Distributed Joint Source and Channel Code with Correlated Information Sources

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Abstract— **In this paper, a new distributed joint source-channel code (DJSCC) is proposed for a communication network with multiple correlated information sources. The DJSCC is performed by puncturing the information bits of a linear block code but leaving the parity bits intact, given the fact that the correlation among the parity bits is usually much lower compared to the corresponding information bits. In recognition of the different roles of the information and parity bits in the DJSCC scheme, we propose to allocate unequal amounts of energy per bit to these two different types of bits. The unequal energy allocation leads to significant performance gains over conventional equal energy transmissions. At the receiver, the sources are jointly decoded with the iterative message passing algorithm. Simulation results demonstrate that the proposed scheme can achieve considerable performance gains over conventional schemes.**

I. INTRODUCTION

The Slepian-Wolf (S-W) theorem [1] states that distributed sources with correlated information can perform encoding separately, yet achieve a code rate that is the same as when the information is encoded jointly. A wide range of applications can benefit from the S-W theorem. For example, in a wireless sensor network, data collected by the spatially distributed sensors are usually correlated due to the redundancy of the underlying monitored object; in a wireless relay network, the signal transmitted by one source might be observed by multiple relays, the information to be transmitted by which is thus correlated. However, the S-W theorem is not constructive, *i.e.*, it provides no practical coding scheme to achieve the optimum performance.

There have been considerable works in the literature devoted to the design of practical distributed source codes (DSC) [2]-[11]. Many practical DSC schemes are designed by using the syndromes of channel codes, such as block and trellis codes [2], turbo codes [3], and low-density parity-check (LDPC) codes [4]. Many syndrome-based DSC designs focus on the asymmetric scenario, *i.e.*, the distributed coding is only applied to one of the sources, and the other source is used as side-information and assumed to be known perfectly at the decoder. Designs of symmetric DSCs are discussed in [5]–[8], with punctured linear block codes or LDPC codes. All of the above work assume distortion-free communications between the encoder and decoder, which rely on a separately designed ideal channel code to protect the signal from channel distortions. It is shown in [9] that the source-channel coding separation theorem does not hold for a multiuser network, thus necessitates the design of distributed joint source-channel code (DJSCC). In [10], a Raptor code is employed for an asymmetric DJSCC over a packet erasure channel, where a correlated video source is assumed to be available at the receiver for decoding. A symmetric DJSCC scheme over the additive white Gaussian channel is proposed in [11].

In this paper, we propose a new symmetric DJSCC coding scheme for multiple correlated sources. The source correlation is utilized to both reduce the energy consumption and to protect the information from channel distortion. The DJSCC is performed by transmitting a subset of the information bits and all the parity bits of a linear block code over a noisy channel. The distortions from source coding and channel impairments can be partly recovered by using the source correlation and the parity bits. Compared to existing schemes in the literature, the newly proposed DJSCC scheme has the following contributions. First, a new unequal energy allocation scheme is proposed for the delivery of the codeword from the transmitter to the receiver. The information bits and parity bits are transmitted with different energy per bit in recognition of their different roles in DJSCC, and significant performance gains are achieved over conventional schemes equal energy allocation. Second, unlike many of the symmetric DSC or DJSCC schemes that puncture both the information and parity bits [7] and [11], only the information bits are punctured in the proposed coding scheme. This is based on our observation that the correlation among the parity bits from different sources are relatively low even if the correlation of the information bits is strong. Therefore puncturing the parity bits with low mutual correlation might deteriorate the overall system performance. Simulations are performed by using the LDPC codes as the constituent code, and the results demonstrate significant performance gains of the newly proposed DJSCC scheme.

The remainder of the paper is organized as follows. Section II introduces the proposed DJSCC scheme with unequal energy allocation. Section III presents the message passing decoding algorithm. Simulation results are given in Section IV, and Section V concludes the paper.

