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On the Performance of Energy-Division Multiple Access Over Fading Channels

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Abstract In this paper we consider a multiple-access scheme in which different users share the same bandwidth and the same pulse, and are discriminated at the receiver on the basis of the received energy using successive decoding. More specifically, we extend the performance analysis from the case of additive white Gaussian noise channels (presented in a previous work Salvo Rossi in Wirel Pers Commun, in press) to the case of fading channels. The presence of channel coefficients introduces a new degree of freedom in the transceiver design: unlike the AWGN case, different ordering among the users provides different transmitted energy, thus different overall system performance. Optimal ordering, in terms of minimum transmitted energy, is derived analytically. Analytical and numerical results, in terms of bit error rate and normalized throughput, are derived for performance evaluation in fading environments with optimal ordering exhibiting significant gains w.r.t. static ordering.

Keywords Amplitude modulation · Bit error rate · Fading channels · Multiple access · Normalized throughput · Successive decoding

1 Introduction

Multiple access systems based on time, frequency or code division techniques have been extensively discussed in the classical literature within the field of wireless communication

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[1]. Large bandwidth requirements of multimedia applications tend to saturate the available resource offered within the classical schemes. However, several users can use simultaneously the same bandwidth with the same baseband pulse (i.e. interfering in time, frequency and code domains) and still be able to employ multiple access at the receiver.

1.1 Related Work

In order to employ a multiple access system without relying on bandwidth expansion, Trellis Coded Multiple Access (TCMA) was first proposed in [2] and its capacity performance was analyzed in [3]. The main concept is to exploit superposition of users transmissions using different symbol-interelaved trellis-coded modulations and perform optimal but extremely complex maximum likelihood sequence decoding at the receiver. In order to avoid exponentially-growing complexity with the number of users, iterative receiver architectures, based on the forward-backward algorithm and interference cancellation techniques, were proposed in [4]. Design rules for individual trellis-coded modulations guaranteeing optimal asymptotical performance in multiuser TCMA are derived in [5].

Aiming at minimal spectral occupancy (according to various bandwidth criteria) with given Quality-of-Service, Bandwidth-Efficient Multiple Access (BEMA) was introduced and studied in [6] and [7]. Quality constraints are expressed in terms of power limitations and upper and lower bounds on the minimum bandwidth requirements are proposed. Signal design of correlated waveforms to be coupled with nonlinear detection is performed at the receiver, assuming the availability of a feedback channel. Time-Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Identical Waveform Multiple Access (IWMA) may be all considered as special cases of the BEMA framework. More specifically, a recursive construction of the correlation matrix of the waveforms is proposed, based on the reverse order which the users are decoded at the receiver. Spectral decomposition of the correlation matrix is then considered for finding an orthogonal set of basis functions and thus signature waveforms. Combinations of signal design and power control techniques coupled with multiuser linear receivers were studied in [8], however the superiority of BEMA approach has been shown in [9].

Another approach is found in the context of Orthogonal Frequency Division Multiplexing (OFDM) systems. MultiSymbol Encapsulation (MSE) OFDM was proposed as a bandwidth-saving variant to standard OFDM in static environments, with multiple OFDM symbols grouped together and protected by the same cyclic prefix [10]. MSE-OFDM has been recently exploited in combination with FDMA in order to propose multiuser communication systems with reduced bandwidth requirements both in uplink [11] and downlink [12].

Finally, still aiming at reducing resources needed for multiuser communications, a different problem was analyzed in [13] where power control was exploited to allow simultaneous transmissions among users with fixed overall spectral occupancy. More specifically, a multiple access scheme allowing several users to transmit simultaneously with the same baseband pulse over Additive White Gaussian Noise (AWGN) channels was analyzed and denoted Energy-Division Multiple Access (EDMA). The information bit transmitted by each user was shown to be recoverable by the receiver exploiting the differences in the received energy from each user. From the receiver point of view, EDMA is equivalent to single *pulse amplitude modulation* (PAM) signaling if each user employes Binary Phase Shift Keying (BPSK) modulation, but the presence of a multiuser scenario requires that appropriate constraints must be introduced to make the receiver problem solvable. A similar approach, i.e. based on different energy levels at the receiver, was considered in the context of Code-Division Multiple Access (CDMA) systems in [14] and [15].

