).

Conversely, if Node A has failed to decode $i_L^B(t-1)$, the transmitted codeword is simply the encoded version of $i_L^A(t)$:

$$C^A(t) = i_L^A(t)\mathbf{G}_L = [i_L^A(t)\ \vec{0}] \begin{bmatrix} \mathbf{G}_L \\ \mathbf{G}_R \end{bmatrix} \tag{3}$$

We assume a "flag bit" is transmitted along with the codeword to alert the receivers which of the two encoding methods ((2) or (3)) was used. (Alternatively, note that (2) and (3) naturally represent two hypotheses, and generalized ML hypothesis testing could be used at the receiver to make that determination.) As will be shown later, Node B can cancel the relayed information $i_R^A(t)\mathbf{G}_R$ and effectively decode only $i_L^A(t)\mathbf{G}_L$.

In an analogous manner, Node B's transmitted codeword is

$$C^B(t) = i_L^B(t)\mathbf{G}_L \oplus i_R^B(t)\mathbf{G}_R = [i_L^B(t)\ i_R^B(t)] \begin{bmatrix} \mathbf{G}_L \\ \mathbf{G}_R \end{bmatrix} \tag{4}$$

if B has decoded $i_L^A(t)$ correctly, where $i_R^B(t) = \pi(i_L^A(t))$, and

$$C^B(t) = i_L^B(t)\mathbf{G}_L = [i_L^B(t)\ \vec{0}] \begin{bmatrix} \mathbf{G}_L \\ \mathbf{G}_R \end{bmatrix} \tag{5}$$

if Node B has failed to decode $i_L^A(t)$.

B. The Decoder at the Source Nodes

The decoder at Node B first checks the "flag bit". If the frame was generated using (3) – i.e., Node A failed to cooperate – then Node B uses the decoder for code $\mathbf{G}_L$ to obtain $i_L^A(t)$. Note that in this case Node B decodes a rate k/n code with full power.

Now suppose the frame was generated using (2), i.e., it represents the XOR of two packets. For hard-decision decoding, the output of the demodulator is

$$\hat{C}^A(t) = C^A(t) \oplus e(t) = i_L^A(t)\mathbf{G}_L \oplus i_R^A(t)\mathbf{G}_R \oplus e(t) \tag{6}$$

where $e(t)$ is the binary error pattern. Note that, because Node B knows $i_R^A(t) = \pi(i_L^B(t-1))$, the codeword $i_R^A(t)\mathbf{G}_R$ can be stripped from the channel decoder input by forming

$$\tilde{C}^A(t) = \hat{C}^A(t) \oplus i_R^A(t)\mathbf{G}_R = i_L^A(t)\mathbf{G}_L \oplus e(t). \tag{7}$$

At this point, the hard-decision decoder for the code $\mathbf{G}_L$ can be used to estimate $i_L^A(t)$ from $\tilde{C}^A(t)$. Note that the *effective code rate* here is k/n.

In the case of soft-decision decoding, the soft demodulator generates the log-likelihood ratio (LLR) of each bit in $C^A(t)$. Let $L[C^A(t)](i)$ denote the LLR of the i-th bit in $C^A(t)$, and let $L[i_L^A(t)\mathbf{G}_L](i)$ denote the (to be determined) LLR of the i-th bit in the codeword $i_L^A(t)\mathbf{G}_L$.

Let $[i_R^A(t)\mathbf{G}_R](i)$ denote the i-th bit in $i_R^A(t)\mathbf{G}_R$. If $[i_R^A(t)\mathbf{G}_R](i)$ is zero, then the i-th bit of $C^A(t) = i_L^A(t)\mathbf{G}_L \oplus i_R^A(t)\mathbf{G}_R$ is the same as the i-th bit of $i_L^A(t)\mathbf{G}_L$. Moreover, if the i-th bit of $i_R^A(t)\mathbf{G}_R$ is one, then i-th bit of $C^A(t)$ is the complement of i-th bit of $i_L^A(t)\mathbf{G}_L$. Recognizing this, we can produce $L[i_L^A(t)\mathbf{G}_L](i)$ from $L[C^A(t)](i)$ and $i_R^A(t)\mathbf{G}_R$ as follows:

$$\begin{aligned} L[i_L^A(t)\mathbf{G}_L](i) &= \log \frac{\mathbb{P}r\{[i_L^A(t)\mathbf{G}_L](i) = 0\}}{\mathbb{P}r\{[i_L^A(t)\mathbf{G}_L](i) = 1\}} \\ &= \begin{cases} L[C^A(t)](i) & \text{when } [i_R^A(t)\mathbf{G}_R](i) = 0 \\ -L[C^A(t)](i) & \text{when } [i_R^A(t)\mathbf{G}_R](i) = 1. \end{cases} \end{aligned} \tag{8}$$

