

Energy-Efficiency Optimization for MIMO-OFDM Mobile Multimedia Communication Systems With QoS Constraints

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Abstract—It is widely recognized that, in addition to the quality-of-service (QoS), energy efficiency is also a key parameter in designing and evaluating mobile multimedia communication systems, which has catalyzed great interest in recent literature. In this paper, an energy-efficiency model is first proposed for multiple-input–multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) mobile multimedia communication systems with statistical QoS constraints. Employing the channel-matrix singular value decomposition (SVD) method, all subchannels are classified by their channel characteristics. Furthermore, the multichannel joint optimization problem in conventional MIMO-OFDM communication systems is transformed into a multitarget single-channel optimization problem by grouping all subchannels. Therefore, a closed-form solution of the energy-efficiency optimization is derived for MIMO-OFDM mobile multimedia communication systems. As a consequence, an energy-efficiency optimized power allocation (EEOPA) algorithm is proposed to improve the energy efficiency of MIMO-OFDM mobile multimedia communication systems. Simulation comparisons validate that the proposed EEOPA algorithm can guarantee the required QoS with high energy efficiency in MIMO-OFDM mobile multimedia communication systems.

Index Terms—Energy efficiency, MIMO-OFDM, multimedia communications, performance analysis.

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I. INTRODUCTION

WITH the rapid development in information and communication technology (ICT), the energy consumption problem of ICT industry, which causes about 2% of worldwide CO₂ emissions yearly and burdens the electrical bills of network operators [1], has drawn universal attention. Motivated by the demand for improving the energy efficiency in mobile multimedia communication systems, various resource-allocation optimization schemes aiming at enhancing energy efficiency have become one of the mainstreams in mobile multimedia communication systems, including transmission power allocation [2], [3], bandwidth allocation [4]–[6], subchannel allocation [7], etc. Multiple-input–multiple-output (MIMO) technologies can create independent parallel channels to transmit data streams, which improves spectral efficiency and system capacity without increasing the bandwidth requirement [8]. Orthogonal frequency-division multiplexing (OFDM) technologies eliminate the multipath effect by transforming frequency-selective channels into flat channels. As a combination of MIMO and OFDM technologies, the MIMO-OFDM technologies are widely used in mobile multimedia communication systems. However, how to improve energy efficiency with a QoS constraint is an indispensable problem in MIMO-OFDM mobile multimedia communication systems.

The energy efficiency has become one of the hot studies in MIMO wireless communication systems in the last decade [9]–[14]. An energy-efficiency model for Poisson–Voronoi tessellation cellular networks considering spatial distributions of traffic load and power consumption was proposed [9]. The energy–bandwidth efficiency tradeoff in MIMO multihop wireless networks was studied, and the effects of different numbers of antennas on the energy–bandwidth efficiency tradeoff were investigated in [10]. An accurate closed-form approximation of the tradeoff between energy efficiency and spectral efficiency over the MIMO Rayleigh fading channel was derived by considering different types of power consumption models [11]. A relay cooperation scheme was proposed to investigate the tradeoff between spectral efficiency and energy efficiency in multicell MIMO cellular networks [12]. The energy efficiency–spectral efficiency tradeoff of the uplink of a multiuser cellular virtual MIMO system with decode-and-forward-type protocols was studied in [13]. The tradeoff between spectral efficiency and energy efficiency was investigated in the relay-aided multicell MIMO cellular network by comparing both the signal

forwarding and interference forwarding relaying paradigms [14]. In our earlier work, we explored the tradeoff between the operating power and the embodied power contained in the manufacturing process of infrastructure equipment from a life-cycle perspective [1]. In this paper, we further investigate the energy-efficiency optimization for MIMO-OFDM mobile multimedia communication systems.

Based on the Wishart matrix theory [15]–[18], numerous channel models have been proposed in the literature for MIMO communication systems [19]–[26]. A closed-form joint probability density function (pdf) of eigenvalues of the Wishart matrix was derived for evaluating the performance of MIMO communication systems [19]. Moreover, a closed-form expression for the marginal pdf (mpdf) of the ordered eigenvalues of complex noncentral Wishart matrices was derived to analyze the performance of singular value decomposition (SVD) in MIMO communication systems with Rician fading channels [20]. Based on the distribution of eigenvalues of a Wishart matrix, the performance of high spectral efficiency MIMO communication systems with multiple phase-shift keying signals in a flat Rayleigh fading environment was investigated in terms of symbol error probabilities [21]. Furthermore, the cumulative density functions (cdfs) of the largest and smallest eigenvalues of a central correlated Wishart matrix were investigated to evaluate the error probability of a MIMO maximal ratio combining (MRC) communication system with perfect channel state information (CSI) at both the transmitter and receiver [22]. Based on the pdf and the cdf of the maximum eigenvalue of double-correlated complex Wishart matrices, the exact expressions for the pdf of the output SNR were derived for MIMO-MRC communication systems with Rayleigh fading channels [23]. The closed-form expressions for the outage probability of MIMO-MRC communication systems with Rician fading channels were derived under the condition of the largest eigenvalue distribution of central complex Wishart matrices in the noncentral case [24]. Furthermore, The closed-form expressions for the outage probability of MIMO-MRC communication systems with and without cochannel interference were derived by using cdfs of a Wishart matrix [25]. Meanwhile, the pdf of the smallest eigenvalue of a Wishart matrix was applied to select antennas to improve the capacity of MIMO communication systems [26]. However, most existing studies mainly worked on the joint pdf of eigenvalues of a Wishart matrix to measure the channel performance for MIMO communication systems. In this paper, subchannels' gains derived from the marginal probability distribution of a Wishart matrix is investigated to implement energy-efficiency optimization in MIMO-OFDM mobile multimedia communication systems.

In conventional mobile multimedia communication systems, many studies have been carried out [27]–[33]. In terms of the corresponding QoS demand of different throughput levels in MIMO communication systems, an effective antenna assignment scheme and an access control scheme were proposed in [27]. A downlink QoS evaluation scheme was proposed from the viewpoint of mobile users in orthogonal frequency-division multiple-access (OFDMA) wireless cellular networks [28]. To guarantee the QoS in wireless networks, a statistical QoS constraint model was built to analyze the queue characteristics

of data transmissions [29]. The energy efficiency in fading channels under QoS constraints was analyzed in [30], where the effective capacity was considered as a measure of the maximum throughput under certain statistical QoS constraints. Based on the effective capacity of the block fading channel model, a QoS-driven power and rate adaptation scheme over wireless links was proposed for mobile wireless networks [31]. Furthermore, by integrating information theory with the effective capacity, some QoS-driven power and rate adaptation schemes were proposed for diversity and multiplexing systems [32]. Simulation results showed that multichannel communication systems can achieve both high throughput and stringent QoS at the same time. Aiming at optimizing the energy consumption, the key tradeoffs between energy efficiency and link-level QoS metrics were analyzed in different wireless communication scenarios [33]. However, there has been few research work addressing the problem of optimizing the energy efficiency under different QoS constraints in MIMO-OFDM mobile multimedia communication systems.

Motivated by aforementioned gaps, this paper is devoted to the energy-efficiency optimization with statistical QoS constraints in MIMO-OFDM mobile multimedia communication systems with statistical QoS constraints, which uses a statistical exponent to measure the queue characteristics of data transmission in wireless systems. All subchannels in MIMO-OFDM communication systems are first grouped by their channel gains. On this basis, a novel subchannel grouping scheme is developed to allocate the corresponding transmission power to each of the subchannels in different groups, which simplifies the multichannel optimization problem to a multitarget single-channel optimization problem. The main contributions of this paper are summarized as follows.