1.2 Contribution and Organization

In this paper we extend our previous work [13] to the case of fading channels. Bit error rate (BER) versus signal-to-noise ratio (SNR) curves for uncoded transmissions over fading channels are analytically derived, confirmed by computer simulations, and compared for different system configurations. More specifically, the contributions of this paper are: (i) derivation of the optimal ordering among the users depending on the channel realization; (ii) analytical and numerical computation of EDMA performance over fading channels in terms of BER versus SNR; (iii) numerical computation of EDMA performance over fading channels in terms of normalized throughput of the system.

The rest of the paper is organized as follows: Sect. 2 introduces the system model; the effect of user ordering on the system is described in Sect. 3; various system performance are derived analytically in Sect. 4; Sect. 5 presents system performance of different system configurations obtained via numerical simulations; some concluding remarks are given in Sect. 6.

Notation—upper-case bold letters denote matrices with $A_{n,m}$ denoting the (n, m)th entry of $\boldsymbol{A}$; lower-case bold letters denote column vectors with a_n denoting the nth entry of $\boldsymbol{a}$; $\Re(a)$ and $\Im(a)$ denote the real and the imaginary parts of a, respectively; $|a|$ denote the absolute value of a; j denotes the imaginary unit; $\mathbf{1}_N$ and $\mathbf{0}_N$ denote column vectors of length N whose entries are 1 and 0, respectively; $\boldsymbol{I}_N$ denotes the identity matrix of order N; $\boldsymbol{I}_N^{(a)}$ denotes the anti-identity matrix of order N; $(.)^T$ denotes the transpose operator; $\otimes$ denotes the Kronecker product; diag$(\boldsymbol{A}, n)$ denotes a column vector containing elements from the nth diagonal of $\boldsymbol{A}$ with $n = -(N-1), \ldots, 0, 1, \ldots, (N-1)$ for $N \times N$ matrices (e.g. diag$(\boldsymbol{A}, 0)$ is the main diagonal); $\mathcal{N}(\mu, \sigma^2)$ denotes a normal distribution with mean μ and variance σ^2; $Ex(\lambda)$ denotes an exponential distribution with mean $1/\lambda$; $\mathcal{N}_{\mathbb{C}}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ denotes a circular symmetric complex normal distribution with mean vector $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Sigma}$; the symbol $\sim$ means "distributed as"; calligraphic letters denote subsets with $|\mathcal{A}|$ denoting the cardinality of $\mathcal{A}$; $\times$ denotes the cartesian product between sets.

2 System Model

We consider a set of N users transmitting to a single receiver over a multiple-access channel using simultaneously the same pulse. The system is assumed synchronous. The analysis of synchronization errors and their effects are beyond the scope of this paper, however synchronism requirements are easy to implement (being the same as for TDMA). More details on synchronization techniques may be found in [16].

The baseband discrete-time signal, after matched filtering and sampling at the symbol rate, is

$$y = \sum_{n=1}^{N} g_n x_n + w = \boldsymbol{g}^T \boldsymbol{x} + w \,, \tag{1}$$

where $w \sim \mathcal{N}(0, \sigma^2)$ is the overall additive noise, x_n and g_n are the symbol transmitted by the nth user and the corresponding gain at the receiver, $\boldsymbol{x} = (x_1, \ldots, x_N)^T$ is the *transmission vector*, and $\boldsymbol{g} = (g_1, \ldots, g_N)^T$ is the *gain vector*. The generic gain is expressed as

