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Uplink energy efficiency analysis for two-tier cellular access networks using kernel function

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Abstract In this paper, the uplink energy efficiency and uplink outage probability for two-tier cellular access networks (TTCANs) are investigated. To model of the uplink energy efficiency and uplink outage probability in TTCANs, a closed-form expression of signal-to-interference ratio (SIR) is derived by considering the on/off states of femtocell access points (APs). Moreover, a second order kernel function is firstly used to solve the analytical interference model with femtocell APs turning on in TTCANs. Simulation results show that femtocell user's intensity has great impact on the uplink energy efficiency and uplink outage probability in a TTCAN. These results provide some guidelines for developing new energy saving schemes in practical TTCANs deployment.

Keywords Femtocell · Energy efficiency · Kernel function · Signal-to-interference ratio

1 Introduction

Recently, two-tier cellular access networks (TTCANs) have been attended by industries and researchers to solve a trade-off between energy efficiency and quality of service (QoS) in cellular access networks. Studies on wireless communication usage showed that more than 50% of voice calls and more than 70% of data traffic originate from indoor environments [1, 2]. Femtocells, which consist of miniature base stations (BSs) and mobile users in an indoor environment, are located within an existing cellular network. In traditional macrocells, the second tier constructed by femtocells could greatly reduce the transmission power and increase the system capacity [3].

Since femtocells are operated in the licensed spectrum owned by wireless operators, all indoor femtocell users are operated in the same bandwidth for cost-effective and flexible deployment [4]. However, a breakdown of operating energy in TTCANs revealed that the approximately 90% energy is consumed by network components. To save the energy consumption of TTCANs, shutting down partial access points (APs) of femtocell during low or no user traffic periods is one of the most popular approaches. Moreover, to maintain the QoS requirement of users, corresponding APs should be turned on during high user traffic periods.

Recently, some research was conducted to analyze the system performance and power consumption in wireless access networks [5–12]. For example, Akhtman and Hanzo

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discussed the tradeoff relationship between energy efficiency and spectrum efficiency in cellular networks and showed the overall network performance was greatly affected by the selected network optimization principles [5]. Cross-layer design and optimization was an effective approach for achieving energy saving in wireless communication systems [6]. It was found in [7] different deployment strategies have a significant impact on the energy consumption of cellular networks, e.g. energy saving in deploying microcells is moderate under full-load scenarios and strongly depends on the offset energy consumption of both macro- and microcells. Meshkati, Poor and Schwartz proposed a game-theoretic model to study the cross-layer problem of joint power and rate control with QoS support, and then derived a Nash equilibrium solution (with a closed-form equation for the utility) for the proposed non-cooperative game [8]. In addition, the impact of co-channel interference on energy efficiency of multi-cell cellular wireless networks was studied in [9] under a simple channel model. Considering the lognormal shadowing, an uplink capacity of two-tier femtocell network was derived in [10]. In reference [11], the power control was discussed to minimize cross-tier interference and ensure acceptable femtocell system performances. The coverage zone was studied in [12] to satisfy QoS requirements from user applications.

With green communication emerging, the energy efficiency of TTCANs has been investigated in [13–18]. The tradeoff between the energy efficiency and the cell throughput was discussed by deploying femtocells in a cellular network [13]. From references [14] and [15], some efficiency resource allocation solutions in OFDMA networks were proposed considering the co-channel interference between femtocells and macrocells. Based on the interference analysis for femtocell deployment, Dr. Lee discussed an optimal power allocation for femtocells with different orthogonal subbands in OFDMA wireless communication systems [16]. For heterogeneous wireless networks, it was found that combining cellular communication systems with femtocell can significantly reduce overall power consumption while the QoS of users remains in a high level [17]. To overcome disadvantages from interference, a two-step interference coordination scheme was proposed to deal with interference with carrier aggregation [18].

However, studies in all aforementioned tiered networks only investigated system performances without considering the uplink energy efficiency. Moreover, little literature considering users within and without femtocells was presented. Therefore, how to evaluate the uplink energy efficiency of TTCANs with co-channel interference is a great challenge for practical deployments of tiered wireless access networks.

