Mobile Netw Appl (2012) 17:29–35
DOI 10.1007/s11036-011-0296-4

Energy Efficiency Analysis of MISO-OFDM Communication Systems Considering Power and Capacity Constraints

Xiaohu Ge · Jinzhong Hu · Cheng-Xiang Wang ·
Chan-Hyun Youn · Jing Zhang · Xi Yang

Abstract In this paper, the energy efficiency of multi-input single-output and orthogonal frequency division multiplexing (MISO-OFDM) communication systems with power and capacity constraints is investigated. By formulating the power allocation problem of MISO-OFDM communication systems, the minimum subchannel transmission power is analyzed with power and capacity constraints. Simulation results indicate that there exists a specific minimum subchannel capacity threshold. Moreover, the energy efficiency of MISO-OFDM communication systems starts to increase only when the minimum subchannel capacity exceeds the specific threshold.

Keywords multi-input single-output (MISO) · orthogonal frequency division multiplexing (OFDM) · energy efficiency · capacity analysis

1 Introduction

Multi-antenna [1] and orthogonal frequency division multiplexing (OFDM) technologies are widely accepted to improve the transmission rate in next generation broadband mobile communication systems, such as Long-Term Evolution (LTE)-Advanced and International Mobile Telecommunications (IMT)-Advanced system [2]. In addition to the transmission rate improvement, energy efficiency is becoming increasingly important for next generation broadband mobile communication systems because of green house effect on the earth [3]. In this case, evaluation of energy efficiency of communication systems with multi-antenna and OFDM technologies is an important research problem.

In traditional wireless networks, e.g., wireless ad hoc networks, the energy saving of wireless networks was implemented by costing Quality of Service (QoS) of wireless networks, such as delay and throughput [4]. Compared with energy efficiency issues of traditional wireless networks, the energy efficiency problem of cellular networks, especially in the next generation cellular network or 4th generation (4G) mobile communication system is expected to save energy without reducing QoS of cellular networks. Considering the limitation of spectrum resource in mobile communication systems [5], in the most case, the energy efficiency of cellular networks is implemented with the spectrum efficiency constraint. Kolding and Wigard proposed a discontinuous reception framework in the LTE communication system to reduce the energy consumption,

---

This research was supported by the National Natural Science Foundation of China (NSFC), contract/grant number: 60872007; National 863 High Technology Program of China, contract/grant number: 2009AA01Z239; The Ministry of Science and Technology (MOST), China, International Science and Technology Collaboration Program, contract/grant number:0903; the UK-China Science Bridges Project: R&D on (B)4G Wireless Mobile Communications from the RCUK; EU FP7-PEOPLE-IRSES, project acronym S2EuNet, contract/grant number: 247083.

X. Ge (✉) · J. Hu · J. Zhang · X. Yang
Department of Electronics and Information Engineering,
Huazhong University of Science and Technology,
Wuhan, Hubei, China
e-mail: xhge@mail.hust.edu.cn

C.-X. Wang
Joint Research Institute for Signal and Image Processing,
School of Engineering & Physical Sciences,
Heriot-Watt University,
Edinburgh EH14 4AS, UK

C.-H. Youn
GRID Middleware Research Center of ICC,
Korea Advanced Institute of Science and Technology,
Taejon 305, South Korea

which is realized by a micro-sleep operation in the user terminal [6]. Reference [7] investigated the relationship between the transmission power and embodied power in base stations of cellular networks. Shun-Ren Yang analyzed power saving of generic access networks (GAN) and Universal Mobile Telecommunications Systems (UMTS) interworking model [8]. Considering the optimization of cell deployment, [9] details a novel concept and architecture of cell zooming in mobile cellular networks to solve the problem of traffic imbalance and reduce the total energy consumption. A new scheme adapting both overall transmit power and its allocation according to the states of all subchannels and circuit power consumption to maximize energy efficiency was proposed in [10]. Moreover, an upper bound on energy efficiency was developed to characterize its variation with bandwidth, channel gain and circuit power [11]. However, users in cellular networks generally do not accept the energy efficiency improvement by the cost of transmission rate. Therefore, how to evaluate the energy efficiency of communication systems with power and capacity constraints is a great challenge for the next generation communication system.

