Low-Complexity Cooperation with Correlated Sources: Diversity Order Analysis

Nariman Farsad and Andrew W. Eckford
Dept. of Computer Science and Engineering, York University
4700 Keele Street, Toronto, Ontario, Canada M3J 1P3
E-mail: nariman@cse.yorku.ca, aeckford@yorku.ca

***Abstract*— Wireless sensor networks, which consist of numerous devices that take measurements of a physical phenomenon, are commonly used to observe phenomena that are correlated in space. In this paper, we devise a low-complexity coding scheme for correlated sources based on Slepian-Wolf compression, and analyze its performance in terms of diversity order. The main idea of this scheme is to use the correlated measurements as a substitute for relay links. Although we show that the asymptotic diversity order is limited by the constant correlation factor, we give experimental results that show excellent performance over practical ranges of SNR.**

I. Introduction

Wireless Sensor Networks [1] (WSNs) are a popular area of research driven by ever increasing applications such as habitat monitoring, industrial monitoring and control, security and military sensing, and health monitoring. Unlike most wireless networks where nodes do not have power constrains to combat effects of fading and noise, WSNs have very limited power and computational resources. Typically each node is a very simple, small, and inexpensive module that is equipped with a sensor to measure a phenomenon. A simple transceiver is used to transmit and receive the measured observations to and from neighboring nodes. Ultimately, the sensor nodes cooperate in transmitting their observations to a data sink where they can be processed. Therefore the challenge of designing a successful WSN is in minimizing the probability of error in transmitting data, subject to constraints in available power and computational resources.

One typical property of WSN is their spatial distribution. Spatially distributed sensor networks have two benefits: first, they have spatial diversity which means the fading on different links are independent; and second they have spatial correlation in the measured data. Spatial diversity can be generalized to cooperative diversity [2], where each node can assist its neighboring nodes in transmitting their information to a common receiver or a data sink. This can result in an increase in system throughput which can lead to a more efficient network. On the other hand, spatial correlation can be exploited by the Slepian-Wolf theorem [3] where the output of two correlated sources can be compressed without any communication between them. This compression permits a reduction in the number of transmitted bits, and hence a power efficient system. Meanwhile, from the node's perspective, Slepian-Wolf compression can be accomplished with relatively low complexity [13].

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The concept of cooperative diversity has attracted much attention in the literature. Usually, to implement cooperative diversity, error correcting codes must be used across different nodes in the network. In [4], error correcting codes were used with cooperative diversity as a more flexible system than just repetition by partners. Zhao et al. [5] showed a practical ARQ-based scheme for improving the performance of relays. In [6], another decoding method over the source-relay link using Raptor codes was suggested. A new scheme using punctured convolutional codes was presented by Stefanov et al. in [7]. Other methods using more powerful error correcting codes, such as capacity approaching turbo codes [8] and optimized LDPC codes [9-11], were also presented. Eckford et al. [12] showed a low complexity fractional cooperation scheme for independent sources using repeat-accumulate (RA) and low density generator matrix (LDGM) codes.

Practical codes performing Slepian-Wolf compression have been studied in detail in literature. In particular, distributed source coding is used for compression of correlated sources, which do not communicate with each other. Pradhan and Ramchandran proposed Distributed Source Coding Using Syndromes (DISCUS) [13] as a method of compression. In [14] and [15], Turbo codes and Low-Density Parity-Check (LDPC) codes were used for compression of binary correlated sources, respectively. Joint source-channel coding using Irregular Repeat Accumulate (IRA) codes [16] and Low-Density Generator-Matrix (LDGM) codes [17] were proposed for joint source compression and channel coding of binary correlated sources. In [18], the authors applied Slepian-Wolf cooperation to a relay system. Since the data sent through the relay is corrupted by noise, and therefore correlated with original data, the authors suggested a method that uses Slepian-Wolf compression as an alternative. Slepian-wolf compression has been applied to wireless networks observing correlated sources in [19], which considered fast Rayleigh fading, and [20], which focused on energy efficiency.

