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Energy Efficiency Consideration for Indoor Femtocell Networks in TV White Spaces

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ABSTRACT The federal communications commission (FCC) took the unprecedented step to approve the usage of TV white spaces, i.e., locally vacant TV channels, in 2012. This TV spectrum will present new opportunities for wireless access technologies and applications, e.g. femtocell networks. The utilization of TV white spaces in femtocell networks also comes with some technical challenges. One of the most fundamental is that how much capacity and energy efficiency can be achieved in TV white spaces network. Prior works only focused on capacity consideration for cellular network in outdoor scenario leaving important femtocell network in indoor scenario largely open for investigation. In this paper, we explore the capacity and energy efficiency for femtocell network by developing a TV white spaces reuse and power allocation scheme. The problem is formulated into an optimization problem with the objective to maximize the energy efficiency achieved by a femtocell network, while keeping the interference to the primary receiver and macro receiver at an acceptable level. We demonstrate the existence of a unique globally optimal transmit power vector for all the femtocells, and propose a gradient ascent algorithm to obtain it. Simulation results show that the femtocell can have a considerable capacity and energy efficiency improvement by using the TV channels.

INDEX TERMS Energy efficiency, femtocell network, gradient ascent algorithm, interference, TV white spaces.

I. INTRODUCTION

The next generation of wireless data traffic will grow explosively resulting from the boom in multimedia applications running on smart phones, tablets, and other wireless devices [1]. More specifically, most of the traffic will come from indoor environment [2]. The demand for higher data rates in indoor wireless networks has triggered the design and development of new technology standards, such as WiMAX, LTE and UMB for cellular. However, the main problem of cellular network is that the network infrastructure is much more expensive. This motivates the development of femtocell network, also called home base station (BS).

Femtocell has been considered as a promising technique to enhance capacity of the LTE macro-cellular network. Due to its lower transmit power, femtocell can prolong the handset

battery life as well as increase the Signal-to-Interference-plus-Noise Ratio (SINR). The main challenge in current femtocell deployment is how to increase the network capacity while keeping the inter-tier interference between macro users and femtocell users low [3]. Some works have been done to consider this kind of interference in femtocell networks, which can be mainly classified into: (i) *Fractional frequency reuse and resource partition*. The entire frequency spectrum is divided into several subbands, with each subband assigned to a macrocell or femtocell in a sub-area [4]; (ii) *Power control*. Femtocell users transmit using power within the allowance to suppress the inter-tier interference [5], [6]; (iii) *Collaborative frequency scheduling*. A Geo-location database obtains locally available spectrum information, and perform a new resource allocation scheme

to mitigate the inter-tier interference [7]; (iv) *Opportunistic access*. A femtocell based on cognitive radio architecture designed for interference management is investigated in [8].

The above approaches are mainly focused on cellular frequency band, which are mostly located at 2.5GHz and 5GHz. Particularly such high carrier frequencies do not easily pass through the obstacles, which will make high signal quality and hence high data rate very difficult to achieve in indoor scenario. To increase the connectivity and data rate, indoor devices are likely to need large transmission power. This is a good servant but a bad master. The indoor device is happy with the higher data rate and reliability but the line-of-sight connectivity may reach a long distance, causing unusual patterns of inter-tier interference to a node which is farther away [9]. This raises the obvious question: why do we not encourage the deployment of a femtocell network on TV white spaces in these locations? Resulting from the transition to digital TV, a substantial amount of TV spectrum that was previously used by analog transmission will become entirely vacant due to the higher spectrum efficiency of digital TV. These newly freed up spectra along with other unused spectrum located in the VHF and UHF bands (50-700MHz) are called “TV white spaces”. In 2010, FCC passed a series of rules that allow cognitive equipment opportunistic to use TV white spaces [10]. In 2012, FCC took the unprecedented step of allocating significant portions of TV white spaces for unlicensed use [11]. Due to the perfect low frequency, the radio signals in TV bands have the ability to penetrate obstacles such as walls, floors and doors well. This excellent penetration property facilitates the deployment of femtocell networks in home or businesses. Thus, it is very important to investigate the networking issues for femtocell over TV white spaces.

So far, research on TV white spaces in femtocell networks are limited to [7], [12]–[14], which are mainly focused on interference mitigation and spectrum allocation using geo-location database. However, according to a recent report, the Small Forum, the power consumption of all Femto Base Stations (FBSs) will reach 2.2×10^{11} KWH by 2016 [15], which will produce millions of tonnes of carbon dioxide very year. Driven by the need to save energy and reduce carbon dioxide emission, it will be extremely important to characterize the network capacity and energy efficiency for TV white spaces networks. Therefore, to fill in this gap, we develop a TV white space reuse scheme and power allocation scheme to study the capacity and energy efficiency issues for femtocell network. Although some works have been done to investigate the energy efficiency with femtocell [16]–[19], most of them are done in WiFi environment. In TV white spaces, the capacity and energy efficiency characterization is much more challenging than that in WiFi scenario due to the coexistence of primary network, macrocell network and femtocell network. In this case, the interference among these three heterogeneous networks should be taken into consideration. In this paper, we explore a fundamental issue pertaining to TV white spaces usage by femtocell and macrocell networks,

that may be succinctly captured by the two questions: 1) *How much capacity can be achieved for indoor femtocell network?* 2) *and how to achieve the maximum energy efficiency subject to the interference constraints for the macro users as well as the primary users.* In summary, this paper’s contributions are as follows:

1) To the best of our knowledge, this paper is the first to study the problem of energy efficiency for femtocell network in TV white spaces, while the interference among the femtocell, macrocell and primary network is taken into consideration. This paper completes the analysis of the capacity maximization problem where the initial part of this work has been done in [20].

2) With the objective to maximize the capacity and energy efficiency for femtocell in TV white spaces, we formulate the problem into an optimization problem subject to a peak power limit. We demonstrate the existence of a unique globally optimal power allocation solution and propose a gradient absent algorithm with fast convergence to obtain this optimum.

3) We evaluate our methods via extensive simulation experiments to demonstrate that our algorithms can achieve considerable capacity and energy efficiency. This indicates that we can improve the capacity as well as the energy efficiency by deploying the femtocell network over TV white spaces.

The rest of this paper is organized as follows. In Section II, the system model is given. In Section III, the interference is analyzed, the capacity and energy efficiency model is characterized. We also formulate the energy efficiency maximization problem in Section III. In Section IV, the optimality condition is given and a gradient absent algorithm is developed for the optimization problem. Simulation results are presented and discussed in Section V. Finally, we conclude this study in Section VI.

II. SYSTEM MODEL

We consider a heterogeneous communication system model that consists of primary network, macrocell network and femtocell network, as shown in Fig. 1. There are six types of network entries in this scenario, namely TV tower, TV antenna receiver, Macro Base Station (MBS), Macro Secondary Users (MSUs), Femto Base Station (FBS) and Femto Secondary Users (FSUs). The TV tower and TV receivers form the primary network, they are the license holders of TV white spaces and have the absolute priority to use it. In each macrocell, the MBS is required to serve each MSU. For each femtocell, there is a FBS to provide service for FSUs. The femtocells and macrocells form the secondary network, which can opportunistically utilize the TV white spaces under the condition of an acceptable interference to the primary users. For simplicity, we assume that only one FSU can be served by the FBS each time, which is the common assumption used by many research work due to the opportunistic scheduling operation [7], [8].

