# A Review of Radio Resource Management in FemtoCell from Interference Control Perspective

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## ABSTRACT

A new and emerging technology called femtocell brings significant improvement in terms of better indoor coverage and higher data rate. Able to be installed and maintained by individual user, femtocell provides a cost effective solution to mobile operators to achieve higher network capacity. However, interference due to two-tier network structure introduces many challenges for successful femtocell deployment. In this article, we summarize various interference and resource management techniques proposed in the context of femtocell. Specifically, we focus on interference avoidance techniques. First, the overview of femtocells, its architecture, and common issues are presented. Next, various interference avoidance techniques are reviewed. At the end, several important research directions are outlined.

## 1. INTRODUCTION

The cellular network is considered to be one of the cost effective technologies in wireless communication in terms of mobility, coverage and resource usage. However, cellular networks are still plagued by the poor indoor coverage, e.g., inside houses and buildings, which are both demanding and potentially profitable environment (i.e., for both voice and data services) [1, 2]. Moreover, mobile user's need for higher data rates presents new challenges for the cellular standards to provide data service similar to that offered by Wi-Fi networks. To overcome these issues, the concept of auto configurable small base station referred to as femtocell was introduced, which can be adopted in wireless technologies, such as Global System for Mobile (GSM), Universal Mobile Telecommunications System (UMTS) and Long Term Evolution (LTE), and recently in Worldwide Interoperability for Microwave Access (WiMAX) [1]. A femtocell consists of femtocell access point (FAP) or home base station (HBS) which is the short-range (tens of meters), low-power (i.e.,15-20 dBm) and low-cost ($100-$200) base station designed to increase the indoor coverage. The FAPs are connected to the network provider through broadband IP-backhaul connection such as DSL router, cable modem, or fiber. A typical network configuration consists of femtocell overlaid over the macrocell (i.e., the underlying cell structure), which can be seen as a two-tier network structure [1]. The use of femtocell is beneficial to both users and operators in terms of better quality of service (QoS) and coverage with higher data rates, increased battery life of mobile device, and reduced operational cost.

As femtocell will use the existing licensed spectrum allocated to network service provider, in this context, femtocell will either use co-channel access scheme or dedicated access scheme [1–4]. In co-channel access scheme, femtocell and macrocell share the same licensed frequency bands (i.e., frequency reuse), which increases the bandwidth utilization. However, this frequency sharing gives rise to *cross-tier interference* and *co-tier interference* [12]. The cross-tier interference is caused by an element of the femtocell tier to the macrocell tier or vice versa, whereas co-tier interference occurs between elements of the same tier, e.g., between neighboring femtocells. Both these interferences will eventually impact existing macrocell user's capacity and performance. On the other hand, in dedicated access scheme, femtocell and macrocell use different non-overlapping spectrum which can completely avoid interference, but result in lower bandwidth utilization. This tradeoff between capacity and interference creates a unique challenge for successful femtocell deployment which is still an active research topic. Moreover, as the femtocell will be self deployable unit, and its location may be unknown, traditional network planning and optimization as well as interference mitigation techniques cannot achieve optimal performance. Therefore, interference and resource management become critical to provide proper network optimization and also to mitigate any interference between the two-tier network. A simple approach would be to apply interference cancelation/suppression techniques at the receiver to cancel the strong interfering signals. However, due to ad hoc deployment of femtocell, these cancelation techniques could be ineffective. Therefore, more focus is given to interference avoidance techniques in form of spectrum and power management, which are more likely to work well with diverse setting of femtocells. Despite this, other aspects such as the access methods, frequency band allocation, timing and synchroniza-

Final manuscript received on November 28, 2017.
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tion, and self-organization characteristics will play an important role in femtocell.

This article presents a comprehensive survey of existing interference and resource management techniques proposed for avoiding the interference caused by femtocells. First, we provide a brief overview of femtocell, followed by its architecture and some general concepts and issues (Section 2). Then, the reviews of related research works and 3rd Generation Partnership Project (3GPP) standardization efforts are summarized (Section 3). We also provide brief analysis and some performance set marks for successful femtocell deployment (Section 4). At the end, possible open research issues are discussed and future research directions are outlined (Section 5).

Since femtocell terminologies are different for different standards (e.g., femtocell is denoted as home NodeB (HNB) for UMTS 3G and as home enodeB (HeNB) for LTE), we define some of the terminologies that would be used throughout the article for consistency. We denote femtocell access point or home base station as *FAP* and macro base station as *MBS*. Femtocell users are denoted as *femto user equipment (FUE)* and macro network users as *macro user equipment (MUE)*. Femtocell refers to the entire femto network with a certain coverage area. *Subscribers* refer to the femtocell users with legitimate access to femtocell whereas, *non-subscribers* denote other macrocell users who do not have direct access to femtocell. These terminologies will be used irrespective of the underlying technologies unless specified in the article. A list of abbreviations is shown in Table 1.

***Table 1:*** *List of Abbreviations*

| **Abbreviations** | Description |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| 3GPP2 | 3rd Generation Partnership Project 2 |
| CDMA | Code Division Multiple Access |
| CSG | Closed Subscriber Group |
| FAP | Femtocell Access Point |
| FMC | Fixed Mobile Convergence |
| FUE | Femto User Equipment |
| GGSN | Gateway GPRS Support Node |
| GPRS | General packet radio service |
| GSM | Global System for Mobile Communications |
| HBS | Home Base Station |
| HeNB | Home eNodeB (LTE) |
| HMS | HNB Management System |
| HNB | Home NodeB (3G) |
| HNB-GW | Home NodeB Gateway |
| LTE | 3GPP Long Term Evolution |
| MBS | Macro Base Station |
| MUE | Macro User Equipment |
| OFDMA | Orthogonal Frequency-Division Multiple Access |
| RNC | Radio Network Controller |
| RSRP | Reference Signal Received Power |
| SeGW | Security Gateway |
| SGSN | Serving GPRS Support Node |
| TD-SCDMA | Time Division Synchronous Code Division Multiple Access |
| UMA | Unlicensed Mobile Access |
| UMTS | Universal Mobile Telecommunications System |
| W-CDMA | Wideband Code Division Multiple Access |
| WiMAX | Worldwide Interoperability for Microwave Access |

## 2. OVERVIEW OF FEMTOCELL

Femtocell is essentially a form of cellular access point deployed by users. As a result, femtocell installation, organization and configuration are some of the important issues. The installation of the femtocell should support plug-and-play, with minimum user intervention. In this regard, the femtocells are required to be able to completely self configure (i.e., selecting initial parameters including transmit power and frequency), self optimize (i.e., monitoring the resource usage) and self heal (i.e., to resolve any problem by itself) for efficient integration within the mobile networks. To achieve these goals, challenges such as managing RF interference, network synchronization, security and reliability must be resolved [2]. In the following subsection, we provide a brief discussion regarding femtocell architecture and its types, access methods, femtocell convergence and deployment.

### *A. Femtocell Architecture*

For scalable, secure, and autonomous deployment of femtocell, femtocell architecture needs to be compliant with standards that define the interfaces with existing cellular network. Further, interoperability among multiple manufacturing vendors presents the need of the standard interface between femtocells and core network [5]. To overcome these issues, different femtocell architectures have been proposed particularly in the context of W-CDMA (Wideband Code Division Multiple Access) by various standard bodies. The 3rd Generation Partnership Project (3GPP) is the primary standard for GSM, UMTS and LTE [5]. Therefore, 3GPP became the pioneer for providing standards for UMTS femtocell architecture in the form of 3GPP TS 25.467 Release 9 [6], thus making it a reference architecture for the evolution to femtocell networks.

The proposed 3GPP femtocell architecture follows an access network-based approach, leveraging the existing *lu* interface (including *lu-CS* for circuit services and *lu-PS* for packet data services) into the core service network [2]. The 3GPP UMTS femtocell architecture defines two new network elements, i.e., the Home NodeB (HNB) and the Home NodeB Gateway (HNB-GW) which are equivalent to femtocell access point and femtocell network gateway, respectively [6]. The communication between these elements is performed via a new interface, i.e., *luh* as shown in Figure 1. HNB Management System (HMS) and Security Gateway (SeGW) are also added to provide autonomous HNB management and to provide secure access to the backhaul IP network. However, all other network entities related to voice and data services follow the same architectural configuration of the proprietary 3G UMTS architecture, thus facilitating interoperability. The proposed standard 3GPP femtocell architecture includes specific functional entities as shown in Figure 1 [6]:

- **Home NodeB (HNB):** HNBs are typical customer premise equipments equipped with NodeB transceiver that provides radio network controller (RNC) functionality. The basic function of HNB is to provide radio coverage for standard 3G handsets within a home over *Uu* interface. It also supports HNB registration to the existing mobile network.
- **HNB Gateway (HNB-GW):** HNB-GW is installed within an operator network to aggregate traffic from different scattered HNBs back into an existing core mobile service network through the standard *lu* interfaces. HNB-GW acts as a single RNC to the core mobile network which provides many-to-one relationship between HNBs and HNB-GW. This functionality of HNB-GW improves scalability of the femtocell network which also offloads the HNB-specific function from the core mobile network.
- **HNB Management System (HMS):** HMS provides cost effective management architecture to control and manage the femtocell devices. The main function of HMS is to provide necessary provisioning data required for configuring HNB remotely. For this, HMS uses *TR-069* standard, that is a traditional interface used for DSL modem configuration. HMS also performs location verification of HNB for authenticating the user location.
- **Security Gateway (SeGW):** SeGW provides a secure link between the HNB and the HNB-GW (over *luh*) and also between HNB and HMS using IPSec [9]. SeGW is responsible for providing the proper authentication of HNB for the core network. However, the SeGW is a logically separate entity and may be implemented either as a separate physical element or integrated into, for example, HNB-GW.

While the above architecture focuses on 3G UMTS, it provides a baseline to all standards, including GSM, CDMA-2000, TD-SCDMA and WiMAX solutions. The principle concept remains the same with certain changes in the terminologies specific to the underlying standards. For example, CDMA 2000 and WiMAX follow the architecture of the Internet Protocol (IP) network by the 3rd Generation Partnership Project 2 (3GPP2) [10]. These include Voice over IP (VoIP) using Session Initiated Protocol (SIP), with RNC function integrated into the femtocell [2]. An overview of femtocell architecture that has been developed for 3GPP and 3GPP2 is summarized in [7, 8]. A major difference between 3GPP [6] and 3GPP2 [10] architecture is that 3GPP2 provides two distinct femtocell architecture for voice and packet data service [11].

*B. Femtocell Access Method*

Apart from using co-channel access scheme or dedicated access scheme, femtocell access methods will also play an important role in mitigating the interference and improving the overall network performance. Spectrum access schemes (i.e., co-channel and dedicated) define the channel access scheme for femtocells, whereas femtocell access methods define rules and policies for accessing the femtocell by its subscribers (e.g., FUE) and other non-subscribers (e.g., MUE). Based on 3GPP standards, femtocell access schemes can be divided into following categories:

- **Closed Access Scheme:** In this access scheme, only a subset of users, defined by the femtocell owner, can connect to the femtocell [12]. For instance, in Figure 2, FUE 1 can access the femtocell, while both MUE 1 and MUE 2 cannot, which is based on the access rule defined by the owner. This insures the user's reliability in terms of QoS, thus also providing secure connection within femtocell and with backhaul connection. However, due to closed subscriber group (CSG) policy (i.e., private access), strong cross-tier interference exists in closed access scheme. The power leaks from the femtocell will cause interference to passing-by macrocell users, thus degrading their signal quality. However, efficient spectrum allocation algorithms using orthogonal frequency-division multiple access (OFDMA) subchannels can help to mitigate this interference [13, 14].
- **Open Access Scheme:** In this access scheme, all the users (e.g., FUE 1, MUE 1 and MUE 2 in Figure 2) located close to femtocell are allowed to connect to femtocell when the macrocell coverage is low [12]. From the interference perspective, open access scheme reduces the cross-tier interference by letting the strong interferers such as passing by users to use the femtocell when necessary. Also, open access scheme is beneficial for operators to expand their network capacities by leveraging third party backhaul for free. However, this brings the concerns to femtocell owners whether to share their resources that may eventually degrade their QoS. As open access scheme provides unconditional access to femtocell by any legacy cellular users, security issue may arise due to this uncontrollable access. Moreover, the number of handoffs and signaling will also increase drastically as a result of providing open access to femtocell. Recent studies show that open access scheme is preferable when the multiple channel access scheme is non-orthogonal, e.g., code division multiple ac-

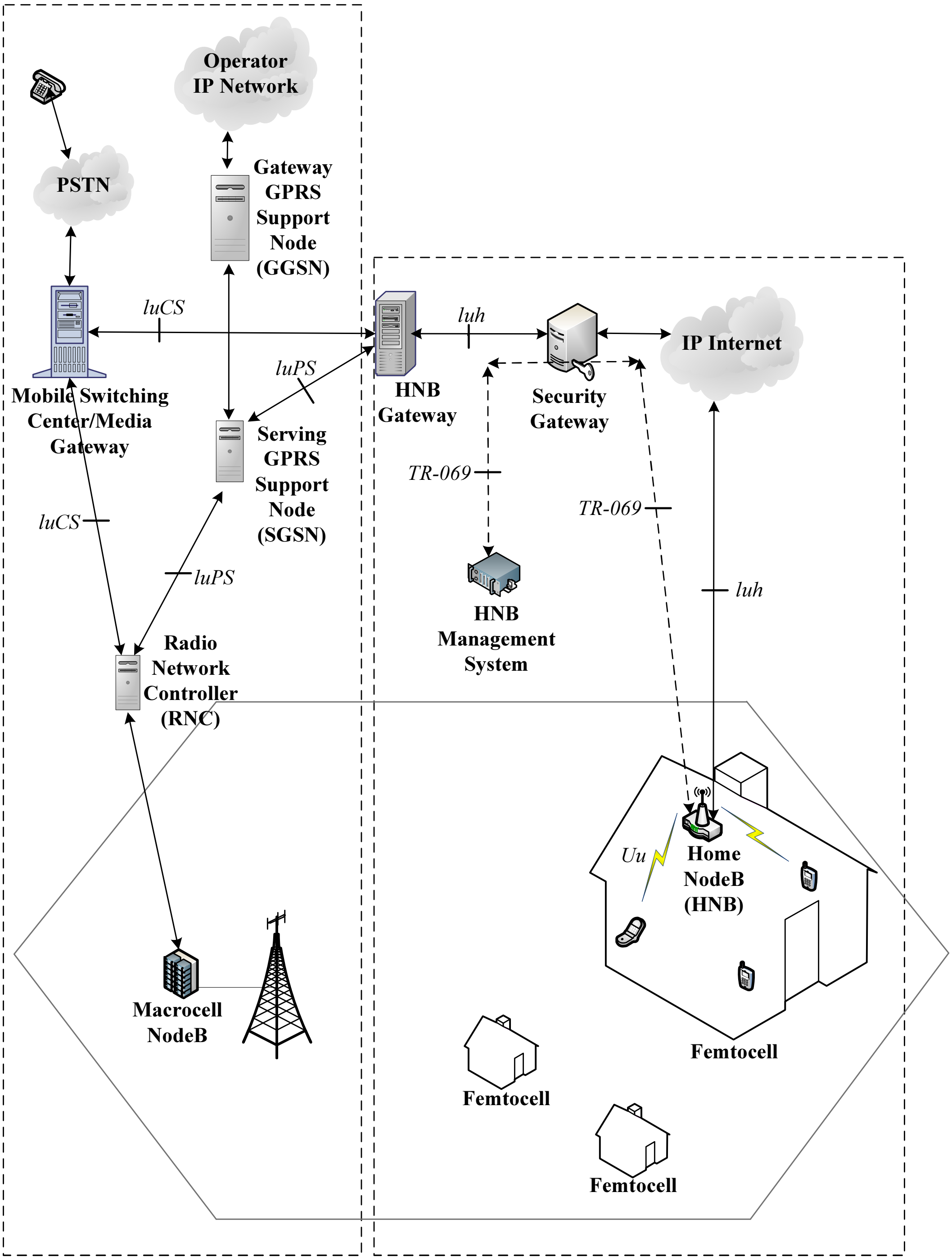



***Fig.1:*** *Femtocell architecture.*

cess (CDMA) [14].

