OFDMA Femtocells: A Roadmap on Interference Avoidance

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ABSTRACT

OFDMA femtocells have been pointed out by the industry as a good solution not only to overcome the indoor coverage problem but also to deal with the growth of traffic within macrocells. However, the deployment of a new femtocell layer may have an undesired impact on the performance of the macrocell layer. The allocation of spectrum resources and the avoidance of electromagnetic interference are some of the more urgent challenges that operators face before femtocells become widely deployed. In this article a coverage and interference analysis based on a realistic OFDMA macro/femtocell scenario is provided, as well as some guidelines on how the spectrum allocation and interference mitigation problems can be approached in these networks. Special attention is paid to the use of self-configuration and self-optimization techniques for the avoidance of interference.

INTRODUCTION

According to recent surveys [1], 50 percent of phone calls and 70 percent of data services will take place indoors in the next years. Therefore, indoor coverage providing high data rates and quality of service (QoS) will soon be needed by operators. Since macrocell coverage becomes expensive to serve indoor customers with large service demands, new solutions for the indoor coverage/capacity problem are required.

One solution to enhance indoor coverage are so-called femtocell access points (FAPs) or home base stations [2]. These are low-power base stations designed for indoor usage that allow cellular network providers to extend indoor coverage where it is limited or unavailable. On the air interface, FAPs provide radio coverage of a given cellular standard (e.g., GSM, UMTS, WiMAX, LTE), while the backhaul connection makes use of a broadband connection such as optical fiber or digital subscriber line (DSL). In this article FAP is used to denote the device itself, while *femtocell* refers to the coverage area.

The use of femtocells will benefit both users and operators. Users will enjoy better signal quality due to the proximity between transmitter and receiver, the result being communications with larger reliabilities and throughputs. Furthermore, this will also provide power savings, reducing electromagnetic interference and energy consumption. This way, more users will access the same pool of radio resources or use larger modulation and coding schemes, while operators will benefit from greater network capacity and spectral efficiency. In addition, since indoor traffic will be transmitted over the Internet Protocol (IP) backhaul, femtocells will help the operator to manage the exponential growth of traffic and increase the reliability of macrocell networks. Moreover, given that they are paid for and maintained by the owers, femtocells will also reduce the overall network cost.

It is estimated that by 2012, there could be around 70 million FAPs installed in homes or offices around the world, serving more than 150 million customers [3]. Consequently, the cochannel deployment of such a large femtocell layer will impact existing macrocell networks, affecting their capacity and performance [4]. Therefore, to mitigate this impact, several aspects of this new technology such as the access methods, frequency band allocation, timing and synchronization, and self-organization need further investigation before FAPs become widely deployed. Since the number and position of the FAPs will be unknown, interference management cannot be further handled by the operator using traditional network planning and optimization techniques. Therefore, special attention must be paid to the mitigation of interference between the macro- and femtocell layers, as well as between femtocells.

In order to handle these issues, orthogonal frequency-division multiple access (OFDMA) femtocells are a more promising solution than code-division multiple access (CDMA) ones, mainly due to its intracell interference avoidance properties and robustness to multipath. In OFDMA systems the available spectrum is divided into orthogonal subcarriers, which are then grouped into subchannels. OFDMA works as a multi-access technique by allocating different users to different groups of orthogonal subchannels. Moreover, OFDMA femtocells can exploit channel variations in both frequency and time domains for the avoidance of interference, while CDMA can only exploit the time domain.

The aim of this article is to provide an overview of the technical challenges faced by operators when deploying an OFDMA femtocell

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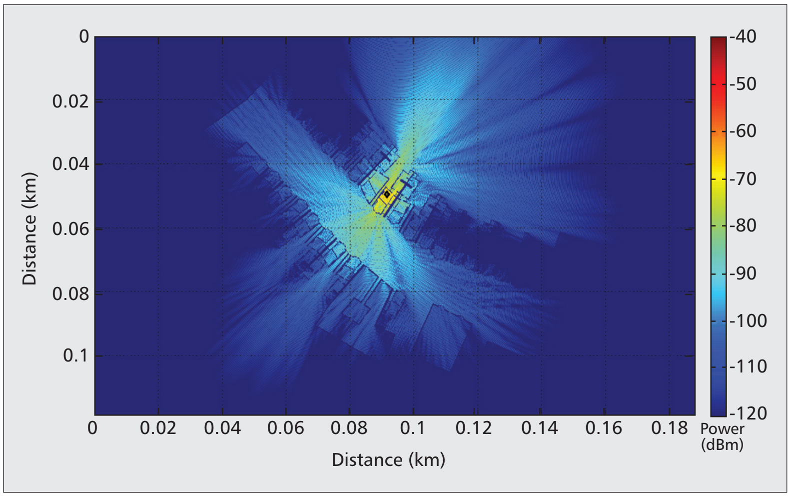


