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Analog Joint Source Channel Coding for Gaussian Multiple Access Channels

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Abstract. We investigate the problem of transmiting independent sources over the Gaussian Multiple Access Channel (MAC) using a CDMA-like access scheme that allows users to transmit at different rates. Rather than using standard digital communications systems, we focus on analog joint source-channel coding techniques to encode each user's source. We analyze the performance of the proposed scheme and demonstrate its optimality. Simulation results with practical analog joint source-channel codes optimized for point-to-point communications show that the resulting performance is very close to the theoretical limits.

Keywords: Analog Joint Source Channel Coding, Multiple Access Channels, CDMA.

1 Introduction

The use of digital communications systems based on the Shannon separation principle between source and channel coding [1] has led to ubiquitous communications in our society. In this framework, continuous signals are first acquired and source encoded in the digital domain, and then sent over a channel using digital transmission methods. It is well known that in point-to-point communications this approach is optimal provided that there are no constraints in terms of complexity and delays. However, to approach the optimal distortion-cost trade-off, sources have to be compressed using powerful quantization and encoding methods, and data has to be transmitted using digital channel codes. The utilization of capacity approaching digital source and channel codes requires significant delay and high computational complexity. Moreover, full redesign of the digital system is required whenever we want to change either the data rate or the distortion target.

Recently, systems based on analog joint source-channel coding have been discussed in the literature [2–4]. In this approach, the concatenation of the (vector) quantizer, the source encoder and the channel encoder typical of digital systems is substituted by an end-to-end analog encoder. This discrete-time, continuous-amplitude system directly processes the acquired samples using a non-linear

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transformation, whose output is transmitted directly through the channel after proper modulation. For the same performance, these schemes may present more robustness and require less encoding/decoding complexity than traditional digital systems.

Most of the work on analog coding (see [2, 3, 5, 6] and references therein) deals with transmission of memoryless sources over AWGN channels or static wireless channels, but recent extensions to optical environments, relay channels and MIMO systems have appeared in the literature [7–9]. In all these cases, the resulting performance is very close to the theoretical limits, while requiring less complexity than traditional digital schemes. In this paper, we extend the use of analog joint source-channel coding to Multiple Access Channels (MAC). Specifically, we encode each user's data by applying space-filling curves as those used in point-to-point analog joint source-channel coding schemes and then utilize a CDMA-like access scheme. Different from standard CDMA, the input to the access scheme is an analog value, but the basic idea of orthogonalizing the channel still holds.

Previous work on analog joint source-channel coding for the MAC has focused on the two user case and includes the work in [10], which extends the Nested Quantization digital technique proposed in [11]. The technique used in [10] is called Scalar Quantizer Linear Coding (SQLC) and, to our knowledge, it provides the best results so far for the two-user MAC using analog joint source-channel coding. Different from this work, our scheme utilizes standard analog mappings (designed for point-to-point communication) and achieves a performance very close to the theoretical limits.

The remainder of the paper is organized as follows. Section 2 presents the proposed CDMA-like access scheme. Analysis is performed and the optimality of the scheme is proved for several cases of interest. Section 3 introduces analog joint source-channel coding, discusses the theoretical limits and proposes practical systems for several cases of interest. Section 4 presents the simulation results and section 5 concludes the paper.

2 Proposed CDMA-Like Access Scheme

Let us assume a Multiple Access Channel (MAC) with N users. User i data, x^i, is transmitted to a common receiver so that

$$y = \sum_{i=1}^{N} x^i + z, \tag{1}$$

where z is i.i.d AWGN with zero mean and variance σ_z^2. Without loss of generality, we assume that the noise power is unity, $\sigma_z^2 = 1$. Let P_i be the i-th user received power per channel use. The different rates users may achieve, R_i, $i = 1, \ldots, N$ must satisfy the following inequalities $\forall J \subset \mathcal{P}(\{1, 2 \cdots N\})$, where $\mathcal{P}(\cdot)$ is the power set [12]

$$\sum_J R_i \leq \frac{1}{2} \log_2(1 + \sum_J P_i) \qquad \forall i \in J. \tag{2}$$

where

Equation (2) defines a polyhedron in N dimensions, and each inequality in (2) defines an edge of the polyhedron. The *maximum* sum rate is

$$\sum_{i=1}^{N} R_i \leq C_{MAC} = \frac{1}{2}\log_2(1 + \sum_{i=1}^{N} P_i). \tag{3}$$

