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A Simulation Framework for Evaluating Interference Mitigation Techniques in Heterogeneous Cellular Environments

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Abstract Femtocells present an attractive solution for the improvement of a mobile network's services providing better data rates and coverage. Since their deployment results to a heterogeneous network where two layers must utilize the available spectrum, issues of interference arise. A method to address this challenge, is investigating the locations of the newly installed FBS, and enforcing a power controlled transmission of all FBSs that achieves optimal and fair overall performance. Another option that becomes available in inter-cell interference cancellation (ICIC) macrocell environments, is utilizing the available spectrum to complete or partly avoid co-channel operation. In this work, we provide a simulation framework that allows the creation of custom, high configurable, user defined topologies of femtocells with power control and frequency allocation capabilities. It allows the investigation of the margin of improvement in interference when these methods are applied and may work as a decision tool for planning and evaluating heterogeneous networks. To showcase the framework's capabilities, we evaluate and study the behaviour of custom deployed femtocells/macrocells networks and examine the cross-tier interference issues. Facilitated by the framework, we enforce and evaluate each interference mitigation technique for different femtocells' deployment densities. Finally, we compare the results of each method in terms of total throughput, spectral efficiency and cell-edge users' performance.

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Abbreviations

ABS	Almost blank subframes
BS	Base station
CSG	Closed subscriber group
FBSs	Femto base stations
4G	Fourth generation
FFR	Fractional frequency reuse
HNBs	Home node-B
IFR3	IFR of factor 3
IFR	Integer frequency reuse
ICIC	Inter-cell interference cancellation ICIC
LTE-A	Long term evolution-advanced
MBS	Macro base station
OFDMA	Orthogonal frequency-division multiple access
SINR	Signal to interference plus noise ratio
SFR	Soft frequency reuse
PL	Path loss
RSRP	Reference signal received power
UE	User equipment
UBPC	Utility-based power control

1 Introduction

Long term evolution-advanced (LTE-A) is a fourth generation (4G) cellular network that was designed to address the demand for higher data rates in mobile communication. One of the benefits of LTE-A is the support of heterogeneous networks, that allow the coverage of the vast macro site without investing in expensive macrocell infrastructure. Instead, the use of low-power nodes that improve locally the capacity and coverage is preferred. Femtocells, also referred to, as femto or femto base stations (FBSs) or Home Node-B (HNBs), are short-range, inexpensive, user-deployed base stations that serve this need [1]. LTE-A has set specifications of femtocells installation and their coexistence with the macrocell infrastructure.

Femtocells have gained enormous attention, mainly due to their low cost of deployment and maintenance and the high spectral efficiency they provide. Femtocells also improve the overall performance of the mobile network by reducing its workload since they use the cable or DSL backhaul connection of the subscribers. Despite its advantages, femtocells may also lead to significant local service degradation due to interference issues. Sharing the same available bandwidth with the macro base station (MBS) may lead to severe interference phenomenon when there is co-channel operation, both between FBSs and the MBS (also known as cross-tier interference), and between FBSs. A way to bypass this problem would be to allow free access to femtocell service for everyone in the proximity of its BS. This way, the service would be unproblematic, and a handover would take place, unperceivably to the user. Femtocells, however are commercially exploited using subscription system charges, a system called closed subscriber group (CSG), making such a solution impractical.

An attractive solution is power management. Since FBSs will be installed in different locations, which means different demands and different impact on the overall network, a common value for power transmission would be inappropriate. Instead, adjusting the power transmission levels of FBSs according to the needs of the specific area, and evaluating their impact on neighbor femtocells and underlying macrocell, leads to a fairer and more efficient network, from an interference perspective. This optimal configuration ensures that both femto and macro users will have access to service and achieve adequate throughput regardless of their position in the network. Another solution is frequency allocation. Allocating different fractions of the bandwidth for users served by the MBS and FBSs, may reduce the available bandwidth for each user, but protects users that are highly affected by interference. This is preferable, when macrocells utilize inter-cell interference cancellation (ICIC), thus leaving unexploited spectrum for the femtocells to use.

In this work, we suggest a simulation framework that incorporates several power control or frequency allocation techniques for interference mitigation on user-defined topologies. The literature review shows that although the available methods to tackle interference are known, their exact impact on interference mitigation depends on many factors, such as the topology of the network, on femtocells' density, pilot configuration, etc. Facilitated by this framework, we study the behavior of co-channel heterogeneous networks, and we evaluate the performance improvement achieved when each technique is enforced for different femtocells' deployment densities. Finally, we compare the approaches for resulting throughput, spectral efficiency and cell-edge users' performance. The framework provides an insight for the performance of custom, user-defined network topologies. The tool is available at [2].

The rest of this manuscript is structured as follows: Sect. 2 describes in detail the work related with our study as well as this work's contribution. The architecture and functionality behind the simulation tool is described in Sect. 3. The system model analysis for interference, path loss and throughput is described in Sect. 4, and the techniques encompassed in the simulator are presented. Section 5 describes the performance evaluation of the experiments that are carried out. Finally in Sect. 6 our conclusions are drawn up and in Sect. 7 some planned or probable proposals for future work are suggested. Abbreviations that were used in this manuscript and their explanation for the reader's convenience.

2 Related Work and Contribution

The success of femtocells' technology and the complexity of their deployment configuration, along with the large number of parameters that affect the final performance of the different network layers, have led to the creation of many simulators available. However, the majority of them are intended for commercial use.

Two well-known frameworks that are available for free are [3] and [4]. The first one offers link and system level simulations for downlink and uplink in LTE-A networks, allowing the adjustment for many settings parameters. Some notable available parameters include:

- The number of users
- The channel model
- The scheduling algorithm and
- Multiple input multiple output (MIMO) capabilities

While it offers outputs such as:

- Throughput
- Signal to interference plus noise ratio (SINR) and
- Bit error rate (BER)

The second one encompasses several aspects of LTE networks, including among others:

- Multi-cell environments
- Heterogeneous networks
- User mobility
- Fractional frequency reuse

and is offered as an open source software.

Beside the available simulation tools, there is also a great amount of individual performance and simulation results of various scenarios. A 3GPP technical report [5] provides an extensive analysis of the different interference scenarios (including femto-to-macro layer) considering open and closed access for WCDMA systems. The study presented in [6] examines interference avoidance when femtocells are deployed over Wi-MAX networks. An analysis of the interference between macrocells and open access femtocells is presented in [7] for cellular UMTS networks. It was concluded that interference problems for co-existing macro and femtocell BSs will not appear in this case, except when fast passing-by macro UE are unable to handover to the nearest femtocell. Closed access femtocells are examined in [8], where an analysis of the different interference scenarios for orthogonal frequency-division multiple access (OFDMA) technologies is provided.

Research on the available options to neglect interference in heterogeneous networks has also been excessive. The work in [9] presents an overview of the general approaches over the power management in self-configured femtocells. A power control method is introduced in [7], that determines the pilot transmit power of each FBS to ensure a constant femtocell radius, taking into account the path loss of the underlying macrocell and the power received from the femtocell. The utility-based non-cooperative femtocell SINR adaptation presented in several works, such as [10], is related to existing game theory literature on non-cooperative cellular power control. The adaptation forces stronger femtocell interference to obtain their SINR equilibria closer to their minimum SINR targets, while femtocells that cause smaller cross-tier interference obtain higher SINR margins. This is similar to the utility-based power control (UBPC) scheme presented in [11], where a distributed power management algorithm is presented that uses soft constraints on target SINR values depending on the traffic, but relaxes them accordingly depending on the feasibility of the system. Another algorithm that seeks the optimal solution is presented in [12] and proposes a similar method when the targets SINR are not feasible. A femtocell coverage coordination method is proposed in [13], that adjusts the femtocell pilot power, based on the number of handover events and the indoor users. For further location management and coverage planning on femtocells, several works exist such as [14], which proposes a coverage mechanism for LTE heterogeneous networks or [15], which suggests a predictive location scheme that reduces the unnecessary handovers.