In this paper, we formulate a new model to describe the power allocation of multi-input single-output (MISO) and OFDM communication systems with power and capacity constraints. Furthermore, a new algorithm is developed to evaluate the energy efficiency of MISO-OFDM communication systems. Simulation results show that the energy efficiency of MISO-OFDM communication systems is increased with the minimum subchannel transmission capacity and is decreased with the total BS transmission power.

The rest of the paper is organized as follows. In Section 2, the system model is illustrated and the power allocation problem of MISO-OFDM communication system is formulated. Moreover, a new power allocation algorithm is developed to obtain a globally optimal solution with power and capacity constraints. In Section 3, the minimum subchannel transmission power constrained by the total power and the minimum subchannel transmission capacity is analyzed based on the new algorithm. In Section 4, total capacity and energy efficiency of MISO-OFDM communication systems are simulated and analyzed with different BS transmission powers. Finally, conclusions are drawn in Section 5.

2 System model and problem formulation

2.1 System model

To investigate the energy efficiency of MISO-OFDM communication systems with power and capacity constrains, a basic MISO-OFDM communication system is illustrated in Fig. 1. Considering that multiple antennas are easier to be integrated into base stations (BSs) than the user terminals in practice, in this paper, we just investigate the energy efficiency of MISO-OFDM communication systems. In Fig. 1, the BS is integrated with M_T antennas and every user terminal just is integrated with one antenna. There are K users and a BS distributed into a MISO-OFDM communication system. In this communication system, all orthogonal N subcarriers are regrouped into N or less N subchannels by the OFDM scheme. Therefore, the interference in this MISO-OFDM communication system is ignored. The total bandwidth of communication system is assumed as B. Every subchannel of MISO-OFDM communication system in Fig. 1 is assumed as a quasi-static channel, which means there is no change within a block of transmission. Every selected user is allocated a subchannel for transmission data. In the following context, the user number K is assumed larger than the maximum subchannel number. Hence, a user scheduling algorithm accounting for the QoS of subchannels, such as [12] is used for user

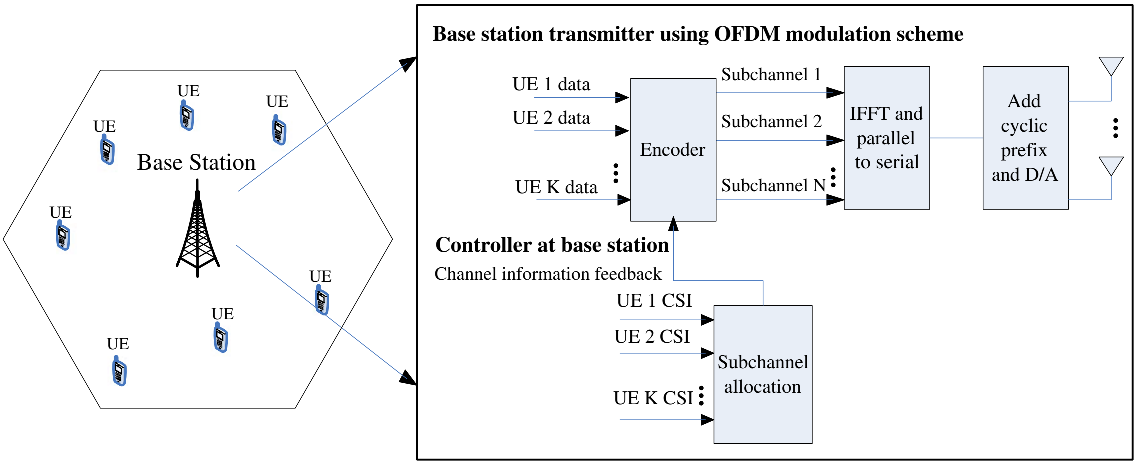

Fig. 1 MISO-OFDM communication system model

selection and subcarriers allocation. In this case, the signal $y_{k,n}$ received by the user UE_k is expressed as follows

$$y_{k,n} = \sqrt{\frac{P_n}{M_T}}\mathbf{H}_{k,n}\mathbf{s}_k + n_0 \tag{1}$$

Where P_n is the transmission power in the subchannel $n \in \{1,\ldots,N\}$, $\mathbf{H}_{k,n}$ is the subchannel vector from BS to UE_k with the subcarrier n, $\mathbf{s}_k$ is the signal vector from BS to UE_k, n_0 is the additive white Gaussian noise (AWGN) with variance N_0 in the wireless subchannels.

