

# QoS Guaranteed Resource Allocation Scheme for Cognitive Femtocells in LTE Heterogeneous Networks with Universal Frequency Reuse

Salman Saadat<sup>1</sup> · Da Chen<sup>1</sup> · Tao Jiang<sup>1</sup>

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**Abstract** In this paper, we propose a novel resource allocation scheme for co-channel interference avoidance in LTE heterogeneous networks with universal spectrum reuse where both macro users (MUs) and cognitive femto base stations (FBSs) within the same macrocell coverage can dynamically reuse whole spectrum. Specifically, resource blocks (RBs) are shared between cognitive FBSs in underlay mode while the resource sharing among FBSs and MUs is in overlay mode. The macrocell is divided into inner and outer regions with the inner region further divided into three sectors. The proposed scheme addresses co-channel interference (CCI) by employing fractional frequency reuse (FFR) for RB allocation in the outer region of the macrocell and increase the distance of users that reuse the same RB within the macrocell. Part of RBs are allocated to the outer region of the macrocell with a FFR factor of 1/3, while the remaining RBs are dynamically allocated to each sector in the inner region of macrocell based on MUs demand to efficiently utilize the available spectrum. A basic macro base station (MBS) assistance is required by the FBS in selection of suitable RB to avoid interference with MU in each sector. With the proposed solution, both macro and femto users

can dynamically access the whole spectrum while having minimum bandwidth guarantee even under fully congested scenarios. Moreover, the proposed scheme practically eliminates the cross-tier interference and the CCI problem in heterogeneous network reduces to inter-femtocell interference. The throughput and outage performances of the proposed scheme are validated through extensive simulations under LTE network parameters. Simulation results show that the proposed scheme achieves a performance gain of more than 1.5 dB in terms of SINRs of both macro user and femto user compared to traditional cognitive and non-cognitive schemes without bandwidth guarantee for femtocells.

**Keywords** Heterogeneous network · Resource allocation · Cognitive radio · Femtocell · LTE · Co-channel interference

## 1 Introduction

While 50 % of cellular traffic occurs in indoor environment as indicated by several studies [1], it is challenging for conventional cellular networks to guarantee the coverage and data rate performances in such environment due to high penetration losses. Increasing the number of macro base stations (MBS) or eNode B (eNB) is not an efficient solution to this problem. As the service providers are shifting towards universal frequency reuse to maximally utilize their licensed spectrum, the network capacity becomes interference limited. Therefore, the performance improvement attained by increasing the number of MBSs is counter balanced by the increase in co-channel interference. Femtocell, a low power plug-n-play base station is proposed as a solution to this shortcoming by 3GPP to improve coverage

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✉ Tao Jiang  
Tao.Jiang@ieee.org

<sup>1</sup> School of Electronics Information and Communications, Huazhong University of Science and Technology, Wuhan, China

and data rates for indoor users. Higher data rates and better coverage are realized by femtocells due to shorter communication distance and the resulting reduced propagation loss compared to a macrocell. Femto base station (FBS) or home eNode B (HeNB) relays user traffic to the cellular network over a broadband backhaul connection and requires minimum coordination from macrocell for operation. Besides improving coverage, femtocells also improve the spectrum utilization by sharing the spectrum with the macrocell and reusing it several times within macrocell coverage. Due to the low transmit power of FBS, only the FBSs that are close to each other have a remarkable interference on each other, therefore higher spectrum reuse efficiency can be realized. For a femtocell network with open access mode, the macrocell user (MU) can connect to a nearby FBS to improve its data rate. With closed access mode, only femto users (FU) can connect with the FBS. The hybrid access mode gives a compromise between the open and closed access modes where only the macro users that meet a certain set of rules can connect with an FBS. Despite advantages of femtocell technology, due to the unplanned deployment and co-channel operation with MBS, the co-channel interference (CCI) is a serious concern for femtocell deployment. Femtocell deployment is not static and FBSs can appear and disappear in the network at anytime. Moreover, users association with an FBS can also change with time based on the access mode implemented at the FBS. Various solutions have been presented in literatures to address the CCI issue including the fractional frequency reuse (FFR) [2, 3], where fixed orthogonal frequency bands are assigned to macrocell and femtocell users, soft frequency reuse where different frequency bands are used in the inner and outer regions of macro/femto cells [4–6], dynamic frequency reuse where resource allocated to macro and femto networks changes dynamically to cope CCI [7, 8], and access control where strongly interfering macro users are transferred to femto network to avoid CCI [1, 9]. Several other CCI mitigation schemes are also presented in literatures such as time division multiple access (TDMA) based approach to share same spectrum in time, power control on femto base station to reduce CCI [10, 11], interference cancellation using multiple-input-multiple-output (MIMO) techniques [12, 13], Q-learning based approach for self organization [14], interference decoding [15, 16] and cognitive radios (CR) for sharing of spectrum by regarding femtocell user as secondary user.

All of the above solutions for CCI either reduce overall spectrum utilization or can not guarantee same quality of service (QoS) to femto users as macro users. Some of these solutions require heavy pre-configuration or too much coordination between FBS and MBS, which is not feasible for most of the practical scenarios where the reliability and security of backhaul are not guaranteed. Radio

access networks (RAN) are shifting towards universal frequency reuse to address always growing user demand and maximally utilize the licensed spectrum but some of the conventional CCI mitigation techniques mentioned above such as frequency partitioning do not support universal frequency reuse. The use of cognitive radio technology is a promising solution to the interference problem as they can work independently and improve overall spectrum utilization. Moreover, the efficiency of CR based solutions can be further improved by employing the advanced transmission modeling [17, 18] and cooperative sensing techniques [19]. Cognitive femtocells are femtocells with dynamic spectrum access based on cognitive spectrum sensing. However, cognitive FBS cannot be treated as secondary users in the conventional cognitive radio networks. Secondary users in traditional CR are unlicensed users without any QoS concerns which is not the case with FBS users. Therefore, the CR concept needs to be modified to be used in femtocell network. Our CR-based approach not only merits the benefits of CR technology, but also remedies the disadvantage of traditional CR method. In detail, the QoS of secondary user can be guaranteed with the proposed approach, which is different from the CR systems considered before. Cognitive radio solutions proposed in literature for avoiding CCI in femtocells can be broadly grouped into three categories, overlay cognitive FBS as SU in which each RB is used only once within the cell, distributed/server based cognitive FBS with FFR, and partly cognitive where a part of available bandwidth is reserved for MU and another for FU while remaining third part is shared cognitively by FBS as SU. Some of the CR based femtocell solutions presented in literature are discussed under the section of related work.

All the works so far on cognitive femtocells in LTE framework [20–37] consider either the eNB (MBS) or HeNB (FBS) as secondary user (SU) in a shared spectrum system which consequently means lower transmission priority/opportunities for one of them and hence no QoS guarantees. Secondary user in cognitive femtocell is different from the one in conventional CR systems as SU here is a licensed user just like the primary user (PU), and is paying for the spectrum and hence should receive the same level of QoS as primary user which in this case is macro user. To the best of our knowledge, this issue was not investigated in the existing literatures. In this paper, we present a solution that ensures a minimum resource availability for both MBS and FBS by combining cognitive resource sharing and dynamic resource allocation to maximize the utilization of available spectrum. The proposed solution guarantees a minimum QoS for cognitive FBS in terms of bandwidth while ensuring universal frequency reuse at the macrocell, which is not previously considered in literature for cognitive femtocell. The proposed solution achieves efficient spectrum utilization, minimizes cross-tier interference while increasing the

number of spectrum opportunities for FU, and improves the throughput and outage performance of FU, as practically there is no PU for cognitive FBS to compete against for resources. Major contributions of the proposed work are listed as follows.

- Traditionally, there is no bandwidth guarantee for femtocell user in CR based schemes. However, with the proposed approach FU always has a fraction of bandwidth available even under full congestion.
- Contrary to FFR approach which ensures minimum bandwidth for both macro/femto users by compromising overall spectrum utilization, the proposed approach does not reserve any bandwidth specifically for MBS or FBS. In this approach both MBS and FBS can dynamically use whole spectrum while ensuring minimum bandwidth availability for each.
- Since FBS-MU CCI is much more significant than FBS-FBS interference due to low received signal strength at MU, in proposed solution two different resource sharing techniques are used for femto-femto and femto-macro channel sharing. The resource blocks are shared between cognitive FBSs in underlay mode while the resource sharing among FBS and MU is in overlay mode.