Experimental results in [21] have shown that the number of TV channels is insufficient seriously. Therefore, it is likely that multiple closely located, heterogeneous femtocells

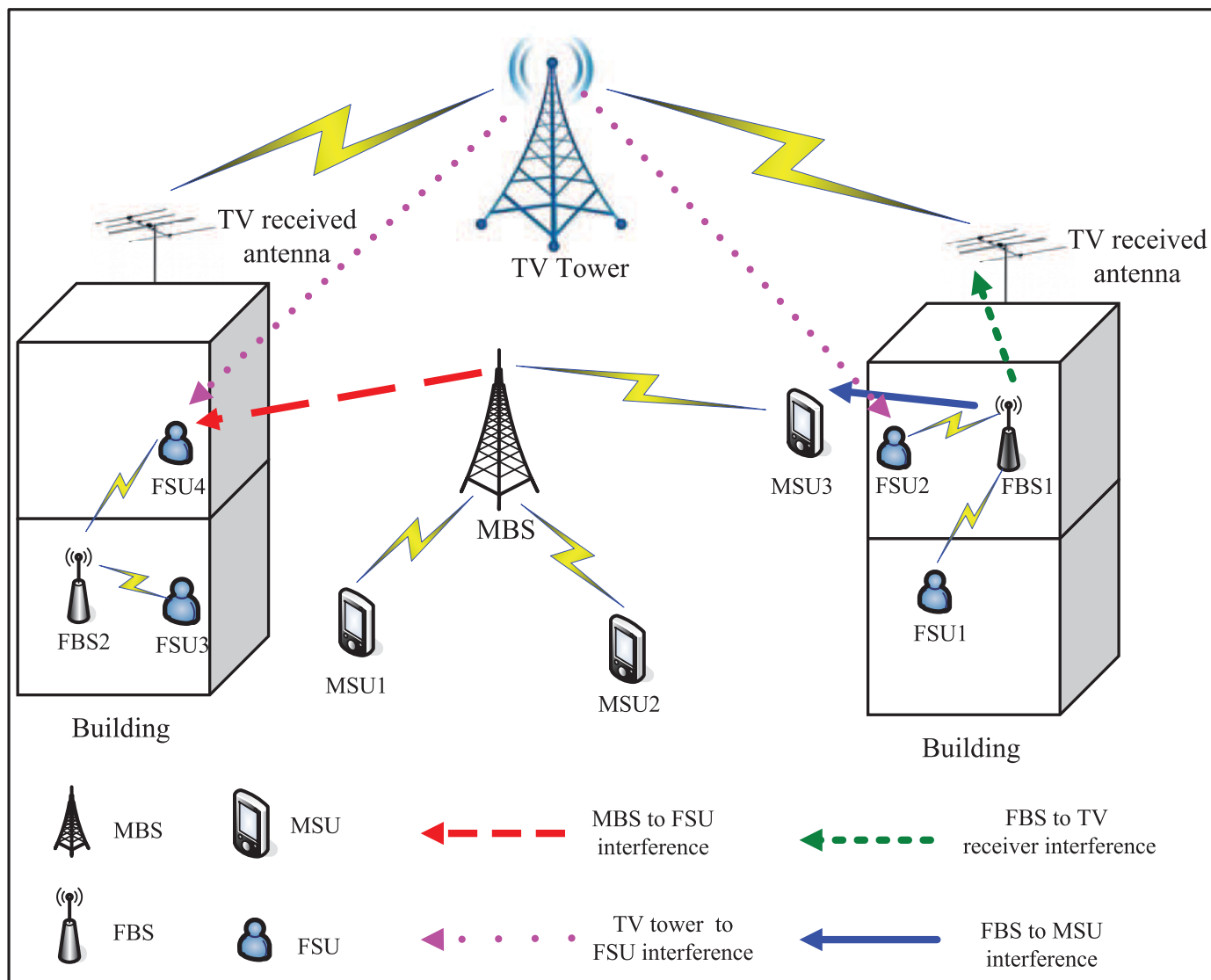


FIGURE 1. Coexistence of femtocell, macrocell and primary networks.

and macrocells are authorized to use the same TV channel. Since so far there has been no regulatory requirement for the coexistence among heterogeneous networks over TV channels [22], [23], if no scheduling carefully, their transmissions may collide, resulting in a serious interference to the primary user and an inefficient use of the TV white spaces. Therefore, from the primary user’s perspective, secondary user is allowed to utilize the TV channel as long as the interference to the primary user is properly regulated. From the secondary user’s perspective, the secondary user should adapt its transmit power in order to achieve a reasonably high capacity without degrading the quality of service (QoS) of the primary user to an unacceptable level. In this paper, we develop a TV white space reuse scheme and power allocation scheme for a coexisting heterogeneous system comprising primary, macrocell and femtocell users. The overall objective is to maximize the capacity as well as the energy efficiency

achieved by femtocell network while keeping the interference to the primary receiver and macro receiver at an acceptable level.

III. PROBLEM FORMULATION

In this section, we will first characterize the capacity and energy efficiency achieved by femtocell network, then analyze the interference for primary receiver and macro receiver, and discuss the conditions of TV white spaces reuse. Thereafter that an optimization problem to maximize the energy efficiency under some interference constraints will be formulated.

A. CAPACITY CHARACTERIZATION

In this paper, we are interested in how much capacity can be achieved by femtocell network using TV white spaces. Assume that there are totally P_{tol} TV channels,

N_{tol} femtocells and M_{tol} macrocells in the heterogeneous network. Due to the limited TV resource, it is likely that $N_{tol} + M_{tol} > P_{tol}$, thus the femtocell and macrocell may contend with each other for the usage of TV channel, leading to a heavy interference. With the consideration of the interference from the MBS and TV tower, the capacity achieved by the femtocell can be calculated using Shannon capacity function, that is

$$R_i = W_0 \log_2(1 + SINR_i). \quad (1)$$

where W_0 denotes the bandwidth of a TV channel, which is specified by each country. For example, each channel has 6MHz in US, 8MHz in Europe and 7MHz at some places. $SINR_i$ represents the received Signal-to-Noise-plus-Interference Ratio (SINR) at FSU in femtocell i , which can be determined by

$$SINR_i = \frac{P_{s,i}}{PL_{indoor}^i (\sigma_1^2 + I_{P2S}^i + I_{M2S}^i)}. \quad (2)$$

where $P_{s,i}$ denotes the transmit power of FBS in femtocell i , and PL_{indoor}^i captures the indoor path loss in the link between the FBS and FSU in femtocell i . σ_1 is the noise power at the receiver front end. Here I_{P2S}^i and I_{M2S}^i represent the interference from the primary TV tower and macro MBS respectively, which will be further analyzed later.

PL_{indoor}^i will be calculated based on the equation in [24] and [25], where it is proposed as an extension of the Keenan Motley (KM) model:

$$PL_{indoor}^i = L_f + L_i + L_g + k_i F(a) + p_i W(a) + L_s. \quad (3)$$

where L_f is the free space path loss, L_i is a linear attenuation factor dependent on the separation distance between the secondary receiver FSU and the secondary transmitter FBS in femtocell i , L_g is the difference between the theoretical and effective gain of the two antennas, 3dB in this case. $F(a)$ is a floor attenuation factor, and k_i is the number of floors to traverse. $W(a)$ is a wall attenuation factor, and p_i is the number of walls crossed by the direct path between the secondary transmitter FBS and the secondary receiver FSU in femtocell i . Shadowing effect from furniture, people, etc. is modeled by a lognormal shadow fading process (L_s) with zero mean, standard deviation σ_2 and correlation distance of 5 meters.

Let \mathbf{R} denote capacity vector for all femtocells, which can be represented as

$$\mathbf{R} = [R_1, R_2, \dots, R_{N_{tol}}]^T. \quad (4)$$

where $[\]^T$ denotes the transpose of a vector. Then the overall capacity achieved by the femtocell network that is exploiting TV channels can be obtained by summing over all femtocells, that is

$$R = \sum_{i=1}^{N_{tol}} R_i = \sum_{i=1}^{N_{tol}} W_0 \log_2(1 + SINR_i). \quad (5)$$

It can be noted that if we increase the transmit power, the $SINR_i$ will increase as well which in turns results in a larger

capacity. Thus, $R_i(P_{s,i})$ is strictly concave and monotonically increasing in $P_{s,i}$. However, the interference caused by the femtocell to the primary receiver and macro receiver will also increase as the transmit power increases. Furthermore, from (1) and (2), we can see that the capacity achieved by the femtocell depends on the path loss as well as the interference from TV tower and MBS. Due to the spatial variation of TV white spaces, it is possible that no TV channel is available for one femtocell, in this case the capacity achieved by this femtocell is zero, we can just exclude this femtocell from being considered.