The OFDM scheme used in Fig. 1 is assumed to adaptively adjust the transmission power over subchannels accounting for the bit error ratio (BER) and transmission rate, which can be expressed as follows

$$P_{\text{total}} = \sum_{n=1}^{N} P_n \tag{2a}$$

$$C_{\text{target}} = \sum_{n=1}^{N} C_n \tag{2b}$$

$$P_{\text{BER\_target}} \geq P_{\text{BER}(n)} \tag{2c}$$

where P_{total} is the total transmission power in a BS, P_n is the transmission power over the given wireless subchannel n; C_{target} is the constraint of total bit number over all subchannels within a block of transmission, C_n is the bit number over a subchannel n within a block of transmission; $P_{\text{BER\_target}}$ is the BER threshold configured by MISO-OFDM communication systems, $P_{\text{BER(n)}}$ is the BER over a given wireless subchannel n.

2.2 Problem formulation

To maximize the total capacity in wireless subchannels, the traditional power allocation scheme always tries to allocate the maximum transmission power into the wireless subchannel with the best quality, such as water-filling algorithm. In the Fig. 1 communication system, we first try to select N users from all K users, whose wireless subchannels are better than other wireless subchannels. In this case, the allocated transmission powers over wireless subchannels are proportional with quality of wireless subchannels, which is expressed as follows

$$\frac{P_n}{P_{\min}} = \frac{\left\|\mathbf{H}_{k,n}\right\|_F^2}{(\|\mathbf{H}\|_F^2)_{\min}} \tag{3}$$

Where $P_{\min}$ is the minimum subchannel transmission power over the worst wireless subchannel in all selected wireless subchannels, $(\|\mathbf{H}\|_F^2)_{\min}$ is the worst wireless subchannel in all selected wireless subchannels.

Moreover, considering the energy efficiency requirement in this MISO-OFDM communication system, the total BS transmission power is fixed. Therefore, the power allocation problem can be formulated as follows

$$\begin{cases} \sum_{n=1}^{N} P_n = P_{\text{total}} \\ P_n = \dfrac{\left\|\mathbf{H}_{k,n}\right\|_F^2}{(\|\mathbf{H}\|_F^2)_{\min}} P_{\min\_P_{\text{total}}} \end{cases} \tag{4}$$

Where $P_{\min\_P_{\text{total}}}$ is the minimum subchannel transmission power derived from the fixed total BS transmission power constraint.

On the other hand, considering the QoS requirement from user applications, the minimum capacity of subchannel is usually constrained by a given user application. All subchannel state information of MISO-OFDM communication systems is assumed to be known by the BS. In this case, the minimum capacity of subchannel constrained by a given user application from MISO-OFDM communication systems can be expressed as follows

$$C_{\min} = \frac{B}{N}\log_2\left[1 + \frac{P_{\min\_C_{\min}}}{N_0}(\|\mathbf{H}\|_F^2)_{\min}\right] \tag{5}$$

where $P_{\min\_C_{\min}}$ is the minimum subchannel transmission power, which corresponds to the worst subchannel in MISO-OFDM communication systems and satisfies the minimum capacity requirement from a given user application.

From (4) and (5), we can derive two minimum subchannel transmission power thresholds for MISO-OFDM communication systems. When the value of $P_{\min\_P_{\text{total}}}$ is larger than or equal to the value of $P_{\min\_C_{\min}}$, the minimum subchannel transmission power is configured by the $P_{\min\_P_{\text{total}}}$. When the value of $P_{\min\_P_{\text{total}}}$ is less than the value of $P_{\min\_C_{\min}}$, the minimum subchannel transmission power is configured by the $P_{\min\_C_{\min}}$ in order to satisfy the QoS requirement from a given user application. Therefore, considering the energy efficiency and QoS requirements from MISO-OFDM communication systems, the power allocation problem can be further formulated as follows

$$\begin{cases} P_{\min\_P_{\text{total}}} \geq P_{\min\_C_{\min}} \\ \sum_{n=1}^{N} P_n = P_{total} P_n = \dfrac{\left\|\mathbf{H}_{k,n}\right\|_F^2}{(\|\mathbf{H}\|_F^2)_{\min}} P_{\min\_P_{\text{total}}} \\ C_{\min} = \dfrac{B}{N}\log_2\left[1 + \dfrac{P_{\min\_C_{\min}}}{N_0}(\|\mathbf{H}\|_F^2)_{\min}\right] \end{cases} \tag{6}$$

Based on the power allocation model in (6), the transmission power over every subchannel can be calculated.