The remainder of this paper is organized as follows. In Section 2, a discussion on related work on cognitive femtocell and how it is different from proposed scheme is presented. System model is introduced in Section 3. In Section 4, problem formulation is presented. In Section 5, resource allocation scheme is proposed and mathematical expressions for average CCI are derived. Simulation results and performance analysis are presented in Section 6. Finally, the paper is concluded in Section 7.

## 2 Related work

Power control based cognitive radio solutions for heterogeneous networks have been vastly studied in literature. Several studies such as [20] consider power allocation to MBS/FBS as a MONLP (Multiple Objective Non-Linear Problem) and try to minimize co-channel interference. Gustavo et. al. presented a power control and game theory based resource allocation scheme in [21] and concluded that the power control alone is not the most effective solution for CCI mitigation. However, the proposed scheme did not ensure any minimum resource availability for femto users.

Several frameworks have been presented in research that try to protect interest of cognitive FBS through FFR implementation. In [22] FUs are considered as secondary users and are allocated a fraction of spectrum that is assigned to a single primary/macro user. Li et al. [23] suggested the use of adaptive channel reuse factor depending

on the femtocell location/environment in the macrocell to avoid inter-femtocell interference. Inter-MBS interference management scheme was presented in [24] for cognitive femtocell, which recommends the use of conventional FFR for resource allocation to macrocells. As previously mentioned, FFR compromises overall spectrum utilization for minimum bandwidth availability.

Clustering solutions have also been proposed in literature for efficient resource management in cognitive femtocell. However, clustering solutions add a lot of overhead to the network in terms of control information exchanges, besides the spectrum utilization is reduced since a resource block cannot be reused more than once within a cluster. All FBSs forward their cognitive sensing results to the cluster head which takes a decision that tries to maximize the overall objective at cluster level. Orthogonal frequencies at macro and femtocells are employed in most of the clustering solutions which significantly decreases the spectral efficiency. DOA (Direction of Arrival) based method is used in [25] for interference estimation and spectrum allocation to cognitive FBS grouped into clusters. Radio resource management (RRM) algorithm presented in [26] adopts a centralized resource allocation scheme at FGW (Femto Gateway). In the assumptions, each MBS has a list of all FBS/FGW and each FBS/FU has a list of all FBS/FU in the same macrocell and requires all FBSs/FUs to regularly sense the radio environment and forward information to FGW. Shin et al. [27] presented a server based resource allocation scheme for femtocells where macro and femto cells use orthogonal RB but femtocells can also statistically reuse a part of the RB reserved for macro users. Server based resource allocation schemes require extensive collaboration between FBSs and are dependent on backhaul network which potentially degrades the network performance as the transmission of backhaul signalling could cause a large delay.

Location-aware models have also been studied to characterize the co-channel interference in cognitive femtocells. In [28], a mathematical model for estimation of macro and femto base stations location using Poisson point process is presented and use of this location awareness is suggested to minimize the interference between them. An artificial neural network (ANN) based algorithm for optimizing cognitive FBS power, FBS radius and antenna pattern selection using FBS location for a target SINR value is studied in [29].

Decoding of signaling exchanges between MBS and MU to extract information regarding frequency assignments has also been studied. These solutions suggest that the decoded control channel provides exact knowledge about the time-frequency slot each macro user terminal is operating along with their location and can be used for accurate interference mitigation. In [30], FBSs can decode high power signaling channel of MBS and have global information of macrocell resource allocations. Using this method, cognitive FBSs

share whole spectrum with MUs as secondary users. The proposed deployment scheme tries to ensure limited interference power to the macrocell while ignoring its impact on the QoS degradation for FU.

Game theoretic approach to formulate a distributed algorithm for resource allocation in LTE system with cognitive femtocells competing for the spectrum as secondary users is presented in [31]. In [32], relay based cognitive femtocells are studied and cooperation of secondary users to relay primary traffic during busy periods that in turn creates more vacant bands for SU transmission is examined. An admission control policy is presented in [33] which selects only the set of FUs that maximizes the overall data rate of cognitive cellular network while guaranteeing a target SINR of PUs. A distributed resource allocation mechanism for cognitive femtocells was proposed in [34] where users independently decide which macro/femto base station to join, depending on how this decision will affect the throughput of the network.

Several solutions have been studied in literature that employ beam-forming with interference shaping at the femto base station to minimize co-channel interference induced on primary user. However, accurate beam-forming for interference cancellation at user deployed plug-n-play FBS without global or local knowledge of channel state information (CSI) remains a challenge. Esfahani and Nakhai [35] studied beam-forming using M-ary antennas at cognitive femto BS to avoid CCI with nearby macro users by maintaining nulls in the directions of channels occupied by the PU outside the femto BS coverage. MIMO with full cognition/cooperation based interference management solution for cognitive femtocells is proposed in [36]. However, it requires heavy coordination overhead on the backhaul network as resource allocation and user admission control are centrally coordinated by the MBS. Also the full CSI assumed in these works at the transmitter side is very difficult to acquire.

### 3 System model

In this section, we introduce system model of our sectored cognitive solution for LTE heterogeneous networks. We consider Time Division Duplex (TDD) OFDMA (Orthogonal Frequency Division Multiple Access) LTE system where available spectrum is divided into  $F$  physical resource blocks (RBs), each comprising of a set of  $G$  subsequent subcarriers. A RB is regarded as the minimum resource unit in the frequency domain and can be used only once within a cell. One RB is defined as 180KHz frequency band and 1ms time duration. Both MBSs and FBSs operate in the same frequency band.  $F$  physical resource blocks are equally divided into four subsets, which are denoted by  $f_1$ ,

$f_2$ ,  $f_3$  and  $f_4$ , where  $F = f_1 + f_2 + f_3 + f_4$ . The MBS has a 3-sectored antenna with full frequency reuse and is divided into 2 regions, inner region and the outer region. Inner region is further divided into 3 sectors. Macrocell uses each RB only once within the cell, using all RBs in total. In the outer region, one RB subset is reused according to a reuse FFR factor of 1/3 by each MBS to avoid CCI with the neighboring macrocells. Remaining RBs are dynamically used by the MBS in the 3 sectors of the inner region. Each available RB in the inner region can be dynamically utilized in any sector based on the user demand. Femtocell (HeNB/FBS) has omnidirectional (isotropic) antenna and cognitively reuses as SU the least interfering RB that is not occupied by the MU in its sector/region. The MBS assists the spectrum selection of FBSs by providing a list of RBs that are not being used by the MU in their region. Cognitive decision at the FBS depends on the classification of interfering node as major interfering node (MBS/MU) that must be avoided or a minor interfering node (FBS/FU) that can be tolerated. Resource sharing among FBSs is in underlay mode and are deployed in open access mode. The radius of the inner region also affects the CCI and overall system performance of the multi-region cellular designs as has been studied in [4, 5], but optimizing the size of the inner region of macrocell is beyond the scope of this research and therefore without loss of generality an inner region with size of  $0.7r_M$  is considered for the study as per [3].

Although FBSs share the spectrum with MBS as secondary users in the proposed work, unlike other cognitive femtocell solutions presented in the literature this approach ensures that at least one RB subset is always available for the use by the FBSs in any sector/region. For example, in case of an FBS in the inner region when all the assigned RBs in the inner region are being fully utilized by the MUs, FU can still use RBs assigned by the MBS to the outer region of the macrocell.

The location of an FBS in the MBSs coverage area affects the RB assignment to that FBS. MBS provides a list of RBs to the FBS that are not assigned to any MU in the sector/region where that FBS is placed. This information is used by the FBS to determine which set of RBs it can cognitively share in underlay mode and which RB sharing must be done in overlay mode. MBS only requires FBS's sector - inner/outer region association information and does not need to have the exact location of the FBS for this information exchange as were required by several studies in literature that take into consideration FBS location for RB allocation. The proposed cell layout and resource allocation scheme reduces the CCI in cognitive femtocell based LTE heterogeneous network to cognitive resource sharing among FBSs. FBS-FBS CCI issue is easier to handle because of low transmit power of FBSs and their smaller interference region.

A simple algorithm for resource allocation to FBSs is proposed for implementation. When an FBS connects to the MBS over broadband connection, MBS provides it with a set of RBs that are not being used in its sector/region by the macro users based on the location of the FBS in MBS coverage. FBS will choose one RB with the minimum received power for a set of observations. Here all FBSs cognitively share bandwidth as secondary users in underlay mode with random back-off timers. Any change in the MU RB allocation is notified to the FBSs with in the sector at regular intervals. FBSs do not need to have an updated list of available RBs at all times as they are cognitively utilizing only the most suitable RB that keeps the interference below a threshold level, therefore this update period can be selected as per the constraining bandwidth of FBS’s backhaul network. All FBSs sense channel at the beginning of each time slot for a fixed duration to identify spectrum opportunities. It is assumed that MBS channel assignment remains static during a time slot. The interference threshold is selected as per SINR requirement for an MU at cell edge. Rayleigh fading channel with path-loss model and log-normal shadowing is considered in this paper. Rayleigh fading is assumed to follow exponential distribution with mean and variance of 1.