For the N users to transmit over the MAC, we propose the utilization of a $K \times K$ orthogonal codebook, $\mathbf{C}_{K\times K}$, with $K \geq N$. To that end, we start off with an orthogonal matrix of size K, such as the Hadamard matrix, and assign m_i columns to user i so that $\sum_{i=1}^{N} m_i = K$. We then scale each user's columns by $\eta_i = \frac{1}{\sqrt{m_i}}$. The scaled columns assigned to user i are denoted by $\underline{\mu}_1^i\ \underline{\mu}_2^i\ \cdots \underline{\mu}_{m_i}^i$. As shown in Figure 1, we group the columns assigned to user i into one submatrix denoted by $\mathbf{C}_{K\times m_i} = [\underline{\mu}_1^i\ \underline{\mu}_2^i\ \cdots \underline{\mu}_{m_i}^i]$. This $\mathbf{C}_{K\times m_i}$ is the access codebook that user i uses to send the data as explained in Figure 2.

$$\mathbf{C}_{K\times K} = [\mathbf{C}_{K\times m_1}|\mathbf{C}_{K\times m_2}\cdots|\mathbf{C}_{K\times m_N}],$$

with

$$\mathbf{C}_{K\times m_i} = [\underline{\mu}_1^i\ \underline{\mu}_2^i\ \cdots \underline{\mu}_{m_i}^i]$$

$$= \begin{bmatrix} \underline{\mathbf{c_1^i}} \\ \underline{\mathbf{c_2^i}} \\ \vdots \\ \underline{\mathbf{c_K^i}} \end{bmatrix} = \begin{bmatrix} c_1^i(1) & c_1^i(2) & \cdots & c_1^i(m_i) \\ c_2^i(1) & c_2^i(2) & \cdots & c_2^i(m_i) \\ \vdots & \vdots & \ldots & \vdots \\ c_K^i(1) & c_K^i(2) & \cdots & c_K^i(m_i) \end{bmatrix}$$

Fig. 1. The codebook $\mathbf{C}_{K\times K}$ is obtained by scaling the Hadamard matrix columns corresponding to user i by the factor $\eta_i = \frac{1}{\sqrt{m_i}}$. The $K \times K$ access codebook is partitioned into N sub matrices, $\mathbf{C_{K\ x\ m_i}}$ with $1 \leq i \leq N$, where $\mathbf{C}_{K\times m_i}$ is the access code for user i.

In the proposed scheme, each user makes use of K time intervals (with $K \geq N$) to send its information. The data user i transmits over this time frame is $\underline{\mathbf{x}}^{\mathbf{i}}=[x_1^i\ x_2^i\ \cdots\ x_{m_i}^i]$ (Note that in general different users may have different channel data rates $\frac{m_i}{K}$). At time $1 \leq k \leq K$, user i utilizes code $\underline{\mathbf{c}}_{\mathbf{k}}^{\mathbf{i}}=[c_k^i(1)\ c_k^i(2)\ \cdots\ c_k^i(m_i)]$ (the k^{th} row of $\mathbf{C_{Kxm_i}}$), and transmits $\underline{\mathbf{x}}^{\mathbf{i}}\underline{\mathbf{c}}_{\mathbf{k}}^{\mathbf{i}\ \mathbf{T}}$, so that the received signal $\underline{\mathbf{y}}=[y_1\ y_2\ \cdots y_K]$ is given by

$$y_k = \sum_{i=1}^{N} \underline{\mathbf{x}}^i \underline{\mathbf{c}}_k^{i\ T} + z_k = \sum_{i=1}^{N}\sum_{j=1}^{m_i} x_j^i c_k^i(j) + z_k, \qquad 1 \leq k \leq K. \tag{4}$$