$$g_n = h_n \sqrt{\mathcal{E}_n} \,, \tag{2}$$

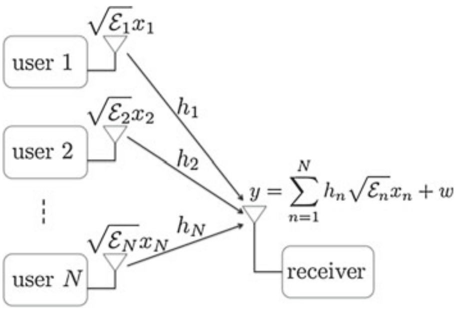


Fig. 1 Multiple-access channel with N users

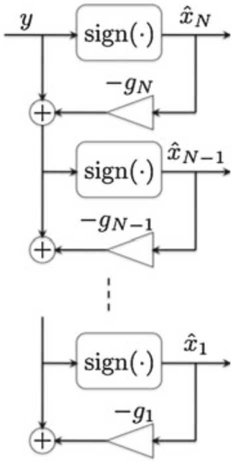


Fig. 2 Decision-feedback receiver

being $\mathcal{E}_n$ and h_n the transmitted energy per bit and the channel coefficient experienced by the nth user, respectively. Figure 1 shows the multiple-access channel under analysis.

Throughout the paper we limit our analysis to fading wireless channels with channel state information available at the transmitter location. Each user is then able to compensate for the channel gain that his own symbols experience over the channel, thus the separability condition for regular constellations analyzed in [13] may be obtained at the receiver location, i.e.

$$g_n = \frac{d}{4} 2^n , \tag{3}$$

where d is the distance between adjacent points in the overall constellation (refer to [13] for more details). Also, we only analyze explicitly the case of uncoded transmission with BPSK modulation for the single user, i.e. the single bit b_n is mapped into the transmitted symbol $x_n = 2b_n - 1$ and the overall system constellation at the base station is a 2^N-PAM with minimum distance d. The extension to other modulation formats is straightforward, as shown explicitly in [13] for two-dimensional modulations. As bits and symbols are mapped to each other biunivocally, we will often confuse them in the following. Then, the receiver is based on a simple decision-feedback structure as shown in Fig. 2, where $\hat{x}_n$ denotes the estimate of x_n.

From Eqs. (2) and (3) we get

$$\mathcal{E}_n = \frac{d^2}{16} \frac{4^n}{\rho_n} , \tag{4}$$

where $\rho_n = |h_n|^2$ and define the average energy per bit spent on each channel use as

$$\mathcal{E}_{\text{av}} = \frac{1}{N} \sum_{n=1}^{N} \mathcal{E}_n \,, \tag{5}$$

while the user SNR and the average SNR, as

$$\Gamma_n = \frac{\mathcal{E}_n}{2\sigma^2} \,, \qquad \Gamma_{\text{av}} = \frac{\mathcal{E}_{\text{av}}}{2\sigma^2} \,, \tag{6}$$

respectively. It is straightforward to obtain from Eqs. (4)–(6)

$$\Gamma_n = \gamma \frac{4^n}{8\rho_n} \,, \qquad \Gamma_{\text{av}} = \gamma \frac{1}{8N} \sum_{n=1}^{N} \left(\frac{4^n}{\rho_n} \right) , \tag{7}$$

being $\gamma = d^2/(4\sigma^2)$.

3 User Ordering

So far we have considered that the position of the generic user w.r.t. the others does not change, i.e. the requested gain at the receiver is fixed. We refer to this transmission mode as the "static" ordering, meaning that the relative position among users is independent of the channel configuration, i.e. independent of the amount of fading that each user will experience.

The same overall PAM constellation may be obtained with different ordering for the users, i.e. changing the user assigned the nth gain at the receiver is arbitrary. All the $N!$ permutations of the N users provide the same equivalent constellation at the receiver location. However, due to the presence of fading and the need to compensate for the channel coefficients, each different ordering (i.e. each assignment for the required gain at the receiver for each user) requires a different amount of transmitted energy. It is then sensible to select the best ordering among users according to the current channel configuration. In a quasi-static scenario, the receiver could easily feed back to the users the channel state information and the position in the ordering, i.e. the requested transmitted energy. Thus a different ordering of the users should be considered depending on the channel configuration.