- **Hybrid Access Scheme:** Hybrid access scheme is a new access concept introduced in 3GPP Release 9 [15]. In this access scheme, a limited amount of the femtocell resources is available to all users (MUE 1 and MUE 2 in Figure 2), while the rest is allocated for the femtocell owners (FUE 2) [12]. This access scheme combines both closed and open approaches to provide trade-off between the impact on the performance of femtocell owners and the level of access granted to other users. Therefore, hybrid access scheme requires fine tuning of the shared spectrum resources among the femtocell owners and other users. The main advantage of this scheme is that it solves the interference problems of closed access method without compromising the performance of femtocell owners. However, extensive research is still needed to apply hybrid access scheme to different deployment scenarios (e.g., how to allocate the resource between femtocell owner optimally).

For identifying the existence of femtocell and its access method, 3GPP has defined a CSG identity (CSG ID) and CSG indicator [16, 17] for both UMTS and LTE systems. The presence/absence of the CSG ID in broadcast system helps to identify a cell as femtocell. Also, combination of CSG indicator is used to identify whether a femtocell is closed/open/hybrid. The various combinations of CSG indicator and CSG ID proposed by 3GPP standard are shown in Figure 2. A detailed summary of the ongoing effort and issues related to access control strategy covered by 3GPP for UMTS and LTE systems is provided in [18].

### *C. Integration of Femtocell into Core-Netork: Fixed Mobile Convergence*

The fixed mobile convergence (FMC) is another emerging concept which allows seamless connectivity between fixed (e.g., local area network) and cellular networks [4]. The ultimate goal of FMC is to optimize transmission of all data, voice and video communications to and among end users, regardless of their locations or devices. The unlicensed mobile access (UMA) (or universal mobile access) is the first 3GPP standardized technology enabling cellular (i.e., licensed) and WiFi (i.e., unlicensed) convergence [19]. However, UMA requires a new (dual mode) handset which should switch efficiently between cellular and WiFi network resulting in an additional cost [2]. On the contrary, femtocell-based deployment will work with the current handsets which only require installation of a new access point (i.e., FAP). Moreover, recent research studies show that UMA can be used to address the core network integration of femtocell into mobile core networks by providing a standard, scalable, IP-based interface [2, 20]. The principle idea is to combine all the functions of a radio access network and core network (e.g., RNC, GGSN, and SGSN) into a single network element, thus making the core network access independent [3]. This convergence architecture is often referred to as "collapsed stack" or "Base Station Router (BSR)" which is being considered in several standards (e.g., 3G UMTS, LTE, and WiMAX) [21].

In the following, we present specific integration of femtocell to existing and new technologies (e.g., 3G UMTS, LTE, and WiMAX).

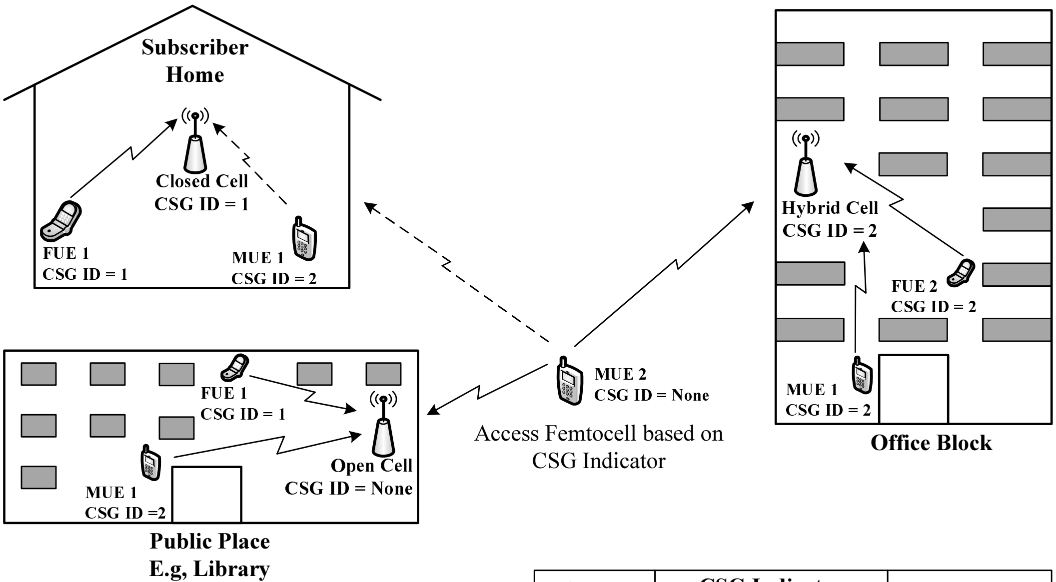
*1) Femtocell in Cellular Networks:* The integration of femtocell into current cellular networks such as 3G UMTS/HSPA or into new 4G LTE is an active research topic which is being constantly pursued by standard bodies such as 3GPP and 3GPP2. In 3GPP, the femtocells are called Home Node B's (HNB) for 3G UMTS/HSPA and Home eNode B's (HeNB) for 4G LTE. However, the H(e)NB functionality and interface are mostly the same. Moreover, for 3G networks based on W-CDMA air interface (i.e., UMTS/HSPA), femtocell can be integrated using collapsed stack architecture as stated by 3GPP standard group. For 3G CDMA 2000, IMS and SIP based approach [22] using full IP-based architecture is more desirable. This approach is adopted by 3GPP2 and is under discussion by 3GPP. For LTE, additional functionality such as hybrid cell concept, inbound mobility and access control, is added in 3GPP Release 9 [15]. However, LTE femtocell will have better advantage than its earlier 3G counterpart as LTE will use OFDMA instead of CDMA. Typically, OFDMA provides higher flexibility and robustness in avoiding intracell and multipath interference. This characteristic becomes beneficial while reducing cross-tier interference due to co-channel deployment [23, 24]. Also, OFDMA femtocell can exploit channel variation in both frequency and time domain unlike CDMA which can exploit channel variation only in time domain for interference avoidance [13].

*2) Femtocell in WiMAX:* WiMAX is a wireless network based on IEEE 802.16 standard that provides higher QoS and data service and becomes an alternative to cable and DSL [25]. However, due to the use of high frequency, WiMAX also suffers from poor indoor coverage. To overcome this, the IEEE 802.16m SDD (system description document) [26] introduces the concept of femtocell for WiMAX. Unlike 3G femtocell, WiMAX femtocell integration is simple as it follows the all IP based service. Depending upon the class of application environment, various types of WiMAX femtocell can be developed. According to recent study, WiMAX femtocell convergence provides improved performance in terms of higher throughput and smaller delay than those of other air interfaces such as UMTS [21, 27].

### *D. Issues in Femtocell*

For the success of femtocell, many challenges have to be addressed. Foremost, femtocell needs to be low cost such that it favors the mass scale deployment. It should also meet all regulatory requirements of underlying implementing technology. Further, it should be reliable and interoperable to handle interference and also support synchronization. In the following, we list some of the important issues in femtocell.

*1) Femtocell Deployment Issues: Cost, Scalability and Security:* For effective femtocell deployment, various technical and financial challenges should be tackled [1]. Basically, femtocell's use of IP connections (i.e., Internet Access) for backhaul access creates network design and integration challenges different from the traditional network design considerations for the operators. Foremost task is to modify the backhaul system to accept and integrate femtocell with full functionality. Moreover, the cost incurred




| Access Mode | CSG Indicator | | CSG ID |
|---|---|---|---|
| | UMTS | LTE | |
| Closed | TRUE | Present | Present |
| Open | FALSE | Absent | Absent |
| Hybrid | FALSE | Absent | Present |

***Fig.2:*** *Access scheme for femtocell with CSG indicator and CSG ID.*

for strategic deployment of femtocell is also important for adoption of femtocell technology. In many ways, femtocell will offer savings to the operators in terms of capital and operation expenditures [3]. However, femtocell installation will incur certain cost to femtocell users. Therefore, proper incentive schemes (e.g., revenue share) should be provided to femto users for adopting the femtocell service. Thus, the need of low cost femtocell development and implementation becomes driving factor for femtocell selection and its scalability. Due to recent advances in integrated technologies, the cost of femtocell can be made very affordable (around $100-$200) [2]. Moreover, the operators can also provide competitive subscription plans for femtocell users as an incentive to compete with the existing Wi-Fi market.

Another important concern arising from network integration perspective is the security issue. As femtocell uses IP connection to connect to core network, security issues such as authentication and network intrusions become vital for network operators. Proper authentication and device provisioning should be provided to mitigate these issues. 3GPP user group has already added secured gateway (SeGW) and HNB management system (HMS) into standard femtocell architecture for providing necessary security and authentication for femtocell [6].

*2) Interference Management:* The RF interference (i.e., cross-tier and co-tier interference) due to sharing of cellular frequency poses major problems for femtocell deployment [2]. The spectrum allocation schemes such as dedicated deployment can mitigate this interference to some extent. Despite its low power radiation and shielding from walls of buildings, femtocell still can cause interference to macrocell users and other femtocell users. These interferences are crucial for femtocell as they degrade the network performance. A cross-tier interference exhibits *dead zone* problem (specially in closed access scheme) where the high power macrocell user causes interference to nearby femtocells or when femtocell users cause unacceptable interference to the macrocell users [28]. Also, due to random placement of femtocell, co-tier interference can degrade the overall performance of the femtocell. Thus, interference should be properly managed. These interference issues can be minimized by using various power control algorithms and resource management techniques which will be discussed in detail in Section 3.

*3)Spectrum Planning:* Spectrum planning is an important issue in femtocell deployment due to the use of legacy licensed spectrum. Proper spectrum policies and access method should be defined to effectively reuse the available spectrum. Also, unlike Wi-Fi technology, femtocell requires regulatory approval to use the licensed spectrum. As the spectrum and radio regulation vary in different countries, international agreements should be made for interoperable operations.

*4)Synchronization:* Network time synchronization is necessary between macrocells and femtocells to minimize multi-access interference and ensure a tolerable carrier offset [1, 13]. Due to lack of centralized coordination between femtocell and macrocell, synchronization is also required for the proper performance of handover. Moreover, providing high precision synchronization for low cost femtocell becomes a challenging issue, where the IP backhaul system in femtocell still inherits the packet jitter problem, thus creating difficulty in obtaining a time reference [1]. Therefore, for femtocell, efficient synchronization solutions are being considered, such as using IEEE-1588 Precision Timing Protocol over IP or using GPS for synchronizing with the macrocell [2].

*E. Market Infiltration*

Femtocells have been attracting lots of attention among the mobile operators due to the extensive demand for better indoor voice and data traffic [2]. However, according to recent market research, femtocell pricing will play an important role in successful femtocell deployment. The pricing issues and opportunity costs should be balanced in such a way that network operators and consumers have the incentive to shift to femtocell [37]. Beside this, many standard bodies (e.g., 3GPP and 3GPP2) are actively working to provide better solution and approach for successful femtocell deployment. A brief summary of standardization activities related to 3GPP and 3GPP2 is presented in [7, 8]. Femto-Forum [38] is another collaborative organization formed by operators, vendors, and content providers to promote and develop open standards for femtocell deployment worldwide. Similarly, many vendors provide competitive solution to this growing industry, such as Alcatel Lucent, Huawei, ZTE, ip.Access, Airvana, Samsung, Ubiquisys, and Qualcomm, to name a few.

## 3. INTERFERENCE AND RESOURCE MANAGEMENT: ISSUES AND APPROACHES

There are many issues of macro-femto interaction to be addressed. Due to profound impact on the QoS of communication links and system capacity, the interference issue (both cross-tier and co-tier) is the main concern [39] and thus, the focus of this article.

Depending upon the mode of transmission and corresponding deployment scenario, the macro-femto interference can be classified into downlink (DL) and uplink (UL) interferences [38]. Figure 3 shows the DL and UL interference scenarios for a typical macro-femto network. The downlink interference can be caused by both MBS and FAP. During the macrocell downlink transmission, the transmit power from the MBS causes cross-tier interference to the nearby FUE receivers (FUE1 in Figure 3) which are prominent for the femtocell users. Similarly, in the case of femtocell downlink transmission, the transmit power from the FAP (FAP1 in the figure) causes cross-tier interference to the nearby MUE (MUE1 in the figure) and also co-tier interference to adjacent FUE (FUE2 in the figure) in dense scenario. In the case of uplink transmission, the uplink signal from MUE and FUE causes interference to the nearby FAP receiver and MBS receiver. For macrocell uplink scenario, the MUE (MUE2 in the figure) close to the femtocell or inside the femtocell coverage area causes cross-tier interference to the FAP receiver (FAP4 in the figure) when transmitting the uplink signal to the MBS. For femtocell uplink scenario, the FUE at cell edge (FUE3 in the figure) transmitting uplink signal to corresponding FAP causes cross-tier interference to the overlaid MBS receiver and co-tier interference to the nearby neighbor FAP receiver (FAP4 in the figure). Both uplink and downlink interferences should be controlled to meet their respective QoS requirements.

