Energy Efficiency Modelling and Analyzing Based on Multi-cell and Multi-antenna Cellular Networks

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Abstract

In this paper, the relationship between the energy efficiency and spectrum efficiency in a two-cell cellular network is obtained, and the impact of multi-antenna on the energy efficiency of cellular network is analyzed and modeled based on two-state Markovian wireless channels. Then, the energy efficiency of multi-cell cellular networks with co-channel interference is investigated. Simulation results verify the proposed model and the energy-spectrum efficiency tradeoffs in cellular networks with multi-antenna and co-channel interference.

Keywords: Energy efficiency, cellular network, multi-cell, multi-antenna, Markovian chain

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1. Introduction

Global warming and climate change has been receiving more and more worldwide attention. Currently, 3% of the world-wide energy is consumed by the ICT (Information and Communications Technology) infrastructure. In comparison to the conventional mobile communication systems, the current mobile industry exhibits potentials to reduce carbon dioxide (CO_2) emissions by minimizing the energy consumption, while reducing costs for the mobile operators and the mobile subscribers. However, recent official studies show that ICT industry accounts for approximately 2% of global CO_2 emissions, which is comparable to the world-wide CO_2 emissions by airplanes [1]. It is reported that the carbon footprint contributed by the mobile industry was at 245 mega-tonnes of carbon dioxide equivalent (Mt CO_2e) in 2009, which was a rise of 155 Mt CO_2e since 2002 [2]. Even worse, the energy consumption in the mobile industry is increasing at a fast rate. Forecasting 8 billion connections from mobile subscribers by 2020, mobile operators and vendors need to ensure sustainable growth in this industry while keeping CO_2 emissions at 2009 level. For this purpose, multi-antenna system is widely accepted as the main technology to increase the spectrum efficiency in the next generation cellular network, in order to satisfy the increasing requirements of mobile subscribers in terms of transmission rate for wireless communications [3][4]. The Recent advances indicate that the multi-antenna system enabling base stations achieve higher transmission rate, yet consume more transmission power without the use of power control [5][6]. Previous investigation reveals that 90% energy is consumed in the core network and base stations, only 10% energy is consumed by user terminals [7]. Therefore, how to improve the energy-efficiency for the multi-antenna enabling base stations by flexible tradeoffs between the energy efficiency and the spectrum efficiency, and how to evaluate the impact of multi-antenna system on the energy efficiency of cellular networks are challenging issues for the next generation cellular network.

In this paper, we first introduce a concept of energy-efficiency-accounting for estimating the energy consumption per transmission bit. Then, the relationship between the energy efficiency and spectrum efficiency in cellular networks is analyzed. Furthermore, the impact of channel parameters and antenna number on the energy efficiency of two-cell cellular network with two-state Markovian wireless channels is investigated. After we build the model of energy efficiency on multi-cell cellular networks, the performance analysis is explored, which provides some practical guidelines for developing new efficient protocols to trade off the energy efficiency and spectrum efficiency performance in next generation cellular networks.

The rest of the paper is organized as follows. In Section 2, we present related work. The definition of energy efficiency is proposed and the relationship between the energy efficiency and spectrum efficiency is detailedly analyzed in Section 3. To simplify the wireless channel parameters, Section 4 introduces a two-state Markovian wireless channel for the performance analysis in the multi-antenna and multi-cell cellular networks. The energy efficiency model of the cellular network with multi-antenna is proposed and analyzed in Section 5. The impact of cell number on the energy efficiency of cellular network with two-state Markovian wireless channels is investigated in Section 6. Finally, we conclude this paper in Section 7.

2. Related Work

Our work is closely related to the energy efficiency in wireless cellular networks [8][9][10][11][12][13][14][15] and the energy saving on the user equipment (UE) of cellular networks [16][17][18][19]. We will give a brief review of the works in these aspects.

As for the work of the energy efficiency in wireless cellular networks, J.T. Louhi analyzed the features of modern cellular networks and illustrated that the energy saving of cellular networks should be focused on the base stations, moreover, three suggestions improving the base station energy efficiency were proposed in [9]. M. A. Marsan evaluated the energy saving that could be achieved with the energy-aware cooperative management of cellular access networks of two operators offering service over the same area [10], and characterized the amount of energy that could be saved by reducing the number of active cells during the periods when traffic was low [11]. Based on the re-arranging user-cell association, K Dufková proposed a concrete methodology to shut down under-utilized parts of cellular network for saving energy, and simulation results showed that up to 50% energy might be saved in less busy periods [12]. Sheng Zhou investigated the centralized and decentralized implementation in mobile access networks, the simulation results demonstrated the energy efficiency of the proposed algorithms and the trade-off between energy saving and coverage guarantee [13]. Considering three different universal mobile telecommunications system (UMTS) scenarios with a simplified traffic model, the reference [14] showed that dynamic planning, consisting in reducing the number of active access devices when traffic was low, could achieve significant energy saving. Furthermore, Luca Chiaraviglio proposed a novel approach for the energy-aware management of UMTS access networks based on the instantaneous traffic intensity [15].