Based on results in aforementioned studies, an uplink energy efficiency model for a TTCAN is proposed. To evaluate the quality of channels, the uplink signal-to-interference ratio (SIR) over lognormal shadowing channels is derived when the corresponding femtocell AP is shut down. Furthermore, a closed form expression of the uplink SIR is approximately derived based on a second order kernel function when the corresponding femtocell AP is turned on. Moreover, a detailed performance analysis considering the energy consumption of TTCANs reveals that the energy efficiency of TTCANs is impacted by the ratio of required uplink power between the macrocell and the femtocell in TTCANs. All of these results provide some practical guidelines for developing new protocols to tradeoff the energy efficiency and QoS in TTCANs.

The study is organized as the following. In Sect. 2, a general system model is introduced and the probability density function (PDF) of user uplink SIR is analyzed subsequently. The energy efficiency and outage probability of users in TTCANs are investigated and derivated in Sect. 3. Simulation results in Sect. 4 provide some guideline for practical uplink power control in TTCANs. Finally, we conclude the paper in Sect. 5.

2 SIR modeling of TTCANs

2.1 TTCANs system structure

A general wireless TTCAN system is described in this section. Without loss of generality, an arbitrary macrocell is selected for illustrated in Fig. 1. A macrocell is assumed to include a BS and M femtocells. Moreover, every femtocell is assumed to include K active users. In this case, there are two types users in a macrocell. One type user is the femtocell user where is located in the circle centered by corresponding femtocell APs. Another type user is the macrocell user where is located in a macrocell but outside of femtocells. Both two types of users are governed by a spatial uniform distribution. To simplify analysis, each femtocell user is equipped with one antenna. To avoid the interference with an infinite estimated value, a "dead-zone" around the AP is assumed to forbid users inside. In Fig. 1, d_i is the distance between the base station of the macrocell and the i-th femtocell AP, r is the radius of femtocells, r_{m_i} is the radius of the "dead-zone" in the i-th femtocell.

Considering the QoS and the energy consumption requirements, it is assumed that the AP of femtocell is automatically turned on during high traffic period and turned off during low traffic period.

2.2 SIR model with turning off APs

During the low traffic period, femtocell APs are shut down to save the energy of TTCANs. By the affection of the variability associated with large scale environmental obstacles,

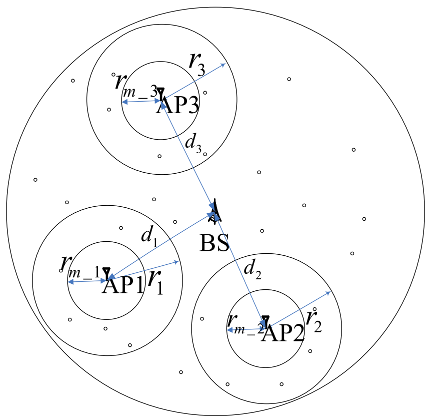

Fig. 1 System structure of a wireless TTCAN

wireless channels suffer from shadowing effect. In this paper, we just focus on the uplink between the user and the BS. Without loss of generality, a macrocell user located outside of femtocells is selected to transmit expected signal to the corresponding BS in a macrocell. In this case, there are some interference transmitted from M active APs and N macrocell users. Considering that the wireless spectrums used in femtocells and macrocells are different, there is no interference between femtocell users and macrocell users.

The interference received by the BS and transmitted from the i-th interfering user can be expressed as

$$I_i = s_i^2 \cdot \omega_i, \tag{1}$$

where s_i and ω_i reflect the shadowing and the fading effect from the i-th interfering user over wireless channels, respectively.

