Source Correlation, Transmit Diversity, and Channel Coding in Wireless Multiple-Access Communications

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Abstract— **In this paper, we study the performance of simple wireless multiple-access communication systems, where two *correlated* sources communicate to an access point (AP) directly or, possibly, by using a relay node. In particular: if no relay is used, then the two sources make use of channel coding; if the relay is used, then the two sources transmit uncoded information and the relay adds redundancy (i.e., parity bits). In particular, we consider the use of low-density parity-check (LDPC) coding, and we compare different systems by keeping fixed the overall coding rate. In all cases, we compare the performance of receivers which, respectively, exploit or do not exploit the source correlation. We analyze the relative impact of transmit diversity (increased when a relay is used) with respect to channel coding, distinguishing, respectively, between scenarios with block-faded communication links and memoryless links. In the latter case, the presence of additive white Gaussian noise (AWGN) or bit-level independent Rayleigh fading is considered.**

I. Introduction

Wireless sensor networks have recently received a lot of attention in the research literature [1]. The efficient transmission of correlated signals observed at different nodes to one or more collectors is one of the main challenges in such networks. In the case of a single collector node, this problem is often referred to as reach-back channel problem in the literature [2], [3], [4]. In its simplest form, this problem can be summarized as follows: two independent nodes have to transmit correlated sensed data to a collector node by using the minimum possible energy, i.e., by exploiting in some way the implicit correlation among the data. In an attempt to exploit such correlation, many works have recently focused on the design of coding schemes that approach the Slepian-Wolf fundamental limit on the achievable compression rates [5], [6], [7], [8]. However, approaching the Slepian-Wolf compression limit requires exact knowledge of the cross-correlation term at each transmitter. In many cases, this is not possible on account of the distributed nature of the problem at hand.

An alternative approach to distributed source coding is represented by joint source-channel coding. In this case, the correlated sources are not source encoded but only channel encoded at a reduced rate (with respect to the uncorrelated case). The reduced reliability due to channel coding rate reduction can be compensated by exploiting intrinsic cross-correlation among different information sources at the channel decoder. To do that, the channel decoder must generate an estimate of the cross-correlation between the transmitted sequences. This can be easily obtained by evaluating the number of zeros of the XOR between the received sequences. Works dealing with joint source-channel coding have so far considered classical turbo or low-density parity-check (LDPC) codes [9], [10], [11], [12], where the decoder can exploit the correlation among sources by performing message passing between the two decoders. This procedure requires a huge implementation complexity at the receiver side, since the decoder must perform several decoding steps before getting the joint estimation of the transmitted sequences.

In the scenario proposed in this paper, two sensor nodes can establish a direct link toward the collector node or they can use a relay (intermediate) node. We assume that the communication links between the sensor nodes and the relay are ideal without any extra-power needs (in an attempt to send information via the direct link, information is also delivered to the relay on account of the broadcast nature of the transmissions). In this context, we first consider the classical joint source-channel coding scheme, where the two sources independently perform *systematic* LDPC coding and the relay does not transmit at all. In this case, the receiver performs message passing between the two LDPC decoders (associated with the two sources), similarly to the scheme proposed in [12]. Then, we consider a network coding scheme where the two nodes send uncoded signals while the relay node, upon reception of the information sequences from both sources, generates and transmits the parity check bits. In this case, at the relay node, we consider a *systematic* LDPC encoder, whose input sequence is obtained by multiplexing the uncoded sequences received from the two sensor nodes, so that the receiver can perform a classical one-step LDPC decoding (i.e., there is only one decoder at the collector), by properly taking into account the correlation between the sources. Of course, this second scheme allows to noticeably reduce the implementation complexity at the decoder side. Comparisons between the two transmitting schemes are provided both on additive white gaussian noise (AWGN) and Rayleigh fading