Aiming at the minimization of the average transmitted energy by the system, the optimum ordering is the one that orders the users according to the coefficients ρ_n, i.e. such that $\rho_1 < \rho_2 < \cdots < \rho_N$, denoted in the following the "bottom-up ordering". The proof is simple. Consider a generic ordering $\{\rho_1, \rho_2, \ldots, \rho_N\}$ and the corresponding average energy

$$\mathcal{E}_\rho = \frac{d^2}{16N} \sum_{n=1}^{N} \left(\frac{4^n}{\rho_n} \right) . \tag{8}$$

Then consider the new ordering obtained with a single change in the user ordering, i.e. flipping the positions of two generic users ℓ and m, associated to the channel coefficients

$$\lambda_n = \begin{cases} \rho_n & n \neq \ell, m \\ \rho_m & n = \ell \\ \rho_\ell & n = m \end{cases} \,, \tag{9}$$

and the corresponding average energy

$$\mathcal{E}_{\lambda} = \frac{d^2}{16N} \sum_{n=1}^{N} \left(\frac{4^n}{\lambda_n} \right) . \quad (10)$$

Without loss of generality, if we assume $\ell > m$, it is then straightforward to compute the energy difference

$$\begin{aligned} \mathcal{E}_{\lambda} - \mathcal{E}_{\rho} &= \frac{d^2}{16N} \left(\frac{4^{\ell}}{\rho_m} + \frac{4^m}{\rho_{\ell}} - \frac{4^{\ell}}{\rho_{\ell}} - \frac{4^m}{\rho_m} \right) \\ &= \frac{d^2}{16N} \frac{(4^{\ell} - 4^m)(\rho_{\ell} - \rho_m)}{\rho_{\ell}\rho_m}, \end{aligned} \quad (11)$$

thus giving

$$\text{sign}(\mathcal{E}_{\lambda} - \mathcal{E}_{\rho}) = \text{sign}(\rho_{\ell} - \rho_m) . \quad (12)$$

Flipping two coefficients such that $\ell > m$ and $\rho_{\ell} < \rho_m$ provides a better ordering with $\mathcal{E}_{\lambda} < \mathcal{E}_{\rho}$. Iterating the process proves the optimality of the bottom-up ordering.

Analogous reasoning shows that the “top-down ordering”, i.e. $\rho_1 > \rho_2 > \cdots > \rho_N$, is the worst ordering in terms of average transmitted energy.

4 Performance Analysis

System performance are evaluated in terms of the single-user BER, in the following denoted $P_e(n)$ when referring to the nth user. It accounts for the error rate on the user bits of a specific user and is averaged over channel statistics assuming a Rayleigh-fading channel model with unitary mean power.

4.1 Performance Under Static Ordering

Exploiting the results in [13], where various performance metrics were computed w.r.t. γ, we can replace the appropriate expression from Eq. (7) and then average over the channel statistics.

Referring to the nth user, the conditional BER expressed w.r.t. the average SNR is given by

$$P_e(n)|\boldsymbol{h} = \frac{2^{N-n+1} - 1}{2^N} \text{erfc} \left(\sqrt{\frac{4N\Gamma_{\text{av}}}{\sum_{k=1}^{N} \left(\frac{4^k}{\rho_k} \right)}} \right) , \quad (13)$$

where

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} \exp(-t^2) dt , \quad (14)$$

while the conditional BER expressed w.r.t. the user SNR is given by

$$P_e(n)|\boldsymbol{h} = \frac{2^{N-n+1} - 1}{2^N} \text{erfc} \left(\sqrt{\frac{\rho_n \Gamma_n}{4^{n-1}}} \right) . \quad (15)$$

Under the assumption of Rayleigh fading with unitary mean power, i.e. $\boldsymbol{h} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}_N, (1/2)\boldsymbol{I}_N)$, coefficients $\{\rho_1, \ldots, \rho_N\}$ are i.i.d. with $\rho_n \sim Ex(1)$, giving the following joint pdf

$$f(\rho_1, \ldots, \rho_N) = \exp\left(-\sum_{n=1}^{N} \rho_n\right)(\rho_1 \geq 0) \ldots (\rho_N \geq 0) \,. \tag{16}$$

Averaging Eqs. (13) and (15) over the joint pdf in Eq. (16), and using the following approximation [17]

$$\text{erfc}(x) \approx \frac{1}{6}\exp\left(-x^2\right) + \frac{1}{2}\exp\left(-\frac{4}{3}x^2\right) \,, \tag{17}$$

we get the (unconditional) BER for the nth user.

