# ANALOG JOINT SOURCE CHANNEL CODING FOR BLOCK FADING MULTIPLE ACCESS CHANNELS

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**ABSTRACT**

We address the transmission of discrete-time analog samples over a block fading Multiple Access Channel (MAC). We propose two practical access schemes to achieve the sum capacity of a MAC channel: opportunistic and Code Division Multiple Access (CDMA). The first one is optimal when the Channel State Information (CSI) from all users is available at all the transmitters. However, it can lead to an unfair distribution of the power and transmission rate for each user. On the other hand, the CDMA access scheme allows setting individual rate constraints while showing excellent performance when transmitting either uncompressed or compressed analog Gaussian samples.

## 1. INTRODUCTION

The transmission of information over a Multiple Access Channel (MAC) is a fundamental problem in wireless communications that arises in many practical situations such as the uplink in a cellular communication system [1]. In the MAC channel, multiple users simultaneously transmit their information to a centralized receiver that faces the problem of estimating the individual information from each user.

Optimal performance in a communication system is achieved when the source information rate equals the channel capacity limit. Such situation is known in the literature as Optimal Performance Theoretically Attainable (OPTA) [2]. In digital communications, OPTA can be achieved using Separate Source and Channel Coding (SSSC). The source encoder compresses the source information down to its ultimate entropy limit whereas the channel encoder ensures its transmission without errors. However, achieving the OPTA with SSSC requires infinite complexity and delay. Moreover, as shown in [3] the optimality of separating source and channel coding is no longer true when transmitting correlated sources over a MAC channel.

Discrete-time analog communication systems based on the transmission of continuous amplitude channel symbols can also achieve the OPTA. An example is the direct transmission of discrete-time uncoded Gaussian samples over AWGN channels, both with the same bandwidth [2]. In many practical situations, however, it is often the case that the source and channel bandwidths are different. When the channel bandwidth is smaller, source symbols should be compressed onto a lower dimensional signal space using an analog Joint Source Channel Coding (JSCC) technique such as those presented in [4–8].

In the literature, most work on analog JSCC focuses on point-to-point channels. References exist that consider analog JSCC for point-to-point fading channels [8, 10–13]. There are also references that consider the transmission of two correlated Gaussian sources over a Gaussian MAC channel [3, 9]. Specific analog JSCC mappings for bandwidth compression have been designed in [18, 19] also for the Gaussian MAC channel but its performance is still far from the OPTA.

In this work we study the utilization of analog JSCC techniques for the transmission of analog samples over a block fading MAC channel. In digital communications, the capacity of a MAC channel can be achieved via SSCC and Successive Interference Cancellation (SIC) [1]. In such scheme, it is possible to decode without errors the information from one of the users as long as its rate is below the capacity limit imposed by the SINR seen by such user. Then, the information is subtracted from the incoming signal to produce a new signal with less interference that is more suitable for the decoding of the remaining users. Nevertheless, it is important to note that SIC is not viable in analog JSCC where a certain distortion remains after the decoding of each user information. Hence the subtracting process does not completely removes the interference from the incoming signal and the performance of SIC is severely degraded.

As an alternative, we explore in this work two access methods, opportunistic and orthogonal Code Division Multiple Access (CDMA). The opportunistic scheme is valid for either analog and digital transmissions but leads to unfair situations where a large number of power and rate resources may be allocated to only few users. On the contrary, with an orthogonal CDMA scheme it is possible to design MAC systems that guarrantee a minimum rate to each user. We show in this work that it is possible approach the OPTA in both access schemes using the analog JSCC mappings for point-to-point communications in [4–8] without requiring specific analog mappings for the MAC channel.

The remainder of this paper is organized as follows. Section II introduces the MAC system model and its capacity limit. Sections III and IV describe the opportunistic and orthogonal CDMA access techniques, respectively. The analog JSCC transmission schemes employed to send the source information are described in Section IV. Finally, Section V presents the results of computer experiments and Section VI is devoted to the conclusions.

