Mobile Sensing and Location Based Services Applied to Femtocell Networks

1. Introduction

Wireless communications are nowadays one of the most skyrocketing sectors in the communications market and research areas. Due to constant technical advances, mobile terminals have become something indispensable. It is already in the past when the number of wireless terminals clearly exceeded the number of fixed terminals for the first time and, in recent years, operators have been experiencing a steady increasing demand for higher data rates and better quality of service.

The advent of 3G wireless networks and its successful introduction in multiple markets all over the world also started the emergence of new and diverse mobile services that generated a great increase in capacity demands. Video streaming and Internet browsing, along with the increase of popularity of the Web 2.0, are currently the main sources for this bandwidth increase requirement. Operators cannot depend or rely on voice services for revenue anymore.

A great increase in capacity and transmission rates is envisioned with the emergence of 4G wireless networks by means of new strategies and technologies inherited from non-mobility wireless networks. OFDMA-based modulations combined with MIMO strategies are the technologies chosen to be the core for the newest access networks. 3GPP standards, such as WiMax, were initially designed to deliver wide band wireless communications providing coverage to rural areas. However, due to their excellent performance in frequency selective channels, they were extended and derived into a mobile standard that makes it possible to deliver such high data rates necessary for 3G and 4G wireless services, especially when combined with MIMO strategies in strong multipath environments. Orthogonal Frequency-Division Multiple Access (OFDM) is the multi-carrier and multiplexing scheme utilized in both WiMax and LTE networks.

On the other hand, parallel improvements in cellular networks capacity are being implemented by reducing the size of the actual cells. In [1] the authors cite Martin Cooper from Arraycomm and mention the breakdown of the gains in cellular networks that proof how, along with gains of 25% with a wider spectrum or an improvement of 25% by designing better modulation schemes, a 1600% improvement is achieved by reducing the size of the area covered by each base station. This has led to the evolution in cellular networks from macro cells to micro and even pico cells. The main problem to this reduction of the cell size in cellular systems is the strong increase in infrastructure costs.

In this context is where current research trends are based. Traditionally, the main goal of new technologies would be to increase the capacity of the channel, in a quest to reach Shannon's limit in terms of bits per second per Herz (bps/Hz). However, a point has been reached in which the marginal cost of a small increase in bps/Hz is too high. Therefore, improvements have to be done in the network architecture, as opposed to modulation and coding schemes, to increase a new metric, the capacity per area (bps/Hz/m^2).

User deployed base stations are the newest answer to such situation. Femtocells [1], also known as home base stations, consist in short range, low cost and low power mobile access points that deliver better indoor coverage to the consumer. Given that femtocells are installed by the customer, there is no cost for the service provider either, making it possible to highly increase the network's capacity per square meter with a near zero cost, especially given the fact that in current deployments, nearly 60% of the mobile traffic is originated indoors [2]. However, as it will be described in the following sections, the use of femtocells present new challenges that have to be addressed, being interference and synchronization the most critical.

Is in this context where the latest advances in Location Based Serices and Mobile Sensing comes into place. With an army of mobile terminals moving around in the network, constantly updating their location through GPS or other systems, one can envision ways to use this available information and resources to solve, or at least mitigate, the synchronization and interference problems in femtocell networks.

2. Introduction to Femtocell cellular networks

A femtocell (FC) is a simple low-power low-cost base station installed at the user's premises that provides local access to the network by means of some cellular technology (2G, 3G, 4G) [3]. A FC has an IP backhaul connection with the main core of the network through the local broadband access the user already has, being DSL, cable or fiber the most common situations.

It is envisioned that in a short term basis, users will start installing their own femtocells in their apartments, offces, etc , and ABI Research predicts 102 million FC users worldwide with over 32 million FC base stations deployed by 2012 [4]. It is interesting to note that this represents an estimate of 3 to 4 users per femtocell. Not much bigger or different than the widely used wifi access points, these femtocells are designed with a target cost of about 200$, so they can be afforded by the majority and, therefore, a wide deployment is possible.

For the end users, these personal base stations will generate improvements in many senses:

- Femtocells cover an indoor area with a radius of 50 to 200 meters [3], this provides high coverage and better signal reception to many indoor users, which results in better QoS for indoor users.
- End users need to transmit less power when being in the range of the FC base station, therefore, great savings in battery life are achieved.
- Most indoor users (e.g. the ones in their own premises) are connected to a FC base station, thus fewer indoor users are transmitting in the macro cell. The overall capacity of the network increases with better QoS.

- QoS is also enhanced by the fact that the indoor users connected to a FC base station transmit low power. Interference is strongly reduced in the macro cell, especially in CDMA-based networks, thus allowing better QoS for MC users.

As it can be seen in Figure 1, femtocell networks consist on a two-tier deployment, where femtocell access points (FCs) overlay on top of the macrocell network. It is a similar structure as in a picocell network deployment, with the difference that the location of the FC APs is random (assumed to follow a Poisson Spatial Point Process.