B. ENERGY EFFICIENCY CHARACTERIZATION

For energy-efficient communications, it is desirable to maximize the amount of data sent with a given amount of energy. Let P_c denote the additional circuit power consumed by the devices during transmissions (e.g., mixers, filters, and digital-to-analog converters, etc), which is assumed to be the same for all femtocells and is independent to the transmit power [26], [27]. Then, the energy efficiency for femtocell i can be expressed as [28]

$$U_i = \frac{R_i}{P_{s,i} + P_c}. \quad (6)$$

The unit of the energy efficiency is bits per Joule, which has been widely used by many researchers for energy-efficient communications [29], [30]. Let $\mathbf{U} = [U_1, U_2, \dots, U_{N_{tol}}]$ denote the energy efficiency vector for all femtocells, the aim is to maximize the energy efficiency by allocating the transmit power for all femtocells, that is

$$\mathbf{P}_s^* = \arg \max_{\mathbf{P}_s} U(\mathbf{P}_s) = \arg \max_{\mathbf{P}_s} \frac{R(\mathbf{P}_s)}{\mathbf{P}_s + P_c}. \quad (7)$$

where $\mathbf{P}_s = [P_{s,1}, P_{s,2}, \dots, P_{s,N_{tol}}]$ is the transmit power vector for all femtocells. The problem can be viewed as deciding the transmit power vector to maximize the energy efficiency.

C. INTERFERENCE ANALYSIS

Since the macrocell and femtocell share the same TV spectrum resources in both time and frequency domain with the primary network, thus to allow the three heterogeneous networks to coexist, interference mitigation has to be taken into consideration. When a MSU is very close to a FBS or even within the coverage of femtocell, it will experience severe interference from nearby FBS operating in the co-channel. As shown in Fig. 1, MSU_3 is located far away from its MBS and is close to FBS_1 . If FBS_1 transmits using the same frequency as MSU_3 , then heavy interference will be experienced by MSU_3 . Similarly, the FSU will also suffer severe interference from the macrocell network. Although the primary users are protected from the undesired interference, they also introduce a significant interference to secondary users working in the same or adjacent bands due to its high transmit power. The interference will arise from:

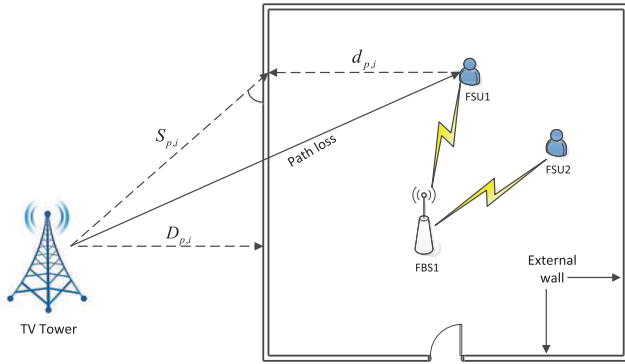


FIGURE 2. COST-231 building penetration model.

- a. Primary-to-Femtocell interference, denoted by I_{P2S}
- b. Macrocell-to-Femtocell interference, denoted by I_{M2S}
- c. Femtocell-to-Primary interference, denoted by I_{S2P}
- d. Femtocell-to-Macrocell interference, denoted by I_{S2M}
- e. Femtocell-to-Femtocell interference, denoted by I_{S2S}

Compared with I_{P2S} , I_{M2S} , I_{S2P} and I_{S2M} , Femtocell-to-Femtocell interference I_{S2S} is relatively smaller and hence it can be ignored in our analysis. Note that our design can easily incorporate the case when femtocell-to-femtocell interference is taken into consideration by adding I_{S2S} in $SINR$ calculation.

1) INTERFERENCE FROM THE PRIMARY TV TOWER I_{P2S}

The level of interference I_{P2S} depends on the distance from the FSU to the nearby TV tower, as well as some other parameters, such as external wall loss and number of penetrated internal walls. The TV transmitter will introduce two kinds of interference to the FSU: co-channel interference and adj-channel interference, due to signal leakage from the TV channel to the lower/upper bands [31]. The aggregate interference for the secondary receiver FSU in femtocell i is:

$$I_{P2S}^i = \sum_{k=1}^{N_p} (1-\eta) \frac{P_{p,t}^k}{PL_{O-I}(d_{p,i}, \Gamma_{p,i})} + \sum_{j=1}^{M_p} \eta \frac{P_{p,t}^j}{PL_{O-I}(d_{p,i}, \Gamma_{p,i})}. \quad (8)$$

where $P_{p,t}^k$ is the transmit power of TV tower on channel k , $PL_{O-I}(d_{p,i}, \Gamma_{p,i})$ is the path loss function between the TV transmitter located in the external part of a building to the secondary receiver FSU in femtocell i inside the building with parameter set $\Gamma_{p,i}$, N_p/M_p is the number of co-channels/adj-channels surrounding the TV tower, and η is the leakage factor for TV transmitter. Note that I_{P2S}^i is hidden inside distance factor $d_{p,i}$ and parameter set $\Gamma_{p,i}$, where $d_{p,i}$ represents the perpendicular distance from the building wall to the indoor receiver FSU in femtocell i , and $\Gamma_{p,i} = \{D_{p,i}, S_{p,i}, K_{p,i}\}$ is a parameter set, and is further defined in the following.

Here we choose the COST-231 building penetration model for initial analysis of path loss from the outdoor environment to indoor environment, as shown in Fig.2. Let $S_{p,i}$ denote the physical distance from the outdoor TV transmitter to

the externally illuminated wall and $D_{p,i}$ be the perpendicular distance from outdoor TV transmitter to the building wall. All the distance parameters are given in meter. The path loss term $PL_{O-I}(d_{p,i}, \Gamma_{p,i})$ can be computed using the following equation [32]:

$$PL_{O-I}(d_{p,i}, \Gamma_{p,i}) = 32.4 + 20 \log(f) + 20 \log(S_{p,i} + d_{p,i}) + W_e + W_{G_e} \left(1 - \frac{D_{p,i}}{S_{p,i}}\right)^2 + \max(\gamma_{p1}, \gamma_{p2}). \quad (9)$$

where

$$\gamma_{p1} = W_{GI} \times K_{p,i}$$

and

$$\gamma_{p2} = \alpha(d_{p,i} - 2) \left(1 - \frac{D_{p,i}}{S_{p,i}}\right)^2$$

where f is the frequency in GHz. W_e is the external wall loss (in dB) when the perpendicular penetration angle equals 90° . W_{G_e} (in dB) is the additional loss in the external wall when the perpendicular penetration angle is 0° . W_{GI} is the loss in the internal walls in dB and $K_{p,i}$ is the number of penetrated internal walls. An additional indoor loss γ_{p2} is determined by α in dB/m.

2) INTERFERENCE FROM THE MBS I_{M2S}

The interference experienced by a indoor receiver FSU in femtocell i from MBS has severe impact on its performance. The total interference suffered by the FSU from the coexist macro transmitters is given by

$$I_{M2S}^i = \sum_{g=1}^G \frac{P_{m,t}^g}{PL_{O-I}(d_{m,i}, \Gamma_{m,i})}. \quad (10)$$

where G is the number of MBSs near the femtocell, and $P_{m,t}^g$ is the transmit power of MBS_g . The outdoor to indoor path loss $PL_{O-I}(d_{m,i}, \Gamma_{m,i})$ can be modeled based on (9) using $(d_{m,i}, \Gamma_{m,i})$ as input. Here $d_{m,i}$ is the perpendicular distance from the building wall to the indoor receiver FSU in femtocell i , thus we have $d_{m,i} = d_{p,i}$. The parameter set $\Gamma_{m,i} = \{S_{m,i}, D_{m,i}, K_{p,i}\}$ is defined similarly as that in (9).

