Qualitative analysis for coverage probability and energy efficiency in cognitive-femtocell networks under macrocell infrastructure

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The network coverage and energy efficiency issues in heterogeneous cognitive-femtocell networks over the macrocell network is studied. Cognitive functions in wireless network nodes are serviceable with the macrocell infrastructure to achieve a balance between two desirable but incompatible features: coverage and energy efficiency. There are two basic but related aspects of cognitive radios (CRs) in the context of wireless communications: optimum CRs for energy efficiency and the act of the functioning of CRs with energy efficiency. To fully utilise the cognitive capability, a dual-tier network architecture is assumed where both the macrocell and the femtocell have a bearing on the cognitive capability. Owing to the salient features of femtocells, they can improve the coverage and enhance the spectrum efficiency by reutilising the frequency spectrum allocated to the macrocell, although, the resulting intercell interference accompanied by the same frequency coverage cannot be underestimated. The effectiveness of the scheme is verified by extensive Matlab simulation.

Introduction: Energy-efficient networks are required in order to protect the environment, cope with global warming, and facilitate sustainable communication growth [1]. Cognitive radio (CR) technology can play an important part in increasing the energy efficiency in radio networks. The cognitive abilities have many salient properties: accounting spectrum sensing, spectrum sharing, and adaptive transmission, which are advantageous to revamp the trade-off among energy efficiency, spectrum efficiency, bandwidth, and deployment efficiency in dual-tier networks [2]. The femtocell has been contemplated as an encouraging technique, and non-discriminatory in current and future radio access networks [3]. Owing to its small transmit–receive path and low transmit power property, the femtocell can reduce the consumption of energy, elongate handset battery life, and enhance the efficiency of network coverage in terms of quality of service (QoS) [4]. In this Letter, we consider energy efficiency in the context of frequency band sharing and power assignment in heterogeneous CR networks with femtocells. As both CR and the femtocell are encouraging technologies to improve energy efficiency in wireless networks, cooperation between them will improve further research. The major contributions of this Letter are:

- We develop a dual-tier network model to provide high-quality coverage to subscribers when the network is suffering from the coverage problem in deep indoor situations, underground structures where the macrocell cannot reach and, particularly, at cell edges where the maximum number of outage users are located due to the large location gap between the service network entity [macro base station (MBS)] and users.
- We propose the analytical view of instantaneous received power and interference power to obtain the final expression of the instantaneous signal-to-interference ratio (SIR). The battery draining issue of mobile operators can be eliminated by means of energy efficiency of the networks resulting in prolongation of the battery life of handsets.
- We present comprehensive numerical outcomes to vindicate the developed simplified network model and to exhibit the effectiveness of our proposed scheme.

System model: A proper functioning of the system relies on a converseance with the interferences from another transmitter inside its accessibility radius, R_{ac} . Owing to the propagation path loss, a transmitter at the external side of the accessibility area experiences only an insignificant amount of interference. Hence, the purpose is to model a sensible interference-limited environment, and the receiver accessibility radius is accounted to be much higher than the cell radius, that is, R_{ac} . Unity gain omnidirectional antennas are assumed throughout the whole Letter. Here, we assume an interference-limited environment; the quality of a signal received at a receiver is typically measured by means of the obtained SIR, which is basically the ratio of the power of the required signal to the total residue power of the unwanted signals. Let the transmit and the received powers be symbolised by P_t and P_r , respectively. The path gain between y (the transmitter) and z (the receiver) is symbolised by G_{yz} . For the sake of simplicity, the node is specified by a single subscript x , y , or z , and a double subscript such as xz specifies the connection of a link between the node x and the node z . A node is an

entity, either a MBS or a femto base station (BS), which is capable of communicating. For one interfering user y illustrated in Fig. 1

$$SIR_z = \frac{P_{tx} G_{xz}}{P_{ty} G_{yz}} \quad (1)$$

Considering fixed transmit powers, $P_{tx} = P_{ty} = \text{Const}$, (1) simplifies to

$$SIR_z = \frac{G_{xz}}{G_{yz}} \quad (2)$$

$$L = \frac{1}{G} \rightarrow SIR_z = \frac{L_{yz}}{L_{xz}} \quad (3)$$

where the path losses between transmitter T_{xy} and R_{xz} , T_{xy} and R_{xz} are symbolised by L_{yz} and L_{xz} , accordingly. The loss parameter L is expressed in terms of propagation loss, shadowing, and multipath fading.