As noted before, the data to be sent by user i, $\underline{\mathbf{x}}^i$, is *repeated* during the K signaling times. Therefore, the overall power received from each is KP_i. Figure 2 illustrates the proposed scheme for the case of a two user case ($N = 2$) with

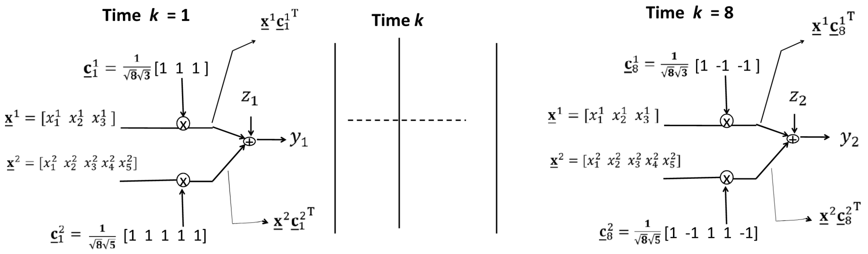

Fig. 2. Proposed scheme for two users ($N = 2$) with $K = 8$, $m_1 = 3$ and $m_2 = 5$. The upper branch corresponds to user 1 and the lower to user 2. Note the data of each user x_j^i is fixed for all the signaling times $1 \leq k \leq 8$.

$$\mathbf{H_{8\times 8}} = \frac{\mathbf{1}}{\sqrt{\mathbf{8}}} \left[\begin{array}{ccc|ccccc} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{array}\right] \tag{5}$$

Fig. 3. 8×8 Hadamard matrix. Here $K = 8$, $m_1 = 3$ and $m_2 = 5$. To generate the matrix $\mathbf{C_{8\times 8}}$, the first 3 columns are assigned to user 1 and then scaled by $\frac{1}{\sqrt{3}}$. The remaining 5 columns are assigned to user 2 and scaled by $\frac{1}{\sqrt{5}}$.

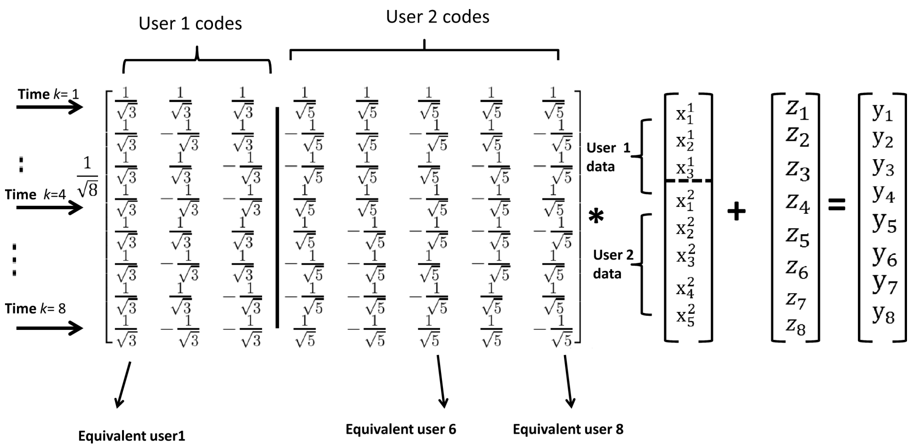

Fig. 4. Equivalent CDMA system corresponding to Figure 2. The first $m_1 = 3$ equivalent users correspond to the 3 different symbols of user 1 in our proposed scheme, while the next $m_2 = 5$ equivalent users correspond to the 5 different symbols of user 2.

$m_1 = 3$ and $m_2 = 5$ using the Hadamard matrix in Figure 3 to construct the access codes.