3) INTERFERENCE FROM THE FBS TO THE TV ANTENNA ON ITS OWN BUILDING I_{S2P}

In the following, we will evaluate the interference that the indoor FBS causes to the primary TV received antenna. There are two kinds of interference: 1) Interference from the indoor FBS to the primary TV antenna located on its own building; 2) Interference from the indoor FBS to the primary TV antenna on the neighboring building. This behavior is depicted in Fig.3. We mainly focus on the interference caused by the indoor FBS to the TV receiver located on the top of its own building, which can be computed using the following general equation, that is

$$I_{S2P}^i = \frac{P_{s,i}}{(PL_{I-T}[d^I] + (n_f + 1)\xi)}. \quad (11)$$

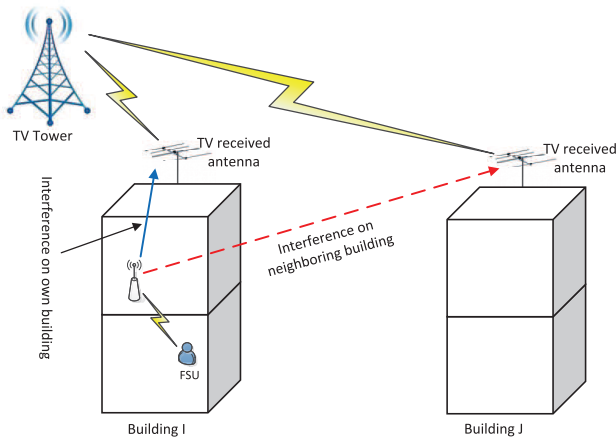


FIGURE 3. Interference from the FBS to the primary TV antenna.

where $P_{s,i}$ is the transmit power of indoor FBS in femtocell i , $PL_{I-T}[d^I]$ is the path loss from indoor FBS to the antenna located on the top of building I , n_f is the number of floors to traverse and ξ denotes the power loss due to shadowing for each floor.

The path loss term $PL_{I-T}[d^I]$ can be computed using the following equation [33]:

$$PL_{I-T}[d^I] = 10\beta \log_{10}(d^I) + 10\beta \log_{10}(f) + X_g. \quad (12)$$

where d^I is the distance from the FBS to the TV antenna in meters, and X_g is a zero-mean random gaussian variable with standard deviation ρ . The terms β and ρ have been studied for a plethora of different frequencies and scenario.

Note that since the FBS transmits with a finite power, we assume that the interference caused by the FBS to the TV received antenna located in the neighboring building is insignificant as compared to I_{S2P}^i in the own building, hence is ignored here.

4) INTERFERENCE FROM THE FBS TO THE MSU I_{S2M}

In the following, we evaluate the interference involved in the MSUs by indoor FBS. Basically, the interference generated on the MSU located in the external part of a building I by a FBS inside building I can be computed as follows:

$$I_{S2M}^i = \frac{P_{s,i}}{PL_{I-O}(d_m, \Gamma_m)}. \quad (13)$$

where $PL_{I-O}(d_m, \Gamma_m)$ is path loss function from indoor transmitter FBS to the outdoor macro receiver MSU using $\{\Gamma_m, d_m\}$ as input, which can be calculated using (9) as well.

D. CONDITIONS OF TV WHITE SPACES REUSE

Since the priority of a primary-macrocell-femtocell coexist heterogeneous network is to protect the QoS of the primary receiver, thus an interference constraint should be imposed for protection. Therefore, the condition to determine TV white spaces reusability is formulated in terms of the interference level allowed by the primary receivers. In order to

provide sufficient protection to the primary receiver, the interference should not exceed a given threshold λ_p . Thus the condition that enables the usage of TV white spaces without disturbing the primary receiver is given by

$$I_{S2P}^i \leq \lambda_p, \quad \forall 1 \leq i \leq N_{tol}. \quad (14)$$

Similarly, the interference to the macro receivers must be considered as well. The interference caused by the FBS to the MSU will be bounded by a threshold λ_M , that is

$$I_{S2M}^i \leq \lambda_M, \quad \forall 1 \leq i \leq N_{tol}. \quad (15)$$

E. POWER CONSTRAINT ENERGY EFFICIENCY OPTIMIZATION

The main objective of this paper is to develop a TV white spaces reuse scheme and power allocation scheme to maximize the energy efficiency of femtocell network while maintaining the constraints on the interference to the primary receiver and macro receiver. The Power Constraint Energy Efficiency Optimization problem can be formulated as

Problem P1:

$$\begin{aligned} \max U &= \sum_{i=1}^{N_{tol}} \frac{W_0 \log_2(1 + \frac{P_{s,i}}{PL_{indoor}^i(\sigma_1^2 + I_{P2S}^i + I_{M2S}^i)})}{P_{s,i} + P_c} \\ \text{s.t. } I_{S2P}^i &\leq \lambda_p, \quad 1 \leq i \leq N_{tol} \\ I_{S2M}^i &\leq \lambda_M, \quad 1 \leq i \leq N_{tol} \end{aligned} \quad (16)$$

In order to provide sufficient protection to the primary receiver as well as the macro receiver, the transmit power of the FBS should be controlled at a suitable level. Thus this is a energy efficiency optimization problem with a peak power limit. Note that if we ignore the portion of denominator $P_{s,i} + P_c$, this problem is equivalent to maximize the overall capacity by performing a power allocation, which can be solved by existing well known water-filling approach. However, the solution is in general different if the objective is to maximize the energy efficiency, the optimality conditions will be further discussed in next section.

IV. OPTIMALITY ANALYSIS AND ALGORITHM DESIGN

In the following, we first demonstrate that a unique globally optimal transmit power vector always exists and give the necessary and sufficient conditions for the transmit power vector to be globally optimal. Then we propose a gradient absent algorithm to obtain this optimal transmit power vector for the energy efficiency maximization problem.

A. CONDITIONS OF OPTIMALITY

We start with the concept of quasiconcavity, which is defined as [28], [34].

Definition 1: A function $f: \Delta \rightarrow \mathfrak{R}$, is called strictly quasiconcave if for any $x_1, x_2 \in \Delta$, $x_1 \neq x_2$, and $0 < \lambda < 1$, we have

$$f(\lambda x_1 + (1 - \lambda)x_2) > \min\{f(x_1), f(x_2)\}. \quad (17)$$

where Δ is a convex set of real n-dimensional vectors.

Based on the above definition of quasiconcave, we will prove that $U_i(P_{s,i})$ is a strictly quasiconcave function in Lemma 1, and further show the conditions for the optimal transmit power to be existed in Theorem 1.

Lemma 1: If $R_i(P_{s,i})$ is strictly concave in $P_{s,i}$, $U_i(P_{s,i})$ is strictly quasiconcave. Furthermore, $U_i(P_{s,i})$ is either first strictly increasing and then strictly decreasing in any $P_{s,i}$ or strictly decreasing.

Proof: Similarly to [28], [34], we denote the α -sublevel sets of function $U_i(P_{s,i})$ as

$$S_\alpha = \{P_{s,i} > 0 | U_i(P_{s,i}) \geq \alpha\}. \quad (18)$$

According to Proposition C.9 in [34], $U_i(P_{s,i})$ is strictly quasiconcave if and only if S_α is strictly convex for any α .

For the case of $\alpha \leq 0$, there exists no point that satisfies $U_i(P_{s,i}) = \alpha$. And for the case of $\alpha = 0$, only $P_{s,i} = 0$ satisfies $U_i(P_{s,i}) = \alpha$. Therefore, S_α is strictly convex when $\alpha \leq 0$.

For the case of $\alpha \geq 0$, S_α can be rewritten as

$$S_\alpha = \{P_{s,i} > 0 | \alpha(P_c + P_{s,i}) - R_i(P_{s,i}) \leq 0\}. \quad (19)$$

Since $R_i(P_{s,i})$ is strictly concave in $P_{s,i}$, which means that $-R_i(P_{s,i})$ is strictly convex in $P_{s,i}$, therefore S_α is also strictly convex. Hence, $U_i(P_{s,i})$ is a strictly quasiconcave function.

Next, we take the first order derivative of $U_i(P_{s,i})$ with respect to $P_{s,i}$, and obtain

$$\begin{aligned} \frac{dU_i(P_{s,i})}{dP_{s,i}} &= \frac{R'_i(P_{s,i})(P_c + P_{s,i}) - R_i(P_{s,i})}{(P_c + P_{s,i})^2} \\ &= \frac{\kappa(P_{s,i})}{(P_c + P_{s,i})^2}. \end{aligned} \quad (20)$$

where $R'_i(P_{s,i})$ is the first order derivative of $R_i(P_{s,i})$ with respect to $P_{s,i}$. Since $U_i(P_{s,i})$ is strictly quasiconcave in $P_{s,i}$, if there exists $P_{s,i}^*$ that satisfies

$$\left. \frac{dU_i(P_{s,i})}{dP_{s,i}} \right|_{P_{s,i}=P_{s,i}^*} = 0. \quad (21)$$

then $P_{s,i}^*$ is the unique optimal transmit power for femtocell i that maximizes the energy efficiency $U_i(P_{s,i}^*)$. In the following, we will only discuss the conditions when $P_{s,i}^*$ exists.

