Energy-Efficient Binary Power Control with Bit Error Rate Constraint in MIMO-OFDM Wireless Communication Systems

Xi Huang[1], Xiaohu Ge[1], Yuming Wang[1*], Frank Y. Li[2] and Jing Zhang[1]
[1]Dept. Electronics & Information Engineering, Huazhong University of Science & Technology, Wuhan, China.
[2]Dept. of Information and Communication Technology, University of Agder, N-4898 Grimstad, Norway.
hbszhzm@163.com, xhge@mail.hust.edu.cn, frank.li@uia.no, zhangjing@mail.hust.edu.cn
*Corresponding author:ymwang@hust.edu.cn

***Abstract*—Motivated by the demand for energy efficiency improvement in mobile communication industry, we explore an idea of optimizing energy efficiency for MIMO-OFDM wireless communication systems while maintaining users' quality of service (QoS) requirement. Based on the binary power control scheme, a power allocation criterion for energy efficiency optimization is derived under the total power constraint. From a bit error rate (BER) point of view, a protection constraint is configured to guarantee the system QoS. With the aim of energy efficiency optimization under QoS guarantee in MIMO-OFDM wireless communication systems, an energy-efficient binary power control with BER constraint (EBPCB) algorithm is proposed based on the power allocation criterion and QoS constraint. Simulations results demonstrate the energy efficiency improvement of EBPCB.**

***Index Terms*—Energy Efficiency; Quality of Service; Power Control; Wireless communication;**

I. Introduction

With the rapid development of information and communication technologies (ICT), the energy consumption of ICT industry has grown up to 3% of worldwide energy consumption, which causes about 2% of worldwide CO_2 emissions [1]. On the other hand, the increasing energy consumption burdens the electricity bill of network operators. To meet both environmental and economical challenges raised by energy consumption, green wireless communication [2] has appeared for energy-efficient design in all stages of cellular networks while guaranteeing users' QoS.

Green wireless communication explores energy savings of cellular networks in hardware design and manufacture, node deployment, and network operation and management. A holistic approach was proposed for component-, link- and network-level energy savings in cellular networks [3]. However, to achieve even higher energy efficiency, network-level optimized allocation of wireless resources is a must, especially for power control. With better exploitation of spatial diversity and reduced transmission power, the adaptive power control achieves higher SINR by an order of magnitude than the equal power allocation, thus resulting in better coverage [4]. Since energy consumption is closely related to network utilization and lifetime [5], the network-level energy efficiency is believed to be one of the promising optimization targets. However, further technical questions are brought forward on the proper compromise between energy efficiency and other efficiency objectives, such as deployment efficiency, spectrum efficiency, delay and QoS [6].

Furthermore, for most power allocation schemes, the acquisition for the perfect centralized knowledge of channel state information (CSI) is a great challenge [7]. To tackle this difficulty, a binary power control (BPC) scheme which leads to a simpler or even distributed solution for performance optimization was proposed in [8]. It is demonstrated that the BPC scheme is optimal with respect to the maximal total rate of a two-cell network. However, the power control algorithm in [8] assumes the channel gain as a random variable rather than considering detail influencing factors, such as the path loss, shadowing and fading effects. Meanwhile, the energy efficiency optimization problem under QoS constraint is not considered in traditional binary power control schemes.

Motivated by the aforementioned gaps, we study in this paper how to optimize energy efficiency in multi-input multi-output and orthogonal frequency division multiplexing (MIMO-OFDM) wireless communication systems with QoS guarantee. We propose a new algorithm to optimize energy-efficient power allocation with BER constraint. Our main contributions are summarized as follows:

1) A power allocation criterion for energy efficiency optimization in MIMO-OFDM wireless communication systems is derived under a total power constraint, considering the path loss, shadowing and fading effects in wireless channels.
2) A new algorithm with BER constraint for users' QoS guarantee is proposed to optimize the energy-efficient power allocation in MIMO-OFDM wireless communication systems.
3) The performance of our algorithm is analyzed and numerical results are presented.

