

# Performance Enhancement of LTE Underlay Cognitive Femtocells System Based on Macro Users Localization

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**Abstract** *LTE* overlay cognitive femtocells system can provide a satisfied throughput for the macro and the femto users. On the other hand, the femto users can assign only the vacated subcarriers from the macro users. This assignment results in a reduced throughput for the femto users. Moreover, their throughput can have a zero value when the macro users operate on all subcarriers. In this paper, an underlay cognitive femtocells operation is proposed. The femtocells can share the subcarriers with the existing macrocells in such a way that their transmission cannot affect the macro users' performance. The macro users' positions can be determined, during their uplink transmission, using the received signal strength at the femto users. Then, the femtocells adapt their emitted power to guarantee a satisfied macro users' performance. The performance of the proposed *LTE* underlay cognitive femtocells system is mathematically analyzed, simulated, and compared with the previous one which applies overlay cognitive femtocells. It can be observed that, the femto users' throughput is existent and has a high value in comparison with the previous *LTE* overlay cognitive femtocells system. Furthermore, the proposed system has a higher macro and femto users' throughput.

**Keywords** *LTE* · Femtocells · *EMI* · Overlay cognitive · Underlay cognitive · Localization

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## 1 Introduction

*LTE* femtocells system can provide a satisfied throughput for the users with a good indoor coverage. Thanks to the deployment of the femtocells inside *LTE* macrocells, the network service can be available anywhere. Moreover, the trapped indoor users can have a satisfied throughput [1–7]. On the other hand, the femtocells' deployment inside *LTE* macrocells leads the available spectrum to be accessed by both macro and femto users. Therefore, a mutual electromagnetic interference (*EMI*) exists between the macrocells and the femtocells. This *EMI* value can degrade the performance of the system. This deployment is called a co-channel deployment or a universal frequency reuse one. In Ref. [6, 7], authors simulated a *LTE* femtocells system and estimated its geometry, signal to interference plus noise ratio, and its throughput applying a co-channel deployment scenario. They developed a recent *LTE* femtocells system level simulator. Subsequently, Ref. [8] presented a new mathematical model for a co-channel deployment *LTE* femtocells system. The authors developed a mathematical formula for the users' geometry and throughput based on a simple capacity concept. Moreover, it presented a novel matlab simulation framework for a *LTE* femtocells system which applies the co-channel deployment scenario.

There are a lot of strategies which can reduce the mutual *EMI* between the femtocells and the macrocells. One of these strategies is the Fractional Frequency Reuse (*FFR*). This strategy depends on distributing the available spectrum bands on the *LTE* femtocells system coverage area, in such a way that, the same frequency band can be reused when a minimum separation distance exists. The *FFR* may be applied in a static or a dynamic manner [9]. Another strategy, used for interference reduction, is the power control. This strategy aims to reduce the radiated power of the femtocells in order to reduce the resulting interference on the neighboring macrocells and femtocells. Authors of Ref. [10] explained, in details, three different power control algorithms. They clarified that the femtocells' emitted power may be reduced in a random manner, according to a new specified femtocells' range, or according to a target value of the femto users' geometry. Subsequently, power control is modified in the self-organizing *LTE* femtocells network, in such a way that, the femtocells start transmission with a nominal power value then, they can adapt their power in order to optimize and reduce the interference levels affecting the neighboring femtocells [11]. In addition, a novel backoff power control scheme, aiming to discover the fake femto base stations, was handled in Ref. [12]. In general, power control algorithms can reduce the mutual *EMI* between the femtocells and the macrocells. On the other hand, they can lower the geometry and throughput of the femto users.

Cognitive radio is a dynamic spectrum access technology developed to increase the utilization of a wireless radio spectrum. It allows low priority secondary users to operate at the portion of the radio spectrum, which is not occupied by high priority primary users [13]. The deployment of cognitive radio technology in a *LTE* femtocellular system is introduced in Ref. [14]. It divided the macro and femto users into primary and secondary users. Moreover, it suggested network architecture for a *LTE* cognitive overlay femtocells system. This architecture combined the conventional femtocell idea with an infrastructure based overlay cognitive radio network paradigm. In addition, it stated a lot of challenges in the *LTE* cognitive overlay femtocells system. These challenges may be the future research work in the topic. The concept of deploying cognitive femtocells in *LTE* networks is extended in Ref. [15]. It handled the two types of interference which are co-tier interference (among the femtocells themselves) and the cross tier interference (between the macrocells and the femtocells). To solve the spectrum scarcity problem, the cognitive

femtocells can use both of licensed and unlicensed bands from the macrocells and the TV white spaces. Other femtocells' management strategies, to reduce the mutual *EMI* between the macrocells and the femtocells, were demonstrated in Ref. [16]. These strategies included; conventional, centralized, and distributed. Furthermore, the paper clarified several cognitive channel assignments for the femtocells. Each femtocell management strategy was simulated and compared with the traditional macrocell system to assure the effect of applying the cognitive radio technology.

In Ref. [17, 18], authors applied the cognitive radio technique in order to reduce the mutual *EMI* value between the macrocells and the femtocells. They explained, in details, the system mathematical model. Moreover, they developed the network architecture, which had been stated before in Ref. [7], to support the cognitive capabilities through using a spectrum management subsystem called a spectrum server. It was a data base to include the radio resource map and the sensing results of the cognitive femto users. It was a great chance to completely eliminate the mutual *EMI* in a *LTE* femtocells system. Moreover, the users' throughput is increased as a result of applying the cognitive radio technique. On the other hand, Ref. [18] demonstrated the interference reduction among the femtocells themselves. The outage probability of macro and femto users, over Nakagami-*m* fading channels, was estimated by applying a novel stochastic model. This model considered the closed access mode and multiple types of cognitive interference management strategies for the femtocells [19]. In general, the overlay cognitive femtocells can operate at 20 dBm which is the maximum allowed transmitted power. The main drawback of this operation is that the femtocells can operate at their maximum power. Moreover, the femto users can only access the free subcarriers, which are not occupied by a macro user. Therefore, the femto users can have a zero throughput when there are no free subcarriers for them, regardless the high values of signal to interference plus noise ratio (*SINR*). It is a main drawback, in the system, to have a zero value of femto users' throughput.