■ **Figure 1.** *Coverage of a femtocell emitting an EIRP = 10 dBm at* f = *3.5 GHz.*

network. Since interference is the main limitation in the deployment of two-layer networks, special attention will be given to those problems in relation to spectrum allocation and interference avoidance.

CHALLENGES FOR OFDMA FEMTOCELLS

Femtocells will face several issues that still need to be addressed in order to guarantee interoperability with existing macrocells. These are analyzed in the following.

THE ACCESS METHOD

Femtocells can be configured in three ways to allow or restrict their usage by certain users:

- **Open access**: All users are allowed to connect.
- **Closed access**: The femtocell allows only subscribed users to establish connections.
- **Hybrid access**: Nonsubscribers use only a limited amount of the femtocell resources.

It has been shown that open access improves the overall capacity of the network [5], mainly because macrocell users can connect to nearby femtocells in locations where the macrocell coverage is deficient. From an interference viewpoint, this avoids femtocells behaving as interferers since outdoor users can also connect to indoor femtocells. As a drawback, open access will increase the number of handoffs and signaling. Furthermore, with this type of access, security issues apply. Moreover, recent customer surveys show that open access is commercially challenging for operators. This is because femtocells are paid for by subscribers, who are not keen to accept nonsubscribers as users of their own femtocells unless they obtain some kind of benefit/revenue.

Closed access femtocells are thus more likely to be deployed in the home environment. However, this implies that power leaks through windows and doors (Fig. 1) will be sensed as interference by passing macrocell users, thus decreasing their signal quality. As will be shown, algorithms for the allocation of OFDMA subchannels can help to solve this problem.

Hybrid approaches allow the connectivity of nonsubscribers while restricting the amount of OFDMA subchannels that can be shared. In this way, most of the interference problems of closed access are eliminated while controlling the impact on the femtocell owner.

TIME SYNCHRONIZATION

Since femtocells are deployed by users, there is no centralized management of their radio resources. However, network time synchronization is necessary between macrocells and femtocells in order to minimize multi-access interference, as well as for the proper performance of handoffs. Without timing, transmission instants would vary between different cells. This could lead to the uplink period of some cells overlapping with the downlink of others, thus increasing intercell interference in the network.

Since FAPs are aimed at the consumer electronics market, they are intended to attain low prices. The manufacture of low-cost femtocells equipped with high precision oscillators is not trivial, so other approaches need to be considered in order to achieve reliable time synchronization.

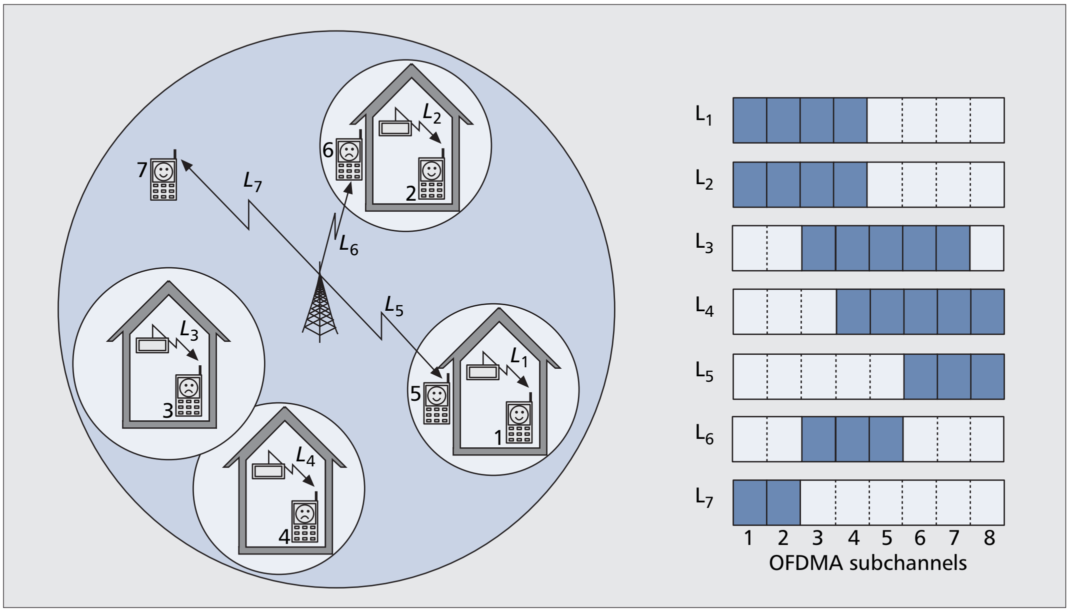
The use of GPS receivers, which provide accurate timing over satellite links, has been proposed as a possible solution. However, their performance depends on the availability of GPS coverage inside user premises. Another solution is the use of the IEEE-1588 Precision Timing Protocol as a feasible method to achieve synchronization [6]. However, some modifications are necessary in order for it to perform efficiently over asymmetric backhaul links such as ADSL.