Table 1 Algorithm $PUJS(P_{\min\_C_{\min}})$

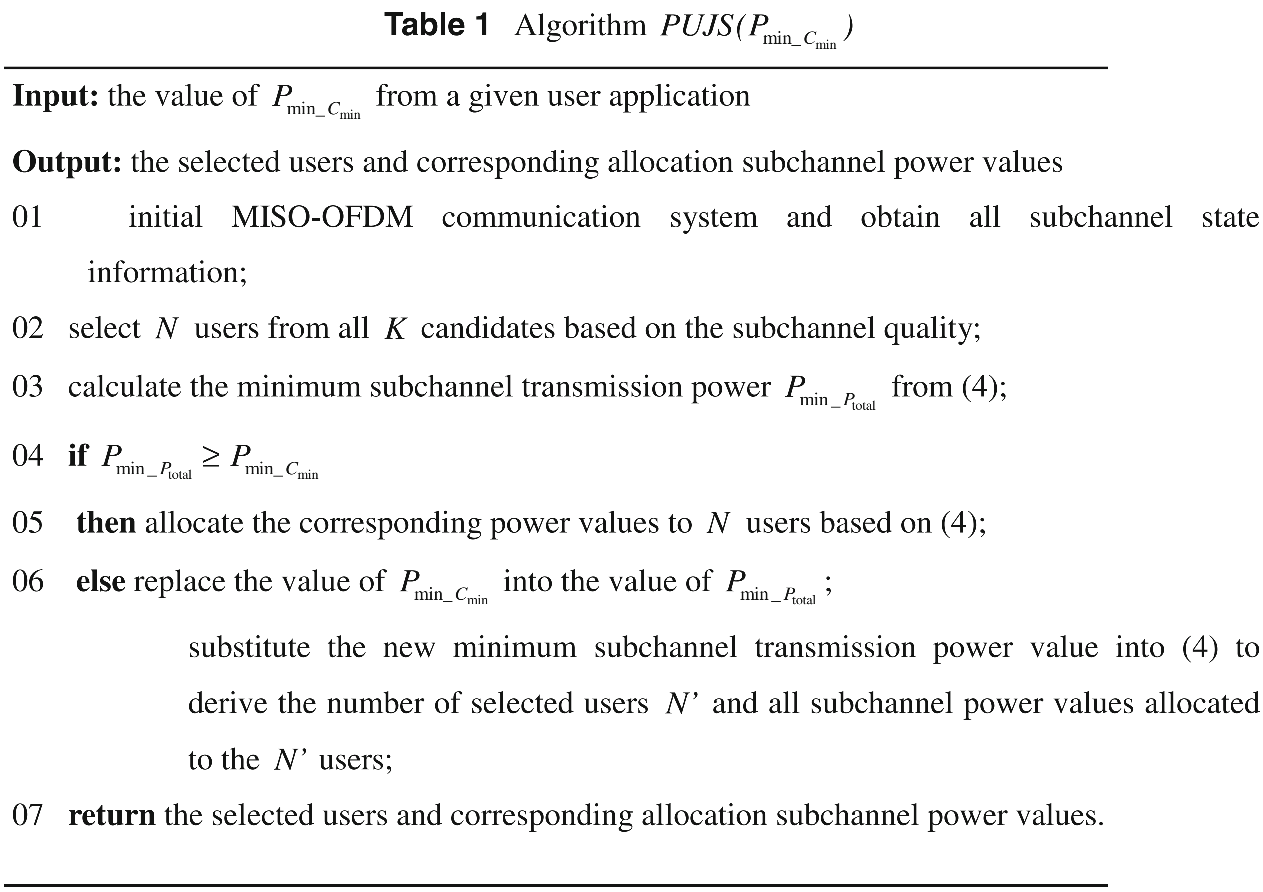

Table 1 Algorithm $PUJS(P_{\min\_C_{\min}})$

```
Input: the value of $P_{\min\_C_{\min}}$ from a given user application
Output: the selected users and corresponding allocation subchannel power values
initial MISO-OFDM communication system and obtain all subchannel state information;
select $N$ users from all $K$ candidates based on the subchannel quality;
calculate the minimum subchannel transmission power $P_{\min\_P_{\text{total}}}$ from (4);
if $P_{\min\_P_{\text{total}}} \geq P_{\min\_C_{\min}}$
    then allocate the corresponding power values to $N$ users based on (4);
    else replace the value of $P_{\min\_C_{\min}}$ into the value of $P_{\min\_P_{\text{total}}}$;
        substitute the new minimum subchannel transmission power value into (4) to derive the number of selected users $N'$ and all subchannel power values allocated to the $N'$ users;
return the selected users and corresponding allocation subchannel power values.
```

Furthermore, the total capacity of MISO-OFDM communication systems can be derived as follows

$$C_{total} = B\sum_{n=1}^{N}\log_2(1+\frac{P_n}{N_0}\left\|H_{k,n}\right\|_F^2) \tag{7}$$

Based on the total capacity of MISO-OFDM communication systems and total BS transmission power, the energy efficiency of MISO-OFDM communication systems can be derived as follows

$$EE = \frac{B\sum\limits_{n=1}^{N}\log_2(1+\frac{P_n}{N_0}\left\|H_{k,n}\right\|_F^2)}{P_{\text{total}}} \tag{8}$$

2.3 Algorithm design considering power and capacity constraints

According to power allocation constraints in (6), a new power allocation scheme is designed accounting for power and capacity constraints. Moreover, the number of selected users is derived from (4) based on the minimum subchannel transmission power. In the following, a new power and user joint schedule (PUJS) algorithm is described in Table 1.

