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System Design and Performance Analysis of LTE Cognitive Femtocells

Mohamed Shalaby[1] · Mona Shokair[1] · Nagy Wadie Messiha[1]

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Abstract Femtocells' deployment can extend the LTE coverage to include indoor areas. Unfortunately, a mutual electromagnetic interference can occur among the macro cells and femtocells due to the co-channel deployment. Moreover, interference among the femtocells themselves can occur due to utilizing the same subcarriers. The two types of interference can degrade the system performance. Femtocells base station power control can reduce the interference, which affects the macro users at the expense of a drop in the femto users' geometry and throughput. A cognitive radio is proposed, as a novel approach, to completely eliminate the mutual interference among the macrocells and femtocells. The system is designed, mathematically analyzed, and simulated considering that the femto users are secondary users for the macro users. Analytical and simulation results show that applying the cognitive radio, to improve the system performance, is better than applying power control algorithms. The interference, which occurs among the femtocells, can be eliminated by different techniques. These novel techniques, which can achieve a maximization of the femto users' geometry, are proposed and illustrated in details.

Keywords LTE · Femtocells · Co-channel deployment · Power control · Cognitive radio

✉ Mohamed Shalaby
Mhmd_Shlpy@yahoo.com

Mona Shokair
mona.sabry@el-eng.menofia.edu.eg

Nagy Wadie Messiha
Dr.nagy_wadie@hotmail.com

[1] Faculty of Electronic Engineering, Menoufia University, Menouf, Egypt

1 Introduction

LTE is the 3GPP standard release which represents the fourth generation of mobile systems. Its downlink data rate can reach 100 Mbps [1, 2]. LTE coverage areas may have dead zones. These zones represent places, inside tunnels or indoor regions, where there is no signal or very poor signals. Femtocells' deployment is the best solution to extend the LTE coverage to include indoors [3–5]. They usually share the spectrum with the macrocells, in such a way that the subcarriers, utilized by the macrocells, can be reused in each femtocell. This type of spectrum assignment is called universal frequency reuse or a co-channel deployment. A mutual electromagnetic interference may occur among the macrocells and the femtocells and among the femtocells themselves due to the operation on the same spectrum. This interference can degrade the macro and the femto users' geometry, signal to interference and noise ratio (SINR), and throughput (bps).

There are previous ways to reduce the interference among the macrocells and the femtocells. Ref. [6–8] stated that a reduction of the femtocells' base station transmission power, as a form of power control, can reduce the interference, which affects the macro users. In other words, power control can improve the macro users' geometry and throughput. On the other hand, the femto users' geometry and throughput may be reduced. Moreover, the interference among the macrocells and the femtocells cannot be completely eliminated, when the power control is applied. In addition, the interference among the femtocells themselves is still a challenge.

In Ref. [9], cognitive radio network was proposed to completely mitigate the mutual electromagnetic interference among the macrocells and the femtocells. It is a dynamic spectrum access technology designed to solve under utilization of any fixed policy wireless network [10–12]. In this network, there is a primary user who has the priority to access the spectrum anytime. On the contrary, a secondary user can access the empty slots after the spectrum sensing process which is the most important stage in the cognitive radio system. The secondary user can be at an idle state until a free spectrum becomes available [13]. In the LTE cognitive femtocells system, there are macro users who are served from the macro base stations and femto users who are served from the femto base stations. Macro users are proposed as primary users, who have the priorities to occupy any subcarrier at any time. Femto users work as secondary users. They can access the subcarriers, which are not occupied by any macro user. Moreover, they have to vacate these subcarriers, when a macro user starts to access them. Femto users have to be smart, and able to be cognitive and reconfigurable. By applying the cognitive radio, the mutual electromagnetic interference, among the macrocells and the femtocells, is completely eliminated. Cancellation of this interference results in an enhancement of the macro and femto users' geometry. The interference becomes limited to the interference among the macrocells and the femtocells themselves.

In this paper, a practical case of applying the cognitive radio concept in a LTE femtocells system is studied. Mathematical analyses of the geometry and the throughput are carried out with respect to the false alarm probability and the missed detection probability. In addition, cancellation of the interference among the femtocells themselves is mathematically analyzed and approved by the simulation results. Shielding the cognitive femtocells, powered controlled cognitive femtocells, and increasing the separating distances among the cognitive femtocells, are proposed to eliminate this type of interference.

This paper is organized as follows: System architecture is explained in Sect. 2. Subsequently, in Sect. 3, the mathematical model, that describes the LTE system with femtocells, is clarified. A discussion of the power control algorithms is held in Sect. 4, and the proposed cognitive radio approach is illustrated and mathematically analyzed in Sect. 5. The proposed ways to eliminate the interference among the femtocells themselves are explained in Sect. 6. The advantages and disadvantages of the proposed system are stated in Sect. 7. The system simulation model and the analysis of the simulation results are handled in Sect. 8. Finally, conclusions are given in Sect. 9.

2 System Architecture

In this section, the LTE system architecture, which supports the cognitive femtocells, is explained in details. The architecture of the proposed system is shown in Fig. 1a, b. There are hexagonal LTE macrocells, which serve macro users. Inside each macrocell, there are femtocells to cover the dead zones and indoor areas. These femtocells can be used to provide a good coverage to the femto users. The macrocells and the femtocells are attached together through the core network (EPC) of the system. The proposed system consists of four parts which are explained as in the following.

2.1 Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Elements

The Home enhanced Node Base Station (HeNB) can provide a lot of functions such as; radio resource management, security, and connection of the femto user to the core network. A secure communication to the core network is provided by the security gateway. The HeNB gateway aggregates the HeNBs towards the core network, if the S1 interface cannot perform this aggregation [7]. The proposed system is designed considering that the interaction between the HeNBs and the macrocells is carried out through the S1 interface or the core network.

2.2 Evolved Packet Core (EPC) Network Elements

The core network is responsible for connecting all the parts of the network elements together. It can provide the switching facility among the different parts of the system [14].

2.3 Closed Subscriber Group (CSG) Provisioning Elements

CSG list server and CSG admin server can be used to hold the data about the femto users as they can be served from the femtocells only.

2.4 Packet Data Network (PDN) Elements

The PDN elements are responsible for connecting the system to the internet or any other IP multimedia system. This connection can interface the system to the outside world.