In this work, we first consider the effects of Slepian-Wolf compression on diversity order of a cooperative network with a single source and a single destination, along with relays and correlated sources. We will show that applying the Slepian-Wolf compression given in [15], the diversity order of such system asymptotically drops to one (compared to two for the no compression case); however, over SNR ranges of practical

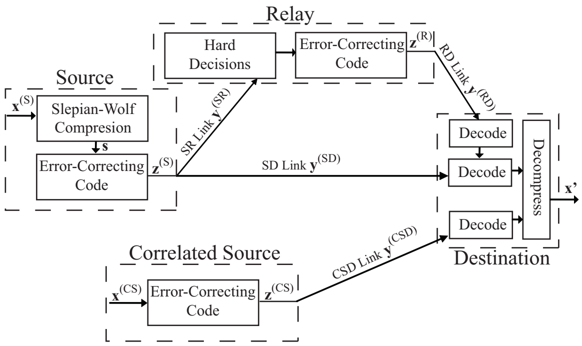

Fig. 1. Single relay, single correlated source model.

interest, the apparent diversity order in the frame error rate can be greater than two. Our main assumption is the stringent constraints on the nodes' computational power. We will show that in spite of the simplicity and adaptability of this scenario, excellent and robust performance can be achieved. Although these results are applicable to general wireless networks, they are perfectly suited for networks with low complexity nodes, such as sensor networks.

II. System Model

Our system models are inspired by the model used in [12]. We consider a sensor network with multiple sensors and one information sink. The task of the sensors is to convey their information as efficiently and accurately as possible to the sink. We assume the sensors possess simple two-way radios, processors of limited complexity, and limited power resources; while the data sink possesses virtually unlimited radio, computational, and power resources, within the limits of contemporary technology. The sensors' limited capabilities, and their ability to communicate with each other, imply that they should co-operate in conveying information to the sink. We also assume that the measured data across different sensors in close vicinity of each other is correlated.

Our system consists of a source, a destination, zero or more relays, and zero or more correlated sources. The purpose of the system is to convey sensor measurements from the source to the destination. The relays receive the source's transmission and assist the source in transmitting its information to the destination. The correlated sources, which observe a physical phenomenon that is correlated with the source's phenomenon, also assist the source in transmitting its information, but *have no radio link with the source*.

A. Single correlated source and relay

Here we give a detailed description of a single relay, single correlated source and multi-relay, multi-correlated-source models.

Our four-node model has a source, a single relay, a correlated source and a destination. As shown in Figure 1, there are four radio links: source to relay (SR), source to destination (SD), relay to destination (RD), and correlated source to destination (CSD). We assume these communication links use binary phase shift keying (BPSK) for data modulation. A particular realization of the channel is parameterized by representing the amplitude on the four links with $(a_{SD}, a_{SR}, a_{RD}, a_{CSD})$.

The length-n information gathered at the source and correlated source sensors are represented by $\mathbf{x}^{(S)} = \{x_1^{(S)}, x_2^{(S)}, ..., x_n^{(S)}\}$ and $\mathbf{x}^{(CS)} = \{x_1^{(CS)}, x_2^{(CS)}, ..., x_n^{(CS)}\}$ where $x_i^{(S)}, x_i^{(CS)} \in \{0,1\}$. To represent the correlation between the source and correlated source we assume $\Pr[x_i^{(S)} \neq x_i^{(CS)}] = p < 0.5$.

The source transmits its information bits in two phases. In the first phase DISCUS [13] source coding is used to compress source's information bits according to Slepian-Wolf theorem. Therefore we will have a length-k vector of syndrome bits $\mathbf{s} = \{s_1, s_2, ..., s_k\}$ where $k \geq nH(x_i^{(S)} \mid x_i^{(CS)})$. The source will then encode the resulting syndrome bits with error correcting codes which results in a length-m codeword $\mathbf{z}^{(S)} = \{z_1^{(S)}, z_2^{(S)}, ..., z_m^{(S)}\}$. The correlated source will also encode all its information bits with error correcting codes and the length-l codeword $\mathbf{z}^{(CS)} = \{z_1^{(CS)}, z_2^{(CS)}, ..., z_l^{(CS)}\}$ will be transmitted to the destination. Since we are using BPSK we assume $z_i^{(S)}, z_i^{(CS)} \in \{+1, -1\}$ and we define $\sigma : \{0,1\} \rightarrow \{+1,-1\}$ as function of translating zero and one to one and minus one respectively. The relay and destination will therefore observe the following real valued vectors

$$\mathbf{y}^{(SR)} = a_{SR}\mathbf{z}^{(S)} + \mathbf{n}^{(SR)}, \tag{1}$$

$$\mathbf{y}^{(SD)} = a_{SD}\mathbf{z}^{(S)} + \mathbf{n}^{(SD)}, \tag{2}$$

$$\mathbf{y}^{(CSD)} = a_{CSD}\mathbf{z}^{(CS)} + \mathbf{n}^{(CSD)}, \tag{3}$$

where $\mathbf{n}^{(SR)}$, $\mathbf{n}^{(SD)}$, and $\mathbf{n}^{(CSD)}$ represent unit-variance additive white Gaussian noise (AWGN) vectors at the relay and destination links respectively.