II. DISTRIBUTED JOINT SOURCE AND CHANNEL CODE

Consider a network with N spatially distributed sources transmitting to an information sink. Denote $b_n(k) \in \mathcal{B}$ as the k-

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th information bit from the n-th source, where $\mathcal{B} = \{0, 1\}$. The binary information of the N sources are mutually correlated. Define the cross probability between users m and n as $p_{mn} = P\{b_m(k) \neq b_n(k)\}$. If the binary information is equal probable, *i.e.* $P(b_m(k) = 1) = P(b_m(k) = 0) = 0.5$, then the covariance coefficient between $b_m(k)$ and $b_n(k)$ is

$$\rho_{mn} = \frac{\mathbb{E}\left[(b_m - \mu_m)(b_n - \mu_n)\right]}{\sigma_m \sigma_n} = 2(1 - p_{mn}) - 1, \qquad (1)$$

where μ_m and σ_m are the mean and standard deviation of $b_m(k)$, respectively.

A. Codeword Structure

Each source encodes its own information *without* the knowledge of the information from the other sources. The proposed DJSCC is a linear block code. Let $\mathbf{b}_n = [b_n(1), \cdots, b_n(M)]^T \in \mathcal{B}^{M \times 1}$ denote a block of M information bits to be encoded at the n-th source. In the proposed DJSCC scheme, M is chosen to be an integer multiple of the number of users N as $M = KN$ with K being an integer. The corresponding DJSCC codeword of the n-th source can then be represented as

$$\mathbf{c}_n^T = \mathbf{b}_n^T \left[\mathbf{T}_n, \mathbf{P}_n\right] = \left[\mathbf{s}_n^T, \mathbf{p}_n^T\right]^T \qquad (2)$$

where $\mathbf{T}_n \in \mathcal{B}^{M \times K}$ is the information compression matrix with $K = \frac{M}{N}$, $\mathbf{P}_n \in \mathcal{B}^{M \times P}$ is the parity generation matrix, $\mathbf{s}_n = \mathbf{T}_n^T \mathbf{b}_n \in \mathcal{B}^{K \times 1}$ is the compressed information vector, $\mathbf{p}_n = \mathbf{P}_n^T \mathbf{b}_n \in \mathcal{B}^{P \times 1}$ is the parity vector, and the matrix operations in (2) are performed in the Galois field of two elements, GF(2). The parity generation matrix $\mathbf{P}_n$ will generate P parity bits from M information bits. The code rate of the DJSCC code is thus $r = \frac{M}{K+P}$.

The information compression matrix $\mathbf{T}_n$ is obtained by removing $M - K = K(N-1)$ columns of a size-M identity matrix $\mathbf{I}_M$. Denote $\mathcal{T}_n = \{n_1, \cdots, n_K\} \subseteq \{1, 2, \cdots, M\}$ as the set of the K indices corresponding to the columns *not* removed from $\mathbf{I}_M$ during the construction of $\mathbf{T}_n$, then $\mathbf{T}_n = [\mathbf{i}_{n_1}, \cdots, \mathbf{i}_{n_K}]$ with $\mathbf{i}_m$ being the m-th column of $\mathbf{I}_M$. In the proposed DJSCC, we have $\mathcal{T}_n \bigcap \mathcal{T}_m = \emptyset$, and $\bigcup_{n=1}^N \mathcal{T}_n = \{1, 2, \cdots, M\}$. When $N = 1$, we have $\mathbf{T}_n = \mathbf{I}_M$, and the DJSCC codeword in (2) degrades to a regular systematic linear block code of code rate $\frac{M}{M+P}$.

When $N > 1$, the codeword structure in (2) combines distributed source code and channel code in a unified structure. The channel code is performed with the combination of the punctured information and the parity vectors. The distributed source code is performed with the information compression matrix $\mathbf{T}_n$, which punctures the length-M information vector $\mathbf{b}_n$ into a length-K vector $\mathbf{s}_n$, with mutually exclusive puncture patterns defined by the index set $\{\mathcal{T}_n\}_{n=1}^N$. The information puncture operation deliberately adds distortion to the information to reduce the amount of information to be transmitted, thus reduce the overall energy requirement. With mutually exclusive puncture patterns, if $b_n(k)$ is punctured, it is guaranteed that there exists $m \neq n$ such that $b_m(k)$ on source m is transmitted. Then $b_n(k)$ can be partly recovered by using the correlation between $b_m(k)$ and $b_n(k)$, as well as the parity vector $\mathbf{p}_n(k)$.