Every interference power Ω_I transmitted from the i-th interfering user can be expressed by a lognormal distribution as follows [19]

$$p_{\Omega_I}(x) = \frac{1}{\sqrt{2\pi}\sigma x} e^{-\frac{(\ln(x)-\ln(\mu))^2}{2\sigma^2}} \quad x \geq 0, \tag{2}$$

where μ is the mean receiving power and related to the path loss in wireless channels; σ is the shadow standard deravation which is given by $\sigma = (\frac{\ln 10}{20}) \cdot \sigma_{\mathrm{dB}}$ and σ_{dB} typically ranges from 4 dB to 9 dB [20]. (2) can be simply expressed as $\Omega_I \sim LN(\mu, \sigma^2)$. Moreover, the mean $E(X)$ and variance $Var(X)$ of (2) are derived as follows

$$E(X) = \exp(\mu + \sigma^2/2), \tag{3}$$

$$Var(X) = \exp(2\mu + \sigma^2) \cdot (\exp(\sigma^2) - 1). \tag{4}$$

When femtocells are turned off, the APs would not connect femtocell users with BS in a macrocell. In this case, it can be assumed as a femtocell user with the same power of macrocell users. The total inference power received by BS is expressed as follows

$$I_{total\_off} = \sum_{i=1}^{M \cdot K+N} I_i. \tag{5}$$

Based on derivations from [21] and [22], the summation of lognormal random variables can be approximated by a single lognormal random variable e^z, where z is a Gaussian random variable with a mean of μ_z and a variance of σ_z^2. Moreover, the μ_z and σ_z^2 are expressed as follows

$$\mu_z = \log\left(\alpha/\sqrt{1+\beta^2/\alpha^2}\right), \tag{6}$$

$$\sigma_z^2 = \log(1 + \beta^2/\alpha^2), \tag{7}$$

with

$$\alpha = \sum_{i=1}^{M \cdot K+N} \exp(\mu_i + \sigma_i^2/2), \tag{8}$$

$$\beta^2 = \sum_{i=1}^{M \cdot K+N} \sum_{j=1}^{M \cdot K+N} \exp(\mu_i + \mu_j + (\sigma_i^2 + \sigma_j^2)/2) \times (\exp(\sigma_{ij}^2) - 1). \tag{9}$$

The distribution of wireless channels between $M \cdot K + N$ interfering users and the BS is an independent identical distribution (i.i.d). The aggregated interference power at the BS I_{total_off} is expressed by a lognormal distribution $I_{total\_off} \sim LN(\mu_{total\_off}, \sigma^2_{total\_off})$.

Since this macrocell is assumed as an interference-limited scenario, the noise component is negligible compared with the co-channel interference from interfering users. The SIR is expressed as follows

$$\gamma_{off} = \frac{S_d}{I_{total\_off}} = \frac{S_d}{\sum_{i=1}^{N} I_i}, \tag{10}$$

where S_d is the power of the expected signal. Moreover, S_d is governed by a lognormal distribution $S_d \sim LN(\mu_d, \sigma_d^2)$ when this expected signal is assumed to pass through a shadowing fading wireless channel.

Since the division result of two independent lognormal random variables is still a lognormal random variable, γ_{off} is also a lognormal random variable which depends on the distribution of S_d and I_{total}. In this case, the PDF of SIR can be simply expressed as $\gamma_{off} \sim LN(\mu_{\gamma\_off}, \sigma^2_{\gamma\_off})$. Based on assumptions of weak turbulence and small correlation values, μ_{γ_off} and $\sigma^2_{\gamma\_off}$ are reduced to

$$\mu_{\gamma\_off} = \mu_d - \log(M \cdot K + N) + \frac{\sigma_n^2}{2}, \tag{11}$$

$$\sigma^2_{\gamma\_off} \approx \sigma_d^2 + \sigma_n^2, \quad (12)$$

with

$$\sigma_n^2 = \frac{1}{(M \cdot K + N)^2} \sum_{k=1}^{M\cdot K+N} \sum_{l=1}^{M\cdot K+N} (\exp(\sigma_{kl}^2) - 1), \quad (13)$$

$$\sigma_{kl}^2 = \mathrm{cov}(I_k, I_l). \quad (14)$$

2.3 SIR model with turning on APs

During the high traffic period, femtocell APs are automatically turned on to maintain users QoS requirements. In this case, femtocell APs just simple repeat the signal received from femtocell user by femtocell users and AP pair channels, and then relay the received signal to the BS by femtocell APs and BS pair channels. Furthermore, interference transmitted from femtocell APs should consider wireless channels effect in femtocell users and APs link pairs.