The relay receives $\mathbf{y}^{(SR)}$ and uses a processing function $\phi : \Re^m \rightarrow \{0,1\}^m$ on $\mathbf{y}^{(SR)}$ to estimate the data sent by the source. The result of the processing function,

$$\mathbf{x}^{(R)} = \phi(\mathbf{y}^{(SR)}), \tag{4}$$

will be encoded using error correcting codes and the resulting length-h codeword $z^{(R)} = \{z_1^{(R)}, z_2^{(R)}, ..., z_h^{(R)}\}$, $z_i^{(R)} \in \{+1, -1\}$, will be transmitted to the destination. Therefore the signal received by the destination will be given by

$$\mathbf{y}^{(RD)} = a_{RD}\mathbf{z}^{(R)} + \mathbf{n}^{(RD)}. \tag{5}$$

To keep the processing function energy efficient and simple we make hard decisions on $\mathbf{y}^{(SR)}$ at the relay. Therefore the processing function is given by

$$\mathbf{x}^R = \phi(\mathbf{y}^{(SR)}) = \sigma^{-1}(sign(\mathbf{y}^{(SR)})), \tag{6}$$

where sign(.) function returns +1 if the argument is positive and -1 if the argument is negative and $\sigma^{-1}(.)$ is the inverse of the $\sigma(.)$ function explained before.

The Rayleigh fading model is parameterized by $\bar{\gamma}$, the average signal-to-noise ratio, assuming unit noise power. Thus, in a fading channel, the four amplitudes $(a_{SD}, a_{SR}, a_{RD}, a_{CSD})$ are a four-dimensional vector of four independent Rayleigh-distributed random variables, parameterized by $(\bar{\gamma}_{SD}, \bar{\gamma}_{SR}, \bar{\gamma}_{RD}, \bar{\gamma}_{CSD})$.

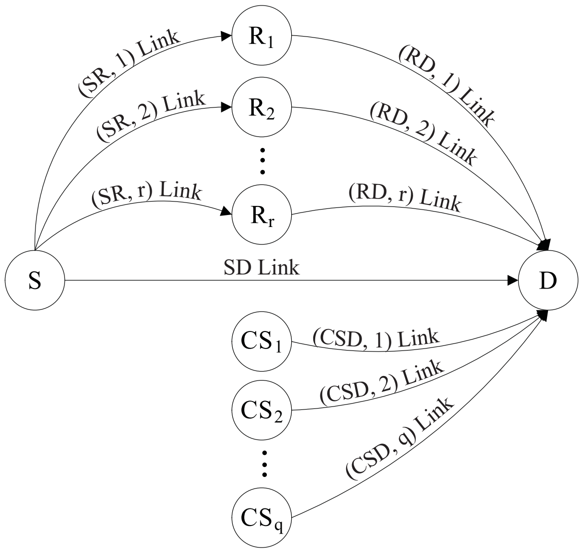

Fig. 2. Multi-relay, multi-correlated-source model.

B. Multi-relay and multi-correlated-source

Here we consider a system with r relays and q correlated sources as shown in Figure 2. Each relay and correlated source behaves as described in last section and the notion is similar to the one-relay case, with the following generalizations:

1) There are two index sets $I^{(R)} = \{1, 2, ..., r\}$ and $I^{(CS)} = \{1, 2, ..., q\}$ containing a unique index for each relay and correlated source respectively.
2) Channel amplitudes are $(a^{(SD)}, \mathbf{a}^{(SR)}, \mathbf{a}^{(RD)}, \mathbf{a}^{(CSD)})$, where $\mathbf{a}^{(SR)} = [a_1^{(SR)}, a_2^{(SR)}, ..., a_r^{(SR)}]$ and $\mathbf{a}^{(RD)} = [a_1^{(RD)}, a_2^{(RD)}, ..., a_r^{(RD)}]$ are the vectors of source-to-relay and relay-to-destination amplitude for each relay in $I^{(R)}$ respectively. Similarly $\mathbf{a}^{(CSD)} = [a_1^{(CSD)}, a_2^{(CSD)}, ..., a_q^{(CSD)}]$ is the vector of correlated source-to-destination amplitudes for each correlated source in $I^{(CS)}$.
3) The equations (1), (3) and (5) are changed as follows while the equation (2) remains unchanged,
$$\mathbf{Y}^{(SR)} = \mathbf{A}^{(SR)}\mathbf{Z}^{(S)} + \mathbf{N}^{(SR)}, \tag{7}$$
$$\mathbf{Y}^{(CSD)} = \mathbf{A}^{(CSD)}\mathbf{Z}^{(CS)} + \mathbf{N}^{(CSD)}, \tag{8}$$
$$\mathbf{Y}^{(RD)} = \mathbf{A}^{(RD)}\mathbf{Z}^{(R)} + \mathbf{N}^{(RD)}, \tag{9}$$
For (7), we define
$$\mathbf{Y}^{(SR)} := \begin{bmatrix} \mathbf{y}^{(SR,1)} \\ \mathbf{y}^{(SR,2)} \\ \vdots \\ \mathbf{y}^{(SR,r)} \end{bmatrix}, \mathbf{A}^{(SR)} := diag(\mathbf{a}^{(SR)}),$$
$$\mathbf{Z}^{(S)} := \begin{bmatrix} \mathbf{z}^{(S)} \\ \mathbf{z}^{(S)} \\ \vdots \\ \mathbf{z}^{(S)} \end{bmatrix}, \mathbf{N}^{(SR)} := \begin{bmatrix} \mathbf{n}^{(SR,1)} \\ \mathbf{n}^{(SR,2)} \\ \vdots \\ \mathbf{n}^{(SR,r)} \end{bmatrix}.$$
The superscript (R, i) for $i \in I^{(R)}$ refers to processes at the ith relay. Using similar technique we can define the $\mathbf{Y}^{(CSD)}$, $\mathbf{Y}^{(RD)}$, $\mathbf{A}^{(CSD)}$, $\mathbf{A}^{(RD)}$, $\mathbf{N}^{(CSD)}$ and $\mathbf{N}^{(RD)}$ for equations (8), (9). For equation (8) the index i is $i \in I^{(CS)}$ instead of $I^{(R)}$. The $\mathbf{Z}^{(CS)}$ and $\mathbf{Z}^{(R)}$, however are defined as
$$\mathbf{Z}^{(R)} := \begin{bmatrix} \mathbf{z}^{(R,1)} \\ \mathbf{z}^{(R,2)} \\ \vdots \\ \mathbf{z}^{(R,r)} \end{bmatrix}, \mathbf{Z}^{(CS)} := \begin{bmatrix} \mathbf{z}^{(CS,1)} \\ \mathbf{z}^{(CS,2)} \\ \vdots \\ \mathbf{z}^{(CS,q)} \end{bmatrix}.$$
where, $\mathbf{z}^{(R,i)}$ and $\mathbf{z}^{(CS,j)}$ are the bits to be transmitted to the destination by the ith relay and jth correlated source respectively.
4) In a Rayleigh fading scenario the channel amplitudes are given by $(\bar{\gamma}^{(SD)}, \bar{\gamma}^{(SR)}, \bar{\gamma}^{(RD)}, \bar{\gamma}^{(CSD)})$, representing respective vectors of average SNRs on each link.

III. Theoretical Results

In this section, we present our theoretical contributions. In particular we will show that the diversity order of the multi-relay multi-correlated-source system described in Section II will asymptotically drop to $\min(r + 1, q)$ (Theorem 1), where r is the number of relays and q is the number of correlated sources. Then in the next section we will propose an efficient way of implementing our system model and then present our simulation results.

Although our theoretical results indicate that the diversity order will asymptotically drop to $\min(r + 1, q)$ our simulations show that diversity order can be greater than $\min(r + 1, q)$ for $q > r + 1$, over SNR ranges of practical interest. Therefore, using correlated sources we can compress source's information bits and reduce the amount of information that needs to be relayed by the system while *increasing the diversity order of the system*. The extra bits being transmitted through the correlated sources belong to other sensors on the network transmitting their own information. Therefore, there is no increase in the system's total power. Finally we mention that using correlated sources the system can outperform a system with no correlated source in terms of frame error rate as it will be shown in our simulations.

A. Key assumptions and definitions

We consider the model given in Section II. We assume for convenience that the average SNR $\bar{\gamma}$ on every link is the same (but as show in [12] relaxing this assumption makes no difference to our results). As before, let r represent the number of relays in the system and q the number of correlated sources.

We define a system outage as the event where the overall probability of error between the source and destination fails to achieve a given frame error rate criterion. To describe asymptotic outage probabilities, designated P_{out}, we will be using the Θ order notation, where $g(x) = \Theta(f(x))$ means that there exists a constant c such that $\lim_{x\to\infty} f(x)/g(x) = c$. In Rayleigh fading, a system with diversity order d has probability of system outage $P_{out} = \Theta(\bar{\gamma}^{-d})$.

