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Research Article

Modeling and Performance Analysis of Energy Efficiency Binary Power Control in MIMO-OFDM Wireless Communication Systems

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The energy efficiency optimization of the binary power control scheme for MIMO-OFDM wireless communication systems is formulated, and then a global optimization solution of power allocation is derived. Furthermore, a new energy efficiency binary power control (EEBPC) algorithm is designed to improve the energy efficiency of MIMO-OFDM wireless communication systems. Simulation results show that the EEBPC algorithm has better energy efficiency and spectrum efficiency than the average power control algorithm in MIMO-OFDM wireless communication systems.

1. Introduction

It is beyond question that information and communication technology (ICT) industries play a significant role in current global economy. Among all energy-consuming industries, the ICT industry takes 2% of global total CO2 emissions while consuming 3% of global energy storage [1, 2]. Within the 3% consumption, 57% is caused in mobile and wireless communication systems [3]. From another perspective of ICT growth, there has risen a high demand for broadband data transmission with high-quality services, which is further triggering the Multi-Input and Multi-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) techniques to be adopted in the next generation wireless communication systems [4–6]. Therefore, the optimization of energy efficiency in MIMO-OFDM wireless communication systems has become an urgent requirement.

In wireless communication systems, the transmission power consumption of base station is controlled by power allocation schemes. In early analog mobile communication systems, the key aim of transmission power allocation scheme is to improve user signal-to-noise (SNR). Therefore, some transmission power allocation schemes of base station are developed to enhance the SNR of terminal users [7–9]. In digital mobile communication systems, the traditional transmission power allocation schemes sought to realize the maximization of wireless channel capacity [10–12]. One of the most popular power allocation schemes of base station is the power water-filling scheme, which performs power allocation based on the state of wireless channels to close the wireless channel capacity to the Shannon capacity limit [10]. To overcome the requirement of continuous-rate adaptation in the power water-filling scheme, a new scheme based on a fixed number of codes, was proposed to maximize average spectral efficiency (ASE) of dual-branch MIMO systems with perfect transmitter and receiver channel state information (CSI) [11]. To formulate the link adaptation problem as a convex optimization problem, Kim and Daneshrad proposed a link adaptation power strategy to maximize energy efficiency or data throughput subject to a given quality of service (QoS) constraint [12]. Considering the complexity of optimization transmission power allocation scheme, a simple transmission power allocation scheme, that is, the binary power control scheme was proposed to maximize wireless channel capacity in practical engineering applications [13, 14]. However, the energy efficiency problem in the traditional binary power control scheme of MIMO-OFDM wireless communication systems is not considered.

In this paper, we investigate the energy efficiency problem of the binary power control scheme and formulate the binary power control scheme with energy efficiency constraint. Moreover, a new algorithm is designed to address the energy efficiency power allocation in MIMO-OFDM wireless communication systems. The contributions and novelty of this paper are summarized as follows.

(1) We formulate the energy efficiency problem of the binary power control scheme in MIMO-OFDM wireless communication systems.

(2) A global optimization solution of power allocation in MIMO-OFDM wireless communication systems is derived. Furthermore, two derivation results can be used for potential engineering application with the low calculation complexity.

(3) A new algorithm is designed to realize the energy efficiency binary power control scheme in communication systems.

(4) Performance of the new algorithm is analyzed and some interesting observations are presented.

The rest of paper is organized as follows. In Section 2, the energy efficiency concept is introduced and the binary power control scheme is introduced. In Section 3, we investigate optimal conditions for energy efficiency transmission with the binary power control scheme. Moreover, the global optimization solution of power distribution model is derived and a new algorithm is proposed. Furthermore, we apply the new algorithm in a MIMO-OFDM communication system and provide simulation results to demonstrate energy efficiency improvement in Section 4. Finally, we conclude the paper in Section 5.

2. Energy Efficiency in Wireless Communication Systems

As introduced in this section, more and more energy efficiency optimization schemes in wireless communication systems were studied. To estimate the energy efficiency, the definition of energy efficiency should be first declared. In this paper, a definition of energy efficiency is described as follows.