- 1) An energy-efficiency model with statistical QoS constraints is proposed for MIMO-OFDM mobile multimedia communication systems.
- 2) A subchannel grouping scheme is designed by using the channel-matrix SVD method, which simplifies the multichannel optimization problem to a multitarget single-channel optimization problem. Based on mpdfs of subchannels in different groups, a closed-form solution of energy-efficiency optimization is derived for MIMO-OFDM mobile multimedia communication systems.
- 3) A novel algorithm is developed to optimize the energy efficiency in MIMO-OFDM mobile multimedia communication systems. Numerical results validate that the proposed algorithm improves the energy efficiency of MIMO-OFDM mobile multimedia communication systems with statistical QoS constraints.

The remainder of this paper is organized as follows. The system model is introduced in Section II. In Section III, the energy-efficiency model of MIMO-OFDM mobile multimedia communication systems with statistical QoS constraints is proposed. Based on the subchannel grouping scheme, a closed-form solution of energy-efficiency optimization is derived for MIMO-OFDM mobile multimedia communication systems in Section IV. Moreover, a novel transmission power-allocation algorithm is presented. Numerical results are shown in Section V. Finally, Section VI concludes this paper.

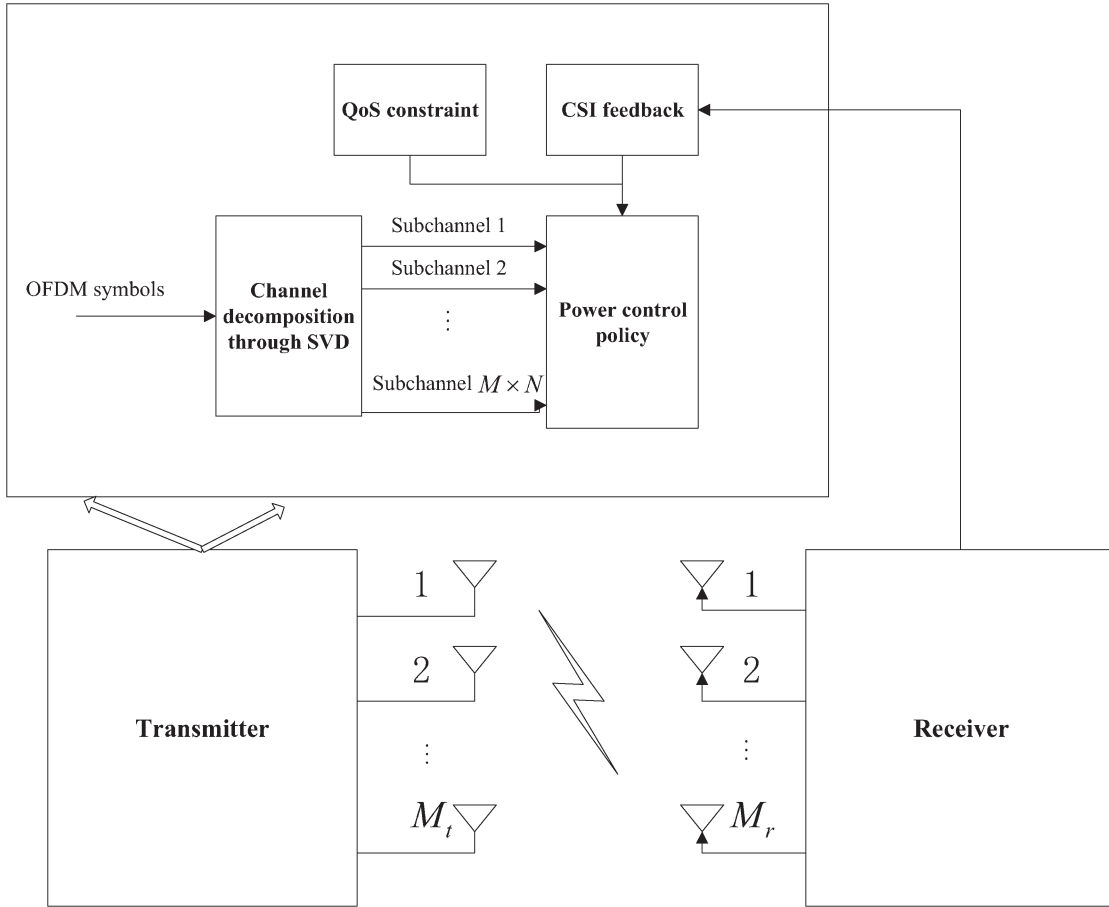


Fig. 1. MIMO-OFDM system model.

II. SYSTEM MODEL

The MIMO-OFDM mobile multimedia communication system is shown in Fig. 1. It has an $M_r \times M_t$ antenna matrix, N subcarriers, and S OFDM symbols, where M_t is the number of transmit antennas, and M_r is the number of receive antennas. We denote B as the system bandwidth and T_f as the frame duration. The OFDM signals are assumed transmitted within frame duration. Then, the received signal of the MIMO-OFDM communication system can be expressed as follows:

$$\mathbf{y}_k[i] = \mathbf{H}_k \mathbf{x}_k[i] + \mathbf{n} \quad (1)$$

where $\mathbf{y}_k[i]$ and $\mathbf{x}_k[i]$ are the received signal vector and transmitted signal vector at the k th ($k = 1, 2, \dots, N$) subcarrier of the i th ($i = 1, 2, \dots, S$) OFDM symbol, respectively. \mathbf{H}_k is the frequency-domain channel matrix at the k th subcarrier, and \mathbf{n} is the additive noise vector. Let \mathbb{C} denote the complex space; then, we have $\mathbf{y}_k \in \mathbb{C}^{M_r}$, $\mathbf{x}_k \in \mathbb{C}^{M_t}$, $\mathbf{H}_k \in \mathbb{C}^{M_r \times M_t}$, and $\mathbf{n} \in \mathbb{C}^{M_r}$. Without loss of generality, we assume $\mathbf{E}\{\mathbf{n}\mathbf{n}^H\} = \mathbf{I}^{M_r \times M_r}$, where $\mathbf{E}\{\cdot\}$ denotes the expectation operator.

Discrete-time channels are assumed to experience a block fading, in which the frame duration is shorter than the channel coherence time. Based on this assumption, the channel gain is invariant within frame duration T_f but varies independently from one frame to another. In each frame duration, the channel at each subcarrier is divided into M ($M = \min(M_t, M_r)$) parallel single-input–single-output (SISO) channels by the SVD

method. As a consequence, a total number of $M \times N$ parallel space–frequency subchannels can be generated in each OFDM symbol. Transmitters are assumed to obtain the CSI from receivers without delay via feedback channels. Furthermore, an average transmission power constraint \bar{P} is configured for each subchannel in the MIMO-OFDM communication system. With this average transmission power constraint, transmitters are able to perform power control adaptively according to the feedback CSI and system QoS constraints so that the energy efficiency in the MIMO-OFDM mobile multimedia communication system can be optimized. To facilitate reading, the notations and symbols used in this paper are listed in Table I.