Some research focus on the energy saving on the user equipment (UE) of cellular networks [16][17][18][19]. A fractional threshold-based wake-up mechanism was proposed, which switched the system into the sleep mode when the packet-receiving queue was empty, and switched the system on when the number of packets in the queue “reached” a fractional threshold value [16]. Hongseok Kim proposed a mechanism to switch between multi-input multi-output (MIMO) with two transmit antennas and single-input multi-output (SIMO) to conserve mobile terminal’s energy, which could save the uplink RF transmission energy of mobile terminals in cellular networks supporting best effort traffic [17]. Using a realistic radio frequency (RF) modem power consumption model for the UE, Troels Kolding investigated proper configuration of discontinuous reception (DRX) parameters for optimizing the balance among user throughput and power saving using a web-browsing session as the reference, and the simulation results showed that a 95% reduction of the UE power consumption with only a moderate and acceptable 10-20% loss of experienced throughput could be optimally achieved [18]. Shun-Ren Yang proposed an analytical model and conducted simulation experiments to investigate the power consumption of a dual-mode mobile station (MS) in term of the power consumption indicator and the mean packet waiting time [19]. However, there is a little study analyzing the impact of multi-cell and multi-antenna on the energy efficiency of cellular networks.

3. Energy Efficiency Model

3.1 Energy Efficiency of Single Cell

To evaluate the energy efficiency of cellular networks, this section first introduces a definition of energy efficiency. Typically, the energy consumption of transmittng 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. Based on the Shannon capacity theory, the maximum achievable capacity for the single cell communication system is given by

$$C_{\text{single}} = BW \log_2\left(1 + \frac{EG}{\sigma^2}\right). \tag{1}$$

Where BW is the bandwidth of the communication system, and the bandwidth of communication system is normalized as $BW = 1(Hz)$ in this paper; E is the transmission power at base station; G is the wireless channel gain which includes the pass loss, fading and shadowing effect in wireless channels; σ^2 is the noise in wireless channels. Therefore, for the single cell communication system without considering interference from adjacent cells, the energy efficiency is defined as

$$EE_{\text{single-cell}} = \frac{C_{\text{single}}}{E} = \frac{\log_2\left(1 + \frac{EG}{\sigma^2}\right)}{E} \tag{2}$$

Note that $EE_{\text{single-cell}}$ has a unit of bit per Joules (bit/J). From the perspective of engineering in real world, this unit is reformed as bits per hertz per milliwatt (bits/Hz/mW), and the unit of energy efficiency in following figures is given as bits/Hz/mW if additional label is not denoted.

In the traditional wireless communication system, the spectrum efficiency is one of the most important metrics and is usually improved by enhancing the transmission power of base stations. For a normalized bandwidth, the spectrum efficiency could be expressed by (1). However, when the energy efficiency of wireless communication system is considered, there is a conflict between the energy efficiency and the spectrum efficiency in the same wireless communication system as showed in **Fig. 1**.

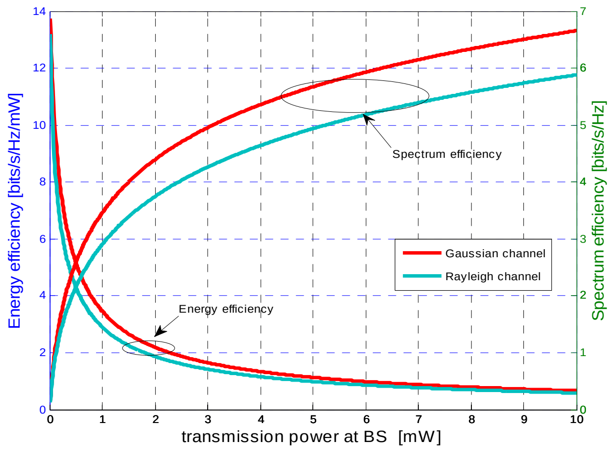


Fig. 1. Relationship between the energy efficiency and spectrum efficiency

In the **Fig. 1**, the energy efficiency and the spectrum efficiency have been evaluated with the transmission power at base station based on (2). Based on reference [20], the wireless channel gain is configured as $G = 10^{-11}$, and the noise in the wireless channel is configured as $\sigma^2 = 10^{-15}$ watt. Considering Gaussian and Rayleigh channels, **Fig. 1** shows that the increased transmission power at base station can improve the spectrum efficiency but reduce the energy efficiency in a single cell communication system. Therefore, considering requirements from green communication, a trade-off should be explored between the energy efficiency and the spectrum efficiency in a wireless communication system. Furthermore, more advanced technologies should be developed to improve the spectrum efficiency constrained by the given energy efficiency in wireless communication systems.

3.2 Energy Efficiency of Two Cells

For the next generation cellular communication system, with the multi-antenna technology integrated at base stations, the performance of cellular communication system has been mainly limited by the interference from adjacent cells. Therefore, the interference from adjacent cells should be considered for evaluation of energy efficiency of multi-antenna cellular networks. A simple two-cell cellular network is considered for exploring the energy efficiency performance with interference from an adjacent cell in **Fig. 2**, where each cell has one base station. In our simulation system, two users are distributed into different cells, such that the users are affected by channel conditions (e.g., the pass loss, fading effect, shadowing effects, and interference, etc.). All these channel conditions are classified into two types of channel gain. One type of channel gain is the service gain denoted by SG_i, $i \in \{1,2\}$, which includes the pass loss, fading and shadowing effect. The other type of channel gain is the interference gain denoted by IG_i, $i \in \{1,2\}$, which includes the interference effect from an adjacent cell. The values of service gain parameter and interference gain parameter in one channel are normalized to satisfy the following condition: $SG_i + IG_i = 1$, $i \in \{1,2\}$.