Hence, there is a need for interference and resource management techniques to minimize various interference issues in femtocell environment. In the following subsections, we focus on various interference and resource management issues and their corresponding approaches to mitigate/avoid the effect.

*A. Spectrum Allocation Techniques*

The excessive cross-tier interference is one of the main factors which limit the co-channel deployment. Dedicated deployment avoids cross-tier interference, thus making it more realistic and becoming a topic of discussion of many research works. For example, some works (e.g., [28, 40, 41]) show that dedicated deployment not only avoids cross-tier interference, but also increases data coverage extension [41] and helps to mitigate femto-to-femto interference (or femtocell co-tier interference) [28]. The dedicated deployment fails to achieve full spectrum utilization that can eventually decrease the overall capacity of the two-tier network. On the other hand, co-channel deployment can achieve higher spatial reuse of spectrum, thus increasing the spectrum utilization, but at the cost of possible high interference. A recent work in [42] shows that co-channel deployment can achieve full spatial reuse of spectrum and higher capacity if the femtocell deployment is limited based on outage probability. Also, the spectrum utilization can be increased by using different spectrum partitioning schemes (i.e., splitting of frequency or time domain), frequency reuse schemes, or other heuristic channel allocation schemes. In the following, we highlight various existing literatures on spectrum allocation techniques.

*1)Spectrum Partitioning:* In the context of macro-femto network, spectrum partitioning refers to as a technique of assigning frequency bands to each FAP and MBS such that the resulting interference can be minimized. This partitioning could be done in frequency or time domain, or a combination of both, which can be static or dynamic. The main concern in spectrum partitioning is how to optimally set the level of sharing between femtocells and macrocells

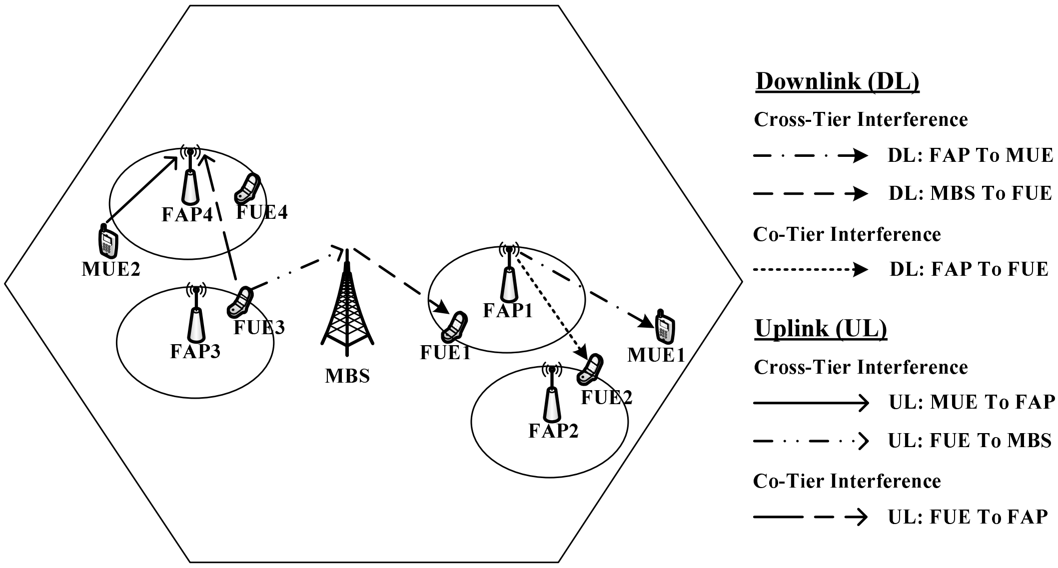



***Fig.3:*** *Cross-Tier and Co-Tier Interference Scenario for DL and UL.*

such that their QoS requirements are guaranteed under certain performance metrics (e.g., capacity, outage probability, and blocking probability). In [43], it is shown that allocating just a small amount of spectrum to femtocell could substantially increase the service availability in the macrocell. The reason is that with femtocell in the overlay scenario, substantial traffic load can be accommodated by the femtocell, thus decreasing the macrocell traffic load and hence lower macrocell blocking probability. Similarly, in [44], it is shown that the higher user capacity can be achieved for femtocell users using co-channel deployment. This approach enforces higher spatial reuse through small femtocell and interference avoidance based on the antenna sectoring and time hopped CDMA in each tier. Basically, this time hopped CDMA is equivalent to splitting the spectrum in the time domain instead of splitting it in the frequency domain.

Another simple alternative would be to use multicarrier concept as stated in 3GPP RAN1 Meeting [45], where at least one carrier called *escape carrier* is reserved for macrocell users. This carrier is free of interference from femtocells. The remaining carriers can be used for co-channel deployment of both MBS and FAPs to maximize the frequency utilization. 3GPP standard group introduces the ways to optimally split the spectrum to achieve higher spectrum utilization. For example, a simple approach is suggested by 3GPP [46] where the downlink interference is managed using directional information between FAP and MBS. The directional information refers to beamforming and frequency domain scheduling. According to this scheme, the MUE uses all the frequencies except the frequency used in FAP for interference management at MBS side, whereas the FAPs use the frequency except frequency used by MBS to manage interference at FAP side. A different concept of assigning frequency called overlap frequency is discussed in 3GPP RAN1 Meeting [47], where FAPs are allowed to use the entire frequency band and MBS is assigned only part of that frequency band. Although it is a heuristic approach, femtocell users will have a protected band which can partly remove macro interference. For co-channel deployment, [47] further suggests using frequency allocation with frequency reuse factor of one. However, to achieve full frequency reuse, it suggests using frequency selective scheduling (FSS) and beamforming. FSS takes advantage of the frequency selective fading of interference, particularly for low-mobility channels, while beamforming takes advantage of the spatial selectivity of the interferers to combat interference. However, FSS and beamforming need channel information which may cause additional signaling overhead and delay. Figure 4 provides a discussion of spectrum allocation techniques.

In LTE system with OFDMA air interface, the mobile users can provide channel quality information to the attached base station (either macro (e)NodeB or H(e)NB) via a dedicated control channel [48]. According to [48], this information can be exploited to determine the level of sharing between femtocells and macrocells. The authors in [48] provide an autonomous algorithm to partition the macro-femto sharing, which performs a combination of frequency and time sharing based on the channel conditions reported by the mobile users. According to 3GPP [49], this spectrum splitting in both time and frequency domains is more dynamic, which could effectively mitigate the associated interference. In this case, the macrocell shares the available channel with femtocells by partitioning it in time and frequency domains. The arising interference due to sharing of the same

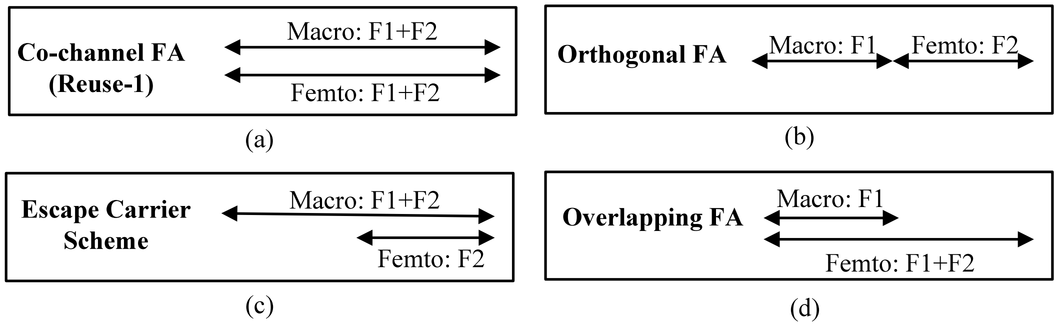



***Fig.4:*** *Various spectrum allocation schemes.*

sub-band is controlled by the request of temporal silencing of the adjacent aggressive FAP operating on requested sub-band, thus decreasing the interference from the interfering FAP.

Similarly, in [50], the available OFDMA spectrum is partitioned into specific subcarriers for macro and femtocells based on performance metrics such as outage probability, spatial throughput, and area spectral efficiency. It is shown that by restricting the femtocell access to only a randomly selected subset of the available channels, both cross-tier and co-tier interferences can be minimized. It is also shown that besides the spectrum allocation policies, spatial density of femtocell and radio propagation channel condition also play important roles to achieve better performance. In general, to maintain certain performance, the fractional reuse of femtocell spectrum usage should be minimized to accommodate more femtocells into overlaid macrocell. More specifically, a recent work in [51] shows that the fraction of spectrum reuse by femtocell is the key parameter to increase link capacity and reliability. From the link capacity perspective, increasing the number of subchannels allocated to femtocell can provide higher capacity, but with higher interference that can degrade the link reliability. An optimization problem is formulated to determine the optimal number of subchannels allocated to a femtocell which could maximize the capacity subject to certain link reliability requirement. It either selects subchannel with higher link gain or the one with lower interference. Depending upon the channel state information, each user selects the preferred subchannel in a distributed manner. Both the channel selection principles (i.e., based on higher link gain or lower interference) are applied to dedicated and co-channel spectrum allocation schemes. The simulation results show that both channel selection schemes perform better for dedicated spectrum allocation due to less cross-tier interference.

*2)Fractional Frequency Reuse:* Another popular scheme for increasing the spectrum utilization is based on a conventional frequency reuse concept which is extensively applied to existing cellular networks [52]. Frequency reuse concept makes the co-channel deployment more practical by reusing the available frequencies such that the same frequencies are not reused in adjacent neighboring cells to avoid any cross-tier interference. Recently, this concept is being adopted by 3GPP LTE and WiMAX systems. In this case, frequency reuse is partitioned such that cell-edge UEs are assigned the resources with higher frequency reuse factors than the UEs at the cell-center to obtain an effective reuse which is greater than one but not too high [53]. This scheme is better known as fractional frequency reuse (FFR) which not only partitions the spectrum resources but also allows concurrent implementation of various frequency reuse schemes and partitioning schemes. However, the conventional FFR scheme should be modified to apply to macro-femto network.

In [54, 55], a modified FFR scheme is proposed for avoiding interference in LTE femtocell. As shown in Figure 5, the macrocell region is divided into inner/center regions and outer/edge regions including three sectors per region, denoted by $C_1, C_2, C_3$ and $E_1, E_2, E_3$ repsectively. The available frequency band is partitioned into two parts (i.e., $F_1, F_2$) where $F_2$ is further divided into three parts (i.e., $F_A, F_B, F_C$). Different frequency sub-band is allocated to each macrocell sector according to FFR concept such that sub-band $F_1$ with reuse factor of one is used in the center region and the remaining sub-bands $F_A, F_B, F_C$ with reuse factor of three are used in the edge regions. The femtocell is allowed to use those sub-bands which are not used in macrocell sectors. For example, when a femtocell is located in edge region $E_1$, it uses sub-bands $F_1, F_B, F_C$, while the macrocell uses sub-band $F_A$. Similarly, when the femtocell is in the center region, the femtocell additionally avoids using the sub-bands $F_1$ already used by macrocell in the center region and also the associated sub-band used by the macrocell in the edge region of current sector.

Such FFR schemes can avoid cross-tier interference, thus enhancing the total throughput of overall network especially for cell-edge users. However, this scheme is static, where the regions are divided based on static distance or SINR. As a result, the scheme

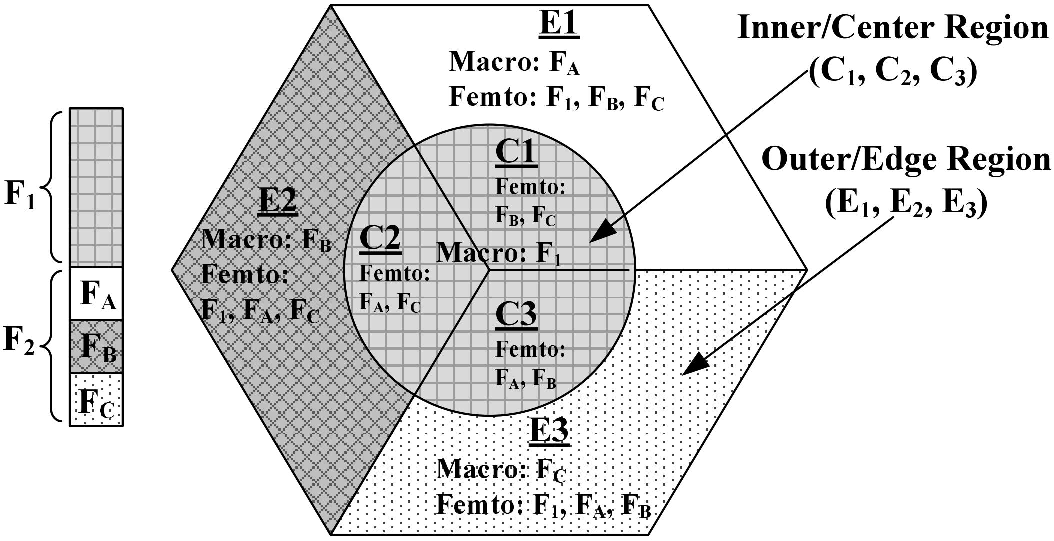



***Fig.5:*** *Fractional frequency reuse (FFR) scheme for femtocell.*

may not be suitable for the dynamic load environment (e.g., number of users is time-varying). Also, this scheme may experience reduced capacity of each region and the complexity will be high if the density of femtocell increases.

In [56], an adaptive FFR scheme is proposed to reduce femtocell co-tier interference. The proposed scheme adjusts the frequency reuse factor based on the knowledge of channel state of the operating environment. The main idea here is to adjust the frequency reuse factor close to one so that the higher spectral efficiency can be achieved. The mutual interference among nearby femtocells is analyzed depending upon the femtocell location information provided by the HNB gateway. This mutual interference information is used to classify the femtocells into different groups according to the interference level. A set of orthogonal subchannels is assigned to each group and the transmit power of each femtocell is adjusted based on the received signal strength indication (RSSI). The simulation results show that the proposed scheme is effective for densely populated femtocell area. Similar approach is considered in [57], where the interfering FAP is determined based on path loss difference to FUE from the serving FAP and neighboring FAPs. This information helps to control the downlink interference of FAP. Based on this information, the FAPs are assigned those sub-bands that are non-overlapping with the interfering neighboring FAPs, thus making interfering FAPs orthogonal. Moreover, based on the SINR limit, the FAP decides which available sub-bands will be reused so that they can be assigned to other FUEs. However, for both schemes, the throughput decreases with the increase of the total number of femtocells in a macrocell. In [58], it is shown that femtocell co-tier interference in dense deployment can be reduced by further dividing the allocated femtocell band (i.e., using FFR scheme) into two separate bands for center and edge users. For this, the center frequency of all the femtocells is the same, while at the edge of neighboring femtocells different frequency bands are used to avoid the co-tier interference. By doing so, the proposed dynamic frequency reuse scheme outperforms simple dedicated and co-channel frequency allocation schemes with much lower outage probability. However, for this scheme, the femtocell network should be self organizing network (SON) based femtocell HNB. The SON based femtocell is still under consideration and is the focus of many research works.