We can obtain the first order derivative of $\kappa(P_{s,i})$ as

$$\frac{\kappa(P_{s,i})}{dP_{s,i}} = R''_i(P_{s,i})(P_c + P_{s,i}). \quad (22)$$

where $R''_i(P_{s,i})$ is the second order derivative of $R_i(P_{s,i})$ with respect to $P_{s,i}$. Since $R_i(P_{s,i})$ is strictly concave in $P_{s,i}$, we have

$$R''_i(P_{s,i}) < 0 \Rightarrow \kappa'(P_{s,i}) < 0. \quad (23)$$

Therefore, $\kappa(P_{s,i})$ is a strictly decreasing function in $P_{s,i}$. In addition, we can calculate the following limitations

for $\kappa(P_{s,i})$ according to the *L'Hopital's* rule [34]

$$\begin{aligned} \lim_{P_{s,i} \rightarrow +\infty} \kappa(P_{s,i}) &= \lim_{P_{s,i} \rightarrow +\infty} \frac{R'_i(P_{s,i})(P_c + P_{s,i}) - R_i(P_{s,i})}{P_{s,i}} \\ &= \lim_{P_{s,i} \rightarrow +\infty} \frac{R'_i(P_{s,i})(P_c + P_{s,i}) - R_i(P_{s,i})}{P_{s,i}} P_{s,i} \\ &= \lim_{P_{s,i} \rightarrow +\infty} \frac{R''_i(P_{s,i})(P_c + P_{s,i})}{1} P_{s,i} \leq 0. \end{aligned} \quad (24)$$

and

$$\begin{aligned} \lim_{P_{s,i} \rightarrow 0} \kappa(P_{s,i}) &= \lim_{P_{s,i} \rightarrow 0} \frac{R'_i(P_{s,i})(P_c + P_{s,i}) - R_i(P_{s,i})}{P_{s,i}} \\ &= \lim_{P_{s,i} \rightarrow 0} \frac{R'_i(P_{s,i}^{(0)})(P_c + P_{s,i}^{(0)}) - R_i(P_{s,i}^{(0)})}{P_{s,i}^{(0)}}. \end{aligned} \quad (25)$$

where $P_{s,i}^{(0)} = 0$.

Case I: When $R'_i(P_{s,i}^{(0)})(P_c + P_{s,i}^{(0)}) - R_i(P_{s,i}^{(0)}) \geq 0$, then we have

$$\lim_{P_{s,i} \rightarrow 0} \kappa(P_{s,i}) \geq 0$$

In this case, we know that $\kappa(P_{s,i})$ is first greater than 0, and then smaller than 0 when the transmit power becomes larger. Together with (20), we can conclude that $U_i(P_{s,i})$ is first strictly increasing and then strictly decreasing in $P_{s,i}$, and $P_{s,i}^*$ exists when $\kappa(P_{s,i}^*) = 0$.

Case II: When $R'_i(P_{s,i}^{(0)})(P_c + P_{s,i}^{(0)}) - R_i(P_{s,i}^{(0)}) < 0$, then we have

$$\lim_{P_{s,i} \rightarrow 0} \kappa(P_{s,i}) < 0$$

In this case, we observe that $\kappa(P_{s,i})$ is always smaller than 0, which indicates that $U_i(P_{s,i})$ always strictly decreases in $P_{s,i}$. Hence the maximum value $U_i(P_{s,i})$ could be obtained when $P_{s,i} = 0$.

According to the property of strictly quasiconcave function, if a solution is the local optimal solution for the quasiconcave function, it is also globally optimal. Therefore, we can give the conditions for the global solution to be existed in following Theorem 1 based on the proof of Lemma 1.

Theorem 1: If $R_i(P_{s,i})$ is strictly concave, there exists a unique globally optimal power allocation $P_{s,i}^*$ for femtocell i to maximize its energy efficiency $U_i(P_{s,i})$, where $P_{s,i}^*$ can be obtained as

Case I: When

$$\left. \frac{dR_i(P_{s,i})}{dP_{s,i}} \right|_{P_{s,i}=P_{s,i}^{(0)}} \geq \frac{R_i(P_{s,i}^{(0)})}{(P_c + P_{s,i}^{(0)})}$$

then we have

$$\left. \frac{dU_i(P_{s,i})}{dP_{s,i}} \right|_{P_{s,i}=P_{s,i}^*} = 0$$

Case II: When

$$\left. \frac{dR_i(P_{s,i})}{dP_{s,i}} \right|_{P_{s,i}=P_{s,i}^{(0)}} < \frac{R_i(P_{s,i}^{(0)})}{(P_c + P_{s,i}^{(0)})}$$

then we have

$$P_{s,i}^* = 0$$

Therefore, based on Theorem 1, we can solve the nonlinear optimization problem, and find the optimal transmit power for femtocell i . Let Γ_i denote the power limit associated with femtocell i , which is given by

$$\Gamma_i = \sup\{P_{s,i} > 0 | I_{S2P}^i \leq \lambda_p \text{ and } I_{S2M}^i \leq \lambda_M\}$$

If the optimal transmit power obtained in Theorem 1 satisfies $P_{s,i}^* \leq \Gamma_i$, it is also the solution to the optimization problem. Otherwise, the one femtocell energy efficiency optimization problem is equivalent to

Problem P2:

$$\max U_i = \frac{R_i(P_{s,i})}{\Gamma_i + P_c} \quad (26)$$

subject to

$$P_{s,i} = \Gamma_i. \quad (27)$$

It should be noted that the objective function in Problem P2 is concave and it takes the form of maximizing subject to a convex domain, we can conclude that Problem P2 is a convex optimization problem [35]. This problem can be easily solved by Lagrangian technique. We define the Lagrangian L associated with problem (26) as

$$L(P_{s,i}, v_i) = f(P_{s,i}) + v_i(\Gamma_i - P_{s,i}). \quad (28)$$

where $f(P_{s,i}) = \frac{R_i(P_{s,i})}{\Gamma_i + P_c}$, and v_i is the Lagrange multiplier associated with the equality constraint. Then the Lagrange dual function is defined as the maximum value of the Lagrangian over $P_{s,i}$; for v_i , that is

$$g(v_i) = \sup_{P_{s,i}} L(P_{s,i}, v_i) = \sup_{P_{s,i}} \{f(P_{s,i}) + v_i(\Gamma_i - P_{s,i})\}. \quad (29)$$

Since $L(P_{s,i}, v_i)$ is a concave function of $P_{s,i}$, we can find the maximizing $P_{s,i}$ from the optimality condition

$$\frac{dL(P_{s,i}, v_i)}{dP_{s,i}} = \frac{df(P_{s,i})}{dP_{s,i}} - v_i = \frac{dR_i(P_{s,i})}{dP_{s,i}} - v_i = 0. \quad (30)$$

Thus the globally optimal $P_{s,i}^*$ is obtained as

$$P_{s,i}^* = \max\{h_i^{-1}(v_i), 0\}. \quad (31)$$

where $h_i(P_{s,i})$ represent the first derivative of $R_i(P_{s,i})$, and its inverse function is denoted as $h_i^{-1}()$. Hence the optimal objective value of the Lagrange dual function (29) is found by substituting $P_{s,i}^*$ into (29). Due to the strong LP duality, the objective value of (26) is found as well. Similarly, we can obtain the optimal transmit power for other femtocells, and get the optimal transmit power vector $\mathbf{P}_s^* = [P_{s,1}^*, P_{s,2}^*, \dots, P_{s,N_{tot}}^*]$.

B. ALGORITHM DESIGN

In Theorem 1, we give the necessary and sufficient conditions for the transmit power vector to be the unique globally optimal. However, due to the nonlinear property of objective function $U(\mathbf{P}_s)$, it is still difficult to directly solve this problem according to Theorem 1. In the following, we develop a low-complexity gradient ascent algorithm to find the optimal transmit power vector \mathbf{P}_s^* .