2.1. Definition of Energy Efficiency in Wireless Communication Systems. Typically, the energy consumption of transmitting per bit is a main concern in evaluating the energy efficiency of a communication system. In addition, the definition should include the transmission power from the base station and the capacity of wireless channels. Considering the Shannon capacity theory [15], the maximum achievable capacity of a wireless channel is related to the transmission power from a base station. Therefore, an energy efficiency used in wireless communication systems is defined as follows:

$$\eta = f(P_i) = \frac{\sum_{i=1}^{n} C_i(P_i)}{\sum_{i=1}^{n} P_i}, \quad i \in [1, n], \tag{1}$$

where η is the energy efficiency of wireless communication systems which is denoted as a function of transmission power P_i over wireless channel $i \cdot n$ is the number of wireless channels in wireless communication systems. $C_i(P_i)$ is a wireless channel capacity which is denoted as a function of transmission power P_i over wireless channel i.

2.2. Binary Power Control Scheme. For wireless communication systems, the transmission power P over wireless channels is allocated from the minimum value $P_{\min}$ to the maximum value $P_{\max}$, that is, $P_{\min} \le P \le P_{\max}$. According to the binary power control scheme of wireless communication systems, the transmission power P over wireless channels is allocated a value from two elements, that is, $P_{\min}$ and $P_{\max}$. Moreover, the binary power control scheme is formulated as follows [16]:

$$P \in \Omega, \quad \Omega = \{P \mid P = P_{\min} \text{ or } P = P_{\max}\}. \tag{2}$$

From research results in [13, 14, 17], when there are many wireless channels in wireless communication systems, the capacity and rate performance of wireless communication systems adopting the binary power control scheme can approximate the Shannon capacity limit. However, when the energy efficiency of wireless communication systems is considered as an optimal aim, how to adopt the binary power control scheme of wireless communication systems to approximate the global energy efficiency optimal solution is a great challenge.

3. Problem Formulation of Energy Efficiency Binary Power Control Scheme

To investigate the binary power control scheme in energy efficiency of wireless communication systems, a single cell MIMO-OFDM wireless communication system is illustrated in Figure 1. One base station integrated with M_T antennas is located in the center of cell. There are K users uniformly scattering in the cell and every user is integrated with M_R antennas. To simplify the modeling complexity of the OFDM scheme, all orthogonal N subcarriers are regrouped into N subchannels by the OFDM scheme. Moreover, interference between users is assumed to be ignored in this single cell. Every subchannel of MIMO-OFDM communication system in Figure 1 is assumed as a quasistatic channel, which means there is no change within a block of transmission. The bandwidth of MIMO-OFDM communication system is normalized as 1. For one moment, without loss of generality, only N subchannels are enabled for data transmission. The CSI of MIMO-OFDM wireless communication system is assumed to be known by the base station in Figure 1. In this paper, our research focuses on the downlink performance of wireless communication systems.

3.1. Problem Formulation. Based on the system model in Figure 1, the total capacity of MIMO-OFDM communication system is described as

$$C_{\text{total}} = \sum_{i=1}^{N} \log_2\left(1 + \frac{P_i}{n_0} \|H_i\|_F^2\right), \tag{3}$$

where P_i is the transmission power over wireless subchannel i, n_0 is the additive white Gaussian noise (AWGN) in

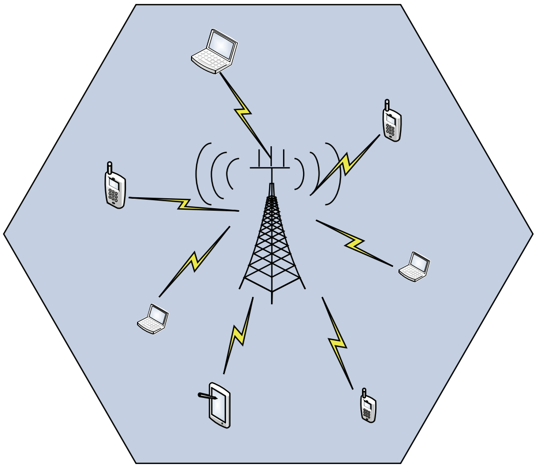

Figure 1: System model of MIMO-OFDM wireless communication systems.

wireless subchannels, and $\|H_i\|_F$ is the F norm over wireless subchannel i.