In summary, for a system employing the DJSCC, the information distortion comes from two sources, the distortion deliberately added by the information puncture operation, and the channel distortion. At the decoder, the distortions are compensated from two aspects, the spatial correlation, and the parity vector. The information correlation is utilized to both reduce the energy consumption and to protect the information from channel distortion. Therefore, the distributed source code and channel code are jointly performed in a single step.

In the proposed DJSCC scheme, only the information vector is punctured and the parity vector is transmitted in its entirety. This is because the punctured information can be partly compensated by the information correlation, yet the correlation among the parity vectors from different sources are relatively low even if the information is strongly correlated. The correlation between two parity bits from different sources is stated in the following lemma.

Lemma 1: If the users use different parity generation matrix, then the probability that two parity bits, p_{nk} and p_{mk} are different is $P(p_{nk} \neq p_{mk}) = 0.5$. If all users share the same parity generation matrix, and the Hamming weight of the k-th column of the parity generation matrix is L, then

$$P(p_{nk} \neq p_{mk}) = \sum_{u=1, u \text{ odd}}^{L} \binom{L}{u} p_{mn}^u \left(1 - p_{mn}\right)^{L-u} \qquad (3)$$

Proof: If the users use different parity generation matrix, then p_{nk} and p_{mk} are mutually independent because the information bits are assumed to be independent in the time domain.

If all the users use the same parity generation matrix, the probability $P(p_{nk} \neq p_{mk})$ is equal to the probability that, for the L bits corresponding to the non-zero positions of the k-th column of $\mathbf{P}_n$, there are an odd number of bits from the m-th user that are not equal to their counterparts from the n-th user. The probability that u bits are not equal to each other follows a binomial distribution as $\binom{L}{u} p_{mn}^u \left(1 - p_{mn}\right)^{L-u}$. The result in (3) follows immediately. ■

As L becomes large, the binomial distribution $\binom{L}{u} p_{mn}^u (1 - p_{mn})^{L-u}$ can be accurately approximated by a normal distribution with mean Lp_{mn} and variance $Lp_{mn}(1 - p_{mn})$. Since the normal distribution is symmetric with respect to Lp_{mn}, the summation in (3) tends to $\frac{1}{2} \sum_{u=1}^{L} \binom{L}{u} p_{mn}^u \left(1 - p_{mn}\right)^{L-u} = 0.5$ when L is large.

This is corroborated by the result in Fig. 1, which shows the cross probability of the parity bits, $P(p_{nk} \neq p_{mk})$, as a function of L with various values of the cross probability p_{mn}. The cross probability of the parity bits is less than the cross probability of the corresponding information bits under all configurations, and they tend to 0.5 as L becomes large.

Based on the above analysis, the parity bits across different users usually have very weak correlations, even if the information bits are strongly correlated. Therefore, puncturing the parity bits will have very little contribution to the distributed source code, yet it will sacrifice the performance of the channel

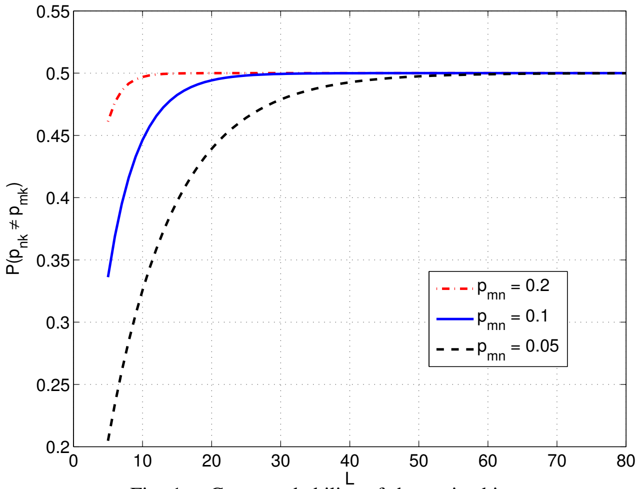

Fig. 1. Cross probability of the parity bits.

code. Therefore, we propose to puncture only the information bits, and transmit the parity bits at its entirety.