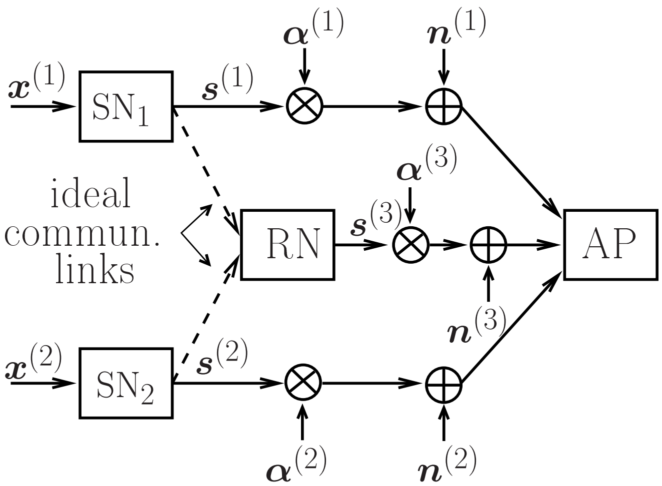

Fig. 1. Proposed multi-access communication scenario: two source nodes communicate directly, and, possibly through a relay node, with the AP.

channels. In particular, the goal of this paper is to shed light on the interrelation between source correlation and transmit diversity.

II. Scenario

Assume to have two spatially distributed sensor nodes which detect two binary information signals $\boldsymbol{x}^{(k)} = [x_0^{(k)}, \dots, x_{L-1}^{(k)}]$, $k = 1, 2$, where L is the signals' length (the same for both sources). The information signals are assumed to be temporally white with $P(x_i^{(k)} = 0) = P(x_i^{(k)} = 1) = 0.5$ and correlation $\rho = P(x_i^{(1)} = x_i^{(2)}) > 0.5$. The information signals, which are assumed to be detectable without error (i.e., ideal sensor nodes), must be delivered to one collector node (access point, AP). To this aim, sensor nodes can establish independent links toward the AP or they can use a relay (intermediate) node. We assume that the communication links between the sensor nodes and the relay are *ideal*. Under this hypothesis, the relay node is able to detect the binary information signals $\boldsymbol{x}^{(1)}$ and $\boldsymbol{x}^{(2)}$ without errors. We denote as "nodes" both the sensors and the relay. Hence, the proposed scenario envisages three nodes where the sensor nodes are indexed by $k = 1, 2$ and the relay node is indexed by $k = 3$. We then assume that communications between the nodes and the AP are affected by independent link gains and additive white Gaussian noise (AWGN) as well. The independence of the fading terms in different links is due to the fact that the nodes are assumed to be spatially separated by more than a wavelength. On the other hand, the independence of the noise terms in different links is due to the fact that the nodes are assumed to transmit over orthogonal multiple access channels (e.g., using time division multiple access).

Referring to the equivalent low-pass signal representation, we denote as $\boldsymbol{s}^{(k)}$ the complex samples transmitted by the node k (either a source or the relay). In Fig. 1, we show a pictorial description of the proposed scenario, where SN stands for "Sensor Node" and RN stands for "Relay Node." The terms $\boldsymbol{\alpha}^{(k)}$ are the complex link gains which encompass both path loss and fading, and $\boldsymbol{n}^{(k)}$ are the complex AWGN samples. Regarding the fading affecting the communication links from the nodes to the AP we assume that $|\boldsymbol{\alpha}^{(k)}|$ are Rayleigh distributed with $E|\boldsymbol{\alpha}^{(k)}| = 1$. As far as the temporal behavior, two possible cases will be considered in the following sections.

- The fading is *constant* for the entire duration of a transmission, so that the channel link gain can be perfectly estimated at the AP. This assumption is reasonable, since in most wireless sensor networks' applications sensor nodes are static or almost static.
- The fading in each link is *independent* from bit to bit. This corresponds, from a practical viewpoint, to the assumption of channel interleaving or very fast fading. This scenario is somewhat less likely for a sensor network. However, the obtained results allow to further characterize the interrelation between source correlation and transmit diversity.