III. ENERGY-EFFICIENCY MODELING OF MULTIPLE-INPUT–MULTIPLE-OUTPUT–ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING MOBILE MULTIMEDIA COMMUNICATION SYSTEMS

By applying the SVD method to the channel matrix \mathbf{H}_k at each subcarrier, where $\mathbf{H}_k \in \mathbb{C}^{M_r \times M_t}$ ($k = 1, 2, \dots, N$), we have

$$\mathbf{H}_k = \mathbf{U}_k \sqrt{\tilde{\Delta}_k} \mathbf{V}_k^H \quad (2)$$

where $\mathbf{U}_k \in \mathbb{C}^{M_r \times M_r}$, and $\mathbf{V}_k \in \mathbb{C}^{M_t \times M_t}$ are unitary matrices. When $M_r \geq M_t$, we have block matrix $\tilde{\Delta}_k = [\Delta_k, \mathbf{0}_{M_r, M_t - M_r}]$; otherwise, when $M_r < M_t$, we have $\tilde{\Delta}_k = [\Delta_k,$

TABLE I
NOTATIONS AND SYMBOLS USED IN THIS PAPER

Symbol	Definition/explanation
M_t	The number of transmit antennas
M_r	The number of receive antennas
M	$M = \min(M_t, M_r)$
N	The number of subcarriers
S	The number of OFDM symbols
B	The system bandwidth
T_f	The frame duration
\mathbf{y}_k	The received signal vector at the k th subcarrier of the i th OFDM symbol
\mathbf{x}_k	The transmitted signal vector at the k th subcarrier of the i th OFDM symbol
\mathbf{H}_k	The frequency-domain channel matrix at the k th subcarrier
\mathbf{n}	The additive noise vector
M	The number of parallel SISO channels at each subcarrier
\bar{P}	The average transmission power constraint for a subchannel
λ	The subchannel gain
$\lambda_{m,k}$	The channel gain of the m th subchannel at the k th subcarrier
Λ	The transmission power allocation threshold over a subchannel
$\Lambda_{m,k}$	The transmission power allocation threshold of the m th subchannel at the k th subcarrier
Λ_n	The transmission power allocation threshold of the n th grouped subchannels
η	The energy efficiency of MIMO-OFDM mobile multimedia communication systems
η_{opt}	The optimized energy efficiency
θ	The QoS statistical exponent
β	The normalized QoS exponent
$C_{\text{total}}(\theta)$	The total effective capacity
$C_e(\theta)_{m,k}$	The effective capacity of the m th subchannel over the k th subcarrier
$C_e(\theta)$	The effective capacity for a subchannel with QoS constraint
$C_e(\theta)_{\text{opt}_n}$	The optimized effective capacity of the n th grouped subchannels
$\mathbf{E}\{P_{\text{total}}\}$	The expectation of the total transmission power
R	The instantaneous bit rate within a frame duration
$\mu(\theta, \lambda)$	The transmission power allocated over a subchannel
$\mu_{m,k}(\theta, \lambda)$	The transmission power allocated over the m th subchannel at the k th orthogonal subcarrier
$\mu_{\text{opt}}(\theta, \lambda)$	The optimized transmission power allocated over a channel
$\mu_{\text{opt}_n}(\theta, \lambda)$	The optimized transmission power allocated for subchannels in the n th group
$p_{\Gamma_{m,k}}(\lambda)$	The channel gain MPDF of the m th subchannel at the k th orthogonal subcarrier
$p_{\Gamma_n}(\lambda)$	The channel gain MPDF of the subchannels over the n th grouped subchannels
$p(\lambda_1, \lambda_2, \dots, \lambda_M)$	The joint PDF of ordered eigenvalues of a Wishart matrix
$K_{M,Q}$	The normalizing factor

$\mathbf{0}_{M_t, M_r - M_t}]^T$, where $\Delta_k = \text{diag}(\lambda_{1,k}, \dots, \lambda_{M,k})$, and $\lambda_{m,k} \geq 0, \forall m = 1, \dots, M, k = 1, \dots, N$. $\{\lambda_{m,k}\}_{m=1}^M$ denotes the subchannel gain set at the k th subcarrier. In this way, the MIMO channel at each subcarrier is decomposed into M parallel SISO subchannels by the SVD method. Therefore, $M \times N$ parallel space-frequency subchannels are obtained at N orthogonal subcarriers for each OFDM symbol.

In traditional energy-efficiency optimization research, Shannon capacity is usually used as the index, which measures the system output. However, in any practical wireless communication systems, the system capacity is obviously less than Shannon capacity, particularly in the scenario with a strict QoS constraint. In this paper, the effective capacity of each subchannel is taken as the practical data rate with a certain QoS constraint. The total effective capacity of $M \times N$ subchannels is configured as the system output, and the total transmission power allocated to $M \times N$ subchannels is configured as the system input. As a consequence, the energy efficiency of MIMO-OFDM mobile multimedia communication systems is defined as follows:

$$\eta = \frac{C_{\text{total}}(\theta)}{\mathbf{E}\{P_{\text{total}}\}} = \frac{\sum_{m=1}^M \sum_{k=1}^N C_e(\theta)_{m,k}}{\mathbf{E}\{P_{\text{total}}\}} \quad (3)$$

where $C_e(\theta)_{m,k} (m = 1, 2, \dots, M, k = 1, 2, \dots, N)$ is the effective capacity of the m th subchannel over the k th subcarrier,

and $\mathbf{E}\{P_{\text{total}}\}$ is the expectation of the total transmission power allocated to all $M \times N$ subchannels. θ is the QoS statistical exponent, which indicates the exponential decay rate of QoS violation probabilities [31]. A smaller θ corresponds to a slower decay rate, which implies that the multimedia communication system provides a looser QoS guarantee, whereas a larger θ leads to a faster decay rate, which means that a higher QoS requirement should be supported.

Practical MIMO-OFDM mobile multimedia communication systems involve multiple services, such as speech and video services, which are sensitive to the delay parameter. Different services in MIMO-OFDM mobile multimedia communication systems have different QoS constraints. In view of this, the effective capacity of each subchannel depends on the corresponding QoS constraint. A statistical QoS constraint is adopted to evaluate the effective capacity of each subchannel, which is calculated as the system practical output in MIMO-OFDM mobile multimedia communication systems. Assuming the fading process over wireless channels is independent among frames and keeps invariant within a frame duration, the effective capacity $C_e(\theta)$ for a subchannel with QoS statistical exponent θ in MIMO-OFDM mobile multimedia communication systems is expressed as follows [31]:

$$C_e(\theta) = -\frac{1}{\theta} \log(\mathbf{E}\{e^{-\theta R}\}) \quad (4a)$$

$$R = T_f B \log_2(1 + \mu(\theta, \lambda)\lambda) \quad (4b)$$

where R denotes the instantaneous bit rate within a frame duration, λ denotes the subchannel gain, and $\mu(\theta, \lambda)$ denotes the transmission power allocated to a subchannel.

After SVD of channel matrices at N orthogonal subcarriers, $M \times N$ parallel subchannels are obtained. The channel gain over each of these $M \times N$ parallel subchannels follows a mpdf. Assuming $p_{\Gamma_{m,k}}(\lambda)$ as the mpdf of channel gain over the m th ($m = 1, 2, \dots, M$) subchannel at the k th ($k = 1, 2, \dots, N$) orthogonal subcarrier, then the corresponding effective capacity $C_e(\theta)_{m,k}$ over the m th subchannel at the k th orthogonal subcarrier is derived as

$$C_e(\theta)_{m,k} = -\frac{1}{\theta} \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1+\mu_{m,k}(\theta, \lambda))} p_{\Gamma_{m,k}}(\lambda) d\lambda \right) \quad (5)$$

where $\mu_{m,k}(\theta, \lambda)$ is the transmission power allocated to the m th subchannel at the k th orthogonal subcarrier.

