A Simulation Framework for LTE-A Systems with Femtocell Overlays

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ABSTRACT

The use of femtocells is an efficient way to improve coverage and quality of service while on the other side the deployment cost for the service provider is kept in extremely low level. Long Term Evolution Advanced (LTE-A) systems with femtocell overlays aim to provide better indoor voice and data coverage and to increase network capacity. One of the major technical challenges that femtocell networks are facing nowadays, is the cross-tier interference, i.e., the interference between the femto base stations and the macrocell infrastructure. To this direction, we have designed and implemented a framework that simulates femtocell overlays integrated over LTE-A macrocellular systems. This framework focuses on the impact of cross-tier interference and furthermore is able to estimate the throughput at every point of integrated femtocell/macrocell LTE-A networks. In this paper, we present the design and implementation of this simulation framework and we provide significant experimental results obtained with the aid of this system.

Categories and Subject Descriptors

I.6 [**Simulation and Modeling**]: Miscellaneous; C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.4 [**Performance of Systems**]: Miscellaneous

General Terms

Design, Experimentation, Measurement, Verification

Keywords

long term evolution advanced, femtocell simulation, cross-tier interference, throughput estimation

1. INTRODUCTION

The newly emerged data-minded cellular standard Long Term Evolution Advanced (LTE-A), which is the most promising candidate for next generation communication, has been derived by the demand of higher data rates and spectral efficiency on mobile networks. Recently, the mobile systems introduced short-range antennas, the so-called femtocells, also called femto or home Base Stations (BSs) or Home eNode-Bs (HeNBs), for indoor coverage extension [2], [3]. The reduced cell sizes and transmit distance that low-power and low-cost femtocells offer, can allow service providers to extend service coverage indoors and highly increase the achieved capacity gain. Therefore subscribers and operators are both satisfied, because of higher data rates and reduced traffic on expensive macrocell network, respectively.

Femtocells can co-operate within a macrocell underlay, by using the same or different frequencies. However, co-channel operation of femtocells introduces interference to macrocells and vice versa, limiting system capacity. So installation of many low-power base stations poses new challenges in terms of interference management and efficient system operation. Many intercell interference avoidance/mitigation mechanisms have been proposed in the literature. Femtocells are customer-deployed, so interference problems can not be handled by using dedicated channel approach, because it would require proper customer network planning knowledge.

Prior research in femtocell networks is mainly focused on the investigation of interference behavior while operating within a macrocell underlay. [6] presents system level simulation results for possible downlink and uplink throughputs at any location of the scenario for both macro and femtocells for co-channel operation. The simulation considers different femtocells deployment density scenarios. [8] describes 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. Also in case of WCDMA HNBs, an extensive theoretical analysis including different cross-tier interference scenarios, is provided by 3GPP technical report [4]. The utility-based non-cooperative femtocell Signal to Interference-plus-Noise Ratio (SINR) adaptation presented in several works, such as [5], 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 causing smaller cross-tier interference obtain higher SINR margins. This is similar to the Utility-Based Power Control (UBPC) scheme presented in [11], where users vary their target SINRs based on the prevailing traffic conditions. The evolution of power and SIÎÎR for different algorithms is simulated, showing that UBPC overcomes the divergence problem and is flexible to achieve fairness and adaptiveness using different parameters and different price coefficient settings.

Although the above works present experimental results based on the theoretical models they propose, none of them depicts a user-friendly simulation mechanism, implemented for the evaluation of a two-tier mobile network. In this paper, we propose a simulation framework that estimates the interference and the throughput in every point of a custom integrated femtocell/macrocell LTE-A network topology, with parameters provided by the user. This framework can be used for studying its interference behavior, based on the presented analytical model analysis. In order to estimate the adjacent macrocell interference, we calculate the SINR by using an analytical model that takes into account the path and penetration loss due to external or internal walls as well as due to signal propagation. The simulation framework is implemented in Matlab and is available to the community through [7].

In order to demonstrate the use and contribution of this simulation framework, three different scenarios are examined in this paper. In the first scenario, we are interested in examining the interference that a femto BS adds to a user served by a macrocell and how this interference affects the achieved throughput. In our second scenario, we examine the opposite deployment: the examination of adjacent cell interference that the macrocell environment adds to a user served by a femto BS. The third scenario simulates the movement of a user that is served by a macro BS, so as to calculate the user's throughput during his route.