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## 2. SYSTEM MODEL

We consider a block-fading MAC with $N$ users sending independent information simultaneously to a common receiver. The channel is assumed to remain static during the transmission of a packet of symbols but independently varies from one packet to another. Thus, the received signal can be expressed as

$$y = \sum_{i=1}^{N} \sqrt{P_i} h_i z_i + w, \tag{1}$$

where $P_i$, $z_i$ and $h_i$, $1 \le i \le N$, are the power, the complex-valued transmitted symbol and the complex-valued channel fading gain corresponding to user $i$, respectively, while $w \sim \mathcal{N}_{\mathbb{C}}(0, N_0)$ represents the Additive White Gaussian Noise (AWGN) at the receiver. Without loss of generality, we assume $\mathbb{E}[|z_i|^2] = \mathbb{E}[|h_i|^2] = N_0 = 1$ and impose the sum power constraint $\sum_{i=1}^{N} P_i = P$. We also assume that $z_i$ are discrete-time samples from analog sources.

We assume that perfect Channel State Information (CSI) from all users is available at the receiver whereas two situations occur depending on wheather perfect CSI is available at the transmitters or not. When CSI is only available at reception, the different rates users may achieve, $R_i$, $1 \le i \le N$ must satisfy the following set of $2^N - 1$ inequalities, one for each possible subset $\mathcal{N}$ of users

$$\sum_{i \in \mathcal{N}} R_i \le \mathbb{E}_{\{h_i\}_{i \in \mathcal{N}}} \left[ \log_2 \left( 1 + \sum_{i \in \mathcal{N}} P_i |h_i|^2 \right) \right] \tag{2}$$

for all $\mathcal{N} \subset \{1, 2, \ldots, N\}$. The maximum sum rate to be achieved in the block fading MAC is limited by the inequality where all users are in the subset $\mathcal{N}$, i.e.

$$R_{\textbf{sum}} = \sum_{i=1}^{N} R_i \le \mathbb{E}_{\{h_i\}_{i=1}^{N}} \left[ \log_2 \left( 1 + \sum_{i=1}^{N} P_i |h_i|^2 \right) \right] \tag{3}$$

When perfect CSI is also available at the transmitters, the optimal transmission strategy is to allow only the user with the best channel to transmit [1]. In such case, the inequality (3) corresponding to the sum rate converts into

$$R_{\text{sum}} \le \mathbb{E}_{\{h_i\}_{i=1}^{N}} \left[ \log_2 \left( 1 + P \max_i |h_i^2| \right) \right] \tag{4}$$

Achieving the sum capacity (3) or (4) is the ultimate objective when designing a MAC access method. In the ensuing sections we consider two access methods suitable for the transmission of discrete-time analog sources over fading MAC channels: opportunistic and orthogonal CDMA.

## 3. OPPORTUNISTIC ACCESS SCHEME

The optimal access scheme over the block fading MAC dynamically allocates the available total power $P$ to the user with the highest channel gain at each time block [20]. Such scheme is usually referred to as opportunistic and can be shown to achieve the theoretical sum capacity limit (4). Opportunistic access is suitable for applications that either perform separation between source and channel coding, or not. Opportunistic access is not affected by Multiple Access Interference (MAI) since the received signal contains information from a single user, i.e.

$$y = \sqrt{P} h_i z_i + w \tag{5}$$

where $z_i$ is the symbol transmitted by the user that experiences the best channel realization. Before proceeding to the decoding of the source information we perform a linear MMSE estimate of the transmitted symbol $z_i$

$$\hat{z}_i = \frac{\sqrt{P} h_i^*}{P|h_i|^2 + 1} z_i \tag{6}$$

As shown in [8], MMSE filtering together with zero-delay Maximum Likelihood (ML) decoding provides an excellent performance when decoding analog JSCC symbols.

It is important to note that the practical implementation of an opportunistic access scheme is difficult because it requires that either all transmitters know all the pair-wise MAC channel responses and that the transmissions be coordinated by the MAC receiver. In any case, a feedback channel is required for the receiver to send all the CSI to all the users or indicate which is the user allowed to transmit at each channel realization.

Fairness is an important issue to have in mind in opportunistic access [1]. In a symmetric fading MAC channel, the total power and the sum rate will be evenly distributed among all users. In an unsymmetric fading MAC, however, it may happen that one user may experience a better channel during a large number of channel realizations. Such user is then forced to consume more power although it achieves a higher rate. There are many practical situations where this unfair behaviour of opportunistic access is unacceptable.