PHYSICAL CELL IDENTITY

Physical cell identity (PCI) is normally used to identify a cell for radio purposes; for example, camping/handoff procedures are simplified by explicitly providing the list of PCIs that mobile terminals have to monitor. Note that this list is usually known as the *neighboring cell list* (see below). The PCI of a cell does not need to be unique across the entire network; however, it must be unique on a local scale to avoid confusion with neighboring cells. This represents a challenge in femtocell networks, since they must select their PCIs dynamically after booting or changing their position in order to avoid collision with other macro/femtocells. Furthermore, in extensive femtocell deployments and due to the limited number of PCIs (e.g., 504 in LTE), the reuse of PCIs among femtocells in a given area may be unavoidable, thus causing PCI confusion.

NEIGHBORING CELL LIST

Since femtocells can be switched on/off or moved at any time, their neighbors vary often. Femtocells must thus be able to set up their neighboring cell list in a dynamic manner. Due to this, the relationships between femtocells must be handled differently than those between macro- and femtocells. In addition, it is expected that the number of neighboring femtocells within a macrocell will grow beyond the 32 that are currently considered in macrocells. Therefore, new



■ **Figure 2.** *Downlink allocation of OFDMA subchannels in a macro/femtocells network with co-channel assignment.*

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techniques must be developed to allow macro- and femtocells to support a larger number of neighboring cells and handle them rapidly.

Mobility Management

In macrocell networks, cell handoffs are triggered when users enter the coverage area of other cells. However, given the coverage size of open/hybrid access femtocells, this occurs more often than in the macrocell case, hence increasing network signaling. Different handoff management procedures are thus needed to allow nonsubscribers to camp for longer periods on nearby femtocells. Furthermore, a hierarchical cell structure (HCS) can also be used to distinguish between macro- and femtocells. In this way, the signaling across layers can be minimized as well as the neighboring cell list that users scan when performing a handoff.

Interference Analysis

In Fig. 1 it can be seen that a femtocell not only provides coverage at the customer premises, but also radiates toward neighboring houses as well as outdoors, introducing interference. Due to this and given that femtocells are deployed within the coverage area of existing macrocells, they can cause strong degradation of the macrocells' performance. Furthermore, the deployment of new femtocells could also disturb the normal functioning of already existing femtocells. Therefore, in order to reduce the appearance of *dead zones* within the macrocells and successfully deploy a femtocell network, interference avoidance, randomization, or cancellation techniques must be applied.

In the following, it is assumed that the clocks of the femtocells are synchronized with that of the umbrella macrocell. Therefore, and considering that these networks define two separate layers (the femtocell and macrocell layers), interference can be classified as follows:

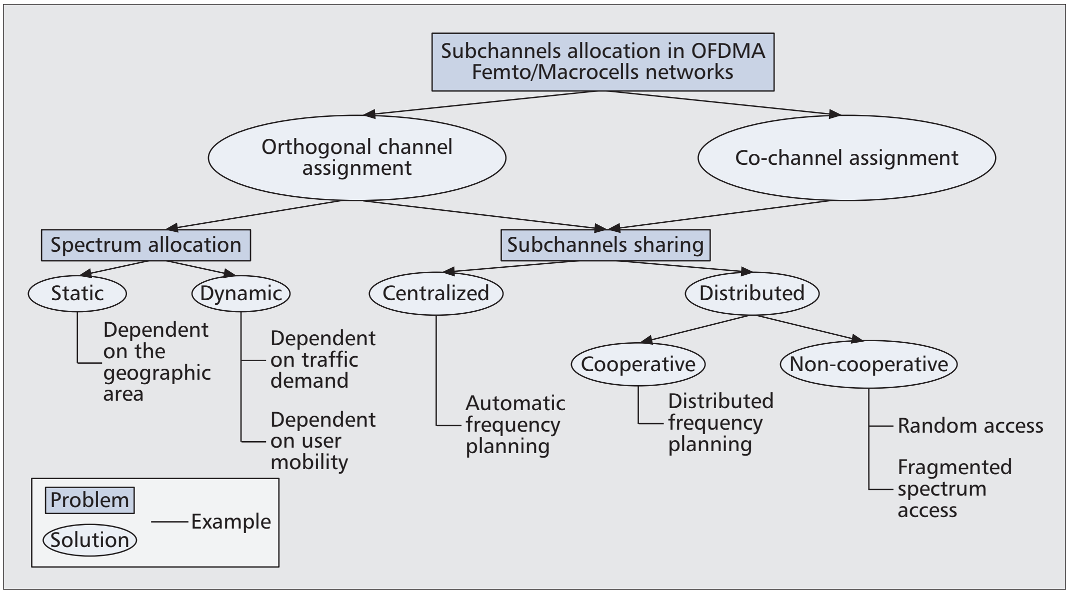
- **Cross-layer**: This refers to situations in which the aggressor (e.g., an FAP) and the victim (e.g., a macrocell user) of interference belong to different network layers.
- **Co-layer**: In this case the aggressor (e.g., an FAP) and the victim (e.g., a neighboring femtocell user) belong to the same network layer.

To overcome the effects of interference, cancellation techniques have been proposed but often disregarded due to errors in the cancellation process [7]. The use of sectorial antennas at the FAP has also been suggested in [8] as a means of reducing interference by decreasing the number of interferers. Similarly, a dynamic selection of predefined antenna patterns has been used in [9] to reduce the power leakage outdoors. However, hardware-based approaches usually imply an increase in FAP cost. On the other hand, strategies based on interference avoidance also represent efficient alternatives, (e.g., power and subchannel management).

Power control algorithms and radio resource management are tools often used in cellular systems to mitigate interference. If they are not applied, users located far from a base station will be jammed by users in much closer positions. These techniques are also necessary in FAPs for the same reasons plus the added problem of cross-layer interference. For example, in closed access femtocells, users located far from the FAP and being asked to raise their power level might produce high levels of interference to neighboring femtocells or even to the macrocell. This is illustrated in the following example.

From the point of view of the frequency allocation in OFDMA systems, Fig. 2 represents a downlink scenario where a loaded macrocell uses all the available subchannels to transmit information to its users. However, when a macrocell user is located close to a femtocell (e.g., user

The presence of hundreds of femtocells makes the optimization problem too complex and latency issues arise when trying to facilitate the femtocells communication with the central sub-channels broker throughout the back-haul.



■ **Figure 3.** *Classification and examples of subchannel allocation techniques for OFDMA femtocells.*

6), the femtocell may also transmit in some or all of the subchannels required by that user. This is illustrated by the spectrum occupation of links L_2 and L_6, which use subchannels 3 and 4 simultaneously, resulting in heavy downlink interference for macrocell user 6. Therefore, more efficient management of the OFDMA subchannels is necessary. Such an approach would help to enhance frequency reuse in the femtocells layer and maximize the overall cell throughput. For instance, the spectrum occupation of users 1 and 5 illustrate how interference can be avoided in OFDMA femtocells while providing sufficient frequency resources for a satisfactory user experience.