The remaining of this paper is structured as follows: in Section 2, we describe the mathematical analysis used for the internal design and implementation of the simulation software. In Section 3 we present the system's architectural design, its individual modules, as well as the interfaces between them. In Section 4, we present the experiments that we have conducted in conjunction with their results. Finally, our conclusions and planned future steps are described in Section 5.

2. ANALYSIS & MODELING

Knowing that femtocells, in most cases, are deployed by home users themselves, the a two-tier system must automatically adjust its parameters without depending on the deployer's technical knowledge on network planning. Otherwise, inappropriate adjustment parameters may cause interference and decrease network capacity. This section presents the analysis that estimates the interference and the throughput in every point of the LTE-A system integrating femto and macrocells. The model takes into account the path loss and propagation models in order to estimate the SINR and therefore the adjacent cell interference of the integrated LTE-A network.

2.1 Path Loss Model

In order to estimate the SINR, first we have to calculate the path loss between a macro BS and a User Equipment (UE) that are in the same apartment stripe and between a femto BS and a UE. The path loss for the first case and for a macro user roaming outdoor in an urban area, can be determined as follows [1]:

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

whereas, for the case of an indoor macro user the path loss is given by:

$$PL(\text{dB}) = 15.3 + 37.6 \log_{10} R + L_{ow} \tag{2}$$

where R is the distance between the transmitter (Tx) and the receiver (Rx) in meters and L_{ow} the penetration loss of an outdoor wall. The path loss between a femto base station and a UE is calculated by the following equation [1]:

$$\begin{aligned} PL(\text{dB}) \quad = \quad & 38.46 + 20 \log_{10} R + 0.7 d_{2D,indoor} + \\ & 18.3 n^{((n+2)/(n+1)-0.46)} + q^* L_{iw} \end{aligned} \tag{3}$$

where n is the number of penetrated floors, q is the number of walls separating apartments between the femto BS and the UE, and L_{iw} is the penetration loss of the wall separating apartments. Also, the term $0.7 d_{2D,indoor}$ takes account of penetration loss due to walls inside an apartment and is expressed in m.

Finally, we consider the case of an outdoor femto user associated to an indoor femto BS. In this case we also consider the outdoor wall loss [1]:

$$\begin{aligned} PL(\text{dB}) \quad = \quad & max(15.3 + 37.6 \log_{10} R, 38.46 + \\ & 20 \log_{10} R) + 0.7 d_{2D,indoor} + \\ & 18.3 n^{((n+2)/(n+1)-0.46)} + q^* L_{iw} + L_{ow} \end{aligned} \tag{4}$$

2.2 SINR Estimation

The estimation of the received SINR of a macro user m on subcarrier k, when the macro user is interfered from neighboring macrocells and all the adjacent femtocells, in our analysis is expressed by the following equation:

$$SINR_{m,k} = \frac{P_{M,k} G_{m,M,k}}{N_0 \Delta f + \sum_{M'} P_{M',k} G_{m,M',k} + \sum_{F} P_{F,k} G_{m,F,k}} \tag{5}$$

where $P_{M,k}$ and $P_{M',k}$ is transmit power of serving macrocell M and neighboring macrocell M' on subcarrier k, respectively. $G_{m,M,k}$ is channel gain between macro user m and serving macrocell M on subcarrier k. Channel gain from neighboring macrocells are denoted by $G_{m,M',k}$. Similarly, $P_{F,k}$ is transmit power of neighboring femtocell F on subcarrier k. $G_{m,F,k}$ is channel gain between macro user m and neighboring femtocell F on subcarrier k. N_0 is white noise power spectral density, and Δf subcarrier spacing.

In case of a femto user f on subcarrier k interfered by all macrocells and adjacent femtocells, the received SINR can be similarly given by (6):

$$SINR_{f,k} = \frac{P_{F,k} G_{f,F,k}}{N_0 \Delta f + \sum_{M} P_{M,k} G_{f,M,k} + \sum_{F'} P_{F',k} G_{f,F',k}} \tag{6}$$

The channel gain G is dominantly affected by path loss, which is different for outdoor and indoor scenarios (1), (2), (3), (4). So, it can be expressed as:

$$G = 10^{-PL/10} \tag{7}$$

2.3 Throughput Calculation

Having estimated the SINR, we can now proceed with the throughput calculation. The practical capacity of macro user m on subcarrier k can be given by the following equation [9]:

$$C_{m,k} = \Delta f \cdot \log_2(1 + \alpha SINR_{m,k}) \tag{8}$$

where, α is a constant for target Bit Error Rate (BER), and defined by $\alpha = -1.5/\ln(5BER)$. In this analysis BER is set to 10^{-6}.