3 Performance analysis of power and capacity constraints

In the PUJS algorithm, the minimum subchannel transmission power is impacted by the total BS transmission power

Table 2 Simulation parameters

Simulation parameter	Symbol	Parameter value
Number of subcarriers	N	50
Number of BS antennas	M_T	4
Number of users	K	100
Total BS transmission power	P_{total}	normalized as 1
System bandwidth	B	normalized as 1
Variance of AWGN	N_0	0.01

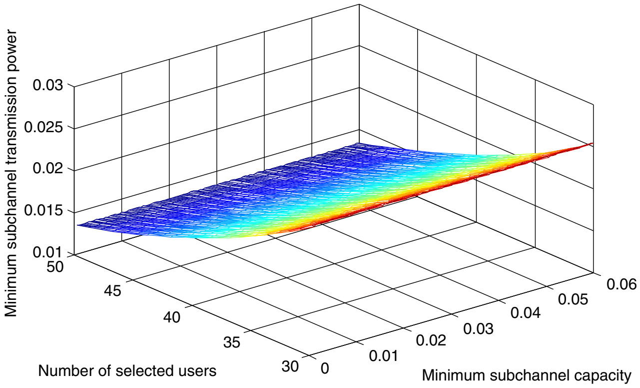

Fig. 2 Minimum subchannel transmission power constrained by the total BS transmission power P_{total}

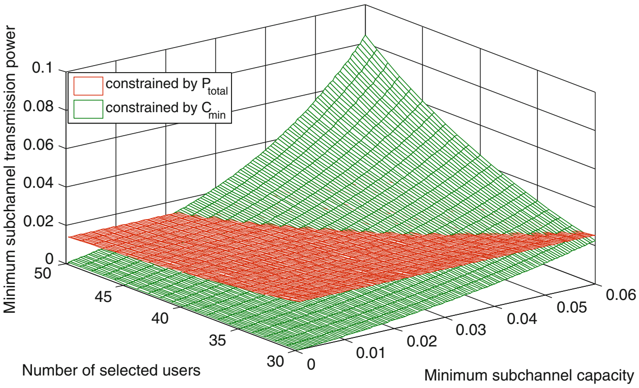

Fig. 4 Minimum subchannel transmission power constrained by the total BS transmission power P_{total} and minimum subchannel capacity $C_{\min}$

and the minimum subchannel capacity constrained by a given user application. Thereby, evaluation of power and capacity constraints in the PUJS algorithm is an interesting problem, which can provide some practical guidelines for developing new efficient algorithms to improve the energy efficiency and system capacity performance. The effect of power and capacity constraints on the minimum subchannel transmission power is analyzed numerically in this section. In our numerical analysis, some parameters of MISO-OFDM communication systems are configured as Table 2. Without loss of generality, the number of subcarriers modulated by the OFDM scheme in this paper is assumed as 50 and every subcarrier is allocated to a corresponding wireless subchannel for data transmission. Based on the Monte Carlo simulation method, every simulation result is obtained by averaging 500 times simulation calculation.