Considering the practical power consumption limitation at transmitters, an average transmission power constraint \bar{P} over each subchannel is derived as

$$\bar{P} = \int_0^{\infty} \mu_{m,k}(\theta, \lambda) p_{\Gamma_{m,k}}(\lambda) d\lambda \quad \forall m = 1, 2, \dots, M; \quad k = 1, 2, \dots, N. \quad (6)$$

With the average transmission power constraint, the expectation of transmission power $\mathbf{E}\{P_{\text{total}}\}$ is given by

$$\mathbf{E}\{P_{\text{total}}\} = \bar{P} \times M \times N. \quad (7)$$

By substituting (6) and (7) into (3), we derive the energy-efficiency model as model as

$$\eta = \frac{\sum_{m=1}^M \sum_{k=1}^N -\frac{1}{\theta} \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1+\mu_{m,k}(\theta, \lambda))} p_{\Gamma_{m,k}}(\lambda) d\lambda \right)}{\bar{P} \times M \times N}. \quad (8)$$

From (8), the energy efficiency of MIMO-OFDM mobile multimedia communication systems depends on the mpdf $p_{\Gamma_{m,k}}(\lambda)$ ($m = 1, 2, \dots, M; k = 1, 2, \dots, N$) over $M \times N$ subchannels. Since there is a relationship between the mpdf $p_{\Gamma_{m,k}}(\lambda)$ and statistical characteristics of the subchannel, the marginal distribution characteristics of each subchannel gain is investigated to optimize the energy efficiency in MIMO-OFDM mobile multimedia communication systems.

IV. ENERGY-EFFICIENCY OPTIMIZATION OF MOBILE MULTIMEDIA COMMUNICATION SYSTEMS

In MIMO wireless communication systems, statistical characteristics of channel gain depend on the eigenvalues' distribution of Hermitian channel matrix $\mathbf{H}\mathbf{H}^H$, where \mathbf{H} is the channel matrix [34]–[36]. When the elements of \mathbf{H} are complex valued with real and imaginary parts each governed by a normal distribution $\mathfrak{N}(0, 1/2)$ with mean value of 0 and

variance value of 1/2, the Hermitian channel matrix $\mathbf{W} = \mathbf{H}\mathbf{H}^H$ is called a central Wishart channel matrix [15]–[17], [19]. In this case, $\mathbf{E}\{\mathbf{H}\} = \mathbf{0}$, and wireless channels have the Rayleigh fading characteristic. If $\mathbf{E}\{\mathbf{H}\} \neq \mathbf{0}$, $\mathbf{W} = \mathbf{H}\mathbf{H}^H$ is a noncentral Wishart channel matrix, and wireless channels have the Rician fading characteristic [20].

Based on SVD results of the wireless channel matrix, subchannels at each orthogonal subcarrier are sorted in a descending order of channel gains. Starting from the joint pdf of eigenvalues of the Wishart channel matrix, the channel gain mpdf of subchannels ordered at the m th position in the descending order of channel gains is derived. Furthermore, all subchannels at N subcarriers are grouped according to their mpdfs. In terms of subchannel grouping results, a closed-form solution is derived to optimize the energy efficiency of MIMO-OFDM mobile multimedia communication systems here.

A. Optimization Solution of Energy Efficiency

To maximize the energy efficiency of MIMO-OFDM mobile multimedia communication systems with statistical QoS constraints, the optimization problem can be formulated as (9), where η_{opt} is the optimized energy efficiency.

From the problem formulation in (9) and (10), shown at the bottom of the next page, it is remarkable that the energy efficiency of MIMO-OFDM mobile multimedia communication systems depends on transmission power-allocation results $\mu_{m,k}(\theta, \lambda)$ over $M \times N$ subchannels. In this case, the optimization problem in (9) and (10) is a multichannel optimization problem, which is intractable to obtain a closed-form solution in mathematics.

In most studies on MIMO wireless communication systems, the energy-efficiency optimization problem is solved by a single-channel optimization model [32]. How to change the multichannel energy-efficiency optimization problem into the single-channel energy-efficiency optimization problem and derive a closed-form solution are great challenges in this paper. Without loss of generality, the optimized transmission power allocation of single subchannel $\mu_{\text{opt}}(\theta, \lambda)$ is expressed as follows [32]:

$$\mu_{\text{opt}}(\theta, \lambda) = \begin{cases} \frac{1}{\Lambda^{\frac{1}{\beta+1}} \lambda^{\frac{\beta}{\beta+1}}} - \frac{1}{\lambda}, & \lambda \geq \Lambda \\ 0, & \lambda < \Lambda \end{cases} \quad (11a)$$

$$\beta = \theta T_f B / \log 2 \quad (11b)$$

where Λ is the transmission power-allocation threshold over a subchannel, and β is the normalized QoS exponent.

It is critical to determine the transmission power-allocation threshold Λ for the implementation of optimized transmission power allocation in (11a). An average transmission power constraint \bar{P} is configured for each subchannel; thus, the transmission power-allocation threshold of each subchannel should satisfy the following constraint:

$$\int_{\Lambda_{m,k}}^{\infty} \left(\frac{1}{\Lambda_{m,k}^{\frac{1}{\beta+1}} \lambda^{\frac{\beta}{\beta+1}}} - \frac{1}{\lambda} \right) p_{\Gamma_{m,k}}(\lambda) d\lambda \leq \bar{P} \quad (12)$$

where $\Lambda_{m,k}(m = 1, 2, \dots, M; k = 1, 2, \dots, N)$ is the transmission power-allocation threshold of the m th subchannel at the k th subcarrier.

Assuming that the channel matrix $\mathbf{H}_k(k = 1, 2, \dots, N)$ at each subcarrier is a complex matrix and its elements are complex valued with real and imaginary parts, each governed by a normal distribution $\mathcal{N}(0, 1/2)$ with a mean value of 0 and a variance value of 1/2, elements of \mathbf{H}_k then follow an independent and identically distributed circular symmetric complex Gaussian distribution with zero mean and unit variance. In this case, wireless channels between transmit and receive antennas are Rayleigh fading channels with unit energy.

Denote $Q = \max(M_t, M_r)$, and set $\widetilde{\mathbf{W}}$ as an $M \times M$ Hermitian matrix as follows:

$$\widetilde{\mathbf{W}} = \begin{cases} \mathbf{H}_k \mathbf{H}_k^H, & M_r < M_t \\ \mathbf{H}_k^H \mathbf{H}_k, & M_r \geq M_t. \end{cases} \quad (13)$$

