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Energy Efficient Multiple Access Scheme for Multi-User MIMO-OFDM System with Improved Gain

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Abstract: ***In this paper, to improve the energy efficiency (EE) of multi-user multiple-input multiple-output (MIMO) orthogonal frequency-division multiple access (OFDMA) system, an Energy-efficient multiple access (EMA) scheme is proposed. It improves EE by selecting either time-division multiple access (TDMA) or space-division multiple access (SDMA) based on the no. of users or power consumption. Here, we introduced normalization process for power in OFDM system to improve the power gain. Numerical results verify that the EE and power gain can be significantly improved through the proposed EMA scheme.***

Keywords*:* Energy efficiency (EE), channel access method, multiple access method, time-division multiple access (TDMA), space-division multiple access (SDMA), orthogonal frequency-division multiple access (OFDMA).

1. Introduction

A multiple-input multiple-output (MIMO) system consists of multiple antennas at the transmitter and receiver. The energy efficient transmission in MIMO system has been paid increasing attention in recent years because multiple-input multiple-output (MIMO) technology provides extra degrees of freedom and brings multiplexing and diversity gains. As a result, multiuser MIMO (MU-MIMO) transmission has attracted a lot of research interest in the past few decades. In the literature, significant efforts have been dedicated to improve the EE of wireless systems. A modulation strategy is introduced that minimizes the total energy consumption for transmitting a given number of bits in a single input and single output (SISO) AWGN channel [1]. A coordinated power allocation method is developed to balance the weighted SINR in a multi-cell massive multiple input single output (MISO) downlink system [2]. An energy-efficient pilot design in downlink system is studied for a single user (SU) case and the optimal overall transmit power and the power allocation between pilots and data symbols are investigated [3]. In SU communications, the quasiconcavity of EE over an achievable rate is well defined [4], [5], [6] but the trend of the MU communications over the rate is unclear.

In this paper, we study the MU EE of TDMA and SDMA for MU-MIMO orthogonal frequency-division multiple access downlink communications. For a given frequency band, the TDMA supports *K* users using *K* TDMA time slots and the SDMA requires less time slots to support the same *K* users by compromising the power consumption (PC). Because of this, TDMA and SDMA requires different amount of energy. So, EMA scheme is proposed which selects either SDMA or TDMA for each sub-band to maximize the EE. Simple algorithms for the EMA are devised and their EE and power gain performances are verified numerically.

2. System Model

Consider an antenna system with *M* transmitters and *U* receivers (users) with *N* orthogonal frequency sub-bands. Denote a channel matrix of sub-band *n* by H_n. The channel is assumed to be static for *T* slots and vary in every *T* slots independently. Each and every sub-band supports *K* users where $K \le T$. Throughout the paper, we assume that $KN \geq U$. The EE of an EMA system is defined as

$$EE = \frac{UR}{c\,\Sigma_{n\in N} P_{tx,n} + \max\{L_n\} P_{fix}} \quad (1)$$

where *R* is a fixed target rate with allowing unlimited transmit power and ideal coding and decoding for each user; *c* represents system inefficiency ($c > 1$) that is caused by overhead PC at RF circuits; $P_{\text{tx},n}$ is transmit power on sub-band *n*; P_{fix} is the fixed PC per time slot; L_n is the number of time slots used for transmission on sub-band *n*; and max$\{\cdot\}$ follows the fact that an RF chain should be turned on if there is at least one time slot to be transmitted over any sub-band.

The first term of the denominator in (1) is a transmit power dependent (TPD) PC term and the second term is a transmit power independent (TPI) PC term. TDMA activates all *T* time slots which results in the high TPI PC, due to which EE significantly decreases. While the SDMA decrease the number of time slots by increasing the achievable rate for each time slot with higher TPD PC. This observation motivates us to propose an multiple access (MA) selection method between TDMA and SDMA, which is EMA for each sub-band. In the next section, we derive the PC of TDMA and SDMA precisely and propose three suboptimal EMA algorithms.

3. EMA Algorithms

We find EMA algorithm that maximizes the *lower bound* of EE in (1) and it is realized by minimizing PC per sub-band *n* defined as

$$PC_n \triangleq cP_{tx,n} + L_n P_{fix} \quad (2)$$

We derive the *minimum* PC of (2) that achieves R for any user in a TDMA or SDMA mode to determine the MA for each sub-band.