In this paper, the femtocells are allowed to operate at the subcarriers even if they are occupied by a macro user. The mutual *EMI*, which occurs between the femtocells and the macrocells, is allowed to grow on condition that its value cannot affect the operation of the nearest macro users. The femto users can receive the emitted power of each macro user during the uplink transmission. The received power, at each femto user, can give an indication about the macro users' positions. The received signal strength (*RSS*), at each femto user, can be sent to the fusion center of the system. At least, three of femto users can actually determine the coordinates of a macro user. When the positions of the macro users are determined, the femtocells can adapt their emitted power in order to reduce the interference on macro users. The reduction of the femtocells' transmitted power allows them to operate at all subcarriers even if the macro users operate on these subcarriers. The femtocells' operation is an underlay cognitive one.

The *LTE* underlay cognitive femtocells system is proposed in this paper. The proposed system is explained in details, mathematically analyzed, and simulated. Moreover, the performance of the proposed system is validated by comparisons with that system which applies the overlay cognitive femtocells. In addition, the determination of macro users' coordinates is clarified using Cramer rule. Furthermore, the mathematical conditions, which allow the proposed underlay cognitive operation, are derived and approved in the simulation results. Finally, the validation of Cramer rule in macro users' positioning is verified in the simulation results.

This paper is organized as follows; Sect. 2 describes the proposed system and the proposed network model. Section 3 gives the explanation of the proposed *LTE* underlay cognitive femtocells algorithm. On the other hand, Sect. 4 handles the path loss models'

calculation. In Sect. 5, the macro users' localization, using Cramer rule, is explained. Subsequently, the mathematical conditions, which can control the operation of underlay cognitive femtocells, are derived in Sect. 6. The power control techniques, which can be applied as realization tools for the proposed underlay operation, are clarified in Sect. 7. However, Sect. 8 deals with the calculation of macro and femto users' throughput. Subsequently, Sect. 9 discusses the simulation results. Finally, conclusions are given in Sect. 10.

## 2 System Architecture

This section explains, in details, the network architecture for a *LTE* underlay cognitive femtocells system. The system and the detailed network architecture are shown in Fig. 1a, b. The *LTE* macrocells has a hexagonal pattern. Inside each hexagonal macrocell, the femocells are randomly distributed in order to extend the network coverage inside indoor zones and the other poor service regions. The macrocells can serve the primary macro users. On the other hand, the femtocells can provide service to the secondary femto users only (closed access mode). The macrocells and the femtocells can be connected together through the core network. In fact, this architecture was developed before in Ref. [17, 18]. However, it can fit well in both overlay cognitive and the proposed underlay cognitive operation. There are four parts and they are;

### 2.1 Evolved Universal Terrestrial Radio Access Network (*E-UTRAN*) elements

The Home enhanced Node Base Station (*HeNB*) is responsible for several functions. These functions include; management of the radio resources, connection establishment between the femto users and the core network, and providing security services through the security gateway. In this network model, the interaction between the femtocells (*HeNBs*) and the macrocells can be carried out at the core network or at the *SI* interface [17, 18].

### 2.2 Evolved Packet Core (*EPC*) Network Elements

Connection of the different parts of the system is the responsibility of the core network. In addition, it can provide the switching facilities among the different parts of the system [17, 18].

### 2.3 Closed Subscriber Group (*CSG*) Provisioning Elements

*CSG* list servers and *CSG* admin servers are the femto users' data base, in such a way that, they can save necessary data about the femto users only [17, 18].

### 2.4 Packet Data Network (*PDN*) Elements

The *PDN* elements can provide connections between the proposed system and Internet or any other *IP* multimedia system [17, 18].

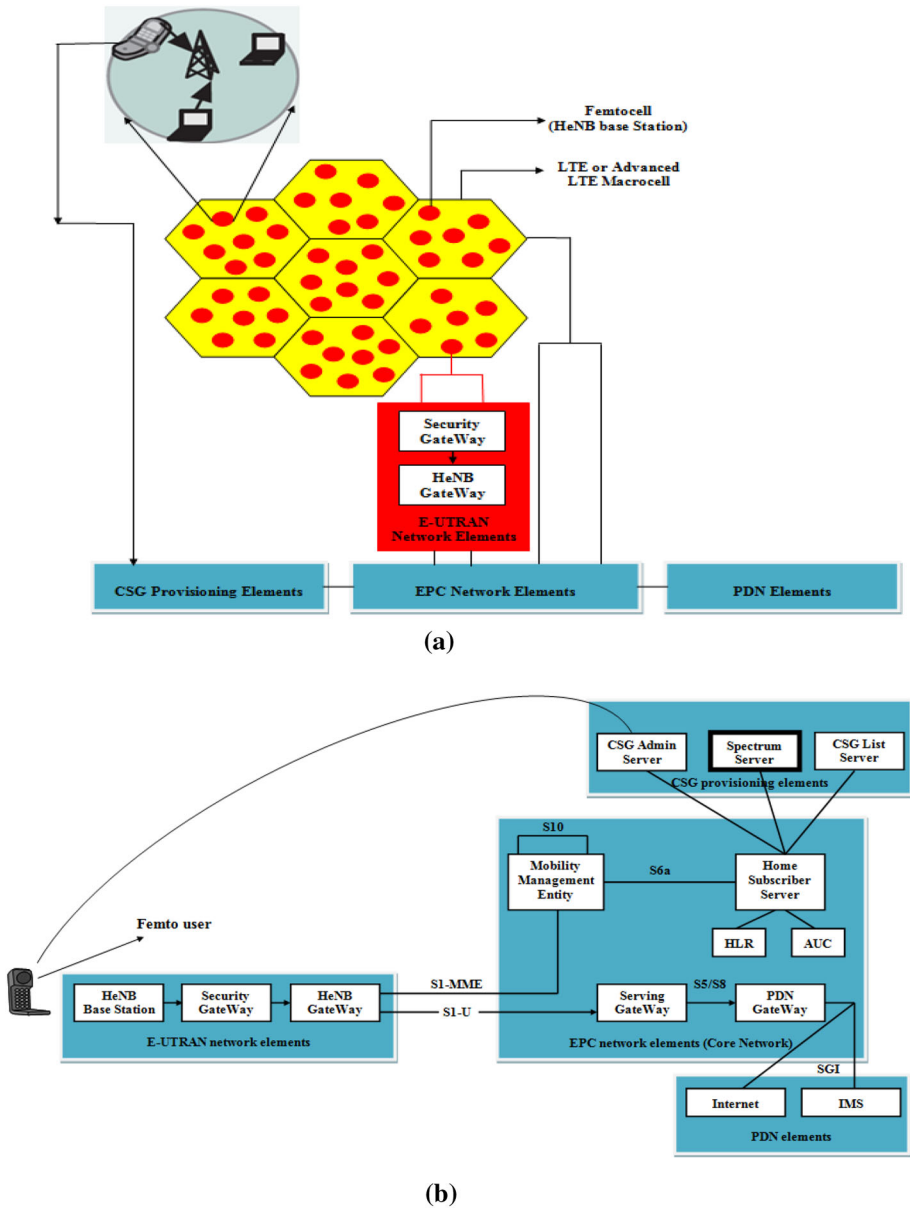
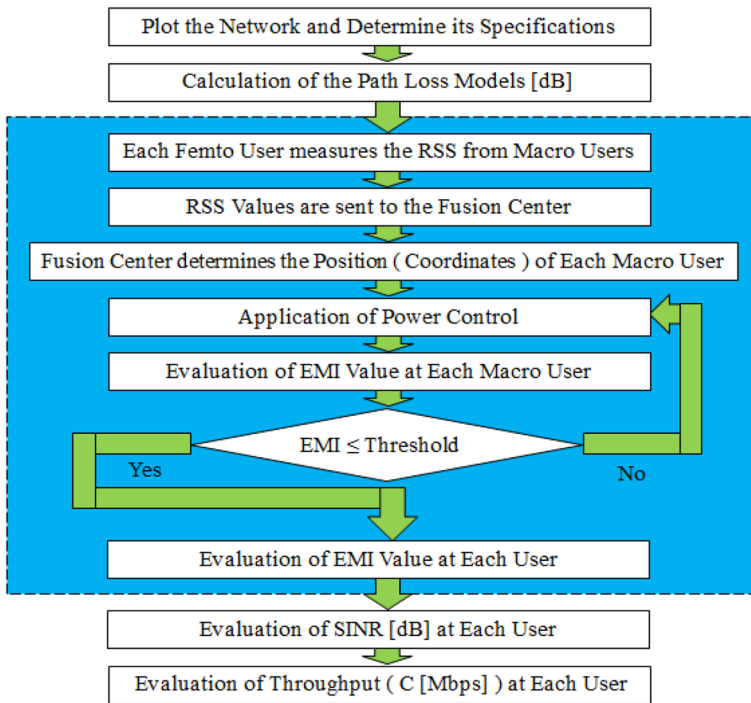