3.1 Minimum subchannel transmission power constrained by the total BS transmission power

Based on (4), the relationship between the minimum subchannel transmission power and the total BS transmission power is illustrated in Fig. 2. From Fig. 2, the minimum subchannel transmission power increases with the decreasing of number of selected users. Values of minimum subchannel transmission power are not impacted by the subchannel minimum capacity. This result can be explained by (4), which implies that the minimum subchannel transmission power is linear with the number of selected users if the total BS transmission power is fixed.

3.2 Minimum subchannel transmission power constrained by the minimum subchannel capacity

Based on (5), the relationship between the minimum subchannel transmission power and the minimum subchannel capacity is illustrated in Fig. 3. From Fig. 3, the minimum subchannel transmission power is impacted by the minimum subchannel capacity and the number of selected users. Moreover, the value of minimum subchannel transmission power increases with the minimum subchannel capacity and the number of selected users.

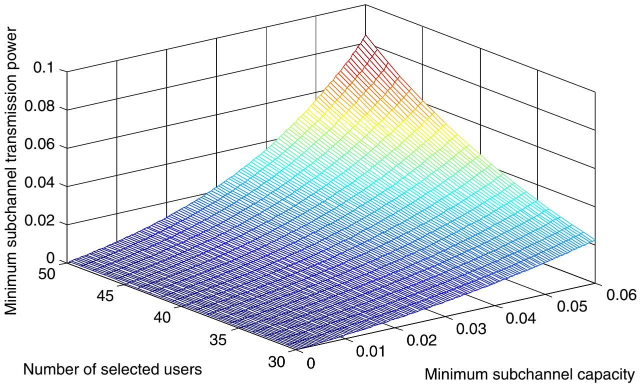

Fig. 3 Minimum subchannel transmission power constrained by the minimum subchannel capacity C_{min}

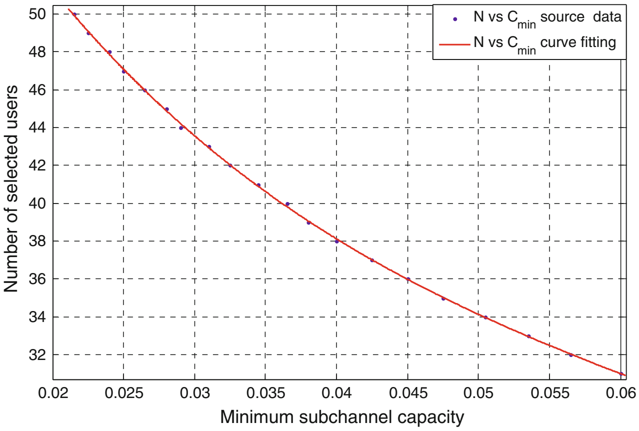

Fig. 5 Fitting the joint line from the two dimensionality space of number of selected users N and minimum subchannel capacity $C_{\min}$

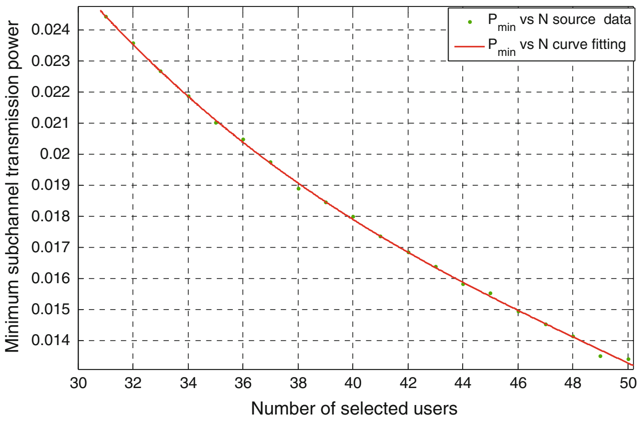

Fig. 6 Fitting the joint line from the two dimensionality space of number of selected users N and minimum subchannel transmission power $P_{\min}$

3.3 Minimum subchannel transmission power constrained by the total BS transmission power and the minimum subchannel capacity

Based on (6), the minimum subchannel transmission power constrained by the total BS transmission power and the minimum subchannel capacity is illustrated in Fig. 4. From Fig. 4, we can find there is a joint line between the minimum subchannel transmission power constrained by the total BS transmission power and the minimum subchannel transmission power constrained by the minimum subchannel capacity. Values in this joint line can simultaneously satisfy the constraints from the total BS transmission power and the minimum subchannel capacity.