Notice that since the input source samples are i.i.d, the proposed scheme is equivalent to a CDMA system with K users and K spread sequences (the columns of the matrix $\mathbf{C}_{K\times K}$), with the first m_1 users of the equivalent scheme corresponding to the m_1 symbols of user 1, the next m_2 users of the equivalent scheme corresponding to the m_2 symbols of user 2, and so on. Figure 4 shows the equivalent CDMA system corresponding to Figure 2.

Note that the off diagonal entries of $\mathbf{C}_{K\times K}{\mathbf{C}_{K\times K}}^T$ are zero because each $\underline{\mu}_j^i$ is a scaled column of an orthogonal matrix. Hence $\mathbf{C}_{K\times K}{\mathbf{C}_{K\times K}}^T = \mathbf{D}$ is a $K \times K$ diagonal matrix with N distinct values (m_i entries of value $\frac{1}{m_i}$, where $1 \le i \le N$). Thus, the proposed scheme is equivalent to K orthogonal Single-Input Single-Output (SISO) channels and its sum rate capacity in terms of bits per channel use is

$$C_{scheme} = \frac{1}{K}\left[\sum_{i=1}^{N}\sum_{j=1}^{m_i}\left(\frac{1}{2}\log_2\left(1+\frac{KP_i}{m_i}\right)\right)\right], \tag{6}$$

where we have divided by K because the proposed system uses the MAC K times. Note that the power of each parallel SISO channel is the power of the spreading sequence ${\underline{\mu}_j^i}^T \underline{\mu}_j^i = \frac{1}{m_i}$ multiplied times the overal power KP_i received from user i.

From (3), the maximum sum rate is

$$\begin{aligned} C_{MAC} = \frac{1}{2}\log_2(1+\sum_{i=1}^{N} P_i) = \\ \frac{1}{2}\log_2\left[1+\sum_{i=1}^{N}\sum_{j=1}^{m_i}(\frac{P_i}{m_i})\right]. \end{aligned} \tag{7}$$

It can be easily shown that C_{scheme} and C_{MAC} are equal if and only if

$$\frac{P_i}{m_i} = \frac{P_j}{m_j} \qquad \forall j \neq i \ \ with \ \ 1 \le i,j \le N. \tag{8}$$

This result is not surprising since the equivalent CDMA scheme achieves the MAC capacity when all the K equivalent users have the same power.

Particularizing the above result for the 2-user case ($N = 2$) gives the optimal m_1 and m_2: $\frac{P_1}{m_1^*} = \frac{P_2}{m_2^*}$, such that $m_1^* + m_2^* = K$. Solving for the optimal m_i, $i = 1, 2$ yields

$$m_i^* = \frac{KP_i}{P_1+P_2} \quad i = 1, 2 \tag{9}$$

Since m_i is the number of columns assigned to user i, it should be an integer. Even though m_i^* may not be integers, if the code size K is chosen large enough (m_1, m_2) can be chosen as close to the optimal (m_1^*, m_2^*) as desired.

We can break up (6) to obtain the rate achieved by each user. For example, for the two user case, $N = 2$, we have

$$R_1 = \frac{1}{K}\Bigg(\sum_{j=1}^{m_1} \frac{1}{2}\log_2(1 + \frac{KP_1}{m_1})\Bigg) \tag{10}$$

$$R_2 = \frac{1}{K}\Bigg(\sum_{j=m_1+1}^{K} \frac{1}{2}\log_2(1 + \frac{KP_2}{m_2})\Bigg). \tag{11}$$

Figure 5 shows the maximal rates achieved by each user for the two user case when $P_1 = 8$ and $P_2 = 1$. The MAC capacity region is obtained from (2). In the Figure, we choose $K = 64$. As indicated in (8), there exists a point in the graph in which the proposed scheme achieves the MAC capacity.