Then, $\widetilde{\mathbf{W}}$ is a central Wishart matrix. The joint pdf of ordered eigenvalues of $\widetilde{\mathbf{W}}$ follows Wishart distributions [37] as

$$p(\lambda_1, \lambda_2, \dots, \lambda_M) = K_{M,Q}^{-1} e^{-\sum_{i=1}^M \lambda_i} \prod_{i=1}^M \lambda_i^{Q-M} \prod_{1 \leq i < j \leq M} (\lambda_i - \lambda_j)^2 \quad (14)$$

where $\lambda_1, \lambda_2, \dots, \lambda_M(\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_M)$ are ordered eigenvalues of $\widetilde{\mathbf{W}}$, and $K_{M,Q}$ is a normalizing factor, which is denoted as follows:

$$K_{M,Q} = \prod_{i=1}^M (Q - i)! (M - i)!. \quad (15)$$

Based on SVD results of channel matrix \mathbf{H}_k , ordered eigenvalues of matrix $\mathbf{H}_k^H \mathbf{H}_k$ are denoted by elements $\lambda_{1,k}, \lambda_{2,k}, \dots, \lambda_{M,k}$ of diagonal matrix $\mathbf{\Delta}_k$. This means that subchannel gains $\lambda_{1,k}, \dots, \lambda_{M,k}$ at the k th subcarrier can be denoted by eigenvalues of the Wishart matrix $\widetilde{\mathbf{W}}$. When subchannel gains at each subcarrier are sorted in descending order, i.e., $\forall 1 \leq i \leq j \leq M, 1 \leq k \leq N, \lambda_{i,k} \geq \lambda_{j,k}$, the

ordered subchannel gains can be denoted by the ordered eigenvalues $\lambda_1, \lambda_2, \dots, \lambda_M(\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_M)$ of Wishart matrix $\widetilde{\mathbf{W}}$, which follow the joint pdf $p(\lambda_1, \lambda_2, \dots, \lambda_M)$ of the ordered eigenvalues of Wishart matrix $\widetilde{\mathbf{W}}$. After subchannel gains at each subcarrier are sorted in descending order, the mpdf of the m th ($1 \leq n \leq M$) subchannel gain at the k th subcarrier $p_{\Gamma_{m,k}}(\lambda)$ is derived as

$$p_{\Gamma_{m,k}}(\lambda) = \underbrace{\int \dots \int}_{M-1} p(\lambda_1, \lambda_2, \dots, \lambda_M) d\lambda_i d\lambda_{i+1} \dots d\lambda_j \quad (1 \leq i < j \leq M \text{ and } i \neq n, j \neq n). \quad (16)$$

After subchannels at each subcarrier are sorted by subchannel gains, subchannels with the same order position at different orthogonal subcarriers have the identical mpdf based on (16). According to this property, a subchannel grouping scheme is proposed for subchannels at different orthogonal subcarriers:

- 1) Sort subchannels at each orthogonal subcarriers by a descending order of subchannel gains: $\lambda_{1,k} \geq \lambda_{2,k} \geq \dots \geq \lambda_{M,k} \geq 0, k = 1, 2, \dots, N$.
- 2) For $n = 1: M$, select the subchannels with the same order position at different orthogonal subcarriers ($\lambda_{n,1}, \lambda_{n,2}, \dots, \lambda_{n,N}$) into different channel groups.
- 3) Repeat steps 1 and 2 for all OFDM symbols.
- 4) M groups with the same order position subchannels are obtained.

Since subchannels in the same group have an identical mpdf, the mpdf of subchannels in the n th group $p_{\Gamma_{n,k}}(\lambda)$ ($1 \leq n \leq M, 1 \leq k \leq N$) is simply denoted $p_{\Gamma_n}(\lambda)$ ($1 \leq n \leq M$).

Based on the proposed subchannel grouping scheme, we can optimize the effective capacity of each grouped subchannels according to their mpdfs in (16), in which all subchannels in the same group have an identical mpdf. In this process, the multichannel joint optimization problem is transformed into a multitarget single-channel optimization problem, which significantly reduces the complexity of energy-efficiency

$$\eta_{\text{opt}} = \max \left\{ \frac{\sum_{m=1}^M \sum_{k=1}^N -\frac{1}{\theta} \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1 + \mu_{m,k}(\theta, \lambda))} p_{\Gamma_{m,k}}(\lambda) d\lambda \right)}{\bar{P} \times M \times N} \right\} \\ = \frac{\max \left\{ \sum_{m=1}^M \sum_{k=1}^N -\frac{1}{\theta} \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1 + \mu_{m,k}(\theta, \lambda))} p_{\Gamma_{m,k}}(\lambda) d\lambda \right) \right\}}{\bar{P} \times M \times N} \quad (9)$$

s.t.

$$\int_0^{\infty} \mu_{m,k}(\theta, \lambda) p_{\Gamma_{m,k}}(\lambda) d\lambda \leq \bar{P} \quad \forall m = 1, 2, \dots, M; \quad k = 1, 2, \dots, N \quad (10)$$

optimization. By substituting (16) into (12), the average power constraint is derived as

$$\int_{\Lambda_n}^{\infty} \left(\frac{1}{\Lambda_n^{\frac{1}{\beta+1}} \lambda^{\frac{\beta}{\beta+1}}} - \frac{1}{\lambda} \right) \times \left(\int \dots \int_{M-1} p(\lambda_1, \lambda_2, \dots, \lambda_M) d\lambda_i d\lambda_{i+1} \dots d\lambda_j \right) \times d\lambda \leq \bar{P}, \quad 1 \leq i < j \leq M; \quad i \neq n; \quad j \neq n \quad (17)$$

where Λ_n ($1 \leq n \leq M$) is the transmission power-allocation threshold of the n th-group subchannels. Based on the transmission power-allocation threshold for each grouped subchannels in (17), the optimized transmission power allocation for the n th-group subchannels is formulated as follows:

$$\mu_{\text{opt}_n}(\theta, \lambda) = \begin{cases} \frac{1}{\Lambda_n^{\frac{1}{\beta+1}} \lambda^{\frac{\beta}{\beta+1}}} - \frac{1}{\lambda}, & \lambda \geq \Lambda_n \\ 0, & \lambda < \Lambda_n \end{cases} \quad (18)$$

where $\mu_{\text{opt}_n}(\theta, \lambda)$ is the optimized transmission power allocated for subchannels in the n th group. Therefore, the optimized energy efficiency of MIMO-OFDM mobile multimedia communication systems with statistical QoS constraints is derived as

$$\eta_{\text{opt}} = \frac{\sum_{n=1}^M -\frac{N}{\theta} \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1+\mu_{\text{opt}_n}(\theta, \lambda))} p_{\Gamma_n}(\lambda) d\lambda \right)}{\bar{P} \times M \times N} \quad (19)$$

$$= -\frac{1}{\theta \times \bar{P} \times M} \sum_{n=1}^M \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1+\mu_{\text{opt}_n}(\theta, \lambda))} p_{\Gamma_n}(\lambda) d\lambda \right). \quad (20)$$

B. Algorithm Design

The core idea of energy-efficiency optimized power-allocation algorithm (EEOPA) with statistical QoS constraints for MIMO-OFDM mobile multimedia communication systems is described as follows. First, the SVD method is applied for the channel matrix \mathbf{H}_k , $k = 1, 2, \dots, N$, at each orthogonal subcarrier to obtain $M \times N$ parallel space-frequency subchannels. Second, subchannels at each subcarrier are pushed into a subchannel gain set, where subchannels are sorted by the subchannel gain in descending order, and then, the subchannels with the same order position in the subchannel gain set are selected into the same group. Since the subchannels within the same group have the identical mpdf, the transmission power-allocation threshold for the subchannels within the same group is identical. Therefore, the optimized transmission power allocation for the grouped subchannels is implemented to improve the energy efficiency of MIMO-OFDM mobile multimedia

communication systems. The detailed EEOPA algorithm is shown in Algorithm 1.

Algorithm 1 EEOPA.

Input: $M_t, M_r, N, \mathbf{H}_k, \bar{P}, B, T_f, \theta$;

Initialization: Decompose the MIMO-OFDM channel matrix \mathbf{H}_k ($k = 1, 2, \dots, N$) into $M \times N$ space-frequency subchannels through the SVD method.