Frequency allocation methods as a means for interference mitigation have also been investigated thoroughly. The authors of [16] describe interference in co-existing macrocell and femtocell networks, providing simulation results for co-channel and hybrid frequency assignments, but for the case of the prior cellular standard of WCDMA. A custom scheme fractional frequency reuse (FFR) variation is presented in [17], while [18] suggests an optimization mechanism for FFR configuration in order to achieve better system performance based on dynamic cluster sizing and frequency allocation. Similarly, the determination of a proper frequency partitioning and time resource partitioning criterion between the cell-center and the cell-edge users, and between the cells with femto-cells is investigated in [19] and a novel time-frequency resource allocation mechanism using FFR is proposed in order to simultaneously increase the capacity and maintain an adequate fairness between the cells. The work in [20] also focus on FFR heterogeneous networks suggesting a spectrum swapping access strategy for protecting the macrocell's performance and for overcoming the typical near-far problem. The advantage of this strategy is that it aims to improve the performance of both cell-center and cell-edge users. Radio management of HeNBs deployed over soft frequency reuse (SFR) coordinated macrocell environment is studied in [21], while [22] searches for the optimal power allocation for femtocells when deployed over OFDMA systems that utilize fractional frequency reuse.

Although these works provide very useful ideas regarding femtocell interference mitigation and simulation, they do not provide a simulator with a point and click graphical interface and 2-D site depiction for easy and fast performance estimation. They also lack the integration of available interference mitigation techniques which will allow the cross comparison of achieved performance for custom networks.

The contribution of this paper that distinguishes it from the current bibliography is summarized in the below points:

- We compare the majority of interference methods for the first time in a variety of scenarios.
- We provide a simulation framework that is user friendly and totally free.
- We investigate the femtocells' degree of compensation in network's performance when combined with macrocell ICIC.
- We offer network management guidelines depending on the macrocell load, femtocells' penetration and many other parameters.

In more detail, in this work, we provide a user-friendly simulation framework designed to reproduce custom heterogeneous networks and examine the cross-tier interference behavior between macrocells and femtocells. We investigate several scenarios of possible user equipment (UE) positions relative to MBS and FBSs for a complete study. We examine scenarios of the impact of FBS on macro UE where user is connected to the MBS and is not a part of the femtocell subscription group, the impact of MBS on femto UE when user is connected to the FBS, as well as a mobile macro UE scenario across the cell, with fluctuant number of femtocells.

We use the framework to study and evaluate available interference mitigation techniques. The methods integrated include power control and frequency allocation. Specifically, with the aid of the tool, we control the transmission power of every FBS in order to achieve constant coverage femtocell radius. We also simulate ICIC coordinated macrocell environments, specifically integer frequency reuse (IFR) and soft frequency reuse and enforce frequency allocation between femtocells and the underlying macrocell. Based on every case of FR scheme we study the network's performance when deployed femtocells utilize parts of the spectrum not used by the nearby macrocell, or the entire bandwidth. We compare the results with the performance achieved by the above approaches for different level of femtocells' deployment density. The resulting throughput is presented graphically for every point of the topology through a 2-D depiction of the entire site, for both types of UE, macro and femto, providing an insight to network planning and the benefits of each of these methods. The above is used to showcase the capabilities of the framework, and to investigate the impact of femto deployment on existing macrocell services and vice versa and the beneficial effect of available interference mitigation techniques.

To our knowledge there is not any simulation tool for femto/macro network integration with the aforementioned capabilities that is available for free, with user-friendly point and click interface and a 2-D graphical representation of the network's performance. It is noted, that the latter also allows instinctive location management for topology planning, i.e. the optimal selection of the position of multiple FBS in order to cover an area with minimal interference phenomena. It should be noted that the simulator's software is available to the interested scientific community at [2]. It can be used either as a tool to test and evaluate femtocell topologies behavior or as basis for further simulation development.

3 Framework Architecture and Functionality

The simulation environment is designed to be user friendly, hiding the complexity behind a simple interface. Compared to the simulation of homogeneous systems, heterogeneous systems prove to be much more complex because of their unplanned, coincidental and large-scale nature. First of all, the number of network entities (base stations, UEs) is much greater, and consequently, their interconnecting links, coordination and relationships become much more complex. Moreover, femtocells are deployed randomly, thus their impact on the network and their simulation becomes scenario-dependent and difficult. Femtocells' flexibility in transmission parameters also adds more possible combinations in scenario deployment, thus burdens the simulation process. The integration of all possible scenarios is an extremely hard task. In this work, we tried to cover a wide range of possible situations, parameters and available schemes that are relative to the issue investigated in this manuscript. Also, the simulator is designed in a structured way that allows easy future expansion, by either scaling existing capabilities or adding new ones.

The user initially, interacts through a simple graphical interface and he is asked to provide the custom parameters. In order to provide high configuration flexibility the tool allows the user to input the parameters of the topology. The required inputs depend on the qualification of the user. For average users, the location coordinates of femtocells, the number of expected users the type of modulation and the number of buildings present are required. For the more experienced user, technical parameters like the channel bandwidth, the desired femtocell range, the target SINR or the default power levels can be adjusted, increasing the application range of the tool.

The inputs trigger the mechanism, and firstly the path loss of the provided custom setup is calculated according to the model that is described in Sect. 4. Afterwards, based on the selection of the user, the selected parameters on power control or frequency allocation are calculated. For the simulation, a full buffer traffic model is considered, since it is the worst case interference scenario and cannot be tackled by scheduling techniques. Since the techniques integrated focus mostly on spectrum management, this also makes the comparison among them easier and fairer, without affecting the validity of the results extracted.

The found values are used to calculate SINR, the capacity and the throughput. When the process stops, the map is colored based on the estimated throughput. This way the user gains an easily comprehensive graphical overview of the resulting performance as illustrated in the examples of Sect. 5. By clicking anywhere in the map, detailed information for the results can be obtained for any point of the topology. The pseudo-code that follows describes the mechanism overview.

//Pseudo-code of simulator structure

```
//define network ICIC and display macro site and buildings
generate_network();
generate_FBSs();  //generate Femto BS based on user 4:input
generate_MUs();  //generate macro users based on user input
generate_FUs();  //generate femto users based on user input
select_user_type(); //select the type of user to examine
//based  on  the  topology,calculate  path  loss  for  every
//point (x,y) of the network
for all x,y
   calculate_PL(x,y);   //calculate path loss based on Eq.3
end
//select power control (if any)
if power_control=false
      for each FBS
           Pfemto = constant;
      end
elseif power_control =true
     for each FBS
        Pfemto = min(Pmacro+Gθ-PLmacro+PLfemto,Pmax);//Eq. 6
     end
end
//select frequency allocation and measure performance
if ICIC = none
     calculate_cochannel_interference();
elseif ICIC= IFR
      calculate_allocated_subcarriers();
      calculate_interference();
elseif ICIC = SFR
      calculate_allocated_subcarriers();
      calculate_interference();
end
Calculate_capacity(x,y);// based on Eq. 4
Calculate_throughput(x,y); based on Eq. 5
//generate and display the coloured map
display_results(x,y);
//select new method for comparison or exit
if choose_new_method()=true;
      repeat_process();
else
      exit();
end
```

Since the calculation of the performance is made for every point of the vast macro site, the needed calculations are grouped in order to minimize execution time. For this reason, we estimate the resulting path loss everywhere, and storing the results for future use. Afterwards, depending on the interference technique chosen, the SINR is calculated, followed by the throughput evaluation. Following the above approach, the most time-consuming calculations