Figure 1 illustrates the cell layout and resource allocation scheme proposed in this paper. Inner region of MBS adopts dynamic frequency reuse and can have any distribution of available RBs in each sector. Here FBS 0 can cognitively choose any frequency from RB subsets  $f_1, f_2, f_3$  and  $f_4$  for transmission as secondary user. Similarly, FBS 1 can select

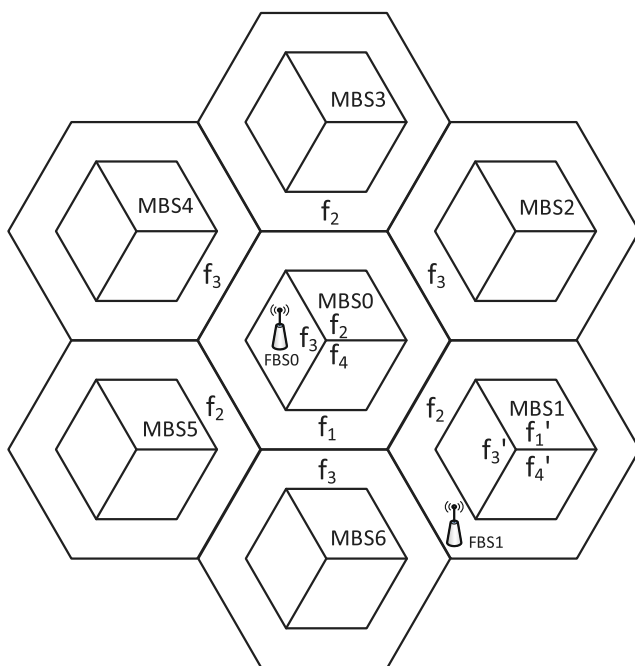


Fig. 1 Cell Layout and RB Allocation

any frequency among  $f'_1, f'_2, f'_3$  and  $f'_4$  for cognitive transmission as secondary user. In the outer region, FFR with reuse factor of 1/3 is implemented to avoid CCI interference among MBSs. Since the distribution of RBs among the three RB subsets assigned to the inner region can change dynamically, therefore  $f_3$  in the inner region of MBS 0 may not be same as  $f'_3$  in the inner region of MBS 1. However, when  $f_1, f_2, f_3$  or  $f_4$  are used in the outer region of MBS, the RBs subset corresponding to them are always the same. This resource allocation scheme offers maximum transmission opportunities for both cognitive FBS and MBS with minimal interference and universal frequency reuse. It provides a minimum bandwidth guarantee for FBS which is not previously done in literature for cognitive femtocells.

### 4 Problem formulation

In this section, we formulate problem to analyze the performance of the proposed resource allocation scheme. We analyze system performance in terms of instantaneous throughput and outage probability of macro and femto users on resource block  $k$ , where  $k$  is the most suitable RB selected by the FBS as the result of cognitive measurements. Channel occupancy of RB  $k$  by the MU and FU is assumed to follow Poisson distribution with two different arrival rates. Since TDD LTE system is studied in this paper, the strongest interference among the uplink and downlink communication links is considered for interference calculations at macro and femto users. It means that the downlink traffic of an FU can be affected by the interference from the uplink transmission of a nearby MU, similarly the downlink transmission of an MU can be interfered by the CCI from a nearby FBS. TDD LTE system enables dynamic allocation of downlink and uplink resources to efficiently support asymmetric traffic and has been studied in several papers such as [21]. The throughput of femto user  $f$  on resource block  $k$  is given by

$$\eta_{fk} = B \log_2(1 + \text{SINR}_{fk}), \tag{1}$$

where  $B$  is the bandwidth and is equal to number of RB assigned to each user multiplied by the bandwidth of a single RB. It is assumed that one RB is assigned per user in both macro and femto networks.  $\text{SINR}_{fk}$  is the signal to interference noise ratio of femto user  $f$  on RB  $k$  and is calculated as

$$\text{SINR}_{fk} = \frac{P_F G_{Ff}}{N_o B + P_m G_{mF} + \text{CCI}_{FF_i}}, \tag{2}$$

where  $P_F, P_m$  are the transmit powers of FBS and MU, respectively.  $\text{CCI}_{FF_i}$  is the co-channel interference (CCI) from interfering FBSs.  $G_{Ff}$  and  $G_{mF}$  are the channel gains

between FBS and FU, and MU and FBS respectively.  $N_o$  is the AWGN with noise variance of  $\sigma_k^2(f)$ .

$$G_{Ff} = X_1 d_{Ff}^\alpha X_a e^{-g_{Ff}}, \tag{3}$$

$$G_{mF} = X_2 \gamma d_{mF}^\beta X_a e^{-g_{mF}}, \tag{4}$$

$$\begin{aligned} \text{CCI}_{FF_i} &= P_F X_2 X_a \gamma^2 \\ &\times \sum_{i=1}^{N_{If}} d_{FF_i}^\beta e^{-g_{FF_i}} e^{-\lambda_F \frac{\lambda_F^n}{n!}} e^{-\lambda_{F'} \frac{\lambda_{F'}^n}{n!}}, \end{aligned} \tag{5}$$

where  $d_{Ff}$ ,  $d_{mF}$  and  $d_{FF_i}$  are the distances between FBS and FU, MU and FBS, FBS and interfering FBS respectively.  $X_1$  and  $X_2$  are path loss components,  $\alpha$  and  $\beta$  are path loss exponents for indoor and outdoor links respectively,  $X_a$  is log normal shadowing factor and  $\gamma$  is wall penetration loss.  $e^{-g_{Ff}}$ ,  $e^{-g_{mF}}$  and  $e^{-g_{FF_i}}$  represent the rayleigh fading factor for the links between FBS and FU, MU and FBS, and FBS and interfering FBS respectively.  $\lambda_F$  and  $\lambda_{F'}$  are the Poisson arrival rates for traffic on target FBS and interfering FBS respectively.

$(r_m, \theta_m)$ ,  $(r_F, \theta_F)$  and  $(r_{F_i}, \theta_{F_i})$  represent the random locations of MU, target FBS and interfering FBS, respectively. The throughput on RB  $k$  is measured as  $\eta_{fk} = B \log(1 + \frac{P_{fk}}{I_{fk}})$ , where

$$P_{fk} = P_F X_1 e^{-g_{Ff}} \{r_F^2 - 2 \cos(\theta_F - \theta_f) r_F r_f + r_f^2\}^{\frac{\alpha}{2}}, \tag{6}$$

$$\begin{aligned} I_{fk} &= \frac{N_o B}{X_a} + [P_m X_2 \gamma e^{-g_{mF}} \\ &\times \{r_m^2 - 2 \cos(\theta_m - \theta_F) r_m r_F + r_F^2\}^{\frac{\beta}{2}}] \\ &+ [P_F X_2 \gamma^2 e^{-g_{FF_i}} e^{-\lambda_F \frac{\lambda_F^n}{n!}} e^{-\lambda_{F'} \frac{\lambda_{F'}^n}{n!}} \\ &\times \sum_{i=1}^{N_{If}} \{r_F^2 - 2 \cos(\theta_F - \theta_{F_i}) r_F r_{F_i} + r_{F_i}^2\}^{\frac{\beta}{2}}]. \end{aligned} \tag{7}$$

Similarly, the throughput of macro user  $m$  on resource block  $k$  is expressed as

$$\eta_{mk} = B \log_2(1 + \text{SINR}_{mk}), \tag{8}$$

where  $\text{SINR}_{mk}$  is the signal to interference noise ratio experienced by macro user  $m$  at RB  $k$  and is given by

$$\text{SINR}_{mk} = \frac{P_M G_{Mm}}{N_o B + \text{CCI}_{M_i} + P_F G_{mF} + \text{CCI}_{mF_i}}, \tag{9}$$

where  $P_M$  is the transmit power of MBS.  $\text{CCI}_{M_i}$  is the CCI from neighboring MBSs in the first tier and  $\text{CCI}_{mF_i}$

is the CCI from interfering FBSs.  $G_{Mm}$  is the channel gain between MBS and MU. Thus, we have

$$G_{Mm} = X_2 d_{Mm}^\beta X_a e^{-g_{Mm}}, \tag{10}$$

$$\text{CCI}_{M_i} = \sum_{j=1}^6 P_m X_2 d_{M_j m}^\beta X_a e^{-g_{M_j m}}, \tag{11}$$

$$G_{mF} = X_2 \gamma d_{mF}^\beta X_a e^{-g_{mF}}, \tag{12}$$

$$\begin{aligned} \text{CCI}_{mF_i} &= P_F X_2 X_a \gamma \\ &\times \sum_{i=1}^{N_{If}} d_{mF_i}^\beta e^{-g_{mF_i}} e^{-\lambda_m \frac{\lambda_m^n}{n!}} e^{-\lambda_{F'} \frac{\lambda_{F'}^n}{n!}}, \end{aligned} \tag{13}$$

where  $d_{Mm}$  is the distance between MBS and MU,  $d_{mF_i}$  is the distance between MU and interfering FBS,  $\lambda_m$  is the Poisson arrival rate for traffic on MU, and  $d_{M_j m}$  is the distance between MU  $m$  and interfering MU being served by the MBS  $M_j$ .