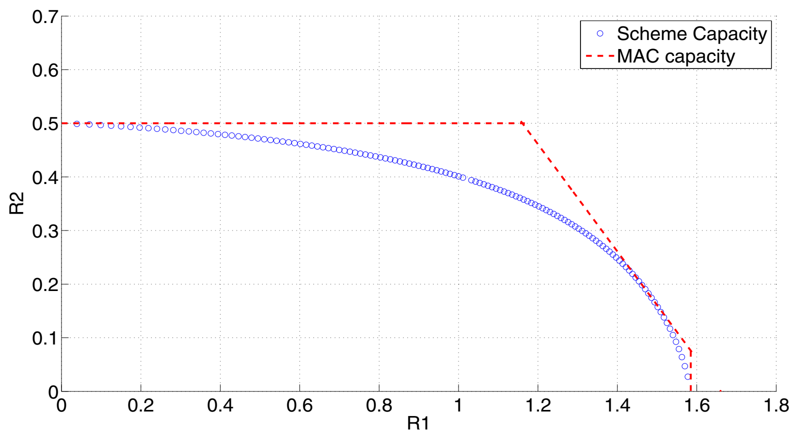

Fig. 5. MAC capacity and the proposed scheme capacity for $P_1 = 8$, $P_2 = 1$ and codebook size $K = 64$. Each point of the blue curve is obtained from (10) and (11) by sweeping m_1 from 0 to 64.

Note that Figure 5 is similar to the one obtained with an orthogonal FDMA (TDMA) system. However, the proposed scheme has the advantage of the relative easiness of the analysis and the potential to extend it to situations where the users are correlated. We also note that orthogonal systems would require the use of different rates in the analog joint source-channel encoder for each user, while here the rate is incorporated into the access scheme itself, which facilitates the design.

3 Analog Joint Source Channel Coding

To simplify the problem, we will consider the case of a MAC with two users transmitting independent Gaussian sources, S, of mean zero and variance σ_S^2.

Previous to the access scheme, we assume each user processes its source using an $M:1$ analog joint source channel encoder. When $M=1$, the source samples, s_j^i, $j=1,\ldots,m_i$ are input directly to the access scheme so that $x_j^i = \sqrt{\frac{P_i}{\sigma_S^2}} s_j^i$, $j=1,\ldots,m_i$ while for $M=2$ two consecutive source symbols (s_{2j}^i, s_{2j+1}^i) are encoded by a space-filling curve to generate the channel symbol x_j^i.

Under the Mean Squared Error (MSE) distortion criteria, the rate distortion function of any of the aforementioned sources is given by [12]

$$R(D_i) = \begin{cases} \frac{1}{2}\log_2(\frac{\sigma_S^2}{D_i}) & \text{for } D_i < \sigma_S^2, \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

where D_i is average MSE distortion incurred by the source of user i.

Considering optimal power allocation for each of the users as given by (8), the theoretical limit for this problem is given by

$$M\left[\frac{m_1}{K}\log(\frac{\sigma_S^2}{D_1}) + \frac{m_2}{K}\log(\frac{\sigma_S^2}{D_2})\right] < \frac{1}{2}\log(1+P_1+P_2). \tag{13}$$

By defining

$$\overline{SDR} = \frac{m_1}{K}\log_{10}(\frac{\sigma_S^2}{D_1}) + \frac{m_2}{K}\log_{10}(\frac{\sigma_S^2}{D_2}), \tag{14}$$

(13) can be re-written as

$$\overline{SDR} < \frac{5}{M}\log_{10}(1+P_1+P_2). \tag{15}$$

Notice the change in the base of the logarithm.

Again, it is important to remark that (15) does not hold for all combinations of P_1 and P_2, but it does when the power allocation for each user is optimized according to (8), and in general it holds for any combination of powers where the sum rate is maximized as indicated in (3). Notice that (15) represents the minimum "average" distortion incurred by the system when user i performs bandwidth compression by a factor of M and utilizes m_i access codes. We will use (15) to represent the Optimum Performance Theoretically Attainable (OPTA) in terms of $\overline{SDR}$ vs $SNR = 10\log_{10}(P_1+P_2)$, and compare this optimal performance with simulation results obtained from the proposed system when, for each SNR value, the power allocation for each user, $SNR_i = 10log_{10}P_i$, is optimized following (8).