These elements are suggested before in Ref. [6, 7]. Alternatively, the proposed network model has a new part called a spectrum server (spectrum broker) [10, 11]. The function of

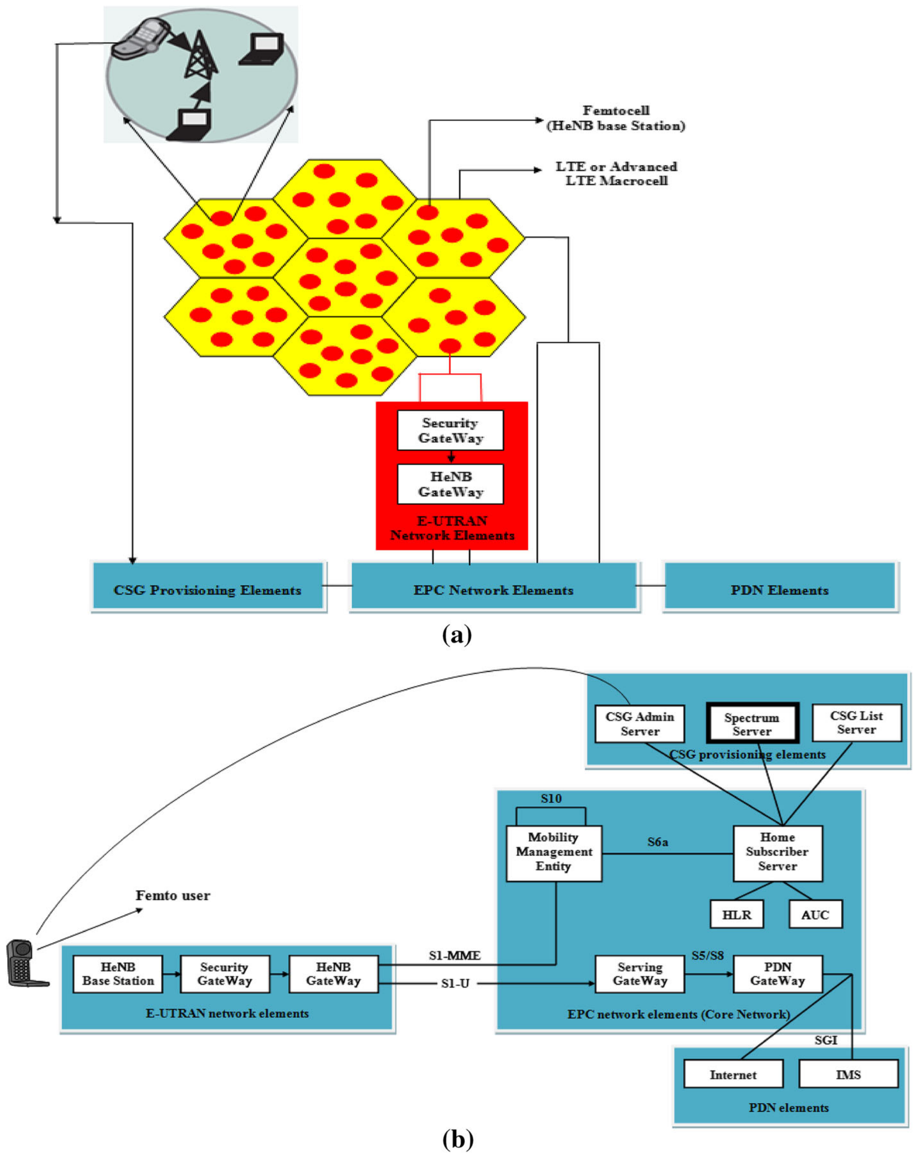

Fig. 1 LTE network architecture which supports the cognitive femtocells

the suggested server is to manage the free subcarriers among the HeNBs. It is the spectrum management part in the proposed LTE Cognitive Femtocells system. This server can collect the free subcarriers from the macro users and distribute them among the femtocells according to a certain procedure, which will be explained in Sect. 5. Moreover by using this server, the femto users cannot access any subcarrier, which is occupied by a macro user. Therefore, the mutual electromagnetic interference among the macro and the femto users can be efficiently reduced.

3 LTE Femtocells System Modelling

The performance of the LTE femtocells system can be evaluated by estimating the geometry (SINR) of the macro users and the femto users, and the obtained throughput [15]. This analysis can be carried out through three steps; the path loss models calculation, the SINR estimation, and the throughput evaluation as shown in Fig. 2. In the following, these steps will be explained.

3.1 Path Loss Models

Path loss maps [1] are used to express the loss in power, when the signals travel from base station to user equipment. These models are provided by 3GPP standard release. In fact, the path loss value (*PL*) is a function of the distance between the user equipment and the base station. Moreover, it depends on the position of the user equipment. The user may be outdoor or indoor. Assuming an urban deployment, these maps can be formed as in Ref [1];

- Macro base station (BS) to user equipment (UE)
  - UE is outside: Both BS and UE are outdoors.

$$PL(dB) = 15.3 + 37.6\log_{10} R \quad (1)$$

where R is the distance between the BS and UE expressed in meters.

  - UE is inside an apartment: The UE is indoor but, the BS is outdoor.

$$PL(dB) = 15.3 + 37.6\log_{10} R + W \quad (2)$$

where W is the wall attenuation loss.

- HeNB to UE
  - UE is inside the same apartment with the HeNB.

$$PL(dB) = 38.46 + 20\log_{10} R + W \quad (3)$$

  - UE is outside the apartment.

$$PL(dB) = \max([15.3 + 37.6\log_{10} R],\quad [38.46 + 20\log_{10} R]) + W \quad (4)$$

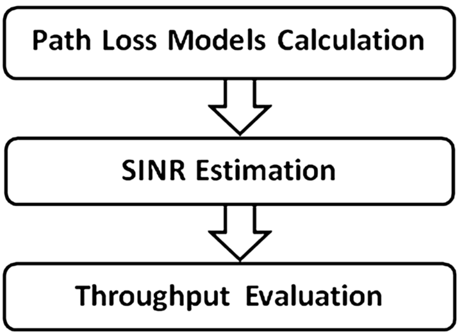

Fig. 2 The analysis steps of a LTE femtocells system

- UE is inside a different apartment.

$$PL(dB) = \max([15.3 + 37.6\log_{10} R], \quad [38.46 + 20\log_{10} R]) + W \tag{5}$$

To estimate W, the following models are used;

- UE is inside the same apartment with the HeNB.

$$W = q * L_{iw} + 18.3n^{\left(\frac{n+2}{n+1} - 0.46\right)} + 0.7d_{2D,indoor} \tag{6}$$

- UE is outside the apartment.

$$W = q * L_{iw} + L_{ow} + 18.3n^{\left(\frac{n+2}{n+1} - 0.46\right)} + 0.7d_{2D,indoor} \tag{7}$$

- UE is inside a different apartment.

$$W = q * L_{iw} + L_{ow1} + L_{ow2} + 18.3n^{\left(\frac{n+2}{n+1} - 0.46\right)} + 0.7d_{2D,indoor} \tag{8}$$

where q is the number of walls separating between the UE and HeNB, n is the number of penetrated floors, R and $d_{2D,\ indoor}$ (indoor distance) are in meters, L_{ow} is the penetration loss of the outer wall, and L_{iw} is the penetration loss of the inner wall.