In this case, the total transmission power in the downlink of MIMO-OFDM communication system is denoted as

$$P_{\text{total}} = \sum_{i=1}^{N} P_i. \tag{4}$$

Furthermore, the energy efficiency of MIMO-OFDM communication system is given by

$$\eta_{\text{total}} = \frac{\sum_{i=1}^{N} \log_2\left(1 + (P_i/n_0)\|H_i\|_F^2\right)}{\sum_{i=1}^{N} P_i}. \tag{5}$$

The wireless subchannel set K is defined as follows:

$$\text{CH}_i \in K, \quad K = \left\{\text{CH} \mid \text{CH} = \bigcup_{i=1}^{N} \text{CH}_i\right\}, \tag{6}$$

where CH is the wireless subchannel element in set K and CH_i is the wireless subchannel i.

Assume that the binary power control scheme is used to allocate the transmission power for the wireless subchannel set K. In this case, the set K is divided into two subsets: one is the maximum power transmission subchannel subset $K_{p\max}^{M}$ with M wireless subchannels; the other is the minimum power transmission subchannel subset $K_{p\min}^{N-M}$ with $N-M$ wireless subchannels. Moreover, the total transmission power of $K_{p\max}^{M}$ is denoted as $P_{\max\_\text{total}}$ and the total transmission power of $K_{p\min}^{N-M}$ is denoted as $P_{\min\_\text{total}}$. The relationship of P_{total}, $P_{\max\_\text{total}}$, and $P_{\min\_\text{total}}$ is described as follow:

$$\begin{gathered} P_{\text{total}} = P_{\max\_\text{total}} + P_{\min\_\text{total}}, \\ P_{\max\_\text{total}} = M \times P_{\max}, \\ P_{\min\_\text{total}} = (N - M) \times P_{\min}. \end{gathered} \tag{7}$$

To optimize the global energy efficiency of MIMO-OFDM wireless communication system, some basic assumptions and a principle are defined as follows.

Assumption 1. The total transmission power of MIMO-OFDM wireless communication system is fixed as a constant.

Assumption 2. $P_{\max\_\text{total}}$ in the maximum power transmission subchannel subset is fixed as a constant.

Principle 1. A wireless subchannel CH_k is assigned into the maximum power transmission subchannel subset $K_{p\max}^{M}$ only when the energy efficiency of $K_{p\max}^{M}$ including CH_k is no less than the energy efficiency of $K_{p\max}^{M}$ without CH_k, otherwise, the wireless subchannel should be assigned into the minimum power transmission subchannel $K_{p\min}^{N-M}$.

3.2. Optimization of Power Allocation.

For the energy efficiency binary power control scheme, how to optimize the power allocation in the maximum power transmission subchannel subset and the minimum power transmission subchannel subset is a key problem. Based on assumption, principle and (7) in Section 3.1, we find that $P_{\max\_\text{total}}$ and $P_{\min\_\text{total}}$ can be derived if the value of $P_{\max}$ is determined. Therefore, the global optimal solution of $P_{\max}$ is a key problem in this binary power control scheme.

When a candidate wireless subchannel CH_k is assigned into the maximum power transmission subchannel subset, the maximum transmission power $P_{\max\_1}$ used for the maximum power transmission subchannel subset is given by

$$P_{\max\_1} = \frac{P_{\max\_\text{total}}}{M}. \tag{8}$$

Furthermore, the energy efficiency of MIMO-OFDM communication system with the wireless subchannel CH_k is derived as

$$\eta_1 = \frac{\sum_{i=1}^{M} \log_2\left(1 + (P_{\max\_1}/n_0)\|H_i\|_F^2\right)}{P_{\max\_\text{total}}}. \tag{9}$$

When a candidate wireless subchannel CH_k is not assigned into the maximum power transmission subchannel subset, the maximum transmission power $P_{\max\_2}$ used for the maximum power transmission subchannel subset is given by

$$P_{\max\_2} = \frac{P_{\max\_\text{total}}}{M - 1}. \tag{10}$$

Furthermore, the energy efficiency of MIMO-OFDM communication system without the wireless subchannel CH_k is derived as

$$\eta_2 = \frac{\sum_{i=1, i\neq k}^{M-1} \log_2\left(1 + (P_{\max\_2}/n_0)\|H_i\|_F^2\right)}{P_{\max\_\text{total}}}. \tag{11}$$