Finally, the overall throughput of serving macrocell M can be expressed as follows:

$$T_M = \sum_{m} \sum_{k} \beta_{m,k} C_{m,k} \tag{9}$$

where, $\beta_{m,k}$ represents the subcarrier assignment for macro users. When $\beta_{m,k} = 1$ means that the subcarrier k is assigned to macro user m. Otherwise, $\beta_{m,k} = 0$. In a macrocell in every time slot, each subcarrier is allocated to only one macro user, as we know from the characteristics of the Orthogonal Frequency-Division Multiple Access (OFDMA) system. This implies that:

$$\sum_{m=1}^{N_m} \beta_{m,k} = 1 \tag{10}$$

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

3. SYSTEM ARCHITECTURE

Based on the mathematical analysis given in Section 2, a simulation framework that applies for the interference and, therefore, the maximum throughput estimation in macrocell environments that integrate femtocell overlay has been implemented. The fundamental principle followed during the design of the framework is modularity. In this way, the implemented simulation software that is available at [7] can be easily modified or extended by any interested researcher.

The analysis presented in Section 2 is used by the core component of the simulation framework which receives as input the macrocell environment's properties, such as the positions of femtocells and attached users, the dimensioning of interfering buildings, as well as other parameters like the macro and femto BS transmission power and modulation scheme. By making use of the equations presented in the previous section and based on the defined macro and femto BS transmission power, the simulation framework's core is able to calculate the received power from serving as well as from the interfering cells. Based on these figures and by taking into account the white Gaussian noise, the core is able to make an estimation of the SINR and throughput at any given position of the examined LTE-A network.

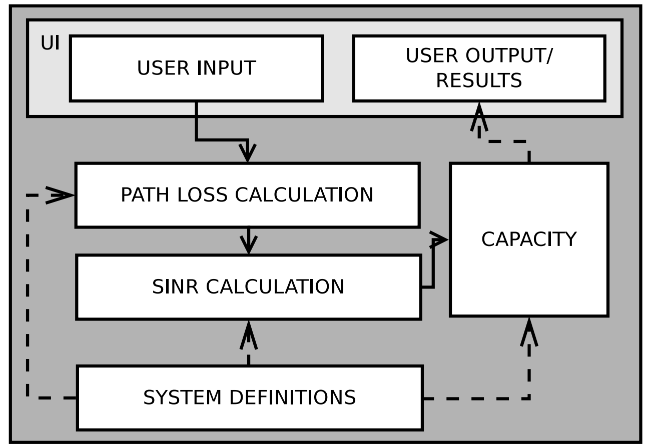

Figure 1: System's architectural diagram.

A simulation environment needs to provide a friendly, comprehensible, and easy-to-use interface for interaction with the user, in terms of input and output. Also the internal architecture of the system, which is not directly accessible by the average user, must be distributed in individual subunits, dedicated in executing a particular function or set of interdependent functions. We consider these subunits as modules, that may be grouped in separate layers. This architectural scheme is mostly preferred from a software developer due to its simplicity and scalability, because it makes easier the case of replacing particular models or extending the whole simulator structure (by taking into account specific and more complex scenarios that require new functions addition).

Our algorithm can be logically divided into two layers. The lower layer is reflected by the mathematical model used for our simulations, in which, given the user parameters all appropriate calculations take place, including a femto or macro user's path and penetration loss, SINR estimation, and by taking into account user's input and system-defined parameters, the channel gain and maximum theoretical throughput. The information obtained, is displayed in real-time. The higher layer is reflected by the graphical user interface which is used for both user input and output. In this layer, no calculations are made that are directly related to the calculation process. In fact, it is used only to define the parameters of the topology, i.e., positions of femtocells, users and buildings, and to output the result.

More specifically, the implemented simulation framework uses the following architectural elements as basis:

- User Input Module
- Path Loss Estimation Module
- SINR Estimation Module
- Capacity Calculation Module
- User Output Module

Figure 1 illustrates the architectural diagram. Most user-defined variables have already been presented in Section 2.