Spectrum Allocation in Two-Layer Networks

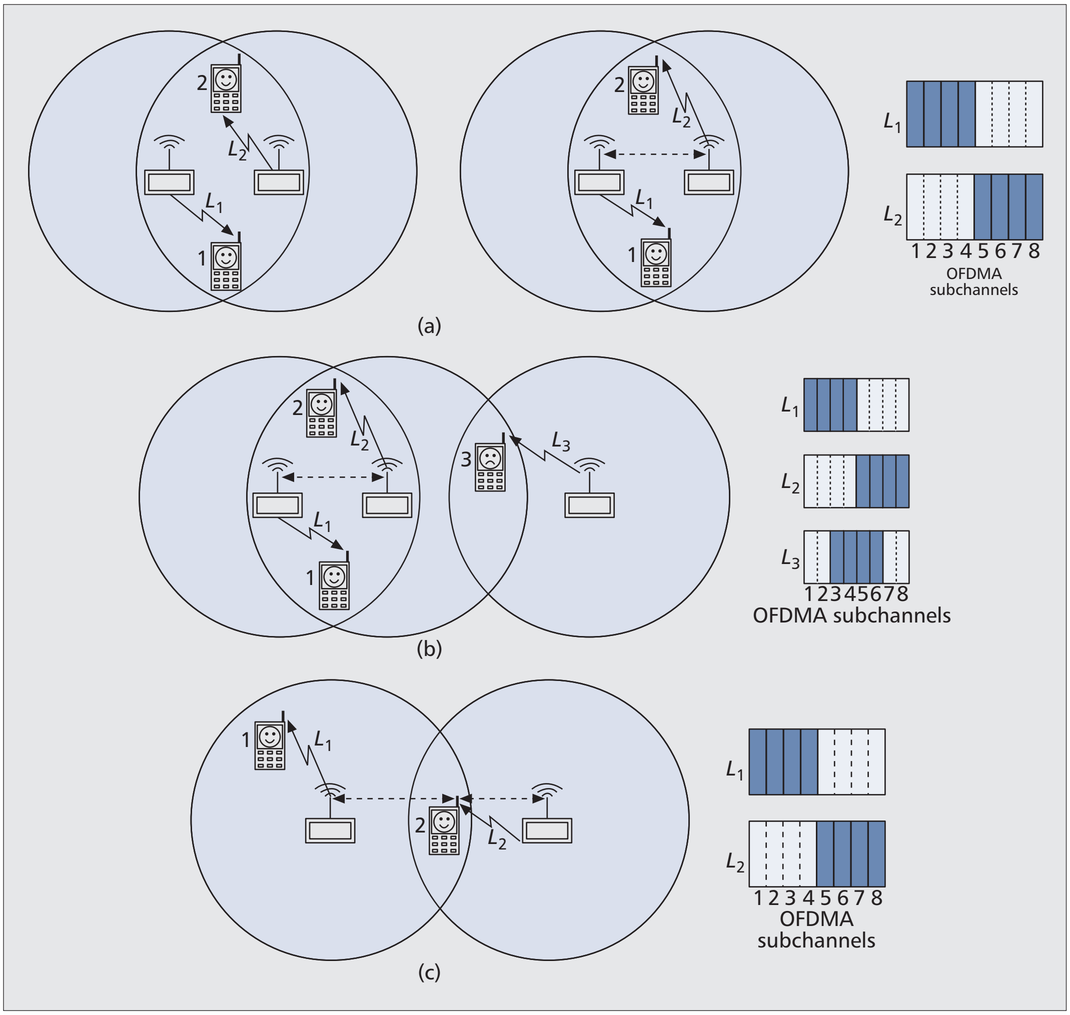
The different approaches that can be adopted to manage the OFDMA subchannels are schematized in Fig. 3. An approach that completely eliminates cross-layer interference is to divide the licensed spectrum into two parts (*orthogonal channel assignment*). This way, a fraction of the subchannels would be used by the macrocell layer while another fraction would be used by the femtocells. This approach is supported by companies such as Comcast, which have acquired spectrum to be used exclusively by their WiMAX femtocells. Although optimal from a cross-layer interference standpoint, this approach is inefficient in terms of spectrum reuse. Therefore, *co-channel assignment* of the macrocell and femtocell layers seems more efficient and profitable for operators, although far more intricate from the technical point of view.

Ideally to mitigate cross- and co-layer interference, there would be a central entity in charge of intelligently telling each cell which subchannels to use. This entity would need to collect information from the femtocells and their users, and use it to find an optimal or a good solution within a short period of time. However, since the number and position of the femtocells are initially unknown due to the individualistic nature of the FAPs, this approach poses some hard problems. The presence of hundreds of femtocells makes the optimization problem too complex, and latency issues arise when trying to facilitate the femtocells' communication with the central subchannels broker throughout the backhaul.