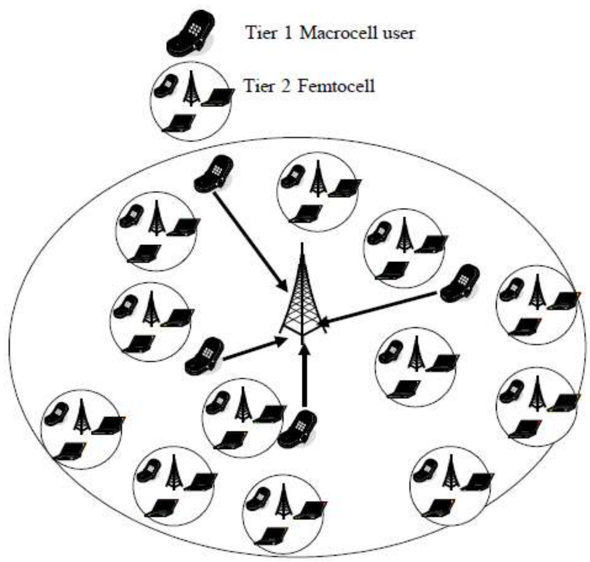

Figure 1: Network architecture of a cellular deployment with femtocells

Despite all the improvements, femtocells arise multiple new challenges in terms of network capacity, architecture and coverage. [1] lists network architecture, interference management and synchronization among the most crucial of these new challenges. As it will be described in further sections, the interference problem becomes a major issue that requires brand new cancelation or mitigation strategies due to the extra degrees of complexity in comparison with standard cellular networks.

3. Interference in Femtocell deployments

As a low-cost device, femtocells are not be provided with some common features of cellular base stations. This presents further challenges for the network design and management, being synchronization highlighted in [1]. Femtocells require synchronization techniques to minimize multi-access interference by aligning the received signals. Synchronization with the rest of the cellular network is also necessary to allow handoffs from the MC to the FC and vice versa.

Some alternatives are being considered, including equipping femtocells with GPS capabilities. However, it is still the main constrain the fact that femtocells have to be assumed as blind base stations with no knowledge about the location of themselves, other femtocells or the macrocell. This means for example that, in terms of OFDMA subcarrier allocation, a given femtocell has no knowledge about the allocation status in other femtocells or in the macrocell. Note that if two users are allocated to the same tone, interference might occur.

In a standard cellular system using an OFDMA-based network access, frequency allocation must take into consideration both inter- and intra-cellular interference. One given frequency should only be allocated to a single user within the cell (or sector) so intra-cellular interference is canceled. In parallel, users from adjacent cells (or sectors) might cause interference to the users in the cell of interest so frequency allocation has to be optimized to minimize the inter-cellular interference. [5] proposes a strategy to mitigate this kind of interference by applying auction-based algorithms to the subcarrier allocation of multicellular OFDMA systems. This approach is followed throughout this project for the actual subcarrier allocation at each MC and FC.

When adding femtocells to a cellular deployment, the complexity of the interference problem increases drastically and new strategies have to be designed. One encounters three extra degrees of complexity in the interference problem. Focusing on the Uplink, there is interference generated by the MC users in the nearby of a femtocell (macro cell to femtocell interference, Figure 2a), by FC users within a femtocell located in the vicinity of the MC base station (femtocell to macro cell interference, Figure 2b) and by FC users transmitting in the nearby of other femtocells (femtocell to femtocell interference, Figure 2c).

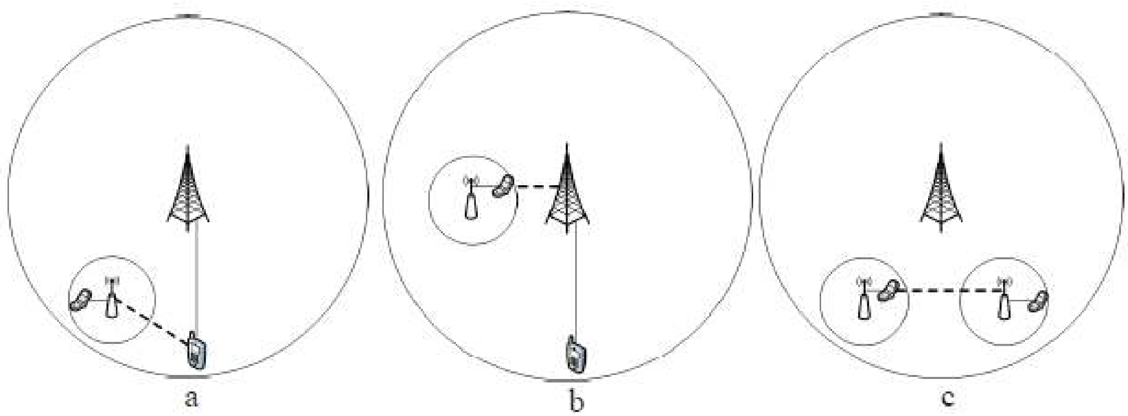

Figure 2: (a) MC user to FC interference, (b) FC user to MC interference, (c) FC to FC interference

[3] states that, in order to guarantee close to 100 percent coverage, elaborated further interference strategies have to be applied. Fractional frequency reuse (FFR) is mentioned as a possible solution, but good synchronization is essential for its implementation, and as already mentioned, that is not always possible when dealing with femtocells. The simulations in [3] show how a dense deployment of femtocells, without the appropriate interference mitigation scheme, deteriorates the overall system performance dropping the coverage to levels as low as 13 percent for the outdoor users.