The light gray area groups the modules that constitute the higher layer of the simulator architecture, the Graphical User Interface. Each architectural module is described in detail below:

User Input Module: The user communicates with the system via a graphical user interface. The initial layout of the user's screen is depicted in Figure 2 listed in the experimental example's section that follows. In order, the appropriate calculations to be made, the framework needs some user input, including the exact location coordinates of the femto BSs in a macrocell area, the total number of femto and macro users and the femto BSs the users are attached to. Also, in order to generate the building map, the framework needs the number of buildings in x-and-y-axes and the road's width. Furthermore, due to multiple configuration modes available in LTE-A, total BS bandwidth and modulation scheme parameters are necessary. Based on the given location coordinates, the distance between UEs and their respective antenna spots are calculated, resulting estimation of the channel path loss. These parameters, i.e., users location, BS units location, as well as the structure of the map, are enough in order to count the interfering walls and therefore to estimate the path loss. The topology considers only the case of an urban area since the deployment of femto BS in other types of areas are not common and therefore due to their density they do not present scientific interest.

Path Loss Estimation Module: The analysis and modeling performed by this module are described in detail in Section 2. This module implements the mathematical models provided by [1] corresponding to all possible cross-tier and intra-tier interference and deployment scenarios that can take place in an urban area. Those cases include: a) outdoor macro user interfered by femto BS, b) indoor macro user interfered by femto BS, c) outdoor femto user interfered by macro BS and d) indoor femto user interfered by macro BS. The selection of the appropriate model is made, based on the user input of the previous module. No matter which scenario is selected, the result of this module, expressed in dB, is forwarded as input to the next module.

SINR Estimation Module: The SINR Estimation Module implements the channel gain and SINR calculation mathematical models, which have been analytically described in Section 2. The Path Loss Estimation Module provides the estimated path loss value, in order to be used for channel gain calculation. This in turn provides the calculated value as it is necessary for the calculation of each user's channel gain.

Capacity Calculation Module: Provided with the result value of the above module, and by taking into account the carrier spacing (system definition) this module implements only the channel capacity estimation model. The final results' matrix is given to the next module, so that it will be presented to the end user.

User Output Module: When the user input is set and the simulation process is performed, the final results are displayed in a new window which presents the topology colored in every point, according to the throughput level. Specifically, as it is also shown in the figures listed in the experimental example's section that follows, the simulator displays a map representing the user-defined topology. In the center of the map, the macrocell antenna is displayed, surrounded by all deployed femto BSs and attached macro and femto users in their respective positions. Also the buildings of the topology's map are displayed, according to the user-defined positions. Next to the map there is a layer that displays analytical properties of the unit hovered by the mouse pointer. After running simulation for every possible position, the whole map is colored according to the throughput levels and a colored bar is displayed next to the map, representing the throughput values spectrum. The lowest throughput value corresponds to blue color on the map, while the highest one to red. All intermediate throughput values correspond to an intermediate color of the color spectrum. By hovering the results window, the panel next to the map is updated with the corresponding analytical simulation values. Figure 4 illustrates the resulting colored map.

Table 1: System level simulation parameters

Parameter	Value					
Mecrocell Radius (R_m)	250 m					
Femtocell Radius (R_f)	20 m					
Frequency	2 GHz					
Macro BS Power	46 dBm					
Femto BS Power	20 dBm					
Outdoor Walls Loss (L_{ow})	20 dB					
Indoor Walls Loss (L_{iw})	5 dB					
Bandwidth (MHz)	20	15	10	5	3	1.4
Modulation Scheme	64QAM		16QAM		QPSK	
Subcarrier Spacing	15 kHz					
White noise power density	-174 dBm/Hz					

4. EXPERIMENTAL RESULTS

As it is already mentioned we have conducted experiments that indicatively show the features and the operation of the simulation framework. The experiments that we present below and examine different interference and throughput scenarios and indicate how the simulator is used as well as the way that metrics are calculated and outputted in real time. At this point it should be noted that the values for the simulation setting parameters that are used by our framework have been based on [10]. Table 1 provides an overview of the simulation parameters along with the selected values.

The femtocell deployment process on the simulation input window is started with the initial screen illustrated in Figure 2.