When all femtocell APs are turned on by multiple femtocell users data transmission, the interference received by the BS is expressed by

$$I_{total\_on} = I_{user} + I_{ap} = \sum_{i=1}^{N} s_i^2 \cdot \omega_i + \sum_{k=1}^{K} s_k^2 \sum_{j=1}^{M} s_j^2 \cdot \omega_j, \quad (15)$$

where I_{user} and I_{ap} are the aggregated interference of interfering users and femtocell APs respectively, s_i and ω_i are the shadowing and the fading effects in wireless channels from the i-th interfering user to the BS, s_k is the shadowing effect in wireless channels from the k-th AP to the BS, s_j and ω_j are the shadowing and fading effects in wireless channels from the j-th femtocell user to the AP.

To simplify the derivation, it is assumed that the mean transmission power of expected signal and interference from macrocell users is statically identical, denoted by ω. Since the distance between macrocell users and the BS is more than the distance between femtocell users to the corresponding femtocell AP, the mean transmission power of femtocell users is $\eta \cdot \omega$ where η is the ratio of the required uplink transmission power in a macrocell over the required uplink transmission power in a femtocell.

Considering that the interference transmitted from femtocell users to the BS is suffered by two shadowing effects in wireless channels, the corresponding interference model has to calculate by a second order kernel function. However, it is difficulty to solve a second order kernel function in numerical analysis. To solve this problem, the second statistical solution is proposed in the following.

If x_1, x_2, x_3, x_4 are random variables, then

$$E[x_1x_2x_3x_4] = E[x_1x_2]E[x_3x_4] + E[x_1x_3]E[x_2x_4] + E[x_1x_4]E[x_2x_3]. \quad (16)$$

That is

$$E[s_j^2 \cdot s_k^2] = E[s_j^2] \cdot E[s_k^2] + 2E^2[s_j \cdot s_k]. \quad (17)$$

Note that $0 \le E^2[s_j \cdot s_k] \le E[s_j^2] \cdot E[s_k^2]$, then

$$E[s_j^2] \cdot E[s_k^2] \le E[s_j^2 \cdot s_k^2] \le 3 \cdot E[s_j^2] \cdot E[s_k^2]. \quad (18)$$

To simply the expression in (18), $E[s_j^2 \cdot s_k^2] = \lambda E[s_j^2] \cdot E[s_k^2]$ with $(1 \le \lambda \le 3)$ is given.

Similarly in Sect. 2.2, the wireless channel is governed by a lognormal distribution. Moreover, wireless channels from macrocell users to the BS can be simple expressed as $LN(\mu_{macro}, \sigma^2_{macro})$, where μ_{macro} is the mean receiving power and σ_{macro} is the shadow standard derivation in macrocell users and the BS link pairs. Wireless channels from femtocell users to APs can be simple expressed as $LN(\mu_{femto}, \sigma^2_{femto})$, where μ_{femto} is the mean receiving power and σ_{femto} is the shadow standard derivation in femtocell users and the corresponding AP link pairs.

Since the multiple result of two independent lognormal random variables is still a lognormal random variable, the total interference power I_{total_on} can also be simply expressed as a lognormal distribution $I_{total\_on} \sim LN(\mu_{total\_on}, \sigma^2_{total\_on})$ based on (10). Furthermore, the PDF of SIR with turning on APs is simple expressed as

$$\gamma_{on} \sim LN\left(\mu_{\gamma\_on}, \sigma^2_{\gamma\_on}\right), \quad (19)$$

with (20)–(24).