Fig. 1 LTE network architecture, which supports the cognitive femtocells [17, 18]

### 3 Proposed Underlay Cognitive Femtocells Algorithm

The proposed algorithm for an underlay cognitive operation in a *LTE* femtocells system passes through a lot of different steps. These steps, which are shown in Fig. 2, can be explained as follow;



**Fig. 2** The proposed underlay cognitive femtocells’ operation in a *LTE* femtocells system

- During the uplink transmission, each femto user detects the received signal strength (*RSS*) of the corresponding macro users. The detected *RSS* values are sent to the fusion center of the system.
- It is assumed that the fusion center of the system has a priori knowledge about the network such as; femtocells’ locations, femto users’ positions, and much more. The received *RSS* at the femto users can be converted to corresponding distances by the following relation;

$$R = 10^{\frac{PL(dB) - W - 15.3}{37.6}} \tag{1}$$

where *R* is the distance between the transmitting macro user and the detecting femto user, *W* is the wall loss of the femtocells, *PL(dB)* is the path loss between the transmitting macro user and the detecting femto user [1]. This path loss value can be calculated by;

$$PL(dB) = 21 - RSS(dBm) \tag{2}$$

where 21 dBm is the transmitted power of the macro user (in the uplink) according to the *3GPP* standard [21] and *RSS(dBm)* is the received signal strength at the detecting femto user expressed in dBm. In fact, Eq. 1 represents the path loss map between a trapped femto user and a macro base station but the macro user, in this situation, replaces the macro base station as the transmission is in the uplink.

- The fusion center can convert each *RSS* value to a corresponding distance value by using Eqs. 1 and 2. It is obvious that; each femto user can detect the *RSS* from each macro user. The determined distances, by the femto users, can help in determination of macro users' coordinates. The fusion center can use Cramer rule to determine the actual coordinates of each macro user. This will be explained in the following sections.
- As soon as the coordinates of the macro users had been determined, the power control could be applied on the femtocells' base stations in order to reduce the interference, which affects the nearest macro users. The power of the femtocells is reduced and the mutual *EMI* level on each macro user, caused by the femtocells' transmission, is estimated. The mutual *EMI* is allowed to grow until a certain value. This value will be mathematically determined and approved in the simulation results.
- The signal to interference plus noise ratio (*SINR*) and throughput of the users can be obtained.

#### 4 Path Loss Models

Path loss equations are provided by the *3GPP* standard releases [1]. These equations can represent the loss in power for the transmitted signals in the downlink. The path loss (*PL*) value depends on; the distance separating between the base station and the user equipment, the location of the user (indoor or outdoor), and the deployment environment [1, 8, 17]. Assuming an urban environment, the path loss models can be expressed as follow;

- Macro base station (*BS*) to user equipment (*UE*)

- *UE* is outside: Both *BS* and *UE* are outdoors.

$$PL(dB) = 15.3 + 37.6 \log_{10} R \quad (3)$$

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.

$$PL(dB) = 15.3 + 37.6 \log_{10} R + W \quad (4)$$

where *W* is the wall attenuation loss.