In order to find the optimal transmit power vector for all femtocells, we design a gradient ascent method to produce a maximizing sequence $\mathbf{P}_s^{[k]}$, that is

$$\mathbf{P}_s^{[k+1]} = [\mathbf{P}_s^{[k]} + \mu \nabla U(\mathbf{P}_s^{[k]})]^+. \quad (32)$$

where $[\mathbf{P}_s]^+$ is a set in which the negative part of the vector \mathbf{P}_s is set to be zero, and $\mu > 0$ is called the step size, $k = 0, 1, 2, \dots$ denotes the iteration number. $\nabla U(\mathbf{P}_s^{[k]})$ is the gradient at iteration k , which represents the iteration direction.

For the step size μ small enough, $U(\mathbf{P}_s^{[k+1]})$ will be always bigger than $U(\mathbf{P}_s^{[k]})$. In other words, in order to move as the gradient, namely up toward the maximum, the term $\mu \nabla U(\mathbf{P}_s^{[k]})$ plus \mathbf{P}_s . Thus, we can start with a guess $\mathbf{P}_s^{[0]}$ for a local maximum, and consider the sequence obtained from (32), such that

$$U(\mathbf{P}_s^{[0]}) < U(\mathbf{P}_s^{[1]}) < U(\mathbf{P}_s^{[2]}) < \dots \quad (33)$$

when $\nabla U(\mathbf{P}_s^{[k]}) = 0$, the sequence $\mathbf{P}_s^{[k]}$ converges to the desired local maximum. Since the function $U(\mathbf{P}_s)$ is strict quasiconcavity in \mathbf{P}_s , the local maximum is also global maximum, so in this case the gradient ascent algorithm can converge to the global optimality of $\mathbf{P}_s^{[k]}$ [35].

However, a sufficiently small step size will lead to slow convergence. Hence, at each $\mathbf{P}_s^{[k]}$, we need an efficient algorithm to find the optimal step size. Denote

$$\varphi_k(\mu) = U([\mathbf{P}_s^{[k]} + \mu \nabla U(\mathbf{P}_s^{[k]})]^+). \quad (34)$$

$\varphi_k(\mu)$ is one variable function with μ , using the proof of Theorem 1, we can shown that $\varphi_k(\mu)$ is also strictly quasiconcave in μ , and has a unique globally maximum μ^* , that is

$$\begin{aligned} \mu^* &= \arg \max_{\mu} \varphi_k(\mu). \\ &= \arg \max_{\mu} U([\mathbf{P}_s^{[k]} + \mu \nabla U(\mathbf{P}_s^{[k]})]^+) \end{aligned} \quad (35)$$

Thus, μ^* can be obtained by solving

$$\frac{\varphi_k(\mu)}{d\mu} = [\nabla U(\mathbf{P}_s^{[k+1]})]^T \frac{d[\mathbf{P}_s^{[k]} + \mu \nabla U(\mathbf{P}_s^{[k]})]^+}{d\mu}. \quad (36)$$

Note that the value of the step size μ^* is allowed to change at every iteration. The gradient ascent algorithm is described in detail in Algorithm 1. Combining with Lemma 1, we can note that each femtocell is able to compute the gradient with respect to its local variable using its own transmit power and proceed to a new variable exchange to repeat the process. Therefore, Algorithm 1 can be implemented in a distributed manner.

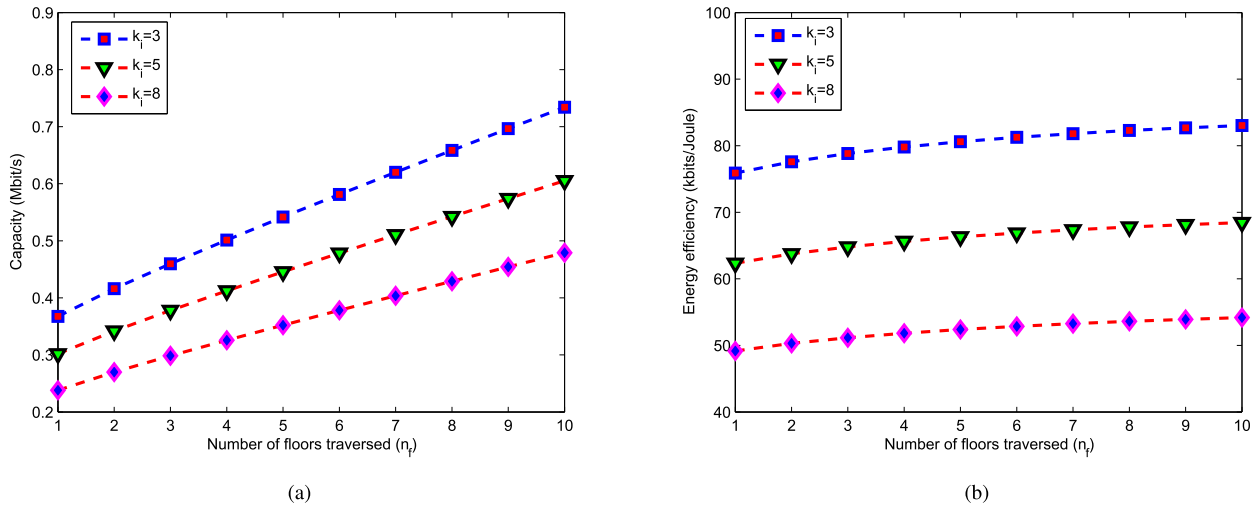


FIGURE 4. Capacity and energy efficiency evaluation for different values of $k_i = \{3, 5, 8\}$. (a) Capacity vs. the number of floors n_f traversed by FBS. (b) Energy efficiency vs. the number of floors n_f traversed by FBS.

Algorithm 1 Gradient Ascent Algorithm

- 1: **Input:** the initial transmit power P_s
- 2: terminate error $\varepsilon, k = 0$;
- 3: $P_s^{[0]} = P_s$;
- 4: **While** $\|\nabla U(P_s^{[k]})\|_2 > \varepsilon$
- 5: **do** find the optimal step size μ^* by solving (36)
- 6: $P_s^{[k+1]} = [P_s^{[k]} + \mu \nabla U(P_s^{[k]})]^+$;
- 7: $k = k + 1$;
- 8: **Return** $P_s^* = P_s^{[k]}, U^* = U^{[k]}$

TABLE 1. Parameter setting.

Parameters	Assumption
Bandwidth of TV channel W_0	6MHz
Floor attenuation factor $F(k)$	18.3dB
Wall attenuation factor $W(k)$	6.9dB
Number of walls crossed by FBS p_i	$\{1, 4, 7\}$
Number of floors traversed by FBS k_i	$\{3, 5, 8\}$
Carrier frequency f	1.5GHz
The external wall loss W_e	7dB
Additional loss in the external wall W_{Ge}	20dB
The loss in the internal walls W_{GI}	10dB
Number of penetrated internal walls $K_{p,i}$	2
Power loss due to shadowing for each floor ξ	20dB
The perpendicular distance $d_{p,i}$	6m
The leakage factor η	1.75×10^{-5}
Distance from the FBS to the TV antenna d^I	$3 * n_f$
Circuit power P_c	1W
Standard deviation ρ	7
Circuit power P_c	1

V. SIMULATION RESULTS

In this section, we will present the simulation results. As it is not yet possible to transmit opportunistically in China on TV white spaces, we calculate the capacity, energy efficiency and interference based on the analytical models as discussed in Section III. A $30m \times 30m$ idealized building is assumed for simulation. The building has 10 floors, each floor is 3 meters high, so for instance at 6 meters the indoor secondary receiver

FSU and the secondary transmitter FBS have 2 floors in between. Unless otherwise stated, the values of some important parameters used are listed in Table I. Note that most of the parameters assumed in the simulation are taken from [36] and [31], which have been proven to be quite conservative regarding the pathloss experienced by experimental studies in [37].