Based on Principle 1, the candidate wireless subchannel CH_k can be finally assigned into the maximum power transmission subchannel subset and the maximum transmission power $P_{\max}$ can be derived under the condition of $\eta_1 \geq \eta_2$. From Principle 1, the optimization relationship of maximum transmission power is derived in the Appendix and is expressed by

$$1+\frac{P_{\max\_2}}{n_0}\,\|H_k\|_F^2 \geq \frac{\prod_{i=1,\,i\neq k}^{M-1}\left(n_0+(P_{\max\_\mathrm{total}}/(M-1))\|H_i\|_F^2\right)}{\prod_{i=1,\,i\neq k}^{M-1}\left(n_0+(P_{\max\_\mathrm{total}}/M)\|H_i\|_F^2\right)}. \quad (12)$$

Compared with the transmission power over wireless subchannels, the value of AWGN n_0 is obviously less than the value of $(P_{\max\_\mathrm{total}})/(M-1)\|H_i\|_F^2$ or $(P_{\max\_\mathrm{total}}/M)\|H_i\|_F^2$. Therefore, the right side of (12) can be approximated as

$$\begin{aligned}1+\frac{P_{\max\_2}}{n_0}\|H_k\|_F^2 &\geq \frac{\prod_{i=1,\,i\neq k}^{M-1}\left(n_0+(P_{\max\_\mathrm{total}}/(M-1))\|H_i\|_F^2\right)}{\prod_{i=1,\,i\neq k}^{M-1}\left(n_0+(P_{\max\_\mathrm{total}}/M)\|H_i\|_F^2\right)} \\ &\approx \frac{\prod_{i=1,\,i\neq k}^{M-1}\left((P_{\max\_\mathrm{total}})/(M-1)\|H_i\|_F^2\right)}{\prod_{i=1,\,i\neq k}^{M-1}\left((P_{\max\_\mathrm{total}}/M)\|H_{\mathrm{i}}\|_F^2\right)}.\end{aligned} \quad (13)$$

Furthermore, (13) can be derived as follows:

$$1+\frac{P_{\max\_2}}{n_0}\|H_k\|_F^2 \geq \frac{\prod_{i=1,i\neq k}^{M-1}(1/(M-1))}{\prod_{i=1,i\neq k}^{M-1}(1/M)}, \quad (14a)$$

$$\Downarrow$$

$$1+\frac{P_{\max\_2}}{n_0}\|H_k\|_F^2 \geq \frac{(1/(M-1))^{M-1}}{(1/M)^{M-1}}, \quad (14b)$$

$$\Downarrow$$

$$1+\frac{P_{\max\_2}}{n_0}\|H_k\|_F^2 \geq (M/(M-1))^{M-1}. \quad (14c)$$

Based on (14c), we can derive a current global optimization solution of maximum transmission power $P_{\max\_2}$ with the CSI of wireless communication system and the subchannel number of the maximum power transmission subchannel subset.

When the number of subchannels M approaches to infinite, we have the following result:

$$\lim_{M\to\infty}\left(\frac{M}{M-1}\right)^{M-1}=e. \quad (15)$$

From the numerical simulation of threshold values $(M/(M-1))^{M-1}$ and limitation values e in Figure 2, the difference between the threshold values $(M/(M-1))^{M-1}$ and limitation values e is less than 1.67% when the number of subchannel is large than or equal to 30. Therefore, we further derive two simple results for possible engineering applications.

Result 1. When the number of current subchannel in the maximum power transmission subchannel subset is less than 30, the value of maximum transmission power $P_{\max}$ is derived by

$$\frac{P_{\max}}{n_0}\|H_i\|_F^2 \geq \left(\frac{M}{M-1}\right)^{M-1}-1. \quad (16)$$

Result 2. When the number of current subchannel in the maximum power transmission subchannel subset is larger than or equal to 30, the value of maximum transmission power $P_{\max}$ are derived by

$$\frac{P_{\max}}{n_0}\|H_i\|_F^2 \geq e-1. \quad (17)$$

From above results, especially from Result 2, the complexity of maximum transmission power derivation can be reduced.

3.3. Algorithm Design. Based on Results 1 and 2, an energy efficiency binary power control (EEBPC) algorithm is designed for improving energy efficiency of MIMO-OFDM wireless communication systems. The detailed EEBPC algorithm is illustrated in Algorithm 1. Morever, an assumption of Algorithm 1 is that all subchannels of wireless subchannel set K are degressively ordered.