3.2 SINR Estimation

The macro user can be interfered by the neighboring macrocells and all adjacent femtocells. In this case, the *SINR* of the received signal of a macro user m, which is loaded on a subcarrier k, is given by [15];

$$SINR_{m,k} = \frac{P_{M,k}G_{m,M,k}}{N_o\Delta f + \sum_{M'} P_{M',k}G_{m,M',k} + \sum_F P_{F,k}G_{m,F,k}} \tag{9}$$

where $P_{M,k}$ and $P_{M',k}$ are the transmitted power of the serving macrocell M and the neighboring macrocell M' on a subcarrier k, respectively. $G_{m,\ M,\ k}$ is the absolute channel gain between the macro user m and the serving macrocell M on a subcarrier k. The absolute channel gain from the neighboring macrocell M' is denoted by $G_{m,M',k}$. $P_{F,\ k}$ is the transmitted power of the neighboring femtocell F on a subcarrier k, and $G_{m,\ F,\ k}$ is the absolute channel gain between the macro user m and the neighboring femtocell F on a subcarrier k. N_o is the additive noise power spectral density and Δf is the subcarriers spacing.

The same analysis is used for the HeNBs, the *SINR* can be expressed as;

$$SINR_{f,k} = \frac{P_{F,k}G_{f,F,k}}{N_o\Delta f + \sum_M P_{M,k}G_{f,M,k} + \sum_{F'} P_{F',k}G_{f,F',k}} \tag{10}$$

The absolute channel gain can be expressed as a function of the path loss (dB) as;

$$G = 10^{-PL/10} \tag{11}$$

3.3 Throughput Evaluation

The throughput of a macro user m on a subcarrier k, $C_{m,\ k}$, can be evaluated by [15];

$$C_{m,k} = \Delta f \cdot \log_2(1 + \alpha \cdot SINR_{m,k}) \tag{12}$$

where α is a constant factor, which is a function of the target bit error rate (BER); $\alpha = -1.5/\ln(5.BER)$. Finally, the overall throughput of the serving macrocell M can be also estimated as in [15];

$$T_M = \sum\nolimits_m \sum\nolimits_k \beta_{m,k} C_{m,k} \tag{13}$$

where $\beta_{m,k}$ is the subcarrier assignment for a macro user. When $\beta_{m,k} = 1$, this means that the subcarrier k is assigned to a macro user m. Otherwise, it becomes zero. In a macro cell, each subcarrier is allocated to only one macro user at any time slot. From the characteristics of OFDMA, it can be observed that;

$$\sum\nolimits_{m=1}^{N_m} \beta_{m,k} = 1 \tag{14}$$

where N_m is the number of macro users in a macrocell.

4 Interference Reduction Using Power Control

Reduction of the HeNB transmission power is the main concept of power control algorithms. These algorithms are exploited to reduce the interference which affects the macro users. The HeNB transmission power can be reduced according to different strategies which are explained in [8];

- The first strategy is based on assigning a fixed value of power, P_f, to every HeNB. This value is less than the maximum allowed power for any HeNB (P_{max}) which is 20 dBm [1] ($P_f \prec 20\,\text{dBm}$).
- The second strategy depends on varying the HeNB transmission power in order to cover a certain range. The power of the HeNB is;

$$P_f = \min([P_M + G_\theta - PL_M(d) + PL_f(r)], \quad [P_{\max}]) \tag{15}$$

  where r is the femtocell radius, P_M is the macro base station transmission power, G_θ is the antenna gain, $PL_M(d)$ is the macrocell path loss at distance d, and $PL_f(r)$ is the femtocell path loss at distance r.
- The third strategy is to vary the HeNB transmission power in order to guarantee a target $SINR$ for user specified range. Suppose that, $SINR_t$ and $SINR_c$ are the target and the current $SINR$, respectively. The algorithm can be implemented as;

$$P(k+1) = \frac{SINR_t}{SINR_c} P(k) \tag{16}$$

  where $P(k)$ is the power level of HeNB at kth iteration.

5 Proposed Cognitive Radio Approach

In the proposed system, a practical case of applying the cognitive radio concept is suggested as an interference mitigation tool between the macrocells and the femtocells. Femto users are cognitive users (secondary users). They have to operate at the free subcarriers which are not occupied by any macro user (primary user). They can allocate the free subcarriers according to the following procedure;

a. Periodically, each femto user senses the wideband spectrum, 20 MHz, around 2 GHz. In this case, it senses 1200 subcarriers, assuming that 15 kHz is the bandwidth of a subcarrier. Assuming $x(t)$ is the macro user signal and $y(t)$ is the received signal at the femto user's receiver. The received signal at the femto user can be considered as;

$$\begin{aligned} y(t) &= n(t) \quad H_o \\ y(t) &= G \cdot x(t) + n(t) \quad H_1 \end{aligned} \tag{17}$$

where $n(t)$ is a noise signal, and G is the channel gain. H_o denotes that the macro user signal is absent, and H_1 gives an indication of the signal presence [16].

b. The femto user can detect each subcarrier, k, with probability of detection (P_{di}) and probability of false alarm (P_{fai}). This femto user takes a decision of 1 or 0 to indicate the sensing result. A decision of 1 means that a subcarrier k is occupied by a surrounding macro user. A decision of 0 means that a subcarrier k is not occupied by any surrounding macro user. This decision is sent to the spectrum server via each femtocell's base station.

c. As soon as the sensing decisions of the femto users reach to the spectrum server, it can apply AND rule to take a decision of the free subcarriers by all macro users [16]. By using the spectrum server, femto users can cooperate with each other to determine the free subcarriers by all macro users. The spectrum server can detect each subcarrier, k, with probability of detection (Q_d) and probability of false alarm (Q_f). Then, it can determine the free subcarriers, which are not occupied by any macro user, and manage these free subcarriers among the femtocells.

In fact, applying AND rule for the cooperation among the femto users, can help in avoiding the interference among the macro users and the femto users. To determine a free subcarrier, all femto users have to govern that this subcarrier is free.