A. PC of TDMA

We first derive the PC of TDMA with OFDMA. To allow the target rate R of user u through the sub-band with bandwidth Ω and variance σ^2, the power control factor p_u is lower bounded as

$$p_u \geq \sigma^2 \left(2^{\frac{R}{\Omega}}-1\right) g_u^{-1} \, \forall u \epsilon U \quad (3)$$

Where g_u is the channel matrix

Therefore, the minimum transmit power for achieving R is derived for the TDMA user u as

$$P_{tx,n}^{TDMA} = g_u \min\{p_u\} = \sigma^2 \left(2^{\frac{R}{\Omega}}-1\right) \quad (4)$$

Since K users are supported through K time slots, the PC in (2) is derived for the TDMA as follows:

$$PC_n^{TDMA} = c\sum_{u\epsilon U_n} P_{tx,u}^{TDMA} + KP_{fix}$$

$$= cK\sigma^2 \left(2^{\frac{R}{\Omega}}-1\right) + KP_{fix} \quad (5)$$

B. PC of SDMA

Next, the PC of SDMA with OFDMA is derived. Since the SDMA can be implemented with L_n time slots ($1 \leq L_n \leq T$), each sub-band supports the K users with less time slots in fair comparison with TDMA. To allow the target rate R of user $u \; \epsilon U_n$ with L_n SDMA slots through the bandwidth Ω, the minimum required transmit power on each sub-band is derived for one SDMA time slot as follows:

$$PC_{tx,n}^{SDMA} = \min\{\sum_{m\epsilon M} \| w_{mn}^r \sqrt{Q_n} \|^2\}$$

$$= \sigma^2 \left(2^{\frac{R}{L_n \Omega}}-1\right) ||W_n||_F^2 \quad (6)$$

where$\|.\|_F$ is the Frobenius norm of a matrix and W_n is the pseudo-inverse of the channel matrix. Since L_n SDMA time slots are used, the PC in (2) is derived for the SDMA as ($1 \leq L_n \leq T$)

$$PC_n^{SDMA} = cL_n PC_{tx,n}^{SDMA} + L_n P_{fix}$$

$$= cL_n \sigma^2 \left(2^{\frac{R}{L_n\Omega}}-1\right) ||W_n||_F^2 + L_n P_{fix} \quad (7)$$

C. EMA Algorithm for each sub-band:

To find the optimal MA for each sub-band n, we need to compare PC_n^{TDMA}in (5) and PC_n^{SDMA} in (7), which requires $\tilde{O}(TN)$ time complexity. For large N, as the complexity is more, we find the optimal number of SDMA slots for each sub-band n, denoted by L_n^o. This can be obtained by assuming a floating value l_n instead of L_n in (7). Now we get a differentiable function over l_n as

$$f(l_n) = cl_n \sigma^2 \left(2^{\frac{R}{L_n\Omega}}-1\right) ||W_n||_F^2 + l_n P_{fix} \quad (8)$$

Now make the first derivative of $f(l_n)$ with respect to $l_n$be zero to find the minimum value of l_n^*.Thus,

$$l_n^* = \frac{R\ln 2}{\Omega\left(W\left(\frac{1}{\exp(1)c\sigma^2 ||W_n||_F^2} \frac{P_{fix}}{}-1\right)+1\right)} \quad (9)$$

Where exp(·) is an exponential function and W(·) ≥ −1 denotes the upper branch of Lambert W function, which is given as z = W(z)$e^{W(z)}$. Finally we obtain the optimal SDMA slot length L_n^o from (9) that is the nearest integer to $l_n^*$and satisfies $1 \leq L_n^o \leq T$.

After finding L_n^o, we compare $PC_n^{TDMA}$and $PC_n^{SDMA}$to determine MA on sub-band n. Here, the complexity is reduced to $\tilde{O}(N)$ as only a pair of comparison is needed for each sub-band.