Fig. 1 Model to derive SIR from single neighbouring cell

The loss parameters for the dual-layer environment [5] can be re-expressed as

$$L = C \left(\frac{d}{d_o} \right)^\gamma e^{(\beta\xi)} \cdot \frac{1}{|H(f)|} \quad (4)$$

Large Scale Pathloss Small Scale Pathloss

where $C \approx \hat{C}/\tilde{C}$ in which $\hat{C}$ is the constant representing the wanted link whereas $\tilde{C}$ is related to the unwanted link which means an interference link. d_o is the distance which is constant and d is the distance which is a random variable, γ is the path loss exponent, ξ is the random variable due to shadowing, $\beta = \ln(10)/10$ and $|H(f)|$ is a random variable modelling the channel envelope. The path loss model considered in this Letter takes into account the incorporation of the large-scale path loss as well as the small-scale fading. Considering, the interference possibility explained in this Section, the path loss for the required path and the path loss between the unwanted (interfering transmitter) y and the receiver z are

$$L_{xy} = \tilde{C} d_{xz}^{\gamma_{xz}} e^{(\beta\xi_{xz})} \cdot \frac{1}{|H_{xz}|} \quad (5)$$

$$L_{yz} = \hat{C} d_{yz}^{\gamma_{yz}} e^{(\beta\xi_{yz})} \cdot \frac{1}{|H_{yz}|} \quad (6)$$

where d_{yz} is considered to represent the distance between the interference caused by the transmitter x and the receiver y , γ_{xz} and γ_{yz} are the path loss exponents, ξ_{xz} and ξ_{yz} are the Gaussian distributed random variables representing the shadow fading with zero mean and variances v_{xz} and v_{yz} , respectively, and H_{xz} and H_{yz} are the channel envelopes representing the channel fading. Using (3) and (5), the SIR can be expressed as

$$\begin{aligned} SIR_z &= \frac{\hat{C} d_{yz}^{\gamma_{yz}} e^{(\beta\xi_{yz})} (1/|H_{yz}|)}{\tilde{C} d_{xz}^{\gamma_{xz}} e^{(\beta\xi_{xz})} (1/|H_{xz}|)} \\ &= \frac{C d_{yz}^{\gamma_{yz}} e^{(\beta\xi_{yz})} (|H_{xz}|)}{d_{xz}^{\gamma_{xz}} e^{(\beta\xi_{xz})} (|H_{yz}|)} \end{aligned} \quad (7)$$

From (7), the SIR has six random variable components, $\Phi_{xz} = d_{xz}^{\gamma_{xz}}$, $\Phi_{yz} = d_{yz}^{\gamma_{yz}}$, $\Lambda_{xz} = e^{(\beta\xi_{xz})}$, $\Lambda_{yz} = e^{(\beta\xi_{yz})}$, $|H_{xz}|$ and $|H_{yz}|$

Theorem 1 [6]: The coverage probability for a typical portable user connecting to the strongest BS, underestimating noise, and including Rayleigh fading is

$$P_{\text{cov}}\left(\max_{x \in \Psi_i} \text{SIR}_x > \beta_i\right) = \frac{\pi}{C(\alpha)} \cdot \frac{\sum_{i=1}^k \lambda_i P_i^{2/\alpha} \beta_i^{-2/\alpha}}{\sum_{i=1}^k \lambda_i P_i^{2/\alpha}} \quad (8)$$

where $C(\alpha) = 2\pi^2 \csc(2\pi/\alpha)/\alpha$ and k represents the number of tiers. Key consideration $\beta_i > 1$ for each tier guarantees that each mobile has at most one BS at which it associates.

Proof: Initially, considering the coverage probability of the single-tier cellular network ($K = 1$) is given by $P_{\text{cov}}(\text{SINR} > \beta) = \pi / C(\alpha) \beta^{2/\alpha}$. Note that SINR and SIR can be placed interchangeably since we have considered an interference-limited environment.