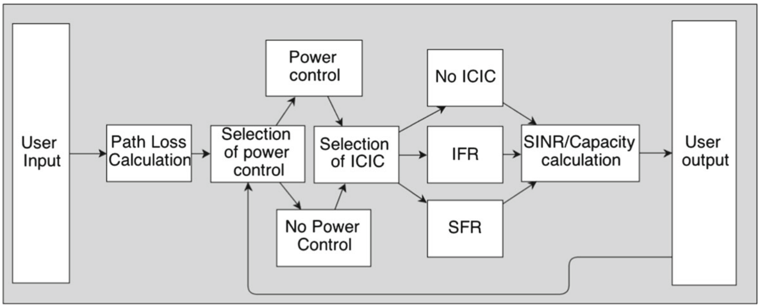

Fig. 1 Framework's architecture overview

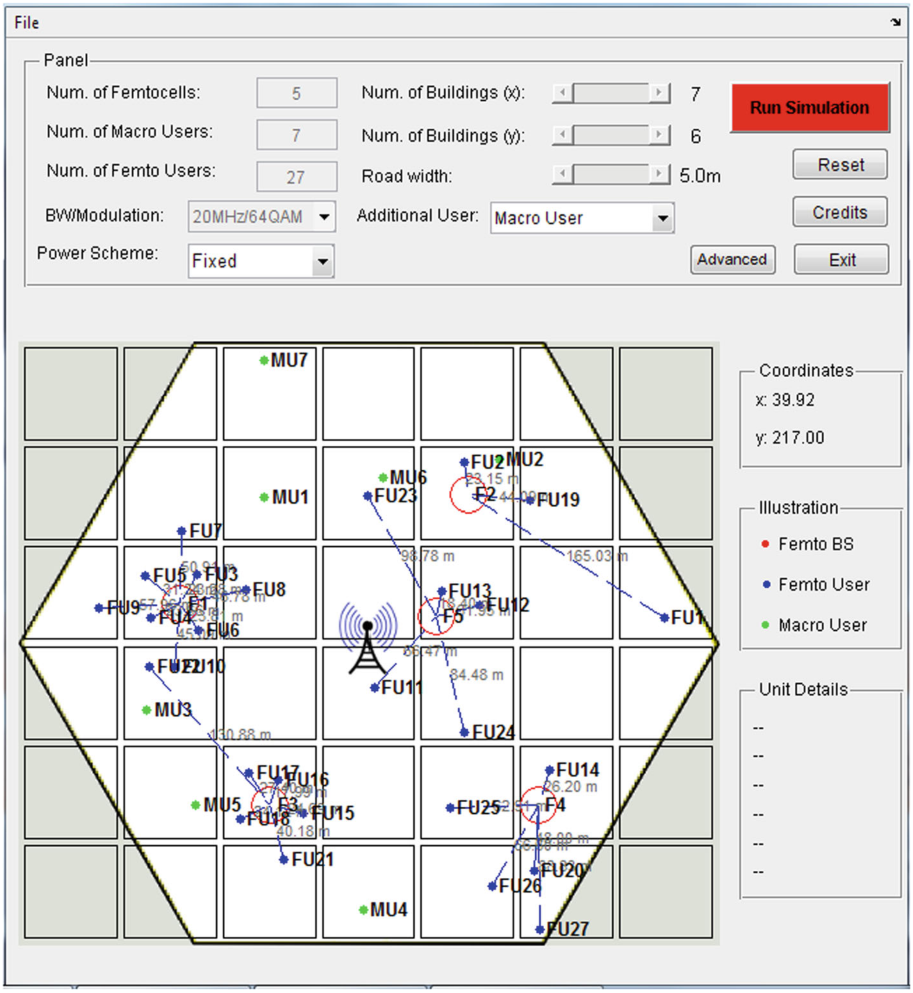

Fig. 2 Instance of the interface during configuration stages

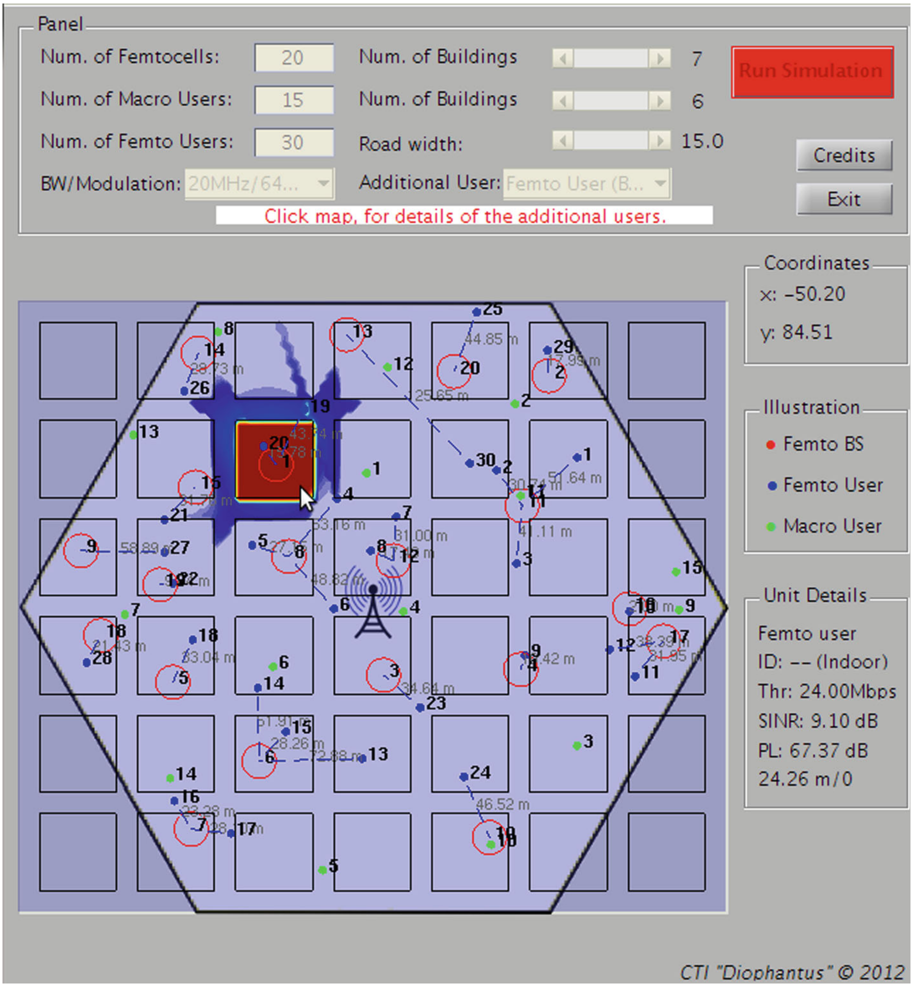

Fig. 3 Example of the graphical presentation of the resulting performance

of path loss are made once but can be used repeatedly, and this allows for fast exchange between different methods and easy cross comparison.

The above mechanism is in line with the scalability and modularity defined earlier and is illustrated in Fig. 1. Every step is a different module that allows its future expansion keeping the connectivity with the rest of the framework intact.

A typical instance of the interface is illustrated in Figs. 2 and 3, displaying the first stages of the process, which include network parameters and topology configuration and the last stage, depicting the resulting performance respectively. In many simulators, 19 cells is a common choice for showcasing the results. In this work however, only one cell is depicted. Since the focus of the paper is the femtocells integration in macrocellular environments and the intra-cell impact of cross-tier interference in heterogeneous networks, we chose our simulator to depict only one cell. This allows better understanding of the situation inside the cell and facilitates the interactive designing process. However, although not shown, all 19 cells and their impact to the cell depicted are considered in the simulation.

4 System Model Analysis

In this section, the models integrated in the simulator for the creation of femtocells networks and the estimation of the resulting performance are described. Firstly, the methods of estimating SINR and maximum throughput are presented. Secondly, the algorithm implemented by the framework to control the transmission power of FBSs is presented and the frequency reuse techniques that are encompassed are described.