B. Transmission with Unequal Energy Allocation

Since the information bits and the parity bits are treated differently during the encoding process, we propose to allocate different amounts of energy per bit to the information and parity bits during transmissions.

Denote $\boldsymbol{\alpha}_n$=mod $[\mathbf{s}_n]$ and $\boldsymbol{\beta}_n$=mod $[\mathbf{p}_n]$, where mod$[\mathbf{b}] \in \mathcal{S}$ maps the binary vector $\mathbf{b}$ to the modulation constellation set $\mathcal{S}$. The codeword after modulation and energy allocation is

$$\mathbf{x}_n = [\sqrt{E_s}\boldsymbol{\alpha}_n^T, \sqrt{E_p}\boldsymbol{\beta}_n^T]^T, \tag{4}$$

where E_s is the energy per punctured information symbol, and E_p is the energy per parity symbol. The average energy per information bit is thus $E_b = \frac{E_s K + E_p P}{M \log_2(S)}$, where $S = |\mathcal{S}|$ is the cardinality of the constellation set $\mathcal{S}$.

Define the energy allocation factor as $\theta = \frac{E_p}{E_s}$. Intuitively, more energy per symbol should be allocated for the punctured information bits to compensate for the punctured bits. This intuition is supported by our simulation results. The energy allocation factor, θ, is used to adjust the energy allocation between the punctured information bits and the parity bits. When $\theta = 0$, no parity bits will be transmitted and the scheme degrades to a punctured transmission scheme without channel code.

The unequal energy allocation between the punctured information and parity symbols is motivated by the fact that the sink can have the entire parity vectors from all the users, but only a punctured version of the original information vector. The punctured information is recovered by using a combination of the parity bits and the information correlation. Therefore, the transmitted information bits from one user are used to recover the punctured bits from the other users. Therefore, more energy can be allocated to the unpunctured bits to compensate the extra distortions introduced by the puncturing operations.

The modulated codeword, $\mathbf{x}_n$, is transmitted to the sink through an orthogonal media access control (MAC) scheme. The signal received from the n-th user is

$$\mathbf{y}_n = \mathbf{x}_n + \mathbf{z}_n, \tag{5}$$

where $\mathbf{z}_n$ is the additive white Gaussian noise (AWGN) with a single-sided power spectral density N_0. The received signal vector at the sink can be expressed as $\mathbf{y}_n = [\mathbf{y}_{\alpha n}^T, \mathbf{y}_{\beta n}^T]^T$, where $\mathbf{y}_{\alpha n}$, $\mathbf{y}_{\beta n}$ are the received signal vectors corresponding to the coded sequence $\boldsymbol{\alpha}_n$ and $\boldsymbol{\beta}_n$, respectively.

III. DJSCC Decoding with the Message Passing Algorithm

The sink recovers the information vector by performing joint decoding with the message passing algorithm based on the received signals from all the N sources.

Before the decoding, we need to calculate the initial log-likelihood ratio (LLR) from the channel observations. The initial LLR of the k-th coded information bit $s_n(k) = b_n(n_k)$, from the channel observation, $\mathbf{y}_{\alpha n}$, can be calculated by

$$\lambda_n(n_k) = \log \frac{\sum_{s \in \mathcal{S}_{r_k}^-} \exp\left[-\frac{1}{N_0}|y_{\alpha n}(m_k) - s|^2\right]}{\sum_{s \in \mathcal{S}_{r_k}^+} \exp\left[-\frac{1}{N_0}|y_{\alpha n}(m_k) - s|^2\right]}, \tag{6}$$

where the k-th bit in a coded vector is mapped to the $m_k = \lfloor \frac{k}{\log_2 S} \rfloor$ modulated symbol, $r_k = k - m_k \log_2 S$, $\mathcal{S}_{r_k}^+ \subset \mathcal{S}$ is the set that contains all the symbols with the r_k-th bit in the demodulated vector being 1, and $\mathcal{S}_{r_k}^- = \mathcal{S} \backslash \mathcal{S}_{r_k}^+$.