To evaluate the characteristics of joint line in the Fig. 4, we fit this joint line into different two-dimensionality spaces to investigate the change trend with different system parameters. In Fig. 5, the number of selected users decreases with the increasing of the minimum subchannel capacity in this joint line. In Fig. 6, the minimum subchannel transmission power decreases with the increasing of selected users, but this decreasing trend is not linear. In Fig. 7, the minimum subchannel transmission power increases with the minimum subchannel capacity in this joint line.

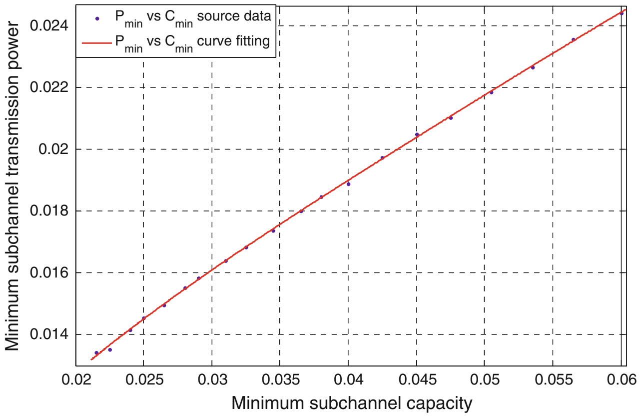

Fig. 7 Fitting the joint line from the two dimensionality space of the minimum subchannel capacity $C_{\min}$ and the minimum subchannel transmission power $P_{\min}$

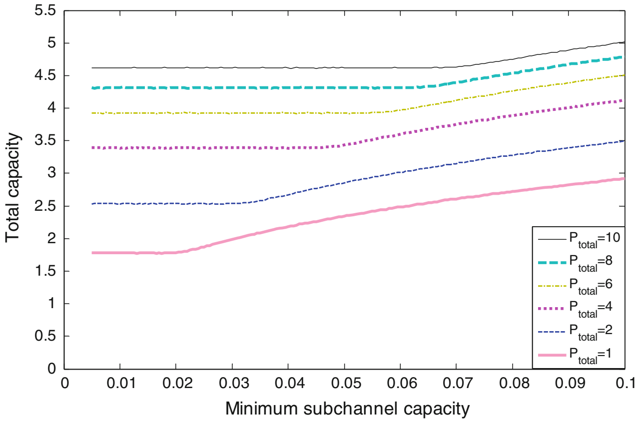

Fig. 8 Impact of minimum subchannel capacity on the total capacity of MISO-OFDM communication system

4 Simulation results and discussion

Based on the simulation configuration in Section 3, we further investigate the total capacity and energy efficiency performance of MISO-OFDM communication systems under different total BS transmission powers. In the following simulations, the total BS transmission power is configured from 1 to 10 to evaluate MISO-OFDM communication systems performance.

In Fig. 8, the value of total capacity remains unchanged when the value of minimum subchannel capacity starts to increase, and then the value of total capacity increases after the value of minimum subchannel capacity exceeds a specific threshold. Moreover, this specific minimum subchannel

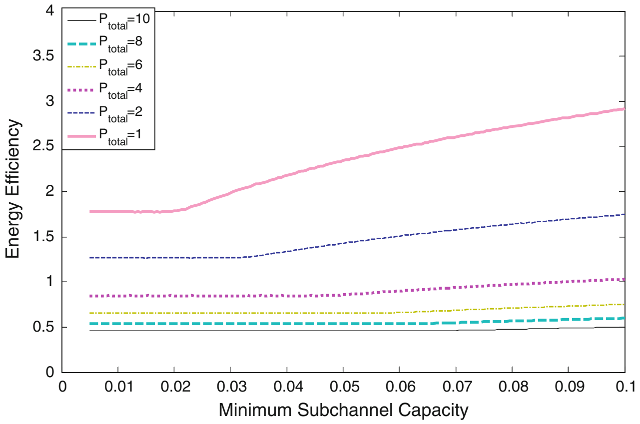

Fig. 9 Impact of minimum subchannel capacity on the energy efficiency of MISO-OFDM communication system

capacity threshold increases with the total BS transmission power. The total capacity of MISO-OFDM communication system increases with the total BS transmission power.