- HeNB to *UE*

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

$$PL(dB) = 38.46 + 20 \log_{10} R + W \quad (5)$$

- *UE* is outside the apartment.

$$PL(dB) = \max([15.3 + 37.6 \log_{10} R], [38.46 + 20 \log_{10} R]) + W \quad (6)$$

- *UE* is inside a different apartment.

$$PL(dB) = \max([15.3 + 37.6 \log_{10} R], [38.46 + 20 \log_{10} R]) + W \quad (7)$$

To estimate *W*, the following equations are used;

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

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

- *UE* is outside the apartment.

$$W = q * L_{iw} + L_{ow} + 18.3n \left( \frac{n+2}{n+1} - 0.46 \right) + 0.7d_{2D,indoor} \tag{9}$$

- *UE* is inside a different apartment.

$$W = q * L_{iw} + L_{ow1} + L_{ow2} + 18.3n \left( \frac{n+2}{n+1} - 0.46 \right) + 0.7d_{2D,indoor} \tag{10}$$

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

### 5 Macro Users' Localization Using Cramer Rule

Cramer rule can be used in the determination of a certain node coordinates [20]. It is used, in this paper, to determine the coordinates of the macro users. The fusion center can determine the macro users' coordinates with the help of the femto users' coordinates and the obtained separating distances between the macro users and the femto users. The fusion center, with the help of Cramer rule, can determine a macro user's coordinates by using the separating distances and the coordinates of the nearest three femto users as shown in Fig. 3. For more clarification, the nearest three femto users, which enclose a macro user, have coordinates;  $(x_1, y_1)$ ,  $(x_2, y_2)$ , and  $(x_3, y_3)$ . The separating distances between the three femto users and the macro user, which its coordinates needed to be determined, are;  $R_1, R_2$ , and  $R_3$ . Then, the coordinates of this macro user,  $(x_u, y_u)$ , can be obtained by the following equations;

$$(x_i - x_u)^2 + (y_i - y_u)^2 = R_i^2 \quad \text{where } i = 1, 2, 3, \dots \text{etc} \tag{11}$$

$$x_u = \frac{\det(A_1)}{\det(A)} \tag{12}$$

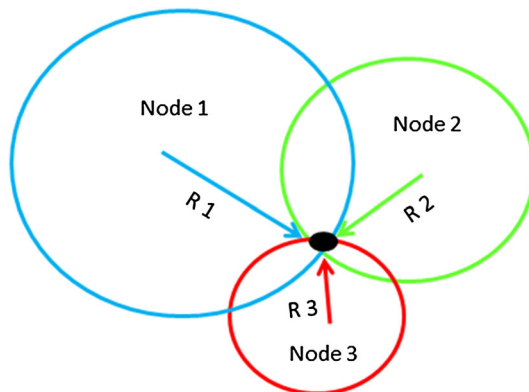


Fig. 3 The basic principle of Cramer rule



$$y_u = \frac{\det(A_2)}{\det(A)} \tag{13}$$

$$\det(A) = \begin{vmatrix} 2 \times (x_3 - x_1) & 2 \times (y_3 - y_1) \\ 2 \times (x_3 - x_2) & 2 \times (y_3 - y_2) \end{vmatrix} \tag{14}$$

$$\det(A_1) = \begin{vmatrix} (R_1^2 - R_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) & 2 \times (y_3 - y_1) \\ (R_2^2 - R_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2) & 2 \times (y_3 - y_2) \end{vmatrix} \tag{15}$$

$$\det(A_2) = \begin{vmatrix} 2 \times (x_3 - x_1) & (R_1^2 - R_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) \\ 2 \times (x_3 - x_2) & (R_2^2 - R_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2) \end{vmatrix} \tag{16}$$

### 6 Femtocells’ Underlay Operation at Specified Conditions

When the cognitive femtocells are operated in an overlay manner, the macro user can be interfered by the neighboring macrocells [13–19]. Therefore, the SINR of the received signal of a macro user  $m$ , which operates on a subcarrier  $k$ , can be expressed as;

$$SINR_{m,k} = \frac{P_{M,k}G_{m,M,k}}{N_o\Delta f + \sum_{M'} P_{M',k}G_{m,M',k}} \tag{17}$$

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  $G_{m,M',k}$ .  $N_o$  is the additive noise power spectral density, and  $\Delta f$  is the subcarriers’ spacing.

By the same way, the SINR of the received signal of a femto user  $f$ , which operates on a subcarrier  $k$ , can be evaluated by;

$$SINR_{f,k} = \frac{P_{F,k}G_{f,F,k}}{N_o\Delta f + \sum_{F'} P_{F',k}G_{f,F',k}} \tag{18}$$

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

$$G = 10^{-PL/10} \tag{19}$$

It can be observed that, the *EMI* occurs among the macrocells themselves and among the femtocells themselves since no mutual *EMI* exists between the macrocells and the femtocells [17, 18].

In the proposed operation, the underlay cognitive femtocells system, the mutual *EMI* at the macro user, is allowed to grow on condition that its value guarantee a suitable performance (*SINR* and throughput) for the macro users. The mathematical condition, which can control the proposed underlay operation, can be given by;

$$\sum_F P_{F,k}G_{m,F,k} \leq \frac{N_o\Delta f + \sum_{M'} P_{M',k}G_{m,M',k}}{10} \tag{20}$$

where  $G_{m,F,k}$  is the absolute channel gain between the macro user,  $m$ , and the interfering femtocell on a subcarrier  $k$ . Equation 20 represents the mathematical condition at which the mutual  $EMI$  level between the macrocells and the femtocells can grow and guarantee a good performance for the existing macro users. The maximum allowed value for the mutual  $EMI$  is;

$$EMI_{Maximum} = \frac{N_o \Delta f + \sum_{M'} P_{M',k} G_{m,M',k}}{10} \tag{21}$$

For a single macrocell system, the maximum allowed  $EMI$  level can be expressed as;

$$EMI_{Maximum} = \frac{N_o \Delta f}{10} \tag{22}$$

By applying the above condition, the  $SINR$  of the proposed underlay cognitive deployment can be approximated to that of the overlay cognitive one. It can be observed that;

$$SINR_{m,k} \downarrow_{Proposed Underlay} \approx SINR_{m,k} \downarrow_{Cognitive Case} \tag{23}$$

The derived conditions in Eqs. 20, 21, 22, and 23 will be approved and validated in the simulation section.

### 7 Power Control Techniques

The main idea of power control algorithms is the reduction of the femtocells' emitted power [10, 17, 18]. This power can be reduced by a lot of techniques which can be explained as follow;

- The first technique is based on assigning a fixed level of power to every femtocell. This level is less than 20 dBm which is the maximum allowed level of power for any femtocell.

$$P_f < 20dBm \tag{24}$$

where  $P_f$  is the transmitted power of the femtocell after employing power control.

