CHAPTER

Cognitive Strategies for Green Two-Tier Cellular Networks: A Critical Overview

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1.1 INTRODUCTION

The success of mobile cellular networks has resulted in wide proliferation and demand for ubiquitous heterogeneous broadband mobile wireless services. While recent studies confirm that more than 60% of mobile traffic is generated indoors [1], customers still access mobile networks by connecting to Macro Base Stations (M-BSs). Nowadays, indoor and cell edge users usually experience very poor performance (see Figure 1.1); therefore, the growth in traffic rate demand and services requires cellular operators to further ameliorate and extend their infrastructure.

Femtocell Access Points (FAPs) are low power access points that offer radio coverage through a given wireless technology (such as LTE and WiMAX) while a broadband wired link connects them to the backhaul network of a cellular operator (see Figure 1.2) [2]. Such a technical solution presents several benefits both to operators and end consumers. Originally envisioned as a means to provide better voice coverage in the home, FAPs represent an efficient way of offloading data traffic from the macrocell network.

In a cellular network, traffic is carried from an end-user device to the cell site and then to the core network using the backhaul of the Mobile Service Provider (MSP). With network offload, cellular traffic from the UE is redirected to a local AP; then, it is carried over a fixed broadband connection, either to the MSP's core network or to another Internet destination. This reduces the traffic carried over the MSP's radio and backhaul networks, thereby increasing available capacity and limiting OPerational EXpense (OPEX) at the mobile operators. Juniper Research forecasts that by 2015, 63% of mobile data traffic will be offloaded to fixed networks through femtocells and WiFi APs [3]. On the other hand, femto users (F-UEs) may obtain larger coverage, better support for high data rate services, and prolonged battery life for their devices. The advantages mainly come from the reduced distance between an end-user terminal and the AP, the mitigation of interference due to propagation and penetration losses, and the limited number of users served by a FAP.

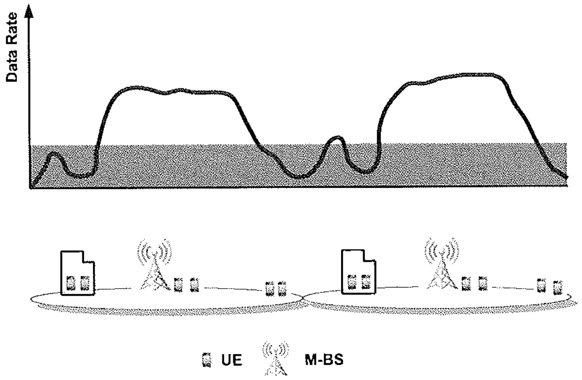

Figure 1.1 User experience challenges for a uniform broadband wireless service.

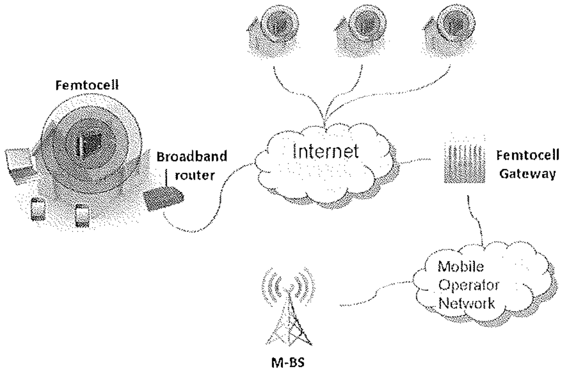

Figure 1.2 A generic femtocell architecture.

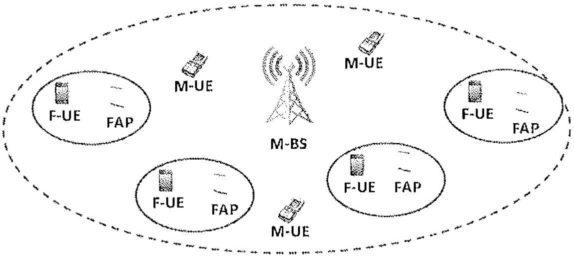

Figure 1.3 Two-tier cellular network.

In this novel network architecture, macrocells and femtocells may share the same spectrum in a given geographical area as a two-tier network (see Figure 1.3). Thus, *cross-tier interference* may drastically corrupt the reliability of communications.

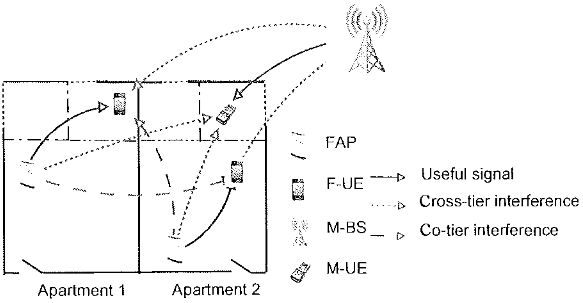

Figure 1.4 Downlink interference scenarios in two-tier cellular networks.