Since the femto users avoid accessing the subcarriers which are occupied by the macro users. The *SINR* of the received signal at a macro user m on a subcarrier k, can be derived from Eq. 9, according to our proposal as;

$$SINR_{m,k} = \frac{P_{M,k}G_{m,M,k}}{N_o\Delta f + \sum_{M'} P_{M',k}G_{m,M',k} + (Q_{m.d})\sum_F P_{F,k}G_{m,F,k}} \tag{18}$$

where $Q_{m.d}$ is the cooperative missed detection probability of the sensing process (at the spectrum server). The *SINR* of the received signal at a macro user m on a subcarrier k, can be modified to;

$$SINR_{m,k} = \frac{P_{M,k}G_{m,M,k}}{N_o\Delta f + \sum_{M\prime} P_{M',k}G_{m,M',k} + (1 - Q_d)\sum_F P_{F,k}G_{m,F,k}} \tag{19}$$

$$SINR_{m,k} = \frac{P_{M,k}G_{m,M,k}}{N_o\Delta f + \sum_{M'} P_{M',k}G_{m,M',k} + \left(1 - \prod_{i=1}^{N_f} P_{di}\right)\sum_F P_{F,k}G_{m,F,k}} \tag{20}$$

where N_f is the number of the femto users in the system. It can be observed that, the interference due to the femtocells is reduced and this reduction depends on the missed detection probability of the cooperative sensing process or the detection probability of each femto user. If the detection probability of each femto user reaches to unity, the interference from the femtocells can be completely cancelled, which results in a *SINR* value of;

$$SINR_{m,k} = \frac{P_{M,k} G_{m,M,k}}{N_o \Delta f + \sum_{M'} P_{M',k} G_{m,M',k}} \tag{21}$$

The same analysis is carried out for the HeNBs (femtocells), the *SINR* of the received signal at a femto user f on a subcarrier k, can be deduced from Eq. 10, as cleared in the following equations;

$$SINR_{f,k} = \frac{P_{F,k} G_{f,F,k}}{N_o \Delta f + (Q_{m.d}) \sum_{M} P_{M,k} G_{f,M,k} + \sum_{F'} P_{F',k} G_{f,F',k}} \tag{22}$$

$$SINR_{f,k} = \frac{P_{F,k} G_{f,F,k}}{N_o \Delta f + (1 - Q_d) \sum_{M} P_{M,k} G_{f,M,k} + \sum_{F'} P_{F',k} G_{f,F',k}} \tag{23}$$

$$SINR_{f,k} = \frac{P_{F,k} G_{f,F,k}}{N_o \Delta f + \left(1 - \prod_{i=1}^{N_f} P_{di}\right) \sum_{M} P_{M,k} G_{f,M,k} + \sum_{F'} P_{F',k} G_{f,F',k}} \tag{24}$$

It can be observed that, the interference due to the macrocells is reduced and this reduction depends on the missed detection probability of the cooperative sensing process or the detection probability of each femto user. If the detection probability of each femto user reaches to unity, the interference from the macrocells can be completely cancelled, which results in a *SINR* value of;

$$SINR_{f,k} = \frac{P_{F,k} G_{f,F,k}}{N_o \Delta f + \sum_{F'} P_{F',k} G_{f,F',k}} \tag{25}$$

The throughput of a macro user, m, which is loaded on a subcarrier, k, can be evaluated by Eq. 12. On the other hand, the throughput of a femto user, f, which is loaded on a subcarrier, k, can be expressed as;

$$C_{f,k} = (1 - Q_f) \cdot (\Delta f \cdot \log_2[1 + \alpha \cdot SINR_{f,k}]) \tag{26}$$

where Q_f is the cooperative false alarm probability of the sensing process. Due to applying the AND rule in the cooperation process, the capacity of a femto user can be modified to;

$$C_{f,k} = \left(1 - \prod_{i=1}^{N_f} P_{fai}\right) \cdot (\Delta f \cdot \log_2[1 + \alpha \cdot SINR_{f,k}]) \tag{27}$$

In the proposed cognitive radio approach, the spectrum server apply the AND rule on the free subcarriers to make the final decision. In other words, a subcarrier is said to be free when all femto users say that it is free. Another cooperation mechanism can be used in the system which depends on applying the OR rule on the occupied subcarriers. This mechanism leads to the same previous performance.

6 Interference Mitigation Among the Femtocells

The interference among the macrocells and femtocells is completely eliminated, when the cognitive radio concept is applied assuming that the missed detection probability of the cooperative spectrum sensing is zero. Unfortunately, the interference among the femtocells themselves is still a challenge. In this section, a method to eliminate this type of interference is introduced. This method aims to maximize each femto user's geometry (*SINR*), in such a way that, the geometry of each femto user is dominated by the noise effect. The conditions and the mathematical analysis, which can help in reducing this type of interference, are derived and explained in details as in the following.

6.1 Interference Mitigation Under Realized Conditions

In this section, a mathematical expression, which represents an interference free femto user, is derived. To neglect the interference, which affects on femto user, *f,* from the neighboring femtocells, the *SINR* of a femto user, *f,* operating on a subcarrier *k* has to be simplified to the *SNR* (signal to noise ratio) value as,

$$SINR_{f,k} \approx SNR_{f,k} \tag{28}$$

The *SINR* is dominated by the noise effect. The previous equation requires that;

$$\sum\nolimits_{F'} P_{F',k} G_{f,F',k} \approx 0 \tag{29}$$

The interference due to the neighboring femtocells may not equal zero exactly, but it can be neglected when it has a very low value compared to the noise value. In other words, when the interference due to the neighboring femtocells becomes at least 10 times (as an assumption) less than the noise value, this interference can be neglected.

$$\sum\nolimits_{F'} P_{F',k} G_{f,F',k} \leq \frac{N_O \Delta f}{10} \tag{30}$$

Equation (30) represents the mathematical condition for maximizing a femto user's geometry and creation of an interference free femtocells.

6.2 Interference Mitigation Under Realized Tools

In this Section, the possible tools, which can be used to verify the above conditions, are discussed. To realize these conditions, the absolute path gain between a femto user, *f,* and all interfering femtocells should equal to zero.

A zero gain, $G = 10^{-PL/10} = 0$, results in $PL = \infty$. Then the following equation has to be verified as,

$$\max([15.3 + 37.6\log_{10} R], \quad [38.46 + 20\log_{10} R]) + L_{ow1} + L_{ow2} = \infty \tag{31}$$

The above equation represents the path loss map between a femto base station and a femto user, who is inside another femtocell assuming that $q = 0$, $n = 0$, and $d_{2Dindoor} = 0$. To satisfy this equation, three methods can be used and they are;

6.2.1 Increasing the Separating Distance Among the Cognitive Femtocells

This method, as a first one, requires that $R = \infty$, which means that a distance among the femtocells has to be very large in order to have interference free femtocells. In a more practical case, the minimum acceptable distance is that one, which satisfies Eq. 30.