The remainder of this paper is organized as follows. The system model is included in Section II. In Section III, the energy efficiency optimization problem is formulated with a BER constraint and a total power constraint and then an optimal criterion is derived for power allocation. Moreover, a new algorithm for energy efficiency optimization with BER constraint is proposed. Simulation results are presented in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL

In this paper, our research focuses on the downlink performance of wireless communication systems. We investigate the BPC scheme to optimize the energy efficiency of MIMO-OFDM wireless communication systems with a BER constraint. A single-cell MIMO-OFDM wireless communication system is illustrated in Fig.1. One base station with M_T antennas is located in the center of the cell. Every antenna of the base station is in general assumed to transmit at the same power level. We set a protection distance d from the base station and assume there are K users uniformly scattering in the $R-d$ circular disk around the base station. Each user is integrated with M_R antennas.

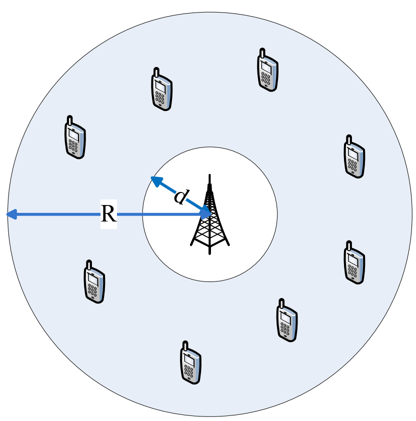

Fig. 1. System model of MIMO-OFDM wireless communication systems.

To simplify the modeling complexity of the OFDM scheme, all orthogonal N subcarriers are re-grouped into N subchannels by the OFDM scheme. Each signal in subchannels experiences independent path loss, shadowing effect and multipath fading. Moreover, interference from other users is ignored in this single cell.

According to the assumptions above, the received signal power S_i in subchannel i is given by

$$S_i = \frac{\omega z_i^2}{{R_i}^{\sigma_r}} P_i \tag{1}$$

where R_i is the distance between the base station and user i, P_i is the transmission power over subchannel i, ω is the lognormal shadowing coefficient, z_i^2 is the Reyleigh fading coefficient of subchannel i and σ_r is the path loss coefficient.

In this paper, energy efficiency in wireless communication systems is defined by the ratio between the system capacity and the total system transmission power. Assuming the maximum achievable channel capacity is Shannon capacity, the energy efficiency of wireless communication systems is derived as follows

$$\eta = \frac{\sum\limits_{i=1}^{N} \log_2(1+\frac{S_i}{n_0})}{P_{total}} \tag{2}$$

where η is the energy efficiency of wireless communication systems, n_0 is the additive white Gaussion noise (AWGN) in wireless subchannels, and P_{total} is the total system transmission power.

In wireless communication systems, the bit error rate depends on the modulation scheme applied. In this paper, we adopt BDPSK modulation to investigate the performance of BER in subchannels. The BER P_{BER} with BDPSK modulation is expressed by

$$P_{BER} = \frac{1}{2} e^{-\frac{\varepsilon_b}{N_0}} \tag{3}$$

where ε_b is the bit energy and N_0 is the noise power spectrum density.

To evaluate the BER performance of wireless communication systems, we define the system average bit error rate as follows

$$P_{aver\_BER} = \frac{\sum\limits_{i=1}^{N} P_{BERi}}{N} \tag{4}$$

where P_{aver_BER} is the system average bit error rate. P_{BERi} is the bit error rate of the received signal in subchannel i.

III. ENERGY EFFICIENCY OPTIMIZATION WITH BER CONSTRAINT

Based on the models described above, we adopt the BPC scheme to allocate the transmission power for subchannels to optimize system energy efficiency while maintaining a given QoS demand.

A. Problem Formulation

Firstly, the set of subchannels enabled for transmission is denoted as C which is expressed as

$$CH_i \in C, C = \{CH_i | 1 \le i \le N\} \tag{5}$$

where CH_i is the subchannel i.