For a single link in Rayleigh fading, and given a minimum SNR γ_{min} to avoid system outage, it is easy to show that P_{out}

is given by

$$P_{out} = \Pr(\gamma < \gamma_{min}) = 1 - e^{-\eta\gamma_{min}/\gamma}, \qquad (10)$$

where η is a positive constant. Given the Taylor series expansion of e^x, it is easy to show that $1 - e^{-\eta\gamma_{min}/\gamma} = \Theta(\bar{\gamma}^{-1})$.

When using error-correcting codes, we assume that there exists an SNR $\gamma > 0$ so that the code (and its decoding algorithm) is equal or superior to using no coding for every SNR greater than γ. In other words, for sufficiently high SNR, the use of the code does not result in a higher probability of error than using no code. Also since we are using DISCUS as method of compression at the source, there is a certain probability of error in decompression, P_{out_Decomp}, given the system parameters, p (probability of decorrelation) and frame size. In other words in practice if the source's compressed syndrome bits and the correlated source's information bits are perfectly available at the destination there is still some probability P_{out_Decomp} that we cannot retrieve source's information bits successfully. We generally assume that $P_{out\_Decomp} = \epsilon$, a small negligible number.

With these definitions and assumptions in mind, we are now ready to present the main theoretical results of the paper.

B. Main Theoretical Results

In this section we start giving our theoretical results. We consider our multi-relay, multi-correlated-source model.

Theorem 1: The diversity order of the multi-relay, multi-correlated-source model with r relays and q correlated sources, described in section II, will asymptotically drop to $\min(r+1, q)$ for $0 \leq r, q < \infty$.

Proof: Let there be $\gamma_\circ^{(SD)}$ such that whenever $\gamma^{(SD)} < \gamma_\circ^{(SD)}$ the S-D link will be in outage. Also, let there be $\gamma_\circ^{(SRD,i)}$ for any relay i such SRD link through relay i is in outage whenever $\gamma^{(SRD,i)} < \gamma_\circ^{(SRD,i)}$. Here the SRD link is the combination of SR link and RD link. Therefore we can consider SRD link as $\gamma^{(SRD,i)} = \min \gamma^{(SR,i)}, \gamma^{(RD,i)}$. Then sufficient condition for system outage is that $\gamma^{(SD)} < \gamma_\circ^{(SD)}$ and $\gamma^{(SRD,i)} < \gamma_\circ^{(SRD,i)}$ for all i. We therefore have

$$P_{synd\_out} = \Pr(\gamma^{(SD)} < \gamma_\circ^{(SD)}) \prod_{i=1}^{r} \Pr(\gamma^{(SRD,i)} < \gamma_\circ^{(SRD,i)}) \qquad (11)$$

where P_{synd_out} is the probability that syndrome bits are not received at the destination. Since, by assumption, the average SNR for every channel is equal $\bar{\gamma}$, we have

$$\begin{aligned} P_{synd\_out} &= (1 - e^{-\eta\gamma_\circ^{(SD)}/\bar{\gamma}}) \prod_{i=1}^{r} (1 - e^{-\eta\gamma_\circ^{(SRD,i)}/\bar{\gamma}}) \\ &= \Theta(\bar{\gamma}^{-1})\Theta(\bar{\gamma}^{-r}) = \Theta(\bar{\gamma}^{-(r+1)}) \end{aligned}$$

Similarly, let there be $\gamma_\circ^{(CSD,j)}$ for any correlated source j such that whenever $\gamma^{(CSD,j)} < \gamma_\circ^{(CSD,j)}$ the CS-D link j will be in outage. Therefore the probability that the CS bits are not received at the destination is given by

$$P_{cs\_out} = \prod_{j=1}^{q} \Pr(\gamma^{(CSD,j)} < \gamma_\circ^{(CSD,j)}) \qquad (12)$$

where P_{cs_out} that correlated source information bits are not received at the destination. Again since the average SNR for every channel is equal $\bar{\gamma}$ we have

$$P_{cs\_out} = \prod_{j=1}^{q} (1 - e^{-\eta\gamma_\circ^{(CSD,i)}/\bar{\gamma}}) = \Theta(\bar{\gamma}^{-q})$$

In order to decode sources information bits both the syndrome and information bits from at least one of the correlated source must be available to the decoder (please note that we have assumed if these information are available perfectly at the decoder, the source's information bits can be decoded without any error). Therefore the system is in outage as a whole when either systematic bits are not available or correlated source's information bits are not available. We have

$$\begin{aligned} P_{out} &= P_{synd\_out} + P_{cs\_out} \\ &= \Theta(\bar{\gamma}^{-(r+1)}) + \Theta(\bar{\gamma}^{-q}) = \Theta(\bar{\gamma}^{-\min(r+1,q)}) \end{aligned}$$

Therefore the system has diversity order equal to $\min(r+1, q)$. ■

Although the system's diversity order drops asymptotically to $\min(r+1, q)$ we will show in the next section through simulations that at practical SNR regions is can be greater for $q > r+1$.