First, the end-user is able to set the number of macro users, the number of femto users associated to each femtocell, the number of femto BSs located within the macrocell area and the preferred channel bandwidth, according to the current LTE-A standards (1.4, 3, 5, 10, 15 or 20 MHz). Also, because of the applied urban environment the end-user has to define the width of the map's streets, in meters. By clicking "Apply to Map", the buildings are set up according to the end-user's input, and a manual femtocell deployment and femto/macro user placement takes place by clicking onto specific points in the macrocell's area. The deployment is considered completed when the end-user has placed the last macro user on the map. After this event, the end-user can view the simulation statistics for every placed unit, by hovering that with the mouse pointer. Now the end-user can also set an additional hypothetical femto or macro user and the already deployed BS he is attached to. The simulation

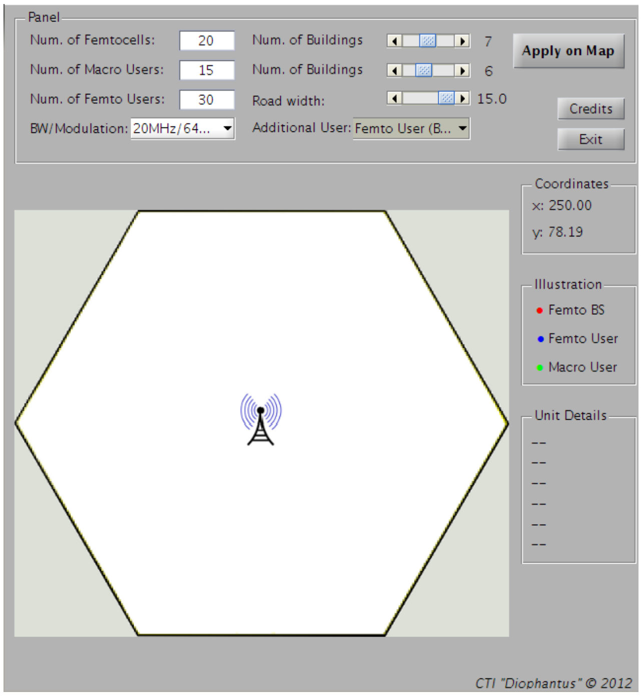

Figure 2: Initial simulator's screen.

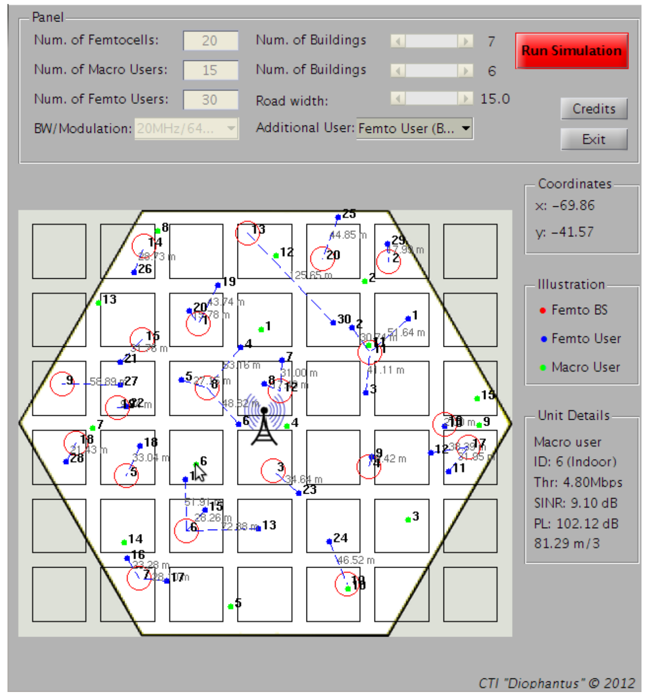

Figure 3: Properties of a selected macro user after finishing deployment process.

process for every possible position of that additional user is executed after clicking "Run simulation". This event triggers a progress bar to pop up, in order to keep the user informed about the simulation's progress. Subsequently, the map appears colored in every point, according to the throughput level (Figure 4). This, particularly, represents the hypothetical throughput achieved for every possible position of the additional user in the macrocell's area. The kind of user and which BS is attached to, is considered by the "Examine as" drop-down menu. By hovering the map, all useful arithmetic values of the simulation (throughput, path loss, SINR etc.) are displayed on the panel next to the map, as well as the coordinates of the current position. In the special case of hovering the macro BS or a deployed femtocell or user, detailed values and properties are displayed in "Obj. Details" field. Below the map, the maximum and minimum possible values of the user throughput are displayed for every possible user's position.