*3)Mixed Spectrum Allocation:* As an alternative way to take advantage of both deployments (dedicated or co-channel), a mixed spectrum usage can be used in which the FAPs can flexibly operate in either co-channel or dedicated mode based on the placement of femtocell or spatial condition (i.e., the distance between the FAP and MBS) inside the macrocell. The main concern would be in finding the appropriate coverage area for allocating either deployment. A straightforward solution is to divide the coverage area into inner and outer regions (similar to FFR scheme). In [59], the coverage of macrocell is split into inner and outer regions, such that the dedicated allocation is applied in inner region and co-channel allocation is applied in outer region (Figure 6). The proposed scheme effectively avoids cross-tier interference. The inner and outer regions are differentiated based on the interference-limited coverage area (ILCA), which is the area within a contour where the received power levels from FAP and MBS are the same. The drawback of this assignment is that it is only applicable to downlink scenario.

In [60, 61], another mixed spectrum usage similar to [59] is proposed, where instead of dividing the

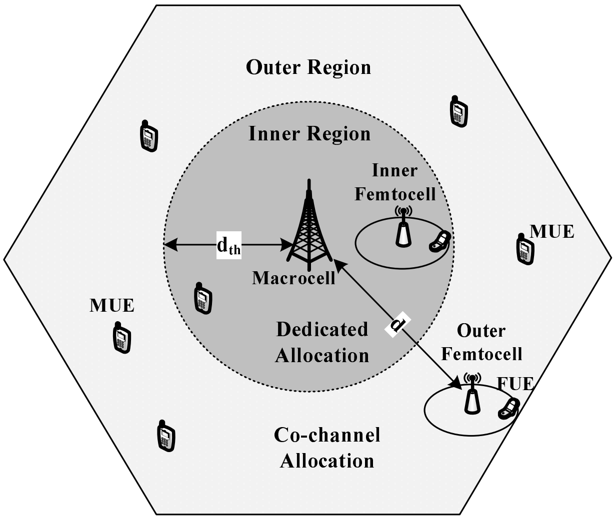



***Fig.6:*** *Mixed deployment scheme for femtocell.*

macrocell coverage, the femtocells are classified into the inner and outer femtocells based on spatial conditions (i.e., the distance between the FAP and MBS). Similar to [59], it is shown that femtocell favors dedicated deployment when it is close to MBS (i.e., inner femtocell) and co-channel deployment when FAP is far from macrocell BS (i.e., outer femtocell) [60]. To differentiate inner and outer femtocells, the threshold distance $d_{th}$ is defined (instead of ILCA). The threshold distance refers to the distance at which the capacity of femtocell for both deployment is the same for both downlink and uplink transmissions. However, for a practical implementation, the threshold distance ($d_{th}$) can be calculated by comparing the estimated reference signal received power (RSRP) ($p_r$) of MBS at FAP with corresponding power threshold ($p_{th}$) in both downlink and uplink directions [61]. To mitigate the downlink cross-tier interference caused by the femtocell users to the nearby macrocell users, the FAP is notified about the interfered macrocell users so that the resource is reallocated to mitigate the interference for macrocell users [60]. However, dividing the inner and outer regions might be difficult in the case of densely populated femtocell environment. Due to possible overlapping of regions, achieving the appropriate spectrum allocation will be more challenging than the simple cases mentioned in [59–61]. Similarly, in [62], the entire OFDMA frequency band is divided into two bands, i.e., co-channel and dedicated bands. The co-channel band is shared by femto and macrocell. On the other hand, dedicated band is used only by the macrocell with combination of dynamic frequency bandwidth division and clustering algorithm (CFCA). The clustering algorithm is used to find the dividing ratio of these two bands. The dedicated macrocell band helps to mitigate the downlink dead zone for MUEs around femtocells and to guarantee macrocell services. In the case of co-channel band which corresponds to reuse portion of the entire bandwidth, different subchannels of that reuse portion are assigned to femtocells in different clusters. However, the femtocell in a particular cluster reuses the same subchannels. The clustering algorithm based on graph method is used to allocate the femtocells into different frequency reuse clusters. Also, the number of clusters and ratio of frequency band are determined. It is shown that due to higher frequency reuse factor, the cross-tier interference is effectively avoided.

The implication of the above mentioned spectrum allocation techniques will definitely depend on the choice of operators and their available resources. Nevertheless, spectrum allocation techniques will also depend upon the choice of access method used by the customers. In the case of dense femtocell network, open access scheme can give rise to adjacent channel interference [60]. Note that the adjacent channel interference can be measured by adjacent channel interference ratio (ACIR) based on the carrier separation. The carrier separation should be maintained to at least 5 MHz to effectively mitigate the adjacent channel interference [63]. However, providing effective carrier separation without compromising available spectrum utilization is still an open issue.

On the contrary, closed access scheme can guarantee higher throughput for the customer [64]. However, at the same time, it also decreases the overall throughput of the network. Moreover, the number of users with transmission error in the case of closed access scheme is higher than that in open access scheme due to higher cross-tier interference. According to the work in [29], it is shown that by limiting the access of OFDMA femtocell resources by non-subscriber for a CSG scheme, the cross-tier interference can be reduced while guaranteeing the performance to the femtocell owner. The proposed scheme is similar to hybrid access scheme introduced in 3GPP Release 9 [15]. The resulting throughput cutback (i.e., reduced number of accesses) for CSG femtocell owners due to sharing of subchannels might not be significant for most applications. It means that all the voice calls and video calls can be made without loss of femtocell throughput. The reason is that the shared subchannels used by the non-subscribers were already unoccupied in the first place. However, the probability to share the femtocell spectrum also depends upon the density of non-subscribers in the vicinity of the femtocell. Thus, limiting the number of shared subchannels helps to guarantee a reliable service from femtocell subscribers, while reducing the outage probability of the non-subscribers.

### *B. Power Allocation and Control Techniques*

Despite the various spectrum allocation techniques, interference management and mitigation is incomplete without proper power allocation and control schemes. They are important especially in the densely populated femtocells over high traffic macrocell environment. The transmit power of femtocell not only dictates its coverage area, but also can cause undesirable interference to macrocell and other neighboring femtocells. The FAP transmitting with fixed power can significantly degrade the macrocell throughput and coverage [66]. Moreover, femtocell power control problem constitutes a multi-level trade-off such that decreasing the FAP transmit power will have negative effect on its coverage area, while increasing the power will increase interference to MBS and coverage overlaps to neighboring FAPs [67]. Also, during uplink transmission, both FUE and MUE signals can cause severe interference to nearby MBS and FAP, given that they are close to FAP/MBS vicinity. Clearly, there is a need of effective power control strategy to set the FAP signal power optimally such that undesirable interference to the legacy macrocell network is minimized while maintaining proper coverage to its own users.

Numerous power allocation strategies are proposed where mostly the femtocell power is adjusted to control the unwanted power leakage. The reason is that macrocell is considered as primary infrastructure, meaning that the foremost concern is to ensure better QoS for its users irrespective of the interfering effects caused by overlaid femtocells. Moreover, due to ad hoc deployment of femtocells, people focus more on decentralized power control schemes where the necessary algorithms are introduced for FAPs and FUEs. Basically, an optimization problem is formulated to adjust and control the signal power, which is subject to some performance constraints (e.g., required SINR, outage probability, and required capacity/throughput). The objective is to maximize the performance such that interference can be minimized or avoided depending upon the proposed constraint. Most of the power control schemes more or less follow this strategy to mitigate the resulting interference caused by femtocells. As part of these strategies, the FAP needs to have a sensing function to measure *link gain, channel state, and received signal strength indicator (RSSI).* This sensing function is known as *self-organizing capability*, which is also one of the important features for successful femtocell deployment (more detail in subsection 3-D). The power is then adjusted based on the knowledge of these system parameters. For example, in [67], a decentralized self optimizing algorithm is proposed, which uses femtocell's user load information to adjust the FAP pilot transmit power. The decision for increment/decrement of the minimum power threshold is performed on the basis of the coverage metrics (e.g., call drop probability and coverage overlap coefficient).

As the first step for reviewing various power allocation and control methods, we first highlight some of the femtocell power control methods proposed and discussed by 3GPP TSG-RAN WG1 standardization for LTE advanced system. We categorize the 3GPP attempts as follow:

**Range Expansion:** For successful co-channel deployment, 3GPP standard highlights the need of cell-association techniques to gain the benefit from the presence of low-powered FAPs. Femto range expansion (RE) [68] has been introduced as one of the cell-association techniques to leverage the interference caused by high-power MBS by allowing MUE to be served from the cell that is not necessarily having the strongest signal. The basic mechanism for femto RE is based on the measurement of reference signal received power (RSRP) plus the offset value. The offset value determines the femto RE such that it is configured to be greater than zero ($offset > 0$) for femtocells and equal to zero ($offset = 0$) for macrocells. A simple illustration of femto RE is shown in Figure 7. With femto RE enabled, the coverage area will be increased to also cover the shaded region as shown in Figure 7.

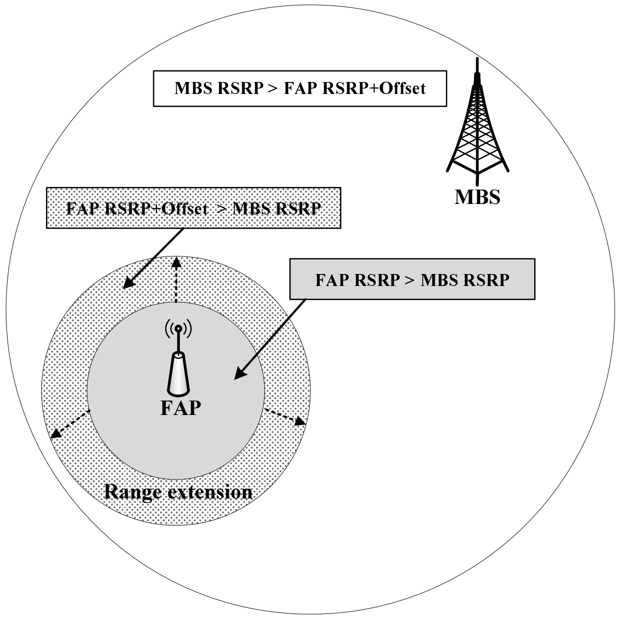



***Fig. 7:*** *Femto Range Expansion Principle.*

The RE helps the low-power FAPs to expand its footprint, thus increasing the number of connections and also offloading the traffic from the macrocell. Moreover, multiple FAPs can simultaneously utilize the bandwidth once macro interference is removed, thus achieving cell-splitting gains. Also in [69], it is shown that range expansion could improve cell-edge UE throughput by balancing the load among macrocell and femtocell. Typically, 8-10dB range expansion is needed to expand the range of FAPs when there are small number of FAPs in the system and UEs are uniformly distributed in the network. Similarly, in [70], another femtocell node range expansion method called *hotzone first (HF)* is proposed. Basic principle of HF is to allow UE to connect to a femto node if the measured downlink SINR is larger than a certain threshold. If there are several femto nodes fulfilling this criterion, then the UE connects to the femto with the highest RSRP. For the case with low SINR, [72] and [73] suggest using smaller bias with macrocell transmit power de-boosting, and limiting the maximum number of MUEs scheduled per subframe in certain subframe. The symbol/subframe shifting, selective scheduling and power attenuation with RB granularity are proposed to enable legacy UEs to use femtocells.

In [71], three schemes of cell-selection are proposed. Scheme A is Rel8-RSRP selection where each UE selects its serving cell with the highest average RSRP. Scheme B is minimum path loss, where each UE selects its serving cell with the smallest path loss. Scheme C is biased RSRP selection, where the proposed scheme biases users in favor of selecting a hotzone cell by adding a cell-selection bias to the RSRP from hotzone cells.

**Cooperative Silencing:** In [74], cooperative silencing scheme is proposed where the FAP pauses its transmission to reduce inter-cell interference to a closely located MUE. This scheme seems to be essential in the case of a closed access scheme, specially for mitigating downlink interference to MUE under the coverage of FAP which is transmitting its own downlink signal concurrently. However, silencing the interfering FAP can cause unaccessibility effect to users of FAPs. Although this scheme mitigates the femto-to-macro interference completely, the denial to service of FUE can raise serious concerns.

**FAP Power Control:** Due to the plug-and-play nature of femtocell, 3GPP emphasizes on controlling the power of FAPs rather than the incumbent MBS. Several FAP power control methods are proposed to 3GPP to avoid unnecessary power leakage of FAP to the surrounding, thus degrading the performance of macrocell. In [75], an adjustable FAP power setting scheme based on path loss is introduced as an alternative to fixed FAP power setting. The FAP adjusts its transmit power based on the environment. Furthermore, the importance of penetration loss due to external/internal walls of building is highlighted. In the real life situations, if the FAP receives a low signal power from the MBS, the FAP would not be able to identify the reason for the low received signal power, whether due to penetration loss of the walls or long distance. Hence, this work proposes the adjustable FAP power setting scheme based on penetration loss to mitigate interference for control channel. Similarly, in [76], two types of FAP power setting methods called proactive and reactive schemes are proposed for downlink scenario. In the case of proactive scheme, the FAP adjusts its transmit power before it starts transmitting to avoid creating macrolayer coverage holes. One strong candidate for proactive FAP power setting is the NLM (network listen mode)-based scheme, where the FAP initializes its maximum transmit power based on measurements towards the strongest co-channel deployed macrocell. On the other hand, reactive scheme relies on sensing from terminals, such that FAP transmit power is adjusted only when an interference problem is first detected. Reactive scheme can be characterized as closed-loop control mechanisms.