4.1 SINR and Throughput Analysis

The SINR that a user receives at one point of the network depends heavily on the interference added by the rest of the cells that have the user within their range. For the case of a macro-user m on sub-carrier k, the impact of both the adjacent macrocells and overlaid femtocells must be considered. As mentioned in [17] the SINR is provided by the following equation:

$$SINR_{m,k} = \frac{P_{M,k} G_{m,M,k}}{N_0 \Delta_f + \sum_{M'} P_{M',k} G_{m,M',k} + \sum_F P_{F,k} G_{m,F,k}} \tag{1}$$

with $P_{X,k}$ the transmit power of serving base station X on subcarrier k, where X can be the macrocell M, the neighboring macrocell M′ or the femtocell F. $G_{x,X,k}$ is the channel gain between user x and serving cell X on subcarrier k, where x can be a femto (f) or a macro-user (m) and X as described above. N_0 denotes white noise power spectral density, and Δ_f the sub-carrier spacing. The expression of a femto-user can be similarly derived by taking into account the interference caused by the macrocells and adjacent femtocells of the topology. In order to determine the channel gain G, the calculation of path loss (PL) is required according to the following expression:

$$G = 10^{-PL/10} \tag{2}$$

Path loss heavily depends on the technology and the environment of the network. Regarding this paper, an urban environment is considered, thus the proposed model for LTE-A systems for an outdoor macro-user in distance R from the transmitter and frequency of 2 GHz, is given by [23]:

$$PL(db) = 15.3 + 37.6 \log_{10} R + L_{ow} \tag{3}$$

where the term L_{ow} is added for the case of an indoor macro user to denote the penetration loss of the external wall. Similarly, the suggested model according to [14] for the case of an indoor and outdoor femto-user is estimated, taking into account the penetration loss due to exterior and interior walls. Values of 7 and 15 dB are a good estimation of the penetration loss for internal and external walls, respectively, and will be used throughout the simulation process [24]. The practical capacity of macro-user m on sub-carrier k is given by [17]:

$$C_{m,k} = \Delta f \cdot \log_2(1 + aSINR_{m,k}) \tag{4}$$

where a is defined by $a = -1.5/\ln(5BER)$. The overall throughput of serving macrocell M can then be expressed as [25]:

$$T_M = \sum_m \sum_k \beta_{m,k} C_{m,k} \tag{5}$$

where $\beta_{m,k}$ notifies the sub-carrier assignment for macrousers. When $\beta_{m,k} = 1$, the sub-carrier k is assigned to macro user m. Otherwise, $\beta_{m,k} = 0$. Similar expression can be derived for femto users, related to the practical capacity and the overall throughput [25].

4.2 Power Control Scheme

When the femtocells are initially deployed, a configuration process must take place for the femtocells to adapt optimally to the specific network parameters. One critical part of this process is determining the pilot and the subsequently operating transmission power of the device. The choice of the method to accomplish the above varies largely, depending on the network topology, the type of femtocell deployment, the desired priorities on performance etc.

For the needs of our simulator, we consider two different power configurations. The first one is the simplest, assigning a fixed value for every FBS, and is used for comparison. Unfortunately, its simplicity comes with major performance inadequateness. The second method followed is introduced in [7], and ensures a constant coverage femtocell radius. Each femtocell sets its power to a value that on average is equal to the power received from the closest macrocell at a target femtocell radius r, subject to a maximum power of P_{max}. The FBS transmit power can be calculated in decibels as:

$$P_f = \min(P_m + G_\theta - PL_m(d) + PL_f(r), P_{max}) \tag{6}$$

where $PL_f(r)$ is the line of sight path loss at the target cell radius r and P_m is the transmit power of the macro BS in which the femtocell is located. G_θ is the antenna gain in direction of the femtocell where θ is the angle to the femtocell with respect to the sector angle and can be calculated for the case of a 3-sector cell site as [7]:

$$G_\theta = G_{max} - \min\left[12\left(\frac{\theta}{\beta}\right)^2, G_s\right] \tag{7}$$

where $-\pi \leq \theta \leq, \beta = 70/180$ the angle where gain pattern is 3 dB down from peak, $G_s = 20$ dB the sidelobe gain level and $G_{max} = 16$ dB the maximum gain level. $PL_m(d)$ denotes the average macrocell path loss at the femtocell distance d (excluding any additional wall losses). This achieves a constant cell range that is independent of the distance to the macrocell [7].

To avoid power levels building up higher and higher when no satisfactory power assignment exists, predefined maximum allowed values are adopted.

4.3 Frequency Allocation

Macrocell ICIC schemes that are investigated when femtocells are deployed upon them include IFR3 and SFR. IFR of factor three allocates different sub-bands for adjacent cells as shown in Fig. 4. Interference is rapidly reduced for cell-edge users and their performance gets improved, at expense of low spectrum utilization. Cell-center users experience performance degradation due to bandwidth division.

The latter is addressed in SFR, where the cell area is divided in two regions: the inner one, which is close to the base station (BS) and outer one, which is situated to the borders of the cell. The bandwidth is divided in three sub-bands that are allocated to the outer regions of the cells identically to the IFR3 distribution, achieving a reuse factor of 3. The inner areas of the cell are allowed to share sub-bands of edge users of adjacent cells. It is best suited for situations where spectrum utilization is of major significance, and small increase in interference compared to IFR can be tolerated.

When IFR of factor 3 (IFR3) is utilized by macro BSs, femtocells may use reference signal received power (RSRP) measurements to determine the frequency sub-bands of the

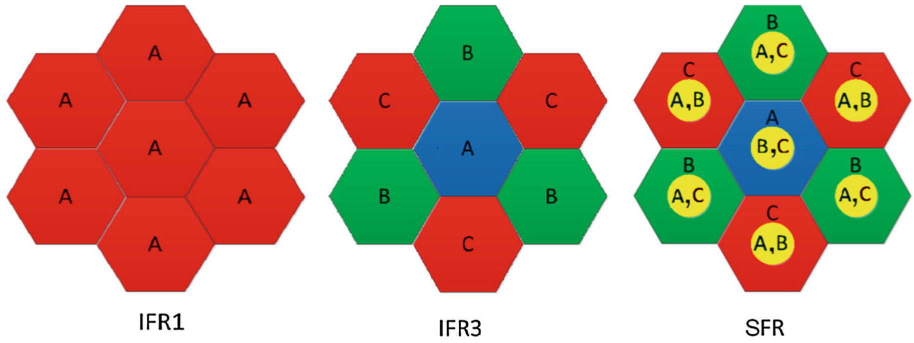

Fig. 4 Frequency allocation schemes

lowest priority, and schedule their transmissions through these sub-bands. Since IFR3 works by allocating different sub-bands for adjacent macro cells, femtocells that are aware of their environment will result in utilizing the frequencies allocated to the neighboring macro cells of the cell that they are located.

When SFR schemes is employed between the macro BSs, femtocells, when capable, utilize the sub-bands that are not used in the cell zone they are located. Since, in SFR the cell area is divided in two regions, the inner one, which is close to the base station and the outer one, which is situated to the borders of the cell, and the sub-bands are distributed non-uniformly to outer region and to inner region of the cells, it means that same frequencies are spared in cell edge macro users and cell center femto cell, and vice versa.

5 Experimental Results

5.1 Network Parameters

The simulator's network configuration consists of a single macro site of radius 250 m, wherein multiple femto base stations are deployed in arbitrary positions. The macro base station is considered to be located at the center of the site, transmitting with a predefined power value of 46 dBm. In accordance to the urban environment model, an appropriate scheme must be considered for the simulator. Thus, the area is divided into rectangles and empty spaces, representing the buildings (walls) and the streets respectively, of a real environment. The specific size and number of the above are subject to the user preferences.

Table 1 summarizes the default values used during the simulation. A few limitations were enforced on the input values to ensure realistic parameters and reliable results. When the network parameters and topology have been defined, the setup is stored and cannot be changed until the user requests a new experiment through the reset button. This way, it is ensured that the different power schemes will apply on the same configuration, for the proper comparison to take place.