## 4. ORTHOGONAL CDMA ACCESS SCHEME

Orthogonal Code Division Multiple Access (CDMA) is a multiple access technique based on the use of orthogonal spreading codes. In analog JSCC, orthogonal access to the MAC is necessary because superimposed transmissions cannot be decoded via SIC as in digital SSCC. In addition, orthogonal access allows to ensure a given rate for each user in the MAC. In this work, CDMA has been selected instead of other orthogonal access schemes such as FDMA or TDMA. On the one hand, CDMA transmits over a single frequency whereas FDMA requires the availability of several frequencies for the MAC. On the other hand, coordination among users in CDMA is siginificantly simpler than in TDMA where it is necessary that all the interfering users remain silent while a given user is transmitting. The advantage of CDMA is that all users synchronous and simutaneously transmit over the MAC while the receiver exploits the orthogonality of the spreading codes to remove the MAI.

To construct the spreading codes in our proposed orthogonal CDMA scheme, we start off with a $K \times K$ unitary matrix $\mathbf{U}$ with $K \ge N$ and assign $k_i$ columns to user $i$. Examples of such unitary matrices are the Hadamard matrix and the DFT matrix. We assume a fully loaded MAC system where all $K$ columns are distributed among all users, i.e. $\sum_{i=1}^{N} k_i = K$. We then scale each user's columns by a factor $1/\sqrt{k_i}$. Let the scaled columns assigned to user $i$ be denoted by $\tilde{\mathbf{c}}_{ij}$, $1 \le j \le k_i$. The code matrix to be used by user $i$ is constructed as $\mathbf{C}_i = [\tilde{\mathbf{c}}_{i1}, \tilde{\mathbf{c}}_{i2}, \cdots, \tilde{\mathbf{c}}_{ik_i}]$ with dimensions $K \times k_i$. We now rewrite this code matrix as

$$\mathbf{C}_i = \begin{bmatrix} \mathbf{c}_{i1} \\ \mathbf{c}_{i2} \\ \vdots \\ \mathbf{c}_{iK} \end{bmatrix} = \begin{bmatrix} c_{i1}(1) & c_{i1}(2) & \cdots & c_{i1}(k_i) \\ c_{i2}(1) & c_{i2}(2) & \cdots & c_{i2}(k_i) \\ \vdots & \vdots & \cdots & \vdots \\ c_{iK}(1) & c_{iK}(2) & \cdots & c_{iK}(k_i) \end{bmatrix} \tag{7}$$

where $\mathbf{c}_{ik}$ is a $1 \times k_i$ vector that represents the $k$-th row of the $i$-th user code matrix $\mathbf{C}_i$. Finally, the overall access code matrix utilized by all users in the MAC is $\mathbf{C} = [\mathbf{C}_1, \mathbf{C}_2, \cdots, \mathbf{C}_N]$.

In the proposed scheme, each user utilizes $K \geq N$ time intervals to send $k_i$ data symbols represented by $\mathbf{x}_i = [x_{i1}, x_{i2}, \cdots, x_{ik_i}]^T$. Hence, the data rate of user $i$ is $R_i = k_i/K$ symbols per channel use. Notice the flexibility of CDMA to select the transmission rate of the sources. By appropriately selecting $k_i$ and $K$ a MAC system with any combination of user data rates can be designed.

At time $k$, user $i$ encodes its data symbols with the vector code $\mathbf{c}_{ik}$ to produce the transmitted symbol $z_i = \mathbf{c}_{ik}\mathbf{x}_i$. Notice that the scaling $1/\sqrt{k_i}$ of the columns in $\mathbf{C}$ ensures $\mathbb{E}[|z_i|^2] = 1$. Hence, the received signal is

$$y_k = \sum_{i=1}^{N} \sqrt{P_i} h_i \mathbf{c}_{ik} \mathbf{x}_i + w_k \quad 1 \leq k \leq K \tag{8}$$

where $h_i$ is the channel block fading gain for user $i$ and $w_k$ is the AWGN at time $k$. We now define

$$\mathbf{h}_k = [\sqrt{P_1} h_1 \mathbf{c}_{1k}, \sqrt{P_2} h_2 \mathbf{c}_{2k}, \cdots, \sqrt{P_N} h_N \mathbf{c}_{Nk}] \tag{9}$$

and $\mathbf{x} = [\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_N]$ which allows us to rewrite (8) as $y_k = \mathbf{h}_k\mathbf{x} + w_k$. Finally, the vector of received symbols $\mathbf{y} = [y_1, y_2, \cdots, y_K]^T$ can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{10}$$

where $\mathbf{H}$ is the equivalent access channel matrix whose $k$-th row is $\mathbf{h}_k$, and $\mathbf{w} = [w_1, w_2, \cdots, w_K]^T$ is the AWGN vector. Similarly to $\mathbf{C}$, $\mathbf{H}$ is a $K \times K$ square matrix with orthogonal columns and non-orthogonal rows, i.e. $\mathbf{H}^H\mathbf{H} = \mathbf{D}$ is a real diagonal matrix whereas $\mathbf{H}\mathbf{H}^H$ is not.