Since the value of transmission power for subchannels is fed from a binary feasible set, we divide the subchannel set C into two subsets. One is the maximum power transmission subchannel subset $K_{p\max}^{M}$ in which the subchannel transmission power is $P_{\max}$ and the other is the minimum power transmission subchannel subset $K_{p\min}^{N-M}$ in which the subchannel transmission power is $P_{\min}$. Moreover, we assume that the number of subchannels in $K_{p\max}^{M}$ is M. The total transmission power of $K_{p\max}^{M}$ is denoted as $P_{\max\_total}$ and the total transmission power of $K_{p\min}^{N-M}$ is denoted as $P_{\min\_total}$. In this case, the relationship of P_{total}, $P_{\max\_total}$ and $P_{\min\_total}$ is described as follows

$$\begin{cases} P_{total} = P_{\max total} + P_{\min total} \\ P_{\max total} = M \times P_{\max} \\ P_{\min total} = (N-M) \times P_{\min} \end{cases} \tag{6}$$

To search for system-wide optimization of the system energy efficiency, a total power constraint P_{total} is set and $P_{\max\_total}$ in the maximum power transmission subchannel subset is assumed to be fixed as a constant.

In practical wireless communication systems, the QoS at user end directly depends on the BER performance. For QoS guarantees, we investigate the optimal solution in energy efficiency subject to a BER constraint as well as a total power constraint described above in the following parts. Then, the whole optimization problem is summarized as follows, where the BER upper bound is denoted as $\tilde{b}$.

$$\max \quad \eta = \frac{\sum_{i=1}^{M} \log_2(1+\frac{S_i}{n_0})}{P_{\max total}} \tag{7}$$

Subject to
Constraint 1: P_{total} and $P_{\max\_total}$ are fixed as constants.
Constraint 2: $P_{aver\_BER} \leq \tilde{b}$.

B. Energy Efficiency Optimal Solution

The core idea of the system energy efficiency optimization lies in that the power allocation based on the BPC scheme should maximize the system energy efficiency. Applying this idea to power allocation, a candidate wireless subchannel CH_k is assigned into $K_{p\max}^{M}$ only when the energy efficiency of $K_{p\max}^{M}$ including CH_k is not less than the energy efficiency of $K_{p\max}^{M}$ without CH_k, otherwise CH_k should be assigned into $K_{p\min}^{N-M}$.

Based on **Constraint 1**, the transmission power of each subchannel in $K_{p\max}^{M}$ when subchannel CH_k is assigned into $K_{p\max}^{M}$ is derived as follows

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

Similarly, the transmission power of each subchannel in $K_{p\max}^{M}$ when subchannel CH_k is not assigned into $K_{p\max}^{M}$ is given by

$$P_{\max\_2} = \frac{P_{\max\_\mathrm{total}}}{M-1} \tag{9}$$

Based on the system energy efficiency model described in Section II, the energy efficiency $\eta_{i\in N}^{a}$ of $K_{p\max}^{M}$ including subchannel CH_k is denoted as

$$\eta_{i\in N}^{a} = \frac{\sum_{i=1}^{\mathrm{M}} \log_2(1+\frac{\frac{\omega z_i^2}{R_i{}^{\sigma_r}}P_{\max\_1}}{n_0})}{P_{\max total}}, \tag{10}$$

and the energy efficiency $\eta_{i\in N, i\neq k}^{b}$ of $K_{p\max}^{M}$ without subchannel CH_k is denoted as

$$\eta_{i\in N, i\neq k}^{b} = \frac{\sum_{i=1, i\neq k}^{\mathrm{M}-1} \log_2(1+\frac{\frac{\omega z_i^2}{R_i{}^{\sigma_r}}P_{\max\_2}}{n_0})}{P_{\max total}} \tag{11}$$