4. Simulation Results and Performance Analysis

Based on the new EEBPC algorithm, the energy efficiency and spectrum efficiency performance of MIMO-OFDM wireless communication systems is simulated and analyzed. In the following simulation, some parameters of the system model in Figure 1 are configured as follows: the total transmission power of base station is ranged from 0.6 to 1.4 watt (W); considering the OFDM scheme used in MIMO wireless communication system, the number of subchannels is ranged from 8 to 128; the AWGN n_0 in wireless subchannels is assumed as 0.1 W. Wireless subchannels are simulated by a Monte Carlo approach based on AWGN wireless subchannels with zero mean values.

From Figure 3, the impact of the number of subchannels on the spectrum efficiency of MIMO-OFDM communication system with the EEBPC algorithm is investigated. The spectrum efficiency of MIMO-OFDM communication system increases with the number of subchannels and the total transmission power of base station.

From Figure 4, the impact of number of subchannels on the energy efficiency of MIMO-OFDM communication system with the EEBPC algorithm is analyzed. The energy efficiency of MIMO-OFDM communication system increases with the number of subchannels, but the energy efficiency of MIMO-OFDM communication system decreases with the total transmission power of base station.

From Figure 5, the EEBPC algorithm is compared with the traditional average power control algorithm [16] in the spectrum efficiency of MIMO-OFDM communication system with different number of subchannels. Assume that the total transmission power of base station is configured as 1 W. When the number of subchannels is less than 12,

```
Input: $P_{\text{total}}, P_{\max\_\text{total}}$
Output: $M, P_{\max}, P_{\min}, K^{M}_{p\max}, K^{N-M}_{p\min}$
Initialization: Create a wireless sub-channel set $K$ with $N$ subchannels, the maximum power transmission subchannel subset $K^{M}_{p\max}$ and the minimum power transmission subchannel subset $K^{N-M}_{p\min}$,
    $K = \{\text{CH} \mid \text{CH} = \bigcup_{i=1}^{N} \text{CH}_i\},$
    $K^{M}_{p\max} = \phi,$
    $K^{N-M}_{p\min} = \phi,$
Begin:
(1) Create a new set $\widetilde{K}$ from the set $K$ by a descending order of $\|H_i\|_F^2$,
    $\widetilde{K} = \{\text{CH} \mid \text{CH} = \bigcup_{i=1}^{N} \text{CH}_i; \forall (1 \le i \le k \le N), \|H_i\|_F^2 \ge \|H_K\|_F^2\}$
(2) for $i = 1 : N$ do
        $P_{\max} = \frac{P_{\max\_\text{total}}}{i-1}$
            if $i < 30$,
                compare $\text{SNR}_i$ with the threshold value,
                $\left(\text{SNR}_i = \frac{P_{\max}}{n_0}\|H_i\|_F^2\right) \ge \left(\frac{i}{i-1}\right)^{i-1} - 1$
            else
                compare $\text{SNR}_i$ with the imitation value,
                $\left(\text{SNR}_i = \frac{P_{\max}}{n_0}\|H_i\|_F^2\right) \ge e - 1$
            end if
            if $\text{SNR}_i$ large than or equal to the threshold or limitation values
                add $\text{CH}_i$ into $K^{M}_{p\max}$,
            else
                $M = i - 1$
                add $\text{CH}_j (M + 1 \le j \le N)$ into $K^{N-M}_{p\min}$,
                break,
            end if
    end for
(3)
    $P_{\max} = \frac{P_{\max\_\text{total}}}{M}, P_{\min} = \frac{P_{\text{total}-P_{\max\_\text{total}}}}{N-M},$
    end Begin
```

Algorithm 1: Energy efficiency binary power control.

the spectrum efficiency of MIMO-OFDM communication system with average power control algorithm is larger than that with EEBPC algorithm. When the number of subchannels is larger than or equal to 12, the spectrum efficiency of MIMO-OFDM communication system with EEBPC algorithm is larger than that with average power control algorithm. Moreover, the spectrum efficiency gain of EEBPC algorithm increases with the number of subchannels.

From Figure 6, the EEBPC algorithm is compared with the traditional average power control algorithm in the energy efficiency of MIMO-OFDM communication system with different number of subchannels. Assume that the total transmission power of base station is configured as 1 W. When the number of subchannels is less than 12, the energy efficiency of MIMO-OFDM communication system with average power control algorithm is larger than that with EEBPC algorithm. When the number of subchannels is larger than or equal to 12, the energy efficiency of MIMO-OFDM communication system with EEBPC algorithm is large than that with average power control algorithm. Moreover, the energy efficiency gain of EEBPC algorithm increases with the number of subchannels.