5.2 Co-channel Simulation

First, we examine the interference experienced from a macro UE (served be the macro BS) that is located in the coverage area of a femtocell and therefore experiences cross-tier interference. For a complete understanding of the impact of interference, the throughput is

Table 1 Simulation parameters

Parameter	Value				
Cellular layout	Single macrocell				
Number of macro BS	1				
Macrocell radius	250 m				
Macro BS TX power	46 dBm				
Carrier frequency	2 GHz				
Femto BS max TX power	20 dBm				
Femto BS default TX power	11 dBm				
Exterior walls loss (low)	15 dB				
Interior walls loss (low)	7 dB				
Bandwidth (MHz)	20	15	10	5	1.4
Modulation type	64QAM		16QAM		QPSK
Subcarrier spacing	15 kHz				
White noise power density	−174 dBm/Hz				

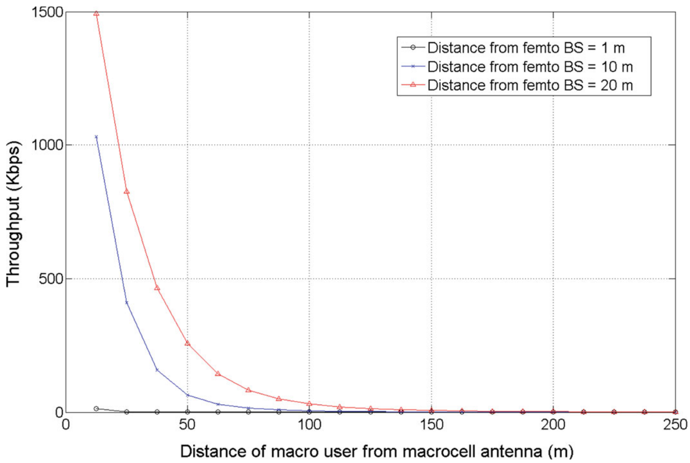

Fig. 5 Throughput for an indoor macro UE against the distance from the macro BS when femtocell interference exists

calculated for several different distances from the macro BS, which ranges from 10 to 250 m. The same is considered regarding the distance of the user from the femtocell since there is a high dependability on the latter. Thus the throughput is also calculated for three different positions inside the area of femtocell's coverage: at distance 1 m from the femto BS, at a distance 10 m and at the femtocell edge (20 m). The results in Figs. 5 and 6 correspond to the case of an indoor macro user and an outdoor one, respectively. This means that in Fig. 5 the user is located inside the building with the femtocell equipment, which implies that beside standard path loss, the macrocell signal is further attenuated by the exterior wall of the building.

The examination of Fig. 5 reveals that the throughput of an indoor macro UE decreases rapidly as the distance from the macro BS increases, especially for the first 100 m from the MBS. When the proximity of the user to FBS is 1 m, the UE never reaches adequate level of

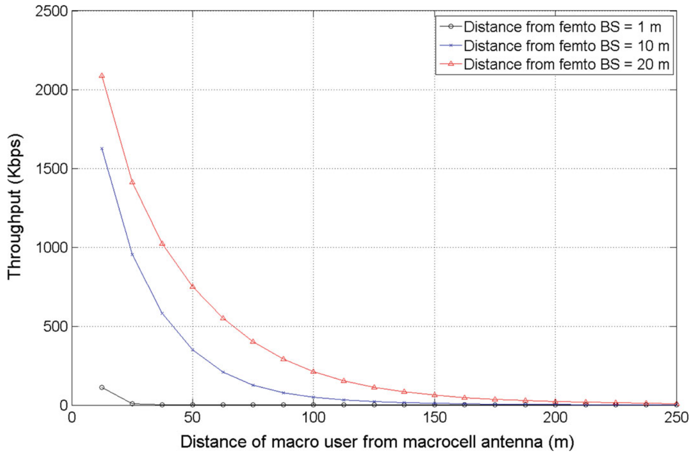

Fig. 6 Throughput for an outdoor macro UE against the distance from the macro BS when femtocell interference exists

service due to strong interference, even when close to macrocell antenna. Specifically, the throughput of the macro UE decreases from 1.5 Mbps to almost 1.1 Kbps (99.93 % decrement), as it moves towards the macrocell edge for the case of 20 m distance between the UE and the femto BS. Indeed, this movement causes the decrement of SINR, which in turn, leads to a decrement in the achieved throughput.

For an outdoor UE (Fig. 6) the results are similar, although there is an improvement over the previous case since there is no exterior wall between the macro BS and the UE. For the case of 20 m from FBS the improvement reaches 25 % at 10 m from MBS (2.1 Mbps), and up to 1,000 % at macrocell edge (10.2 Kbps). Cross-tier interference is still a major issue when the user is 1 m from FBS, and despite the improvement, the user never has satisfying access to service.

Next, we present the interference experience from a femto UE point of view. We follow the same approach as before, studying several distances of the user from the femto BS and the macrocell antenna, and we conduct the experiment for both the cases of an indoor UE (Fig. 7) and an outdoor UE (Fig. 8) FBS is considered to be located inside the building.

In the first case (Fig. 7), the exterior wall acts in favor of the user's achieved throughput, degrading macrocell's impact within the building. Path loss decreases when the user draws away from FBS, especially for the first 10 m from femtocell antenna. However, contrary to the macro user case, the decrease is smoother and even at the femtocell edge the throughput is high enough to serve the user. More specifically, for the case where the distance between the indoor UE and the macro BS is 250 m, the achieved throughput decreases by 97.83 % (from 1.9 Mbps to 41.3 Kbps). For an outdoor UE (Fig. 2) the decrement reaches 96.2 % (from 1.10 Mbps to 41.75 Kbps). Cross-tier interference has a stronger impact as the distance to macrocell antenna shortens, nullifying access completely at 10 m from MBS.

Besides the exterior wall, intermediate walls between apartments and floors affect the throughput of the femto UE. Table 2 presents the throughput values when the user roams in a distance of 10 m from the femto BS. The UE is interfered by a macro BS, which is located in a distance of 125 m. The rows of the table represent the apartments among the femto BS and the UE, while the columns represent the floor difference between them.

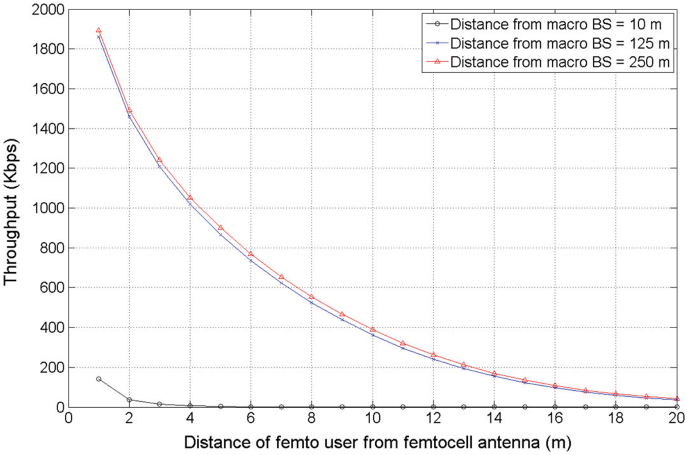

Fig. 7 Throughput for an indoor femto UE against the distance from the femto BS when macrocell interference exists

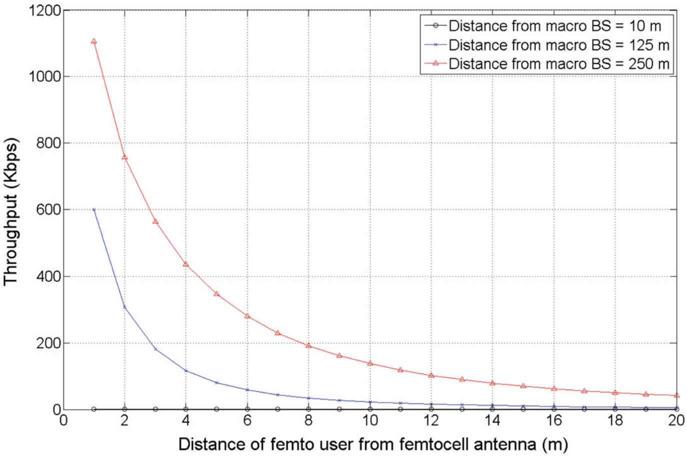

Fig. 8 Throughput for an outdoor femto UE against the distance from the femto BS when macrocell interference exists

Table 2 Throughput of an outdoor femto user against the number of intermediate floors and apartments

No. of Apts.	No. of floors (Kbps)			
	1	2	3	4
0	22.59	7.36	2.34	0.74
1	0.35	0.11	0.03	0.01
2	0.01	0.00	0.00	0.00

It is obvious that the existence of intermediate structures has a great impact in the femtocell performance and a careful selection of the FBS's location should be made to ensure coverage.