Considering these results and recalling that femtocells are defined as in-home base stations with minimal synchronization, one can see that brand new approaches are necessary for the interference and synchronization problems in cellular femtocell networks.

4. *Mobile sensing*

4.1. Real Time Location Systems

Real-Time Locating Systems provide the location of devices or assets on a constant and recurrent basis. The system is composed by a set of receivers used to determine the position of a given node in the network.

A real time location system (RTLS) [7] refers to the use of RF signals for locating and tracking resources that are tagged in real time. These resources come in many different forms, from high valued assets, semi-finished goods, raw materials to tracking of people. There are several variations of these technologies, but they are all categorized as RTLS technologies due to their features of offering the capacity to track objects, assets, and people in real time using RF. RTLS systems can offer the tracking of solutions at an enterprise level, both indoors or outdoors depending on the type of the RTLS chosen.

Several technologies are used to build up Real Time Location Systems. Some use dedicated RFID tags and readers while others use existing WLAN networks and add RTLS ability to those networks. RTLS applications are extremely interesting due to the wide range of problems that can be solved with these systems.

4.2. Location Based Services and Mobile Marketing

The applications of location-based services have widely expanded due to the recent advent of smart phones and great expansion of WiFi coverage areas. Entire new markets coexist and generate extra revenue based on the current deployments of wireless networks. This is how cellular phones have evolved to become a large army of small sensors that create the biggest and most advanced wireless sensor network (WSN) of all.

The authors of [8] analyze the large span of possibilities with such an amount of sensors and start by analyzing one individual node. Current smart phones come equipped with up to eight sensors that include gyroscope, compass, accelerometer, proximity sensors and often GPS. As it will be discussed below, in this project we will focus on the applications of mobile sensing with GPS to Femtocell networks.

Among the possible applications of the new mobile sensor networks, the authors of [8] focus on transportation, health and well being and the increasingly popular social networks. With such a large number of sensors deployed, these applications can be expanded to achieve even greater results. One can envision elaborated collaborative algorithms and systems that combine the available computing and sensing resources in a similar way as the World Community Grid [9]. This research-oriented initiative, similar to other well known ones, aims to gather all the unused CPU time of multiple users throughout the World to run multiple simulations and processes in materials research.

5. *Mobile sensing applied to Femtocell networks*

In this section I proceed to propose some algorithms and strategies in which a network provider could take advantage of the large amount of "voluntary" sensors that can be used to synchronize Femtocell networks and to mitigate the interference in this kind of two-tier deployments.

5.1. *Femtocell coverage control*

A FC, as already described, is a low-power low-range base station that the user installs in the premises to provide wireless coverage to shadow areas or simply to increase the QoS or reduce its cost. It is important to highlight that FCs emit in licensed spectrum, therefore a very strict protocol has to be implemented to make sure that a given FC radiates only in a geographical area where the network provider owns the spectrum.

Some of the currently available access points, such as AT&T's 3G MicroCell [10], are equipped with a GPS receiver. This way, the system ensures that it's radiating in an authorized area. Despite being this the simplest way to enforce the spectrum, it has clear drawbacks. As it is well known, locking a GPS signal is rather challenging when located indoors, so this forces the user to place the femtocell next to a window, for example. And there it might still be challenging to acquire the signal.

I propose a simple algorithm that would mitigate this problem and very likely completely solve it.

In any given femtocell deployment, the FC is most likely in the range of multiple mobile terminals, both users registered in that FC and MC users that roam around the FC location. Assuming that all the mobile terminals in the network are mobile phones (or at least equipped with a GPS receiver), one can assume that there will always be at least one user in the range of the FC locked to the GPS satellites at all time.

In parallel, there is inherent communication channels already existing between the FC and a MC user that perform the authentication and authorization of a user to transmit through a femtocell. This channels and protocols involve multiple messages, responses, handshakes, etc. Without making any changes in the HW, a simple update in the firmware would include a new request message from the FC. By means of this transmission, a FC access point could send periodic location requests that would be answered by multiple mobile phones with their current coordinates.

Just one set of coordinates would be enough to locate the FC in a geographical area and determine if it is legal that it radiates in that spectrum there. Multiple sets of coordinates averaged (perhaps in a smart way if the FC is equipped with multiple/directive antennas) could provide a very accurate location of the FC.