A hybrid power setting scheme is proposed in [77], which consists of *open-loop power setting (OLPS)* mode and *closed-loop power setting (CLPS)* mode. In the OLPS mode, FAP adjusts transmit power based on its measurement results or predetermined system parameters in an open-loop manner. On the other hand, in the CLPS mode, FAP sets its transmit power primarily based on the coordination with MBS. FAP applies a hybrid power setting scheme, if it switches between power setting modes according to the operation scenarios. In [78, 79], a per-cluster based opportunistic power control algorithm is proposed for mitigating aggregate femtocell interference to macrocell in densely deployed femtocell environment. The per-cluster based opportunistic power control has two sensing algorithms. The first algorithm is self-configuration in which by using centralized sensing, MBS can estimate the number of active femtocells per cluster. The second algorithm is self-optimization, which uses distributed sensing such that each femtocell senses whether other femtocells are active in the same cluster. This scheme helps to mitigate the aggregate interference (AGGI) by estimating the effective AGGI lever per cluster and opportunistically allocating the FUE power. As a result, the total throughput increases.

Beside the aforementioned techniques, there are many works in literature dealing with various power control schemes to mitigate the underlying interference in macro-femto network. A short summary of different power control techniques is presented in Tables 2 based on recent contributions to research community [66], [80] - [84]. All the works mentioned in Tables 2 apply power control schemes to FAP or FUE. Most of the techniques such as those presented in [66], [80] - [82] use *self-organizing capability* to acquire required information to provide better femtocell power control. However, they differ in the granularity of information sensed from the surround RF environment. For example, in [66], femtocell location is used to calculate the transmit power of the FAP, which can be achieved during the activation of the femtocell by the MBS through the DSL backhaul connection. Downlink RSRP from the nearest MBS and uplink reception/interference power from FUE and MUE are used to adjust FAP and FUE power in [80, 81]. In [82], RF measurement information such as RSSI is used to provide power adjustment for both downlink and uplink directions. The works in [83,

***Table 2:*** *Summary of Power Allocation Techniques*

| Publication | Interference Scenario | Spectrum Allocation/Access Method | Sensing Information | Approach | Remark |
|---|---|---|---|---|---|
| Arulselvan et al. [66] | Downlink: FAP to MUE | Co-channel / Closed | Uses femtocell location information and required bit rates computed locally based on macrocell load, number of active FAPs, distance of FAP to MBS, and fading environment | FAP data channel power is controlled distributively based on the knowledge of femtocell location (geo-static scheme) and based on constraint of targeted bit rates (adaptive power control) | FAP power is increased (decreased) based on MUE distance from FAP and required bit rate constraint |
| Morita et al. [80] | Downlink: FAP to MUE | Co-channel / Closed | Uses DL co-channel RSRP from the strongest MBS and UL reception power form neighboring MUE to calculate path loss and penetration loss | Adaptively controls FAP power setting based on the estimated penetration loss | FAP power is increase (decrease) if the penetration loss is high (small). |
| Jo et al. [81] | Uplink: FUE to nearby MBS | Co-channel / Closed | Uses DL signal power and effective isotropic transmit power of MBS to calculate the path loss and uplink interference power from MUE and FUE to calculate the noise and interference (NI) level | The FUE uplink power is adjusted by limiting the cross-tier interference to MBS to predetermined allowable level (open loop) and also combining NI level at the MBS (closed loop) | Closed loop technique provide better throughput for FUE than open loop with minimal degradation to macrocell throughput |
| Yavuz et al. [82] | Downlink: FAP to MUE/FAP and Uplink: FUE/MUE to FAP | Co-channel / Closed. | Uses RF measurement information such as received signal strength indicator (RSSI) for interference mitigation | Downlink: Multiple carrier selection and FAP transmit power self calibration based on path loss, link budget, QoS constraint is used<br>Uplink: Adaptive attenuation at FAP and limiting FUE transmit is proposed | More stable RF environment sensing is achieved using feedback of FUE and MUE measurements to FAP |
| Chandrasekhar et al. [83] | Uplink | Co-channel / Closed | Not mentioned | A utility based SINR adaptation is used to form per-tier SINR contour such that SINR equilibrium (Nash Equilibrium) is achieved which limits the increase in transmit power of any strong interfering femtocells | Distributive algorithm is proposed to progressively reduce the SINR target of the strongest interfering femtocell when the utility based SINR adaptation fails to provide the target macrocell SINR |
| Hong et al. [84] | Downlink: FAP to MUE and neighboring FAPs | Co-channel / Closed | Not mentioned | A non-cooperative game model is formulated to fairly assign FAP transmit power distributively based on revenue/cost payoff function | The best response power selected by each FAP considering the interference power from other femtocells to maximize its payoff function will always converge to an Nash Equilibrium |

84] use game theoretic approach to resolve the cross-tier interference in two-tier network. However, [83] focuses on achieving SINR equilibria distributively at FAP, whereas [84] focuses on providing fairness among the femtocell users.

*C. Joint Power and Spectrum Allocation Techniques*

A simple joint power and spectrum allocation scheme is suggested by 3GPP [86], where power control is applied jointly with spatial resource reuse such as overlapping carrier [47]. For multiple carrier allocation, the MUE near to femtocell uses orthogonal frequency, whereas the MUE far from femtocell uses all the available carrier frequencies. The downlink interference from far MUE is avoided by reducing the transmit power of that particular carrier, which is used by femtocell. Furthermore, in [87, 88], soft frequency reuse (SFR) method is proposed to provide better spectrum utilization. SFR follows the concept of FFR such that the frequency is allocated differently in cell edge and cell center. Both cell edge and cell center bands are made orthogonal to avoid interference from adjacent cells and also from the cell edge users to cell center users. The transmit power is adjusted such that cell center users transmit lower power to limit the interference.

The work in [89] provides an analytical framework for joint power control and channel reallocation scheme to maintain the QoS requirement of MUE, especially in the dead zone. In the context of macro-femto network with co-channel deployment, an optimization problem for distributed downlink power control is formulated, with a silencing scheme (similar to that proposed in 3GPP R1-102430 [74]) to mitigate the cross-tier interference. The objective is to maximize the energy efficiency of FAPs by suppressing the interference to both the MUEs and FUEs while guaranteeing the target QoS of both users. The QoS for both users is measured in terms of their received SINR. The feasibility condition of the power control problem is derived for single and multiple femtocell scenarios such that the optimal transmit power of the FAP is achieved, if there is a feasible solution. If the power control problem is not feasible (i.e., femtocell power is still interfering), then the proposed algorithm requests the interfering FAP to switch channel and the feasibility check is performed again. However, in any worst case that the feasibility solution does not exist, the proposed algorithm tries to silence the interfering FAP to meet the required QoS of MUE. Also, in [82], downlink femtocell carrier selection and femtocell downlink transmit power calibration techniques are proposed to mitigate the downlink interference caused by closed-access UMTS femtocells to the macrocell users. A self calibrating adjustable algorithm is proposed where the FAP transmit power is determined based on the measurement of the *received signal strength indicator (RSSI)* from other MBS and FAP. It is shown that depending upon the number of registration attempts by MUE, the FAP transmit power can be reduced to limit the interference to the MUE.

In [90], another distributed dynamic spectrum allocation and power allocation algorithm is proposed to minimize the downlink interference suffered by MUEs and FUEs. The dynamic spectrum allocation scheme is applied to the femtocell users, whereas power allocation scheme is applied to both macrocell and femtocell. An optimization model is formulated for which a near-optimal solution is obtained by utilizing the time-sharing property. Both the femtocell and macrocell downlink interference is considered in finding the optimal channel access for FUEs and power allocation vectors for MUEs and FUEs. By neglecting the co-tier femtocell interference, the optimization problem is made simpler such that the transmit powers of MBS and FAPs for MUEs and FUEs are only dependent on their access channels. The constraints of target SINRs of MUE and FUE receivers and tolerable MUE and FUE interference levels are considered. A similar approach is followed in [91], where an optimization problem is formulated to maximize the weighted sum rate of multiple OFDMA femtocell users. The proposed algorithm jointly allocates subchannels, rate, and power resources to FAPs, which are subject to interference and rate constraints of MUEs. However, co-tier interference between femtocells is not considered in the interference threshold. By using the Lagrangian dual decomposition, the power and subchannel are allocated with prices. Thus, by adjusting these prices, the transmit power of the FAP can be coordinated for each subchannel. The MBS increases the price of subchannel if the macrocell interference exceeds a threshold, thus reducing the resource used by femtocell. Otherwise, MBS will reduce the price to allow the femtocell to use more resource.

However, the proposed schemes in [90, 91] do not consider the co-tier femtocell interference that may increase the complexity of the algorithm as the number of femtocells and the number of channels increase. To characterize this interference, a similar approach is proposed in [92] to mitigate the co-tier femtocell interference in dense environment by using centralized joint power and subchannel allocation scheme. Even though the distributed scheme is simpler and more practical, the centralized scheme is more efficient for optimizing system performance. Moreover, 3GPP femtocell architecture also considers coordinated multi-point transmission/reception, which can be categorized as centralized node. An optimization problem is formulated to maximize the system capacity, which is the sum of capacity of all links. The underlined idea is to allow each FUE to choose an appropriate FAP as a serving node based on the average received signal strength. Then, FAPs allocate power based on each allocation scheme. The formulated non-convex optimization problem is solved using power allocation and subchannel allocation sub-problems. The power allocation sub-problem is solved first assuming that the subchannel allocation is known by the respective FAPs for which the solution is found to be binary power allocated (BPA). Then, the subchannel allocation sub-problem is solved assuming that the power is allocated in a BPA form. The solution of this problem provides the best FAP to transmit and the best FUE to receive signal for each subchannel. The work in [93] provides a distributed power control and scheduling algorithm to control FAP downlink transmit power in OFDMA femtocell to minimize femtocell co-tier interference. The FAP transmit power is minimized with constraint of individual rate and power of a user. The optimal power level on each subchannel is determined by exploiting the multiuser diversity of OFDMA, thus acquiring the link gains from the serving FAP and also from the interfering FAPs. By using cooperative relaying, the same link gain information is distributed among all the common users within their enclosed coverage area. Based on this information, each FAP tries to find a feasible transmit power on each subchannel by solving the power optimization problem. If the optimal solution exists, then that power level is used by the FAP on each subchannel. However, if FAP fails to achieve the link gain information, a heuristic algorithm is proposed to determine the admissible subsets of users on each subchannel by deferring the transmission of the users causing high interference. The high interfering user is assumed to be the one with the lowest nominal SINR which is calculated locally. The high interfering power level is eliminated by the scheduling algorithm, thus providing suboptimal solution that is proved to be close to global optimal solution (with global link information).

Similarly, in [94], two optimization problems (called MaxPwr and MaxCap) are formulated to maximize the sum of FAP transmit power and its associated capacity. Beside optimizing the power and spectrum allocation of each FAP, the proposed scheme also provides the optimal FAP-to-FUE association pair. A centralized resource management is assumed which collects the required information for network optimization for a Korean version of mobile WiMAX called WiBro [95]. The proposed optimization is subject to the constraint of indoor coverage and interference caused by FAP to outside MUE. The MaxPwr maximizes the sum of FAP transmit power, whereas MaxCap maximizes the femtocell capacity based on specific limited SINR degradation to MUE. Both optimization problems complement each other such that femtocell maintains enough coverage without degrading the transmission of nearby MUE. Similarly, the work in [96], provides a game-theoretical approach to design decentralized strategies for an OFDM femtocell system. In this case, FAPs compete against each other to obtain the optimal spectrum allocation under the constraint on maximum interference to MUEs. The proposed decentralized strategies allow each player (here FAP) to optimize its own opportunistic throughput (payoff) based on the channel information subject to detection threshold and vector power allocation jointly. Moreover, the proposed approach is also generalized for the case where the channel is not known exactly (e.g., due to channel estimation errors). It is shown that adding a proper pricing term for each user's utility function can prevent greedy behavior among two FUEs for occupying the whole bandwidth. The pricing term increases with the fraction of bandwidth usage such that the one occupying larger bandwidth pays more as penalty.

### *D. Self-Organizing Capability*

Due to random and distributed nature of femtocell deployment, conventional cellular configuration and optimization techniques may not be suitable to adjust the femtocell network parameters (e.g., transmit power and frequency allocation). Therefore, it becomes necessary to include appropriate sensing capabilities in FAP so that FAP can automatically observe the radio environment and perform self-organization of radio parameters [3, 81, 97, 98]. Technically, self-organization is the ability of the system to configure itself to perform certain functionality without any external supervision or central dedicated control entity [99]. The main characteristic of self-organized system is that each entity operates based only on the local information retrieved from other entities in the vicinity. The self-organization capability has been regarded as one of the prerequisites for the femtocell network and there are many researches which acknowledge its necessity (e.g., [48, 58, 66, 80, 82, 93]) discussed in subsections 3-A, 3-B, and 3-C. Therefore, self-organization plays an important role in femtocell networks including self-configuration in initial state, self-optimization in operational state and self-healing in case of failure of network element, thus reducing the overall operational and capital expenditure cost [97].

In the following, we provide the insight and importance of self-organization capability for the self-optimization of the femtocell networks. For instance, a recent work in [100] provides a simple method for self-configuring the femtocell to recognize the network environment. The proposed algorithm highlights the need of sensing the radio environment information which should be properly processed to set its initial power, frequency allocation and the optimum location inside the building to maintain optimum operation. To further refine the coverage of femtocell, the implementation of self-optimization approach based on the collected information from the FUEs and MUEs is proposed. To achieve the femtocell's self-configuration and self-optimization, a low cost 6-element antenna solution is proposed. It is shown that self-configuration approach can optimize the coverage and reduce interference at the same time.

In [64], a self-optimization scheme for frequency planning in the context of OFDMA femtocells is proposed. It is shown that OFDMA femtocells are capable of facilitating the deployment of such self-organization mechanisms. On the other hand, [101] presents a self-optimization coverage coordination scheme for CDMA femtocell that adjusts the FAP pilot power based on the mobility events of the passing-by MUEs, and also from FUEs. For initial configuration, measurement based auto-configuration is used where the initial pilot power is measured using the built-in measurement capability of the FAP. For self-optimization of reducing the excessive mobility signaling, the FAP counts the number of mobility events and classifies them into wanted and unwanted events over time. The pilot power is adjusted accordingly. A similar self-optimization coverage coordination scheme is proposed in [98] based on the statistics of the signal and interference power measured at a femtocell downlink to prevent any unnecessary mobility event in advance. As opposite to the scheme based on the mobility events, the proposed scheme uses the interference power from other neighboring macrocells and femtocells to continually adjust the transmit power of FAP so that it does not leak into the surrounding while sufficiently providing the femtocell coverage. For this, an analytical expression for the coverage leakage probability of the femtocell is derived, which is verified by simulation.