We now assume that a linear filter $\mathbf{F}$ is used at the MAC receiver to produce estimates of the transmitted symbols, i.e. $\hat{\mathbf{x}} = \mathbf{F}\mathbf{y}$. In particular, we will use the Minimum Mean Square Error (MMSE) linear filter, i.e. $\mathbf{F} = \left(\mathbf{H}^H\mathbf{H} + \mathbf{I}\right)^{-1} \mathbf{H}^H = (\mathbf{D} + \mathbf{I})^{-1}\mathbf{H}^H$. Hence

$$\hat{\mathbf{x}} = \mathbf{F}\mathbf{y} = (\mathbf{D} + \mathbf{I})^{-1}\mathbf{D}\mathbf{x} + \mathbf{v} \tag{11}$$

where $\mathbf{v} = (\mathbf{D} + \mathbf{I})^{-1}\mathbf{H}^H\mathbf{n}$ is the noise at the decoder output which is also white and Gaussian. Notice from Equation (11) that the linear MMSE filter removes the MAI present in the received vector $\mathbf{y}$. Hence, Equation (11) can be rewritten component-wise as follows

$$\hat{x}_{ij} = \frac{P_i|h_i|^2}{k_i + P_i|h_i|^2} x_{ij} + v_{ij} \quad 1 \leq i \leq N,\ 1 \leq j \leq k_i \tag{12}$$

where $v_{ij}$ is the AWGN affecting $x_{ij}$. The variance of such noise is $\sigma_v^2 = k_i P_i |h_i|^2/(k_i + P_i|h_i|^2)$ and the Signal to Noise Ratio (SNR) corresponding to the decoding of $x_{ij}$ is

$$\gamma_{ij} = \frac{P_i}{k_i}|h_i|^2 \quad 1 \leq i \leq N,\ 1 \leq j \leq k_i \tag{13}$$

As shown in [8], MMSE filtering not only removes MAI but also provides an excellent performance when combined with zero-delay Maximum Likelihood (ML) analog JSCC decoding.

Orthogonal multiple access schemes are in general suboptimum in the sense that the maximum sum rate that can be obtained is less than the theoretical limit in equation (3). However, it is possible to achieve such sum capacity limit if the power allocated to each transmitter satisfies the following condition

$$R_i = \frac{P_i|h_i|^2}{\sum_{l=1}^{N} P_l|h_l|^2} \quad 1 \leq i \leq N \tag{14}$$

together with the power constraint $\sum_{l=1}^{N} P_l = P$.

It should be noticed that in order to implement the dynamic power allocation strategy in (14) the transmitters need to know the MAC CSI. Again, a feedback channel is required for the receiver to send all the CSI to all users or, alternatively, the transmit power they should utilize.

When CSI is not available at the transmitters, it is sensitive to assume $|h_i|^2 = 1$, $\forall i$ in which case the power allocation condition in (14) reduces to $R_i = P_i/P$, i.e. the optimum strategy for the Gaussian MAC [21]. Such power allocation strategy is very attractive in practical implementations because it is non-adaptive, i.e. it does not need to be updated at each channel realization. On the contrary, it is clearly suboptimum for the block fading MAC and causes a degradation in performance as shown in Section 6.

## 5. ANALOG JOINT SOURCE CHANNEL CODING

The access schemes presented in the previous sections can be used to transmit discrete-time analog samples. In particular, we consider analog sources that produce i.i.d. Gaussian samples with zero mean and variance $\sigma_s^2$. We assume each user encodes the source samples using an $M : 1$ analog Joint Source Channel Coding (JSCC) scheme. When $M = 1$, the source samples $s_{ij}$, $j = 1, \ldots, k_i$, are input directly to the MAC. Hence $x_{ij} = s_{ij}/\sqrt{\sigma_s^2}$. When $M > 1$, $M$ consecutive source symbols are compressed into one channel symbol using an analog JSCC encoder such as those described in [6].