Similarly, the initial LLR of the k-th parity bit, $p_n(k)$, can be calculated from $y_{\beta n}$ as

$$\lambda_n(M+k) = \log \frac{\sum_{s \in \mathcal{S}_{r_k}^-} \exp\left[-\frac{1}{N_0}|y_{\beta n}(m_k) - s|^2\right]}{\sum_{s \in \mathcal{S}_{r_k}^+} \exp\left[-\frac{1}{N_0}|y_{\beta n}(m_k) - s|^2\right]}. \tag{7}$$

The LLRs of the punctured bits of one user can be calculated from their correlated counterparts transmitted by a different user. Assume $k \in \mathcal{T}_n$, *i.e.*, the bit b_{nk} is transmitted by the n-th user, and b_{mk} is punctured at the m-th user, $\forall m \neq n$. Then the LLRs of the punctured bits can be calculated as

$$\hat{\lambda}_m(k) = \log \frac{(1-p_{mn})P(b_n(k)=1) + p_{mn}P(b_n(k)=0)}{p_{mn}P(b_n(k)=1) + (1-p_{mn})P(b_n(k)=0)}, \tag{8}$$

where $P(b_n(k) = 1) = \frac{1}{1+\exp[\lambda_n(k)]}$ and $P(b_n(k) = 0) = 1 - P(b_n(k) = 1)$.

The initial LLR of the information and parity bits can then be expressed by

$$\delta_n(k) = \begin{cases} \lambda_n(k), & k \in \mathcal{T}_n \text{ or } M < k \leq M+P, \\ \hat{\lambda}_n(k), & \text{otherwise}, \end{cases} \tag{9}$$

The message passing will be performed on a bipartite graph defined by an extended parity check matrix $\mathbf{H} = [\mathbf{P}_n^T, \mathbf{I}_P]^T \in \mathcal{B}^{(M+P)\times P}$. It should be noted that $\mathbf{H}$ is not the parity check matrix for the codeword defined in (2). It is the parity check matrix of the unpunctured codeword with the generation matrix $[\mathbf{I}_M, \mathbf{P}_n]$.

The tanner graph corresponding to $\mathbf{H}$ has $(M+P)$ variable nodes and P check nodes. The k-th variable node is connected to the p-th check node if the (k, p)-th element of $\mathbf{H}$ is 1. Denote $\mathcal{V}_p$ as the set of variable nodes that are connected to the p-th check node, and $\mathcal{C}_k$ as the set of check nodes that are connected to the k-th variable nodes.

For the information from the n-th user, the message from the k-th variable node to the p-th check node during the i-th iteration is

$$\eta_{kp}^{(i)}(n) = \delta_n(k) + \sum_{p' \in \mathcal{C}_k \backslash p} \mu_{p'k}^{(i-1)}(n), \tag{10}$$

where $\mu_{pk}^{(i)}(n)$ is the message from the p-th check node to the k-th variable node during the i-th iteration,and it can be calculated as

$$\mu_{pk}^{(i)}(n) = 2\text{atanh} \prod_{k' \in \mathcal{V}_p \backslash k} \tanh \frac{\eta_{k'p}^{(i)}(n)}{2} \tag{11}$$

During the first iteration, $\mu_{pk}^{(0)}(n) = 0$.

For the message passing algorithm [12], eqns. (10) and (11) are performed iteratively for a single codeword, and the values of $\delta_n(k)$ are the same for all the iterations. At the i-th iteration, the n-th user will output a soft decision for its information bits, as

$$l_n^{(i)}(k) = \delta_n(k) + \sum_{p' \in \mathcal{C}_k} \mu_{p'k}^{(i)}(n). \tag{12}$$

At the final iteration, the hard decision with I iterations is obtained as $\hat{b}_n(k) = 1$ if $l_n^{(I)}(k) > 0$ and $\hat{b}_n(k) = 0$ otherwise.