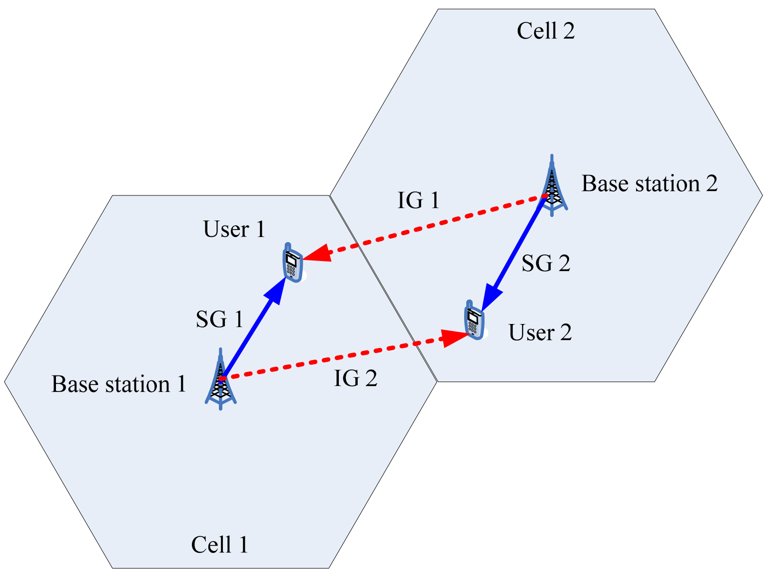


Fig. 2. Two-cell cellular network system model

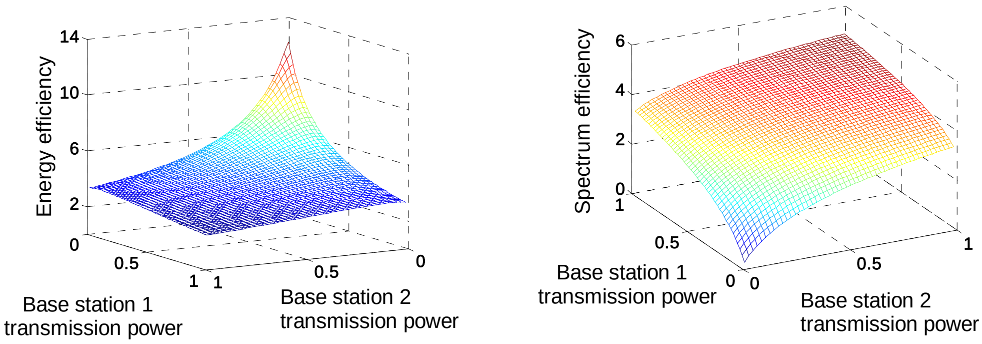
Given the two-cell cellular network system model shown in **Fig. 2**, the two-cell cellular network energy efficiency model based on the maximum achievable capacity is built by

$$EE_{\text{two-cell}} = \frac{\log_2\left(1+\dfrac{E_1 \times SG_1}{\sigma_1^2 + E_2 \times IG_1}\right) + \log_2\left(1+\dfrac{E_2 \times SG_2}{\sigma_2^2 + E_1 \times IG_2}\right)}{E_1 + E_2} \tag{3}$$

where E_1 and E_2 are the transmission power at two base stations respectively; SG_1 and SG_2 are the service parameters due to the pass loss, fading and shadowing effect, IG_1 and IG_2 are interference parameters, σ_1 and σ_2 are noise parameters in channels 1 and 2 between corresponding users and base stations respectively.

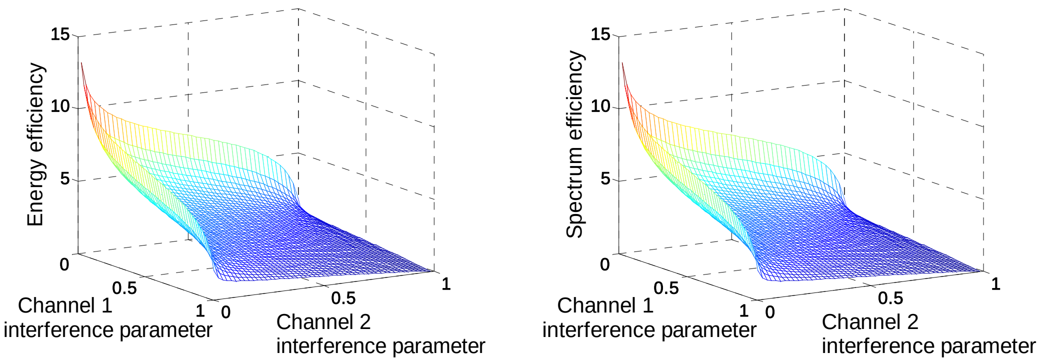
From the two-cell cellular network energy efficiency model, the impact of base stations transmission power on the energy efficiency and spectrum efficiency is illustrated by **Fig. 3(a)-(b),** where two types of channel gain parameters are set to be specified values for the simplicity of illustrating the energy efficiency and spectrum efficiency changes. Without loss of generality, the exact channel gain parameters are configured as: $SG_1 = SG_2 = 0.9$; $IG_1 = IG_2 = 0.1$; $\sigma_1^2 = \sigma_2^2 = 0.1$. Moreover, values of base station transmission power are normalized from 0 to 1. In **Fig. 3(a)**, the energy efficiency is influenced by the transmission power of both base stations. With the increase of the transmission power, the energy efficiency is non-linearly decreased. The transmission power of both base stations also has impact on the spectrum efficiency, as shown in **Fig. 3(b)**. And the spectrum efficiency is non-linearly increased when the transmission power of the base stations is increased. Furthermore, the smaller the value of the transmission power, the greater the impact on the energy efficiency and spectrum efficiency.