$(r_M, \theta_M)$  represents the coordinates of MBS, MU throughput on RB  $k$  is then measured as  $\eta_{mk} = B \log(1 + \frac{P_{mk}}{I_{mk}})$ , where

$$P_{mk} = P_M e^{-g_{Mm}} \{r_M^2 - 2 \cos(\theta_M - \theta_m) r_M r_m + r_m^2\}^{\frac{\beta}{2}}, \tag{14}$$

$$\begin{aligned} I_{mk} &= \frac{N_o B}{X_2 X_a} + \sum_{j=1}^6 P_m d_{M_j m}^\beta e^{-g_{M_j m}} \\ &+ [P_F \gamma e^{-g_{mF}} \{r_m^2 - 2 \cos(\theta_m - \theta_F) r_m r_F + r_F^2\}^{\frac{\beta}{2}}] \\ &+ [P_F \gamma e^{-g_{mF_i}} e^{-\lambda_m \frac{\lambda_m^n}{n!}} e^{-\lambda_{F'} \frac{\lambda_{F'}^n}{n!}} \\ &\times \sum_{i=1}^{N_{If}} \{r_m^2 - 2 \cos(\theta_m - \theta_{F_i}) r_m r_{F_i} + r_{F_i}^2\}^{\frac{\beta}{2}}]. \end{aligned} \tag{15}$$

The outage probability of FU  $f$  on RB  $k$  is calculated as

$$OP_{fk} = P(\text{SINR}_{fk} \leq \psi), \tag{16}$$

where  $\psi$  is the threshold set for the SINR.

Similarly, the outage probability of MU  $m$  on RB  $k$  is given by

$$OP_{mk} = P(\text{SINR}_{mk} \leq \psi). \tag{17}$$

Through the proposed resource allocation and cell layout we try to achieve the following two objectives,

$$\begin{aligned} \max \quad & \eta_{mk}, \eta_{fk}, \forall m, f \\ \text{s.t.} \quad & \eta_{fk} \geq \kappa, \forall f \\ & \text{resource/access constraints (20)-(25),} \\ & \text{power constraints (26)-(30),} \\ & \text{channel constraints (31)-(33),} \\ & \text{flow constraints (34), (35),} \end{aligned} \tag{18}$$

and

$$\begin{aligned}
 \min \quad & OP_{mk}, OP_{fk}, \forall m, f \\
 \text{s.t.} \quad & OP_{fk} \leq \Psi, \forall f \\
 & \text{resource/access constraints (20)-(25),} \\
 & \text{power constraints (26)-(30),} \\
 & \text{channel constraints (31)-(33),} \\
 & \text{flow constraints (34), (35),} \tag{19}
 \end{aligned}$$

where  $\kappa$  is the minimum throughput guaranteed to the MU and  $\Psi$  is the worst case outage probability maintained for the MU by the system. The first objective function aims to maximize the macro and femto user throughputs, under the constraint that the instantaneous throughput of FU  $f$  is at least equal to the minimum throughput guaranteed to the MU. The second objective function minimizes the macro and femto user outage probabilities, under the constraint that the instantaneous outage probability of FU  $f$  is not greater than the worst case outage probability maintained for the MU.

#### 4.1 Resource allocation/access control constraints

Following are the constraints of resource allocation within a cell and user admission to the network under the proposed work. As universal frequency reuse is implemented, all the RBs are utilized by MUs within a macrocell. This can be expressed as

$$N_{M1}^t \cup N_{M2}^t \cup N_{M3}^t \cup N_{Mout}^t = N_{RB}, \tag{20}$$

where  $N_{M1}^t, N_{M2}^t, N_{M3}^t$  are RBs occupied by MU at time  $t$  in MBS sector 1, sector 2 and sector 3 in the inner region respectively,  $N_{Mout}^t$  is the set of RBs occupied by MU at time  $t$  in outer region of MBS coverage and  $N_{RB}$  represents total number of available RB in the system. In order to avoid CCI interference between FBS and MU within the same sector, FBSs cannot occupy a RB assigned to an MU in the sector, i.e.,

$$N_M^t \cap N_F^t = \phi, \tag{21}$$

where  $N_M^t, N_F^t$  are the RBs occupied by MU and FBSs respectively at time  $t$  in an MBS sector. Moreover, the same RB cannot be reused more than once by an MU within MBS coverage, i.e.,

$$N_{M1}^t \cap N_{M2}^t \cap N_{M3}^t \cap N_{Mout}^t = \phi. \tag{22}$$

FBSs on the other hand can reuse the same RB several times within a macrocell, under the constraint that the CCI does not exceed a threshold. Then, we have

$$N_{F_i}^t \cup N_{F_j}^t = N_{RB}, \text{ for } i, j \in \{1, 2, \dots, K\}, \tag{23}$$

where  $N_{F_i}^t$  is the set of RBs occupied by FBS  $i$ . Since the open access mode is assumed on all FBSs, macro users can

connect with the FBS that offers the highest performance gain. This assumption can be summarized as

$$U_M^t \cap U_{F_i}^t \neq \phi, \text{ for } i, j \in \{1, 2, \dots, K\}, \tag{24}$$

where  $U_M^t$  is the set of users admitted to connect with MBS and  $U_{F_i}^t$  is users allowed to connect with FBS  $i$ . Similarly, open access mode implementation is considered between FBSs, i.e.,

$$U_{F_i}^t \cap U_{F_j}^t \neq \phi, \text{ for } i, j \in \{1, 2, \dots, K\} \ \& \ i \neq j. \tag{25}$$

The open access implementation between MBS & FBS and among FBSs also avoids the near far problem faced with closed access implementation. The power, channel and flow constraints that govern this resource allocation and access control scheme are listed in the following part.

#### 4.2 Power constraints

We assume uniform power distribution by the MBS and FBS. Uniform power distribution by MBS can be represented as

$$K P_{M,in}^c(t) + L P_{M,out}^c(t) = P^{\max}, \tag{26}$$

where  $P_{M,in}^c(t)$  and  $P_{M,out}^c(t)$  are MBSs transmission powers on RB  $c$  in the inner and outer region of MBS coverage at time  $t$ , respectively.  $P^{\max}$  is the maximum transmission power of MBS to have tolerable CCI.  $K$  is the number of RBs assigned to the inner region of MBS coverage and  $L$  is the number of RBs assigned to the outer region. The uniform power distribution by the FBS is expressed as

$$J P_F^c(t) = P_F^{\max}, \forall c, \tag{27}$$

where  $P_F^c(t)$  is power FBS  $F$  uses on RB  $c$ .  $P_F^{\max}$  is the maximum transmission power of FBS  $F$  to have tolerable CCI.  $J$  is the number of RBs being used by the FBS  $F$ . To avoid CCI interference to MUs in neighboring macrocells the power received by MUs on each RB should not exceed the tolerance level  $\beta$ , i.e.,

$$P_{M,in}^c(t) G_{Mm}^c(t) S_m^c(t) \leq \beta, \forall m, c, \tag{28}$$

where  $G_{Mm}^c(t)$  is channel gain from MBS  $M$  to MU  $m$  at RB  $c$ .  $S_m^c(t)$  is channel state on time slot  $t$ .  $S_m^c(t) = 1$  means MU  $m$  is using RB  $c$ . Otherwise,  $S_m^c(t) = 0$ . In order to avoid interference to MU and FUs in neighboring femtocells the power received by FUs on each RB should not exceed the tolerable level  $\alpha$ .