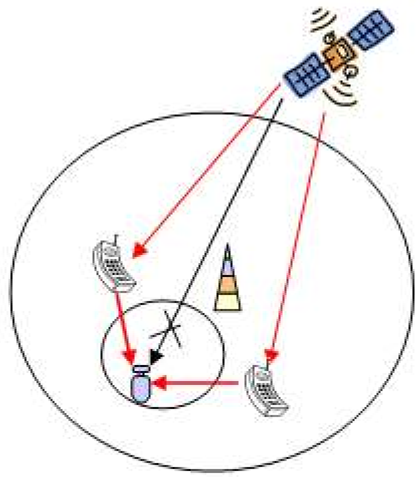

Figure 3: Femtocell 2-D location via mobile sensing

5.2. *Femtocell synchronization*

Expanding the last approach, one can envision further applications to gathering the location and GPS signal from a diverse group of mobile sensors or smart phones in the vicinity of the FC.

As opposed to European GSM-based protocols, the TDMA wireless networks in the US territory perform the synchronization of the base stations by means of GPS signals. This allows a very accurate timing acquisition of the system's clock under which the whole network functions. Femtocells, despite being low-power access points in the user's premises, are still a small scale of a regular MC base station, so they require very accurate synchronization.

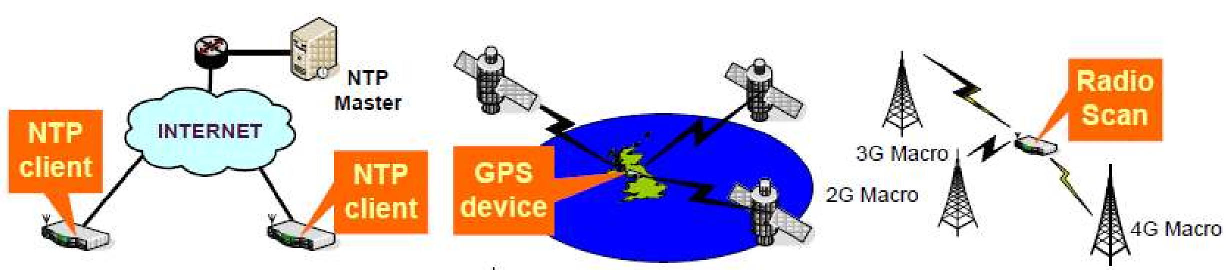

Figure 4: Femtocell current synchronization solutions [11]

There are different solutions for this problem being currently applied, but none of them has proven to be the perfect candidate yet. In [11] Timing Over Packet and the enhanced Network

Time Protocol (NTP) are described as a feasible solution that is often combined with, precisely, sensing of adjacent and neighboring wireless terminals (GSM, WCDMA, LTE).

By means of a radio scan and communication with neighboring mobile terminals with a GPS receiver, a more complex strategy could be achieved to recover the timing information of the system's clock from the GPS information.

5.3. Frequency allocation in OFDMA-based access networks

Despite not being much work done in subcarrier allocation for OFDMA-based femtocell networks, it is very important to note that most of the literature assumes that the spectrum is divided in two segments so macrocells and FCs do not share any frequencies. This is, given the set of possible subcarriers to be used, a portion of them is allocated for MC users and the rest is allocated to FC users. In [12] the spectrum division is optimized to maximize the Area Spectral Efficiency subject to a certain QoS with respect of the parameter ρ. This parameter represents the ratio between the number of subcarriers allocated for FC users and the total number of available subcarriers.

Spectrum splitting allocation strategies achieve good results and mitigate interference levels but their main drawback is that they present very low spectral efficiency. Most of the publications in the literature assume an average of 3 to 4 users per femtocell. Also, by definition, femtocells are located indoors either in residential apartments or in offices. Without any lack of generality, one can assume that any given user will spend long periods of time outside of their homes or work places. This translates in the fact that every single subcarrier reserved for transmissions within femtocells is idle for most of the time. Given the well known scarcity of spectrum, this is an issue that must be addressed. In this work we present a simple interference mitigation strategy that performs a reuse of the spectrum.

A further improvement is presented by Piqueras Jover et al. in [13]. Game theoretic applications, combined with a simple algorithm to mitigate the inter-tier interference (MC to FC and vice versa), are applied to perform the subcarrier allocation in OFDMA-based networks. This still results in some residual interference due to the randomness of the network topology and the fact that none of the nodes is aware of the actual location of most of the rest of the access points.

Based on this solution, I propose here an expansion of the algorithms in [13] in which each femtocell uses the algorithm presented in section 5.1 to determine its location. Then, this location is disseminated throughout the double-layer network following a Wireless Sensor Network approach so a great number of the FC access points and especially the MC base station are aware of this information. This data dissemination is performed periodically and initiated by a femtocell when its frequency allocation status experiences a significant change (i.e. a user leaves the premises, an inbound handover occurs, etc.).

