

# Correlated Sources over a Noisy Channel: Cooperation in the Wideband Limit

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**Abstract**—”THIS PAPER IS ELIGIBLE FOR THE STUDENT PAPER AWARD”. This paper studies cooperation amongst transmitters in a two-user Gaussian multiple access channel (MAC) with correlated sources in the wideband limit. The paper’s findings can be intuitively stated as follows: if the two sources are sufficiently (highly) correlated, then full cooperation amongst the transmitters is possible in the wideband limit incurring an arbitrarily small *bit error rate* during the process of communicating them to the receiver, i.e., the system behaves like a two-antenna single user system.

The core idea behind this paper is to use pulse-position modulation and to allow signals from the two transmitters to coherently combine with one another. This result also emphasizes the difference between bit-error and block-error rates. Whereas cooperation is very difficult to establish when achieving arbitrarily small block error rates, it can be enabled when the objective is to achieve arbitrarily small bit error rates and the sources are highly correlated.

## I. INTRODUCTION

There are significant advantages to enabling cooperation amongst nodes in a network, and a multitude of different strategies for doing so have been investigated in literature [1]–[10]. Cooperation is, however, typically difficult to accomplish in a multiple access channel where there is no additional interaction between the transmitters [11].

Hitherto, a majority of the literature on cooperation, and in general in Information Theory, is based on the goal of achieving an arbitrarily small maximal block error rate in the system. In some systems such as the single user communication system, the choice of block-error vs. bit-error as being constrained has limited impact on the asymptotic energy per bit required in the system in the wideband limit. Interestingly, this paper finds that, for multiple access channels, the choice of constraint makes all the difference - with bit-error rates being constrained to be arbitrarily small, full cooperation may be possible amongst two distributed nodes in the network with no information exchange between the nodes of the network.

Our motivating scenario for this study is a sensor network as shown in Fig. 1. The two transmitters are neighboring sensors, intending to communicate highly related information to the receiver. (This notion of highly related, as well as that of bit error rate is formally defined in Section II) The data to be transmitted by each transmitter is assumed to be integer valued. Such an integer value, may, for instance, results from

the quantization of a real observation<sup>1</sup> While minimize block error is highly relevant for data transfers, bit-error usually takes on a more important role in communicating digitized versions of otherwise real-valued sources.

The results in this paper are motivated in part by the results obtain in [12]. A modified pulse position modulation scheme (PPM) is used in this paper to achieve coherent combining of signals. PPM is a relatively popular scheme for sensor networks [13], and, as it emerges, well suited for correlated source transmission on these networks.

This paper follows a relatively straightforward progression. Section II describes the system model, while Section III presents the main theorem and its proof. The paper concludes with Section IV.

## II. SYSTEM MODEL

Our focus in this paper is on a two-user Gaussian MAC as follows:

$$y(t) = x_1(t) + x_2(t) + z(t), \quad (1)$$

where  $x_i(t)$  is User  $i$ ’s ( $i = 1, 2$ ) transmit signal and  $z(t)$  the channel noise (assumed Gaussian).

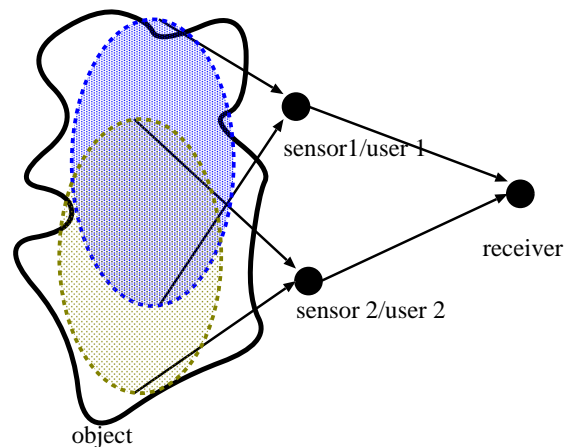


Fig. 1. System model

<sup>1</sup>There are varied origins for the correlation between the integer-valued sources, most of which go beyond the scope of this paper.