Let us introduce the following terms: $E_c^{(k)} = 0.5\mathbb{E}(|s_i^{(k)}|^2)$ is the energy per sample transmitted by k-th node and $0.5\mathbb{E}(|n_i^{(k)}|^2) = N_0$ is the variance of the AWGN. Assume that each transmitter uses a binary antipodal channel coding scheme to protect information from channel errors, and denote as $\boldsymbol{y}^{(k)} = (y_0^{(k)}, y_1^{(k)}, \dots, y_{N^{(k)}-1}^{(k)})$, with $y_i^{(k)} = \pm 1$, the coded sequences for k-th node, $N^{(k)}$ being the codeword length.[1] According to the above considerations, for the sensor nodes' transmitters (i.e., for $k = 1, 2$) $\boldsymbol{y}^{(k)}$ is a function of the information signal $\boldsymbol{x}^{(k)}$, while for the relay node transmitter (i.e., for $k = 3$) $\boldsymbol{y}^{(k)}$ is a function of both information signals $\boldsymbol{x}^{(1)}$ and $\boldsymbol{x}^{(2)}$.

The coded sequence is transmitted into the channel with a binary phase shift keying (BPSK) modulation scheme, i.e., $s_i^{(k)} = y_i^{(k)}\sqrt{2E_c^{(k)}}$. Hence, denoting as $r_i^{(k)}$ the observable at the AP after matched filtering, it follows:

$$r_i^{(k)} = |\alpha^{(k)}|\sqrt{E_c^{(k)}}y_i^{(k)} + \eta_i^{(k)} \tag{1}$$

where $\eta_i^{(k)}$ is an AWGN variable with zero mean and variance $N_0/2$. Note that the same model could be applicable also to a more efficient quaternary phase shift keying (QPSK) scheme, where two coded symbols are transmitted at the same time in the real and imaginary components of the complex transmitted sample.

III. Coding and Decoding Schemes

In this section, we characterize in more detail the LDPC-coded communication schemes in the cases with and without a relay. In particular, we properly modify the decoding algorithms to take into account the correlation between the source nodes.

[1]Note that while the *information* sequence length is L, the *coded* sequence length might vary from source to source.

A. Scenario with No Relay

In the scenario with no relay, the information sequences are separately encoded using the same LDPC code and transmitted over the communication links. In this case, $N^{(1)} = N^{(2)} = N$, and we assume that the code rate is $L/N = 1/2$, i.e., $N = 2L$. At the AP, each LDPC-coded sequence is decoded by using the classical sum-product algorithm. Under the assumption of perfect channel state information (CSI), the channel log-likelihood ratio (LLR) at the input of the i-th variable node [13] can be expressed as

$$\mathscr{L}_{i,\mathrm{ch}}^{(k)} = \ln \frac{p(r_i^{(k)}|x_i^{(k)} = 1)}{p(r_i^{(k)}|x_i^{(k)} = -1)} = \frac{2r_i^{(k)}\left|\alpha_i^{(k)}\right|}{\sigma^2} \tag{2}$$

where $\sigma^2 = N_0/2$. In particular, we denote as $n_{\mathrm{it}}^{\mathrm{int-max}}$ the maximum number of decoding iterations in each component LDPC decoder.

The a priori information about the correlation between the sources is exploited by applying the following iterative decoding steps between the two component decoders:

- the a posteriori reliability (i.e., LLR) on the *information*[2] bits of the first decoder is properly modified, taking into account the correlation (as will be explained later), and used as a priori reliability for the information bits at the input of the second decoder;
- the a posteriori reliability on the information bits of the second decoder is properly modified, taking into account the correlation (as will be explained later), and used as a priori reliability for the information bits at the input of the first decoder;
- the algorithm stops when a maximum number of external iterations (denoted as $n_{\mathrm{it}}^{\mathrm{ext}}$) is reached.