IV. Experimental Results

In this section we will give an efficient implementation of the system model given in section II. Then we will give our simulation results.

A. System Model Implementation

From Figure 1, we can see that in order to implement the system model we must specify a Slepian-Wolf compression method and a channel coding method for error correction. Since we are considering a sensor node with limited computation power the compression encoder and the channel encoder must have low complexity. Furthermore, the codes chosen need to be as powerful and efficient as possible. With these requirements, we will give a detailed explanation of each code.

For Slepian-Wolf compression DISCUS method [13] using low-density parity-check (LDPC) codes given in [15] are considered. In particular we will use regular LDPC codes. The encoder complexity is therefore in the order of $O(n)$ where n is the number of information bits at the source. Repeat-accumulate (RA) [19] codes are considered for channel coding and error correction. They are Turbo-like codes with a very simple encoding method, and have excellent performance, especially in low-SNR channels. Code rates are made adaptive by puncturing and therefore punctured systematic repeat accumulate codes (PSRA) are used.

Our simulation are all performed with the following parameters, unless specified otherwise. The number of information bits to be transmitted by the source and correlated source at each iteration is 4096. For compression, (3,6) regular LDPC codes are used. The repeat factor for PSRA code is 3. The SNR on all the links are the same. We also use normalized SNR which means $E_b/N_o = 1/(2R\sigma_n^2)$ where R is the total

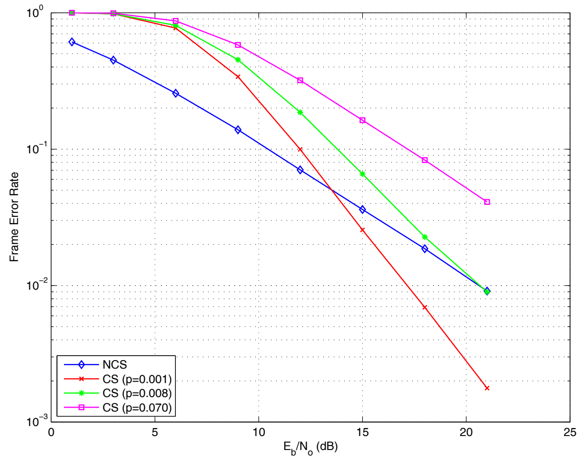

Fig. 3. Frame error rate of a system with no relay and three correlated sources in Rayleigh fading.

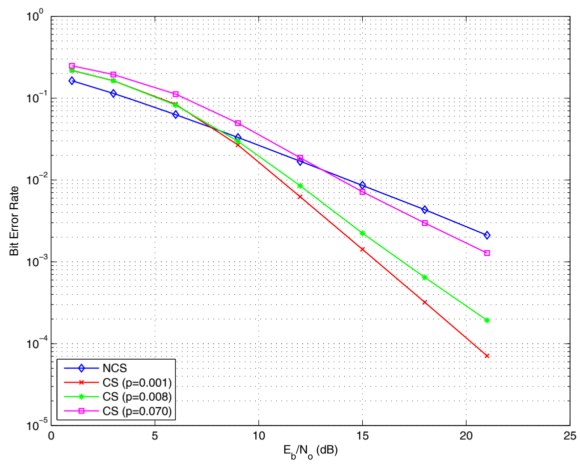

Fig. 4. Bit error rate of a system with no relay and three correlated sources in Rayleigh fading.

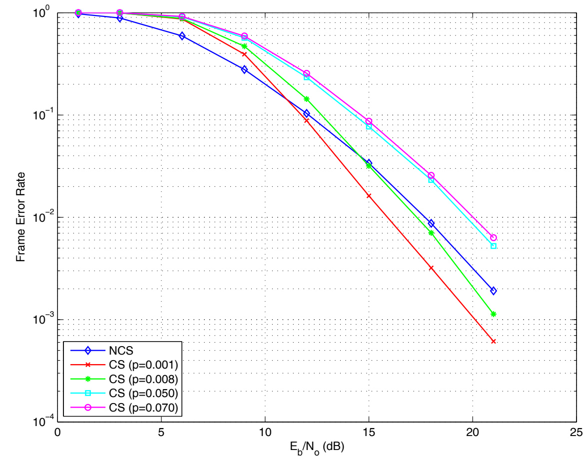

Fig. 5. Frame error rate of a system with a relay and three correlated sources in Rayleigh fading.