Consequently, the impact of channels gain on the energy efficiency and spectrum efficiency is illustrated by **Fig. 4(a)-(b)**, where base stations transmission power parameters and noise parameters are configured in specified values for easily illustrating the energy efficiency and spectrum efficiency changes. Without loss of generality, two base stations transmission power parameters are configured as: $E_1 = E_2 = 1$; and the two channels noise parameters are configured as: $\sigma_1 = \sigma_2 = 0.1$. Considering the conflict between the service gain and interference gain in the same wireless channel, the normalized service parameters and interference parameters in the same wireless channel are constrained by: $SG_i + IG_i = 1,\ i \in \{1,2\}$. In this case, the impact of service gain parameters on the energy efficiency and spectrum efficiency can be derived by the impact of interference gain parameters on the energy efficiency and spectrum efficiency. Therefore, we just illustrate the impact of interference gain parameters on the energy efficiency and spectrum efficiency by **Fig. 4(a)-(b)**. From **Fig. 4(a)-(b)**, it is shown that the energy efficiency and spectrum efficiency are degraded with the increase of channel interference parameters. Moreover, channels interference parameters have great impact on the energy efficiency and spectrum efficiency when values of channels interference parameter are small, and vice versa.



(a) (b)

Fig. 3. Energy efficiency VS. transmission power in the two-cell cellular network



(a) (b)

Fig. 4. Spectrum efficiency VS. transmission power in the two-cell cellular network

4. Markovian Wireless Channels

To investigate the basic energy efficiency performance of two-cell cellular network, a simple two-state Markovian wireless channel model is introduced in this paper. In this case, a user's channel of two-cell cellular network is modeled into good and bad states due to channel conditions. Moreover, a transition from one state to the next state only depends on the current state. Thus, the user's channel could be modeled into a two-state homogeneous Markovian channel with the state space {0, 1}, where '0' corresponds to a good state and '1' corresponds to a bad state in **Fig. 5**. Based on properties of Markovian processes, a channel transition probability matrix is given by

$$\mathbf{P}^{(n)} = \begin{bmatrix} P_{00}{}^{(n)} & P_{01}{}^{(n)} \\ P_{10}{}^{(n)} & P_{11}{}^{(n)} \end{bmatrix} = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}^{(n)} \tag{4}$$

where $P_{i,j}$, i and $j \in \{0,1\}$, is a one-step transition probability from the state i into the state j, and $P_{i,j}^{(n)}$, i and $j \in \{0,1\}$, is a probability from the initial state i into the state j after n steps transition.

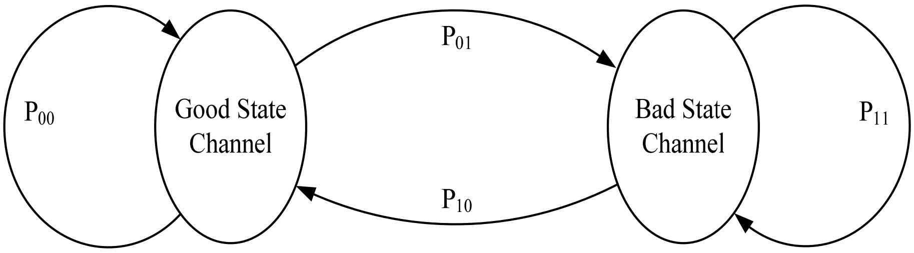


Fig. 5. State transition diagram of two-state Markovian wireless channel

5. Energy Efficiency Performance on Multi-antenna Cellular Networks

Based on the two-cell cellular network system model in **Fig. 2**, the impact of multi-antenna on the energy efficiency performance is investigated in Section 4. Because a multi-antenna system is easier to be integrated into base stations than to be integrated into a user communication terminal in practical engineering designs, in this section we focus our research on multi-input single-output (MISO) cellular networks. Furthermore, N_t antennas are assumed to be integrated into base stations. In this case, service parameters and interference parameters are extended from a variable to a vector with element $1 \times N_t$. Using the Shannon capacity theory, the maximum achievable cell capacity for two-cell cellular network is given by

$$\mathbf{C}_{\mathrm{MISO\_cell\_1}} = \log_2\left(1 + \frac{E_1^{MISO} \times \left\|\mathbf{SG_1}\right\|_F^2}{\sigma_1^2 + E_2^{MISO} \times \left\|\mathbf{IG_2}\right\|_F^2}\right) \tag{4a}$$