- In the second technique, the transmitted power of the femtocell is varied in order to cover a certain range. The emitted power of the femtocell can be calculated as follow;

$$P_f = \min([P_m + G_\theta - PL_m(d) + PL_f(r)], [P_{max}]) \tag{25}$$

where  $r$  is the femtocell radius,  $P_m$  is the macro base station transmission power,  $G_\theta$  is the antenna gain,  $PL_m(d)$  is the macrocell path loss at distance  $d$ , and  $PL_f(r)$  is the path loss at distance  $r$ .

- On the contrary, the third technique depends on varying the emitted power of the femtocell 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 algorithm can be implemented as;

$$P(k + 1) = \frac{SINR_t}{SINR_c} P(k) \tag{26}$$

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

## 8 Calculation of Users' Throughput

The throughput of a macro user,  $m$ , which is operated on a subcarrier,  $k$ , can be evaluated by Eq. 27 [17, 18] as follows;

$$C_{m,k} = \Delta f \cdot \log_2(1 + \alpha \cdot SINR_{m,k}) \quad (27)$$

On the other hand, the throughput of a femto user,  $f$ , which is operated on a subcarrier,  $k$ , can be expressed as [17, 18];

$$C_{f,k} = \Delta f \cdot \log_2(1 + \alpha \cdot SINR_{f,k}) \quad (28)$$

where  $\alpha$  is a constant factor and it depends on the target bit error rate ( $BER$ ) as;  $\alpha = -1.5 / \ln(5 \cdot BER)$ .

## 9 Simulation Results

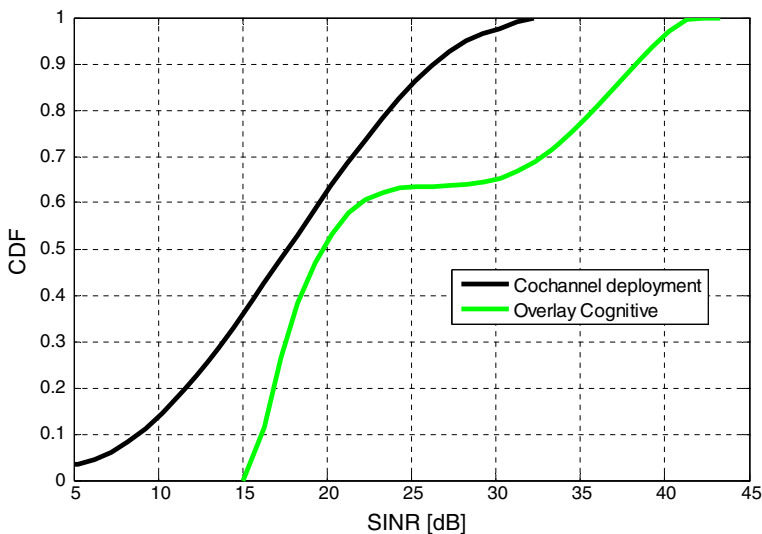
In this section, the *LTE* femtocells system is simulated applying the previous overlay cognitive femtocells' concept, and the proposed underlay cognitive femtocells' operation. Moreover, the derived mathematical conditions, which allow the proposed underlay cognitive femtocells' operation, are approved and validated. In addition, the performance of Cramer rule in macro users' localization in the proposed system is estimated and validated. The proposed system is simulated using the parameters which are included in Table 1. There are 19 macrocells, each of them can serve eight macro primary users. There are four femtocells inside each macrocell. Each femtocell serves two cognitive femto users. The *LTE* macrocell is plotted in a hexagonal pattern with a radius value of 250 m. On the other side, the femtocell has a radius value of 20 m. The macrocell and the femtocell base station can emit power till 46 and 20 dBm, respectively. The transmitted data is mapped with 16-QAM modulation over 10 MHz bandwidth. The *LTE* overlay cognitive femtocells system is simulated and its performance is clarified. The *CDF* is used in order to describe the system performance, geometry and throughput. It is the Cumulative Distribution Function for a specified distribution. It can be given for a real valued random variable,  $X$ , by;

$$CDF = P(X \leq A) \quad (29)$$

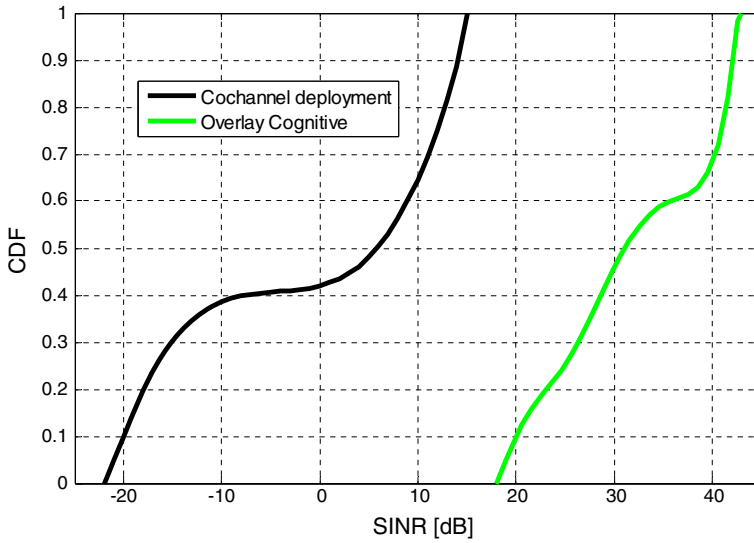
It can be defined as the probability of a random value,  $X$ , takes on a value less than or equal to  $A$  [22]. As a result, the *CDF* is the probability of a user's geometry and throughput becomes below a certain value. Figure 4 shows the *SINR* of the macro users applying the cochannel deployment and the overlay cognitive deployment. On the other hand, Fig. 5 displays the *SINR* of the femto users applying the cochannel deployment and the overlay cognitive deployment. It can be observed that, applying the overlay cognitive radio concept in a *LTE* femtocells system can increase the *SINR* for both of macro and femto users in comparison with that system which applies the cochannel deployment. Moreover, the *LTE* overlay cognitive femtocells system can provide a great macro users' throughput, as shown in Fig. 6, especially when the macro users are allowed to operate at all available subcarriers. The macro users are primary users so they have the priority to operate at any subcarrier anywhere at any time. The femto users are secondary users so they can operate at the subcarriers which are vacated from the macro users. Really, the macro users' throughput is very good as displayed in Fig. 6. On the other hand, the femto users' throughput becomes zero as there are no free subcarriers for them as clarified in Table 2,