According to the core idea of the system energy efficiency optimization described above, only satisfying the condition $\eta_{i\in N}^{a} \geq \eta_{i\in N, i\neq k}^{b}$ can the candidate wireless subchannel CH_k be finally assigned into $K_{p\max}^{M}$. This condition is expressed by

$$\frac{\sum_{i=1}^{\mathrm{M}} \log_2(1+\frac{\frac{\omega z_i^2}{R_i{}^{\sigma_r}}P_{\max\_1}}{n_0})}{P_{\max total}} \geq \frac{\sum_{i=1, i\neq k}^{\mathrm{M}-1} \log_2(1+\frac{\frac{\omega z_i^2}{R_i{}^{\sigma_r}}P_{\max\_2}}{n_0})}{P_{\max total}} \tag{12}$$

Since $P_{\max\_1} \leq P_{\max\_2}$ and the AWGN n_0 is obviously less than the received signal in subchannel i , we can approximate (12) and then derive the optimal power allocation criterion for system energy efficiency as follows

$$\frac{\frac{\omega z_k^2}{R_k{}^{\sigma_r}}P_{\max\_2}}{n_0} \geq (\frac{M}{M-1})^{M-1} - 1 \tag{13}$$

To simplify expression (13), we set it as follows

$$SNR_k \geq \gamma \tag{14}$$

where the left side of expression (14) is the signal to noise ratio (SNR) of the candidate wireless subchannel CH_k, which is denoted as SNR_k. The right side of expression (14) is the power allocation threshold value, which is denoted as γ.

Based on (14), the system energy efficiency optimization can be carried out by comparing the SNR_k of the candidate subchannel CH_k with the threshold value γ. If the comparison result satisfies expression (14), the candidate subchannel CH_k is assigned into the maximum power transmission subchannel subset $K_{p\max}^{M}$. Otherwise, CH_k is assigned into the minimum power transmission subchannel subset $K_{p\min}^{N-M}$.

C. Algorithm Design

Based on **Constraints 1** and **2**, an energy-efficient binary power control with bit error rate constraint (EBPCB) algorithm is designed for energy efficiency optimization in MIMO-OFDM wireless communication systems while maintaining the system QoS. Firstly, all subchannels of wireless subchannel set C are degressively ordered according to their CSI. Then the process of power allocation optimization with BER constraint begins. The key idea of the power allocation optimization is to assign a candidate wireless subchannel CH_k into the maximum power transmission subchannel subset $K_{p\max}^{M}$, then calculate the system average BER and SNR_k. If the calculation results satisfy **Constraint 2** and the power allocation criterion, the candidate wireless subchannel CH_k is finally added to $K_{p\max}^{M}$. Otherwise, CH_k is assigned into the minimum power transmission subchannel subset $K_{p\min}^{N-M}$. The detailed EBPCB algorithm is illustrated in Algorithm 1:

ALGORITHM 1: Energy-efficient binary power control with BER constraint

Input: P_{total},$P_{\max\_\mathrm{total}}$,γ
Output: $P_{\max}$,$P_{\min}$,$K_{p\max}^{M}$,$K_{p\min}^{N-M}$
Initialization: Create a wireless sub-channel set C with N subchannels, the maximum power transmission subchannel subset $K_{p\max}^{M}$ and the minimum power transmission subchannel subset $K_{p\min}^{N-M}$:

$$C = \{CH_i | 1 \leq i \leq N\}, K_{p\max}^{M} = \phi, K_{p\min}^{N-M} = \phi.$$

Begin:

1) Create a new set $\tilde{C}$ from the set C by a descending order of $\frac{\omega z_i^2}{R_i^{\sigma r}}$: $\tilde{C} = \left\{ CH_i | \forall (1 \leq i \leq k \leq N), \frac{\omega z_i^2}{R_i^{\sigma r}} \geq \frac{\omega z_k^2}{R_k^{\sigma r}} \right\}$.