As is conventional with analysis of communication systems in the wideband regime, our goal is to determine the minimum energy per bit ( $\mathcal{E}_b|_{min}$ ) required to *collaboratively* communicate the two transmit messages to the receiver. As an example, in a wideband point-to-point system the  $\mathcal{E}_b|_{min}$  is  $\log 2 = -1.59\text{dB}$  [14].

In the next two subsections, we detail the most important parts of our system - bit-error rate and source-correlation models.

#### A. Bit Error Rate

The sources  $U, V$  at each transmitter are assumed to be non-negative integer valued *uniform sources* with *exactly* equal alphabet sizes<sup>2</sup>;  $\mathcal{U} = \{0, 1, \dots, 2^n - 1\}, \mathcal{V} = \{0, 1, \dots, 2^n - 1\}$ .

Consider a function  $B(k)$  which returns the minimum number of necessary bits to represent an integer  $k$  of either source  $U$  or  $V$ . If  $\hat{k}$  is the decoded work for  $k$ , we define *bit error rate*  $P_e$  as

$$P_e \triangleq \mathbb{E}_{\hat{k}, k} \frac{B(|k - \hat{k}|)}{B(k)} \quad (2)$$

where  $\mathbb{E}$  is expected value over the joint distribution of  $k$  and  $\hat{k}$ , and  $|\cdot|$  returns the absolute value of a number.

To provide further insight into this definition, consider the following example. Given that  $U$  is a uniform source, we have  $B(k) = n$ . Further, if our communication strategy ensures that every  $k \in \mathcal{U}$  has an error bounded as  $|k - \hat{k}| \in \{0, 1, \dots, o(2^n)\}$  then we have

$$P_e = \mathbb{E}_{\hat{k}, k} \frac{B(|k - \hat{k}|)}{B(k)} \leq \frac{\log_2 o(2^n)}{n} = \frac{o(n)}{n} \rightarrow 0 \quad (3)$$

as  $n \rightarrow \infty$ .

#### B. Correlation Model

The two sources  $U$  and  $V$  are assumed to be heavily correlated, with a correlation behaving as:

For  $i \in \mathcal{U}$  and  $j \in \mathcal{V}$

$$|i - j| \in \{0, \dots, O(n^\alpha)\} \text{ s.t. } 0 \leq \alpha < 1. \quad (4)$$

In words, this means that if  $2^n$  messages are to be transmitted from both sources, the two messages, when represented as integers, are less than or equal to  $K_1 n^\alpha$  apart for a constant  $K_1$  for large  $n$ , i.e. they are highly correlated.

#### C. The Transmission Process

The transmitters are also assumed to be constrained by energy limits per symbol as  $\mathcal{E}_s$ . Time is assumed to be slotted and the transmitters are assumed to be time-synchronized. Each transmitter sends a  $2^n + n^\beta - 1$ -length vector signal, where the entry  $j$  in the vector is the transmit-signal at time instant  $j$ . In this setting,  $\beta$  is any positive real number such

that  $1 > \beta > \alpha$ . If  $k$  is the message for Transmitter  $i \in \{1, 2\}$ , this vector is given by:

$$x(k) = \left( 0, \dots, \underbrace{\frac{\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}}, \dots, \frac{\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}}}_{n^\beta}, \dots, 0 \right), \quad (5)$$

where the nonzero entries are from the  $(k)$ th position to the  $(k+n^\beta)$ th position in the  $2^n + n^\beta - 1$  vector. In essence, a "pulse" is transmitted, where the position of the pulse emitted by Transmitter  $i$  depends on its message  $k$ .

#### D. The Receive Chain

We use  $n^\beta$ -sized detection windows at the receiver to decode the received signal as illustrated in Fig. 3. There are a total of  $2^n$  such (overlapping) windows, characterized by

$$w_m = \begin{cases} 1 & [m \dots m + n^\beta] \\ 0 & \text{otherwise} \end{cases}$$

$$\forall m \in \{0, 2^n - 1\}.$$

The detection scheme to be used is a simple inner product based scheme given by:

$$\hat{k} = \arg \max_{m \in \{0, \dots, 2^n - 1\}} y \circ w_m, \quad (6)$$

where  $\circ$  is the inner-product between the two vectors.