**Table 1** The simulation parameters

Parameter	Value
Number of macrocells	19
Macrocell base station's antenna type	Omni direction
Number of femtocells per each macrocell	4
Number of macro users per macrocell	8
Number of femto users per femtocell	2
Femtocell radius	20 m
Macro and femto Users' distribution inside the network	Uniform
Channel model	3 GPP TR 36.814 [1]
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	16 QAM
Bandwidth	10 MHz
Subcarriers number	600
Outer wall loss	5 dB
Number of penetrated floors, Inner walls number, and Indoor distance	0
Simulation run	1000

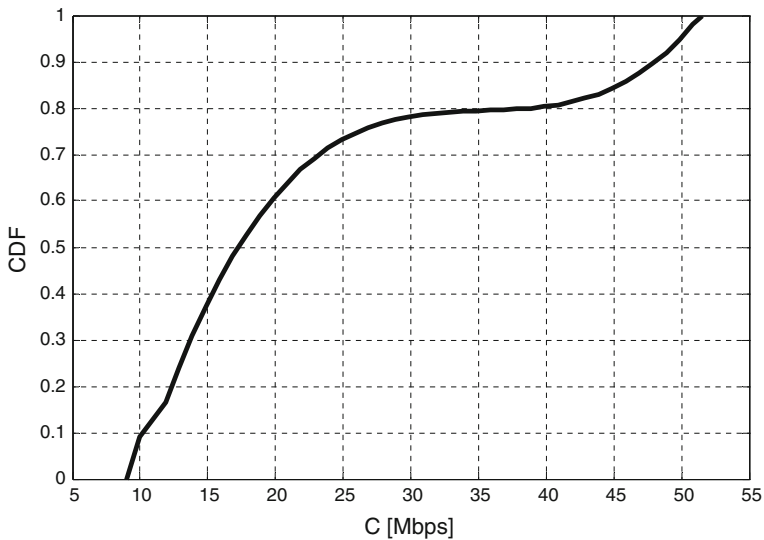
**Fig. 4** The *SINR* of the macro users applying the cochannel deployment and the overlay cognitive one

which presents the average of the femto users' throughput when the macro users operate at all subcarriers. It is a great disadvantage in the *LTE* overlay cognitive femtocells system to have a zero femto users' throughput value, however the high values of the *SINR*.



**Fig. 5** The SINR of the femto users applying the cochannel deployment and the overlay cognitive one

The performance of the proposed *LTE* underlay cognitive femtocells system is simulated. The power control is applied and the femto users are allowed to operate at the subcarriers which are occupied by the macro users. The mutual *EMI* between the macrocells and the femtocells exists. This *EMI* level can grow and build up on condition that it cannot exceed the maximum value which is mathematically determined in Eqs. 21 and 22. The maximum value of the femtocells' emitted power is examined and tested. It can be observed that, the maximum value of the femtocells' emitted power becomes  $-6.4$

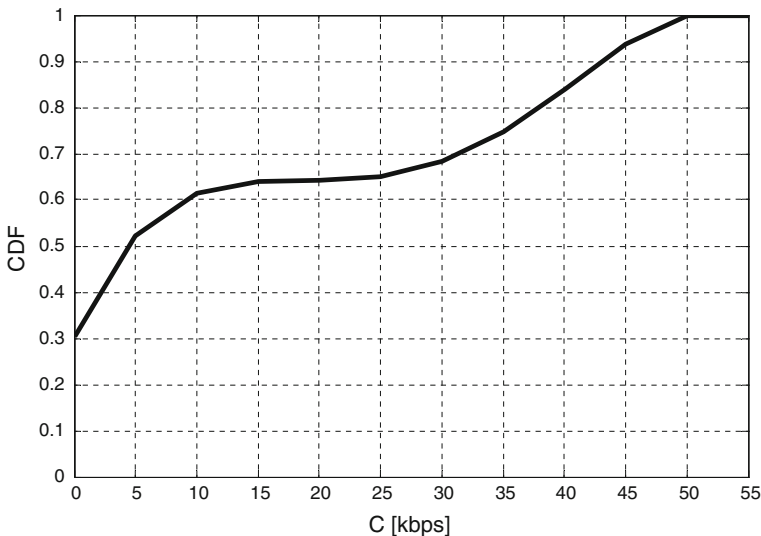


**Fig. 6** The throughput of the macro users applying the overlay cognitive deployment when they operate at all available subcarriers

**Table 2** The average of macro and femto users' *SINR* and throughput

	Average <i>SINR</i> (dB)	Average throughput (Mbps)					
		Subcarriers ratio available for the femto users					
		0	0.2	0.4	0.6	0.8	1
Macro users	26.3097	26.1736	20.9389	15.7042	10.4695	5.2347	0
Femto users	33.6024	0	7.3431	14.6861	22.0292	29.3723	36.7153

dBm. In other words, the femtocells can operate at the subcarriers, which are occupied by the macrocells, on condition that their transmitted power cannot exceed the value of  $-6.4$  dBm. In fact, the permission of the mutual *EMI* to exist and grow between the macrocells and the femtocells can decrease the *SINR* of the macro users. The challenge is to make the *EMI* effect on the macro users very small, in such a way that, it can be neglected. The proposed underlay cognitive operation is simulated. It can be observed that, the proposed underlay operation can solve the problem of a zero value of femto users' throughput which may occur when the overlay cognitive femtocells are employed as shown in Fig. 7. The reason for the existence of femto users' throughput is that the femto users are allowed to operate at all subcarriers even if they were occupied by macro users. On the contrary, the previous overlay cognitive deployment allows the femto users to operate at the free subcarriers only. The femto users' throughput, in the proposed cognitive underlay operation, exists and has a suitable value. On the other hand, the *EMI* level on the femto users increases and the *SINR* of the femto users decreases as a result of applying the proposed underlay cognitive operation as displayed in Figs. 8, and 9. For more clarification, applying the proposed underlay cognitive operation can increase the *EMI* level on the femto users. Therefore, it can decrease the *SINR* of the femto users. On the other hand, the