2) **for** $i = 1 : N$ **do**

$$P_{\max} = \frac{P_{\max\_total}}{i-1}, SNR_i = \frac{\frac{\omega z_i^2}{R_i^{\sigma r}} P_{\max}}{n_0},$$

$$P_{BERi} = \frac{1}{2} e^{-\frac{\varepsilon_{bi}}{N_0}}, P_{aver\_BER} = \frac{sum(P_{BER1} : P_{BERi})}{i}.$$

if $P_{aver\_BER} > \tilde{b}$

$$M = i - 1,$$

break

else if $SNR_i < \gamma$

$$M = i - 1,$$

break

end if

end if

end for

3) add $CH_j \, (1 \leq j \leq M)$ into $K_{p\max}^{M}$,
add $CH_j \, (M+1 \leq j \leq N)$ into $K_{p\min}^{N-M}$,
$P_{\max} = \frac{P_{\max\_total}}{M}$,$P_{\min} = \frac{P_{total} - P_{\max\,total}}{N-M}$.

end Begin

IV. SIMULATION RESULTS AND PERFORMANCE EVALUATION

Based on the system models described in Section II, we will now evaluate the proposed EBPCB algorithm performance in MIMO-OFDM wireless communication systems through Monte Carlo simulations. To evaluate the performance thoroughly, we compare the performance of the EBPCB algorithm with two other power control schemes: the binary power control scheme without optimization aim (BPC) and the energy-efficient binary power control scheme without BER constraint (EBPC).

In our simulations, we assume that users are uniformly distributed in a circular disk around the base station since we set an protection distance d for the base station. The radius of the single-cell is ranged from 300 to 500m and the protection distance d is assumed as 50m. Further simulation details are configured as follows: the system bandwidth is assumed as 1 MHz; the bit rate is assumed as 10kb/s in all subchannels for simplicity; the BER upper bound is configured as $10^{-11}\%$ [9]; the total transmission power of the base station is ranged from 0.6 to 1.4 watt (W); the path loss coefficient is ranged from 3.8 to 4.1; Considering the OFDM scheme used in MIMO wireless communication systems, the number of subchannles is ranged from 8 to 128; the AWGN n_0 is configured as 0.1W.

Fig.2 shows the energy efficiency comparison of EBPCB, BPC and EBPC as a function of the number of subchannels.

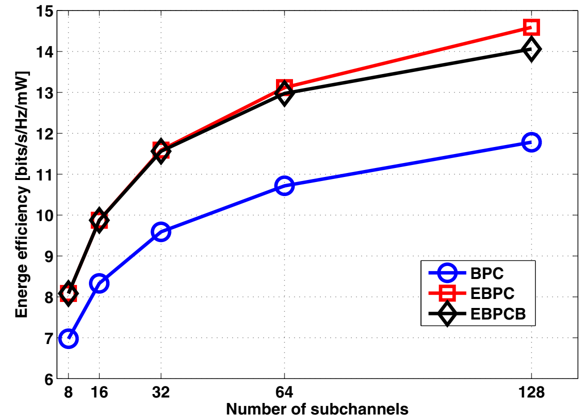

Fig. 2. Comparison energy efficiency of EBPCB, BPC and EBPC with different number of subchannels.

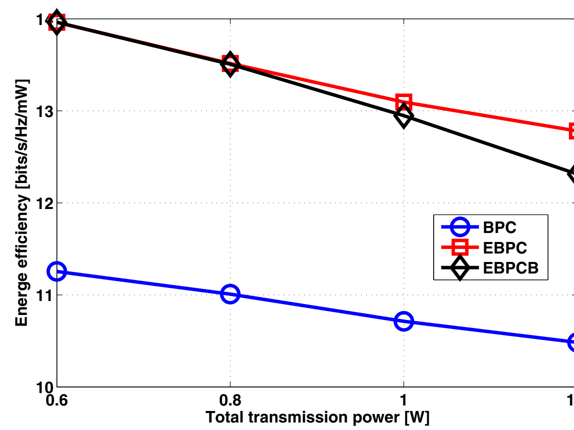

Fig. 3. Comparison energy efficiency of EBPCB, BPC and EBPC with different total transmission power.