In Fig. 9, the value of energy efficiency remains unchanged when the value of minimum subchannel capacity starts to increase, and then the value of energy efficiency increases after the value of minimum subchannel capacity exceeds a specific threshold. Moreover, this specific minimum subchannel capacity threshold increases with the total BS transmission power. However, the energy efficiency decreases with the total BS transmission power.

5 Conclusion

In this paper, we have investigated the energy efficiency of MISO-OFDM communication systems considering power and capacity constraints. From these two constraints, we have formulated a power allocation model for a MISO-OFDM communication system and developed a new PUJS algorithm to realize the power allocation in the BS. Moreover, the minimum subchannel transmission power performance constrained by the total BS transmission power and minimum subchannel capacity has been analyzed. Based on numerical simulations, there is a joint line which can simultaneously satisfy requirements from the total BS transmission power and minimum subchannel capacity and the basic performance of joint line is investigated by the numerical fitting approach. Furthermore, energy efficiency and total capacity performance of MISO-OFDM communication systems with power and capacity constraints have been analyzed by simulations. From simulations, we find there is a minimum subchannel capacity threshold to impact on energy efficiency and total capacity of MISO-OFDM communication systems. When the value of minimum subchannel capacity is less than a specific threshold, the energy efficiency and total capacity of the MISO-OFDM communication systems remain unchanged. Otherwise, the energy efficiency and total capacity of MISO-OFDM communication systems increase with the minimum subchannel capacity.

References

1. Cheng X, Wang C-X, Laurenson DI, Salous S, Vasilakos AV (2009) An adaptive geometry-based stochastic model for non-isotropic MIMO mobile-to-mobile channels. IEEE Trans Wireless Commun 8(9):4824–4835
2. Wang C-X, Hong X, Ge X, Cheng X, Zhang G, Thompson JS (2010) Cooperative MIMO channel models: a survey. IEEE Comm Mag 48(2):80–87
3. Correia LM, Zeller D, Blume O, Ferling D, Jading Y, Gódor I, Auer G, VanDerPerre L (2010) Challenges and enabling technologies for energy aware mobile radio networks. IEEE Comm Mag 48(11):66–72
4. Chen M, Leung V, Mao S, Xiao Y, Chlamtac I (2009) Hybrid geographical routing for flexible energy-delay trade-offs. IEEE Trans Veh Technol 58(9):4976–4988
5. Wang C-X, Hong X, Chen H-H, Thompson JS (2009) On capacity of cognitive radio networks with average interference power constraints. IEEE Trans Wireless Commun 8(4):1620–1625
6. Kolding T, Wigard J, Dalsgaard L (2008) Balancing power saving and single user experience with discontinuous reception in LTE. In Proc. IEEE International Symposium on Wireless Communication Systems. New York, USA, pp. 713–717
7. Humar I, Ge X, Lin X, Jo M, Chen M (2011) Rethinking energy-efficiency models of cellular networks with embodied energy. IEEE Network Magazine, accepted for publication
8. Yang SR, Lin P, Huang PT (2008) Modeling power saving for GAN and UMTS interworking. IEEE Trans Wireless Commun 7 (12)
9. Niu Z, Wu Y, Gong J, Yang Z (2010) Cell zooming for cost-efficient green cellular networks. IEEE Commun Mag 48(11):74–79
10. Miao GW, Himayat N, Li YG, Bormann D (2008) Energy efficient transmission in frequency-selective channels. IEEE Proc Conf GlobeCom 1–5
11. Miao GW, Himayat N, Li GY (2010) Energy-efficient link adaptation in frequency-selective channels. IEEE Trans Commun 58(4):545–554
12. Rhee W, Cioffi JM (2000) Increase in capacity of multiuser OFDM system using dynamic subchannel allocation. In Proc. IEEE Vehic. Tech. Conf., Tokyo, Japan, pp. 1085–1089