We now describe how the a posteriori reliability at the output of each decoder is "transformed" before being used at the input of the other decoder, in order to take into account the information on the correlation between the sources. Let us denote as $\mathscr{L}_{i,\mathrm{out}}^{(k)}$ the LLR of the i-th information bit at the output of the k-th decoder, i.e.,

$$\mathscr{L}_{i,\mathrm{out}}^{(k)} = \ln \frac{P(x_i^{(k)} = 1)}{P(x_i^{(k)} = -1)} \qquad i = 0, \ldots, L-1$$

from which one can write

$$P(x_i^{(k)} = 1) = \frac{e^{\mathscr{L}_{i,\mathrm{out}}^{(k)}}}{1 + e^{\mathscr{L}_{i,\mathrm{out}}^{(k)}}}. \tag{3}$$

In other words, expression (3) for the probability of the i-th information bit is the probability estimated by the first decoder. The a priori component of the LLR at the input of the next decoder (more precisely, the ℓ-th decoder, with $\ell, k = 1, 2$ and $\ell \neq k$) can be written as

$$\begin{aligned} \mathscr{L}_{i,\mathrm{ap}}^{(\ell)} &= \ln \frac{P(x_i^{(\ell)} = 1)}{P(x_i^{(\ell)} = -1)} \\ &= \frac{\rho P(x_i^{(k)} = 1) + (1-\rho) P(x_i^{(k)} = -1)}{(1-\rho) P(x_i^{(k)} = 1) + \rho P(x_i^{(k)} = -1)} \end{aligned} \tag{4}$$

where we have used the fact that $P(x_i^{(\ell)} = x_i^{(k)}) = \rho$ and, therefore,

$$\begin{aligned} P(x_i^{(\ell)} = 1) &= \underbrace{P(x_i^{(\ell)} = 1 | x_i^{(k)} = 1)}_{P(x_i^{(\ell)} = x_i^{(k)})} P(x_i^{(k)} = 1) \\ &\quad + \underbrace{P(x_i^{(\ell)} = 1 | x_i^{(k)} = -1)}_{P(x_i^{(\ell)} \neq x_i^{(k)})} P(x_i^{(k)} = -1) \\ &= \rho P(x_i^{(k)} = 1) + (1-\rho) P(x_i^{(k)} = -1). \end{aligned}$$

Using (3) into (4), after a few manipulations one obtains

$$\mathscr{L}_{i,\mathrm{ap}}^{(\ell)} = \ln \frac{1 - \rho(1 - e^{\mathscr{L}_{i,\mathrm{out}}^{(k)}})}{e^{\mathscr{L}_{i,\mathrm{out}}^{(k)}} + \rho(1 - e^{\mathscr{L}_{i,\mathrm{out}}^{(k)}})}$$

and the total LLR at the input of each variable node of the factor graph underlying the ℓ-th LDPC decoder can be expressed as follows:

$$\mathscr{L}_{i,\mathrm{in}}^{(\ell)} = \begin{cases} \mathscr{L}_{i,\mathrm{ch}}^{(\ell)} + \mathscr{L}_{i,\mathrm{ap}}^{(\ell)} & i = 0, \ldots, L-1 \\ \mathscr{L}_{i,\mathrm{ch}}^{(\ell)} & i = L, \ldots, N-1. \end{cases}$$

In other words, the LLR at the input of the variable nodes associated with the information bits ($i = 0, \ldots, L-1$) includes, besides the channel reliability, the "suggestion" from the other decoder.

B. Scenario with Relay

In a scenario with the relay, the information sequence is transmitted uncoded by each source, i.e., no channel coding is considered at the sources. As anticipated in Section II, due to the broadcast nature of the communication from the sources, we assume that the information sequences are also received by the relay. In particular, we assume that the source-relay links are *error-free*—this is reasonable assuming that the relay is relatively much closer to the sensors than the AP. At this point, the relay multiplexes the data received from the sensors creating an information sequence $\boldsymbol{x}$, encodes it using a "classical" LDPC code, and sends the parity bits of the code to the AP. In the presented results, two possible multiplexing strategies at the relay are considered: (i) $\boldsymbol{x}$ is generated by appending $\boldsymbol{x}^{(2)}$ to $\boldsymbol{x}^{(1)}$ (sequence multiplexing) and (ii) $\boldsymbol{x}$ is generated by mixing the two sequences bit by bit (bit multiplexing).