From Fig.2, it is clearly seen that EBPCB and EBPC outperform the BPC scheme in terms of energy efficiency. This result demonstrates the effect of energy efficiency optimization by optimal power allocation. For EBPCB and EBPC, the curves show that the energy efficiency of these two schemes is approximately the same when the number of subchannels is less than 32. Nonetheless, when the number of subchannels is larger than 32, EBPCB yields a marginal loss in energy efficiency as compared with EBPC.

Fig.3 shows the energy efficiency comparison of EBPCB, BPC and EBPC as a function of total transmission power. From Fig.3, it is clearly seen that EBPCB and EBPC outperform the BPC scheme in terms of energy efficiency. This result demonstrates the effect of energy efficiency optimization by optimal power allocation. For EBPCB and EBPC, the curves show that the energy efficiency of the two schemes is approximately the same when the total transmission power is less than 0.8 W. Nonetheless, when the the total transmission power is larger than 0.8 W, EBPCB yields a marginal loss in energy efficiency as compared with EBPC.

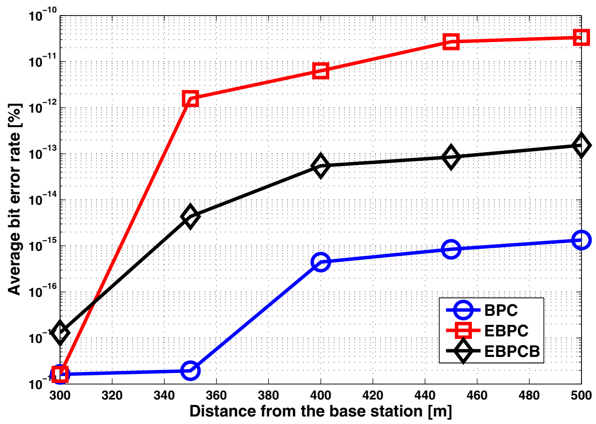

Fig. 4. Comparison average bit error rate of EBPCB, BPC and EBPC with different distance from the base station.

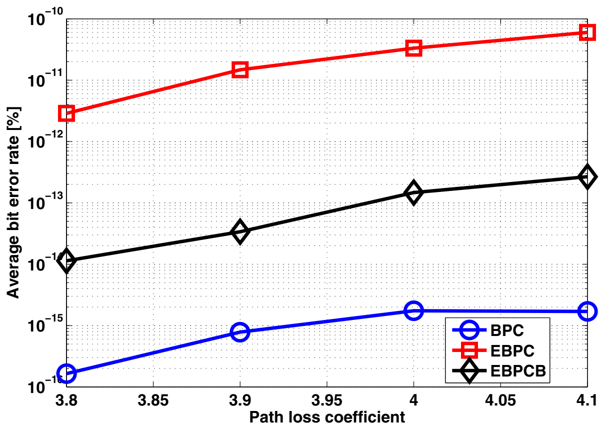

Fig. 5. Comparison average bit error rate of EBPCB, BPC and EBPC with different path loss coefficient.

Fig.4 shows the average bit error rate comparison of EBPCB, BPC and EBPC as a function of distance from the base station. From Fig.4, it is remarked that the BPC scheme outperforms EBPC and EBPCB in average bit error rate. This result demonstrates the fact that there is a fundamental trade-off between energy efficiency optimization and the BER performance. In terms of EBPCB and EBPC, it is noted that EBPC yields better performance in average bit error rate when the distance from the base station is less than 312 m. Nonetheless, EBPCB outperforms EBPC in average bit error rate when the distance from the base station is larger than 312 m. It is notable that the average bit error rate of EBPCB is always below $10^{-13}\%$ due to the bit error rate **constraint 2**.

Fig.5 plots the average bit error rate curves of EBPCB, BPC and EBPC as a function of path loss coefficient. As expected, it can be immediately observed that larger values of path loss coefficient lead to higher BER values. Agreeing with Fig.4, it is notable that the average bit error rate curve of EBPCB lies between the curves of BPC and EBPC. This ulteriorly shows the compromise between energy efficiency optimization and the BER performance. In terms of EBPCB and EBPC, it is remarked that EBPCB significantly outperforms EBPC in average bit error rate. So EBPCB provides better QoS guarantee as compared with EBPC.