Once this information is shared, the frequency allocation table of each FC would be periodically disseminated throughout the network to achieve an eventual centralized control on the frequency allocation strategy that aims zero interference.

In this situation, as depicted in Figure 5, each FC in the system would act as a sensor in a WSN. Periodically, each sensor needs to disseminate its location and frequency allocation table to the MC base station and, if possible, other FCs. This way, subcarrier allocation could be done in such a way that two or more adjacent or neighboring FCs do not allocate the same subcarriers.

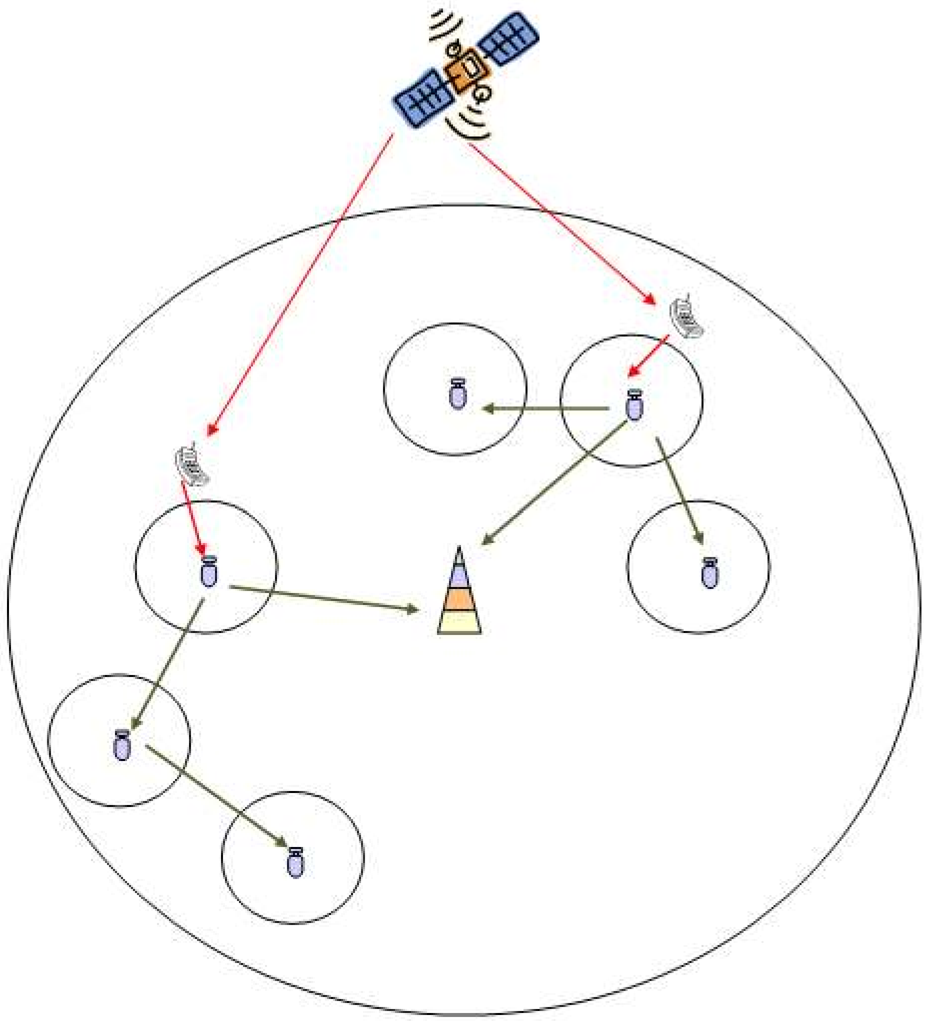

Figure 5: Femtocell deployment as WSN disseminating location information

Figure 5 depicts a situation in which only two FC base stations can accurately determine their location from the GPS signal of neighboring users. At the beginning of the following iteration, these two nodes have information to report and they will start disseminating it through the network. This way, two nodes of clusters are defined. The FCs within these two nodes can collaborate and make sure they do not allocate the same subcarriers.

Through a data dissemination algorithm, the wireless sensor network connects to the sink that, in this case, is located at the MC base station. This way, the central controller can obtain the frequency allocation of all the FCs and apply a subcarrier allocation for the MC users that minimizes inter-tier interference. This final step is no entirely required, though. As it can be seen in [13], a very simple algorithm based on the path-loss and Radio Signal Strength Indicator (RSSI) measurements can achieve a complete cancellation of the inter-tier interference.