Begin:

1) Sort subchannel gains of each subcarrier in decreasing order as follows:

$$\lambda_{1,k} \geq \lambda_{2,k} \geq \dots \geq \lambda_{M,k} \quad (k = 1, 2, \dots, N). \quad (21)$$

2) Assign $\lambda_{n,1}, \lambda_{n,2}, \dots, \lambda_{n,N}$ from all N subcarriers into the n th-group subchannel set as follows:

$$\text{Group}_n = \{\lambda_{n,1}, \lambda_{n,2}, \dots, \lambda_{n,N}\}, \quad n = 1, 2, \dots, M. \quad (22)$$

3) **for** $n = 1 : M$ **do**

 Calculate the optimized transmission power-allocation threshold Λ_n for Group $_n$

 according to the average power constraint as follows:

$$\int_{\Lambda_n}^{\infty} \left(\frac{1}{\Lambda_n^{\frac{1}{\beta+1}} \lambda^{\frac{\beta}{\beta+1}}} - \frac{1}{\lambda} \right) p_{\Gamma_n}(\lambda) d\lambda \leq \bar{P}. \quad (23)$$

 Execute the optimized transmission power-allocation policy for Group $_n$ as follows:

$$\mu_{\text{opt}_n}(\theta, \lambda) = \begin{cases} \frac{1}{\Lambda_n^{\frac{1}{\beta+1}} \lambda^{\frac{\beta}{\beta+1}}} - \frac{1}{\lambda}, & \lambda \geq \Lambda_n \\ 0, & \lambda < \Lambda_n. \end{cases} \quad (24)$$

 Calculate the optimized effective capacity for Group $_n$: as follows:

$$C_e(\theta)_{\text{opt}_n} = -\frac{N}{\theta} \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1+\mu_{\text{opt}_n}(\theta, \lambda))} p_{\Gamma_n}(\lambda) d\lambda \right). \quad (25)$$

end for

4) Calculate the optimized energy efficiency of the MIMO-OFDM mobile multimedia communication system as follows:

$$\eta_{\text{opt}} = -\frac{1}{\theta \times \bar{P} \times M} \sum_{n=1}^M \log \left(\int_0^{\infty} e^{-\theta T_f B \log_2(1+\mu_{\text{opt}_n}(\theta, \lambda))} p_{\Gamma_n}(\lambda) d\lambda \right). \quad (26)$$

end Begin

Output: $\Lambda_n, \eta_{\text{opt}}$.

V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In the proposed algorithm, the transmission power-allocation threshold Λ_n is the core parameter to optimize the energy efficiency of MIMO-OFDM mobile multimedia communication systems. The configuration of the transmission power-allocation threshold Λ_n depends on the mpdf of each grouped subchannels. Without loss of generation, the number of transmitter and receiver antennas is configured as $M_t = 4$ and $M_r = 4$, respectively. Based on the extension of (16), mpdfs of each grouped subchannels are extended as

$$\begin{aligned}
 p_{\Gamma_1}(\lambda) &= -4e^{-4\lambda} - (1/36)e^{-\lambda} \\
 &\times (144 - 432\lambda + 648\lambda^2 - 408\lambda^3 + 126\lambda^4 - 18\lambda^5 + \lambda^6) \\
 &+ (1/12)e^{-3\lambda} \\
 &\times (144 - 144\lambda + 72\lambda^2 + 56\lambda^3 + 46\lambda^4 + 10\lambda^5 + \lambda^6) \\
 &- (1/72)e^{-2\lambda}(864 - 1728\lambda + 1728\lambda^2 - 192\lambda^3 \\
 &\quad + 96\lambda^4 - 96\lambda^5 + 32\lambda^6 - 4\lambda^7 + \lambda^8) \quad (27)
 \end{aligned}$$

$$\begin{aligned}
 p_{\Gamma_2}(\lambda) &= 12e^{-4\lambda} - (1/6)e^{-3\lambda} \\
 &\times (144 - 144\lambda + 72\lambda^2 + 56\lambda^3 + 46\lambda^4 + 10\lambda^5 + \lambda^6) \\
 &+ (1/72)e^{-2\lambda}(864 - 1728\lambda + 1728\lambda^2 - 192\lambda^3 \\
 &\quad + 96\lambda^4 - 96\lambda^5 + 32\lambda^6 - 4\lambda^7 + \lambda^8) \quad (28)
 \end{aligned}$$

$$\begin{aligned}
 p_{\Gamma_3}(\lambda) &= -12e^{-4\lambda} + (1/12)e^{-3\lambda} \\
 &\times (144 - 144\lambda + 72\lambda^2 + 56\lambda^3 + 46\lambda^4 + 10\lambda^5 + \lambda^6) \quad (29)
 \end{aligned}$$

$$p_{\Gamma_4}(\lambda) = 4e^{-4\lambda}. \quad (30)$$

By substituting (27)–(30) into (12), the transmission power-allocation threshold Λ_n can be calculated. To analyze the performance of the transmission power-allocation threshold, some default parameters are configured as $T_f = 1$ ms and $B = 1$ MHz. The numerical results are shown in Figs. 2 and 3. Fig. 2 shows numerical results of the transmission power-allocation threshold Λ_n with respect to each grouped subchannels considering different QoS statistical exponents θ . For each of the grouped subchannels, the transmission power-allocation threshold Λ_n decreases with the increase in the QoS exponent θ . Considering subchannels are sorted by the descending order of subchannel gains, the subchannel gain of subchannel groups decreases with the increase in group indexes. Therefore, the transmission power-allocation threshold Λ_n increases with the increase in subchannel gains in subchannel groups when the QoS exponent $\theta \leq 10^{-3}$. When the QoS exponent $\theta > 10^{-3}$, the transmission power-allocation threshold Λ_n starts to decrease with the increase in subchannel gains in subchannel groups.

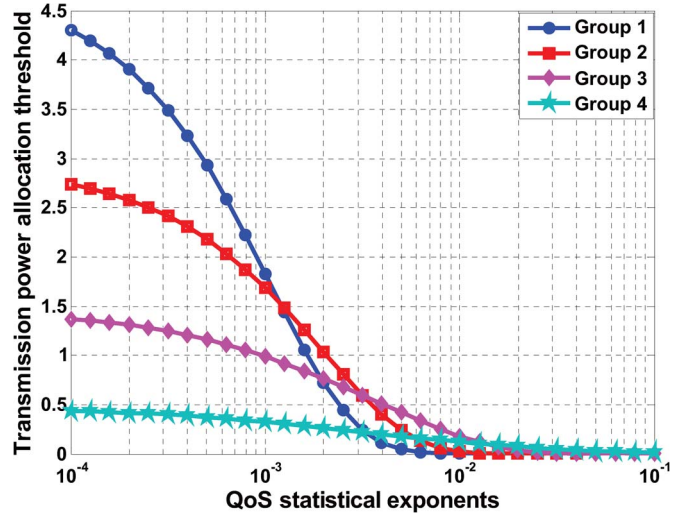


Fig. 2. Transmission power-allocation threshold Λ_n with respect to each grouped subchannels considering different QoS statistical exponents θ .