The (unconditional) BER for the nth user expressed w.r.t. the average SNR is then given by

$$\begin{aligned} P_e(n) \approx \frac{2^{N-n+1}-1}{3 \cdot 2^{N+1}} \int_0^\infty d\rho_1 \cdots \int_0^\infty d\rho_N \exp\left(-\sum_{k=1}^{N}\rho_k - \frac{4N\Gamma_{\text{av}}}{\sum_{k=1}^{N}\left(\frac{4^k}{\rho_k}\right)}\right) \\ + \frac{2^{N-n+1}-1}{2^{N+1}} \int_0^\infty d\rho_1 \cdots \int_0^\infty d\rho_N \exp\left(-\sum_{k=1}^{N}\rho_k - \frac{16N\Gamma_{\text{av}}}{3\sum_{k=1}^{N}\left(\frac{4^k}{\rho_k}\right)}\right) \,, \end{aligned} \tag{18}$$

while the analogous BER expressed w.r.t. the user SNR is given by

$$P_e(n) \approx \frac{2^{N-n+1}-1}{2^{N+1}}\left(\frac{1}{3(1+4^{1-n}\Gamma_n)} + \frac{3}{3+4^{2-n}\Gamma_n}\right) \,. \tag{19}$$

4.2 Performance Under Optimal Ordering

It is crucial to notice that when optimal ordering is assumed, the system behaves fairly w.r.t. the users. In the long term, users will experience different channel coefficients thus each of them will visit all positions in the ordering. More specifically, it is reasonable to assume for symmetric scenarios that each user will visit the nth position in the ordering for $1/N$ of the total transmission time. The system with optimal ordering is then asymptotically fair and the single-user performance will be the same for each user.

Denote λ_n the nth order statistic of the set of channel coefficients with increasing (bottom-up) ordering, i.e. $\lambda_n = \rho_{(n)}$, then under Rayleigh statistics with unitary mean power, the pdf of the λ_n can be shown to be [18]

$$f_{\lambda_n}(\lambda) = n\binom{N}{n}e^{-(N-n+1)\lambda}\left(1-e^{-\lambda}\right)^{n-1}(\lambda \geq 0) \,. \tag{20}$$

Denote $B_e(n)|\boldsymbol{h}$ the conditional BER associated to the nth position when using optimal ordering among the users. The expressions w.r.t. the average SNR and the user SNR are given replacing ρ_n with λ_n in Eqs. (13) and (15), respectively. Averaging such expressions over the joint pdf of the elements λ_n and using Eq. (17) we get the (unconditional) BER associated to the nth position when using optimal ordering, denoted $B_e(n)$. The expression w.r.t. the average SNR is then given by

$$B_e(n) \approx \frac{2^{N-n+1}-1}{2^{N+1}} \int_0^\infty d\lambda_1 \cdots \int_0^\infty d\lambda_N \prod_{k=1}^{N} \left[k \binom{N}{k} e^{-(N-k+1)\lambda_k} \left(1 - e^{-\lambda_k}\right)^{k-1} \right]$$
$$\times \left[\frac{1}{3} \exp\left(-\frac{4N\Gamma_{\text{av}}}{\sum_{k=1}^{N} \left(\frac{4^k}{\lambda_k}\right)} \right) + \exp\left(-\frac{16N\Gamma_{\text{av}}}{3\sum_{k=1}^{N} \left(\frac{4^k}{\lambda_k}\right)} \right) \right], \quad (21)$$

while the analogous expression w.r.t. the user SNR is given by

$$B_e(n) \approx \frac{2^{N-n+1}-1}{2^{N+1}} \left(\frac{1}{3} \prod_{k=0}^{n-1} \left[\frac{1}{1+\frac{\Gamma_n}{(N-k)4^{n-1}}} \right] + \prod_{k=0}^{n-1} \left[\frac{1}{1+\frac{\Gamma_n}{3(N-k)4^{n-2}}} \right] \right), \quad (22)$$