Similarly, a self organized uplink power control is proposed in [81] to mitigate the cross-tier interference in femtocell networks. Although the power control scheme helps to mitigate the interference issues in femtocell network, it is hard for macrocell users to detect a macrocell BS in vicinity. In [102], a new preamble structure for the IEEE 802.16e (WiMAX) based femtocell is proposed which enables the macrocell users to detect the macrocell BS even though they are located very close to the FAPs. For this, a self-initialization algorithm is proposed. At first, the FAP adjusts its transmit power based on the coverage of femtocell and the received power from the macrocell. This received power is determined by the distance between the macrocell and femtocell. The power control method is similar to that in [106]. As OFDMA is used, the subcarriers of the preamble are allocated according to the cell specific segment. Each segment uses a set of preambles which should be unique to avoid interference. However, there might be high probability of using the same segment as the neighboring femtocells which may cause performance degradation in femtocell search. To overcome this, the punctured preamble is proposed where the existing preamble is punctured into predetermined manner resulting in virtual segment of existing segments. Thus, femtocell using different virtual preambles in the same segment makes two subsegments which do not interfere with each other. Once the power is allocated, the femtocell measures the energy of each segment and the subsegment with the least power is selected as the femtocell segment. Then the femtocell selects the preamble based on cross-correlation between the received signal and the femtocell.

Similarly, in [97], a framework based on self-organization jointly self-optimizes the spectrum assignment and the transmit power in the context of downlink OFDMA femtocell deployments. The self-optimization is performed based on user's reported measurements of interference from other femtocells and macrocells. The measurement reports are collected by users using an uplink control channel which is used to estimate the channel status and cell status. For self-organization capability, two time-scale perspective called short-term and medium-term is considered. In the short-term period, the FAP performs packet scheduling and link adaptation to exploit multi-user diversity, whereas, in medium-term period, each FAP executes a self-optimization algorithm to determine suitable spectrum and transmit power assignment for the femtocell depending upon other cell's perceived interference. For spectrum assignment, the self-optimization algorithm selects random subchannels according to the interference perceived by its users. Once the spectrum assignment is decided, the transmit power is adjusted such that the average SINR is maintained at a certain predefined threshold. It is shown that the proposed low complexity self-optimization framework using simple inclusion of autonomous and adaptive mechanism can improve overall spectral efficiency and also reduce the interference.

### *E. Power Saving Mechanisms*

In recent years, the rising energy cost coupled with increased awareness in energy conservation has resulted in many efforts in reducing the use of energy (i.e., improving energy efficiency). In this regard, it has been shown that open access femtocells deployment in conjunction with macrocell can decrease the total network energy consumption by up to 60% [113]. The reason is that most of the traffic load is shared by femtocell, which eventually reduces the macrocell's energy consumption. In addition, the energy consumption of femtocell is paid by the customers, which in turn reduces the network cost for the operators. However, assuming that each femtocell at least consumes a power of 12 W (e.g., 105.12 kWh/year) [114], increase in femtocell deployment will have negative impact on the overall energy consumption such that the contribution of the femtocell to the total energy consumption increases linearly with the increase in femtocell deployment [113]. Thus, efficient methods are required to reduce the energy consumption while maintaining the core benefits and functionality of femtocells.

In [114, 116], a femtocell driven dynamic idle mode procedure for reducing the adaptive femtocell energy consumption is proposed. The proposed procedure allows the individual FAP to completely switch off its radio transmission and associated processing in idle mode, while keeping the femtocell to core network connection alive. However, switching the femtocell pilot transmission on and off introduces additional core network signaling overhead due to macrocell-to-femtocell handover initiated when a registered femtocell user tries to make a call. To mitigate this effect, core-network-driven and user-equipment-driven approaches are proposed in [115]. In the case of core network driven approach, the core network sends wake-up control message to control the idle/active mode of the FAP using the backhaul connection. This method helps to provide centralized decision not only based on particular mobile but also taking into account the macrocell traffic behavior, user subscription, and user's location information. However, this approach also incurs additional control signal over the backhaul to wake up the femtocell. On the contrary, in the case of user-equipment-driven approach, the mobile equipment is allowed to broadcast the wake-up signal in an on-demand basis (e.g., in an absence of sufficient macrocell coverage). This approach helps to activate the FAP without relying on the macrocell coverage.

## 4. PERFORMANCE ANALYSIS OF FEMTOCELL DEPLOYMENT

The performance analysis of femtocell provides an accurate characterization and understanding of complexity associated with the femtocell deployment. Based on the reviews of existing research works, we summarize some of the important key points and directions related to the performance analysis in this section.

Based on 3GPP TR 25.820 [103] under Release 8, the femtocell deployment typically depends upon the choice of spectrum policies (dedicated, co-channel, or orthogonal), access method (open, closed, or hybrid), and power allocation (fixed, adaptive, or controlled). Therefore, performance analysis to investigate the impact of these factors on the interference and capacity will be crucial for achieving optimal performance under specific conditions. For femtocell, capacity/throughput and coverage are the main aims of the analysis.

A recent work in [105] provides capacity and coverage analysis of femtocell network based on detailed indoor path loss model. The evaluation results indicate that the system performances of femtocell are significantly affected by the surrounding environments (e.g., wall structures, separation between macro and femtocell). This type of analysis would be beneficial in understanding the effect of outage probability, interference and bandwidth requirements on femtocell and macrocell networks, which can be used for femtocell network planning [42]. Depending upon the femtocell deployment criterion, we provide some of the insight directions and trends followed by many existing literatures.

### *A. Spectrum Allocation Policies (Dedicated or Co-channel)*

For femtocells, selection of spectrum access policies (using dedicated, co-channel, or recently orthogonal) has always been an important issue and focus of many works. According to an analysis by Nokia Siemens Networks [40] on E-UTRA system with 10MHz system bandwidth, it is shown that macrocell capacity degradation depends entirely on the number of FAPs placed randomly inside the macrocell and spectrum policy used. An important observation in this experiment is that unlike co-channel deployment, dedicated channel deployment has negligible effect on macrocell capacity degradation. The reason for this is due to separate frequencies used. Dedicated channel deployment mostly eliminates potential interference from macrocell users, thus increasing the capacity for both users. However, dedicated channel deployment has the limitation due to the scarcity of available spectrum and high cost of the new spectrum licensing. Therefore, it is impractical following the current frequency reuse approach. Co-channel deployment, on the other hand, is more suitable due to the potentially significant increased spectral efficiency per area through spatial frequency reuse, but at the cost of co-channel interference [106]. Therefore, for successful co-channel deployment, the key issue remains as how to optimize the interference and available resources to ensure low impact on the performance of existing macro cellular network [40, 106].

Many works (e.g., [1, 44, 104, 106]) and standard bodies such as 3GPP have given significant attention to the managing and mitigating interference in co-channel deployment. Some of the key points of the performance analysis for using either co-channel or dedicated channel are highlighted below:

- To achieve theoretical femtocell capacity for both uplink and downlink, femtocell should be able to configure, provide open access, and provide certain power control strategies automatically. It is also recommended to adopt high-order modulation scheme such as 64-QAM in the future version of cellular standards (e.g., HSPA) [106].
- For dedicated channel deployment, optimal spectrum partitioning by limiting the femtocell

spectrum usage based on certain performance metrics (such as outage probability, capacity, and spatial throughput) can guarantee better QoS to both macrocell and femtocell users [42, 43], [45]-[51].
- For co-channel deployment, enforcing higher spatial reuse in the form of adaptive FFR schemes based on measurement of RF environment (e.g., channel state and path loss) rather than mixed spectrum allocation can achieve higher femtocell capacity [44], [57]-[61].
- Despite the cross-tier interference, the higher spectrum utilization and throughput associated with co-channel deployment makes it better contender for spectrum allocation [104], [54]-[64].

Based on these key points and discussions by several works in literature (e.g., [1, 44, 104, 106]), it can be concluded that the increase in bandwidth gained from co-channel deployment and/or providing better interference avoidance strategy can reduce the interference, thus making co-channel deployment a viable approach in practical femtocell networks.

*B. Access Method (Open, Closed, or Hybrid)*

The choice for femtocell access scheme must be carefully adopted. The selection of access scheme depends on the interference as well as the adaptation of customer and the network operators. Based on various research literature, some key points for selecting the appropriate access scheme are given below:
- For private and home usage, closed access femtocell with dedicated channel deployment provides better QoS and higher return of investment to the customers.
- The underlying interference is mostly caused by closed access with co-channel deployment which can be mitigated to some extent using OFDMA approach [14].
- For commercial or public usage, open access femtocell with either deployment provides better reduction in interference which is beneficial to operators as it increases their coverage and capacity without any additional cost [21, 40, 44, 103, 104, 107].
- For open access co-channel deployment, spectrum usage can be increased by taking into account the available bandwidth, interference caused, link quality [107] and the instantaneous load of the network [108] that can reduce the interference.
- Hybrid access scheme which limits the open access to macrocell users and minimizes the femtocell resource loss is more beneficial than complete closed access or open access scheme [12, 13, 103, 107].

Based on these analysis, hybrid scheme seems to be preferable in many ways. However, it still requires further detailed analysis [107]. Despite the inheriting issues, the choice of specific access scheme (i.e., closed, open, or adaptive) depends upon the specific configuration of femtocell, nearby macro base stations, and location of mobile stations, and the required connectivity and throughput [108].

*C. Adaptive Power Allocation vs. Joint Power and Spectrum Allocation*

To address the interference issues related to co-channel, cross-tier and co-tier, power allocation strategy plays an important role. To guarantee femtocell deployment with minimum interference, the power radiation by FAPs must be tuned to ensure sufficient transmit power for femtocell coverage while minimizing the unnecessary power leakage. Thus, adaptive transmit power control instead of fixed power scheme is desirable where the FAP can adjust the transmit power based on the interference caused/received to/from the macrocell and other neighboring femtocells. Moreover, as discussed in subsections 3.combining both power and spectrum allocation techniques can result in even better interference mitigation solutions. Some of the key points for using either adaptive power control techniques or joint power and spectrum allocation techniques are highlighted below:
- For effective power control techniques, there is a need to standardize the FAPs self measurement capability such that transmit power can be controlled based on information about various system parameters (e.g., RSRP, RSSI, interference level, path loss, penetration loss and location) [68], [75]-[82], [106].
- More stable RF environment sensing can be achieved using feedback of FUE and MUE measurements to FAP [82].
- For joint power and spectrum allocation technique, power allocation should follow spectrum allocation such that optimal power is allocated to assigned subchannels [90]-[93].

## 5. OPEN RESEARCH ISSUES AND DIRECTIONS

In this section, the ongoing and possible future research directions for femtocell are outlined.

*A. Mobility Management*

The femtocell handover process, as in traditional cellular network, should be able to ensure seamless connectivity when user moves into or out of a femtocell. However, due to different backhaul network with no direct communication between the femtocell and macrocell, the femtocell handover is challenging problem. Moreover, frequency of handover depends on the nature of access method (e.g., higher handover in open access and comparably lower in closed and hybrid access schemes [29]). Three types of handover take place in femtocell, namely inbound (i.e., macrocell to femtocell), outbound (i.e., femtocell to macrocell) and femtocell to femtocell handover. Among these, the inbound handover (for open access) is more crucial as macrocell users passing by femtocell can experience an outage due to frequent handover to uncorrelated femtocells [1].

To overcome these issues, many handover techniques such as multiple carrier deployment [11], prediction of dwelling time before handing off the macrocell user to nearby femtocell [1], cooperative measurement to generate neighboring handoff list [30], and femtocell reselection cache scheme [31], are proposed as the solutions. In [32], intracell handover scheme is proposed for OFDMA femtocell using closed access scheme, which allows the non-subscriber (or macrocell users) to transfer from interfered channel to a clear or less-faded channel. In [33], an intermediate node is introduced to provide mobility management scheme for LTE femtocells. Similarly, different handover techniques for UMTS femtocell are also proposed in [34, 35]. For WiMAX femtocells, [36] proposes a probabilistic mobility prediction based on global positioning system (GPS) to identify the mobility pattern of the macrocell and femtocell users. Although femtocell coverage is small, the random deployment and consequently dense scenarios will create intra-cell handover which should be tackled properly to overcome call drops during handovers.

### B. Smart Antenna System for Femtocell

Due to prevailing interference issue in macro-femto network, using smart antenna in FAP can provide an alternative solution to avoid cross-tier interference. Smart antennas (also known as multiple input multiple output (MIMO)) are antenna arrays with intelligent signal processing algorithms that help to exploit the spatial diversity of the wireless channel. Smart antenna techniques are already used in cellular systems (e.g., W-CDMA and UMTS). MIMO spatial link adaptation will enable a femtocell to achieve high data rates and optimum coverage [1]. An initial investigation to provide possible antenna configuration that would be compatible with MIMO systems suitable for femtocell application is presented in [109]. A MIMO configuration of up to $6 \times 2$ antenna elements is modeled for this purpose. Similarly, in [110], femtocell coverage optimization is achieved using a simple switched multi-element antenna system. A low cost multi-element antenna prototype is built to generate a set of different gain patterns by simply switching between one or multiple antennas. Also, in [111], E-plane horns based reconfigurable directional antenna is used to reduce the two-tier interference and enhance the femtocell capacity. Further, in [112], femtocell based distributed antenna system (DAS) is proposed to reduce the co-channel interference introduced by frequency reuse among the femtocells, thus maintaining high spectral efficiency. To leverage the advantage of both femtocell and DAS, remote antenna units are deployed on each floor of the building such that they are connected to FAPs. Clearly, using smart antenna can provide necessary diversity in the transmitting signals that can restrict the radio interference within an antenna sector. However, for effective and smart antenna integration, maintaining low cost with easy end-user deployment is the key challenges faced by many femtocell vendors.

### C. Toward Cognitive Femtocells

Based on the access method and use of spectrum, femtocells exhibit a close correlation with the cognitive radio (CR) technology. The analogy lies in the fact that both CR and femtocell are introduced to achieve better capacity enhancements by means of various spectrum management and interference mitigation techniques. By considering the femtocell deployed by user as a secondary user (SU) and macrocell as primary user (PU), cognitive channel sensing capability of CR can be exploited to sense the radio usage of the macrocell network to mitigate any interference induced by the femtocell deployment [118–120]. For instance, in [118], cognitive sensing is used to identify the channel reuse pattern in OFDMA based femtocell to allocate low-interference spectrum to the femtocell users. The cognition capability is used to recognize the interference signature from the network so that the channels can be reused to avoid the interference to other femtocells. Similarly, in [121], the cognitive sensing capability is used to autonomously monitor the traffic load and radio resource allocation correlation probability of the macrocell users so as to allocate non occupied spectrum to the femtocell.