6.2.2 Shielding the Cognitive Femtocells

This method, as a second one, achieves that $L_{ow1} = L_{ow2} = \infty$, which means that there is a perfect isolation among the femtocells. In other words, when the outer wall loss has a very high value, interference free femtocells can be created regardless the near far effect of them. In a more practical case, the outdoor wall losses can be modified to satisfy the Eq. 30. The higher values of outer wall losses can degrade the geometry and the throughput of a macro user, who is trapped indoor. This degradation can be solved by allowing handover from the macrocell to the femtocell. This handover can be carried out easily provided that the femtocells are in an open access mode.

6.2.3 Power Controlled Cognitive Femtocells

In this method, as a last one, the adjustment of distances among the femtocells or the outer wall losses are not required. Moreover, this method can be implemented for any femtocells' deployment and it depends on adapting the femtocells transmission power according to any power control technique in order to guarantee an interference free neighboring femtocells.

The first power control algorithm, which was stated in Ref. [8], can be applied to achieve the concept of Eq. 30. The femtocell transmission power can be adjusted to reduce the interference which is introduced to other femtocells. The femtocell transmission power (P_f) becomes;

$$8\,\mathrm{dBm} \leq P_f \leq 20\,\mathrm{dBm} \tag{32}$$

where 20 dBm is the maximum transmission power allowed by the femtocell according to 3GPP specifications [1, 17] and 8 dBm is an acceptable value of femtocell transmission power (It is not the minimum value) according to 3GPP specifications [17].

The third power control algorithm, which was also stated in Ref. [8], can be applied to achieve the concept of Eq. 30. This algorithm depends on varying the femtocell transmission power in order to guarantee a target *SINR* for a user specified range. Suppose that, $SINR_t$ and $SINR_c$ are the target and the current *SINR*, respectively. The power level can be implemented as;

$$P(k+1) = \frac{SINR_t}{SINR_c} P(k) \tag{33}$$

where $P(k)$ is the power level of femtocell at *kth* iteration. The iterations are continued till;

$$SINR_t \approx SNR \tag{34}$$

In all of these iterations, the femtocells transmission power cannot exceed the values which are specified before in Eq. 32.

7 Advantages and Disadvantages of the Proposed System

In the proposed system, the interference among the macrocells and the femtocells is mitigated. Moreover, the interference among the femtocells themselves is cancelled. Therefore, It has the advantages of overcoming both types of interference. On the contrary, there are a lot of disadvantages in the proposed system. These disadvantages can be stated as follows;

- The femto user becomes as a cognitive user. It should have a cognitive capability and a reconfigurability.
- The femto user has to be empowered by a sensor which continuously senses the spectrum around 2 GHz.
- The femto user should be able to cooperate with other femto users to detect the free subcarriers.
- The femto base station should have a data base and a fusion center to collect the free subcarriers from its serving femto users.
- LTE core network should have a spectrum server (spectrum broker) which represents a data base and a spectrum management device in the proposed system.
- Part of the spectrum may be wasted in the traffic which carries the cooperative sensing information among the femto users and the femto base stations.

8 Simulation Results

In this section, the proposed system is simulated to evaluate its performance. This performance is the macro and femto users' geometry and throughput (Mbps). A single macrocell, which serves eight macro users, is used. Inside this macrocell, there are four femtocells. Each femtocell serves two femto users. The simulation parameters, which are stated in Table 1, are chosen to satisfy the requirements of 3GPP 36.814 [1]. The performance of this system is estimated after applying the co-channel deployment, the power control, and the proposed cognitive radio. The flow charts of these algorithms are shown in Fig. 3a–c.

Figure 4a, b displays the CDF of macro users' geometry and femto users' geometry applying the co-channel deployment (C.D), the power control (P.C), when HeNB transmission power is 17 and 14 dBm, and the concept of cognitive radio (C.R), respectively. From Fig. 4(a), it can be observed that applying the power control can increase the macro users' geometry and this increase is a function of the HeNB transmission power. This result is due to the reduction of the HeNB transmission power can lower the interference that affects the macro users. In Fig. 4(b), it is clear that the power control can reduce the femto users' geometry. This means that, the serving power for each femto user is decreased and the interference from the neighboring femtocells is reduced. But the loss in the serving power is more than the loss in the interference, which is the reason for reducing the femto users' geometry. On the contrary, by applying the proposed cognitive radio approach, the interference from the macrocell is completely avoided, which results in an improvement in the femto users' geometry as depicted in Fig. 4(b). Moreover, applying the suggested cognitive radio can improve both of the macro and the femto users' geometry.

Figure 5 shows the CDF of the macro users' throughput. It can be observed that, the power control can improve the macro users' throughput. The increase in the macro users' throughput is due to the increase in the macro users' geometry. The improvement in throughput depends on the available subcarriers for the macro users. Portioning the subcarriers among the macro and the femto users in a dynamic manner is not exceeding an acceptable tool to illustrate the concept and the effect of applying the cognitive radio approach. It also can be concluded that, our macro users' throughput is better than the

Table 1 The simulation parameters

Simulation parameters	
Parameter	Value
Number of macrocells	1
Number of femtocells	4
Number of macro users per macrocell	8
Number of femto users per femtocell	2
Femtocell radius	20 m
Macro and femto user distribution	Random
Deployment	An Urban
Macrocell base station power	46 dBm
Femtocell base station power	20 dBm
Bit error rate	10^{-6}
Noise power spectral density	−174 dBm/Hz
Subcarriers spacing (subcarrier Bandwidth)	15 kHz
Modulation type	64QAM
Bandwidth	20 MHz
Subcarriers number	1200
Outer wall loss	10 dB
Number of penetrated floors	0
Inner walls number	0
Indoor distance	0
Detection probability of each femto user	1
False alarm probability of each femto user	0

corresponding one employing co-channel deployment or power control algorithm, when 40 % (or more) of subcarriers are available to be accessed by the macro users.

Figure 6 clarifies the average of femto users' throughput at different deployments. It can be concluded that, the power control can degrade the femto users' average throughput. This degradation is due to the reduction in the femto users' geometry as a result of utilizing the power control. On the other hand, employing the proposed cognitive radio can increase the average throughput, even when there are a small number of subcarriers, which are available to the femto users. Moreover, the average femto users' throughput in the proposed system is better than the corresponding one utilizing the co-channel deployment or the power control, even if 20 % subcarriers only are available to be accessed by the femto users (20 % S.F.U).