6. *System Model*

Using MATLAB, a unicellular femtocell network is simulated. The system parameters are the ones listed in Table 1. The setup consists of a single cell system with a base station equipped with one single antenna. There is an average of K_{MC} macro cell users located randomly following a Spatial Poisson Point Process (SPPP) [14], and the system assigns N_{fusr} subcarriers per user. The femtocells overlay on top of the macrocell forming a hierarchical cell structure. The location of the FC base stations is also determined following a SPPP. The number of available subcarriers at each femtocell is N_{fFC}=256 out of a total N_f=1024. The number of users in each femtocell K_{FC} is randomly chosen from the set f={0;1;2;3;4} and it is assumed that 64 tones are allocated to each FC user, thus $N_{fFCused}$=K_{FC}x64. These users are also positioned within the femtocell following a SPPP.

System parameters	
Scenario	
MC radius (R_M)	500m
FC radius (R_{FC})	30m
Channel model	
Carrier frequency (f_c)	2.5GHz
Bandwidth (BW)	10MHz
Number of subcarriers (N_f)	1024
Noise power density (N_0)	-174dBm/Hz
MC base station	
Transmitted power*	43dBm
Gain	16dB
FC base station	
Transmitted power (max)	20dBm
Mobile terminal	
Transmitted power*	23dBm
Gain	0dB
FC transmitted power	17dBm

Table 1: System parameters for a typical deployment of WiMax-OFDMA
(*rms value)

The channels are multipath fading Rayleigh with a doppler spread that considers pedestrian users moving at a speed of v_{usr} = 1.5 meters per second. The multipath profile for indoor propagation is extracted from the model B in [n], with a delay spread of 100 nanoseconds. The profile for outdoor propagation has a delay spread of 45 nanoseconds.

Two cases are considered for the shadowing slow fading, with standard deviation σ_{dB}=8.9dB, being a typical value used in Rappaport's model. The propagation loss is also computed following Rappaport's model, considering two values of the path loss exponent, one for indoor propagation (α_{in}=3.4) and one for the outdoors propagation (α_{out}=2.9).

Assume an urban environment with femtocells located inside of buildings. The average penetration loss through the building walls is 16dB [16]. We assume as well that any femtocell is located no closer than $d_{FC\_to\_MC}$=30 meters from the MC base station and a MC user will always be further than $d_{MC\_to\_FC}$=10 from the edge of any femtocell.

7. *Simulation results*

In this section I proceed to simulate the aforementioned system implementing the frequency allocation algorithm described in section 5.3 and compare it a simple random frequency allocation that does not take into consideration the position of each FC within the macrocell. Let's assume that K_{MC} = 50 (MC users), but only the FC frequency allocation status is periodically disseminated through the network. In this case, there are K_{FC} = 4 users at each femtocell with 32 tones allocated to each one of them. Figure 6 shows the average signal to interference and noise ratio (SINR) and its standard deviation for the FC users present in the system as a function of the number of femtocells n_{FC} in the case of allocating the frequencies randomly or by means of the approach described in section 5.3.

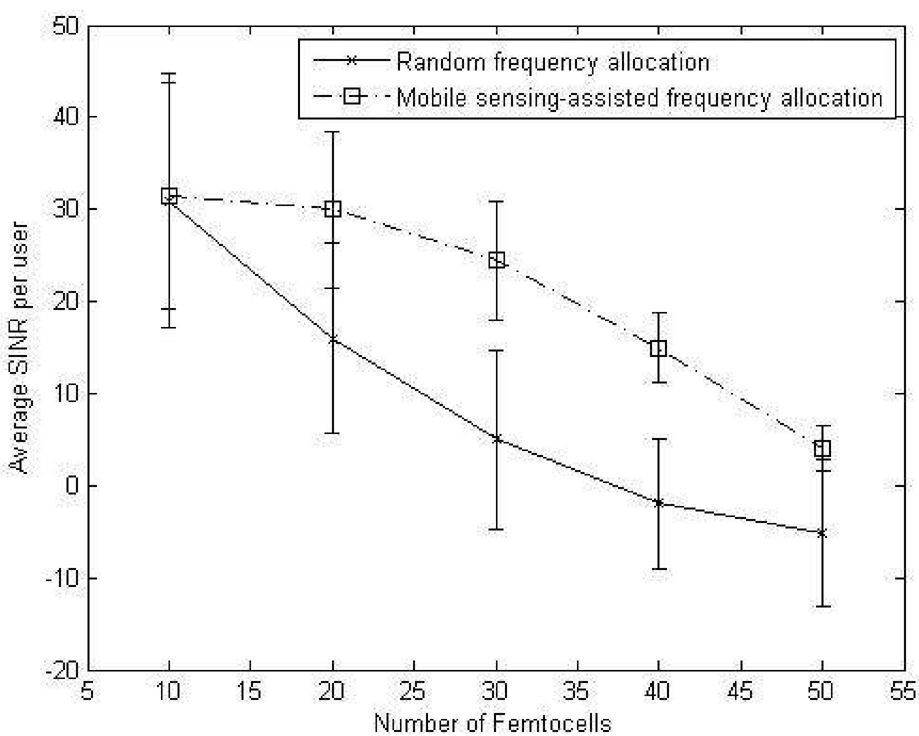

Figure 6: Average SINR [dB] per user for different numbers of femtocells

The value of the average SINR per femtocell user is always at least 10dB higher for any value of n_{FC} when using a mobile sensing-assisted approach, being this improvement of 20dB when there are 30 femtocells in the system. For low values of n_{FC}, the femtocell deployment is sparse and therefore, even using a random approach, the probability of two neighboring femtocells selecting the same tone is very low. In this case the system is mostly constrained by the Gaussian noise, thus both the random and the auction-based approaches present very similar values of SINR. Note that the high standard deviation for the random allocation is due to the fact that users and femtocells are located following a SPPP and that the allocation of tones is done in a random fashion. The lower standard deviation for the auction algorithm is only due to the position of the users.