$$\mathbf{C}_{\mathrm{MISO\_cell\_2}} = \log_2\left(1 + \frac{E_2^{MISO} \times \left\|\mathbf{SG_2}\right\|_F^2}{\sigma_2^2 + E_1^{MISO} \times \left\|\mathbf{IG_1}\right\|_F^2}\right) \tag{4b}$$

where $\mathbf{C}_{\mathrm{MISO\_cell\_1}}$ is the maximum achievable capacity of cell 1, $\mathbf{C}_{\mathrm{MISO\_cell\_2}}$ is the maximum achievable capacity of cell 2. The transmission power from one base station is distributed averagely for all antennas, and E_1^{MISO} and E_2^{MISO} are the transmission power per antenna at base station 1 and base station 2 respectively. Following parameters exist in channel 1 and channel 2 between users and base stations: σ_1 and σ_2 are noise parameters. $\left\|\square\right\|_F^2$ is the Frobenius norm; $\mathbf{SG_1}$ and $\mathbf{SG_2}$ are service vector parameters, which correspond to a $1 \times N_t$ channel matrix with the pass loss, fading and shadowing effect; $\mathbf{IG_1}$ and $\mathbf{IG_2}$ are interference vector parameters, which correspond to a $1 \times N_t$ interference channel matrix. Considering a two-state Markovian wireless channel model in **Fig. 5**, channel vector parameters can be further specified as: for a good state channel, service vectors and interference vectors are configured as $\mathbf{SG}_1^{good} = \mathbf{SG}_2^{good} = \begin{bmatrix} 0.9 & 0.9 & \cdots & 0.9 \end{bmatrix}_{1 \times N_t}$ and $\mathbf{IG}_1^{good} = \mathbf{IG}_2^{good} = \begin{bmatrix} 0.1 & 0.1 & \cdots & 0.1 \end{bmatrix}_{1 \times N_t}$; for a bad state channel, service vectors and interference vectors are configured as $\mathbf{SG}_1^{bad} = \mathbf{SG}_2^{bad} = \begin{bmatrix} 0.6 & 0.6 & \cdots & 0.6 \end{bmatrix}_{1 \times N_t}$ and $\mathbf{IG}_1^{bad} = \mathbf{IG}_2^{bad} = \begin{bmatrix} 0.4 & 0.4 & \cdots & 0.4 \end{bmatrix}_{1 \times N_t}$.

Due to the memory-less property of two-state Markovian wireless channel model, without loss of generality, the initial state of channel 1 is configured as a good state and the initial state of channel 2 is configured as a bad state in this section. Furthermore, a stable network capacity after n step state transition is given by

$$\begin{aligned} C_{MISO\_two-cell} &= P_{00}^{(n)} C_{\text{MISO\_cell\_1}} + P_{01}^{(n)} C_{\text{MISO\_cell\_1}} + P_{10}^{(n)} C_{\text{MISO\_cell\_2}} + P_{11}^{(n)} C_{\text{MISO\_cell\_2}} \\ &= P_{00}^{(n)} \log_2 \Big(1 + \frac{E_1^{MISO} \times \left\| \mathbf{SG_1^{\mathit{good}}} \right\|_F^2}{\sigma_1^2 + E_2^{MISO} \times \left\| \mathbf{IG_2^{\mathit{good}}} \right\|_F^2}\Big) \\ &+ P_{01}^{(n)} \log_2 \Big(1 + \frac{E_1^{MISO} \times \left\| \mathbf{SG_1^{\mathit{bad}}} \right\|_F^2}{\sigma_1^2 + E_2^{MISO} \times \left\| \mathbf{IG_2^{\mathit{bad}}} \right\|_F^2}\Big) \\ &+ P_{10}^{(n)} \log_2 \Big(1 + \frac{E_2^{MISO} \times \left\| \mathbf{SG_2^{\mathit{good}}} \right\|_F^2}{\sigma_2^2 + E_1^{MISO} \times \left\| \mathbf{IG_1^{\mathit{good}}} \right\|_F^2}\Big) \\ &+ P_{11}^{(n)} \log_2 \Big(1 + \frac{E_2^{MISO} \times \left\| \mathbf{SG_2^{\mathit{bad}}} \right\|_F^2}{\sigma_2^2 + E_1^{MISO} \times \left\| \mathbf{IG_1^{\mathit{bad}}} \right\|_F^2}\Big) \end{aligned} \tag{5}$$

Furthermore, the model of energy efficiency for MISO two-cell cellular network with Markovian wireless channels is expressed by

$$EE_{\text{MISO\_two-cell}} = \frac{C_{MISO\_two-cell}}{N_t (E_1 + E_2)} . \tag{6}$$

To analyze the impact of number of antennas on the energy efficiency of two-cell cellular network with Markovian wireless channels, some basic parameters are configured as follows: the transmission power per antenna is normalized as one, i.e. $E_1^{MISO} = E_2^{MISO} = 1$; and the noise parameters are set as $\sigma_1^2 = \sigma_2^2 = 0.1$. Moreover, a initial state transition probability matrix of two-state Markovian chain channels is shown as:

$$\mathbf{P} = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 0.8 & 0.2 \\ 0.4 & 0.6 \end{bmatrix} . \tag{7}$$

Based on above parameter values, the energy efficiency performance analysis of MISO two-cell cellular network is illustrated by **Fig. 6**. In numerical simulations, when the number of antennas integrated at a base station increases from 1 to 8, the energy efficiency of MISO two-cell cellular network non-linearly decreases with the increase of antenna number. The reason of this result is that the capacity of MISO two-cell cellular network logarithmically increases with the antenna number considering the interference from an adjacent cell, when the system power of two-cell cellular network linearly increases with the antenna number.