Now, the EMA algorithm is designed by comparingPC_n^{TDMA} and PC_n^{SDMA} as follows:

$$EMA_n = \begin{cases} SDMA, if \; ||W_n||_F^2 \leq \xi_n \\ TDMA, otherwise \end{cases} \quad (10)$$

$$\text{where } \xi_n = \frac{(T-L_n^o)P_{fix}}{cL_n^o\sigma^2\left(2^{\frac{R}{L_n^o\Omega}}-1\right)} + \frac{K\left(2^{\frac{R}{\Omega}}-1\right)}{L_n^o\left(2^{\frac{R}{L_n^o\Omega}}-1\right)} \quad (11)$$

Since ξ_n in (11) is a monotonically increasing function over R, while$||W_n||_F^2$ is independent of R, larger R increases the probability to select SDMA in (10).

To guarantee EE improvement, we further compare the EE of a pure TDMA with EE of the EMA algorithm for each sub-band, and then determine the MA technique that achieves the higher EE.

D. EMA Algorithm for the whole sub-band

In this algorithm, we consider an EMA algorithm that selects either pure TDMA or SDMA for the *whole* sub-band. This further reduces the complexity. The total PC of SDMA for all sub-bands is defined from (8) as

$$f(\{L_n\}) = c\sum_{n\epsilon N} L_n\sigma^2 \left(2^{\frac{R}{L_n\Omega}}-1\right) ||W_n||_F^2 \max\{L_n\} P_{fix} \quad (12)$$

Now make the first derivative of f({Ln}) with respect to L_n be zero to find the optimal {L_n^*}. The optimal L_n's that minimize (12) are identical to one another, i.e., L_n^*=L^*. This allows one-dimensional line search from 1 to T to find L^* optimally, which requires $\tilde{O}$(T) time complexity.

Firstly, for L_o, we get l^* by substituting $\sum_{n\epsilon N} ||W_n||_F^2$for $||W_n||_F^2$in (9). Next, we get ξ instead of ξ_n in (11) by replacing L_n^o and K with L and U, respectively. Finally, we get an EMA algorithm for the whole sub-band from the comparison of $\sum_{n\epsilon N} ||W_n||_F^2$ with ξ in (10).

E. Normalized EMA algorithm:

The general communication system is depicted as

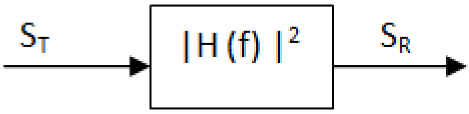

Figure 1: Block diagram of simple communication system

Based on the transmit power S_T and receive power S_R, the channel power gain is defined as S_R / S_T. For a non-ISI channel, using a flat transmit power spectrum, the channel power gain is defined as

$$\frac{S_R}{S_T} = \int_{-\infty}^{\infty} |H(f)|^2 \, df \quad (13)$$

which is usually normalized to unity.

One should be aware that the channel gain can be greater than unity in frequency ranges near the peak of the frequency response.

When dealing with real channels, it is common to normalize the frequency response so that the maximum value is unity. Thus, we shall also normalize the power frequency to unity. This ensures that the minimum E_b/N_0 is always -1.6 dB. That is, we shall normalize the frequency response such that the -3 dB bandwidth is 1 Hz. We shall call this as peak bandwidth normalization.

For an m-tap channel with unit energy normalization $|H(f)|^2$, the frequency response with peak bandwidth normalization is given as

$$|G(f)|^2 = \frac{1}{M}\left|H\left(\frac{f}{n}\right)\right|^2 \quad (14)$$

where M is the maximum value of $|H(f)|^2$ and n is the scaling factor which makes the -3 dB bandwidth of $|G(f)|^2$ equal to 1. Normalization by the maximum value ensures the channel maximum power gain is unity. Thus, no particular channel has a gain over another channel in the frequency ranges where the transmit power is concentrated.

4. Numerical Results

We assume that the channel is AWGN with zero mean and unit variance. For the transmit antenna correlation, we apply a correlation matrix with a correlation factor 0.3. A noise variance is defined such that each received antenna achieves 20 dB SNR. The overall bandwidth is 10 MHz. We set the overhead PC parameter as $c = 5.26$.