Despite CR underlying issues (e.g., sensing reliability, regulating policies, and susceptibility to interference), FAP equipped with CR capability can use multiple access schemes (i.e., multimode operation) and multi-operator service deployment, hence supporting a communication convergence [119, 120]. The convergence can provide diverse enhancements to conventional femtocell access facilities such as adaptive operation, higher throughput, better interference management, and flexible energy throughput trade-off [120]. Further, the cognitive capability can create different femtocell economic model by altering femotcells into more advanced entities. For example, native femtocell users can be provided with proper compensation by network operator for allowing service to its legacy users (i.e., non subscriber) depending upon how much the femtocell resource is allowed to be used by non-subscribers. A cognitive radio based femtocell architecture is proposed in [119, 120], which utilizes the CR capability to achieve better throughput using power allocation and dynamic spectrum access techniques. A more insight in various technical issues for cognitive femtocell deployment is summarized in [120]. Table 3 highlights some of advantages and the associated challenges related to cognitive femtocell. A cognitive femtocell architecture will minimize the underlying issues of both technologies [120].

*D. Hybrid of Resource Partitioning and Power Control*

As mentioned in subsection 3. the combination of spectrum allocation and power control schemes provide more effective interference mitigation solution to the two-tier networks. Specifically, the combination of resource partitioning and power control scheme has more potential than the co-channel counterpart. Resource partitioning mitigates interference not only on control channel but also on data channel between macrocell and femtocell since the resource for MBS and FAP is not overlapped. Although, it reduces the spectrum utilization, the complete interference avoidance provides a better solution to the resource management issues. Thus, hybrid scheme that combines the power control and resource partitioning (in all frequency/time/space domain) will be a promising solution for current and future standard activities.

## 6. CONCLUSION

Driven by need for better indoor coverage and higher data rates, femtocell stands as a cost effective alternative for both mobile operators and consumers. The two-tier interference issue is one of the biggest challenges faced by femtocell that is confronting with its successful deployment. This article has provided a comprehensive survey on the relevant research works relating to interference and radio resource management that could provide the basis for an effective solution. The future of femtocell will also depend upon the mobile operator's revenue model. With cost effective solutions and better interference management techniques, femtocell will soon be an important part of the current and future cellular and wireless broadband systems.

### References


[1] V. Chandrasekhar, J. Andrews, and A. Gatherer, "Femtocell networks: a survey," in *IEEE Communications Magazine*, vol.46, no.9, pp.59-67, Sep. 2008.

[2] Picochip, "The Case for Home Base Stations," in *White paper*, April 2007.

[3] H. Claussen, L. T. W. Ho, and L. G. Samuel, "An overview of the femtocell concept," in *Bell Labs Technical Journal - Next-Generation Wireline Access Networks*, Vol. 13, Issue 1, March 2008.

[4] S. F. Hasan, N. H. Siddique, and S. Chakraborty, "Femtocell versus WiFi - A survey and comparison of architecture and performance," in *1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE)*, pp.916-920, 17-20 May 2009.

[5] Airvana, "Femtocell Standardization," *White Paper*, Internet Access: `http://www.airvana.com/default/assets/File/WHITEPAPER-Femtocell\_Standardization.pdf`, May 2010.

[6] 3GPP Technical Specification 25.467, "UTRAN architecture for 3G home NodeB", in *3rd Generation Partnership Project Technical Specification Group Radio Access Network*, stage 2, Release 9, December 2008.

[7] D. Knisely, T. Yoshizawa, and F. Favichia, "Standardization of femtocells in 3GPP," in *IEEE Communications Magazine*, vol.47, no.9, pp.68-75, Sep. 2009

[8] D. Knisely, and F. Favichia, "Standardization of femtocells in 3GPP2," in *IEEE Communications Magazine*, vol.47, no.9, pp.76-82, Sep. 2009.

[9] RFC 4301, "Security Architecture for the Internet Protocol", December 2005.

[10] 3GPP2 X.S0059-0, "Femto Network Specification", February 2009.

[11] Qualcomm, "Femtocells - Architecture & Network Aspect," *White Paper*, Internet Access: `http://www.qualcomm.com/common/documents/white\_papers/Femto\_Overview\_Rev\_C.pdf`, January 2010.

[12] G. de la Roche, A. Valcarce, D. Lopez-Perez, and J. Zhang, "Access control mechanisms for femtocells," in *IEEE Communications Magazine*, vol.48, no.1, pp.33-39, January 2010.

[13] D. Lopez-Perez, A. Valcarce, G. de la Roche, and J. Zhang, "OFDMA femtocells: A roadmap on interference avoidance," in *IEEE Communications Magazine*, vol.47, no.9, pp.41-48, Sep. 2009.

[14] P. Xia, V. Chandrasekhar, and J. Andrews, "Open vs. Closed Access Femtocells in the Uplink," in *IEEE Transactions on Wireless Communications*, vol.PP, no.99, pp.1-12, 2010.

[15] 3GGP Release 9, Internet Access: `http://www.3gpp.org/Release-9`, Decemeber 2009.

[16] 3GPP TS 25.367, "Mobility Procedure for HNB," Internet Access: `http://www.3gpp.org/ftp/specs/html-info/25367.htm`.

[17] 3GPP TS 25.367, "UTRA RRC Protocol Specification," Internet Access: `ftp://ftp.3gpp.org/specs/html-info/36331.htm`.

[18] A. Golaup, M. Mustapha, L. B. Patanapongpibul, "Femtocell access control strategy in UMTS and LTE," in *IEEE Communications Magazine*, vol.47, no.9, pp.117-123, Sep. 2009.

[19] Kineto Wireless, "The Role of UMA in Mobile Network Evolution," *White Paper*, August 2006.

[20] Kineto Wireless, "The Case for UMA-Enabled Femtocells," *White Paper*, August 2006.

[21] S. P. Yeh, S. Talwar, S-C. Lee, and H. Kim, "WiMAX Femtocells: A Perspective on Network architecture, Capacity and Coverage," in *IEEE*

***Table 3:*** *Advantages and Challenges of Cognitive femtocell Architecture*

| **Advantages** | **Challenges** |
|---|---|
| Multiple access scheme and multi-operator service deployment for better spectrum utilization for the network operators | Requires FAP based on software defined radio architecture which can modify both firmware and application software for network requirement. Handsets with proper support for cognitive mode is necessary. |
| Minimization of femtocell interference due to better sensing capability | Requires reliable sensing capability which is still an open problem in CR communication. |
| Provision for new business models due to opportunistic spectrum access | Requires more practical and streamline business model to encourage femtocell users to share their resources. A basic charging model and service agreement should be defined for cognitive femtocell architecture. |
| Better network stability as primary network does not have to change | Requires fundamental changes in the RF front ends, signal processing circuits, protocol stacks to support the interoperability |

*Communications Magazine*, vol. 46, no. 10, pp. 58-65, October 2008.

[22] M. Neruda, J. Vrana, and R. Bestak, "Femtocells in 3G Mobile Networks," in *16th International Conference on Systems, Signals and Image Processing (IWSSIP)*, pp.1-4, 18-20 June 2009.

[23] T. Villa, R. Merz, and P. Vidales, "Performance evaluation of OFDMA femtocells link-layers in uncontrolled deployments," in *European Wireless Conference (EW)*, pp.825-832, 12-15 April 2010.

[24] S. Huan, K. Linling, and L. Jianhua, "Interference avoidance in OFDMA-based femtocell network," in *IEEE Youth Conference on Information, Computing and Telecommunication (YC-ICT)*, pp.126-129, 20-21 Sep. 2009.

[25] WiMAX Forum, Internet: `http://www.wimaxforum.org/`, Access: Nov 2010.

[26] IEEE 802.16 Broadband Wireless Access Working Group, "IEEE 802.16m System Description Document [Draft]," IEEE 802.16m 08/003r1, 2009.

[27] Q. Kalhoro, M. A. Kalhoro, S. Abbasi, K. Khoumabti, "Analysis of femtocells deployment with different air-interfaces," in *12th International Conference on Computer Modelling and Simulation (UKSim)*, pp.439-443, 24-26 March 2010.

[28] V. Chandrasekhar, and J. Andrews, "Spectrum allocation in tiered cellular networks," in *IEEE Transactions on Communications*, vol.57, no.10, pp.3059-3068, October 2009.

[29] A. Valcarce, D. Lopez-Perez, G. De La Roche, and J. Zhang, "Limited access to OFDMA femtocells," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.1-5, 13-16 Sep. 2009.

[30] K. Han, S. Woo, Duho Kang, and S. Choi, "Automatic neighboring BS list generation scheme for femtocell network," in *Second International Conference on Ubiquitous and Future Networks (ICUFN)*, pp.251-255, 16-18 June 2010.

[31] H-Y. Lee, and Y-B. Lin, "A cache scheme for femtocell reselection," in *IEEE Communications Letters*, vol.14, no.1, pp.27-29, January 2010.

[32] D. Lopez-Perez, A. Valcarce, A. Juttner, and J. Zhang, "OFDMA Femtocells: Intracell Handover for Interference and Handover Mitigation in Two-Tier Networks," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, April 2010.

[33] L. Wang, Y. Zhang, and Z. Wei, "Mobility Management Schemes at Radio Network Layer for LTE Femtocells," in *IEEE 69th Vehicular Technology Conference*, pp.1-5, 26-29 April 2009.

[34] M. Z. Chowdhury, R. Won, R. Eunjun, and J. M. Yeong, "Handover between macrocell and femtocell for UMTS based networks," in *11th International Conference on Advanced Communication Technology*, vol.01,pp. 237-241, 15-18 February 2009.

[35] K. Jin-Seok, and L. Tae-Jin, "Handover in UMTS networks with hybrid access femtocells," in *12th International Conference on Advanced Communication Technology*, pp. 904-908, 7-10 February 2010.

[36] C-J. Huang, P-C. Chen, C-T. Guan, J-J. Liao, Y-W. Lee, Y-C. Wu, I-F. Chen, K-W. Hu, H-X. Chen, and Y-J. Chen, "A Probabilistic Mobility Prediction Based Resource Management Scheme for WiMAX Femtocells," in *International Conference on Measuring Technology and Mechatronics Automation (ICMTMA)*, vol.1, pp.295-300, 13-14 March 2010.

[37] N. Shetty, S. Parekh, and J. Walrand, "Economics of Femtocells," in *IEEE Global Telecommunications Conference*, pp.1-6, November 2009.

[38] Femto-Forum, Internet access: `http://www.femtoforum.org/femto/`.

[39] FemtoForum, "Interference Management in UMTS femtocells," *White Paper*, Internet: `http://www.femtoforum.org/femto/Files/File/Interference\%20Management\%20in\%20UMTS\%20Femtocells.pdf`, December 2008.

[40] Nokia Siemens Networks, "Initial home nodeB coexistence simulation results," in *3GPP TSG-RAN WG4 R4-070902*, June 2007.

[41] K. Cho, W. Lee, D. Yoon, K, Hyu, and Y-S. Choi, "Resource alloation for orthogonal and co-channel femtocells in a hierarchical cell structure," in *IEEE 13th International Symposium on Consumer Electronics*, pp.655-656, 25-28 May 2009.

[42] Y. Kim, S. Lee, and D. Hong, "Performance analysis of two-tier femtocell networks with outage constraints," *IEEE Transactions on Wireless Communications*, vol. 9, no. 9, pp. 2695-2700, September 2010.

[43] Y. Zhang, "Resource Sharing of Completely Closed Access in Femtocell Networks," in *IEEE Wireless Communications and Networking Conference (WCNC)*, pp.1-5, 18-21 April 2010.

[44] V. Chandrasekhar and J. Andrews, "Uplink capacity and interference avoidance for two-tier femtocell networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, pp. 3498-3509, July 2009.

[45] 3GPP R1-101924, "Macro+HeNB performance with escape carrier of dynamic carrier selection," in *3GPP RAN1 Meeting, Beijing, China*, April 2010.

[46] 3GPP R1-103497, "DL Interference Mitigation via Direction Information in Het-Net," in *3GPP RAN1 Meeting, Dresden, Germany*, June 2010.

[47] 3GPP R1-101123, "Performance of indoor HeNB(CSG) Deployment and Technical Aspects Observations," in *3GPP RAN1 Meeting, San Francisco*, February 2010.

[48] M. Andrews, V. Capdevielle, A. Feki, and P. Gupta, "Autonomous Spectrum Sharing for Mixed LTE Femto and Macro Cells Deployments," in *INFOCOM IEEE Conference on Computer Communications Workshops*, pp.1-5, 15-19 March 2010.

[49] 3GPP R1-103685, "Performance evaluation of dynamic Home eNB ICIC function based on time domain silencing," in *3GPP RAN1 Meeting, Dresden, Germany*, June. 2010.

[50] X. Chu, Y. Wu, L. Benmesbah, W-K. Ling, "Resource Allocation in Hybrid Macro/Femto Networks," in *IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, pp.1-5, 18-18 April 2010.

[51] C. Lee, J-H. Huang, and L-C. Wang, "Distributed Channel Selection Principles for Femtocells with Two-Tier Interference," in *IEEE 71st Vehicular Technology Conference (VTC)*, pp.1-5, 16-19 May 2010.

[52] K. Begain, G. I. Rozsa, A. Pfening, and M. Telek, "Performance analysis of GSM networks with intelligent underlay-overlay," in *Proceedings of Seventh International Symposium on Computers and Communications (ISCC)*, pp. 135-141, Jul. 2002.

[53] M. Rahman, H. Yanikomeroglu, and W. Wong, "Interference Avoidance with Dynamic Inter-Cell Coordination for Downlink LTE System," in *IEEE Wireless Communications and Networking Conference,(WCNC)*, pp. 1-6, Apr. 2009.

[54] P. Lee, T. Lee, J. Jeong, and J. Shin, "Interference management in LTE femtocell systems using Fractional Frequency Reuse," in *The 12th International Conference on Advanced Communication Technology (ICACT)*, vol. 2, pp. 1047-1051, Feb. 2010.

[55] R-T. Juang, P. Ting, H-P. Lin, and D-B. Lin, "Interference management of femtocell in macro-cellular networks," in *Wireless Telecommunications Symposium (WTS)*, pp.1-4, 21-23 Apr. 2010.