In the specific case $M = 2$, we can use space-filling curves to encode two consecutive source symbols from user $i$, i.e. ($s_{i,2j}$, $s_{i,2j+1}$), into one channel symbol $x_{ij}$. Hence, user $i$ transmits $2k_i$ source symbols over $K$ signaling intervals. Analog mappings based on the use of space-filling curves were proposed independently by Shannon and Kotel'nikov [22, 23]. For a 2:1 compression, a spiral mapping is shown to be optimal [24]. More specifically, we consider the non-linear doubly interleaved Archimedean spiral [5, 6], which is parametrically defined as

$$\mathbf{z}_{\delta_i}(\theta) = \left[\text{sign}(\theta)\frac{\delta_i}{\pi}\theta \sin\theta, \frac{\delta_i}{\pi}\theta\cos\theta\right]^T, \tag{15}$$

where $\delta_i$ is the distance between two neighboring spiral arms in the curve corresponding to user $i$, and $\theta$ is the angle from the origin to the point $\mathbf{z} = [z_1, z_2]^T$ on the curve. The mapping function $M_{\delta_i}(\cdot)$ takes a source pair, $\mathbf{s}_{ij} = (s_{i,2j}, s_{i,2j+1})$, and calculates the angle from the origin to the point on the spiral that minimizes the (euclidean) distance to $\mathbf{s}_{ij}$. Hence,

$$\hat{\theta}_{ij} = M_{\delta_i}(\mathbf{s}_{ij}) = \underset{\theta}{\text{argmin}}\, \|\mathbf{s}_{ij} - \mathbf{z}_{\delta_i}(\theta)\|^2. \tag{16}$$

After the mapping, we use the stretching function $T_{\alpha_i}(\hat{\theta}_{ij}) = (\hat{\theta}_{ij})^{\alpha_i}$ to transform the compressed samples. In [4, 6] $\alpha_i = 2$ was proposed but, as shown in [7], system performance can be improved if $\alpha_i$ is optimized together with $\delta_i$. Finally, the coded value is normalized by $\sqrt{\eta}$ used to ensure the average transmitted power is equal to one. Hence, the input symbols to the MAC are

$$x_{ij} = \frac{T_{\alpha_i}(M_{\delta_i}(\mathbf{s}))}{\sqrt{\eta}} \tag{17}$$

Optimal performance of a communication system is obtained when the information rate of the sources equals the capacity of the channel. This situation is referred to as the Optimal Performance

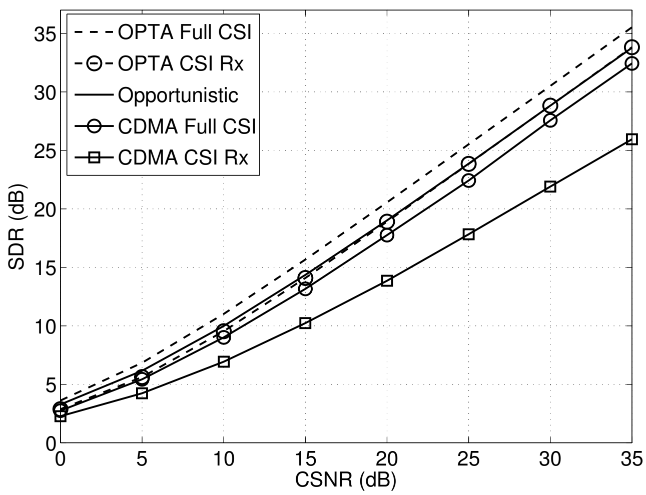


**Fig. 1**. Performance of the proposed access schemes for uncoded analog transmission ($M = 1$).

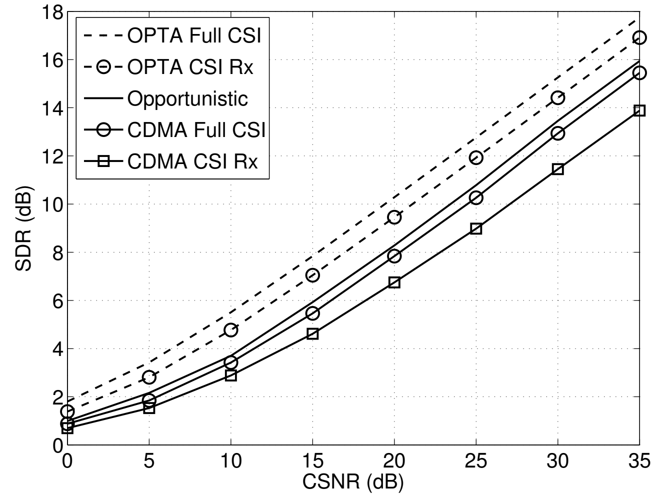


**Fig. 2**. Performance of the proposed access schemes for a 2:1 compression using Archimedean spiral ($M = 2$).

Theoretical Attainable (OPTA) [25]. For analog sources, the rate distortion function determines the source information rate for given distortion target, $D$. In the case of memoryless complex-valued Gaussian sources and considering the Mean Square Error (MSE) as the distortion criterion, the rate distortion function is [26]