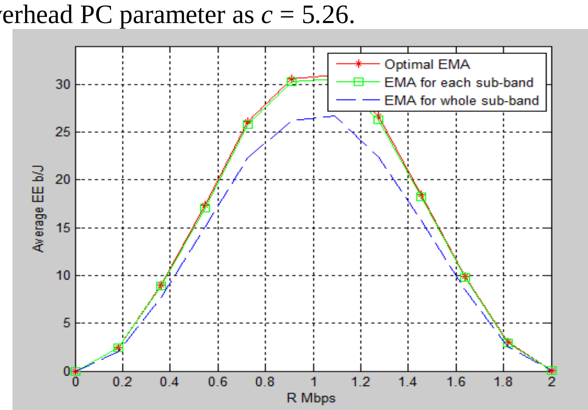

Figure 2: Comparison of the average EE of different MA methods for $M = T = 2$, $N = 4$, $U = 12$, and $P_{fix} = 45$ dBm.

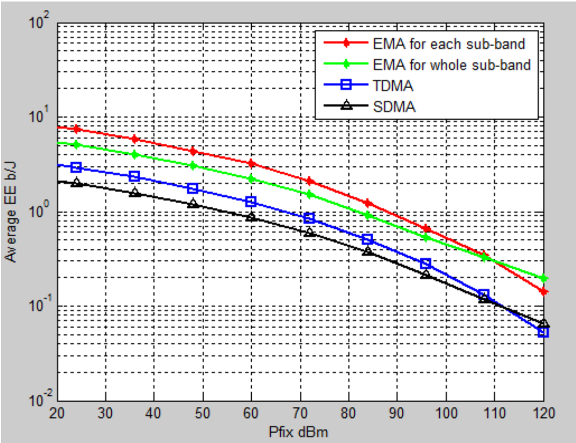

Figure 3: Comparison of the average EE of different MA methods for $M = T = 30$, $N = 40$, and $U = 700$.

In Fig. 2, to compare the proposed EMA algorithms with the optimal EMA strategy, we evaluate the EEs for a small-size system with $M = T = 2$ and $N = 4$. As mentioned previously, EMA algorithm for the whole sub-band reduce the complexity of optimal strategy from $\tilde{O}(TN)$ to $\tilde{O}(N)$ and $\tilde{O}(1)$. Based on the results of the small-size system, we surmise that the proposed EMA algorithms work properly for a large-size system without significant performance loss compared to the optimal EMA.

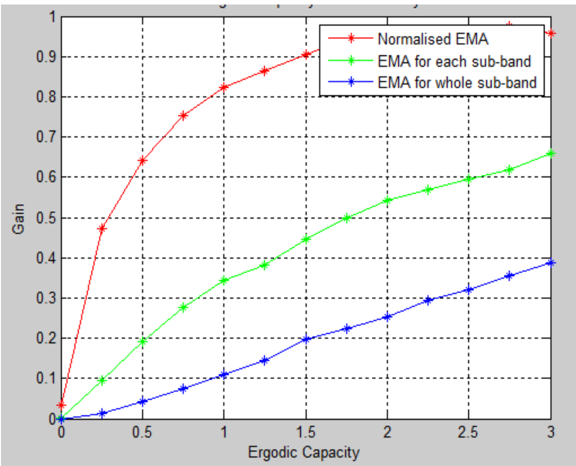

Figure 4: Comparison of gains of different MA methods for $M = T = 30$, $N = 40$, and $U = 700$.

In Fig. 3 and 4, we show the EE of a larger-size system with $M = 30$, $T = 30$, $N = 40$, and $U = 700$. Fig.3 shows EEs over P_{fix} with $R = 1$ Mbps and it shows that SDMA is preferable if the TPI term is dominant. Fig.4 shows that the gain is improved to unity after normalization process.

5. Conclusion

In this paper, we have proposed energy efficiency (EE)-aware multiple access (EMA) scheme. Based on the required power consumption to achieve the fixed feasible target rates, the EMA chooses either a time-division multiple access or spatial-division multiple access (SDMA) for each sub-band. For the EE-aware SDMA, optimal number of SDMA slots has been derived. It has been shown that the SDMA is most likely selected if i)the target rate is high, ii) the transmit-power-independent power consumption is high, or iii) the channel quality is good. Simple EMA algorithms have been devised and their impact on EE and gain improvement has been verified by simulation. The results have provided valuable insight to extend EE-aware system with the consideration of i) the uncertainty of channel state information and ii) power consumption of uplink communications.

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