In the considered scenario with the relay, at the AP there is a single LDPC decoder. However, the channel LLRs have to be properly modified to take into account the correlation at the sources. More precisely, since $x_i^{(k)}$ (for the k-th source) is

[2] Note that only the information bits are considered in the exchange of reliability information between the component LDPC decoders, since the coded bits are not directly correlated.

correlated to $x_i^{(\ell)}$, it follows that $x_i^{(k)}$ depends on $r_i^{(\ell)}$ (besides, obviously, on $r_i^{(k)}$). Therefore, the LLR at the input of each variable node can be computed as

$$\mathscr{L}_{i,\mathrm{in}}^{(k)} = \ln \frac{P(x_i^{(k)}=1|r_i^{(k)},r_i^{(\ell)},|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)}{P(x_i^{(k)}=-1|r_i^{(k)},r_i^{(\ell)},|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)}$$

where the generic term $P(x_i^{(k)}|r_i^{(k)},r_i^{(\ell)},|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)$ can be computed, by using the total probability theorem and the Bayes formula [14], as[3]

$$\begin{aligned}
P(x_i^{(k)}|r_i^{(k)},r_i^{(\ell)},|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)
&= \sum_{x_i^{(\ell)}=\pm 1} P(x_i^{(k)},x_i^{(\ell)}|r_i^{(k)},r_i^{(\ell)},|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)\\
&= \underbrace{\frac{P(|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)}{p(r_i^{(k)},r_i^{(\ell)},|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)}}_{\Omega_i}\\
&\quad \cdot \left[\sum_{x_i^{\ell}=\pm 1} p(r_i^{(k)},r_i^{(\ell)}|x_i^{(k)},x_i^{(\ell)},|\alpha_i^{(k)}|,|\alpha_i^{(\ell)}|)\right]\\
&= \Omega_i \sum_{x_i^{\ell}=\pm 1} p(r_i^{(k)}|x_i^{(k)},|\alpha_i^{(k)}|)p(r_i^{(k)}|x_i^{(\ell)},|\alpha_i^{(\ell)}|)\\
&\quad \cdot P(x_i^{(k)},x_i^{(\ell)})
\end{aligned} \quad (5)$$

where the conditional independence of $r_i^{(k)}$ and $r_i^{(\ell)}$ has been used and Ω_i *does not* depend on $x_i^{(k)}$ and $x_i^{(\ell)}$. After a few manipulations, one obtains

$$\mathscr{L}_{i,\mathrm{in}}^{(k)} = \begin{cases} \mathscr{L}_{i,\mathrm{ch}}^{(k)} + \mathscr{L}_{i,\mathrm{corr}}^{(\ell)} & i=0,\dots,L-1 \\ \mathscr{L}_{i,\mathrm{ch}}^{(k)} & i=L,\dots,N-1. \end{cases}$$

where $\mathscr{L}_{i,\mathrm{ch}}^{(\ell)}$ is defined as in (2) and

$$\mathscr{L}_{i,\mathrm{corr}}^{(\ell)} = \ln \frac{\rho \exp\left\{r_i^{(\ell)}|\alpha_i^{(\ell)}|/\sigma^2\right\} + (1-\rho)\exp\left\{-r_i^{(\ell)}|\alpha_i^{(\ell)}|/\sigma^2\right\}}{(1-\rho)\exp\left\{r_i^{(\ell)}|\alpha_i^{(\ell)}|/\sigma^2\right\} + \rho\exp\left\{-r_i^{(\ell)}|\alpha_i^{(\ell)}|/\sigma^2\right\}}$$

IV. Numerical Results

In this section, we evaluate the performance, in terms of bit error rate (BER), of the schemes described in Section II and Section III. In particular, the following setting is common for all considered schemes:

- the correlation coefficient is $\rho = 0.9$;
- in a scenario with no relay, each of the source sequences is encoded using a regular (3,6) LDPC code with rate 1/2 and $L = 1000$;
- in a scenario with relay, each of the source sequences has length $L = 1000$ and the relay uses a regular (3,6) LDPC code with rate 1/2 and information sequence length given by 2000;
- each component decoder performs a maximum number of internal iterations $n_{\mathrm{it}}^{\mathrm{int-max}}$ equal to 50, and, in scenarios with no relay, the number $n_{\mathrm{it}}^{\mathrm{ext}}$ of external iterations between the two decoders is set to 20.