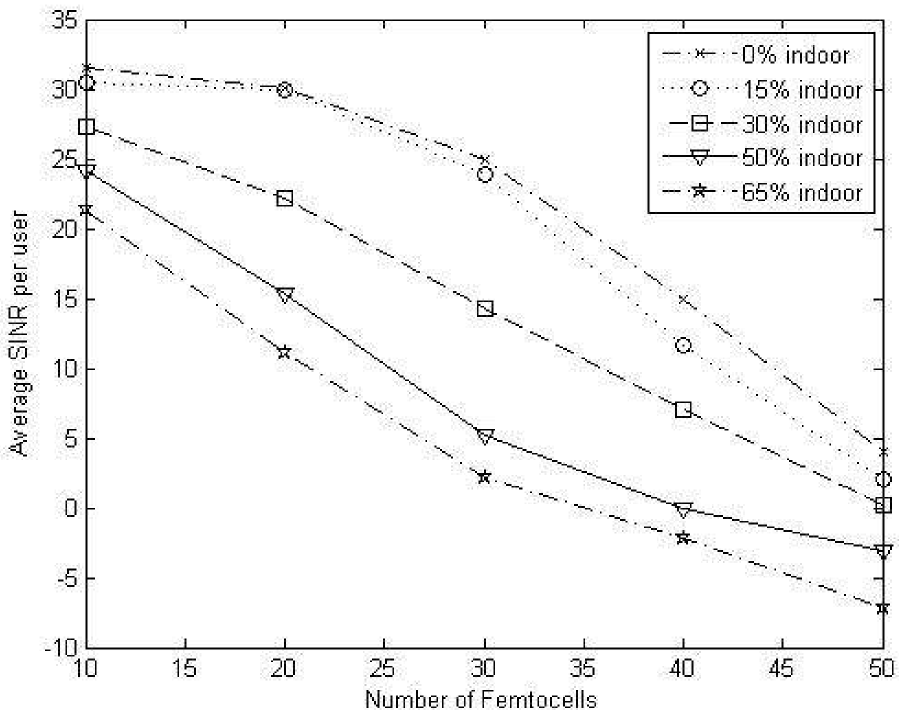

Figure 7: Performance of the algorithm with an increasing of indoor MC users

Figure 7 plots the results of a study of the algorithm's performance under an increasing number of macrocell users that are located indoors. This is done by assuming that no indoor macrocell user is transmitting through a FC access point, so the only users with its traffic backhauled through the broadband are the actual users labeled as FC users.

It is expected that the performance will deteriorate as the number of indoor users grows, because the number of users able to lock a GPS signal and therefore set an accurate location is smaller. Also, we assume that indoor users do not assist to the dissemination of the frequency allocation data. Finally, it is assumed that an indoors MC users can still estimate its location from the transmissions of neighboring nodes.

As it can be seen in the graph, the performance decreases, as expected, with the number of MC indoor users, and the slowdown is especially strong when there is 30% or more indoor users. However, for a medium load of femtocell systems present in the scenario – i.e. 30 femtocells in the simulated system -, the average SINR per user, after 100 iterations, is above acceptable values and is still higher that the values obtained when the algorithm under study is not applied (random case).

One has to consider than, in a real deployment, most of the macrocell indoor users will be handed over to a femtocell and its traffic will be forwarded through that second tier of the network. Therefore, one can expect the total number of actual macrocell indoor users to be very low and the average SINR above required values.

8. Conclusions

After a brief introduction on femtocell cellular networks and Location-Based Mobile Sensing, an analysis of the Uplink interference and synchronization problems for OFDMA-based femtocell networks is performed in this project. Interference and lack of synchronization are shown to be two of the main issues to address in two-tier wireless networks due to three extra degrees of complexity in the problem (see Appendix A).

Two mobile sensing-based approaches are presented to solve or mitigate both the synchronization problems. By means of the geolocation capabilities of most of the current smart-phones, a femtocell can acquire and estimate its position to be able to synchronize itself to the system's clock.