$$P_F^c(t) G_{Ff}^c(t) A_f^c(t) \zeta_f^c(t) \leq \alpha, \forall f, c, \tag{29}$$

where  $G_{Ff}^c(t)$  is channel gain from FBS  $F$  to FU  $f$  at RB  $c$ , and  $A_f^c(t)$  is channel accessibility information.  $A_f^c(t) = 1$  if FU  $f$  can access RB  $c$ . Otherwise,  $A_f^c(t) = 0$ .  $\zeta_f^c(t)$  is binary variable capturing the assignment of RB  $c$  to FU  $f$

for the transmission. Since a RB can only be used once with in a single FBS coverage

$$0 \leq \sum_{f=1}^M \zeta_f^c(t) \leq 1, \forall c. \tag{30}$$

### 4.3 Channel constraints

The constraint imposed by the channel availability with regards to the transmission on RB  $c$  based on cognitive sensing results on each FBS can be shown as

$$\mu_m^c(t) \leq \rho_F^c(t) \mu_m^c(t) \leq \rho_F^c(t), \forall m, f, c, \tag{31}$$

where  $\rho_F^c(t)$  indicates cognitive sensing results on whether the power received by FBS  $F$  exceeds the threshold  $\varepsilon$  on RB  $c$ . If so, channel  $c$  should not be used. Here,  $\mu_m^c(t)$  is binary variable capturing the assignment of RB  $c$  to MU  $m$  for the transmission.

$$\rho_F^c(t) = \begin{cases} 1, & \text{if } P_m^c(t)G_{mF}^c(t) + \sum_{f=1}^M P_i^c(t)G_{FF_i}^c(t) \leq \varepsilon \\ 0, & \text{otherwise} \end{cases}, \tag{32}$$

where according to channel reciprocity  $G_{FF_i}^c(t) = G_{F_iF}^c(t)$  and  $G_{FF}^c(t) = 0$  for  $F = 1, 2, \dots, K$ . Moreover, as a RB can only be used once within a single MBS coverage

$$0 \leq \sum_{m=1}^N \mu_m^c(t) \leq 1, \forall c, \tag{33}$$

### 4.4 Flow constraints

Flow constraint indicates that the data flow on the channel between MU and MBS should not exceed the macro link capacity. This constraint is represented as

$$F_m^c(t) \leq W_m^c(t), \forall n, c, \tag{34}$$

where  $F_m^c(t)$  is flow rate that the MBS transmits to MU  $m$  over RB  $c$  in time slot  $t$  and  $W_m^c(t)$  is macro transmission link capacity. Similarly, data flow on the channel between FU/MU and FBS should not exceed the femto link capacity, i.e.,

$$f_f^c(t) \leq w_f^c(t), \forall m, c, \tag{35}$$

where  $f_f^c(t)$  is flow rate that the FBS transmits to FU  $f$  over RB  $c$  in time slot  $t$  and  $w_f^c(t)$  is femto transmission link capacity.

## 5 Proposed resource allocation scheme

For the design objectives of throughput and outage probability, the SINR of FU  $f$  on RB  $k$  should always be equal

to or greater than the worst case SINR of MU  $m$  on RB  $k$  ( $\text{SINR}_{fk} \geq \text{SINR}_{mk}$ ) under the constraints outlined in the previous section, i.e.,

$$\text{SINR}_{fk}(t) \geq \frac{P_M G_{Mm}(t) S_m^k(t) \mu_m^k(t)}{\{N_o B + \sum_{j=1}^6 P_m G_{Mjm}(t) S_m^k(t) \mu_m^k(t) + P_F G_{mF}(t) \rho_f^k(t) A_f^k(t) + \sum_{i=1}^{N_{If}} P_F G_{mF_i}(t) \rho_{f_i}^k(t) A_{f_i}^k(t)\}} \tag{36}$$

where  $G_{Mjm}$  is the channel gain between MU  $m$  and interfering MU being served by MBS  $M_j$ , and  $G_{mF_i}$  is propagation gain between MU  $m$  and interfering FBS  $F_i$ . Since uniform power allocation is assumed in this work for both the MBS and the FBSs, in order to maximize  $\text{SINR}_{mk}$  and  $\text{SINR}_{fk}$  within above constraints, the CCI must be minimized. The co-channel interference at MU  $m$  on RB  $k$  ( $\text{CCI}_{mk}$ ) and co-channel interference at FU  $f$  on RB  $k$  ( $\text{CCI}_{fk}$ ) is minimized by increasing the reuse distance of RB  $k$  in both macro and femto networks under the proposed resource allocation strategy as illustrated in Fig. 1. The following Algorithm 1 explains the proposed resource allocation scheme.

---

### Algorithm 1 RB selection by the FBS

---

**Input:**  $N_{RB}$ , FBS location, sensing thresholds  $\sigma_m, \sigma_f$  for interfering MU and FU, respectively such that  $\sigma_m < \sigma_f$ .

- 1:  $N_{Mout}^t = \frac{N_{RB}}{4}$ , such that,
  - 2:  $N_{Mout}^t \cap N_{Mout\_neighbor}^t = \phi$
  - 3:  $N_{M1}^t + N_{M2}^t + N_{M3}^t = N_{RB} - N_{Mout}^t$ , such that,
  - 4:  $N_{M1}^t : N_{M2}^t : N_{M3}^t = \frac{N_{RB} - N_{Mout}^t}{U_{M2}^t U_{M3}^t} : \frac{N_{RB} - N_{Mout}^t}{U_{M1}^t U_{M3}^t} : \frac{N_{RB} - N_{Mout}^t}{U_{M1}^t U_{M2}^t}$ , and
  - 5:  $N_{M1}^t \cap N_{M2}^t \cap N_{M3}^t \cap N_{Mout}^t = \phi$
  - 6: MBS updates FBS regarding the set  $R^t$  of RB's assigned to the MU's in its region.
  - 7: FBS performs cognitive sensing for most suitable RB  $k$ , such that,
  - 8:  $\text{CCI}_k < \sigma_f$ , for all RB's not assigned to MU's in its region.
  - 9:  $\text{CCI}_k < \sigma_m$ , for set of RB's assigned to MU's in its region.
  - 10: **if** no suitable RB is found **then**
  - 11:     **goto** 7 after the random back-off timer expires
  - 12: **else if**  $k \notin R^t$  **then**
  - 13:     spectrum sharing mode  $\rightarrow$  cognitive underlay
  - 14: **else**
  - 15:     spectrum sharing mode  $\rightarrow$  cognitive overlay
  - 16: **end if**
-



### 5.1 Mathematical derivations for average CCI<sub>mk</sub> and CCI<sub>fk</sub>

In this subsection, we drive mathematical expressions for average CCI and then use them later in simulation results section for validation. For  $T$  different locations of an MU within MBS coverage, average CCI on target FU can be calculated as

$$\begin{aligned} \overline{\text{CCI}}_{fk} &= \frac{1}{T} \sum_{m=1}^T (P_m X_2 X_a \gamma d_{mF}^\beta \\ &+ \sum_{i=1}^{N_{If}} P_F X_2 X_a \gamma^2 d_{FiF}^\beta e^{-\lambda_{Fi}} \frac{\lambda_{Fi}^n}{n!} e^{-\lambda_F} \frac{\lambda_F^n}{n!}), \end{aligned} \quad (37)$$

where  $N_{If}$  is the total number of interfering FBSs. The rayleigh fading assumed in this study follows exponential distribution with mean and variance of 1, therefore, the factor representing rayleigh fading can be safely ignored in the average co-channel interference measurement. Since uniform power allocation is assumed and the path-loss, log-normal shadowing and wall penetration factors remain the same for each measurement, above expression can be simplified as

$$\begin{aligned} \overline{\text{CCI}}_{fk} &= P_m X_2 X_a \gamma \frac{1}{T} \sum_{m=1}^T d_{mF}^\beta \\ &+ \frac{1}{T} \sum_{m=1}^T P_F X_2 X_a \gamma^2 \sum_{i=1}^{N_{If}} d_{FiF}^\beta e^{-\lambda_{Fi}} \frac{\lambda_{Fi}^n}{n!} e^{-\lambda_F} \frac{\lambda_F^n}{n!}. \end{aligned} \quad (38)$$

For independent Poisson distribution of traffic arrival on each interfering FBS, the expression for average CCI can be simplified as below

$$\begin{aligned} \overline{\text{CCI}}_{fk} &= P_m X_2 X_a \gamma \frac{1}{T} \sum_{m=1}^T d_{mF}^\beta \\ &+ P_F X_2 X_a \gamma^2 e^{-\lambda_{Fi}} \frac{\lambda_{Fi}^n}{n!} e^{-\lambda_F} \frac{\lambda_F^n}{n!} \frac{1}{T} \sum_{m=1}^T \sum_{i=1}^{N_{If}} d_{FiF}^\beta, \\ &= P_m X_2 X_a \gamma \frac{1}{T} \sum_{m=1}^T d_{mF}^\beta \\ &+ P_F X_2 X_a \gamma^2 e^{-\lambda_{Fi}} \frac{\lambda_{Fi}^n}{n!} e^{-\lambda_F} \frac{\lambda_F^n}{n!} \sum_{i=1}^{N_{If}} d_{FiF}^\beta. \end{aligned} \quad (39)$$