[3]Note that only the LLRs at the input of the variable nodes associated with the information bits has to be modified in order to take into account the correlation between source nodes.

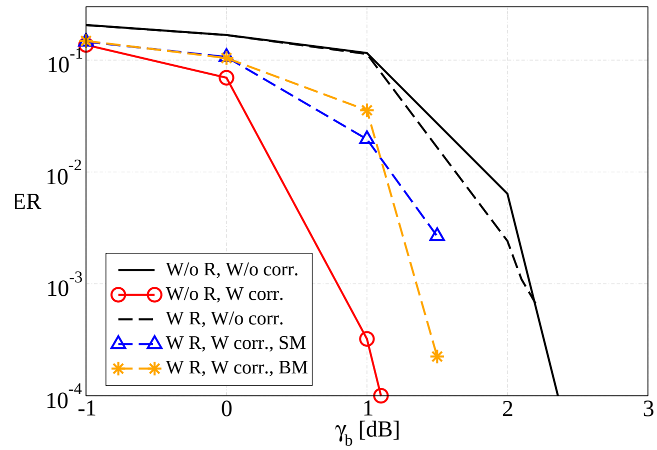

Fig. 2. BER, as a function of the SNR at the AP, in a scenario with AWGN sensor-AP links. The correlation between the sources is $\rho = 0.9$. Various systems are considered: (i) without relay, without exploiting the correlation at the AP (W/o R, W/o corr.); (ii) without relay, exploiting the correlation (W/o R, W corr.); (iii) with relay, without exploiting the correlation (W R, W/o corr.), (iv) with relay, exploiting the correlation, and considering sequence multiplexing at the relay (W R, W corr., SM), and (v) with relay, exploiting the correlation, and considering bit multiplexing at the relay (W R, W corr., BM).

In Fig. 2, the BER is shown, as a function of the signal-to-noise ratio at the AP, in a scenario with $\rho = 0.9$ and AWGN sensor-AP links. The $E_c(k)$ term is set equal to E_c for all the links, and the Energy-per-bit to noise-spectral-density term, denoted as γ_b, is given by $\gamma_b = E_c/N_0 \times 2N/2L = 2E_c/N_0$. Various systems are considered: (i) without relay, without exploiting the correlation at the AP (W/O R, W/O corr.); (ii) without relay, exploiting the correlation (W/O R, W corr.); (iii) with relay, without exploiting the correlation (W R, W/O corr.), (iv) with relay, exploiting the correlation, and considering sequence-level multiplexing at the relay (W R, W corr., SM), and (v) with relay, exploiting the correlation, and considering bit-level multiplexing at the relay (W R, W corr., BM). As one can observe, all the schemes which exploit the source correlation show a significant improvement with respect to the corresponding schemes (with and without relay, respectively) where the correlation is not exploited. Moreover, the system with no relay has a performance better than that of the system with the relay. In fact, the iterative decoder in the case without relay (with the two LDPC sub-decoder) has a complexity significantly higher than that of the "simple" LDPC decoder used in the presence of the relay. Moreover, since there are AWGN links, no diversity effect is present.