The iterative message passing algorithm is summarized as follows.

I) **Initialization**
   i) Calculate the initial LLRs of the transmitted information bits, $\lambda_n(k)$, with (6), for $k \in \mathcal{T}_n$, $n = 1, \cdots, N$.
   ii) Calculate the initial LLRs of the parity bits, $\lambda_n(M + k)$, with (7), for $k = 1, \cdots, P$, $n = 1, \cdots, N$.
   iii) Calculate the LLRs of the punctured information bits, $\hat{\lambda}_m(k)$, with (8).
   iv) Set $i = 1$.

II) **Iterations**
   i) Calculate the message from the variable node to the check node, $\eta_{kp}^{(i)}(n)$, with (10), for $k = 1, \cdots, N$, $p = 1, \cdots, P$, and $n = 1, \cdots, N$.
   ii) Calculate the message from the check node to the variable node, $\mu_{pk}^{(i)}(n)$, with (11), for $k = 1, \cdots, N$, $p = 1, \cdots, P$, and $n = 1, \cdots, N$.
   iii) Calculate the soft decisions, $l_n^{(i)}(k)$, with (12).
   iv) If $i < I$, go back to step II.i); otherwise go to the next step.

III) **Detection**
   Make hard decision as $\hat{b}_n(k) = 1$ if $l_n^{(I)}(k) > 0$ and $\hat{b}_n(k) = 0$ otherwise.

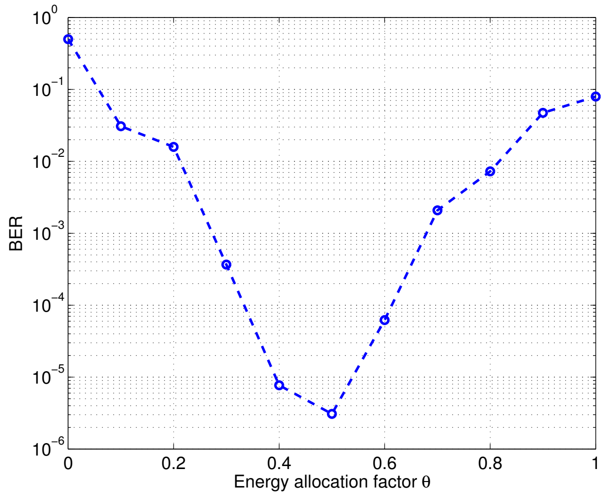

Fig. 2. BER as a function of the energy allocation factor θ (E_b/N_0 of the source-sink link is -0.65 dB).

IV. Simulation Results

Simulation results are presented in this section to demonstrate the performance of the proposed DJSCC scheme. In the simulation, an irregular LDPC with a 32400-by-64800 parity-check matrix is used to generate the DJSCC codeword. In the simulation, the pairwise covariance coefficient between any pair of users is the same, *i.e.*, $\rho_{mn} = \rho$, or $p = p_{mn}$, $\forall m \neq n$. The mutually correlated information of the N users is generated by passing the a length-M binary vector through N independent and identically distributed (i.i.d.) binary symmetric channel (BSC) channels. The cross probability of the BSC channel is $p_0 = \frac{1}{2} - \frac{1}{2}\sqrt{1 - 2p}$. It can be easily shown that the cross probability between the output of any pair of BSC channels is p. It should be noted that the proposed DJSCC scheme can be applied to sources with arbitrary correlations.

We first study the impact of the unequal energy allocation on the performance of the DJSCC scheme in Fig. 2, where the bit error rate (BER) is shown as a function of the energy allocation factor, θ, for a network with two users. The covariance coefficient between the two users is $\rho = 0.9$. The source-sink communication links are AWGN channels with $E_b/N_0 = -0.65$ dB. It can be seen that the optimum performance is achieved at $\theta = 0.5$, e.g., the energy of one parity bit is half of that of one transmitted information bit. The performance degrades significantly with equal energy allocation at $\theta = 1$.