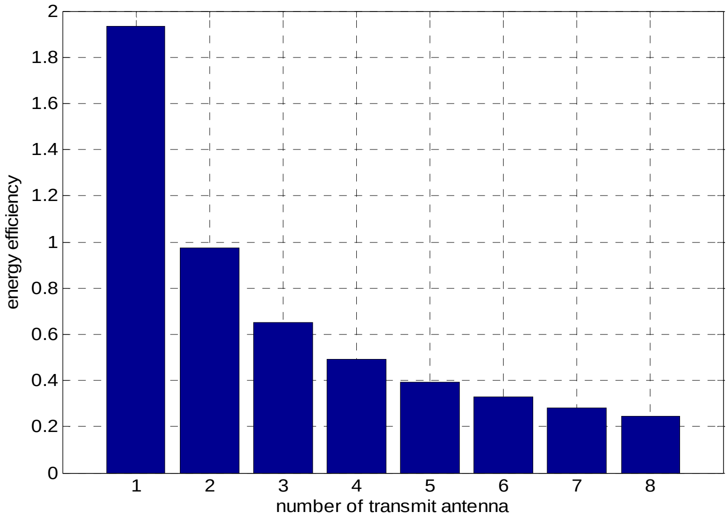


Fig. 6. Impact of number of antennas on energy efficiency

6. Energy Efficiency Performance on Multi-cell Cellular Networks

Considering the interference from the adjacent multi-cell, the impact of cells number on the energy efficiency of multi-cell cellular networks is investigated in Section 5. In this multi-cell cellular network system, every cell is assumed to include one base station with one antenna and one user terminal with one antenna. The user can receive expectation signal from a base station in the same cell, and also receive the interference from other base stations in adjacent cells. The base station covering range is configured as a typical hexagonal cell. In this case, the main interference is assumed to be transmitted from six adjacent cells. The detailed system model of multi-cell cellular network is illustrated in **Fig. 7**.

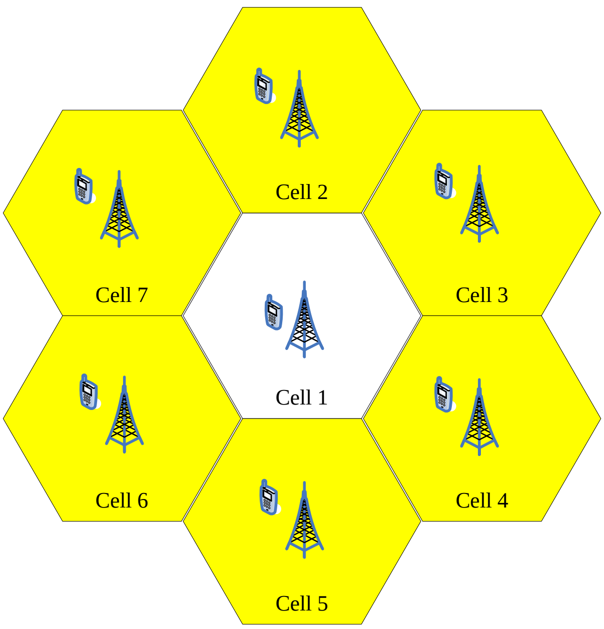


Fig. 7. System model of multi-cell cellular network

From the definition of energy efficiency for single cell communication system, the energy efficiency for multi-cell cellular networks is similarly defined by

$$EE_{\text{multi-cell}} = \frac{\sum_{i=1}^{n} \log_2\left(1 + \frac{E_i \times SG_i}{\sigma_i^2 + \sum_{j=1, j \neq i}^{n} E_j \times IG_{ij}}\right)}{\sum_{i=1}^{n} E_i} . \tag{8}$$

where n is the number of cells; E_i is the transmission power from base station i; SG_i is the service parameter due to the pass loss, fading and shadowing effect in cell i; IG_{ij} is the interference parameter in cell i where is interfered by a base station from cell j; σ_i is the noise in cell i.

When wireless channels of multi-cell cellular network are assumed as two-state Markovian wireless channels illustrated in **Fig. 5**, due to the memory-less property of two-state Markovian wireless channel model, initial channels of all cells are configured as good states. Furthermore, after a n steps state transition in two-state Markovian wireless channels, a model of energy efficiency of multi-cell cellular network is given by

$$EE_{\text{multi-cell}} = \frac{\sum_{i=1}^{n} \left\{ \log_2\left(1 + \frac{E_i \times SG_i^{good}}{\sigma_i^2 + \sum_{j=1, j \neq i}^{n} E_j \times IG_{ij}^{good}}\right) P_{00}^{(n)} + \log_2\left(1 + \frac{E_i \times SG_i^{bad}}{\sigma_i^2 + \sum_{j=1, j \neq i}^{n} E_j \times IG_{ij}^{bad}}\right) P_{01}^{(n)} \right\}}{\sum_{i=1}^{n} E_i} \tag{9}$$

where E_i and E_j are the transmission power at base stations i and j respectively; SG_i^{good} and SG_i^{bad} are the service parameters over good and bad state channels; IG_{ij}^{good} and IG_{ij}^{bad} are interference parameters over good and bad state channels; σ_i^2 is the noise in cell i; $P_{00}^{(n)}$ and $P_{01}^{(n)}$ are n steps transition probabilities of two-state Markovian channels from an initial good state to a good and bad state respectively.