A distributed approach to mitigate cross- and co-layer interference, where each cell manages its own subchannels, is thus more suitable in this case (i.e., self-organization). In a non-cooperative solution, each femtocell would plan its subchannels so as to maximize the throughput and QoS for its users. Furthermore, this would be done independent of the effects its allocation might cause to neighboring femtocells, even if it supposes larger interference. The access to the subchannels then becomes opportunistic, and it is possible that the method decays to greedy. On the other hand, in a cooperative approach, each FAP gathers information about its neighboring femtocells and may perform its allocation taking into account the effect it would cause to its neighbors. In this way, the average femtocells' throughput and QoS, as well as their global performance can be locally optimized.

Self-Configuration and Self-Optimization

As discussed above and due to the uncertainty in the femtocells' number and positions, FAPs must be self-configurable and self-optimizing units [10], capable of integrating themselves into the existing radio access network causing the least interference to existing systems. In this case the FAPs must be capable of *sensing* the air interface and *tuning* their own parameters according to changes in the network or channel.



■ **Figure 4.** *Different approaches for the sensing of OFDMA sub-channels: a) self-sensing and relay-sensing; b) sensing problem in non-overlapping femtocells; and c) measurement reports.*

The combination of these sensing strategies together with other statistics such as the number of mobility events or packet drop ratio can be used to enhance the reliability of the sensing phase and therefore the quality of the femtocell tuning.

SENSING PHASE

FAPs must be aware of the presence of neighboring cells (i.e., macros or femtos) as well as their respective spectrum allocations. Different strategies can be used to achieve this *cognitive* radio stage, in which the femtocell is able to learn about the state of the network (e.g., architecture and load) and channel conditions (e.g., interference and fading). Note that the following approaches can be used not only to obtain information about the resource allocation of other femtocells, but also of nearby macrocells.

A first approach consists of building the sensing capability into the FAP itself. As represented in Fig. 4a (left), the FAPs will sense the air interface and identify which cells and subchannels are active within their range. Then the femtocells use this information to configure itself and perform its resource allocation. This can be done using a network listening mode, similar to a user terminal operating in idle mode.

A second approach is based on the exchange of information between femtocells. As represented in Fig. 4a (center), the FAPs could directly exchange information about their subchannel usage, spectrum needs, and so on. This way, femtocells can be aware of the present actions and future intentions of their neighboring cells, and act accordingly. These messages can be exchanged through the femtocell gateway, using a direct link between cells (similar to the X2 interface in LTE), but also broadcasting messages or using mobile terminals to relay information.

However, none of these would work in situations where the FAPs are not within the coverage area of other femtocells. For instance, in Fig. 4b, user 3 is located at the cell edge of two overlapping femtocells whose FAPs are not visible to each other. In this situation, such a user might suffer from interference because the femtocells are not able to coordinate their resource allocation as a result of the lack of information obtained during the sensing phase.

A third approach that can avoid this problem is the use of *measurement reports*, which are periodically performed by users and then sent back to their FAPs. They contain information such as the received signal strength and active subchannels of the serving and strongest neighboring cells (both macros and femtos). They can thus be post-processed and used to establish interference relationships between *neighboring cells* as well as to identify *forbidden subchannels*. With this technique, users can forward information

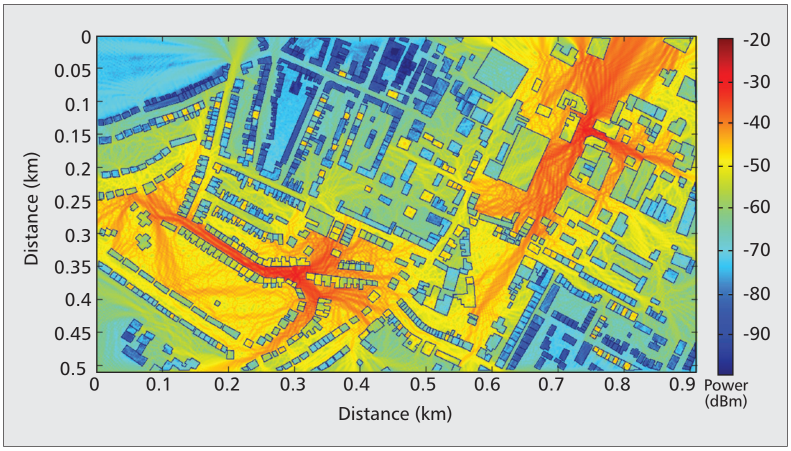


Figure 5. *Coverage plot of two WiMAX macrocells with an EIRP of 30 dBm, in an scenario with a femtocells penetration of 10.25 percent of the households and femtocell EIRP of 10 dBm. The work frequency is that of WiMAX in Europe,* f = *3.5 GHz.*