In the next experiment, in order to examine the interference in situations that reflect the additive nature of the phenomenon, we explore large-scale femtocell deployments that

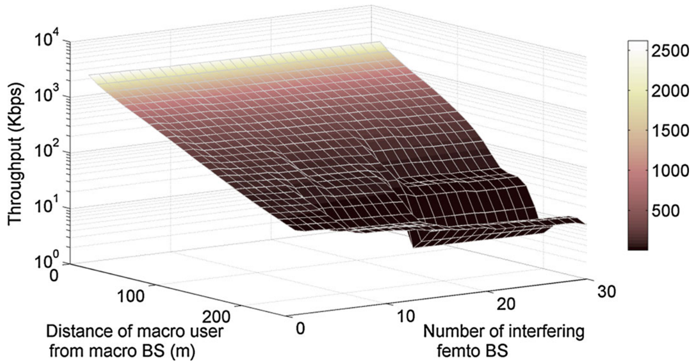

Fig. 9 Throughput for a moving user against the distance from the macro BS and the number of femtocells

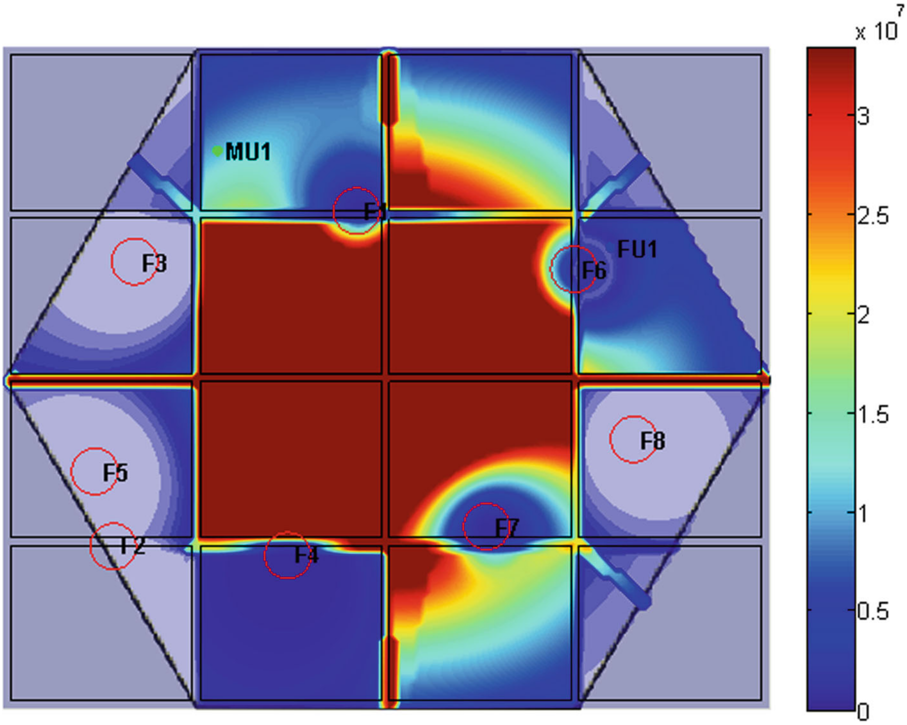

Fig. 10 Throughput with common power levels for all FBSs (macro user)

simulate better the real-life circumstances. Specifically, we investigate the interference levels experienced by a macro user, travelling across the macro site, starting from the cell center and reaching the cell edge. Inside the cell, 30 femto BS are randomly located. In order to investigate thoroughly the additive interference, we activate the femtocells sequentially, and measure macro UE throughput at each step, until all FBSs are activated.

As depicted in Fig. 9, the throughput of the macro user decreases drastically when the user moves towards the cell edge. However, it is clear that the decrement is bigger when the number of transmitting femto BSs increases.

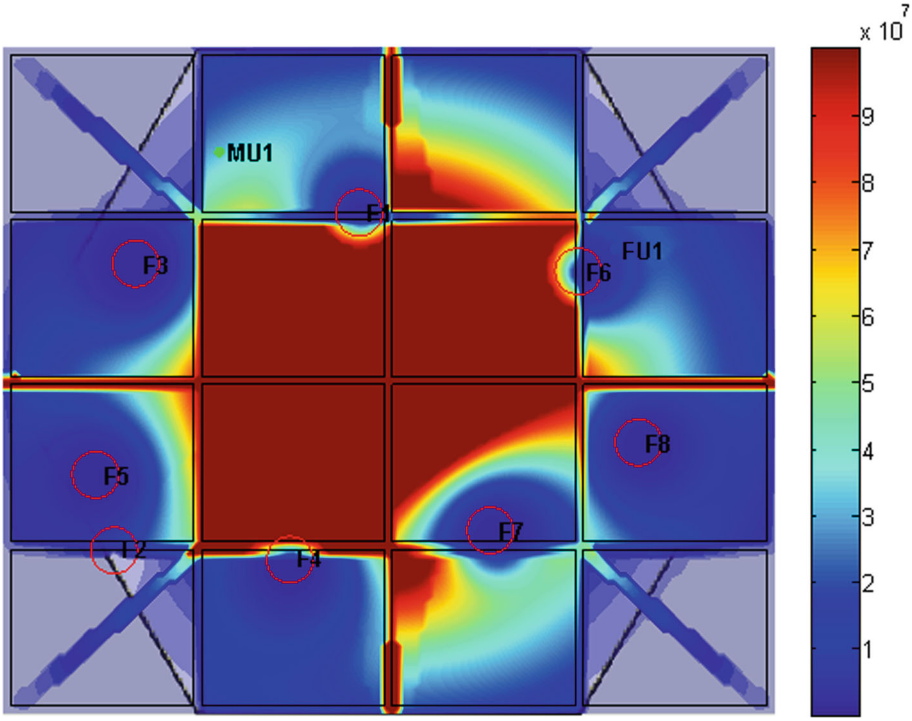

Fig. 11 Throughput with power configuration for steady radius of service (macro user)

Two abrupt decrements in the achieved throughput around the 150 m distance (when the number of interfering femto BS is 10 and 19), and two when distance is approximately 200 m (when the number of interfering femto BS is 7 and 17), can be attributed to the activation of close-by femtocells. It is obvious from the above experiment, that the cross-tier interference between macro and femto layer may affect the overall performance of the system and therefore should be taken into account during the system configuration.

5.3 Power Control Simulation

Throughout the previous results, it is obvious that interference is highly dependable on the location of the femtocell relative to the macrocell antenna, thus a common power configuration is inappropriate. Instead, controlling the power transmission of each FBS separately, adjusting it to the custom conditions is preferable. In this section, we present the results of the simulator, which we designed to encompass power control, as described in Sect. 4. For the needs of the experiments in this section, we considered available bandwidth of 20 MHz, and 64QAM modulation. Femtocell default transmit power was set to 11 dBm.