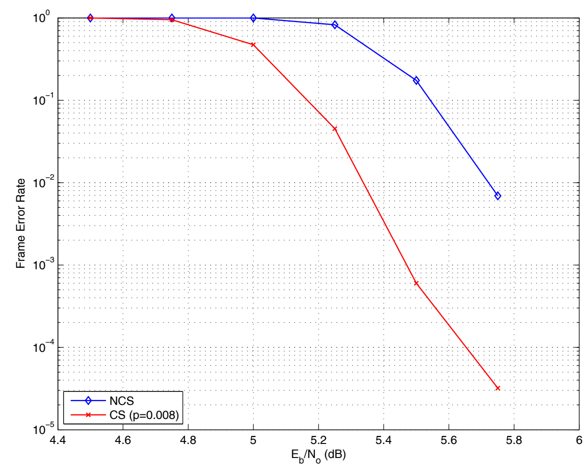

Fig. 6. Frame error rate of a system with a relay and three correlated sources in AWGN channel.

rate of the system and σ_n^2 the noise variance. As usual let r be the number of relays and q the number of correlated sources. With these coding schemes and parameters we are ready to present our simulation results in the next section.

B. Simulation Results

First we consider a system with zero relays. Therefore according to theorem 1 the diversity order of the system is 1 for $q \geq 1$. Figure 3, shows the frame error rate of such a system in Rayleigh fading channel. The 'NCS' curve is the system where there is no correlated source and no compression (i.e. there is a source and a destination node only). The source encodes its information bits using PSRA code and transmits them at the rate $R_S = 1/4$. Three bottom curves present systems with three correlated sources (i.e. a source, a destination and three correlated sources). The source's information bits are first compressed using the LDPC codes. The resulting syndrome bits are encoded using PSRA codes and are transmitted at the rate $R_S = 1/2$. Each correlated source will also encode its information bits using PSRA codes and transmit them at rate $R_{CS} = 1/2$. Therefore, the overall rate of the system for all 'CS' curves is $R_{sys} = 1/7$. From top to bottom each 'CS' represents $p = 0.07$, $p = 0.008$, and $p = 0.001$ respectively. Although the overall power of the two systems are not the same (i.e. the 'CS' systems transmit more bits than 'NCS'), nevertheless theorem 1 must hold. However, from simulation result we can see the slope of 'CS' curves go above one and they intersect the 'NCS' curve. As the value of the SNR increases to 21dB the middle curve 'CS (0.008)' begins to flatten towards diversity order one which is what theorem 1 predicted. Furthermore, as the correlation between source and correlated sources increases the pseudo diversity order increases. The bit error rates also roughly follows the same pattern as shown in Figure 4.

A system with one relay is considered next. Figure 5 shows the frame error rate of such a system in Rayleigh fading channel. Again the 'NCS' curve represents a system that does not have a correlated source and does not use compression while, 'CS' curves represent the system with correlated sources and compression. As explained before the source will encode its transmission bits (compressed syndrome bits or uncompressed information bits) using PSRA codes and transmits them at the rate $R_S = 1/2$. The relay will make hard decisions on the received bits re-encodes them using PSRA codes and transmits at the rate $R_R = 1/2$. Each of the three correlated source will also encode its information bits using PSRA codes and transmits at the rate $R_{CS} = 1/2$. The overall rate of the 'NCS' curve is therefore $R_{NCS} = 1/6$ while the overall rate of the 'CS' curves are $R_{sys} = 1/9$. From top to bottom each 'CS' represents $p = 0.07$, $p = 0.05$, $p = 0.008$, and $p = 0.001$ respectively. Although the overall power of the two systems are not the same (i.e. the 'CS' systems transmit more bits than 'NCS') according to theorem 1 the diversity order of both systems must asymptotically drop to two. However, from Figure 5 we can clearly see at practical SNR values, the diversity order of more than two is achievable.

The final figure, Figure 6, compares the performance of a system with no correlated source and no compression versus a system with a correlated source and compression in AWGN channel. The 'CS' curve has a single relay and a single correlated source while 'NCS' curve has a single relay and no correlated source. The rates of transmission are $R_S = 1/2$, $R_R = 1/2$ and $R_{CS} = 1/2$. The overall rate of the 'NCS' curve is therefore $R_{NCS} = 1/6$ while the overall rate of the 'CS' curve is $R_{sys} = 1/5$. The correlation between the source and correlated source is given by $p = 0.008$. Although in this case the 'CS' curve has higher rate and hence lower power requirements we can see it outperforms the 'NCS' curve.