From Figure 7, the EEBPC algorithm is compared with the traditional average power control algorithm in the spectrum efficiency of MIMO-OFDM communication system with different total transmission power of base station. Assume that the number of subchannels is configured as 64. The spectrum efficiency of MIMO-OFDM communication system with EEBPC algorithm is large than that with average power control algorithm. Moreover, the spectrum efficiency gain of EEBPC algorithm is invariable with the total transmission power of base station.

From Figure 8, the EEBPC algorithm is compared with the traditional average power control algorithm in the energy efficiency of MIMO-OFDM communication system with different total transmission power of base station. Assume that the number of subchannels is configured as 64. The energy efficiency of MIMO-OFDM communication system with EEBPC algorithm is large than that with average power control algorithm. Moreover, the energy efficiency gain of

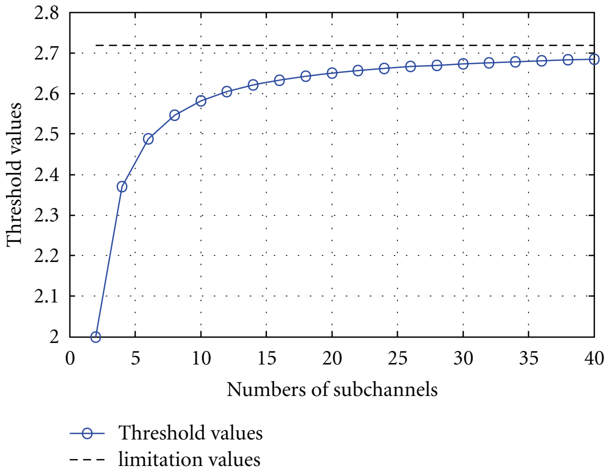

Figure 2: Threshold values versus number of subchannels.

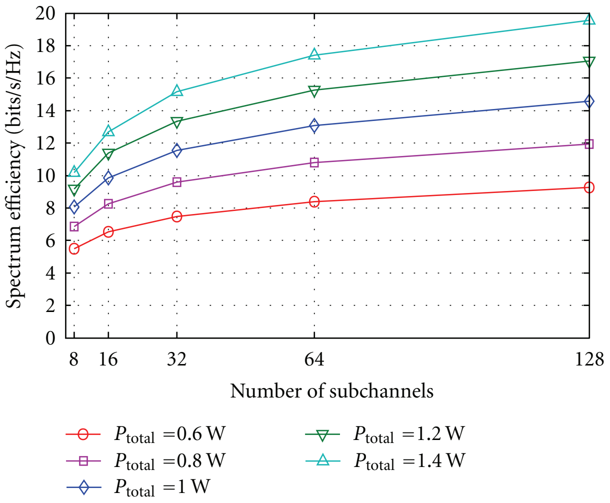

Figure 3: Spectrum efficiency analysis with number of subchannels limited by different total transmission power.

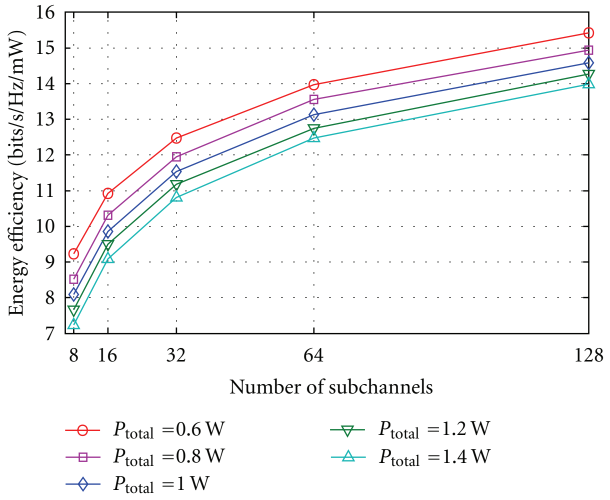

Figure 4: Energy efficiency analysis with number of subchannels limited by different total transmission power.