where we used the following relation [19]

$$\int_0^\infty \exp(-\alpha t)\,(1-\exp(-t))^\beta dt = \frac{\Gamma(\alpha)\Gamma(\beta+1)}{\Gamma(\alpha+\beta+1)}, \quad (23)$$

being $\Gamma(x) = \int_0^\infty t^{x-1} \exp(-t)dt$ is the Gamma function with $\Gamma(n) = (n-1)!$ for any integer n.

Finally, assuming that each user will visit the nth position in the ordering for $1/N$ of the total transmission, we write

$$P_e(n) = \frac{1}{N} \sum_{n=1}^{N} B_e(n). \quad (24)$$

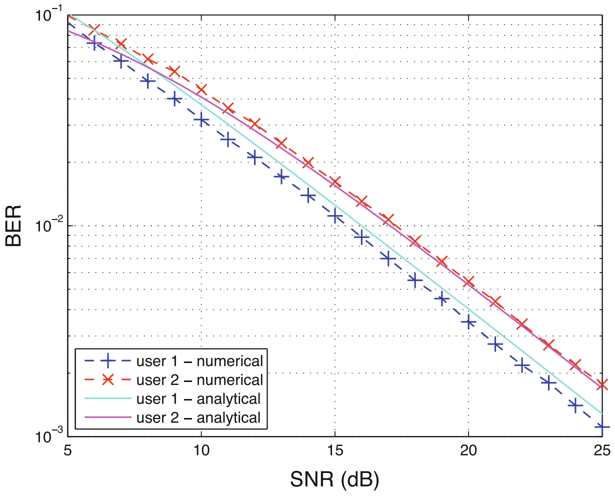
When using the expression w.r.t. the user SNR, i.e. Eq. (22), keeping only the dominant terms, it is straightforward to obtain

$$P_e(n) \approx \frac{2^N-1}{2^{N+1}} \left(\frac{1}{3N+3\Gamma_n} + \frac{3}{3N+4\Gamma_n} \right). \quad (25)$$

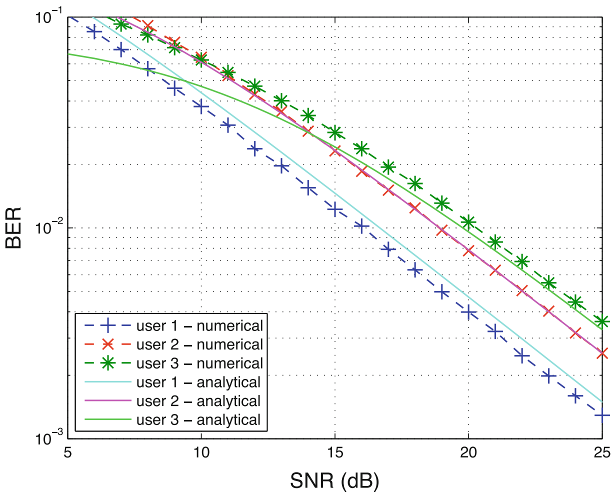
5 Simulations and Discussion

Monte Carlo simulations have been performed with MATLAB software to obtain numerical performance besides analytical expressions. Independent channel coefficients have been generated according to Rayleigh fading statistics with unitary mean power [20]. As for the performance of the nth user, independent AWGN whose variance is dependent on the nth user SNR is generated and added to the signal to be processed at the receiver. Decision-feedback receiver is considered both for static and optimal ordering, with the order of the signum decisions changed accordingly. Results have been averaged over 5×10^6 independent realizations.