Similarly, average CCI on the MU can be expressed as

$$\begin{aligned} \overline{\text{CCI}}_{mk} &= \frac{1}{T} \sum_{m=1}^T \left( \sum_{M=1}^6 P_m X_2 X_a d_{Mm}^\beta \right. \\ &+ P_m X_2 X_a \gamma d_{mF}^\beta \\ &+ \left. \sum_{i=1}^{N_{If}} P_F X_2 X_a \gamma d_{mFi}^\beta e^{-\lambda_{Fi}} \frac{\lambda_{Fi}^n}{n!} e^{-\lambda_m} \frac{\lambda_m^n}{n!} \right), \\ &= P_m X_2 X_a \frac{1}{T} \sum_{m=1}^T \sum_{M=1}^6 d_{Mm}^\beta \\ &+ P_m X_2 X_a \gamma \frac{1}{T} \sum_{m=1}^T d_{mF}^\beta \\ &+ P_F X_2 X_a \gamma e^{-\lambda_{Fi}} \frac{\lambda_{Fi}^n}{n!} e^{-\lambda_m} \frac{\lambda_m^n}{n!} \frac{1}{T} \sum_{m=1}^T \sum_{i=1}^{N_{If}} d_{mFi}^\beta. \end{aligned} \quad (40)$$

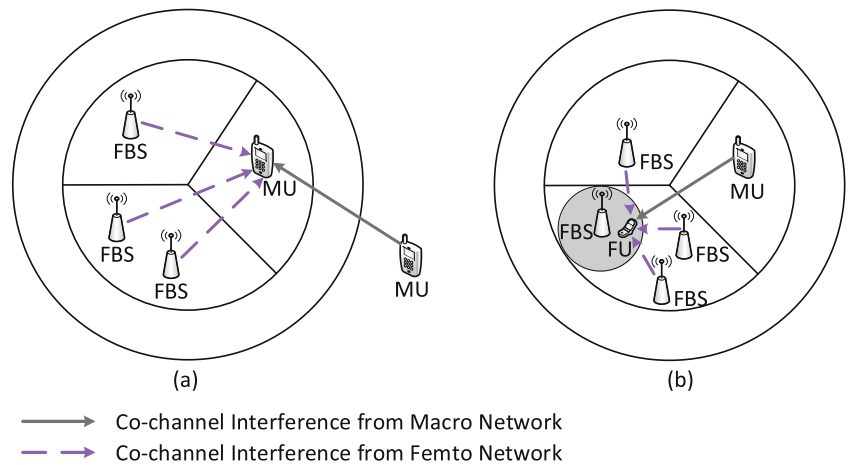
### 6 Simulation results

In this section, the performance of the proposed scheme is verified by simulations under LTE system parameters [5, 38]. The detailed simulation parameters are given in Table 1. The number of physical resource blocks in LTE system depends on the size of macrocell. A larger cell radius would mean less number of RB as more power is required per RB to realize communication with the users at the cell edge. Therefore, a 2.5MHz LTE system with 12 RBs is considered in the study to have a minimum SINR of 10dB per RB at the edge of macrocell with a radius of 1000m. In the simulation environment MUs are considered to be uniformly distributed within the macrocell coverage area and

**Table 1** Simulation parameters

LTE System/RB Bandwidth	2.5MHz/180KHz
Number of RB	12
Macro/Femto Cell Radius $r_M, r_F$	1000/20m
Radius of Inner Region	$0.7r_M$
MBS/FBS Transmit Power	46/20dBm
MU Transmit Power	21dBm
Log-normal Shadowing $X_a$	8dB
Wall Penetration Loss	10dB
Indoor/Outdoor Path Loss Component $X_1/X_2$	(38.46+0.7d)/15.3dB
Indoor/Outdoor Path Loss Exponent $\alpha/\beta$	2/3.76
SINR at Cell Edge	10dB
Channel	Rayleigh Fading
Noise Power Spectral Density $N_o$	174dB
Average Number of MU/FU	25/5

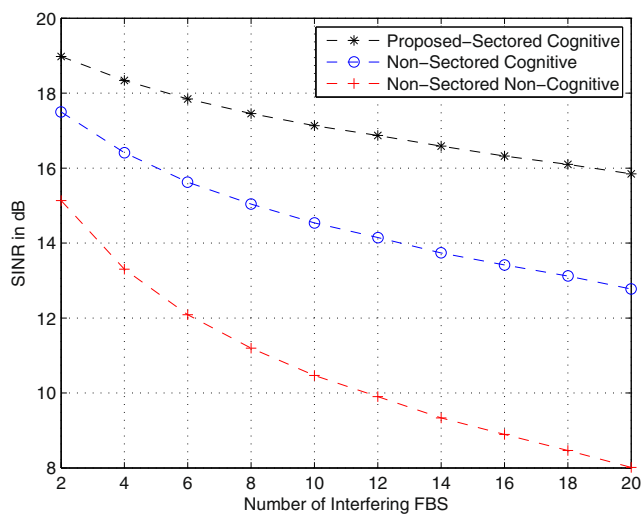
**Fig. 2** Co-channel interference scenarios. (a) a MU with multiple interfering FBS's along with interfering MU's from the neighboring MBS, (b) a target FU with an interfering MU and multiple interfering FBS's



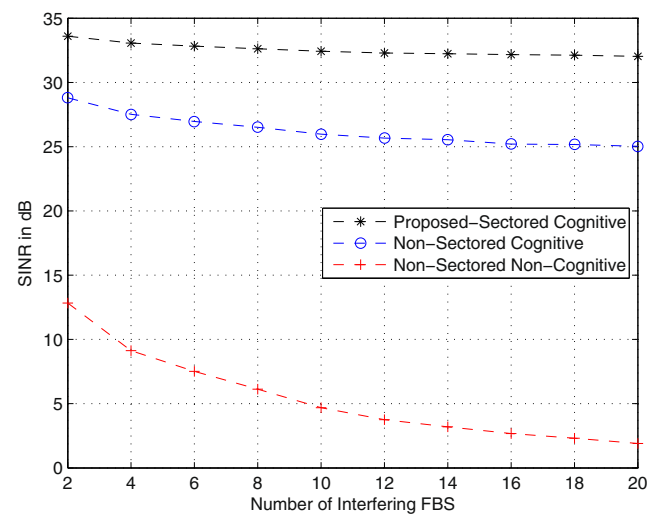
a fair scheduler is assumed for resource distribution among users associated with a base station which assigns one RB per user. Only the interfering FBSs are considered in the study and it is assumed that all the interfering FBSs have the same RB as most suitable through cognitive sensing results. Fully loaded scenario is considered, which means MUs and target FBS are using all the RBs that are assigned to them. Interfering FBSs have to cognitively sense and compete for each RB to exploit spectrum opportunities. For comparison with the typical femtocell solutions, it is assumed that the MU and the target FU always have CCI. Channel occupancy of interfering nodes is simulated using Poisson distribution. The effect of sectored and non-sectored designs is simulated using different Poisson arrival rates for macro user channel occupancy. As a RB can be reused only once by the macro user within a macrocell – free channel availability of a specific RB within the macrocell coverage is assumed to be

one-third for the non-sectored solution as compared to the 3-sectored design. Decision by the interfering FBS (CR SU) to use a RB for transmission is made based on periodic sensing of the most suitable RB to check whether it is currently under use and if the CCI is below the thresholds for underlay or overlay transmission.