about their immediate radio environment (user location) to their FAPs and aid them to mitigate interference (Fig. 4c).

The combination of these sensing strategies together with other statistics such as the number of mobility events or packet drop ratio can be used to enhance the reliability of the sensing phase and therefore the quality of the femtocell tuning.

TUNING PHASE

FAPs should be able to select and modify their parameters in different situations. In this article a distinction is made between self-configuration and self-optimization. Self-configuration provides the initial settings of the FAP when it is turned on, while self-optimization updates the configuration of the FAP in order to adapt its parameters to the environment.

Self-Configuration — After powering on, the femtocell is registered into the network of the operator, and its radio parameters are set to a default configuration. This is done over the backhaul, which provides fundamental information such as the carrier frequency and other network parameters (e.g., location, routing and service area, initial PCI, and neighboring list). Afterward, the sensing of the environment is done throughout the network listening mode. By decoding the control channels, the femtocell is able to synchronize with the external network. Moreover, the femtocell also uses this information to reselect its PCI, and optimize its neighbor list and handoff parameters. Finally, the FAP adapts its power and selects its subchannels according to the obtained sensing information in order to ensure that it provides the dominant signal in the desired coverage area.

Self-Optimization — It is well known that the radio channel conditions can change rapidly due to shadowing and multipath fading. In addition, the network load and user traffic vary quickly depending on the location and time, and because of the packet nature of the services. Due to this fluctuating behavior, OFDMA femtocells must dynamically adapt their radio resources to their environments in order to optimize the performance of the network. Such changes can be detected during the sensing phase (e.g., increase in traffic or interference, decrease in mobility events or dropped calls). Taking into account this information, the FAPs tune their parameters (power or subchannel assignment) online in order to mitigate interference across cells.

EXPERIMENTAL EVALUATION

In this section system-level simulations are used to aid network designers and operators to understand the advantages and drawbacks of the orthogonal and co-channel assignment. Furthermore, the different features of centralized vs. distributed, and cooperative vs. non-cooperative approaches to frequency planning are also illustrated.

The simulations presented here were carried out based on the simulation framework presented in [5], and they are based on a realistic WiMAX (IEEE 802.16e) network comprising two macrocells and a large number of femtocells (Fig. 5). It operates in the 3.5 GHz band with a 5 MHz bandwidth. Moreover, the number of femtocells has been selected according to recent forecasts that indicate a femtocell penetration of 10 percent.

Adaptive modulation and coding (AMC) has been selected as a permutation scheme, where the subchannels comprise contiguous subcarriers. In this case the number of OFDMA subchannels in the DL subframe is set to 8, while the number of OFDM data symbols is 20. Moreover, closed access has been selected as the access method to the femtocells and a large number of end-users has been spread over the scenario. The number of outdoor users has been selected according to a density of 40 users/km^2, while a random number of indoor users between 2 and 4 has been placed per femtocell/house. Outdoor users have a minimum throughput requirement of 64 kb/s (video), whereas the indoor users' minimum throughput requirement is 350 kb/s (data).

Interference will occur only if several users are allocated to the same subchannel and OFDM symbol. Furthermore, an indoor-to-outdoor propagation model calibrated with femtocell measurements [11] has also been built into the simulation tool. The key performance indicators used to analyze the behavior of the network in this experimental evaluation is the network capacity in terms of user outage and throughput.

The details of the subchannel allocation strategies evaluated in this section are:

- **Orthogonal assignment**: The spectrum is divided into two independent fragments: one used by the macrocells and another by the femtocells. For the first setup, $S_M = 5$ subchannels have been assigned to the macrocell layer and $S_F = 3$ to the femtocells. For the second setup, $S_M = 6$ and $S_F = 2$.
- **Co-channel assignment** FRS_1: In this scheme the spectrum is not fragmented, so all the macrocells and femtocells have access to all available subchannels. Therefore, interference coordination is neglected.