### III. SYSTEM ANALYSIS

In this section, we show that the two-user Gaussian MAC as described in Section II that uses "pulse-position" based transmission and reception schemes has full cooperation enabled for a large enough  $n$  in the wideband limit. To do this, we first characterize the net transmit signal when both transmitters apply the transmission scheme. We then analyze the bit-error rate of the decoding scheme, showing that the minimum energy per bit required for it to decay is  $0.5 \log 2$ .

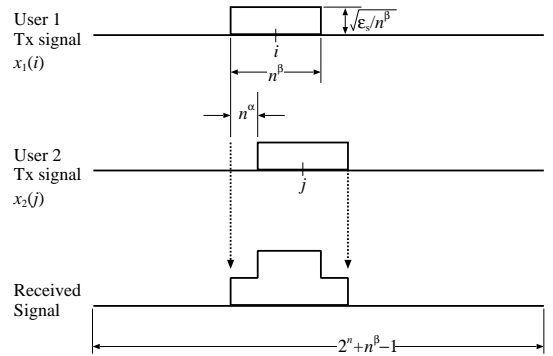


Fig. 2. Transmitted and Received signals by a modified PPM. AWGN is not shown here.

<sup>2</sup>This assumption can be relaxed, but such a relaxation complicates notation and diverts attention from the core of the solution.

### A. Synchronized Transmit Signal

Let  $i \in \mathcal{U}$  and  $j \in \mathcal{V}$  be the correlated messages as in subsection II-B. The "worst-case" scenario is when the two sources are as far apart as possible, i.e., when  $|i - j| = \Theta(n^\alpha)$ . For illustrative purposes and concreteness, we set  $|i - j|$  to exactly equal  $n^\alpha$ . Note that we will proceed with the remainder of our analysis under this setting. The generalization of the proof to  $|i - j| = o(n^\alpha)$  is straightforward (grunge-work) and is thus omitted from the document.

Without loss of generality, we have  $i \leq j$ . A synchronized transmit signal from two transmitters is the following expression as in Fig. 2:

$$= \begin{pmatrix} x_1(i) + x_2(j) \\ 0, \dots, \frac{\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}}, \dots, \underbrace{\frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}}, \dots, \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}}}_{n^\beta - n^\alpha \text{ duration}}, \frac{\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}}, \dots, 0 \end{pmatrix}, \quad (7)$$

where non-zero entries above are from ( $i$ )*th* until the ( $j + n^\beta$ )*th* positions.

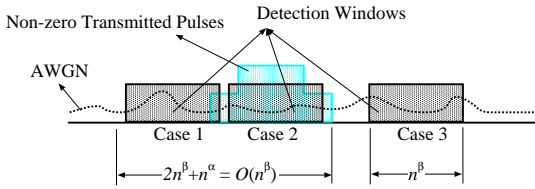


Fig. 3. Received signals with AWGN and detection windows

### B. Received Signal with the Detection Windows

**Important:** Note that although two messages  $i, j$  are sent, *only one message* is  $\hat{k}$  is detected by the receiver using the policy given by 6).

The ser of all possible received signals using this detection window are divided into three cases as in Fig. 3.

- 1) A portion of the detection window overlaps with in the non-zero entries of the net transmit pulse (7). This is Case 1 in Fig. 3
- 2) The detection window is fully located in the inside the non-zero portion of the net transmit pulse, which is Case 2 in Fig. 3. In this case, the received signal  $y \circ w_m$  can be simplified to the expression

$$y \circ w_m = \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} (n^\beta - n^\alpha) + \frac{\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} \cdot n^\alpha + \sum_{i \in I_m} Z_i, \quad (8)$$

where  $I_m$  is the index set for the detection window  $w_m$  and  $Z_i$ 's are i.i.d. Gaussian noise variables with zero mean and unit variance, i.e.,  $Z_i \sim \mathcal{N}(0, 1)$ .

- 3) The detection window is completely outside the non-zero portion of the net transmit signal as depicted in Case 3 in Fig. 3. In this case, the received signal purely a sum of Gaussian (noise) variables, i.e. it equals

$$y \circ w_m = \sum_{i \in I_m} Z_i \quad (9)$$

In summary, after its first step of processing the receiver ends up with a length  $2^n$  vector containing values that are either a) just a sum of noise elements; or b) sum of noise with some portion of signal or c) sum of noise and signal given by (8). It then picks the largest value from this vector, declaring the position at which it occurs as the message. If multiple positions offer the maximum, it picks any one of those at random as its decoded message.