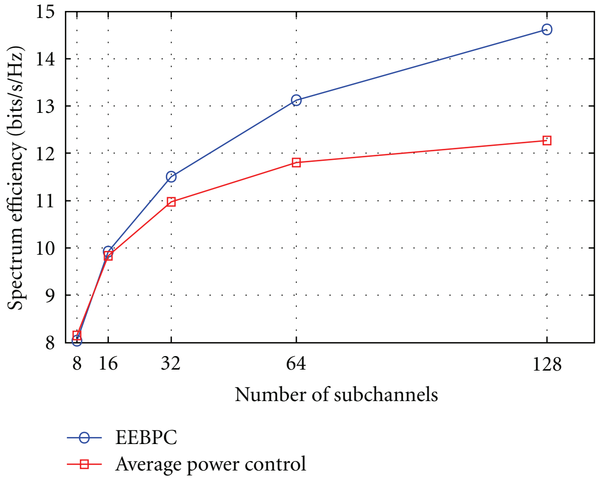

Figure 5: Comparison spectrum efficiency of EEBPC and average power control algorithms with different number of subchannels.

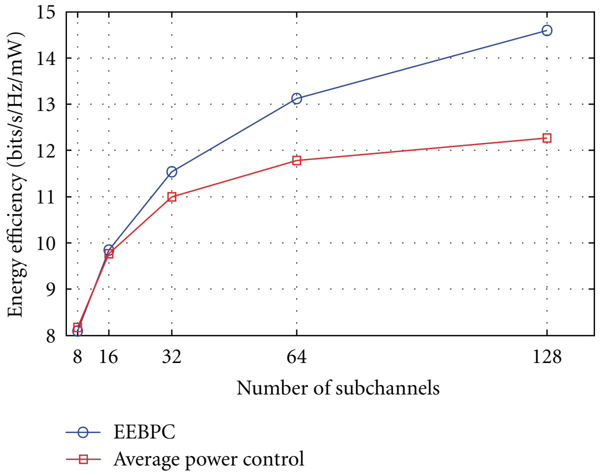

Figure 6: Comparison energy efficiency of EEBPC and average power control algorithms with different number of subchannels.

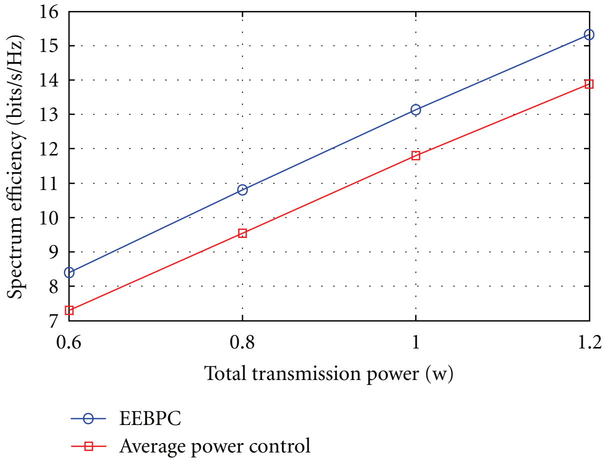

Figure 7: Comparison spectrum efficiency of EEBPC and average power control algorithms with different total transmission power.

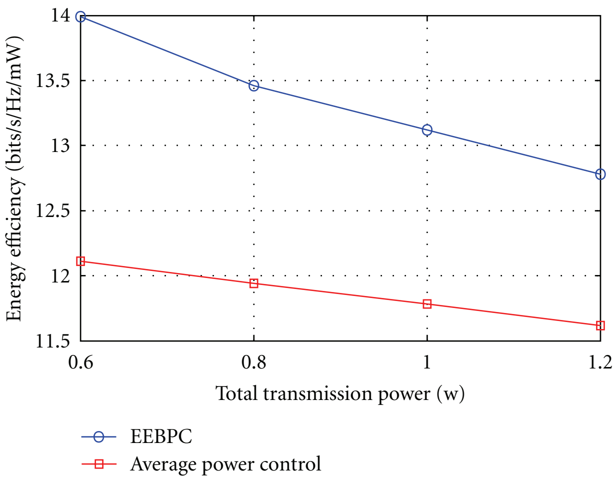

FIGURE 8: Comparison of energy efficiency of EEBPC and average power control algorithms with different total transmission power.

EEBPC algorithm decreases with the total transmission power of base station.