$$R(D) = \begin{cases} \log_2(\frac{\sigma_s^2}{D}) & \text{for } D < \sigma_s^2, \\ 0 & \text{otherwise} \end{cases} \qquad 1 \le i \le N \tag{18}$$

where $R(D)$ represents bits per analog source sample. In the MAC scenario considered in this work, the OPTA is given by

$$M \sum_{i=1}^{N} k_i R(D_i) = K R_{\text{sum}} \tag{19}$$

where $R_i = k_i/K$ and $D_i$ is the distortion target of the source symbols from user $i$. Since MSE is a linear distortion metric, we define the sum distortion as $D_{\text{sum}} = \sum_{i=1}^{N} D_i$.

It is important to note that for the considered analog JSCC system to approach the OPTA, the encoder parameters $\delta_i$ and $\alpha_i$ have to be conveniently optimized. We have empirically determined [8], via computer simulations, that using $\alpha_i = 1.3$ provides a good overall performance for the case of 2:1 compression in AWGN channels and a wide range of SNR and $\delta_i$ values. Since choosing $\alpha \neq 2$ makes the analytical optimization of the other encoder parameter $\delta_i$ extremely difficult [5], we obtained the optimum $\delta_i$ values for different SNRs using off-line computer simulations. Such values are presented in [13]. In the opportunistic access scheme, the SNR is $P|h_i|^2$ whereas in CDMA the SNR is given by Equation (13). In a practical setup, the SNR can be estimated at the receiver and sent to the transmitter over a feedback channel.

## 6. SIMULATION RESULTS

In this section, we present the results of several computer simulations carried out to assess the performance of the proposed access schemes: opportunistic and orthogonal CDMA. In the second approach, we can in turn consider either dynamic power allocation –when the CSI is available at both the transmitter and receiver– or a non-adaptive strategy –if the channel is unknown at the transmitter or if the cooperation between users and receiver is not feasible–. We consider a two-user MAC scenario where users directly transmit analog uncoded samples ($M = 1$) or compress the analog samples with rate 2:1 ($M = 2$). In the case of orthogonal CDMA, an access code of length $K = 4$ is considered.

Fig. 1 and Fig. 2 show the performance of the three proposed schemes for the uncoded transmission and 2:1 compression, respectively. The system performance is measured in terms of the Signal-to-Distortion Ratio (SDR), which is computed as $10\log_{10}(P/D_{\text{sum}})$. In addition, the OPTA when full CSI is available (i.e. $R_{\text{sum}}$ is given by equation (4)) and the OPTA when CSI is only available at reception (i.e. $R_{\text{sum}}$ is given by equation (3)) are plotted.

As observed in both figures, the three proposed strategies approach the theoretical limits for the whole SNR range. The gap between the performance curve for the opportunistic case and its corresponding OPTA is quite smaller as well as in the case of CDMA scheme and optimal power allocation. This gap increases if the transmit power is not allocated according to the CSI –about 4 dB in the uncoded transmission and less than 2 dB for compression–. This degradation comes from the fact that the CDMA strategy is suboptimal in such case. On the contrary, this allocation policy always guarantees a fair transmission for all users.

## 7. CONCLUSIONS

In this work, we have studied the transmission of discrete-time analog samples over block fading MAC channels. We considered two access schemes: opportunistic and orthogonal CDMA. The first scheme is optimal when the CSI from all users is available at all the transmitters. However, it can lead to an unfair distribution of the transmission rate for each user. On the other hand, orthogonal CDMA allows setting individual rate constraints while showing excellent performance when transmitting either uncompressed or compressed analog samples. Both access schemes closely approach the theoretical limits, specially in the case of dynamic allocation of the individual transmit powers. In this paper, we assumed perfect CSI at the transmitter but the impact of using inaccurate CSI on the system performance constitutes an interesting further research line.

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