In Fig. 10 and in Fig. 11 an example of the simulation results is given, highlighting the different approach between the power control models. In the first case, fixed power levels for femto base stations are applied, and the throughput of a potential macro-user is displayed throughout the entire map. Fixed power scheme proves unsuitable, especially for the cell-edge areas with a close-by femtocell. In this case, the received power from MBS is significantly reduced due to path loss, and gets easily dominated by the FBS transmission, even on the outside of the buildings. The situation can get even worse for the case of indoor environment,

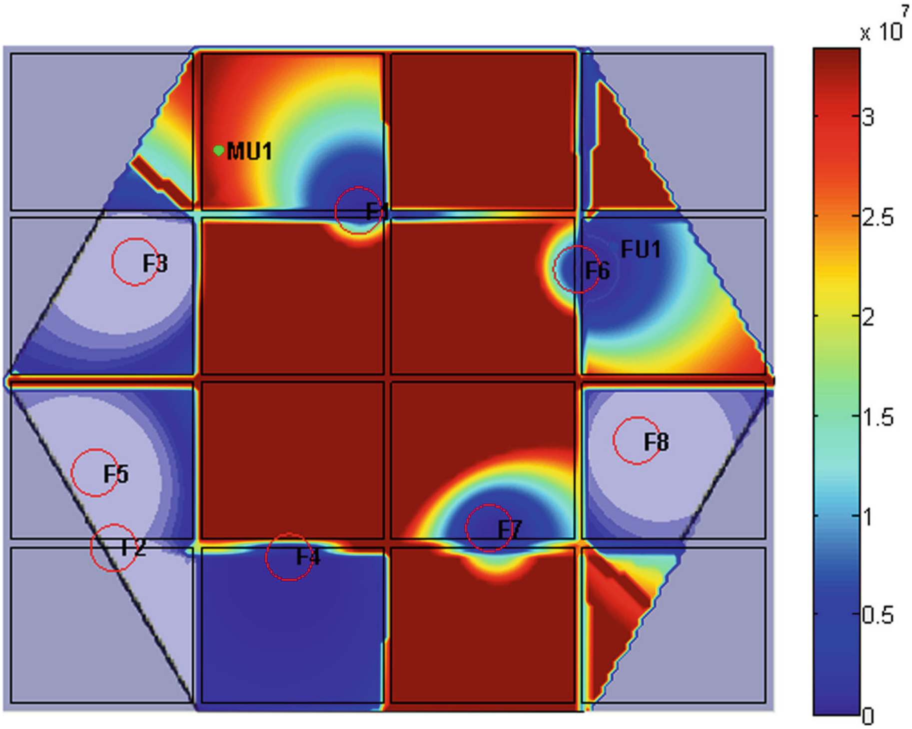

Fig. 12 Data-rate map of IFR with femtocells utilizing the entire bandwidth

since the received power from the macro BS decreases even further due to increased path loss added by the outer walls. These results comply with the findings of the previous subsection. In Fig. 11 instead, femtocells' transmit power is oppressed or enhanced when needed, in respect for macrocell performance, maintaining a constant radius of FBS coverage, as described in Sect. 4.

As a result, the ratio of macrocell and femtocell signal strength is independent of where the latter is located relative to the macrocell and depends solely on the distance between the UE and the attached FBS. On the other hand, since an upper limit for femto transmitting power is set, its domination by a close-by macrocell antenna cannot be avoided, especially when multiple users are served by the FBS.

5.4 Frequency Allocation Simulation

For the same network considered above we studied the case of a possible ICIC situation and the respective subcarrier allocating for the femtocells. Since IFR3 with femtocells utilizing the available spectrum showcases co-channel interference, there is no point for the data rate map. Instead, Fig. 12 presents the data rate map of the IFR with femtocells utilizing the entire bandwidth. When macrocell ICIC is utilized in macrocell layer, it is important for deployed femtocells to be aware of it either by sensing their environment or during their initial configuration. Otherwise, fractioned bandwidth along with interference originating from transmitting femtocells, will result to extremely poor SINR as the figure shows. The latter is valid for all frequency partition schemes, including SFR.

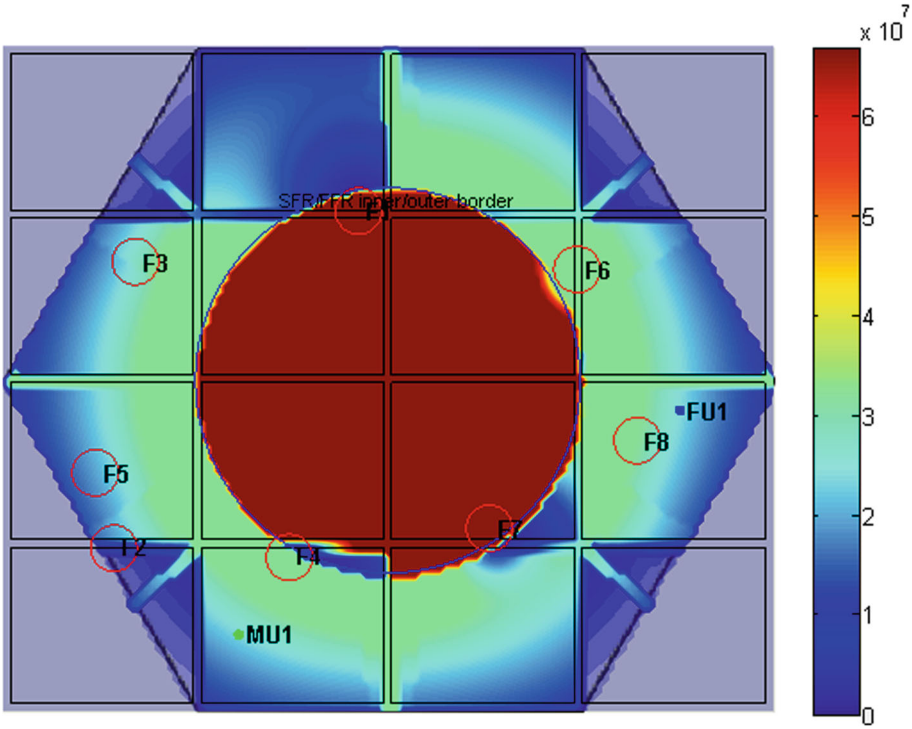

Fig. 13 Data rate map of SFR with adapted femtocells

On the other hand, Fig. 13 depicts aware femtocells in SFR environment. It is obvious that the conflicts are neglected, and the only source of interference exists when there are femtocells near the inner/outer borderline, and their range overlaps the neighboring area. In order to study when the benefits of interference mitigation compensates for the bandwidth division, we compare the overall network's performance for each case and for increasing number of femtocells.

Figure 14 presents a collective comparison of all possible scenarios, versus the number of femtocells deployed in the cell. We are interested to find the degradation of network's performance for small number of deployed femtocells when spectrum division is used, and the femtocells density, beyond which the latter is compensated by the interference mitigation it offers. For small-scale femtocells deployment, power control and no provision, showcase two times the throughput when FR is employed, however, their advantages decrease rapidly. Simple co-channel operation becomes worse as early as for 20 femtocells, while power control is the best choice for 35 and less. Beyond these densities, co-channel interference becomes a more significant factor than macrocell spectral efficiency, making FR schemes the preferable choice. Small cells' utilization of the available spectrum offers both overall spectral efficiency, and maximum network throughput, for large-scale femtocell deployment.

IFR compared to SFR presents slightly worse behavior, since SFR is characterized by greater spectral efficiency. There is a small decrease in SFR though, when femtocell number increases, a phenomenon attributed to the fact that when the number of femtocells increases the probability of them to be located near borders, where they can affect neighboring areas becomes larger, thus increasing the interference levels.