To analyze the impact of cell number on the energy efficiency of multi-cell cellular networks, without loss of generality, some default parameter values are fixed for simplifying the performance evaluation as follows: every base station transmission power is fixed as $E_i = E_j = 1(mW)$, $\mathrm{i,j} \in [1,\mathrm{n}]$; for a good state channel, $SG_i^{good} = 0.9$ and $IG_{ij}^{good} = 0.1$; for a bad state channel, $SG_i^{bad} = 0.6$ and $IG_{ij}^{bad} = 0.4$; n steps transition probabilities of two-state Markovian channels are fixed as $P_{00}^{(n)} = 0.8$ and $P_{01}^{(n)} = 0.2$; and the noise is set as $\sigma_i^2 = 0.1(mW)$. For traditional hexagon cellular networks, in the most cases, the main interference for a cell is originated from adjacent six cells, so we first investigate the impact of adjacent six cells on the energy efficiency of cellular networks. In this case, the system model of multi-cell cellular network is composed by seven cells, and more detailed system structure is illustrated in **Fig. 7**. Moreover, distances between interference transmitters and a user terminal are approximated equalization when the user terminal is located in the center cell and interference transmitters, i.e. interference base stations are located only in six adjacent cells. Wireless channels used for numerical simulations are assumed as a two-state Markovian model illustrated in **Fig. 5**. Numerical results are analyzed in **Fig. 8**.

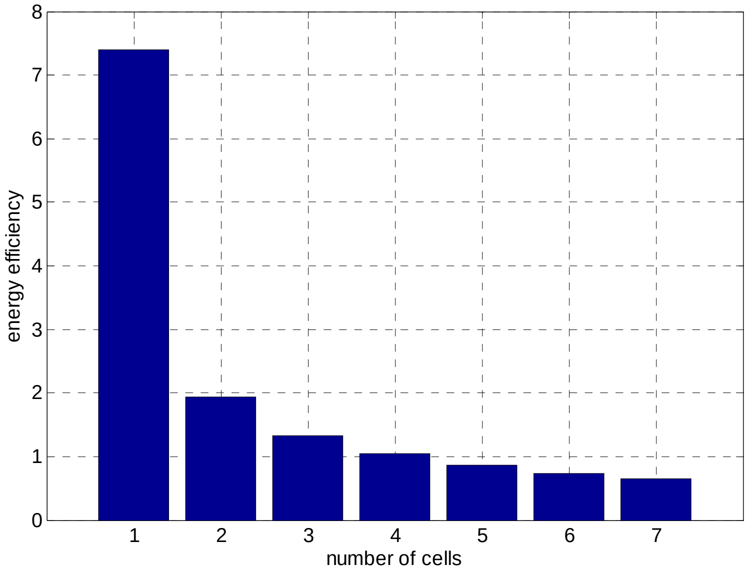


Fig. 8. Impact of number of cells on Energy Efficiency

From **Fig. 8**, the single cell system, i.e. the number of cells is one, has the highest energy efficiency, and this highest energy efficiency is 7.3 (bits/Hz/mW). The energy efficiency performance of multi-cell cellular network with cell number from 2 to 7 is obviously less than the energy efficiency performance of single cell communication system. Therefore, the interference from adjacent cells has great influence on the energy efficiency of multi-cell cellular network. When the interference from adjacent cells is considered, the energy efficiency of cellular networks will gradually approximate 0.65 (bits/Hz/mW) in Fig.8. Because the main interference for a traditional hexagon cell is originated from adjacent six cells in cellular networks, the down-bound of energy efficiency, i.e. 0.65 (bits/Hz/mW) approximated from Fig.8, can be used as guideline for some general cellular networks design with more than seven cells.

7. Conclusions

In this paper, we generalize models of energy efficiency for multi-cell and multi-antenna cellular networks based on the energy consumed by every transmission bit. Simulation results verify the compromising relationship between energy efficiency and interference in multi-cell cellular networks. The energy-spectrum efficiency trade-off relationship is first obtained for the single cell communication system. Based on two-state Markovian wireless channels, the impact of multi-antenna and multi-cell on the energy efficiency of cellular networks is further investigated, and numerical results show the interference from adjacent cells can obviously degrade the energy efficiency of multi-cell cellular networks. All of these results provide practical guidelines for developing new efficient protocols to trade-off the energy efficiency and spectrum efficiency considering the antenna number and co-channel interference from adjacent cells. Currently, we just find some basic energy efficiency performance trends with simple good and bad channel states, from the perspective of two-state Markovian wireless channels. Thus, our future work will further explore the impact of detailed channel parameters, such as path loss parameter, fading parameter and shadowing parameter, on the energy efficiency of multi-cell cellular networks. In addition, the detailed interference model should be considered in the energy efficiency of multi-antenna multi-cell cellular networks.