Figures 7 and 8 display the variation of macro and femto users' average throughput with the system bandwidth at different modulation techniques, respectively. It can be concluded that, more available bandwidth leads to more throughput. Moreover, by using higher order modulation techniques, the users' throughput can be increased. It may be a tradeoff between the available bandwidth and the modulation type to obtain a certain throughput. In other words, the macro and the femto users' throughput can be increased by allowing more frequency bands in the system or by using higher order modulation techniques.

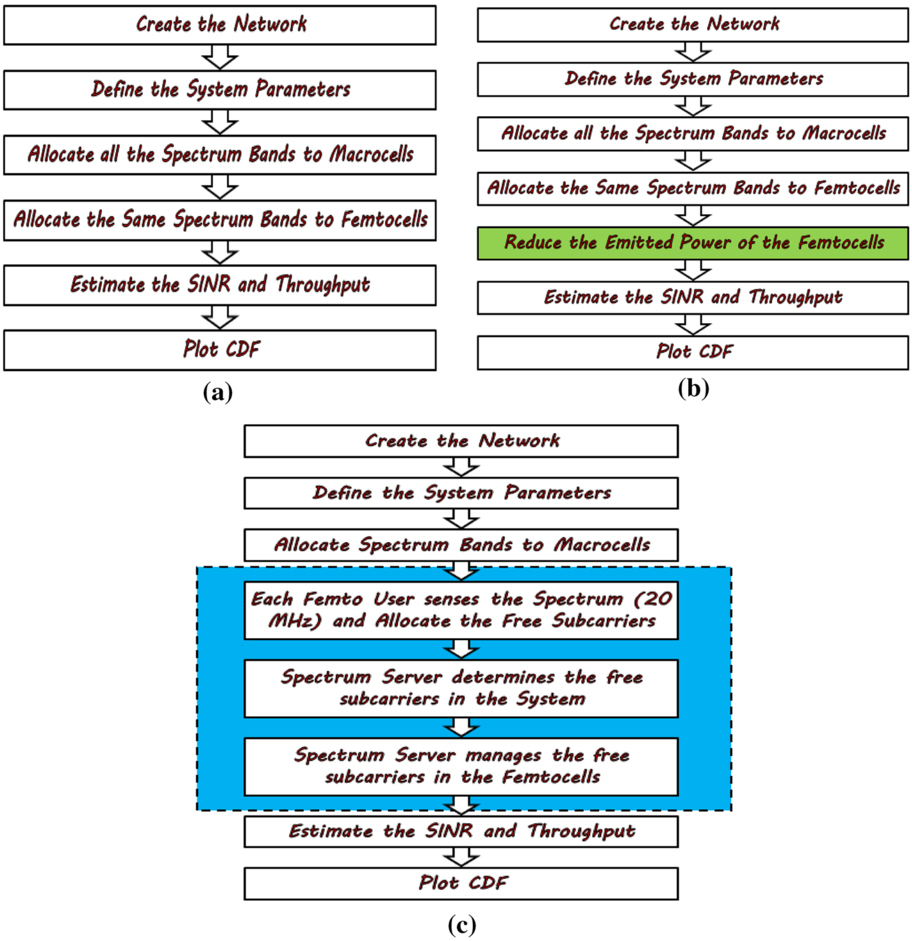

Fig. 3 Flowcharts of algorithms of co-channel deployment, power control, and cognitive radio

In the following paragraphs, the interference mitigation problem among the femtocells themselves is handled and simulated to determine the system performance. Moreover, the tools, which can be used for mitigation of this interference, are simulated.

The simulation model still has the same number of macro users and the same distribution (Random deployment). There are three femtocells which are equally spaced. The outer wall loss is set to an initial value of 44 dB. Each femtocell serves two femto users. The femto users are placed at the femtocell edge to enable the practical study of the system performance, especially at the power control cases. The distances among the femtocells are continuously changed and take values of 100, 50, and 40 m. At each distance, the possible ways, which can be used to mitigate the interference among these femtocells, are discussed assuming 20 % of subcarriers available to the femto users.

Figure 9 presents the macro user's geometry and throughput, when a macro user is at a certain distance from the macro base station. The distance among the femtocells is assumed to be 100 m. It is clear that, the macro users, which are near to the macro base station, can obtain a good geometry and hence a high throughput. On the other hand, the

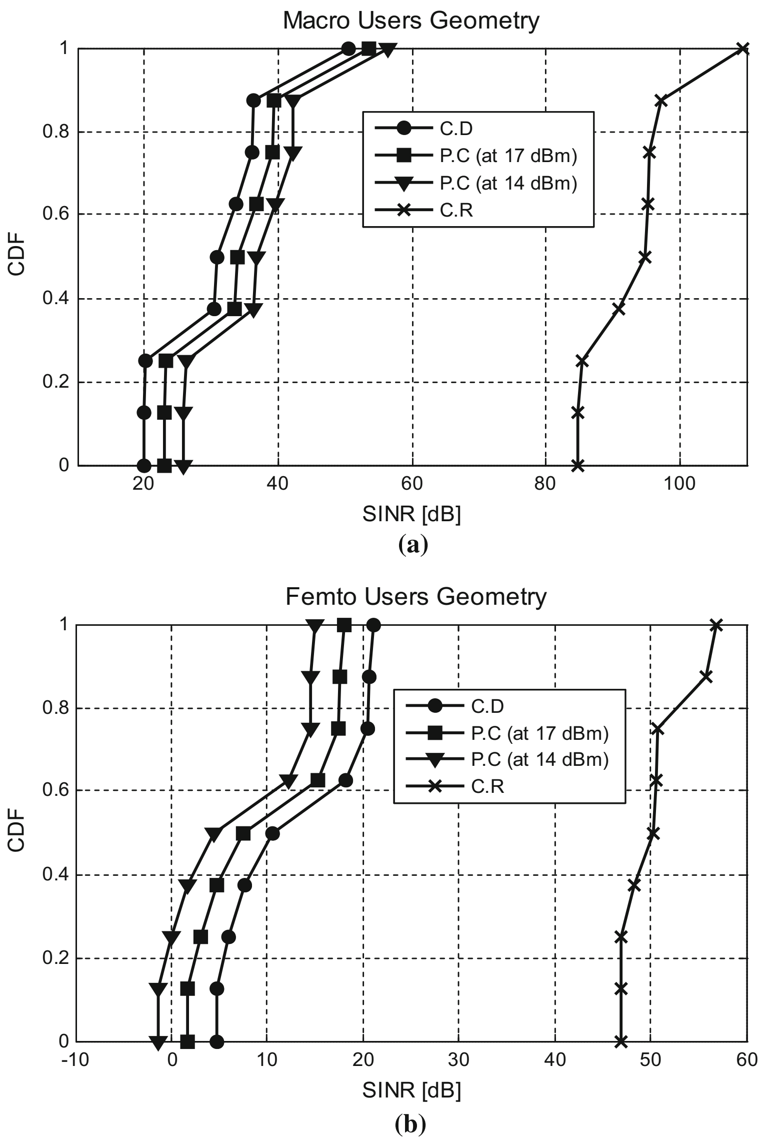

Fig. 4 CDF of the macro users' geometry and the femto users' geometry at different deployments

geometry and the throughput of macro users will be reduced, when they are far from the macro base station.