3 Performance analysis of TTCANs

In this section, the energy consumption of TTCANs is first analyzed. Furthermore, based on the proposed PDF expression of SIR, the uplink energy efficiency and uplink outage probability of TTCANs are discussed in different scenarios.

$$\mu_{\gamma\_on} = \mu_d - \log\left(\log(\lambda\eta N \cdot M \cdot K) - \frac{2\lambda^2\eta^2(\sigma^2_{macro} + \sigma^2_{femto})}{K \cdot M} - \frac{2\sigma^2_{macro}}{N}\right) + \frac{\sigma_f^2}{2}, \quad (20)$$

$$\sigma^2_{\gamma\_on} = \sigma_d^2 - \sigma_f^2, \quad (21)$$

$$\sigma_f^2 = \log((\eta K \cdot M)^{2/\ln 10} + N^{2/\ln 10} + 2(\eta K \cdot M)^{2/\ln 10} \cdot N^{2/\ln 10}) + \varphi, \quad (22)$$

$$\varphi = \log((\eta K \cdot M)^{2/\ln 10} \cdot e^{4\eta(\sigma^2_{macro} + \sigma^2_{femto})/KM}$$

$$+ N^{2/\ln 10} \cdot e^{4\sigma_{macro}^2/N} + \theta), \quad (23)$$

$$\theta = 2(\eta K \cdot M)^{2/\ln 10} \cdot e^{2\eta(\sigma_{macro}^2+\sigma_{femto}^2)/KM} \cdot N^{2/\ln 10} \times e^{2\sigma_{macro}^2/N}. \quad (24)$$

3.1 User uplink energy consumption in TTCANs

The uplink energy consumption of a user terminal in TTCANs varies in different states. For example, the femtocell user transmits the signal to femtocell AP when femtocell APs are turned on and directly transmits the signal to the BS when femtocell APs are turned off. The power amplifier (PA) of user terminal is expected to work in different states in which the peak value of the signal corresponds with the possible peak power consumption of the user terminal. However, the user power consumption of signal processing is substantially unchanged in different states. Thus, a user uplink energy consumption of TTCANs can be modeled by

$$P_{user} = \left(\frac{P_T}{\mu_{PA}} + P_{SP}\right) \cdot (1 + C_B), \quad (25)$$

where P_T is the user transmission power of PA, P_{SP} is the user signal processing power, μ_{PA} is the efficiency of the power amplifier in user terminals, C_B is the power supply loss in user terminals.

When femtocell APs of TTCANs are turned off, the total users uplink energy consumption is expressed by

$$P_{total\_off} = (M \cdot K + N)\, P_{user} = (M \cdot K + N)\left(\frac{P_T}{\mu_{PA}} + P_{SP}\right) \cdot (1 + C_B). \quad (26)$$

When femtocell APs of TTCANs are turned on, the required uplink transmission power of user terminals in femtocells is decreased due to a shorted distance between the femtocell AP and the femtocell user. However, additional power consumption is inevitable to maintain femtocell APs operation. Therefore, the total users uplink energy consumption with femtocell APs turning on is expressed by

$$\begin{aligned} P_{total\_on} &= N \cdot P_{macro\_user} + K \cdot P_{ap} + M \cdot K \cdot P_{femto\_user} \\ &= N\left(\frac{P_T}{\mu_{PA}} + P_{SP}\right) \cdot (1 + C_B) + K \cdot P_{ap} \\ &\quad + M \cdot K \cdot \left(\frac{\eta P_T}{\mu_{PA}} + P_{SP}\right) \cdot (1 + C_B), \end{aligned} \quad (27)$$

where P_{ap} is the transmission power of femtocell APs.

3.2 Uplink energy efficiency of TTCANs

If the channel state information is assumed to be only known by BSs and the channel is assumed to be ergodic, an ergodic Shannon capacity for the wireless uplink of TTCANs can be achieved by

$$C = \int_0^{\infty} \log_2(1 + \gamma) \cdot f(\gamma)\, d\gamma, \quad (28)$$

where γ is the SIR of TTCANs. Moreover, considering the characteristic of shadowing and fading wireless channels in TTCANs, γ is a lognormal distributed random variable.

To evaluate the uplink energy efficiency of TTCANs, the uplink energy efficiency of TTCANs is defined by

$$E = \frac{C}{P} \quad (29)$$

where C is the uplink capacity of TTCANs, P is the total users uplink energy consumption.