3.1 Uncoded Transmission ($M = 1$)

As explained before, the source samples, s_j^i, $j=1,\ldots,m_i$, are input directly to the access scheme so that $x_j^i = \sqrt{\frac{P_i}{\sigma_S^2}} s_j^i$, $j=1,\ldots,m_i$. Notice that with this scheme user i transmits m_i source symbols using K signaling intervals.

At the receiver site, we perform MMSE decoding on the received vector $\underline{\mathbf{y}}$ to obtain the MMSE estimate of the transmitted vector $\mathbf{s}$ comprising user 1 and user 2 data. We observe that the received vector $\underline{\mathbf{y}}$ can be expressed as $\underline{\mathbf{y}} = \mathbf{H\Gamma s} + \mathbf{z}$, where $\mathbf{\Gamma}$ is a diagonal scaling matrix containing either $\sqrt{\frac{P_1}{\sigma_S^2}}$ or $\sqrt{\frac{P_2}{\sigma_S^2}}$. The MMSE estimate of the transmitted data is given by

$$\hat{\underline{\mathbf{s}}} = ((\mathbf{H\Gamma})^T \mathbf{H\Gamma} + 2\mathbf{I})^{-1} (\mathbf{H\Gamma})^T \underline{\mathbf{y}}. \tag{16}$$

Since $\mathbf{H}^T\mathbf{H} = \mathbf{I}$, (16) reduces to

$$\hat{\underline{\mathbf{s}}} = (\mathbf{\Gamma}^T \mathbf{\Gamma} + 2\mathbf{I})^{-1} (\mathbf{H\Gamma})^T \underline{\mathbf{y}}, \tag{17}$$

which, given the orthogonalization produced by the CDMA-like access scheme, is just the result of applying a matched filter.

3.2 2:1 Bandwidth Reduction ($M = 2$)

As indicated before, in this case each one of the users utilizes a space-filling curve to encode two consecutive source symbols (s^i_{2j}, s^i_{2j+1}) into symbol x^i_j. Therefore, user i transmits $2m_i$ source symbols over $m_1 + m_2$ signaling intervals. Systems based on the use of space filling curves were proposed independently by Shannon and Kotelnikov [14, 15]. Here, we consider the non-linear Archimedean spiral defined parametrically as

$$\begin{cases} u = \frac{\Delta_i}{\pi}\theta\sin\theta \\ v = \frac{\Delta_i}{\pi}\theta\cos\theta \end{cases} for\ \theta \geq 0, \qquad \begin{cases} u = -\frac{\Delta_i}{\pi}\theta\sin\theta \\ v = \frac{\Delta_i}{\pi}\theta\cos\theta \end{cases} for\ \theta < 0, \tag{18}$$

where Δ_i is the distance between two neighboring spiral arms in the curve corresponding to user i and θ is the angle from the origin to the point (u, v) on the curve. The Archimedean spiral is studied in detail in [5]. Notice that if Δ_i is fixed, then there is a one to one mapping between the angle, θ, and the pair on the curve (u, v). The mapping function $M_{\Delta_i}(s^i_{2j}, s^i_{2j+1})$ takes any source pair (s^i_{2j}, s^i_{2j+1}) and projects it to the closest point on the spiral, that is

$$\begin{aligned} &\hat{\theta}^i_j = M_{\Delta_i}(s^i_{2j}, s^i_{2j+1}) = \\ &\arg\min_{\theta}\{(s^i_{2j} \pm \frac{\Delta_i}{\pi}\theta\sin\theta)^2 + (s^i_{2j+1} - \frac{\Delta_i}{\pi}\theta\cos\theta)^2\}. \end{aligned} \tag{19}$$

After the mapping, $\hat{\theta}^i_j$ is processed by the function $T_{\alpha_i}(\hat{\theta}^i_j) = (\hat{\theta}^i_j)^{\alpha_i}$ to produce x^i_j. For each user, both parameters (Δ_i, α_i) are optimized according to the corresponding power allocation P_i [6], where, for each SNR, P_i, the optimal power allocation, is chosen according to (8).