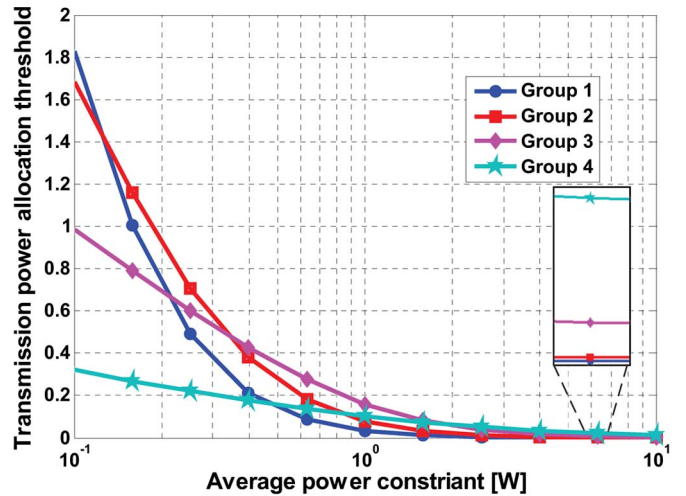


Fig. 3. Transmission power-allocation threshold Λ_n with respect to each grouped subchannels considering different average power constraints \bar{P} .

Fig. 3 shows the transmission power-allocation threshold Λ_n with respect to each grouped subchannels considering different average power constraints \bar{P} . For each grouped subchannels, the transmission power-allocation threshold Λ_n decreases with the increase in the average power constraint \bar{P} . When $\bar{P} \leq 0.13$, the transmission power-allocation threshold Λ_n increases with the increase in subchannel gains in subchannel groups. When $\bar{P} > 0.13$, the transmission power-allocation threshold Λ_n start to decrease with the increase in subchannel gains in subchannel groups.

To evaluate the energy efficiency and the effective capacity of MIMO-OFDM mobile multimedia communication systems, three typical scenarios with different antenna numbers are configured in Figs. 4 and 5: 1) $M_t = 2$ and $M_r = 2$; 2) $M_t = 3$ and $M_r = 2$; and 3) $M_t = 4$ and $M_r = 4$. Fig. 4 shows the impact of QoS statistical exponents θ on the effective capacity of MIMO-OFDM mobile multimedia communication

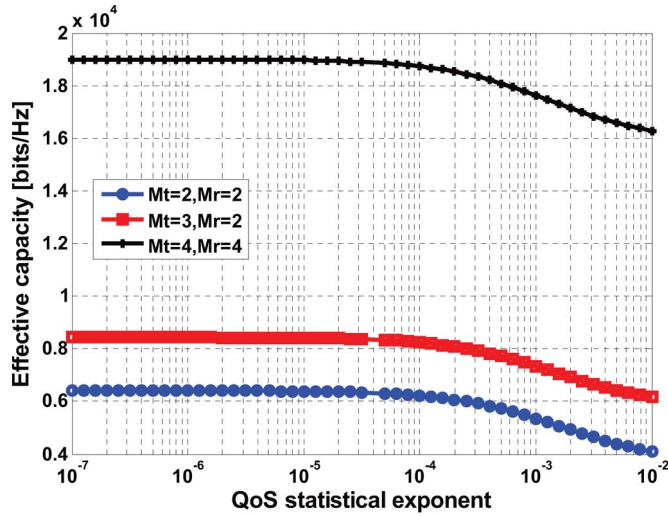


Fig. 4. Effective capacity $C_{total}(\theta)$ with respect to the QoS statistical exponent θ considering different scenarios.

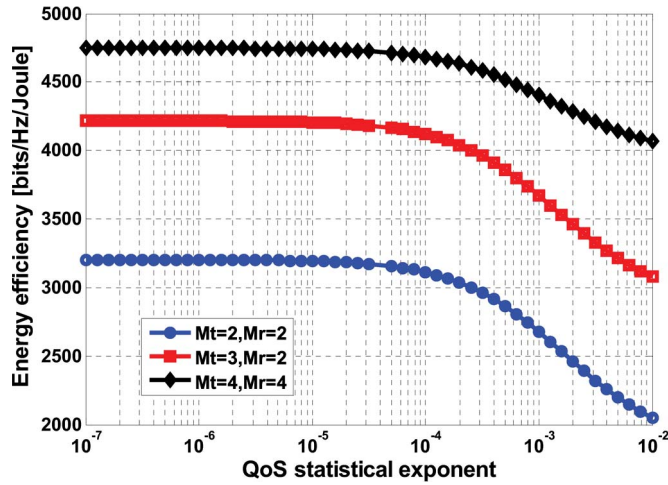


Fig. 5. Energy efficiency η with respect to the QoS statistical exponent θ considering different scenarios.

systems in three different scenarios. From the curves in Fig. 4, the effective capacity decreases with the increase in the QoS statistical exponent θ . This happens because the larger values of θ correspond to the higher QoS requirements, which result in a smaller number of subchannels being selected to satisfy the higher QoS requirements. When the QoS statistical exponent θ is fixed, the effective capacity increases with the number of antennas in MIMO-OFDM mobile multimedia communication systems. This result indicates the channel spatial multiplexing can improve the effective capacity of MIMO-OFDM mobile multimedia communication systems.

Fig. 5 shows the impact of QoS statistical exponents θ on the energy efficiency of MIMO-OFDM mobile multimedia communication systems in three different scenarios. From the curves in Fig. 5, the energy efficiency decreases with the increase in the QoS statistical exponent θ . This occurs because the larger values of θ correspond to the higher QoS requirements, which result in fewer subchannels being selected to satisfy the

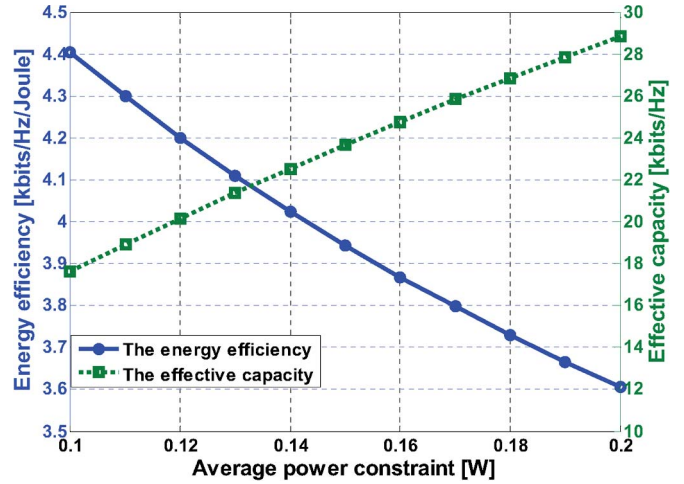


Fig. 6. Impact of the average power constraint on the energy efficiency η and the effective capacity $C_{total}(\theta)$.

higher QoS requirements. This result conduces to the effective capacity is decreased. If the total transmission power is constant, the decreased effective capacity will lead to the decrease in the energy efficiency in communication systems. When the QoS statistical exponent θ is fixed, the energy efficiency increases with the number of antennas in MIMO-OFDM mobile multimedia communication systems. This result indicates that the channel spatial multiplexing can improve the energy efficiency of MIMO-OFDM mobile multimedia communication systems.

When the QoS statistical exponent is fixed as $\theta = 10^{-3}$, the impact of the average power constraint on the energy efficiency and the effective capacity of MIMO-OFDM mobile multimedia communication systems is investigated in Fig. 6. In Fig. 6, the energy efficiency decreases with the increase in the average power constraint, and the effective capacity increases with the increase in the average power constraint. This result implies that there is an optimization tradeoff between the energy efficiency and effective capacity in MIMO-OFDM mobile multimedia communication systems: As the transmission power increases, which leads to larger effective capacity, the energy consumption of the system also rises; therefore, the larger power input results in the decline of energy efficiency.