In Fig. 3, the BER is shown, as a function of the SNR at the AP, in a scenario with $\rho = 0.9$ and sensor-AP links with bit-level independent Rayleigh fading. The same system configurations presented in Fig. 2 are considered. As one can observe, also in this case the system with no relay has a performance

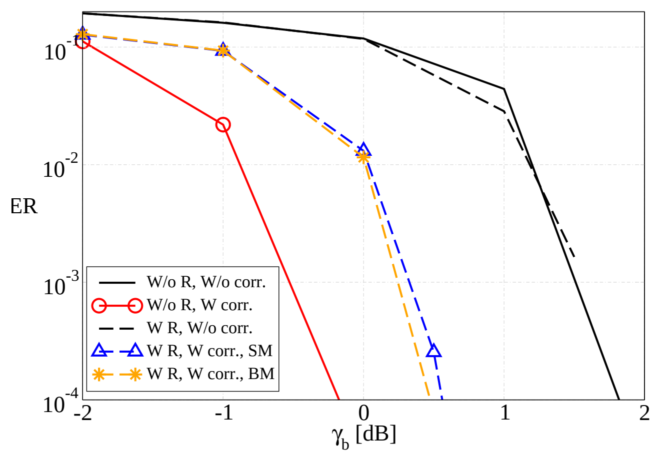

Fig. 3. BER, as a function of the SNR at the AP, in a scenario with sensor-AP links with bit-level independent Rayleigh fading. The correlation between the sources is $\rho = 0.9$. The same systems of Fig. 2 are considered.

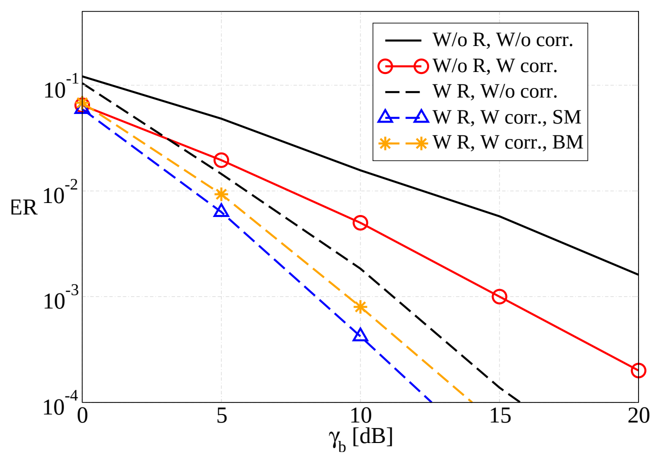

Fig. 4. BER, as a function of the SNR at the AP, in a scenario with sensor-AP links with *block-constant* Rayleigh fading (independent from link to link). The correlation between the sources is $\rho = 0.9$. The same systems of Fig. 2 are considered.

better than that of the system with the relay. In fact, owing to the assumption of bit-level independent Rayleigh fading and perfect CSI at the AP, the considered system behaves similarly to the equivalent system with AWGN.

In Fig. 4, the BER is shown, as a function of the SNR at the AP, in a scenario with $\rho = 0.9$ and sensor-AP links with *block-constant* Rayleigh fading (independent from link to link). The same system configurations presented in Fig. 2 are considered. Unlike Fig. 3, the fading samples are now exactly the same for all the bits in a packet and change in an independent manner from link to link. In this case, the scenario with relay presents a higher transmit diversity and, therefore, the performance is better than that of the scenario with no relay. This is due to the fact that, even if a link is heavily faded, there might be two other reliable communication links available at the AP, allowing the latter to succesfully recover the information sequences by exploiting their correlation. On the other hand, in the scenario with no relay, if one link is heavily faded, only one supplementary reliable link could be available and this could not be sufficient for the AP.

V. Conclusions

In this paper, we have analyzed multiple-access communication systems where two sources communicate to an access point, with or without an intermediate relay. In the absence of a relay, the two sources LDPC-encode independently their input information sequences, whereas in the presence of a relay, the sources transmit uncoded information and the relay adds redundancy. In both scenarios, we have derived effective receiver structures at the AP. Our results show clearly that transmit diversity (i.e., the use of a relay) has a stronger impact, with respect to channel coding, in scenarios with block-faded links. Moreover, the proposed receiver in the presence of the relay has a complexity significantly lower than that of the iterative receiver considered in the scenarios with no relay and memoryless links.

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