V. CONCLUSIONS

In this paper, we explore the idea of optimizing the energy efficiency for MIMO-OFDM wireless communication systems while maintaining a given QoS demand. Assuming that perfect CSI is presented in each subchannel, we adopt the BPC scheme for energy efficiency optimization and a criterion for power allocation is derived under a total power constraint. To guarantee the system QoS, a protection constraint is configured from a BER point of view. Base on the power allocation criterion and QoS constraint, an EBPCB algorithm is proposed with energy efficiency optimization and QoS guarantee in MIMO-OFDM wireless communication systems. A comparison of EBPCB, BPC and EBPC schemes by simulations shows the proposed EBPCB algorithm provides better performance in terms of energy efficiency with guaranteed system QoS.

ACKNOWLEDGMENT

The authors would like to acknowledge the support from the RCUK for the UK-China Science Bridges Project: R&D on (B)4G Wireless Mobile Communications; the EU FP7- PEOPLE-IRSES program, project acronym S2EuNet (Grant no.: 247083); the National Natural Science Foundation of China (NSFC) (Grant No.: 60872007); National 863 High Technology Program of China (Grant No.: 2009AA01Z239); the Ministry of Science and Technology (MOST), China, International Science and Technology Collaboration Program (Grant No.: 0903); the National Natural Science Foundation of China (NSFC) (Grant No.: 61103177); the Fundamental Research Funds for the Central Universities (Grant No.: 2011QN020); and the Hubei Provincial Science and Technology Department (Grant No.: 2011BFA004).

REFERENCES

[1] I. Humar, X. Ge, X. Lin, M. Jo and M. Chen, "Rethinking energy-efficiency models of cellular networks with embodied energy," *IEEE Network Magazine*, vol. 25, no. 2, pp. 40-49, March 2011.

[2] Y. Chen, S. Zhang and S. Xu, "Fundamental Trade-offs on Green Wireless Networks," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 30-37, June 2011.

[3] L. M. Correia, D. Zeller, O. Blume, D. Ferling and Y. Jading, "Challenges and Enabling Technologies for Energy Aware Mobile Radio Networks," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 66-72, Nov. 2010.

[4] R. Chen, J. G. Andrews, R. W. Heath and A. Ghosh, "Power Control for Cellular MIMO Systems," in *Proc. IEEE Global Telecommunications Conference, 2006 (GLOBECOM '06)*, pp. 1-5, Nov. 2006.

[5] J. Feng, C. Chang, S. Sayilir, Y. Lu, B. Jung, D. Peroulis and Y. C. Hu, "Energy-Efficient Transmission for Beamforming in Wireless Sensor Networks," in *Proc. IEEE Communication Society Conference on Sensor Mesh and Ad Hoc Communication and Networks, 2010 (SECON)*, pp.1-9, June 2010.

[6] H. Bogucka, A. Conti, "Degrees of Freedom for Energy Savings in Practical Adaptive Wireless Systems," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 38-45, June 2011.

[7] B. Zayen, M. Haddad, A. Hayar and G. E. Oien "Binary power allocation for cognitive radio networks with centralized and distributed user selection strategies" *Physical Communication Journal*, vol.1, no.3, pp.183-193, Sep.2008.

[8] S. G. Kiani, G. E. Oien and D. Gesbert, "Maximizing Multicell Capacity Using Distributed Power Allocation and Scheduling," in *Proc. IEEE Wireless Communications and Networking Conference, 2007 (WCNC 2007)*, pp.1690-1694, March 2007.

[9] Y. Zhao, S. G. Haggman, "BER Analysis of OFDM Communication Systems with Intercarrier Interference," in *Proc. International Conference on Communication Technology, 1998 (ICCT '98)*, pp. 1-5, Oct. 1998.