Note the amplitude of $L[i_L^A(t)\mathbf{G}_L](i)$ is identical to that of $L[C^A(t)](i)$. Only the signs of the LLRs are changed based on Node B's knowledge of $\pi(i_L^B(t-1))\mathbf{G}_R$. For this reason,

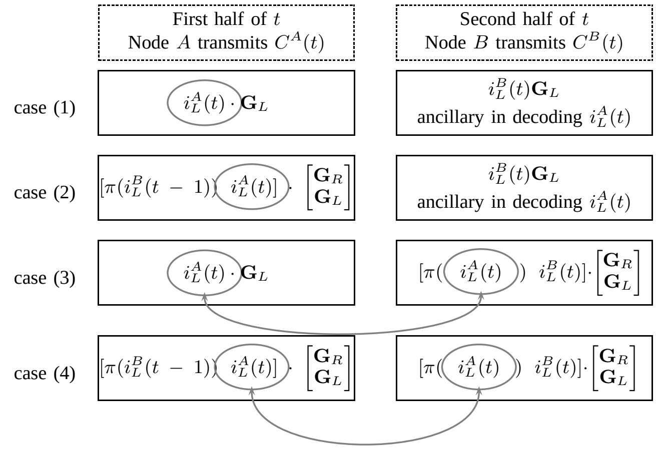

Fig. 4. The decoding operation at Node D for $i_L^A(t)$. In cases (1) and (2), $C_L^B(t)$ does not contain information about $i_L^A(t)$ and is not used in decoding. In cases (3) and (4), iterative decoding is adopted to exploit spatial diversity, represented by the double arrows. The extrinsic information about $i_L^B(t-1)$ received from $C^B(t-1)$ is used as a priori information in cases (2) and (4).

we refer to the operation in (8) as the *flipping operation*. (This operation can be viewed as a special case of the box-plus operation introduced in [7].) In this case, the known information $i_R^A(t)\mathbf{G}_R$ is cancelled from the observed LLRs via the flipping operation. With the LLR for $i_L^A(t)\mathbf{G}_L$ now available, Node B can employ a soft-decision decoder for $\mathbf{G}_L$ to estimate $i_L^A(t)$. Once again, the *effective code rate* is k/n.

In summary, for either hard decoding or soft decoding, the relayed codeword that was XORed with the locally generated codeword can be cancelled prior to decoding, and this operation is transparent to the channel decoder. No resources are wasted, and the useful information to Node B, $i_L^A(t)$, is protected by a rate k/n code with full power P. As a result, the probability of successful cooperation in the new design is higher than that in the time division based approach or the scheme based on signal superposition. The transceiver structure at Node B is shown in Figure 3.

C. The Decoder at the Destination Node

Without loss of generality, consider the decoding of $i_L^A(t)$ at Node D. Note that both $C^A(t)$ and $C^B(t)$ potentially carry information about $i_L^A(t)$: $C^A(t)$ as "local" information and $C^B(t)$ (in interleaved form) as "relayed" information. There are four possible ways that $C^A(t)$ and $C^B(t)$ could have been formed, as illustrated in Fig. 4.