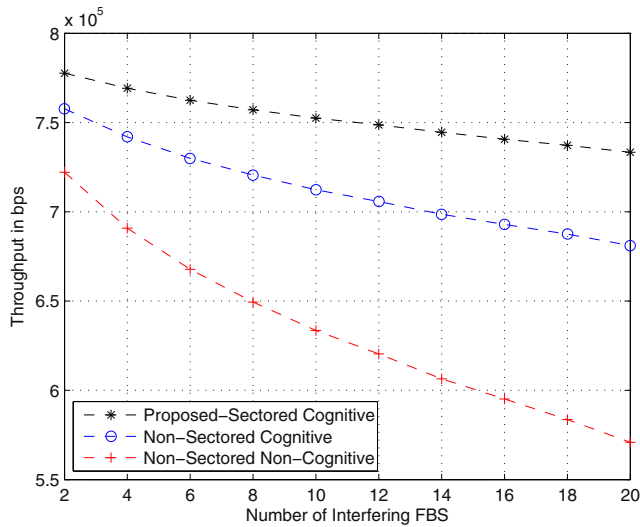
Two interference scenarios are considered in the study within a single MBS coverage as demonstrated in Fig. 2. The CCI on an MU includes multiple interfering FBSs and inter-cell CCI from MUs associated with neighboring MBSs in the first tier as shown in Fig. 2a. The CCI interference scenario on the target FU is expressed in Fig. 2b which includes an interfering MU along with multiple interfering FBSs. For CCI from neighboring MBS, a worst case scenario in which three out of six MBSs in the first tier having interfering MU in the outer region and remaining 3 having interfering MU in the inner region is considered. As macrocell radius is large



**Fig. 3** SINR performance of Macro User in dB for varying number of interfering Femto Users

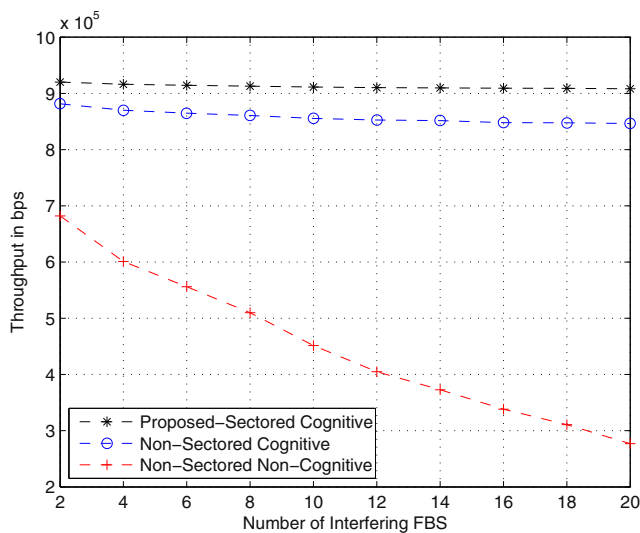


**Fig. 4** SINR performance of Femto User in dB for varying number of interfering Femto Users

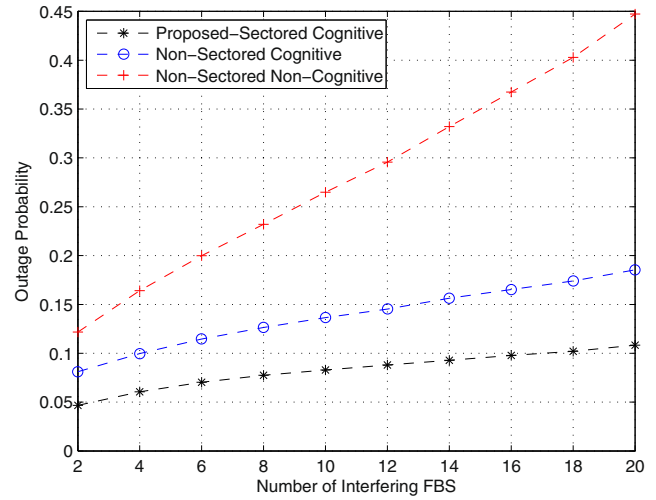


**Fig. 5** Throughput of Macro User in bps for varying number of interfering Femto Users

compared to femtocell and a minimum RB reuse distance with in MBS is implemented by the proposed RB allocation strategy, CCI from adjacent MBS on FU is neglected in this paper. Although several studies ignore femto-femto interference due to small transmission power of FBSs, such interference is not always negligible as this type of interference can be the performance limiting factor in dense deployment scenarios such as in an enterprise environment. Therefore interference region up to second tier depending on the femtocell radius is considered for FBSs in this study. Although the results are presented for the CCI in the inner region of macrocell, similar results can be extended to the outer region.

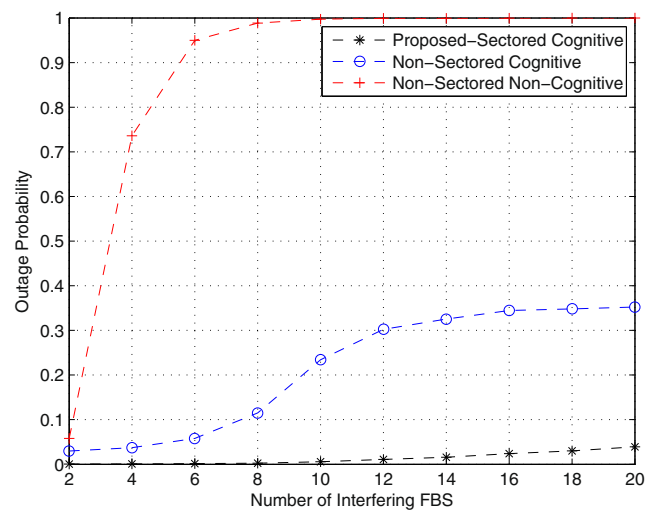


**Fig. 6** Throughput of Femto User in bps for varying number of interfering Femto Users



**Fig. 7** Outage Probability of Macro User for different number of interfering Femto Users

Results of the proposed framework are compared to typical cognitive and non-cognitive solutions. A cognitive solution without dynamic resource allocation and sectoring in the inner region of MBS and a non-cognitive-non-sectoring solution are considered for evaluating the performance of the proposed scheme. Each result is averaged over 100 thousands iterations, each with a random MU location within macrocell for a target FBS and a set of interfering FBSs. Location of the target FBS is kept constant throughout simulation. Throughput and outage probability are studied for varying number of interfering FBS. Proposed framework achieves performance improvement of at least 1.5dB in terms of SINR for MU, while the SINR improvement in



**Fig. 8** Outage Probability of Femto User for different number of interfering Femto Users

**Table 2** Comparison of theoretical and simulation results for average CCI

Interfering FBS's	Simulation		Theoretical	
	$CCI_{mk}$	$CCI_{fk}$	$CCI_{mk}$	$CCI_{fk}$
2	-127.4114	-130.0672	-127.4114	-130.0672
4	-126.7738	-129.5405	-126.7738	-129.5405
6	-126.2818	-129.3176	-126.2818	-129.3176
8	-125.8829	-129.1091	-125.8829	-129.1091
10	-125.5607	-128.9115	-125.5607	-128.9115
12	-125.2978	-128.7702	-125.2978	-128.7702
14	-125.0127	-128.7225	-125.0127	-128.7225
16	-124.7519	-128.6494	-124.7519	-128.6494
18	-124.5202	-128.5870	-124.5202	-128.5870
20	-124.2715	-128.5211	-124.2715	-128.5211

the case of FU is even better. The performance differences between proposed solution and other non-cognitive and cognitive solution gets larger as the number of interfering FBS increases as demonstrated in Figs. 3 and 4. This increase in SINR is mainly due to lower macro-femto CCI, as the proposed resource allocation strategy ensures higher reuse distance for a specific RB between macro and femto users. The results also indicate that the CCI from MU is the major performance limiting factor for the FU and that the CCI from neighboring FBS is not as significant since a gain of at least 4.8dB in terms of SINR at the FU is achieved by the proposed framework by limiting the CCI from the MU.

Figures 5 and 6 illustrate the throughput of MU and target FU for varying number of interfering FBSs, respectively. As can be seen, the proposed sectorized-cognitive solution with dynamic resource allocation gives the best results followed by non-sectorized cognitive solution. However, as the number of interfering FBS grows, the difference in throughput achieved by these solutions also increases. For the case of MU, the throughput provided by other solutions decays exponentially while for the proposed solution the decrease in throughput relative to increasing number of FBS is almost linear. Throughput improvement for both macro and femto users under the proposed framework is 0.06Mbps higher compared to the non-sectorized cognitive solution. Moreover, it can be seen through comparison that proposed framework provides highest throughput for both MU and FU while ensuring that the FU throughput is no less than MU throughput.

In Figs. 7 and 8, results of outage probability of MU and FU as a function of interfering FBS are presented for a fixed SINR threshold, respectively. There is significant difference in worst case outage probability maintained by the proposed solution compared to other solutions. It can be seen that outage probability increases as the number of interfering FBS increase while the proposed solution provides the minimum outage probability for both MU and FU. This

improvement can be explained by the decrease in macro-femto CCI and availability of higher number of RB for the use by FBSs through efficient resource allocation under the proposed solution. Sharp increase in the outage probability for non-sectorized-non-cognitive solution of FU can be attributed to significant increase in CCI between FBSs within a sector. The difference between the outage probability of both macro and femto users under proposed method and other solutions increases as the number of interfering nodes grows. The improvement in outage performance of MU for the proposed framework is as much as 7.7 %, and this difference gets larger for higher number of interfering FBSs. Similarly, the outage probability decreases by 31.35 % for the FU under the proposed solution as can be seen from Fig. 8.