Similarly, neighbor femtocells belonging to same operators may also interfere with each other thus generating *co-tier interference*. These interference scenarios are further illustrated in Figure 1.4.

The impact of interference is highly related to the femtocell access control mechanism. Three different approaches have been investigated in the past: *closed access*, *open access*, and *hybrid access* [4]. In closed access, only a restricted set of users is allowed to connect to the femtocell; in open access femtocells, a subscriber is always allowed to connect to the closer FAP; in the hybrid access approach, femtocells allow access to all users but a certain group of subscribers maintain higher access priority. In closed access femtocells, the issue of interference can become an important bottleneck with respect to QoS and performance of communications. On the contrary, open access limits the interference problem while security issues and high signaling due to handover procedures can reduce the overall performance. Furthermore, due to resource sharing, open access limits benefits for the femtocell owner. Henceforth, according to a recent market research [5], the closed access scheme is the favourite access method of potential customers. Thus, further solutions that limit both *cross-tier* and *co-tier interference* have to be investigated.

In recent years, Cognitive Radio (CR) has been proposed as a powerful instrument to improve the Spectral Efficiency (SE) and permit the coexistence of heterogeneous wireless networks in the same region and spectrum [6]. A CR terminal can monitor the wireless environment and inform the resource allocation controller about local and temporal spectrum availability and quality. Thus, agile AP can dynamically select available channels and adapt transmission parameters to avoid harmful interference between contending users. In CR taxonomy, nodes that are licensed to operate in a certain spectrum band are usually named as primary users, while opportunistic users are often referred to as secondary users. Associating secondary users to F-UEs and primary users to M-UEs is straightforward, although recent work [7] investigates a scenario in which opportunistic M-UEs coexist with licensee F-UEs.

This chapter aims to describe the benefits of cognitive principles towards the successful deployment of femtocells. The main functionalities of a CR (i.e., spectrum sensing, dynamic resource allocation, spectrum sharing, and spectrum mobility) represent the natural answer to issues that rely on the ad hoc nature of FAPs. Spectrum sensing enables cognitive devices to be aware of spectrum usage at nearby macro and femtocells, and to maintain a dynamic picture of available resource. In the investigated scenarios, the heterogeneous nature of the interference results in channel availability time–space dependency, which introduces new challenges with respect to the classic cellular network. Dynamic resource allocation schemes take advantage of spectrum awareness to satisfy QoS constraints while limiting the generated interference and power consumption. Spectrum access strategies deal with contention between heterogeneous users in order to avoid harmful interference. A cognitive FAP can exploit the characteristic of an M-UE's transmissions to detect the presence of nearby victims. Spectrum mobility allows a FAP to vacate its channel when an M-UE is detected, and to access an idle band where it can reestablish the communication link.

It is important to note that all these functionalities should be distributed at both the FAP and its serving UEs. Accordingly, the appropriate reconfiguration process should be cooperatively implemented in order to achieve a robust decision. An example of such cooperation is given in [8], where FAPs and associated UEs cooperate to gather reliable information on the radio environment. Furthermore, the femtocell architecture can reliably assist the configuration of cognitive networks. For instance, the cellular network backhaul could be used to deploy infrastructure-based agile solutions such as the Cognitive Pilot Channel (CPC) [9] or a geolocation database [10].

Few frameworks that assess the major benefits and research challenges in cognitive femtocell networks have been presented in literature. In [11], the authors focus on the characteristics of an infrastructure-based architecture that enables dynamic access in the next generation broadband wireless system. In [8, 12], the authors discuss the drawbacks of traditional interference management schemes in heterogeneous cellular networks; therefore, they show the advantages of implementing cognitive interference mitigation schemes in such environment.

In this chapter, we asses the fundamental goals of cognitive two-tier networks and review existing works in the field. We focus on both industrial and academic contributions.

In particular, Section 1.2 critically presents existing algorithms dealing with spectrum usage awareness and victim detection. Section 1.3 analyses Radio Resource Management (RRM) strategies proposed for cognitive two-tier networks. Section 1.4 discusses spectrum sharing solutions and Section 1.5 analyses green communication issues in two-tier cellular networks and gives an overview of the strategies proposed to enhance the system Energy Efficiency (EE). Finally in Section 1.6, we conclude the chapter by discussing some important open issues.

1.2 SPECTRUM AWARENESS AND VICTIM DETECTION

In this section we overview CR-based functionalities that enable FAPs to be aware of spectrum usage at nearby (macro and femto) cells and detect the presence of UEs that are served by neighboring APs. Accordingly, cognitive APs can dynamically select available channels and adapt transmission parameters to avoid harmful interference towards contending cells.