1) Both $C^A(t)$ and $C^B(t)$ were constructed from local information only – i.e., $C^A(t) = i_L^A(t)\mathbf{G}_L$ and $C^B(t) = i_L^B(t)\mathbf{G}_L$. In this case, $C^B(t)$ is not helpful in estimating $i_L^A(t)$. Using a decoder for $\mathbf{G}_L$ to process the noisy version of $C^A(t)$ is sufficient.
2) $C^A(t)$ was constructed from both local and relayed information while $C^B(t)$ was constructed from only local information – i.e., $C^A(t) = i_L^A(t)\mathbf{G}_L \oplus i_R^A(t)\mathbf{G}_R$ and $C^B(t) = i_L^B(t)\mathbf{G}_L$. Once again, $C^B(t)$ is not helpful in estimating $i_L^A(t)$. Note that $i_R^A(t)$ is an interleaved version of $i_L^B(t-1)$, which has already been processed. We can use the extrinsic information about $i_L^B(t-1)$ obtained from $C^B(t-1)$ as *a priori* information for $i_R^A(t)$ and decode $i_L^A(t)$ using a maximum a posteriori probability (MAP) decoder.
3) $C^A(t)$ was constructed from only local information while $C^B(t)$ was constructed from both local and relayed information – i.e., $C^A(t) = i_L^A(t)\mathbf{G}_L$ and $C^B(t) = i_L^B(t)\mathbf{G}_L \oplus i_R^B(t)\mathbf{G}_R$. Iterative decoding can be used to exchange extrinsic information about $i_L^A(t)$ and $i_R^B(t) = \pi(i_L^A(t))$ between $C^A(t)$ and $C^B(t)$ using soft-in-soft-out decoders. An estimate of $i_L^B(t)$ will be made in the next decoding step; we use zero as *a priori* information in the soft decision decoding of $C^B(t)$.
4) Finally, both $C^A(t)$ and $C^B(t)$ were constructed from both local and relayed information – i.e., $C^A(t) = i_L^A(t)\mathbf{G}_L \oplus i_R^A(t)\mathbf{G}_R$ and $C^B(t) = i_L^B(t)\mathbf{G}_L \oplus i_R^B(t)\mathbf{G}_R$. Iterative decoding can be used in this case using the soft-in-soft-out decoder for $\mathbf{G}$. Since $i_R^A(t) = \pi(i_L^B(t-1))$ has already been processed, extrinsic information obtained from $C^B(t-1)$ can be used as *a priori* information in processing $C^A(t)$, while zero *a priori* information is used for $i_L^B(t)$. The soft decoders processing $C^A(t)$ and $C^B(t)$ exchange extrinsic information about $i_L^A(t)$.

Cooperative diversity is obtained with iterative decoding when Node B has relayed $i_L^A(t)$ during its time frame. The decoding of B's packet $i_L^B(t)$ makes use of the observation of both $C^B(t)$ and $C^A(t+1)$.

IV. Code Search and Simulation Results

Although the general framework proposed in Section III is valid for any binary linear code, we constrain the codes $\mathbf{G}_L$ and $\mathbf{G}_R$ to be binary convolutional codes for two reasons. First, the soft-in, soft-out ML and MAP decoders for convolutional codes are simple to implement. Second, convolutional codes can be used as building blocks for capacity achieving codes.

We have the following two observations regarding the choice of code. First, the code $\mathbf{G}_L$ is required to be as strong as possible, since the source nodes decode each other's information using this code. Moreover, if the link from Node A to Node D is in a deep fade, the destination node must make decisions about both A's bits and B's bits based on the codeword $C^B(t) = [i_L^B(t)\, i_R^B(t)]\begin{bmatrix}\mathbf{G}_L\\ \mathbf{G}_R\end{bmatrix}$. It is thus desirable to also make $\mathbf{G} = \begin{bmatrix}\mathbf{G}_L\\ \mathbf{G}_R\end{bmatrix}$ a strong code.

To find good codes, the best known convolutional code for a given rate and constraint length is used for $\mathbf{G}_L$. Then an exhaustive search is carried out among all appropriate choices of $\mathbf{G}_R$ to find the "nested" code $\mathbf{G}$ yielding the largest free distance and fewest number of nearest neighbors among all non-catastrophic encoders. For the simulation results presented below, the optimum 8-state encoder $\mathbf{G}_L = [1, \frac{13}{15}, \frac{17}{15}]_8$ was chosen, and a computer search found that the 8-state encoder $\mathbf{G}_R = [\frac{02}{15}, \frac{07}{15}, 1]_8$ optimized $\mathbf{G}$.