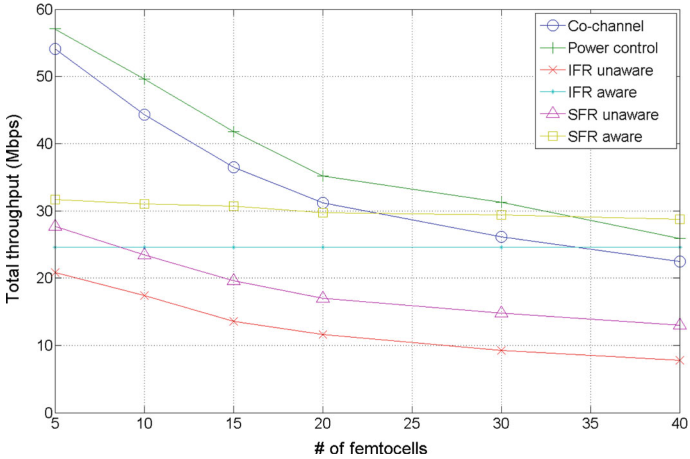

Fig. 14 Average throughput performance for macro users

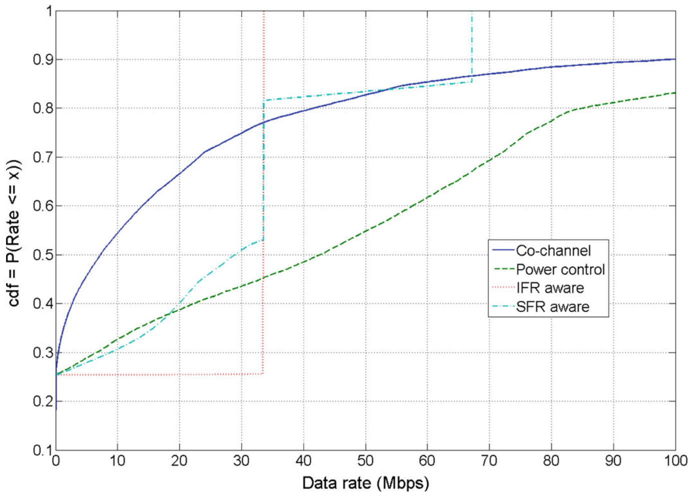

Fig. 15 CDF of throughput for different scenarios

Figure 15 presents the CDF of data rate when 15 femtocells have been scattered in the cell. Although as we saw power control behaves best regarding average throughput, it cannot provide protection to the worst-case users, as FR schemes do by allocating them exclusive bandwidth.

The majority of worst-case users are located near the cell edge. In addition, due to weak signal received, it is the area where the use of femtocells is most needed, thus an increased femtocell density is expected in these areas. We consider a cell-edge user when he is located at distance greater than 120 m from the macrocell antenna. The average throughput of cell-edge users for increasing femtocell density deployment is shown in Fig. 16. The figure is similar with the total cell average throughput, but femtocell density is a more important parameter now, since inter-cell interference makes the area already substandard. Frequency partition methods (IFR, SFR) demonstrate better performance than simple co-channel for less than 15 femtocells, while power control stops being the best solution for less than 25 femto BSs.

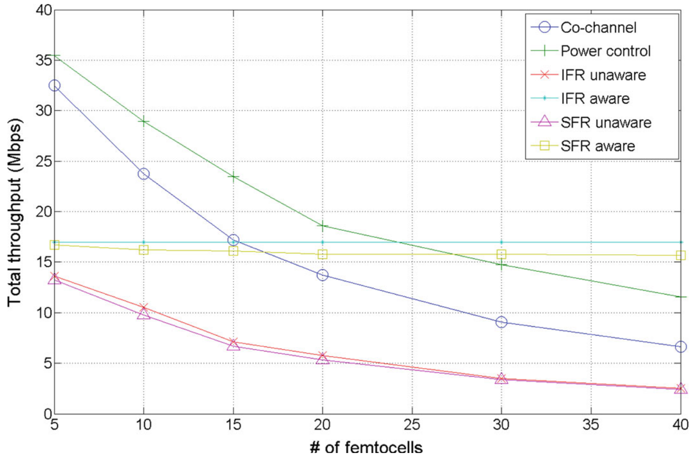

Fig. 16 Overall throughput performance for macro users for each ICIC at cell's borders

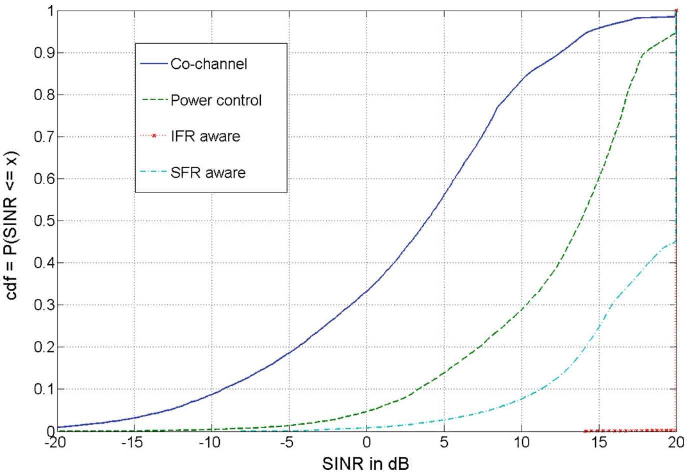

Fig. 17 CDF of SINR at cell's borders for different scenarios

Beside the average throughput we focus on the worst-case users. Figure 17 demonstrates the CDF of the SINR for cell - edge users when 15 femtocells have been scattered over the cell. Dedicated bandwidth to macro users through FR ensures the protection of every macro user in the cell. Otherwise, many users would not be able to maintain the minimum SINR required for access to service.

6 Conclusions

In this work, we presented a simulation framework for custom femtocell overlays over LTE-A systems and to study interference behaviour. The framework is designed for reproducing highly configurable femtocell topologies over macrocellular infrastructure. The purpose of the framework is to allow the investigation of cross-tier and inter-tier interference phenomena. Moreover, it is used to evaluate available options to overcome this problem. The graphical interface may also be used to investigate for appropriate locations for future femtocell deployment and configuration.

The simulation framework incorporates the main available techniques designed to mitigate interference and allocate available resources equitably, ensuring access to service throughout the cell. The methods incorporated included power control for constant femtocell coverage radius, and frequency allocation when unexploited spectrum was available. The simulation results showcased the advantages and disadvantages of each method, and concluded on their suitability for different network situations. Specifically, it was shown that simple self-configured power control yields the best results when a small number of femtocells is deployed. However, when a large-scale deployment is expected, it would be preferable to encompass the ICIC approach and allocate the available spectrum to femtocells. The simulator also showed that complex SFR proves slightly better than simpler IFR, in terms of overall throughput, but the situation reverses when cell-edge performance is examined. The simulator proved that the selection of the optimal configuration depends on multiple parameters, and the usage of a high-configurable simulation framework is necessary to evaluate custom complex heterogeneous networks.

7 Future Work

Possible future steps could be the extension of the simulator in several ways. One possible enhancement would be the integration of location management of new FBSs. This may include a search for the optimal location of a FBS given the target area to cover and the nearby sources of interference, or the optimal dispersion of multiple FBSs regarding coverage and capacity given the layout of a large area, i.e. replicating a company building. Another option would be the extension of the tool to include the usage of Almost Blank Subframes (ABS) as a means of interference mitigation. The latter are subframes during which the femtocell transmits no data except some necessary signals method allowing macro users to be served with no interference. Finally, while this work focused on downlink study and simulation, where there are more interference mitigation techniques available and are more effective and flexible for testing and combinations, interference in uplink is also a major issue and it should be tackled. The differences between downlink and uplink and the inclusion of MIMO capabilities to enhance uplink possibilities are some of the issues that may be addressed in future steps.

The framework's software is available at [2] and the interested researchers can download it for using it either as a tool to test and evaluate femtocell topologies behavior or as basis for further simulation development.

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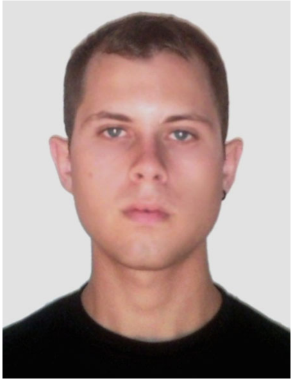

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