3.3 Uplink outage probability of TTCANs

In general, the uplink outage probability of TTCANs can be expressed as [20]

$$P_{out} = \int_0^{y_{th}} f(\gamma)\, d\gamma, \quad (30)$$

where γ is the SIR of TTCANs, $f(\gamma)$ is the PDF of SIR in TTCANs, and y_{th} is the system protection threshold to satisfy the specified user QoS. Considering shadowing and fading wireless channels in TTCANs, γ is a lognormal distributed random variable and is expressed as $\gamma \sim LN(\mu, \sigma^2)$. Furthermore, the uplink outage probability of TTCANs can be derived as

$$P_{out} = 1 - Q\left(\frac{10\log(y_{th}) - \mu}{\sigma}\right), \quad (31)$$

$$Q(x) = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right), \quad (32)$$

where $erfc(\cdot)$ is the complementary error function.

4 Numerical simulations

Numerical simulations are analyzed for evaluating the impact of system parameters on the uplink energy efficiency and uplink outage probability of TTCANs in this section. The system parameters are configured as follows: the number of macrocell users is 150 (i.e., $N = 150$), the number of femtocells in a macrocell is 5 ($K = 5$), the shadow standard derivation of wireless channels is assumed as $\sigma =$

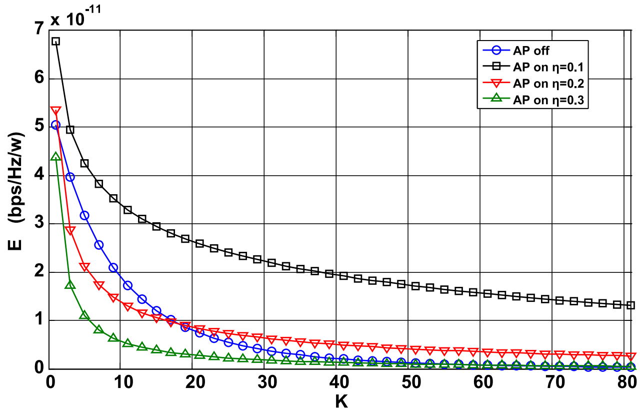

Fig. 2 Impact of femtocell users number on the uplink energy efficiency of TTCANS

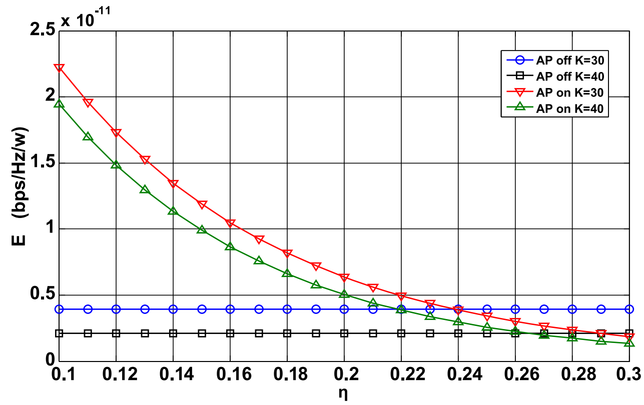

Fig. 3 Impact of the ratio of the required uplink transmission power in a macrocell over the required uplink transmission power in a femtocell on uplink energy efficiency of TTCANs

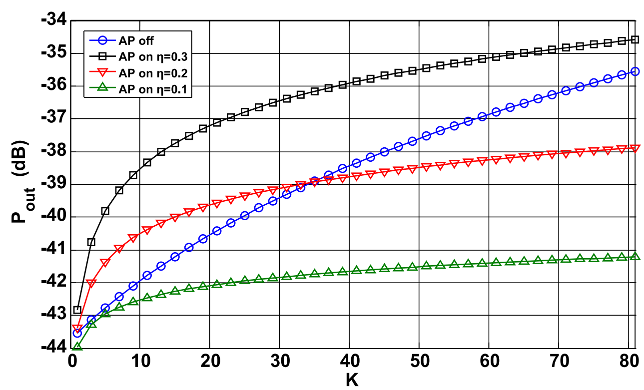

Fig. 4 Impact of femtocell users number on the macrocell user outage probability in TTCANs