Simulations were carried out to compare the performance of four different approaches by which a pair of source nodes could convey information to a common destination: non-cooperative transmission, cooperative transmission based on time-division multiplexing [4], cooperative transmission based on signal superposition [6], and the cooperative system based on code superposition proposed in this paper. Each packet consisted of $k = 500$ bits. A CRC-12 code was used in the cooperative systems to identify decoding failures. All systems used BPSK modulation, with the exception of the cooperative system based on signal superposition, for which (unequal error protected) 4-PAM was employed. All channels were subject to additive white Gaussian noise (AWGN) plus block Rayleigh fading with the same average power. The channels between different pairs of nodes were assumed to be independent. Moreover, the following assumptions were built into the simulations:

- In the non-cooperative, point-to-point reference system, the rate $1/3$ convolutional code with generator matrix $[15, 13, 17]_8$ was used.
- The same $[15, 13, 17]_8$ code was used as a mother code for the time-division cooperative scheme. To leave half of the transmission period available for relay purposes, this code was punctured to rate $2/3$. If the decoding was successful at the partner node, the punctured bits were recovered and relayed. The destination node D thus decoded either a punctured rate $2/3$ convolutional code or its rate $1/3$ mother code, depending on whether a relayed copy was received or not.
- In the cooperative system based on signal superposition, the locally generated bits were encoded using a recursive convolutional code with generator matrix $[1, \frac{13}{15}, \frac{17}{15}]_8$. If the partner node's information was successfully decoded, these bits were interleaved by an s-random interleaver with spread 13 and re-encoded with the same code. The relay was allocated 15% of the total transmission power, as indicated in [6]. Iterative decoding with ten iterations was adopted at the destination node to exploit diversity if a relayed copy was received.
- An s-random interleaver with spread 13 was used in the newly proposed scheme. Ten iterations were carried out at the destination node.

Figures 5 and 6 show the packet error probabilities and the bit error probabilities for all four systems. Although all the cooperative diversity systems studied have the same error curve slope at high average signal-to-noise ratio (SNR), the merit of the new design is clear. It is observed from Figure 5 that the new system design outperforms the cooperative diversity schemes based on signal superposition and time division by 2 dB and 4 dB, respectively, at a packet error rate of 10^{-3}. In terms of bit error probability, the new design based on code superposition has fewer than half of the bit errors of the signal superposition design at an average SNR of 20 dB. In the low SNR regime, the new design exhibits a steeper slope than the other cooperative design thanks to the superior protection between partner nodes.

V. Conclusion

A novel system design for cooperative diversity that makes efficient use of available resources has been proposed. By transmitting the XOR of the locally generated codeword and the relayed codeword, thereby making possible different effective rates for the decoding at the partner node and the destination node, the proposed scheme works in a collaborative mode more often than in previously proposed designs. The result is significant coding gain compared with existing approaches.

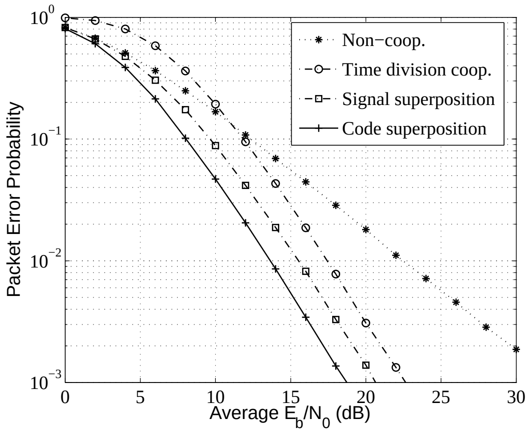

Fig. 5. Packet error probabilities for one noncooperative and three cooperative diversity systems.

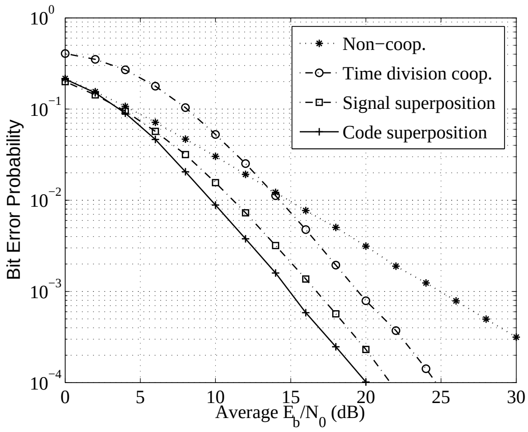

Fig. 6. Bit error probabilities for one noncooperative and three cooperative diversity systems.

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