Indicatively, we present simulation scenario for both types of transmission. We consider the case in which the topology has 20 femtocells deployed in random spots, 15 macro users and totally 30 femto users. Also, all base stations operate at 20 MHz/64QAM. By selecting a deployed BS or a user, the corresponding properties are displayed. In this example (Figure 3) we select the macro user with user_id equal to 6 so that we can mainly view his throughput. As we can see, user6 is 81.29 m away from the macrocell antenna and is located indoors. Also there are three walls, degrading signal power by 20 dB each. By taking into account, the cross-tier interference due to the neighboring femto BSs and that there are 14 more users that are simultaneously serviced by the same BS, decreasing the available subcarriers, the throughput is dropped to 4.8 Mbps.

Finally, we examine the case of an additional femto user attached to femtocell1, interfered by all other femtocells (Figure 4) and the macrocell for every possible location. Figure 4 illustrates the map colored accordingly. It reveals that the throughput of the femto user is highly decreased at the building's surrounding environment, due to cross-tier interference and path loss. It can be easily noticed that the signal is almost completely faded, inside the neighboring buildings, basically due to additional path loss. More specifically, for the case when the distance between the indoor femto user and the femto BS is 24.26 m, there are no physical obstacles/walls between them and there are two more femto users attached to that cell, the achieved throughput is 24 Mbps.

The description of the experimental process presented above, demonstrates the user-friendliness and the efficiency of the implemented simulation framework. The input of the network topology can be easily provided by the end-user to the software through the graphical user interface. Calculations are performed easily, just with one click on the panel and the execution time is very short providing results in real-time. The results are graphically outputted and once the user wishes to receives more detailed information is able to be issued again through the graphical user interface.

5. CONCLUSIONS & FUTURE WORK

In this paper, we have presented a simulation framework for LTE-A macrocell topologies with femtocell overlays. This simulation framework enables the user to easily set-up his two-tier network topology of an LTE-A system and is able to perform various interference and throughput estimations. The framework takes into account both types of cross-tier interference, i.e., the femtocell interference to users attached to macrocell and the macrocell interference to users attached

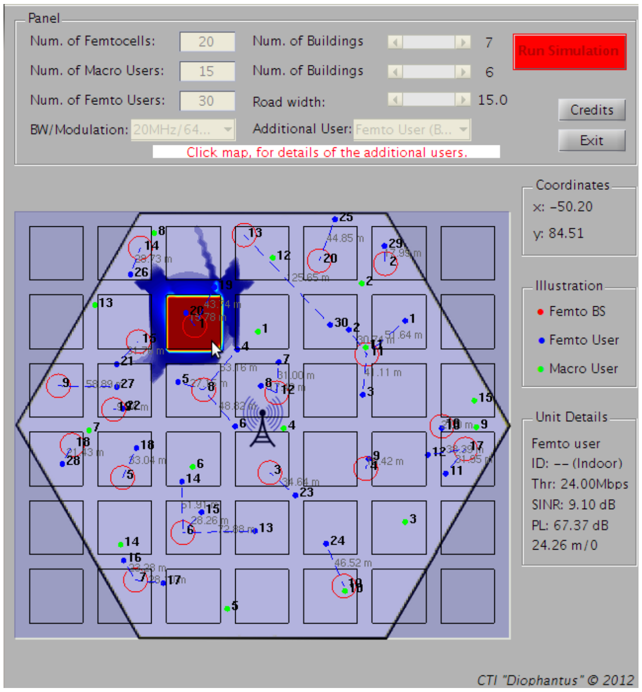

Figure 4: Hypothetical additional user properties in a random spot.

to femtocell. Our simulator is available at [7] and estimates the maximum theoretical throughput that can be achieved for each case based on the distance from the serving and the interfering BSs and provides an overview of the impact that cross-tier interference has on LTE-A macrocell networks that integrate femtocells. Additionally, we have conducted experiments for both cases of interference scenarios in custom femtocells deployment and macro users location and we have evaluated the simulation results in terms of throughput.

The implemented simulation software has been designed and implemented in a way that allows researchers to easily modify or extend the provided simulation software. An interesting future step that could follow this work is the investigation of radio allocation strategies that reduce the interference and therefore increase the total throughput in the topology. These strategies could include fractional frequency reuse or self-organizing methods for the frequency allocation in the femtocell overlay.

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