[56] H-C. Lee, D-C. Oh, and Y-H. Lee, "Mitigation of Inter-Femtocell Interference with Adaptive Fractional Frequency Reuse," in *IEEE International Conference on Communications (ICC)*, pp.1-5, 23-27 May 2010.

[57] R. An, X. Zhang, G. Cao, R. Zheng, and L. Sang, "Interference Avoidance and Adaptive Fraction Frequency Reuse in a Hierarchical Cell Structure," in *IEEE Wireless Communications and Networking Conference (WCNC)*, pp.1-5, 18-21 Apr. 2010.

[58] M. Z. Chowdhury, Y. M. Jang, and Z. J. Haas, "Interference mitigation using dynamic frequency re-use for dense femtocell network architectures," in *Second International Conference on Ubiquitous and Future Networks (ICUFN)*, pp.256-261, 16-18 Jun. 2010.

[59] I. Guvenc, M-R. Jeong, F. Watanabe, and H. Inamura, "A hybrid frequency assignment for femtocells and coverage area analysis for co-channel operation," in *IEEE Communications Letters*, vol.12, no.12, pp.880-882, Dec. 2008

[60] Y. Bai, J. Zhou, L. Liu, L. Chen, and H. Otsuka, "Resource coordination and interference mitigation between macrocell and femtocell," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.1401-1405, 13-16 Sep. 2009.

[61] Y. Bai, J. Zhou, and L. Chen, "Hybrid spectrum sharing for coexistence of macrocell and femtocell," in *IEEE International Conference on Communications Technology and Applications (ICCTA)*, pp.162-166, 16-18 October 2009.

[62] H. Li, X. Xu, D. Hu, X. Qu, X. Tao,

and P. Zhang, "Graph Method Based Clustering Strategy for Femtocell Interference Management and Spectrum Efficiency Improvement," in *6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM)*, pp.1-5, 23-25 Sep. 2010.

[63] J. Espino, and J. Markendahl, "Analysis of macro – femtocell interference and implications for spectrum allocation," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.2208-2212, 13-16 Sep. 2009.

[64] D. Lopez-Perez, A. Valcarce, G. De La Roche, E. Liu and J. Zhang, "Access methods to WiMAX femtocells: A downlink system-level case study," in *11th IEEE Singapore International Conference on Communication Systems (ICCS)*, pp.1657-1662, 19-21 November 2008.

[65] 3GPP R1-103155, "Downlink ICIC in heterogeneous networks," in *3GPP RAN1 Meeting, Montreal, Canada*, May, 2010.

[66] N. Arulselvan, V. Ramachandran, S. Kalyanasundaram, G. Han, "Distributed Power Control Mechanisms for HSDPA Femtocells," in *IEEE 69th Vehicular Technology Conference (VTC)*, pp.1-5, 26-29 April 2009.

[67] I. Ashraf, H. Claussen, and L. T. W. Ho,"Distributed Radio Coverage Optimization in Enterprise Femtocell Networks," in *IEEE International Conference on Communications (ICC)*, pp.1-6, 23-27 May 2010.

[68] 3GPP R1-101506, "Importance of Serving Cell Selection in Heterogeneous Networks," in *3GPP RAN1 Meeting, San Francisco, CA USA*, February 2010.

[69] 3GPP R1-105712, "Pico cell range expansion in Macro-Pico scenario," in *3GPP RAN1 Meeting, Xi'an, China*, October 2010.

[70] 3GPP R1-105552, "Discussion of Pico Node Range Extension Benefits," in *3GPP RAN1 Meeting, Xi'an, China*, October 2010.

[71] 3GPP R1-102111, "Outdoor Hotzone Cell Performance: A Cell Selection Analysis," in *3GPP RAN1 Meeting, Beijing, China*, April 2010.

[72] 3GPP R1-103181, "On Range Extension in Open-access Heterogeneous Networks," in *3GPP RAN1 Meeting, Montreal, Canada*, May 2010.

[73] 3GPP R1-104126, "FDM Range Extension in Open-access Heterogeneous Networks," in *3GPP RAN1 Meeting, Dresden, Germany*, May 2010.

[74] 3GPP R1-102430, "Extending Rel-8/9 ICIC for heterogeneous networks," in *3GPP RAN1 Meeting, Beijing, China*, April 2010.

[75] 3GPP R1-103838, "Adjustable HeNB power setting in MeNB-HeNB deployment," in *3GPP RAN1 Meeting, Dresden, Germany*, June 2010.

[76] 3GPP R1-104463, "Autonomous Power Setting for HeNB Cells," in *3GPP RAN1 Meeting, Madrid, Spain*, August 2010.

[77] 3GPP R1-105238, "Further discussion on HeNB downlink power setting in HetNet," in *3GPP RAN1 Meeting, Xi'an, China*, October 2010.

[78] 3GPP R1-106052, "Per Cluster Based Opportunistic Power Control," in *3GPP RAN1 Meeting, Jacksonville, USA*, November 2010.

[79] M. S. Jin, S. Chae, and D. I. Kim, "Per Cluster Based Opportunistic Power Control for Heterogeneous Networks," in *Proceeding in IEEE VTC 2011*, May 2011.

[80] M. Morita, Y. Matsunaga, and K. Hamabe, "Adaptive Power Level Setting of Femtocell Base Stations for Mitigating Interference with Macrocells," in *IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall)*, pp.1-5, 6-9 Sept 2010.

[81] H-S. Jo, C. Mun, J. Moon, and J-G. Yook, "Interference mitigation using uplink power control for two-tier femtocell networks," in *IEEE Transactions on Wireless Communications*, vol.8, no.10, pp.4906-4910, October 2009.

[82] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariyal, N. Johnson, B. Raghothaman, and A. Richardson, "Interference management and performance analysis of UMTS/HSPA+ femtocells," in *IEEE Communications Magazine*, vol.47, no.9, pp.102-109, Sep. 2009.

[83] V. Chandrasekhar, J. G. Andrews, T. Muharemovic, Z. Shen, and A. Gatherer, "Power control in two-tier femtocell networks," in *IEEE Transactions on Wireless Communications*, vol.8, no.8, pp.4316-4328, August 2009.

[84] E. J. Hong, S. Y. Yun, and D-H. Cho, "Decentralized power control scheme in femtocell networks: A game theoretic approach," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.415-419, 13-16 Sep. 2009.

[85] 3GPP R1-103836, "Comparison of control channel protection schemes in MeNB-HeNB deployment," in *3GPP RAN1 Meeting, Dresden, Germany*, June 2010.

[86] 3GPP R1-101369, "Considerations on interference coordination in heterogeneous networks," in*3GPP RAN1 Meeting, San Francisco, USA*, February 2010.

[87] 3GPP R1-101875, "HetNet R8/9 Data Channel Performance," in *3GPP RAN1 Meeting, Beijing, China*, April 2010.

[88] 3GPP R1-101391, "Interference Coordination for HetNet with One or Multiple Component Carriers," in *3GPP RAN1 Meeting, San Francisco, USA*, February 2010.

[89] X. Li, L. Qian, and D. Kataria, "Downlink power control in co-channel macrocell femtocell overlay," in *43rd Annual Conference on Information*

*Sciences and Systems (CISS)*, pp.383-388, 18-20 March 2009.

[90] Q. Su, A. Huango, Z. Wu, G. Yu, Z. Zhang, K. Xu, and J. Yang, "A distributed dynamic spectrum access and power allocation algorithm for Femtocell networks," in *International Conference on Wireless Communications & Signal Processing (WCSP)*, pp.1-5, 13-15 November 2009.

[91] J. Zhang, Z. Zhang, K. Wu, A. Huang, "Optimal Distributed Subchannel, Rate and Power Allocation Algorithm in OFDM-Based Two-Tier Femtocell Networks," in *IEEE 71st Vehicular Technology Conference (VTC)*, pp.1-5, 16-19 May 2010.

[92] J. Kim, and D-H. Cho, "A joint power and subchannel allocation scheme maximizing system capacity in dense femtocell downlink systems," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.1381-1385, 13-16 Sep. 2009.

[93] T. Akbudak, and A. Czylwik, "Distributed power control and scheduling for decentralized OFDMA networks," in *International ITG Workshop on Smart Antennas (WSA*, pp.59-65, 23-24 February 2010.

[94] K. Han, Y. Choi, D. Kim, M. Na, S. Choi, and K. Han, "Optimization of femtocell network configuration under interference constraints," in *7th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, (WiOPT)*, pp.1-7, 23-27 June 2009.

[95] D-Y. Kwak, J-S. Lee, Y. Oh, and S-C. Lee, "Development of WiBro (Mobile WiMAX) Femtocell and Related Technical Issues," in *IEEE Global Telecommunications Conference (GLOBECOM)*, pp.1-5, 4 Dec 2008.

[96] S. Barbarossa, S. Sardellitti, A. Carfagna, and P. Vecchiarelli, "Decentralized interference management in femtocells: A game-theoretic approach," in *Proceedings of the Fifth International Conference on Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM)*, pp.1-5, 9-11 June 2010.

[97] F. Bernardo, R. Agustí, J. Cordero, and C. Crespo, "Self-Optimization of Spectrum Assignment and Transmission Power in OFDMA Femtocells," in *Sixth Advanced International Conference on Telecommunications (AICT)*, pp.404-409, 9-15 May 2010.

[98] H-S. Jo, C. Mun, J. Moon, and J-G. Yook, "Self-Optimized Coverage Coordination in Femtocell Networks," *IEEE Transactions on Wireless Communications*, vol.9, no.10, pp.2977-2982, October 2010.

[99] C. Prehofer and C. Bettstetter, "Self-organization in communication networks: principles and design paradigms," in*IEEE Communication Magazine*, vol. 43, no. 7, pp. 78-85, July 2005.

[100] Y. Li, Z. Feng, Q. Zhang, L. Tan, and F. Tian, "Cognitive Optimization Scheme of Coverage for Femtocell Using Multi-Element Antenna," in *IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall)*, pp.1-5, 6-9 Sept 2010.

[101] H. Claussen, L. Ho, and L. Samuel, "Self-optimization of coverage for femtocell deployments," in *Wireless Telecommunications Symposium*, pp. 278-285, April 2008.

[102] Y. J. Sang, H. G. Hwang, K. S. Kim, "A Self-Organized Femtocell for IEEE 802.16e System," in *IEEE Global Telecommunications Conference (GLOBECOM)*, pp.1-5, November 2009.

[103] 3GPP TR 25.820, "3rd Generation Partnership Project; Technical Specification Group Radio Access Networks; 3G Home NodeB Study Item Technical Report (Release 8)," March 2008.

[104] H. A. Mahmoud, and I. Guvenc, "A comparative study of different deployment modes for femtocell networks," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.1-5, 13-16 Sep. 2009.

[105] N. O, S-W. Han, and H. Kim, "System Capacity and Coverage Analysis of Femtocell Networks," in *IEEE Wireless Communications and Networking Conference (WCNC)*, pp.1-5, 18-21 April 2010.

[106] H. Claussen, "Performance of Macro- and Co-Channel Femtocells in a Hierarchical Cell Structure," in *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp.1-5, 3-7 Sep. 2007.

[107] H. A. Mahmoud, I. Guvenc, and F. Watanabe, "Performance of Open Access Femtocell Networks with Different Cell-Selection Methods," in *IEEE 71st Vehicular Technology Conference (VTC 2010-Spring)*, pp.1-5, 16-19 May 2010.

[108] D. Choi, P. Monajemi, S. Kang, and J. Villasenor, "Dealing with Loud Neighbors: The Benefits and Tradeoffs of Adaptive Femtocell Access," in *IEEE Global Telecommunications Conference, (GLOBECOM)*, pp.1-5, Nov-Dec 2008.

[109] L. Ndikumasabo, "MIMO antenna configuration for Femtocell application," in *Antennas & Propagation Conference*, pp.125-128, 16-17 November 2009.

[110] H. Claussen, and F. Pivit, "Femtocell Coverage Optimization Using Switched Multi-Element Antennas," in *IEEE International Conference on Communications*, pp.1-6, 14-18 June 2009.

[111] A-H. Tsai, J-H. Huang, L-C. Wang, and R-B. Hwang, "High Capacity Femtocells with Directional Antennas," in *IEEE Wireless Communications and Networking Conference (WCNC)*, pp.1-6, 18-21 April 2010.

[112] T. Alade, H. Zhu, and J. Wang, "Uplink Co-Channel Interference Analysis and Cancellation in Femtocell Based Distributed Antenna System,"

in *IEEE International Conference on Communications (ICC)*, pp.1-5, 23-27 May 2010.

[113] H. Claussen, L. T. W. Ho, F. Pivit, "Effects of joint macrocell and residential picocell deployment on the network energy efficiency," in *IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.1-6, 15-18 Sep. 2008.

[114] I. Ashraf, L. T. W. Ho, and H. Claussen, "Improving Energy Efficiency of Femtocell Base Stations Via User Activity Detection," in *IEEE Wireless Communications and Networking Conference (WCNC)*, pp.1-5, 18-21 April 2010.

[115] I. Ashraf, F. Boccardi, and L. T. W. Ho, "Power savings in small cell deployments via sleep mode techniques," in *IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC) Workshops*, pp.307-311, Sep. 2010.

[116] H. Claussen, I. Ashraf and L. T. W. Ho, "Dynamic idle mode procedures for femtocells," in *Bell Labs Technical Journal*, 2010.

[117] I. Haratcherev, C. Balageas, and M. Fiorito, "Low consumption home femto base stations," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.1-5, 13-16 Sep. 2009.

[118] Y-Y. Li, M. Macuha, E. S. Sousa, T. Sato, and M. Nanri, "Cognitive interference management in 3G femtocells," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.1118-1122, 13-16 Sep. 2009.

[119] N. Sung, J. P. M. Torregoza, W. Hwang, S. Lee, and H. Yoon, "A joint power control and converge scheme in a cognitive-femtocell architecture for wireless networks for throughput maximization," in *8th IEEE International Conference on Industrial Informatics (INDIN)*, pp.1025-1030, 13-16 July 2010.

[120] G. Gur, S. Bayhan, and F. Alagoz, "Cognitive femtocell networks: an overlay architecture for localized dynamic spectrum access [Dynamic Spectrum Management]," in *IEEE Wireless Communications*, vol.17, no.4, pp.62-70, August 2010.

[121] S-Y. Lien, C-C. Tseng, K-C. Chen, and C-W. Su, "Cognitive Radio Resource Management for QoS Guarantees in Autonomous Femtocell Networks," in *IEEE International Conference on Communications (ICC)*, pp.1-6, 23-27 May 2010.

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