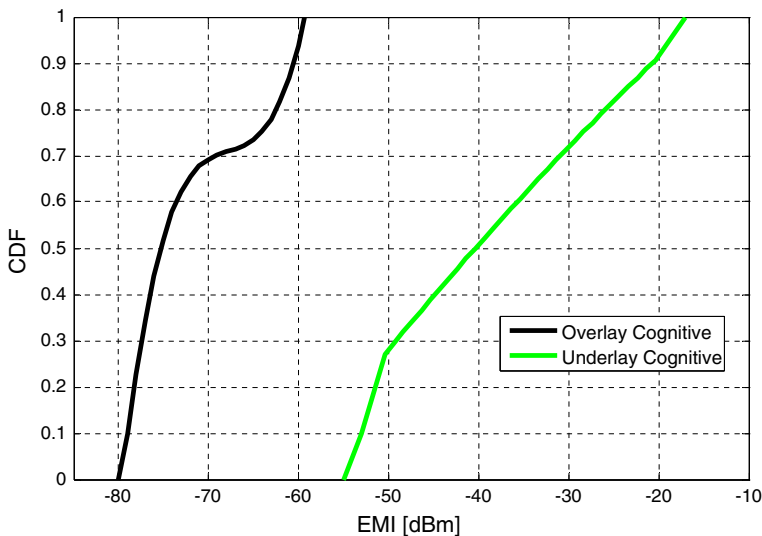


**Fig. 7** The throughput of the femto users in the proposed underlay cognitive deployment

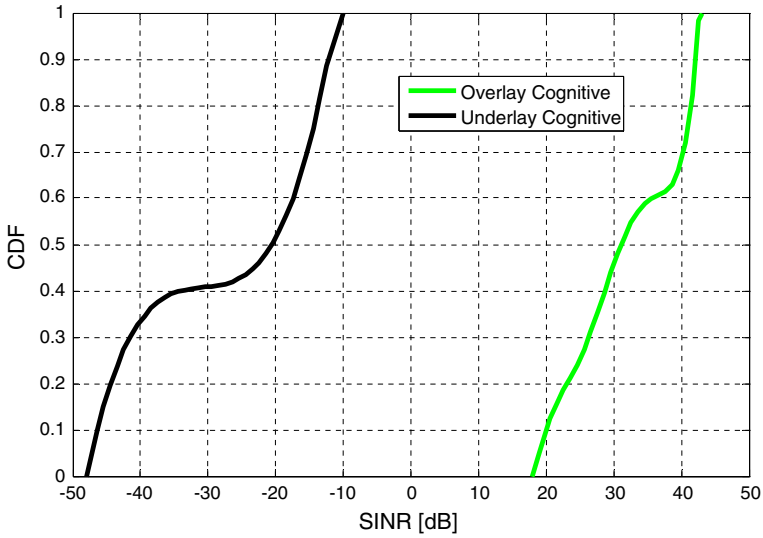
increased level of the  $EMI$  and the loss of the  $SINR$  can be paid as a price for the existence and the suitable value of the femto users' throughput.

The performance of the proposed  $LTE$  underlay cognitive femtocells system is validated by comparisons with that system which applies the overlay cognitive deployment. From Figs. 10, 11, it can be concluded that, the proposed  $LTE$  underlay cognitive femtocells' system can provide a better macro users' throughput than the corresponding one which applies the overlay cognitive femtocells when the macro users are allowed to operate at half of the subcarriers of the system. Moreover, the proposed  $LTE$  underlay cognitive femtocells system can provide a satisfied value of femto users' throughput and it can overcome the problem of a zero femto users' throughput value which could exist when deploying the overlay cognitive femtocells.

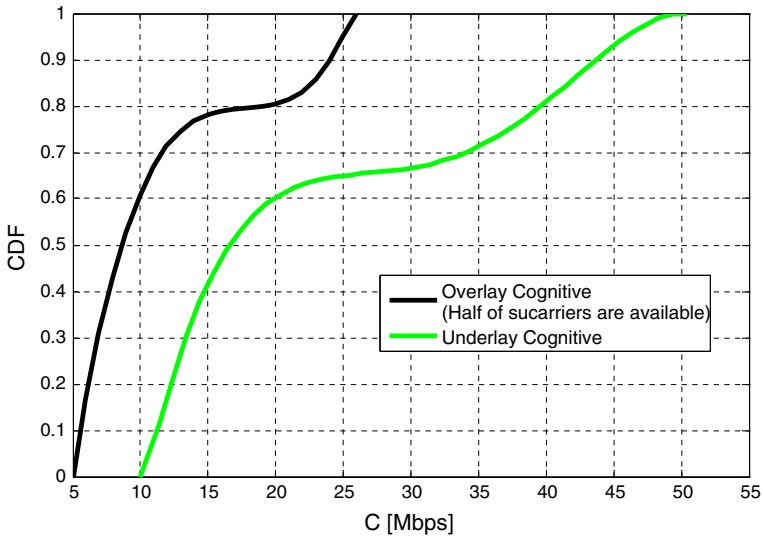
Equations 21 and 22 represent the derived mathematical conditions, which allow an underlay operation of the cognitive femtocells in a  $LTE$  system. These conditions are verified in Table 3. This table studies the average of  $EMI$  value, which affects the macro users, in the proposed system with and without the mutual  $EMI$  level due to the proposed underlay operation. In other words, this table demonstrates the level and the effect of the resulted mutual  $EMI$ , which appears because of the proposed underlay operation, on the macro users'  $SINR$  and throughput. It can be noticed that, applying an underlay operation for the cognitive femtocells system can increase the  $EMI$  level from  $-62.4018$  to  $-62.2592$  dBm. On the other side, this  $EMI$  value cannot decrease the macro users'  $SINR$  and throughput. The value of  $0.1425$  dB loss in the macro users'  $SINR$ , because of the underlay operation, can be neglected. Moreover, the value of  $0.2005$  Mbps loss in the macro users' throughput, because of the underlay operation, can be neglected. It can be concluded that, the macro users'  $SINR$  and throughput cannot be affect by allowing the mutual  $EMI$  to grow because of the proposed underlay cognitive femtocells' operation in a  $LTE$  system. Therefore, the derived mathematical conditions are valid and effective.