Furthermore, an interference mitigation scheme based on a mobile sensing-based frequency allocation strategy is proposed. The strategy includes a complete reuse of the spectrum, solving this way the waste of resources in the subcarriers reserved for the femtocells. The proposed scheme gathers and disseminates the frequency allocation status of the different entities in the system and combines this information with position estimations that each femtocell performs based on the eventual neighboring mobile sensors (i.e. smart-phones) actual GPS-determined location.

It is shown through simulation studies that the proposed algorithm highly mitigates the effect of intra-tier interference. Inter-femtocell interference is highly mitigated by spatially distributing the frequencies allocated at each femtocell, thus reducing the probability of two neighboring/adjacent femtocells having allocated the same tone and ensuring an improvement of at least 10dB in the SINR with respect to a random frequency allocation. Also, the system is robust in front of an increasing number of indoor macrocell users assuming that there is a medium load of femtocells in the system. Also, one can expect that, with such a femtocell deployment, many indoor macrocell users will be handed over to a FC access point.

To reach a higher interference mitigation and to avoid inter-tier interference (macrocell to femtocell and viceversa), the path-loss measurements-based model in [13] is recommended.

9. References

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Appendix A: Interference in Femtocell Networks

MC user to FC base station interference

In any OFDM-based system, there is a power control algorithm for the uplink. Despite being a much simpler control than CDMA-based networks, this algorithm ensures that, at any time, a user (MC user) is transmitting enough power to achieve a minimum SNR at the receiver (MC base station) given the current channel conditions, which are measured by the system periodically.

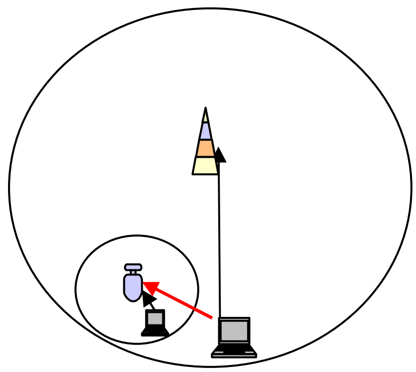

Figure A.1: MC user to FC base station interference

If a MC user is located "far away"[1] from the MC base station, the power control algorithm will set its transmitted power to a high level, so the signal to noise ratio at the MC base station is at least SNR_{min}. This value of the minimum SNR will depend on the QoS that is provided to the user.

If this user happens to be in the nearby of a femtocell, this transmitted signal might be high enough to propagate through the walls of the building where the FC base station is located and generate interference. This will only happen if a FC user in that neighboring femtocell and the MC user transmitting high power are using the same frequency.

FC user to MC base station interference

Assume one FC user and one MC user are using the same frequency. If the femtocell is located in the nearby of the MC base station, its low power transmitted signal might cause interference. Despite the penetration loss through the wall, the signal might reach the MC base station with enough power to deteriorate the received SNR. This would cause interference.

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[1] By "far away" one understands that the power loss that the user experiences is high, therefore it can be a user standing in a far away position or an indoor user with high penetration loss through the wall.

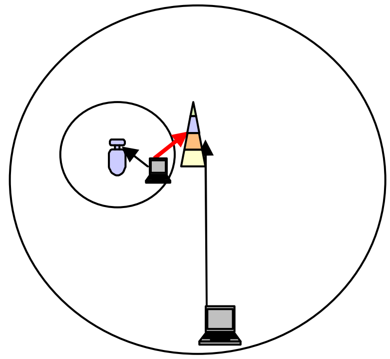

Figure A.2: FC user to MC base station interference

However, if the power control algorithm is applied, the system will measure that channel (i.e. frequency) and will determine that the MC user needs to transmit higher power in order to achieve SNR_{min} at the receiver. Therefore, the interference problem will be solved by increasing the transmitted power of the MC user, unless the required transmitted power is higher than the maximum possible transmitted power by a user. This could happen if the FC was very close to the MC base station.

Femtocell to femtocell interference

A femtocell is, by definition, located indoors; therefore, interference is highly mitigated. Any signal coming from one FC user should go through at least one wall (penetration loss) to reach the base station of any other femtocell. If we assume that FC users indoor transmit very low power, it is clear that interference levels will not be really high for many femtocells. In fact, between two non neighboring femtocells, the signal to interference ratio will always be at least twice the value of the penetration loss through a wall.

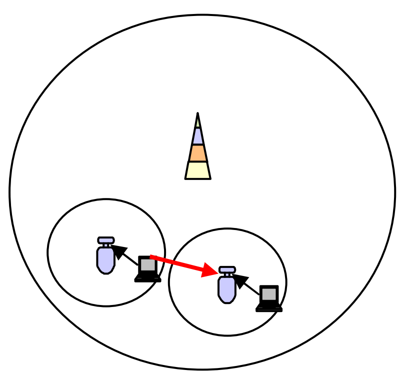

Figure A.3: Femtocell to femtocell interference

With no loss of generality, it can be assumed that the interference is zero between any two femtocells that are not located very close to each other. This is, for example in a building, there would be only interference only between femtocells in adjacent apartments.