The femto users' geometry and throughput are estimated, when the distance among the femtocells is 100 m. It was observed that, the interference level at any femto user is less than the noise level, in such a way that the interference can be neglected and the *SINR* at any femto user is dominated by the noise effect. There is no need for applying power control or an adjustment of the outer wall loss (shielding). Table 2 displays the femto users' geometry and throughput before and after neglecting the interference. It can be

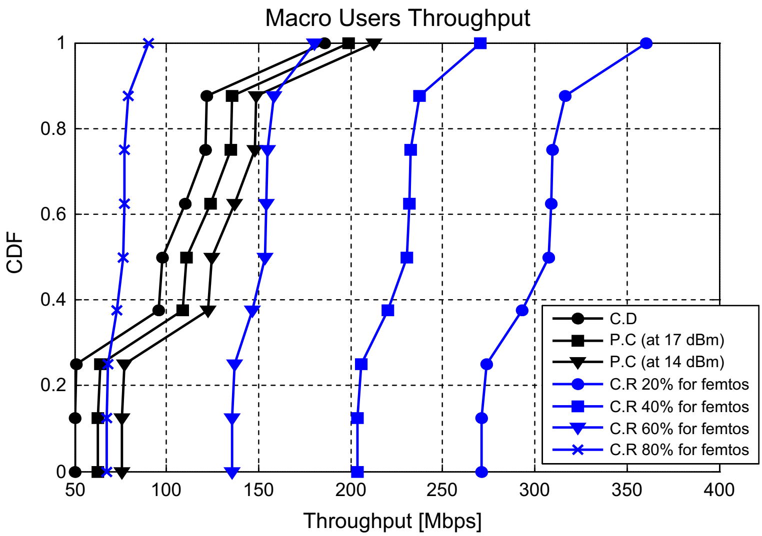

Fig. 5 CDF of the macro users' throughput at different deployments

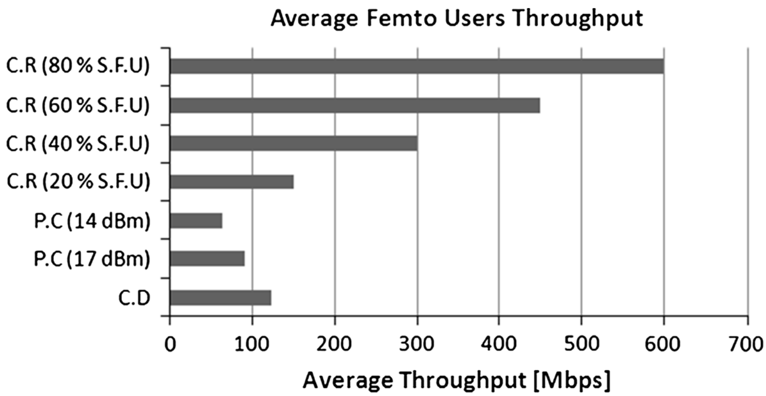

Fig. 6 The average of femto users' throughput at different deployments

observed that when the separating distance among the femtocells is high (infinity), the interference among the femtocells can be neglected and the femto users' geometry can be maximized. From Table 2, it can be concluded that neglecting the interference has a small effect on increasing the femto users' geometry and capacity, which confirm the theoretical analysis in Sect. 6.

A study of the proposed system performance is carried out, when the distance among the femtocells becomes 50 m. It can be observed that, the relation between the noise and interference at any femto user cannot allow the interference to be neglected. To mitigate the interference in this case, there are two possible ways. The first way is applying a power control algorithm. By using the power control, the maximum transmission power of the femtocell base station becomes 16 dBm. The value of 16 dBm is the maximum value which allows the interference to be neglected. The second method is the femtocell

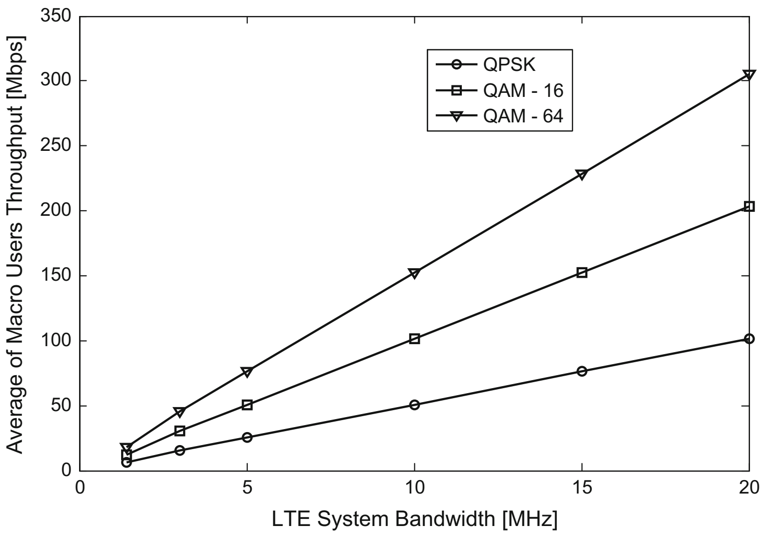

Fig. 7 The average of macro users' throughput at different bandwidths and modulation techniques