Figure 3a, b compare numerical and analytical curves for user BER w.r.t. user SNR for systems with $N = 2$ and $N = 3$ users, respectively, under static ordering, while Fig. 4 compares analogous numerical and analytical performance under optimal ordering. Analytical curves under static and optimal ordering rely on Eqs. (19) and (25), respectively. A close matching between numerical and analytical curves is shown, especially at large SNR, as provided by the complementary error function approximation that has been considered via Eq. (17). Also, for a system with N users, Fig. 3 shows N curves, one per user, while Fig. 4 shows only



(a)



(b)

Fig. 3 Numerical and analytical performance in terms of user BER w.r.t. user SNR under static ordering. **a** System with $N = 2$ users, **b** system with $N = 3$ users

1 curve, as the curves for each user are the same. It is then apparent how the simulations confirm the fairness w.r.t. the users of the system behavior under optimal ordering.

Differently, unequal performance experienced by each users under static ordering requires a periodic rotation of the users themselves for fairness issues in the long term.

Figure 5 shows numerical curves for average-user BER w.r.t. average SNR for systems with $N = 2$ and $N = 3$ users under both static and optimal ordering. With average-user BER we mean the user BER averaged over the different users of the system.[1] The analogous

[1] Again, for systems under optimal ordering the average-user BER equals the generic user BER; for systems under static ordering the average-user BER equals the long-term generic user BER if periodic rotation among the users themselves is assumed.

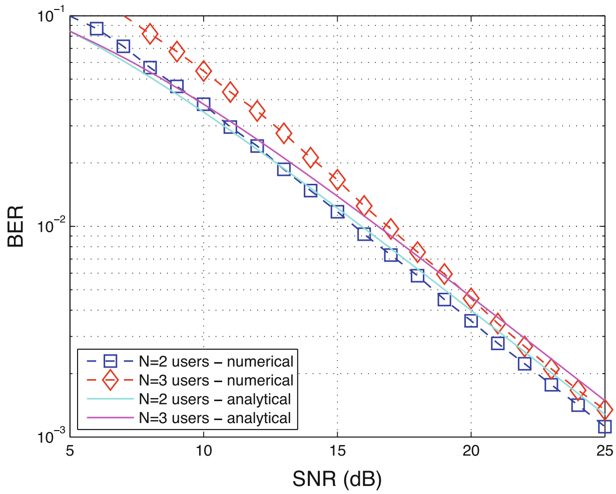


Fig. 4 Numerical and analytical performance in terms of user BER w.r.t. user SNR for systems with $N = 2$ and $N = 3$ users under optimal ordering

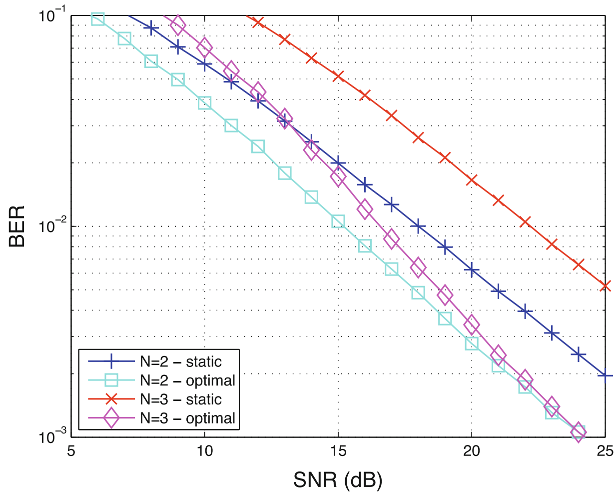


Fig. 5 Numerical performance in terms of average user BER w.r.t. average SNR for systems with $N = 2$ and $N = 3$ users under static and optimal ordering

analytical curves have not been shown as they rely on Eqs. (18) and (21) that do not correspond to a closed-form expression. It is apparent how systems under optimal ordering exhibits 4 dB gain and 8 dB gain w.r.t. systems under static ordering, respectively for the cases with $N = 2$ and $N = 3$ total users.