V. Conclusion and Future Work

Data gathered by sensor networks usually have strong spatial correlation. Therefore, this paper has studied the effects of Slepian-Wolf compression on the diversity order of a cooperative wireless sensor network. Our theoretical and practical results suggest several interesting avenues for future and continuing work, such as exploring the effects of correlated sources on fractional cooperation proposed in [12]. Furthermore, future work will investigate the diversity order at practical SNR values given the system parameters. In particular given a system parameters at which SNR regions we will see an increase in diversity order.

References

[1] C.-Y. Chong and S. P. Kumar, "Sensor networks: evolution, opportunities and challenges," *Proc. IEEE*, vol. 91, pp. 1247-1256, Aug. 2003.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-part I: system description," *IEEE Trans. Commun.*, vol. 51, pp. 1927-1938, Nov. 2003.

[3] D. Slepian and J. Wolf, "Noiseless coding of correlated information sources," *IEEE Trans. Inform. Theory*, vol. 19, pp. 471-480, July 1973.

[4] M. Janani, A. Hedayat, T. E. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: space-time transmission and iterative decoding," *IEEE Trans. Signal Processing*, vol. 52, pp. 362-371, Feb. 2004.

[5] B. Zhao and M. C. Valenti, "Practical relay networks: a generalization of Hybrid-ARQ," *IEEE J. Select. Areas Commun.*, vol. 23, pp. 7-18, Jan. 2005.

[6] J. Castura and Y. Mao, "Rateless coding over fading channels," *IEEE Commun. Lett.*, vol. 10, pp. 46-48, Jan. 2006.

[7] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1470-1476, Sept. 2004.

[8] Z. Zhang and T. M. Duman, "Capacity-approaching Turbo coding and iterative decoding for relay channels," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1895-1905, Nov. 2005.

[9] G. Kramer, "Distributed and layered codes for relaying," *in Proc. 39th Asilomar Conf. on Signals, Systems and Computers*, Pacific Grove, CA, pp. 1752-1756, Nov. 2005.

[10] P. Razaghi and W. Yu, "Bilayer low-density parity-check codes for decode-and-forward in relay channels," *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 37233739, 2007.

[11] J. Hu and T. M. Duman, "Low density parity check codes over halfduplex relay channels," *in Proc. IEEE Int. Symp. Info. Theory*, Seattle, WA, pp. 972-976, July 2006.

[12] A. W. Eckford, J. P. K. Chu, and R. S. Adve, "Low complexity and fractional coded cooperation for wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1917-1929, May 2008.

[13] S. Pradhan and K. Ramachandran, "Distributed source coding using syndromes (discus): Design and construction," *In Proc. IEEE DCC*, pp. 158-167, march 1999.

[14] J. Garcia-Frias and Y. Zhao, "Compression of correlated binary sources using turbo codes," *IEEE Commun. Lett.*, vol. 5, no. 10, pp. 417-419, 2001.

[15] A. Liveris, Z. Xiong, and C. N. Georghiades, "Compression of binary sources with side information using low-density parity-check codes," *in Proc. IEEE Global Telecommunications Conference (GLOBECOM '02)*, vol. 2, pp. 1300-1304, November 2002.

[16] A. D. Liveris, Z. Xiong, and C. N. Georghiades, "Joint sourcechannel coding of binary sources with side information at the decoder using IRA codes," *in Proc. IEEE Multimedia Signal Processing Workshop*, pp. 53-56, St. Thomas, Virgin Islands, USA, December 2002.

[17] W. Zhong and J. Garcia-Frias, "LDGM Codes for Channel Coding and Joint Source-Channel Coding of Correlated Sources," *EURASIP Journal on Applied Signal Processing*, pp. 942-953, May 2005.

[18] R. Hu and J. Li, "Exploiting slepian-wolf codes in wireless usercooperation," *in IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, vol. 2005, pp. 275–279, 2005.

[19] Y. Zhao, W. Zhong, and J. Garcia-Frias, "Transmission of correlated senders over a Rayleigh fading multiple access channel," *Signal Processing*, vol. 86, no. 11, pp. 3150–3159, Nov. 2006.

[20] M. Sartipi and F. Fekri, "Source and channel coding in wireless sensor networks using LDPC codes," in *Proc. Conference on Sensor and Ad Hoc Communicaitons and Networks (SECON)*, pp. 309–316, 2004.

[21] D. Divsalar, H. Jin, and R. J. McEliece, "Coding theorems for 'Turbo-like'codes," *in Proc. 36th Annual Allerton Conference on Communications, Control, and Computing*, Monticello, IL, USA, pp. 201–210, Sept. 1998.