### C. Error Analysis

The stage is now set for us to determine the net probability of error incurred from this process.

Given that messages  $i$  and  $j$  were sent from Transmitters 1 and 2 respectively and were jointly decoded to a message  $\hat{k}$ , an error occurs if either  $|\hat{k} - i|$  or  $|\hat{k} - j|$  behaves as  $\Omega(n)$ . In short, if the (real-valued) distance between the decoded message and either of the two messages is large, we incur an error.

Note that

$$P_e \leq P_{e,1} + P_{e,2}, \quad (10)$$

where  $P_e$  is the overall bit-error rate and  $P_{e,k}$ 's are the bit-error rates for the message of Transmitter  $k$ , i.e.,  $P_{e,1} = \frac{B(|i - \hat{k}|)}{B(i)}$  and  $P_{e,2} = \frac{B(|j - \hat{k}|)}{B(j)}$ . Note that if both  $P_{e,i} \rightarrow 0$  for  $i = 1, 2$ , then  $P_e \rightarrow 0$ .

Next, consider the following error events,  $S_e$ , as

(3).

$$S_e = \left\{ \hat{k} : \frac{B(|i - \hat{k}|)}{B(i)} > \delta \right\} \cup \left\{ \hat{k} : \frac{B(|j - \hat{k}|)}{B(j)} > \delta \right\}, \quad (11)$$

for some positive  $\delta$ . It is clear that if  $\mathbb{P}(S_e)$  decreases to zero as  $n$  increases, then  $P_e$  can be made arbitrarily small.

It is with this motivation that we introduce the following four sets: For  $0 < \alpha < \beta < 1$ , we have:

$$\begin{aligned} S_1 &= \left\{ \hat{k} : |i - \hat{k}| = \omega(n^\beta) \ \& \ |j - \hat{k}| = \omega(n^\beta) \right\} \\ S_2 &= \left\{ \hat{k} : |i - \hat{k}| = \omega(n^\beta) \ \& \ |j - \hat{k}| = O(n^\beta) \right\} \\ S_3 &= \left\{ \hat{k} : |i - \hat{k}| = O(n^\beta) \ \& \ |j - \hat{k}| = \omega(n^\beta) \right\} \\ S_4 &= \left\{ \hat{k} : |i - \hat{k}| = O(n^\beta) \ \& \ |j - \hat{k}| = O(n^\beta) \right\}. \end{aligned}$$

*Lemma 1:*  $S_2$  and  $S_3$  are empty sets for large  $n$  given that  $|i - j| = O(n^\alpha)$ .

*Proof:* Intuitively,  $S_2$  and  $S_3$  correspond to scenarios where the decoded word is "close" to one of the messages and "far" from the other. In other words,  $\hat{k}$  represents one of them with a small bit-error while the other has a possibly non-diminishing bit error. Noting that the two sources are correlated, this is not possible as it contradicts the triangular inequality.

Formally, Let us show first that  $S_2$  is an empty set. Since the absolute value of difference between two integers satisfies

the properties of a distance metric, it satisfies the following triangle inequality property:

$$|i - \hat{k}| \leq |i - j| + |j - \hat{k}|, \quad (12)$$

For  $S_2$ , we have  $|i - \hat{k}| = \omega(n^\beta)$ ,  $|i - j| = O(n^\alpha)$  and  $|j - \hat{k}| = O(n^\beta)$ . From (12), we get

$$\omega(n^\beta) \leq O(n^\alpha) + O(n^\beta),$$

which is impossible for large  $n$ . Therefore  $S_2$  is an empty set. Similarly,  $S_3$  is also an empty set. ■

*Lemma 2:* If the decoded message  $\hat{k} \in S_4$ , then the error in transmission can be reduced to an arbitrarily small value for a large enough  $n$ .