Fig. 3 shows the BER performance of the proposed DJSCC scheme under various values of ρ. There are two users in the system. The energy allocation factor is $\theta = 0.6$. The performances of systems with equal energy allocation are also shown for comparison. The curve labeled as conventional LDPC is obtained without DJSCC, thus its performance is independent of the number of users. As expected, the performance improves as ρ increases. With unequal energy allocation and at a BER = 10^{-4}, the DJSCC obtains 0.1 dB, 0.5 dB, and 1 dB performance gains over conventional LDPC coded system at $\rho = 0.7, 0.8$, and 0.9, respectively. The DJSCC with unequal

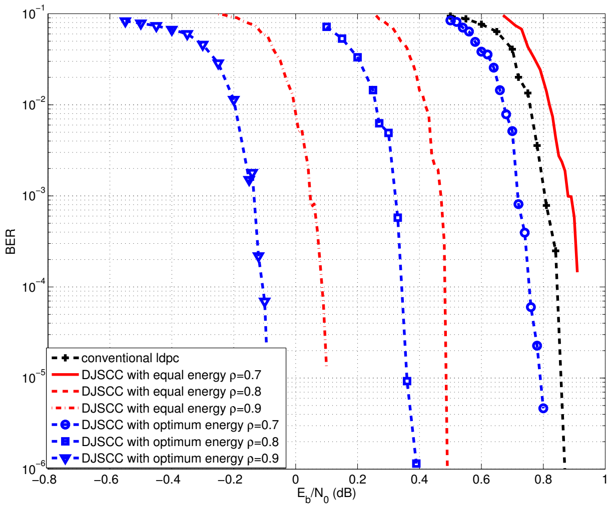

Fig. 3. The performance of equal and optimum energy for two users

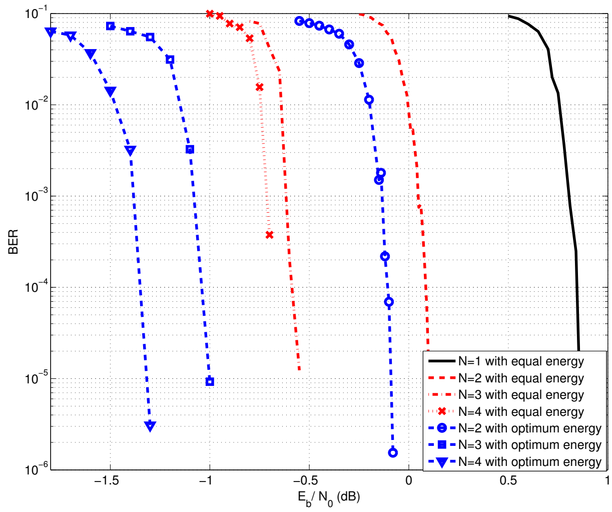

Fig. 4. The BER under varies number of users N (covariance coefficient $\rho = 0.9$)

energy allocation outperform their equal energy counterparts by about 0.18 dB.

The impact of the number of users on the performance is shown in Fig. 4. The covariance coefficient is $\rho = 0.9$. No puncture operation is employed in the $N = 1$ case and it is the same as the conventional LDPC code. The proposed DJSCC scheme benefits from the presence of more users, due to the better compression ratio of the distributed source code. The DJSCC systems with $N = 2$, 3, and 4 outperform the conventional LDPC coded system by 1 dB, 1.9 dB, and 2.3 dB, respectively.

V. Conclusion

A new DJSCC scheme based on linear block code for a communication network with correlated information sources and operating over noisy channels was proposed in this paper. It was demonstrated that the correlation among the parity bits of a linear block code was usually very low even when the correlation among the information bits is high. Therefore, the DJSCC was performed by puncturing the information bits but transmitting the parity bits in its entirety. The information and parity bits were transmitted with unequal energy per bit to achieve additional performance gain. The message passing algorithm was used at the receiver to jointly recover the information from all the sources. Simulation results demonstrated that the proposed DJSCC scheme with unequal energy allocation can achieve significant performance gains over conventional schemes, and the performance improves as the number of users increases.

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