The above results indicate that the proposed framework provides the best results in terms of both throughput and outage probability. Table 2 compares the theoretical and simulation results for average co-channel interference at the macro and femto users for the proposed scheme. The theoretical and simulation results match for CCI at both the MU and the FU validating the simulation model used for studying other performance metric. Since uniform power allocation is considered in this paper, these results only indicate the minimum possible gain under the proposed solution and employing advanced power allocation schemes will further improve the overall system performance.

## 7 Conclusion

In this paper, we proposed a novel resource allocation framework for cognitive macro-femto heterogeneous network that achieves full spectrum utilization at both femto and macro networks. The proposed framework combined dynamic resource allocation at MBS with cognitive FBSs to maximally utilize the available spectrum. Different resource

sharing methods, i.e., underlay/overlay, were employed for macro-femto and femto-femto resource block sharing based on the significance of their corresponding CCI on the system performance. The major research contribution include a resource allocation scheme that achieves universal frequency reuse at the macrocell and also ensures a minimum resource availability to the femtocells. Simulation results indicate the superior performance of proposed solution compared to traditional cognitive and non-cognitive solutions in terms of throughput and outage probability. In detail, the SINR improvement of at least 1.5dB at the MU and 4.8dB at the FU is achieved.

## References

- Zhou D, Song W (2011) Interference-controlled load sharing with Femtocell relay for macrocells in cellular networks. *IEEE Globecom*
- Bharucha Z, Haas H, Auer G, Cosovic I (2009) Femto-cell resource partitioning. *IEEE Globecom Workshops*
- Fradi N, Najeh S, Boujemaa H (2014) Resource allocation in OFDMA networks with Femto and macro-cells coexistence using fractional frequency reuse (FFR). *IEEE ComNet*
- Chen D, Jiang T, Zhang Z (2015) Frequency partitioning methods to mitigate cross-tier interference in two-tier Femtocell networks. *IEEE Trans Veh Technol* 64(5):1793–1805
- Sathya V, Gudivada HV, Narayanan H, Krishna BM, Tamma BR (2013) Enhanced distributed resource allocation and interference management in LTE Femtocell networks. *IEEE WiMob*
- Feng M, Chen D, Wang Z, Jiang T (2012) Throughput improvement for OFDMA Femtocell networks through spectrum allocation and access control strategy. *IEEE ComComAP*
- Kalbkhani H, Alamdari SJ, Solouk V, Shayesteh MG (2014) Interference management and six-sector macrocells for performance improvement in Femto-macro cellular networks. *Springer Wireless Personal Commun J* 75(4):2037–2051
- Feng M, Jiang T, Chen D, Mao S (2014) Cooperative small cell networks: high capacity for hotspots with interference mitigation. *IEEE Wireless Commun* 21(6):108–116
- Akyildiz IF, Reyes EC, Estevez DMG, Balakrishnan R, Krier JR (2013) Enabling next generation small cells through Femto-relays. *Phys Commun* 9:1–15
- Shahid A, Aslam S, Kim HS, Lee KG (2014) Distributed joint resource and power allocation in self-organized Femtocell networks: a potential game approach. *J Netw Comput Appl* 46:280–292
- Madan R, Sampath A, Khandekar A, Borran J, Bhushan N (2010) Distributed interference management and scheduling in LTE-A Femto networks. *IEEE Globecom*
- Huang M, Xu W (2012) Macro-Femto inter-cell interference mitigation for 3GPP LTE-A Downlink. *IEEE WCNCW*
- Li H, Wu K, Zhang Q, Ni LM (2014) CUTS: Improving channel utilization in both time and spatial domains in WLAN. *IEEE Trans Parallel Distrib Syst* 25(6):1413–1423
- Serrano AG, Giupponi L (2014) Self-organized femtocells: a fuzzy Q-learning approach. *J Wireless Netw* 20(3):441–455
- Wu K, Tan H, Liu Y, Zhang J, Zhang Q, Ni LM (2012) Side Channel: Bits over interference. *IEEE Trans Mob Comput* 11(8):1317–1330
- Wu K, Tan H, Ngan HL, Liu Y, Ni LM (2012) Chip error pattern analysis in IEEE 802.15.4. *IEEE Trans Mob Comput* 11(4):543–552
- Wu K, Li H, Wang L, Yi Y, Liu Y, Chen D, Luo X, Zhang Q, Ni LM (2013) hJam: attachment transmission in WLANs. *IEEE Trans Mob Comput* 12(12):2334–2345
- Wu K, Xiao J, Yi Y, Chen D, Luo X, Ni LM (2013) CSI-based indoor localization. *IEEE Trans Parallel Distrib Syst* 24(7):1300–1309
- Wang L, Wu K, Xiao J, Hamdi M (2014) Harnessing frequency domain for cooperative sensing and multi-channel contention in CRAHNS. *IEEE Trans Wirel Commun* 13(1):440–449
- Bo L, Cheng YD (2011) Inter-cell downlink co-channel interference management through cognitive sensing in heterogeneous network for LTE-A. *J China Univ Posts Telecommun* 18(2):25–32
- da Costa GWO, Cattoni AF, Roig VA, Mogensen PE (2010) Interference mitigation in cognitive Femtocells. *IEEE Globecom Workshop on Femtocell Networks*
- Oh DC, Lee YH (2012) Cognitive radio based resource allocation in Femto-cells. *IEEE J Commun Netw* 14(3):252–256
- Li YY, Macuha M, Sousa ES, Sato T, Nanri M (2009) Cognitive interference management in 3G Femtocells. *IEEE PIMRC*
- Ma Y, Lv T, Zhang J, Gao H, Lu Y (2012) Cognitive interference mitigation in heterogeneous Femto-macro cell networks. *IEEE PIMRC*
- Bartoli G, Fantacci R, Marabissi D, Pucci M (2014) Physical resource block clustering method for an OFDMA cognitive Femtocell System. *Phys Commun* 11:67–77
- Pramudito W, Alsusa E (2013) Joint dynamic energy-efficient spectrum allocation and routing in two-tiered 4G cellular systems. *IEEE Globecom*
- Shin DK, Choi W, Yu T (2013) Statistically controlled opportunistic resource block sharing for Femto cell networks. *IEEE J Commun Netw* 15(5):469–475
- Lee CH, Shih CY (2014) Coverage analysis of cognitive Femtocell networks. *IEEE Wireless Commun Lett* 3(2):177–180
- Zhang Q, Feng Z, Liu B, Zhang Y (2014) ANN based joint coverage self-optimization for random-deployed cognitive Femto-cell networks. *Pervasive Comput Networked World ICPCAS/SWS* 8351:790–802
- Huang L, Zhu G, Du HX (2013) Cognitive Femtocell networks: an opportunistic spectrum access for future indoor wireless coverage. *IEEE Wireless Commun* 20(2):44–51
- Huang JW, Krishnamurthy V (2011) Cognitive base stations in LTE/3GPP Femtocells: a correlated equilibrium game-theoretic approach. *IEEE Trans Commun* 59(12):3485–3493
- Urgaonkar R, Neely MJ (2012) Opportunistic cooperation in cognitive Femtocell networks. *IEEE J Selected Areas Commun* 30(3):607–616
- Vargas AM, Andrade AG, Sepulveda R, Ross OM (2014) An admission control and channel allocation algorithm based on particle swarm optimization for cognitive cellular networks. *Recent Adv Hybrid Approaches Design Intell Syst* 547:151–162
- Gharehshiran ON, Attar A, Krishnamurthy V (2013) Collaborative Sub-channel allocation in cognitive LTE Femto-cells: a cooperative game-theoretic approach. *IEEE Trans Commun* 61(1):325–334
- Esfahani AZ, Nakhai MR (2012) Secondary spectrum access and cell-edge coverage in cognitive cellular networks. *IET Commun* 6(8):845–851
- Tzelatis I, Berberidis K (2014) Cross-tier interference management schemes in cognitive heterogeneous networks. *EURASIP Journal on Wireless Communications and Networking*
- Feng M, Mao S, Jiang T (2015) Duplex mode selection and channel allocation for full-duplex cognitive Femtocell networks. *IEEE WCNC*
- Shalaby M, Shokair M, Abdo YSE (2014) Enhancement of geometry and throughput in LTE Femtocells cognitive radio networks. *Springer Wireless Personal Commun J* 77(1):649–659