The decoder is composed of two main components. First, the MMSE outer detector (similar to the MMSE detector that was used in section 4.B) that decouples the two users data. Secondly, the inner decoder after the MIMO detector which performs Maximum Likelihood (ML) decoding on the 2:1 spiral compression system. Given the received vector $\underline{\mathbf{y}}$, the MMSE estimate of the transmitted

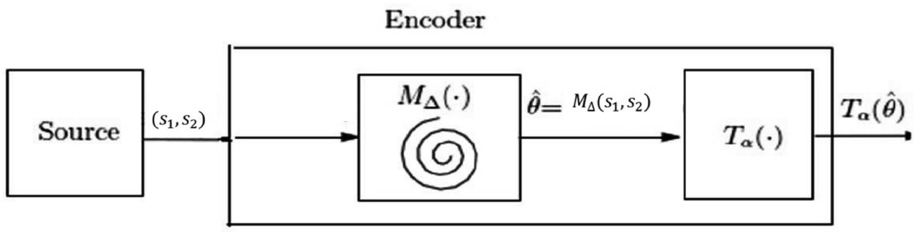

Fig. 6. System diagram of an encoder based on the 2:1 Archimedean spiral

vector $\underline{\mathbf{x}}$ is obtained as in (16). Then the ML estimate of θ of user i is calculated by inverting the transformation $T_{\alpha_i}(\cdot)$

$$(\hat{\theta}_j^i)_{ML} = {T_{\alpha_i}}^{-1}(\hat{x}_j^i). \tag{20}$$

Finally, we perform the inverse mapping on $(\hat{\theta}_j^i)_{ML}$ according to (18) to obtain the ML estimates of the original transmitted source pair $(\hat{s}_{2j}^i, \hat{s}_{2j+1}^i)$ of each user.

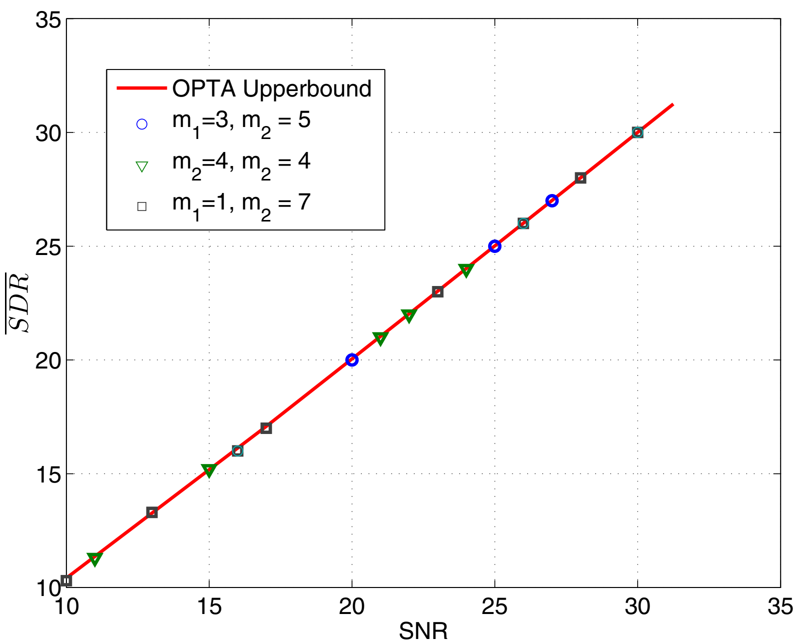

Fig. 7. System performance for $M = 1$ and different values of m_1 and m_2 when $K = 8$. Note that irrespectively of the values of m_1 and m_2 the scheme achieves the SDR upperbound exactly.