To analyze the performance of the EEOPA algorithm, the traditional average power allocation (APA) algorithm [38], i.e., every subchannel with the equal transmission power algorithm is compared with the EEOPA algorithm in Figs. 7–10. Three typical scenarios with different antenna numbers are configured in Figs. 7–10: 1) $M_t = 2$ and $M_r = 2$; 2) $M_t = 3$ and $M_r = 2$; and 3) $M_t = 4$ and $M_r = 4$. In Fig. 7, the effect of the QoS statistical exponent θ on the energy efficiency of EEOPA and APA algorithms is investigated with constant average power constraint $\bar{P} = 0.1$ W. Considering changes of the QoS statistical exponent, the energy efficiency of the EEOPA algorithm is always higher than the energy efficiency of the APA algorithm in three scenarios. In Fig. 8, the impact of the average power constraint on the energy efficiency of EEOPA and APA algorithms is evaluated with the fixed QoS statistical exponent

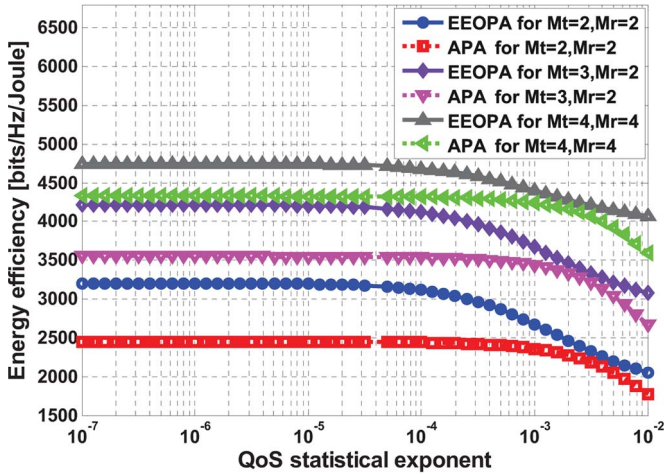


Fig. 7. Energy efficiency η of the EEOPA and APA algorithms as variation of QoS statistical exponent θ under different scenarios.

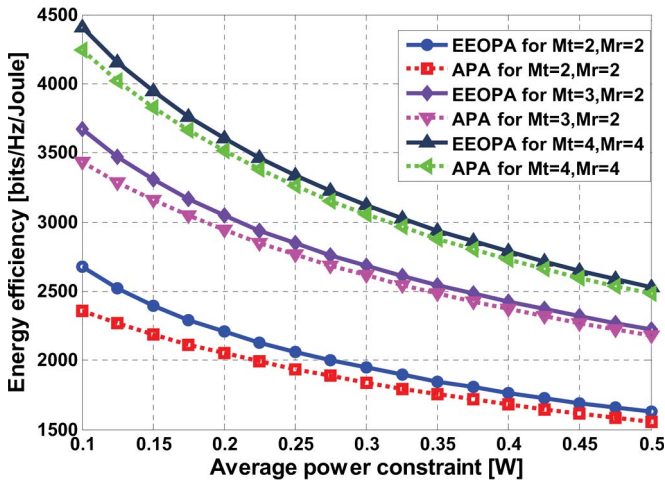


Fig. 8. Energy efficiency η of the EEOPA and APA algorithms as variation of average power constraint \bar{P} under different scenarios.

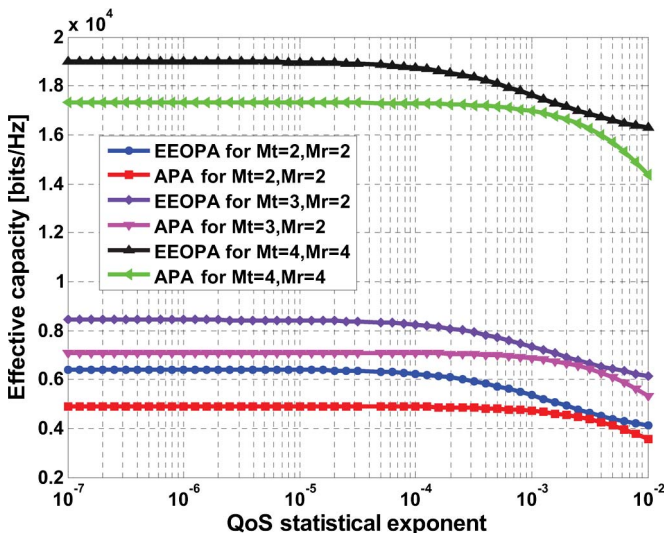


Fig. 9. Effective capacity $C_{total}(\theta)$ of the EEOPA and APA algorithms as variation of QoS statistical exponent θ under different scenarios.

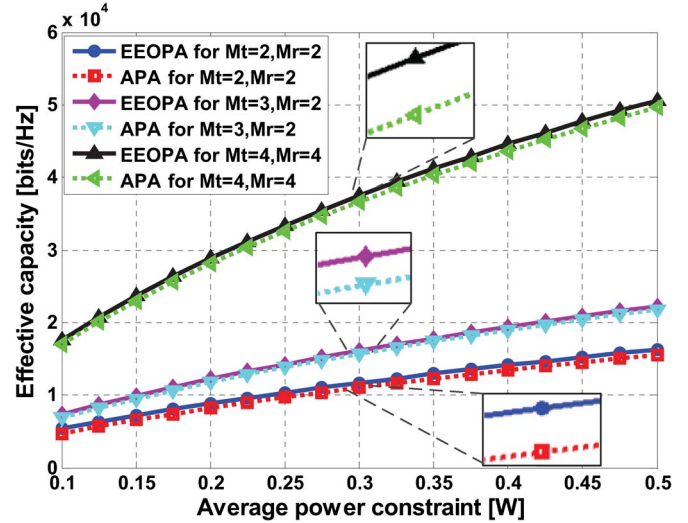


Fig. 10. Effective capacity $C_{total}(\theta)$ of the EEOPA and APA algorithms as variation of average power constraint \bar{P} under different scenarios.

$\theta = 10^{-3}$. Considering changes of the average power constraint, the energy efficiency of the EEOPA algorithm is always higher than the energy efficiency of the APA algorithm in three scenarios. In Fig. 9, the effect of the QoS statistical exponent θ on the effective capacity of the EEOPA and APA algorithms is compared with constant average power constraint $\bar{P} = 0.1$ W. Considering changes of the QoS statistical exponent, the effective capacity of the EEOPA algorithm is always higher than the effective capacity of the APA algorithm in three scenarios. In Fig. 10, the impact of the average power constraint on the effective capacity of EEOPA and APA algorithms is evaluated with the fixed QoS statistical exponent $\theta = 10^{-3}$. Considering changes of the average power constraint, the effective capacity of the EEOPA algorithm is always higher than the effective capacity of the APA algorithm in three scenarios. Based on the given comparison results, our proposed EEOPA algorithm can improve the energy efficiency and effective capacity of MIMO-OFDM mobile multimedia communication systems.

VI. CONCLUSION

In this paper, an energy-efficiency model is proposed for MIMO-OFDM mobile multimedia communication systems with statistical QoS constraints. An energy-efficiency optimization scheme is presented based on the subchannel grouping method, in which the complex multichannel joint optimization problem is simplified into a multitarget single-channel optimization problem. A closed-form solution of the energy-efficiency optimization is derived for MIMO-OFDM mobile multimedia communication systems. Moreover, a novel algorithm, i.e., EEOPA, is designed to improve the energy efficiency of MIMO-OFDM mobile multimedia communication systems. Compared with the traditional APA algorithm, simulation results demonstrate that our proposed algorithm has advantages on improving the energy efficiency and effective capacity of MIMO-OFDM mobile multimedia communication systems with QoS constraints.

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