A. TV WHITE SPACES REUSABLE VALIDATION

Fig. 4(a) and Fig.4(b) display the femtocell capacity and energy efficiency as a function of the number of floors n_f traversed by FBS for different values of $k_i = \{3, 5, 8\}$. As can be seen from Fig.4(a), the larger the value of n_f , the higher the achieved capacity which is reasonable because building floors attenuate signals propagating through them. Thus, if the FBS is far away (e.g., with larger n_f) from the TV receiver located in the top of building, it can transmit with a larger power P_s without degrading the QoS of primary users, which results in a higher capacity. Moreover, it is easy to note that the capacity increases as k_i decreases. This is reasonable due to the fact that a lower value of k_i indicates that the FSU is close to FBS, thus the power will not be attenuated before it reaches FSU leading to a higher capacity. From Fig.4 (b), it can be noticed that the energy efficiency also increases as k_i decreases. As been stated above, smaller k_i will results in a larger capacity with the same power leading to a higher energy efficiency achieved. However, compared with capacity, energy efficiency tends to have relatively smaller improvement rate. This is because that energy efficiency is a ratio that takes into account capacity and power consumption. Thus as the transmit power increases, the capacity also increases, which results in a lower growth rate.

B. OPTIMALITY ANALYSIS

The performance of femtocell network in terms of its energy efficiency over the transmit power of FBS is evaluated in

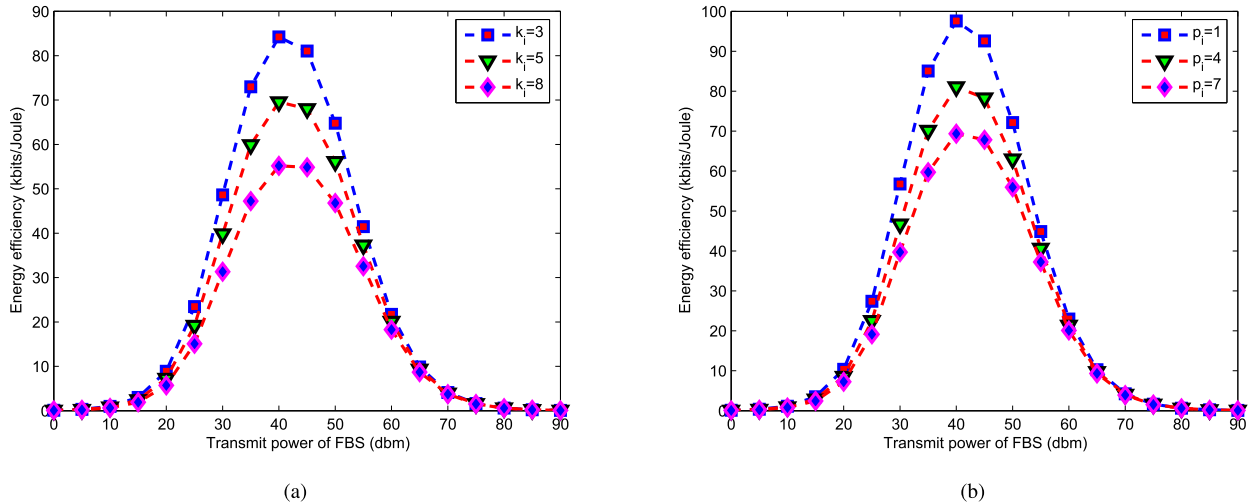


FIGURE 5. Relationship between energy efficiency and transmit power. (a) Energy efficiency achieved for different values of k_i . (b) Energy efficiency achieved for different values of ρ_i .

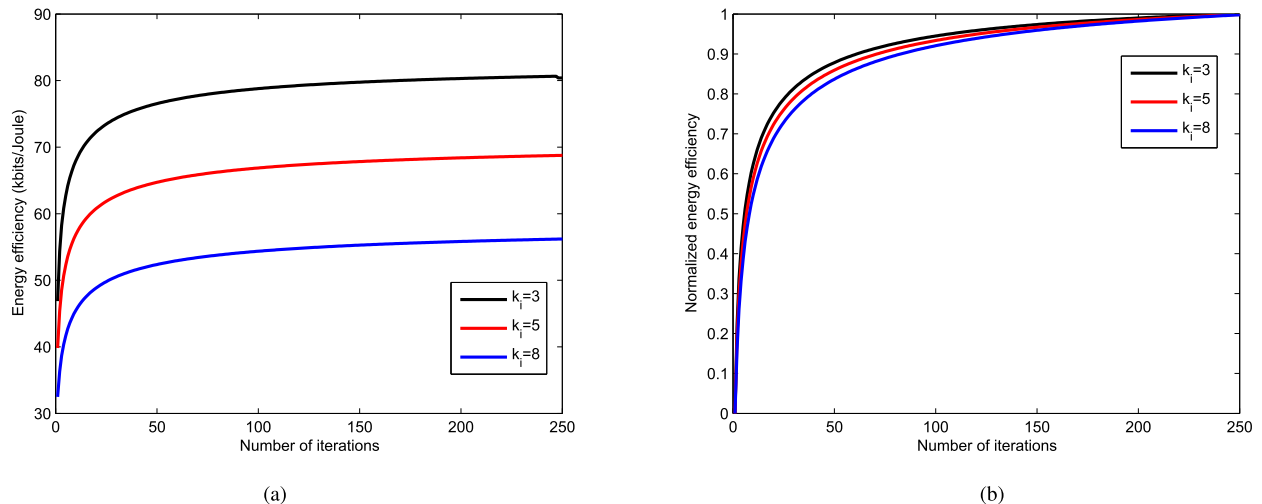


FIGURE 6. Convergence rate evaluation. (a) Relationship between energy efficiency and iterations. (b) Relationship between normalized energy efficiency and iterations.

Fig. 6. From Fig.6(a) and Fig.6(b), we can see that the energy efficiency first increases as transmit power increasing. Then when the transmit power reaches a certain value, the energy efficiency begins to decrease, which is in accordance with Lemma 1. Hence, we observe the tradeoff phenomenon. Therefore, the optimal transmit power balances the conflict between improving the capacity and reducing power consumption. Usually, we are more interested in the operating point where the optimal transmit power achieves the maximum energy efficiency for femtocell network. From Fig.6(a), it can be observed that the simulation curve has an optimal value of transmit power around $P_{s,i}^* = 40\text{dbm}$; while the mathematical calculation result from solving (21) gives $P_{s,i}^* = 39.18\text{dbm}$. It can be seen that the computed optimal transmit power is consistent with the simulated one. Hence, there exists an optimal value of transmit power, such that the energy efficiency of the femtocell network can be maximized,

which illustrates the validity of the gradient ascent algorithm. Also, we can see from the figures that less power is needed for the FBS with smaller value of k_i to obtain the same energy efficiency.

C. THE RATE OF CONVERGENCE

Due to the nonconcavity of $U(P_s)$, it seems very difficult to theoretically analyze the global convergence rate of the proposed algorithm. We instead resort to numerical simulations and obtain the convergence rate. Fig.7(a) depicts the energy efficiency as a function of iterations for different values of $k_i \in \{3, 5, 8\}$. It is easy to observe that the energy efficiency increases with the iterations, which means that $U(P_s^{[k+1]})$ will be always larger than $U(P_s^{[k]})$ until it converges to the desired global maximum. This can be achieved within 250 iterations. Furthermore, Fig.7(b) illustrates the improvement energy efficiency with iterations. Here the energy

efficiency is normalized by the maximum value. We can observe that given the initial transmit power, the algorithm can get the optimal value after several iterations. From these two figures, we can verify that the algorithm converges very fast to the global optimum.

VI. CONCLUSION

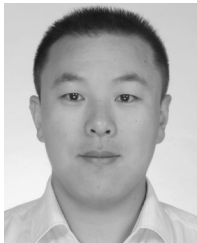
In this paper, we focus on the fundamental problem in TV white spaces used by femtocell network, i.e. How much capacity and energy efficiency can be achieved? We analyze the interference among the femtocell users, macrocell users as well as the primary TV users by considering the effect of building structure. We formulate the problem into an optimization problem, which maximizes the capacity and energy efficiency achieved by a femtocell network while providing sufficient protection to the primary receiver and macro receiver from unacceptable interference. We demonstrate the existence of a unique globally optimal transmit power vector for all the femtocells, and propose a gradient descent algorithm to obtain it. For indoor femtocell network, the building structure provides a sufficient level of signal attenuation. The TV white spaces can be reused by the FSUs without interfering with the primary TV receiver and macro receivers, which indicates that we can improve the capacity and energy efficiency by deploying the femtocell network over TV white spaces.