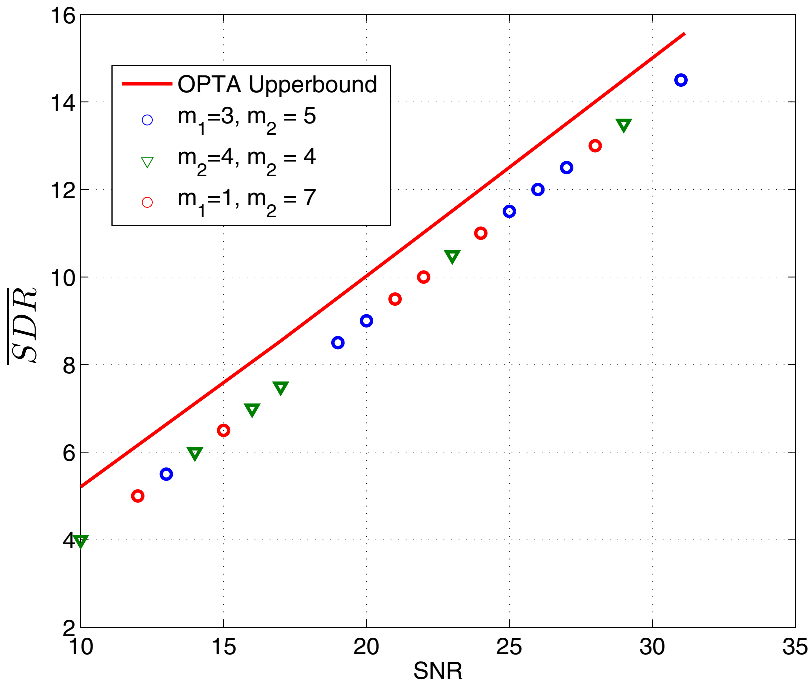

Fig. 8. System performance for $M = 2$ and different values of m_1 and m_2 when $K = 8$. Notice that irrespectively of the values of m_1 and m_2, the achieved SDR is only 1 dB away from the theoretical upperbound.

4 Simulation Results

In this section we present simulation results for the proposed system for different values of m_1 and m_2 when $K = 8$ and the source symbols of each user are transmitted either directly ($M = 1$) or using a 2:1 spiral curve ($M = 2$). As described before, in our simulations we utilize the optimal power allocation as given in (8) for an overall system power specification $SNR = 10\log_{10}(P_1 + P_2)$, and compare the "average" distortion $\overline{SDR}$ as defined in (14) with the theoretical limit obtained in (15). Notice that this limit does not depend on the specific values of m_1 and m_2. The results for $M = 1$ and different values of m_1 and m_2 are shown in Figure 7. Notice that the proposed scheme is *optimal*, i.e. it achieves the distortion bound for all SNRs irrespectively of the values of m_1 and m_2.

The above shown result is very interesting indeed. It was shown by Gobblick [16] that for point-to-point communications, uncoded transmission of Gaussian sources through Gaussian channels is optimal when one source symbol is transmitted per channel use. Our system achieves this optimal performance since the use of the access codes converts the MAC channel into K orthogonal parallel SISO channels.

Simulation results for the $M = 2$ case and different values of m_1 and m_2, with $K = 8$, are shown in Figure 8. Notice that irrespectively of the values of m_1 and m_2, our system is only about 1 dB away from the OPTA for a wide range of SNRs.

5 Conclusion

We have proposed the use of a CDMA-like access scheme for the transmission of independent users through a MAC using analog joint source-channel coding. The proposed access scheme allows for the use of different rates for each user, and achieves the theoretical limit when the power is allocated optimally to each user. The sources are encoded by standard space-filling curves optimized for point-to-point AWGN channels. Simulation results show the optimality of the practical analog coding schemes when each user transmits the source symbols directly through the channel. The resulting performance when 2:1 spiral mappings are used to encode each source lies within 1 dB of the theoretical limit.

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