**Fig. 8** The  $EMI$  effect on the femto users applying the overlay cognitive and the proposed underlay cognitive deployment



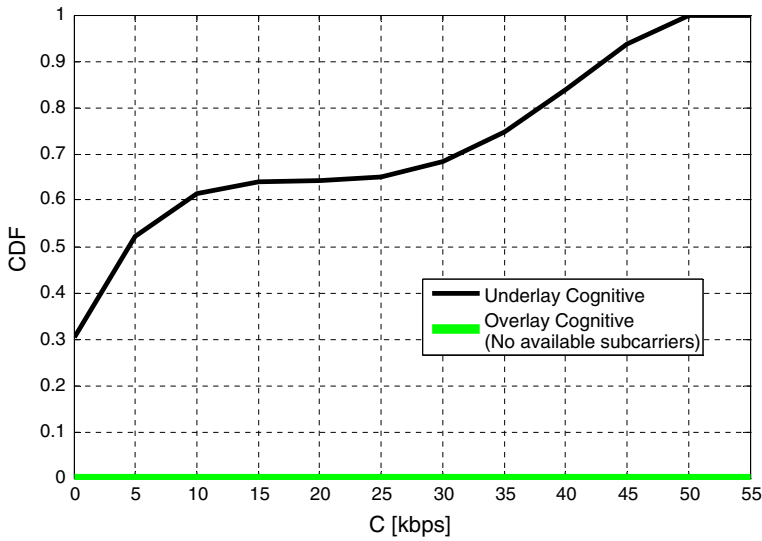
**Fig. 9** The SINR of the femto users applying the overlay cognitive and the proposed underlay cognitive deployment



**Fig. 10** The macro users' throughput applying the overlay cognitive and the proposed underlay cognitive deployment

The validation of Cramer rule in the determination of macro users' coordinates is tested. Table 4 presents the real coordinates of the macro users, especially which are inside the central macrocell, and the estimated ones using Cramer rule. It can be concluded that, the estimation of the coordinates, at the fusion center of the system, using Cramer rule can provide a good accuracy since the difference between the real coordinates and the estimated ones is very small and cannot be observed. For more clarification, Tables 5, 6, and 7





**Fig. 11** The femto users' throughput applying the overlay cognitive and the proposed underlay cognitive deployment

**Table 3** The average of macro users' *EMI*, *SINR*, and throughput of the proposed *LTE* underlay cognitive femtocells system with and without the mutual interference value which appears due to the proposed underlay operation

	Average <i>EMI</i> (dBm)		Average <i>SINR</i> (dB)		Average <i>C</i> (Mbps)	
	Underlay	Overlay	With <i>EMI</i>	Without <i>EMI</i>	With <i>EMI</i>	Without <i>EMI</i>
Macro users	-62.2592	-62.4018	26.1672	26.3097	25.9731	26.1736

**Table 4** The real coordinates of the macro users, which are inside the central macrocell, and the estimated ones using Cramer rule

Macro users	Real coordinates		Estimated coordinates	
	X	Y	X	Y
1	100	-20	100.0572	-19.9756
2	110	10	109.9956	10.0016
3	30	0	29.9943	-0.0081
4	-5	-20	-4.9817	-19.9677
5	-10	-100	-9.9975	-99.9984
6	-30	20	-29.9980	19.9995
7	-80	40	-80.0187	39.9884
8	40	60	40.0013	59.9957

study the validation of Cramer rule in the estimation of coordinates in a *LTE* femtocells system at cochannel deployment, overlay cognitive deployment, and underlay cognitive deployment, respectively. From these tables, it can be noticed that, Cramer rule can fit well in the estimation of coordinates in a *LTE* femtocells system.

**Table 5** The average of macro users' *EMI*, *SINR*, and throughput in a cochannel deployment *LTE* femtocells system using the real coordinates of the macro users and the estimated ones using Cramer rule

	<i>EMI</i> (dBm)	<i>SINR</i> (dB)	<i>C</i> (Mbps)
Macro users			
Real coordinates	-54.6981	18.6021	16.6025
Estimated coordinates	-54.6984	18.6034	16.6067

**Table 6** The average of macro users' *EMI*, *SINR*, and throughput in a *LTE* overlay cognitive femtocells system using the real coordinates of the macro users and the estimated ones using Cramer rule

	<i>EMI</i> (dBm)	<i>SINR</i> (dB)	Average throughput (Mbps)					
			Subcarriers ratio available for the femto users					
			0	0.2	0.4	0.6	0.8	1
Macro users								
Real	-62.4015	26.3094	26.1725	20.9380	15.7036	10.4691	5.2345	0
Estimated	-62.4018	26.3097	26.1736	20.9389	15.7042	10.4695	5.2347	0

**Table 7** The average of macro users' *EMI*, *SINR*, and throughput in the proposed *LTE* underlay cognitive femtocells system using the real coordinates of the macro users and the estimated ones using Cramer rule

	<i>EMI</i> (dBm)		<i>SINR</i> (dB)		<i>C</i> (Mbps)	
	Underlay	Overlay	With <i>EMI</i>	Without <i>EMI</i>	With <i>EMI</i>	Without <i>EMI</i>
	Macro users					
Real coordinates	-62.2589	-62.4015	26.1665	26.3094	25.9728	26.1730
Estimated coordinates	-62.2592	-62.4018	26.1672	26.3097	25.9731	26.1736

## 10 Conclusions

The proposed *LTE* underlay cognitive femtocells system is explained. The system is mathematically analyzed and simulated. Moreover, the mathematical conditions, which can allow a good underlay operation for the cognitive femtocells, are derived and approved by simulation. Furthermore, the power control algorithms, which are the realization tools of an underlay cognitive operation, are explained in details. In addition, Cramer rule, which is used in the macro users' positioning, is tested and validated. The proposed *LTE* underlay cognitive femtocells system can overcome the limitation of the overlay one when there are no available subcarriers to be accessed by the femto users. In the proposed system, the femto users' throughput has an acceptable value as the femto users can operate at all available subcarriers. Moreover, the macro and the femto users' throughput are higher than the corresponding system which is operated by overlay cognitive femtocells. It can be observed that, the mutual *EMI*, which affects the macro users because of the femtocells' underlay operation, cannot decrease the macro users' *SINR* and throughput. In addition, Cramer rule can best fit in the coordinates' determination in a *LTE* femtocells system at different deployments.

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