The effective advantage of using EDMA is more convincing when considering the performance in terms of normalized throughput of the overall system, as shown in [13] where EDMA-based and TDMA-based systems over AWGN channels were compared. Similarly to [13] and [21], assuming that each user transmits packets containing L symbols, the normalized throughput (η) is computed as

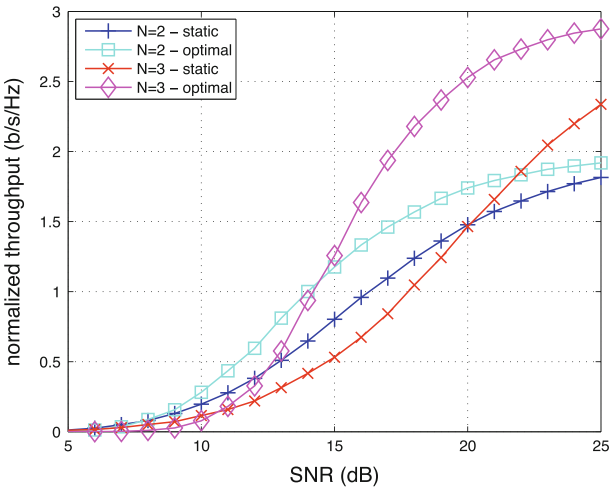


Fig. 6 Numerical performance in terms of normalized throughput w.r.t. average SNR for systems with $N = 2$ and $N = 3$ users under static and optimal ordering

$$\eta = \sum_{n=1}^{N} (1 - P_e(n))^L \ . \tag{26}$$

Figure 6 shows the normalized throughput w.r.t. average SNR for systems with $N = 2$ and $N = 3$ total users and packet length $L = 50$. Again, the advantage of systems employing optimal ordering w.r.t. systems employing static ordering is significant.

Finally, it is worth noticing that both analytical and numerical performance refer to uncoded transmissions over fading channels without any form of diversity, thus low BER values achieved even at large SNR are not surprising. More specifically, it is interesting to point out that EDMA may be combined with various communication techniques without any restriction. The advantages of EDMA can be added for instance to the benefits provided by channel coding (i.e. coding gain), multicarrier modulation (i.e. frequency diversity), etc. When using coded transmissions, EDMA processing follows the channel encoder at the user location and precedes the channel decoder at the receiver; when using multicarrier modulation, EDMA design is to be applied over each subcarrier. However, the analysis of the performance of EDMA design in combination with other communication techniques falls beyond the scope of this paper.

6 Conclusion

EDMA over AWGN channels was previously shown to be feasible with simple reception using successive decoding. The same concept has been extended to the case of fading channels, however in such cases the ordering among the various users affects the overall system performance. Optimal ordering among users has been derived depending on the set of channel coefficients. Analytical and numerical performance of EDMA, for systems under both static and optimal ordering among the users, has been obtained for uncoded transmission over fading channels, both in terms of BER and normalized throughput. Large gains are achieved by systems under optimal ordering w.r.t. systems under static ordering.

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Francesco Palmieri received his Laurea in Ingegneria Elettronica cum laude from Università degli Studi di Napoli Federico II, Italy, in 1980. In 1983, he was awarded a Fulbright scholarship to conduct graduate studies at the University of Delaware, Newark, where he received a M.S. degree in applied sciences and a Ph.D. in electrical engineering in 1985 and 1987, respectively. In 1981, he served as a 2nd Lieutenant in the Italian Army in fulfillment of draft duties. In 1982 and 1983, he was with the ITT firms: FACE SUD Selettronica in Salerno (currently Alcatel), Italy, and Bell Telephone Manufacturing Company in Antwerpen, Belgium, as a designer of digital telephone systems. He was appointed Assistant Professor in Electrical and Systems Engineering at the University of Connecticut, Storrs, in 1987, where he was awarded tenure and promotion to associate professor in 1993. In the same year, after a national competition, he was awarded the position of Professore Associato at the Dipartimento di Ingegneria Elettronica e delle Telecomunicazioni at Università degli Studi di Napoli Federico II, Italy, where he has been until October 2000. In February 2000, he was nominated Professore Ordinario di Telecomunicazioni after a national competition and appointed in November 2000 at Dipartimento di Ingegneria dell'Informazione, Seconda Università di Napoli, Aversa, Italy. His reaserch interests are in the areas of signal processing, communications, information theory and neural networks.