REFERENCES

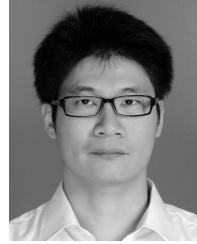
- [1] Cisco Inc. (Feb. 7, 2017). *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021*. [Online]. Available: <http://www.cisco.com/c/en/us/solutions/collateral/serviceprovider/visual-networking-index-vni/mobile-white-paper-c11-520862.html>
- [2] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: A survey," *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59–67, Sep. 2008.
- [3] F. Mhiri, K. Sethom, and R. Bouallegue, "A survey on interference management techniques in femtocell self-organizing networks," *J. Netw. Comput. Appl.*, vol. 36, no. 1, pp. 58–65, 2013.
- [4] P. Lee, T. Lee, J. Jeong, and J. Shin, "Interference management in LTE femtocell systems using fractional frequency reuse," in *Proc. 12th Int. Conf. Adv. Commun. Technol.*, vol. 2, Feb. 2010, pp. 1047–1051.
- [5] W. Zheng, T. Su, H. Zhang, W. Li, X. Chu, and X. Wen, "Distributed power optimization for spectrum-sharing femtocell networks: A fictitious game approach," *J. Netw. Comput. Appl.*, vol. 37, no. 1, pp. 315–322, 2014.
- [6] S. Xiao, X. Zhou, Y. Yuan-Wu, G. Y. Li, and W. Guo, "Robust resource allocation in full-duplex-enabled OFDMA femtocell networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 10, pp. 6382–6394, Oct. 2017, doi: 10.1109/TWC.2017.2723399.
- [7] F. Peng, N. Wang, Y. Gao, L. Cuthbert, and X. Zhang, "Geo-location database based TV white space for interference mitigation in LTE femtocell networks," in *Proc. 14th IEEE Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Madrid, Spain, Jun. 2013, pp. 1–6.
- [8] R. Xie, F. R. Yu, H. Ji, and Y. Li, "Energy-efficient resource allocation for heterogeneous cognitive radio networks with femtocells," *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 3910–3920, Nov. 2012.
- [9] J. Robinson, M. Singh, R. Swaminathan, and E. Knightly, "Deploying mesh nodes under non-uniform propagation," in *Proc. IEEE INFOCOM*, Mar. 2010, pp. 1–9.
- [10] *Second Memorandum Opinion and Order*, document FCC 10-174, 2010.
- [11] *In the Matter of Unlicensed Operation in the TV Broadcast Bands: Third Memorandum Opinion and Order*, FCC Standard 12-36, Apr. 2012.
- [12] F. Peng, Y. Gao, Y. Chen, and L. Cuthbert, "Using TV white space for femtocell aided future mobile network," in *Proc. GreenIT*, Singapore, Oct. 2010, pp. 25–28.
- [13] Z. Zhao, M. Schellmann, H. Boulaaba, and E. Schulz, "Interference study for cognitive LTE-femtocell in TV white spaces," in *Proc. Tech. Symp. Telecom World*, 2011, pp. 153–158.
- [14] X. Li, C. Guo, D. Li, C. Feng, and Y. Guo, "A database-assisted spectrum aggregation algorithm in TV white spaces for femtocells," in *Proc. Int. Symp. Wireless Pers. Multimedia Commun.*, 2013, pp. 1–5.
- [15] Informa Telecoms & Media. (Feb. 2013). *Small Cell Market Status*. Accessed: Apr. 2015. [Online]. Available: <http://goo.gl/iGYrd9>
- [16] Y. Wang, X. Dai, J. M. Wang, and B. Bensaou, "Energy efficient medium access with interference mitigation in LTE femtocell networks," *Comput. Sci.*, Aug. 2015.
- [17] Y. Zhang, Y. Wang, Y. Chen, and X. Wang, "Optimal switching strategy for heterogeneous energy supplying energy-efficient two-tier femtocell networks," *Wireless Pers. Commun.*, vol. 95, no. 2, pp. 1635–1654, Jul. 2017, doi: 10.1007/s11277-016-3872-x.
- [18] T. Alskaf, M. G. Zapata, and B. Bellalta, "Game theory for energy efficiency in wireless sensor networks: Latest trends," *J. Netw. Comput. Appl.*, vol. 54, pp. 33–61, Aug. 2015.
- [19] Y. Wang, Y. Zhang, Y. Chen, and R. Wei, "Energy-efficient design of two-tier femtocell networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2015, p. 40, Dec. 2015.
- [20] W. Zhang, L. Xie, and Y. C. Kiat, "Capacity consideration for indoor femtocell networks in TV white spaces," in *Proc. Wireless Telecommun. Symp. (WTS)*, Chicago, IL, USA, Apr. 2017, pp. 1–5.
- [21] K. Harrison and A. Sahai, "Allowing sensing as a supplement: An approach to the weakly-localized whitespace device problem," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DYSpan)*, Apr. 2014, pp. 113–124.
- [22] A. S. Cacciapuoti, M. Caleffi, and L. Paura, "Optimal strategy design for enabling the coexistence of heterogeneous networks in TV white space," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7361–7373, Sep. 2016.
- [23] A. S. Cacciapuoti and M. Caleffi, "Interference analysis for secondary coexistence in TV white space," *IEEE Commun. Lett.*, vol. 19, no. 3, pp. 383–386, Mar. 2015.
- [24] C. Tornevik, J.-E. Berg, F. Lotse, and M. Madfors, "Propagation models, cell planning and channel allocation for indoor applications of cellular systems," in *Proc. 43rd IEEE Veh. Technol. Conf.*, May 1993, pp. 867–870.
- [25] E. O. Gamarra and J. Zander, "Short range white space utilization in broadcast systems for indoor environments," in *Proc. IEEE DySPAN*, Apr. 2010, pp. 1–6.
- [26] A. Y. Wang, S. Cho, C. G. Sodini, and A. P. Chandrakasan, "Energy efficient modulation and MAC for asymmetric RF microsensor systems," in *Proc. Int. Symp. Low Power Electron. Design*, Huntington Beach, CA, USA, 2001, pp. 106–111.
- [27] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.
- [28] G. Miao, N. Himayat, and G. Y. Li, "Energy-efficient link adaptation in frequency-selective channels," *IEEE Trans. Commun.*, vol. 58, no. 2, pp. 545–554, Feb. 2010.
- [29] S. Verdú, "Spectral efficiency in the wideband regime," *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp. 1319–1343, Jun. 2002.
- [30] F. Meshkati, H. V. Poor, S. C. Schwartz, and N. B. Mandayam, "An energy-efficient approach to power control and receiver design in wireless data networks," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1885–1894, Nov. 2005.
- [31] F. Hesar and S. Roy, "Capacity considerations for secondary networks in TV white space," *IEEE Trans. Mobile Comput.*, vol. 14, no. 9, pp. 1780–1793, Sep. 2015.
- [32] M.-J. Ho, S. M. Berber, and K. W. Sowerby, "Reusability of primary spectrum in buildings for cognitive radio systems," in *Proc. Virginia Tech Symp. Wireless Pers. Commun.*, Jun. 2011, pp. 1–7.
- [33] C. Phillips, D. Sicker, and D. Grunwald, "A survey of wireless path loss prediction and coverage mapping methods," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 255–270, 1st Quart., 2013.
- [34] E. Wolfstetter, *Topics in Microeconomics: Industrial Organization, Auctions, and Incentives*. Cambridge, U.K.: Cambridge Univ. Press, 1999.
- [35] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.
- [36] F. Novillo, H. Galeana, R. Ferrus, and R. Agusti, "Spectrum availability in indoor locations for opportunistic spectrum access in dense urban scenarios," in *Proc. IEEE Veh. Technol. Conf.*, Apr. 2009, pp. 1–5.
- [37] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Englewood Cliffs, NJ, USA: Prentice-Hall, 2001.



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