From Theorem 1, it also proceeds ahead with an interference-limited condition then $P_{\text{cov}}(\max_{x \in \Psi_i} \text{SIR}_x > \beta) = \pi / C(\alpha) \beta^{2/\alpha}$ if $\beta_i = \beta, \forall i$. It signifies that the coverage probability is not influenced by the number of tiers. Hence, it is possible to increase the network sum rate by adding the number of BSs in any tier keeping unaffected coverage.

Theorem 2: The energy efficiency for keeping the number of macro users constant and remaining users are served by cognitive femto BS (CFBS) under the interference control and the cooperation deployment of CFBS

$$\eta = \frac{C_c}{E_c} \quad (9)$$

$$E_c = \frac{E_c^s + (T_s - 1)(\lambda_c E_c^t + (1 - \lambda_c) E_c^i)}{T_s} \quad (10)$$

where the energy consumed by the sensing component is symbolised by E_c^s with the sensing period of T_s and the non-sensing components symbolised as E_c^t and E_c^i for transmission (if traffic for CFUs) and idling (if no traffic for CFUs), respectively. In reception mode, λ_c represents a receiving component if some traffic interrupts

$$C_c = \frac{T_s - 1}{T_s} \cdot F_c \cdot \log_2(1 + \text{SIR}_2) \quad (11)$$

where F_c is the frequency available for CFBS users.

Proof: Three states responsible for energy consumption are sensing, transmission, and idling. The non-sensing time period can be considered as $(T_s - 1)$ for periodic sensing with T_s and the non-receiving component in reception mode can be considered as $(1 - \lambda_c)$ without any traffic interruption. Hence, (10) is justified.

Let n_c be considered to be the number of interferers of type y to type z while communicating with type x . In general, the total throughput of the cross-layer network can be considered as $C_c = T_s - 1/T_s \cdot F_c / n_{\text{clog}2}(1 + \text{SIR}_2)$. As per the system model (Fig. 1), $n_c = 1$, hence, (11) is justified.

Fig. 2 Coverage probabilities for provided area of network (Fig. 2a) and provided coverage radius of network (Fig. 2b)

Results and discussion: In this Section, we demonstrate interpretative numerical results to validate the effectiveness of the proposed network model. The network parameters and location of the MBS and the FBS

for our simulations are shown in Fig. 1, whereas MBS users and FBS users are randomly located in a $100 \times 100 \text{ m}^2$ network grid.

In Fig. 2a, the coverage probability of dual-tier networks is shown against the number of mobile users in which different coverage areas are set for simulation. The coverage probability increases gradually at a certain point of time for a particular number of users and then it decreases with a further increase in the number of users by maintaining the same slope where the coverage probability is relatively higher for the $100 \times 100 \text{ m}^2$ grid as compared with the $120 \times 120 \text{ m}^2$ grid at any instant.

In Fig. 2b, the coverage probability of dual-tier networks is shown against the number of mobile users in which different coverage radii are set for simulation. The coverage probability is higher for a large coverage radius at any instant for a specific number of users.

In Fig. 3a, the energy efficiency of the proposed network is shown against the number of mobile users in which different coverage areas are set for simulation. The energy efficiency increases with increase in the number of users and it is highest for the largest coverage area.

Fig. 3 Energy efficiency for provided area of network (Fig. 3a) and provided coverage radius of network (Fig. 3b)

In Fig. 3b, the energy efficiency of the proposed network is shown against the number of mobile users in which different coverage radii are set for simulation. The energy efficiency increases with increase in the number of users and it has the highest value for the largest coverage radius.

Conclusion: We have developed a novel dual-layer network system model where an execution environment is configured for simulation to demonstrate the difficulties of reducing energy consumption subject to a QoS constraint in terms of coverage probability. Using the simplified cognitive-femtocell-based network model, we formulate the coverage probability and energy efficiency under the environment of heterogeneous two-tier networks. We conclude that the energy efficiency is influenced only by the consumption of power and the coverage within the network.

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