References

[1] W. Feng, H. Alshaer, J.M.H. Elmirghani, "Green information and communication technology: energy efficiency in a motorway model," *IET Communications*, vol.4, No.7, pp.850-860, 2010.
[2] W. Feng, Y. Li, S. Zhou, J. Wang, "On Power Consumption of Multi-user Distributed Wireless Communication Systems," in *Proc. of IEEE Communications and Mobile Computing (CMC)*, pp.366-369, 2010.
[3] I. Telatar, "Capacity of multi-antenna Gaussian channels," *European Transactions Telecommunications*, vol. 10, no. 6, pp. 585-595, Nov. 1999.
[4] S. Catreux, P. F. Driessen, and L. J. Greenstein, "Attainable throughput of an interference-limited multiple-input multipleoutput (MIMO) cellular system," *IEEE Transactions on Wireless* Communications, vol. 49, no. 8, pp. 1307–1311, 2001.
[5] F. Richter, A. J. Fehske, G. P. Fettweis, "Energy Efficiency Aspects of Base Station Deployment Strategies for Cellular Networks," in *Proc. of IEEE 70th Vehicular Technology Conference Fall*, 2009.
[6] E. Weidman, S. Lundberg, "Life-cycle assessment of Ericsson Third-generation Systems," in *Proc. of IEEE International Symposium on Electronics and the Environment*, pp. 136-142, 2000.
[7] J. Malmodin, L. Oliv, P. Bergmark, "Life cycle assessment of third generation (3G) wireless telecommunication systems at Ericsson," in *Proc. of Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, pp. 328-334, 2001.
[8] C. E. Jones, K. M. Sivalingam, P. Agrawal and J. C. Chen, "A survey of energy efficient network protocols for wireless networks," *Wireless Networks*, vol.7, pp.343-358, July, 2001.
[9] J.T. Louhi, "Energy efficiency of modern cellular base stations," in *Proc. IEEE International Conference of Telecommunications Energy (INTELEC)*, pp.475-476, 2007.
[10] M. Ajmone Marsan, M. Meo, "Energy Efficient Management of two Cellular Access Networks," in *Proc. of GreenMetrics 2009 Workshop*, pp. 1150-1165, 2009.
[11] M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo, "Optimal Energy Savings in Cellular Access Networks," in *Proc. of IEEE International Workshop on Green Communications (GreenComm)*, pp.1-5, 2009.
[12] K. Dufková, M. Bjelica, B. Moon, L. Kencl, J. L. Boudec, "Energy Savings for Cellular Network with Evaluation of Impact on Data Traffic Performance," in *Proc. of 16th European Wireless Conference*, pp. 916-923, 2010.
[13] S. Zhou, J. Gong, Z. Yang, Z. Niu, P. Yang, "Green Mobile Access Network with Dynamic Base Station Energy Saving," in *Proc. of ACM MobiCom'09*, 2009.
[14] L. Chiaraviglio, D. Ciullo, M. Meo, M. Ajmone Marsan, "Energy-Aware UMTS Access Networks," in *Proc. of IEEE W-GREEN*, pp.1-8, 2008.
[15] L. Chiaraviglio, D. Ciullo, M. Meo, M. Ajmone Marsan,"Energy-Efficient Management of UMTS Access Networks," in *Proc. of IEEE 21st International Teletraffic Congress (ITC2009)*, pp.1-8,2009.
[16] Xiao, Y., Chen, C.L.P., Kinateder, K.J, "An Optimal Power Saving Scheme for Mobile Handsets," in *Proc. of Sixth IEEE Symposium on Computers and Communications (ISCC'01)*, pp.192-197, 2001.
[17] H. Kim, C.B. Chae, G. Veciana, R. W. Heath, "A Cross-Layer Approach to Energy Efficiency for Adaptive MIMO Systems Exploiting Spare Capacity," *IEEE Transactions on Wireless Communications*, vol. 8, no. 8, pp. 4264-4275, 2009.
[18] S. R. Yang, P. Lin, P. Huang, "Modeling Power Saving for GAN and UMTS Interworking,"

IEEE Transactions on Wireless Communications, vol. 7, no. 12, pp. 5326-5335, 2008
[19] Kolding T, Wigard J, Dalsgaard L, "Balancing Power Saving and Single User Experience with Discontinuous Reception in LTE," in *Proc. of IEEE International Symposium on Wireless Communication Systems (ISWCS 2008)*, pp.713-717, 2008.
[20] A. Gjendemsj, D. Gesbert, G.E. Oien, S.G. Kiani, "Binary Power Control for Sum Rate Maximization over Multiple Interfering Links," *IEEE Transactions on Wireless Communications*, vol.7, no.8, pp. 3164-3173, 2008.

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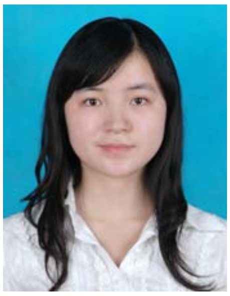

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