*Proof:* In this case,

$$B(|i - \hat{k}|) = \log_2 O(n^\beta) = O(\log_2 n) = o(n).$$

Similarly,  $B(|j - \hat{k}|) = o(n)$ . Then from (10)

$$P_e \leq \frac{B(|i - \hat{k}|)}{B(i)} + \frac{B(|j - \hat{k}|)}{B(j)} = \frac{o(n)}{\Theta(n)} + \frac{o(n)}{\Theta(n)} \rightarrow 0$$

as  $n \rightarrow \infty$ . ■

In summary, *Lemma 1* and *Lemma 2* show that  $S_e \subset S_1$ . Thus, to characterize the probability of  $S_e$ , it is in fact sufficient to bound it by the probability of  $S_1$ . Mainly, showing that the probability of  $S_1$  can be made arbitrarily small is sufficient to show that the same is true for the probability of  $S_e$ .

Now, let us investigate what  $\hat{k} \in S_1$  translates into for the decoding algorithm. Define sets  $R_i$ ,  $i = 1, 2, 3$  for  $\hat{k}$  as follows:

$$R_i = \{m : w_m \text{ belongs to Case } i\}. \quad (13)$$

Also, let  $\mathcal{I}_i$  be the set of index sets of all  $w_m \in \text{Case } i$ . *Lemma 2* indicates that *neither*  $\hat{k} \in R_1$  nor  $\hat{k} \in R_2$  result in an error at the receiver. Specifically, the only case when error is possible is when  $\hat{k} \in R_3$ . Please note that not every  $\hat{k} \in R_3$  leads to an error, but that all the  $\hat{k}$  that result in error belong to  $R_3$ .

Define the event  $R_e$  as

$$R_e = \left\{ \max_{l \in R_3} y \circ w_l > (y \circ w_m, m \in R_2) \right\}.$$

From the definition of  $R_3$ , we automatically have that  $\mathbb{P}(R_3) \leq \mathbb{P}(R_e)$ . In addition, we also know that

$$S_e \subseteq S_1 \subseteq R_3. \quad (14)$$

And thus we get

$$\mathbb{P}(S_e) \leq \mathbb{P}(R_e). \quad (15)$$

This enables us to say that if  $\mathbb{P}(R_e) \leq \epsilon$  for large  $n$ , then  $P_e \leq \epsilon$ .

Here, we introduce the main theorem of this paper.

*Theorem 3:*  $P_e$ , the probability of bit error for a two user Gaussian MAC can be made arbitrarily small if  $\mathcal{E}_b|_{\min} > \frac{1}{2} \log 2$ . That is to say, half of minimum bit energy for

point-to-point AWGN wideband communication is needed to communicate two highly correlated sources across the channel.

*Proof:* Let us rewrite  $\mathbb{P}(R_e)$  as:

$$\begin{aligned} \mathbb{P}(R_e) &= \mathbb{P} \left( \max_{I \in \mathcal{I}_3} \frac{\sum_{i \in I} Z_i}{n^\beta} \right. \\ &> \left. \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} + \frac{\sum_{i \in I'} Z_i}{n^\beta} \text{ s.t. } I' \in \mathcal{I}_2 \right). \end{aligned} \quad (16)$$

Note that all  $Z_i$ 's are i.i.d.  $\mathcal{N}(0, 1)$  random variables, and so

$$N_I \triangleq \frac{\sum_{i \in I} Z_i}{n^\beta} \sim \mathcal{N} \left( 0, \frac{1}{\sqrt{n^\beta}} \right)$$

since the detection window index set is  $n^\beta$ -sized. Then (16) has the following expression

$$\mathbb{P} \left( \max_{I \in \mathcal{I}_3} N_I > \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} + N_{I'} \text{ s.t. } I' \in \mathcal{I}_2 \right) \quad (17)$$

For any real number  $\gamma$  we get the following relation:

$$\begin{aligned} &\mathbb{P} \left( \max_{I \in \mathcal{I}_3} N_I > \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} + N_{I'} \text{ s.t. } I' \in \mathcal{I}_2 \right) \\ &\leq \mathbb{P} \left( \max_{I \in \mathcal{I}_3} N_I > \gamma \right) + \mathbb{P} \left( \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} + N_{I'} \leq \gamma \right). \end{aligned} \quad (18)$$

Pick a  $\gamma$  as follows:

$$\gamma = \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} - \delta \quad (19)$$

where  $\delta > 0$ .