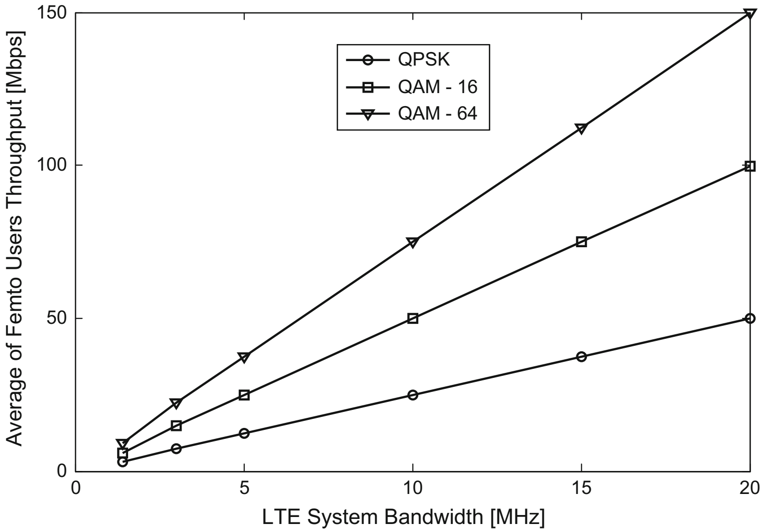

Fig. 8 The average of femto users' throughput at different bandwidths and modulation techniques

shielding (increasing the outer wall loss). It was noticed that, the minimum value of the outer wall loss becomes 46 dB. Table 3 presents the average of femto users' geometry and throughput of the cognitive case, cognitive case combined with power control, and cognitive case combined with shielding. It is clear that applying the power control can degrade the femto users' geometry and throughput. On the other hand, a good shielding of the femtocells can improve the femto users' geometry and throughput. Moreover, after

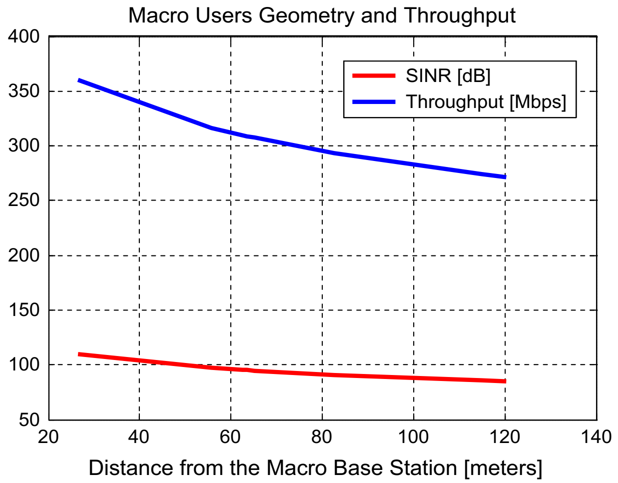

Fig. 9 Macro users' geometry and throughput variation with their distances from the macro base station

Table 2 The femto users' geometry and throughput before and after neglecting the interference

Average of femto users' geometry and throughput		
	Average SINR (dB)	Average throughput (Mbps)
With Interference	88.6505	285.3845
Without Interference	88.6736	285.4675

Table 3 The femto users' geometry and throughput at the cognitive case, cognitive case combined with power control, and cognitive case combined with shielding (distance = 50 m)

Average of femto users' geometry and throughput						
	Cognitive case		Applying power control		Applying shielding	
	Average SINR (dB)	Average throughput (Mbps)	Average SINR (dB)	Average throughput (Mbps)	Average SINR (dB)	Average throughput (Mbps)
With interference	88.2517	283.9538	84.4977	270.4856	88.4977	284.8363
Without interference			84.6736	271.1168	88.6736	285.4675

applying the power control or the shielding, there is a small change in the femto users' geometry and capacity. This confirms the theoretical analysis and the condition of neglecting the interference, when its value becomes less than or at least equal to 0.1 of the noise effect.

A study of the proposed system performance is carried out, when the distance among the femtocells decreased to 40 m. It can be observed that, the relation between the noise and interference at any femto user cannot allow the interference to be neglected. To eliminate the effect of this interference, there are two possible ways. The first way is applying a power control algorithm. By using the power control, the maximum

Table 4 The femto users' geometry and throughput at the cognitive case, cognitive case combined with power control, and cognitive case combined with shielding (distance = 40 m)

Average of femto users' geometry and throughput

	Cognitive case		Applying power control		Applying Shielding	
	Average SINR (dB)	Average throughput (Mbps)	Average SINR (dB)	Average throughput (Mbps)	Average SINR (dB)	Average throughput (Mbps)
With interference	87.5239	281.3427	78.5292	249.0727	88.5292	284.9495
Without interference			78.6736	249.5907	88.6736	285.4675

transmission power of the femtocell base station becomes 10 dBm. The value of 10 dBm is the maximum value, which allows the interference to be neglected. The second method is the femtocell shielding. It was noticed that, the minimum value of the outer wall loss becomes 49 dB. Table 4 presents the average of femto users' geometry and throughput of the cognitive case, cognitive case combined with power control, and cognitive case combined with shielding. It is clear that, applying the power control can degrade the femto users' geometry and throughput. On the other hand, a good shielding of the femtocells can improve the femto users' geometry and throughput.

9 Conclusions

The practical case of applying the cognitive radio concept was proposed as an interference reduction technique among the macrocells and the femtocells in a LTE Femtocells system. It was observed that, applying the cognitive radio can improve the performance of the LTE femtocells system. The interference, which occurs among the femtocells themselves, can be mitigated through different techniques. These techniques include; increasing the separating distance among the cognitive femtocells, shielding the cognitive femtocells by increasing the outer wall loss, and applying the adaptive power control in the cognitive femtocells. It can be concluded that the shielding can improve the femto users' geometry and throughput at the expense of a degradation in the performance of the macro user who is trapped indoor (inside a femtocell). On the contrary, applying power control can degrade the femto users' geometry and throughput.

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Mohamed Shalaby was born in Menoufia, Egypt, in 1986. He received the B.Sc. degree in electronics, and electrical communications engineering from Menoufia University, Menoufia, Egypt, in 2008. His research interests include wireless communications, broadband technologies, mobile communications, and next generation networks.

Mona Shokair received B.Sc., and M.Sc. degrees in electronics engineering from Menoufia University, Menoufia, Egypt, in 1993, and 1997, respectively. She received the Ph.D. degree from Kyushu University, Japan, in 2005. She received VTS chapter IEEE award from Japan, in 2003. She received the Associated Professor degree in 2011. Recently, she is an Associate Professor at Menoufia University. Her research interests include AAA, CDMA system, WIMAX system, OFDM system, Cognitive Radio Networks, M2M networks and wireless sensor Networks. She published about 67 papers until 2015.

Nagy Wadie Messiha received the B.S. in Electrical Engineering Telecommunication Department, Ein Shams University, Cairo, Egypt, June 1965, and M.S. in telecommunication engineering, Helwan University, Cairo, Egypt, 1973, and the german (Dipl. Ing.) and (Dr. Ing.) from University of Stuttgart, in 1978 and 1981 respectively. From 1981 to 1987. Currently, he is a professor at the Department of Communication Engineering, Menoufia University, Menouf, Egypt. His research interested is traffic modeling and performance enhancement in communication and computer networks, cognitive networks, and network security.