5. Conclusion

In this paper, the energy efficiency of binary power control scheme is investigated and formulated by three principles. Furthermore, a global optimalsolution of the maximum transmission power of MIMO-OFDM wireless communication system is derived. Moreover, a simple engineering application result is proposed for reducing the complexity of calculation. Based on them, a new EEBPC algorithm is designed for performance analysis. The exact impact of EEBPC algorithm on the spectrum efficiency and the energy efficiency has been fully investigated under different number of subchannels and total transmission power of base station. Simulation results have shown that the energy efficiency and spectrum efficiency of EEBPC algorithm is better than that of traditional average power control algorithm when the number of subchannels is larger than 11. Our future work includes a further investigation of the impact of multicell on the EEBPC algorithm.

Appendix

Appendix of (12)

In this appendix, we derive the optimization relationship of maximum transmission power. Based on Principle 1, only satisfying the condition of $\eta_1 \geq \eta_2$, the candidate wireless subchannel CH_k can be finally assigned into the maximum power transmission subchannel subset. Therefore, this condition is expressed by

$$\frac{\sum_{i=1}^{M}\log_2\left(1+(P_{\max\_1}/n_0)\|H_i\|_F^2\right)}{P_{\max\_\text{total}}} \geq \frac{\sum_{i=1,i\neq k}^{M-1}\log_2\left(1+(P_{\max\_2}/n_0)\|H_i\|_F^2\right)}{P_{\max\_\text{total}}}. \tag{A.1}$$

Based on (A.1), we can further derive this expression as follows:

$$\sum_{i=1}^{M}\log_2\left(1+\frac{P_{\max\_1}}{n_0}\|H_i\|_F^2\right) \geq \sum_{i=1,i\neq k}^{M-1}\log_2\left(1+\frac{P_{\max\_2}}{n_0}\|H_i\|_F^2\right), \\ \Downarrow \tag{A.2}$$

$$\log_2\prod_{i=1}^{M}\left(1+\frac{P_{\max\_1}}{n_0}\|H_i\|_F^2\right) \geq \log_2\prod_{i=1,i\neq k}^{M-1}\left(1+\frac{P_{\max\_2}}{n_0}\|H_i\|_F^2\right), \\ \Downarrow \tag{A.3}$$

$$\prod_{i=1}^{M}\left(1+\frac{P_{\max\_1}}{n_0}\|H_i\|_F^2\right) \geq \prod_{i=1,i\neq k}^{M-1}\left(1+\frac{P_{\max\_2}}{n_0}\|H_i\|_F^2\right). \tag{A.4}$$

Assume that the total transmission power of the maximum power transmission subchannel subset $P_{\max\_\text{total}}$ is fixed, so we can derive the following expression considering (8) and (10):

$$P_{\max\_2} \geq P_{\max\_1}. \tag{A.5}$$

Based on (A.5), and (A.4) is further derived as follows:

$$\begin{gathered}\left(1+\frac{P_{\max\_2}}{n_0}\|H_k\|_F^2\right)\prod_{i=1,i\neq k}^{\mathrm{M}-1}\left(1+\frac{P_{\max\_1}}{n_0}\|H_i\|_F^2\right) \\ \geq \prod_{i=1}^{M}\left(1+\frac{P_{\max\_1}}{n_0}\|H_i\|_F^2\right) \geq \prod_{i=1,i\neq k}^{M-1}\left(1+\frac{P_{\max\_2}}{n_0}\|H_i\|_F^2\right), \\ \Downarrow \\ 1+\frac{P_{\max\_2}}{n_0}\|H_k\|_F^2 \geq \frac{\prod_{i=1,i\neq k}^{M-1}\left(1+(P_{\max\_1}/n_0)\|H_i\|_F^2\right)}{\prod_{i=1,i\neq k}^{M-1}\left(1+(P_{\max\_2}/n_0)\|H_i\|_F^2\right)}, \\ \Downarrow \\ 1+\frac{P_{\max\_2}}{n_0}\|H_k\|_F^2 \\ \geq \frac{\prod_{i=1,i\neq k}^{M-1}\left(n_0+(P_{\max\_\text{total}}/(M-1))\|H_i\|_F^2\right)}{\prod_{i=1,i\neq k}^{M-1}\left(n_0+(P_{\max\_\text{total}}/M)\|H_i\|_F^2\right)}.\end{gathered} \tag{A.6}$$

This completes the derivation.

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