$\ln 10 \cdot \sigma_{dB} t/20$ and the values of σ_{dB} are ranged from 4 dB to 9 dB. During the period of femtocell APs turning on, $\lambda = 3$ is chosen to minimize the SIR of TTCANs. Moreover, to evaluate the power consumption in TTCANs, some parameters in (26) and (27) are configured as follows: the power supply loss is assumed as 10% ($C_B = 0.1$), the power amplifier efficiency is assumed as 35% (i.e., $\mu_{PA} = 35\%$), the signal processing power is assumed as $P_{SP} = 380$ mW, and the transmission power of femtocell APs is assumed as $P_{ap} = 20$ W to maintain femtocell APs operating during femtocell APs turning on. When macrocell users and femtocell APs are scattered in a macrocell with 1500 meters radius, the macrocell user transmit power is configured as $P_T = 600$ mW.

4.1 Uplink energy efficiency simulations

First, the uplink energy efficiency of TTCANs is numerically simulated based on the model of (29). In Fig. 2 and Fig. 3, the uplink energy efficiency E is evaluated accounting for the impact from femtocell users number K and the ratio η of the required uplink transmission power in a macrocell over the required uplink transmission power in a femtocell.

From Fig. 2, it can be found that during the period of high traffic, the uplink energy efficiency of TTCANs is improved when femtocell APs are turned on. When the femtocell users number is less than a specified value which is related with η, it is suggested that Femtocell APs should be turned of to saving uplink energy efficiency of TTCANs. In Fig. 3, simulation results show that the uplink energy efficiency of TTCANs decreases with the coverage of femtocell increasing when femtocell APs are turned on.

4.2 Outage probability simulations

Furthermore, the impact of system parameters K and η on the macrocell user outage probability is simulated in this section. From simulation results shown in Fig. 4, it is found that the macrocell user outage probability increases with the femtocell users number. Moreover, the macrocell user outage probability increases more quickly when femtocell APs are turned off.

From Fig. 5, it is found that the macrocell user outage probability increases linearly with the femtocell radius when femtocell APs are turned on. However, when the radius of femtocell is large enough, then the macrocell user outage probability with femtocell APs turning on becomes more than the macrocell user outage probability with femtocell APs turning off.

5 Conclusions

Uplink energy efficiency and outage probability models in TTCANs is proposed and analyzed in this paper. To derive uplink energy efficiency and outage probability models of TTCANs, a second order kernel function is used for building a closed-form of SIR expression in TTCANs considering femtocell APs turning on or off. Considering the

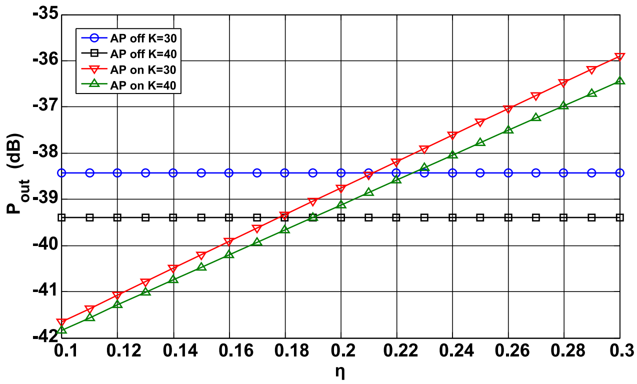

Fig. 5 Impact of the ratio of the required uplink transmission power in a macrocell over the required uplink transmission power in a femtocell on the macrocell user outage probability in TTCANs

interference from other macrocell users, the uplink energy efficiency and the uplink outage probability of TTCANs are analyzed in scenarios with femtocell APs turning on or off. Simulation results show that the number of users and the coverage of femtocells have great impact on the uplink energy efficiency and uplink outage probability in a TTCAN. This result provides a guideline for new protocols in TTCANs to improve the energy efficiency and QoS of users.

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