First, let us focus on the  $\mathbb{P} \left( \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} + N_{I'} \leq \gamma \right)$ .

Then

$$\begin{aligned} \mathbb{P} \left( \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} + N_{I'} \leq \gamma \right) &= \mathbb{P}(N_{I'} \leq -\delta) \\ &= Q(\sqrt{n^\beta} \delta) \end{aligned} \quad (20)$$

where  $Q(x)$  is Q-function from Gaussian distribution, i.e.,

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt.$$

Since (20)  $\rightarrow 0$  as  $n^\beta \rightarrow \infty$ , we have for large enough  $n$

$$\mathbb{P} \left( \frac{2\sqrt{\mathcal{E}_s}}{\sqrt{n^\beta}} - \frac{\sqrt{\mathcal{E}_s} n^\alpha}{\sqrt{n^\beta} n^\beta} + N_{I'} \leq \gamma \right) \leq \epsilon.$$

Next, let us look at the  $\mathbb{P}(\max_{I \in \mathcal{I}_3} N_I > \gamma)$ . We find conditions under which  $\mathbb{P}(\max_{I \in \mathcal{I}_3} N_I > \gamma) \rightarrow 0$ . We have the following inequalities:

$$\mathbb{P} \left( \max_{I \in \mathcal{I}_3} N_I > \gamma \right) < 2^n \cdot \mathbb{P}(N_I > \gamma) \quad (21)$$

$$= 2^n \cdot Q(\sqrt{n^\beta} \gamma) \quad (22)$$

$$\leq 2^n \cdot \frac{1}{2} \exp \left( -\frac{\gamma^2 \cdot n^\beta}{2} \right) \quad (23)$$

$$\leq 2^n \cdot \exp \left( -\frac{\gamma^2 \cdot n^\beta}{2} \right), \quad (24)$$

where we use the fact that  $|\mathcal{I}_3| < 2^n$  and use a Chernoff bound on the Q-function.

Here,  $2^n = \exp(n \log 2)$  and  $\mathcal{E}_s = n\mathcal{E}_b$  from  $2^n$  symbols. Then (24) is expressed from (19) as

$$\exp\left(n \log 2 - \frac{\gamma^2 \cdot n^\beta}{2}\right) \quad (25)$$

$$= \exp\left(-\frac{\left(\frac{2\sqrt{n\mathcal{E}_b}}{\sqrt{n^\beta}} - \frac{\sqrt{n\mathcal{E}_b}n^\alpha}{\sqrt{n^\beta n^\beta}} - \delta\right)^2 n^\beta - 2n \log 2}{2}\right)$$

$$= \exp\left(-\frac{4n\mathcal{E}_b - 2n \log 2 + (\text{rest terms})}{2}\right) \quad (26)$$

$$= \exp\left(-\frac{4n\left(\mathcal{E}_b - \frac{1}{2} \log 2\right) + o(n)}{2}\right), \quad (27)$$

where (rest terms) above are as follows:

$$\frac{n\mathcal{E}_b}{n^{2(\beta-\alpha)}} + n^\beta \delta^2 - \frac{4n\mathcal{E}_b}{n^{\beta-\alpha}} - 4n^{\frac{\beta+1}{2}} \mathcal{E}_b \delta + \frac{n^{\frac{\alpha+1}{2}}}{n^{\frac{\beta-\alpha}{2}}} 2\sqrt{\mathcal{E}_b} \delta$$

Therefore if  $\mathcal{E}_b > \frac{1}{2} \log 2$ , then (27) goes to zero as  $n \rightarrow \infty$ . ■

This means that only half of energy per bit is necessary to communicate using two distributed sources with correlated information, which is as if the two transmitters were "fully cooperating".

#### IV. CONCLUSION

In this paper, we find that full cooperation (i.e., half the energy-per-bit compared to a single user setting) is possible in a Gaussian two-user MAC if the bit-error-rate is constraint to an arbitrary non-negative value. This is enabled with only timing synchronization among transmitters, and with no other coordination or information exchange between them, provided the sources at each transmitter are highly correlated.

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