	Orthogonal channel assignment		Co-channel assignment				
	$(S_M, S_F) = (5, 3)$	$(S_M, S_F) = (6, 2)$	FRS_1	FRS_3	FRS_4	D-DFP	C-DFP
Successful users (%)	93.14	88.44	94.10	95.43	87.49	96.32	97.92
Users in outage (%)	4.89	4.45	5.40	3.94	11.24	2.73	2.35
Macrocell throughput (Mb/s)	4.07	4.57	3.93	4.32	4.06	4.54	4.81
Femtocells throughput (Mb/s)	122.02	112.50	123.47	123.32	113.67	123.60	123.64
Total throughput (Mb/s)	126.09	117.07	127.4	127.64	117.73	128.14	128.45

Table 1. *Performance of various resource allocation algorithms.*

- **Co-channel assignment** FRS_x: The spectrum is divided into x fragments. Macrocells can use all the spectrum, but each femtocell only uses one randomly selected fragment. This way, the collision probability between neighboring femtocells is reduced by a factor x. In this evaluation $x = 3$ and $x = 4$ have been tested.
- **Co-channel assignment and distributed planning**: In the distributed-dynamic frequency planning (D-DFP) approach, measurement reports are used to sense the environment. Using this information, each femtocell independently configures its own subchannels priority list, which is sorted by priority (subchannels suffering the least interference go first) and is periodically updated. To achieve a stable solution and avoid different femtocells making changes on their list at the same time, a random time counter is used to wake up the femtocell and take action.
- **Co-channel assignment and centralized planning**: In the centralized DFP (C-DFP) approach, measurements reports are also used to sense the environment. Then the interference information is sent from the femtocells to a centralized subchannel broker, which plans the frequency usage and passes it on to the femtocells.

Orthogonal assignments remove cross-layer interference and perform well when the load of the network is low or the subchannel demand is less than the availability. In Table 1 it can be seen that when switching from a (5, 3) to a (6, 2) scheme, the macrocell layer throughput increases and the femtocell layer throughput decreases. This behavior is because the resources of the macrocell layer have increased, while the resources of the femtocells layer have decreased. As a result, some users cannot access their cells or carry their services due to the lack of resources. Therefore, when using an orthogonal assignment approach, the size of the fragments must be carefully planned according to the traffic forecast for each layer.

On the other hand, when using a co-channel deployment, the capacity problems of the macrocell and femtocell layers disappear due to the larger spectrum availability. However, cross-layer interference comes up, and the macrocell users suffer from interference due to the presence of nearby femtocells.

It can be seen that when interference coordination is neglected (FRS_1), the macrocell network performance is strongly degraded. Since there is a heavy traffic load and no interference coordination, the probability of subchannel collision between macrocells and femtocells is large. The result is thus poor signal quality (reduced throughput) and an increase in the outage probability for some users.

When using FRS_3 the throughput in the macrocell layer increases, since the probability of collision has been reduced by a factor of 3. On the other hand, when using FRS_4, problems due to the lack of resources appear in the femtocells because the fragments are too small. Therefore, the trade-off between capacity and probability of subchannel collision should be taken into account.

Finally, DFP results in the best network performance. This is logical since a dynamic frequency planning strategy has been used, able to adapt the system resources to the changing conditions of the traffic and channel. Note that the centralized approach performs better than the distributed one, since the optimization process gathers information not only from neighboring cells, but using a more global viewpoint of the network.

CONCLUSION

The multi-subcarrier nature of OFDMA is more than appropriate to cope with the interference problems that arise between femtocells and macrocells. While femtocells configure themselves to reduce interference with neighboring cells, this technology can help to minimize the impact of the deployment of femtocells in a macrocell network.

It has been shown that co-channel assignment of the spectrum can lead to higher cell throughputs thanks to the greater availability of subchannels. However, this will be in exchange for a higher computational load in the network nodes (femtocells and macrocells). With OFDMA, and since the number and positions of the femtocells are unknown, traditional network planning needs to be replaced with efficient spectrum allocation algorithms for the purpose of interference avoidance, since novel algorithms are still needed to perform such allocation in realistic scenarios.

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BIOGRAPHIES

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