A major misconception in CR literature is that detecting the signal of the legacy transmitter is equivalent to discovering transmission opportunities [13]. On the contrary, even when such a signal can be perfectly detected, this discovery is affected by three main problems: the *hidden transmitter*, the *exposed transmitter*, and the *hidden receiver*. These are well-known issues and have been investigated in depth in ad hoc wireless networks literature [14]. Nevertheless, although the former problems have been solved, there are still not feasible solutions for the hidden receiver. Due to wall attenuation, the occurrence of these problems is even higher in femtocell deployment scenarios. Furthermore, it is expected that the M-BS likely allocates all frequency resources when there is a high number of end-users to serve. Hence, a sensing analysis based on the classic *energy detection*[15] operations may detect few spectrum opportunities. However, since many M-UEs can be located far away from the FAP, their channels can be effectively reused in the femtocell [16]. More sophisticated and effective detection schemes, based on the knowledge of legacy users' signal characteristics, have been presented in CR literature (cf. [17,18]). Furthermore, infrastructure-based solutions such as the Cognitive Pilot Channel (CPC) [9] and the geolocation database [10] have been proposed to assist cognitive networks across different Radio Access Technologies (RATs) and available spectrum resources.

1.2.1 Sensing and LTE User Detection

Sensing performance is limited by hardware and physical constraints. For instance, only cognitive devices equipped with two transceivers can transmit and sense simultaneously (such as in [19]). Moreover, in order to limit sensing overhead, only a partial state of the network is usually monitored. There is a fundamental trade-off between the undesired overhead and *spectrum holes* detection effectiveness: the more bands that are sensed, the higher the number and quality of the available resource. In order to improve the sensing process reliability in two-tier deployment scenarios, several approaches have been investigated in literature.

Lien et al. propose a mechanism that optimizes both sensing period and frequency resource allocation to statistically guarantee users' QoS [20]. Barbarossa et al. introduce a strategy that jointly optimizes the energy detection thresholds and the power allocation under a constraint on the maximum generated interference [21]. Sahin et al., on the contrary, investigate an agile strategy that jointly exploits spectrum sensing and scheduling information obtained by the M-BS [16]. Uplink sensing is used to individuate frequency resources that have been allocated to nearby M-UEs. Then uplink/downlink scheduling information is exploited to identify these M-UEs and their downlink frequency resources, respectively. Hence, this algorithm permits a reliable detection of the available spectrum opportunities at FAPs. However, it presents some drawbacks: first, the proposed coordination between M-BS and FAPs and limited availability of backhaul bandwidth result in scalability and security issues; second, the technique presented above may be ineffective in practice.

This is due to dense femtocells deployment with a consequent large population of interferers expected to be coordinated by the cellular operator. Due to such unsolved problems, direct coordination among femto and macrocells was not implemented in 3GPP Release 10 [22].

Lotze et al. consider a scenario in which LTE-like femtocells are deployed in the GSM spectrum in order to avoid cross-tier interference [23] towards LTE M-UEs. In this scenario, neighboring femtocells have to dynamically adapt their spectrum usage to prevent harmful co-tier interference. The authors propose a spectrum sensing technique that permits a FAP to detect the presence of neighboring interferers without decoding their signals. The proposed approach combines the classic energy detection operations with a feature detection approach that enables descrimination between LTE transmissions (that have to be avoided) and other signals (that have no priorities). This technique allows the detection of weak signals at a complexity cost slightly higher than the classic energy detector. The proposed detection algorithm has been successfully implemented in the frame of the Iris platform [24].

Several studies related to *victim* aware interference management have been recently proposed in the 3GPP frame. DoCoMo investigates a method for determining whether there are M-UEs in close proximity of a FAP [25,?]. In this scheme M-UEs detect the cell IDentification (ID) of interferers by listening to the Broadcast CHannel (BCH) of neighboring FAPs. Then, based on the received Reference Signal Received Power (RSRP), each M-UE identifies the most harmful FAPs and feedbacks this information to its serving M-BS. PicoChip and Kyocera propose a method where FAPs determine the presence of an M-UE by detecting its uplink reference signal [27]. Furthermore, the authors propose to exploit the properties of the uplink reference signal in order to discriminate between a single dominant transmission of a nearby victim and the aggregated power due to further away users. Note that a victim M-UE is often easy to detect because it likely transmits with relatively high power due to the experienced attenuation (composed mainly of path loss and wall losses). However, the above solutions are ineffective in the presence of an idle mode M-UE. An idle M-UE neither transmits nor is able to report the presence of neighboring femtocells, thus, protecting M-BS downlink control channels is necessary. For instance, Qualcomm proposes to introduce orthogonality between FAPs and M-BS control channels [28]. Further potential solutions are presented in [29].

1.2.2 Architectures towards Geographical-Based Interference Mapping

SpectrumHarvest is a novel architecture that manages spectrum access in cognitive femtocell networks [30]. This architecture is composed of four components: a Multi-Operator Spectrum Server (MOSS), a Femto Coordination/controller Server (FCS), a cognitive FAP, and associated end-user terminals. The MOSS combines information on spectrum availability at different cellular operators with local measurements performed by different femtocells. After processing these inputs, the MOSS indicates to each FCS local available resources. The FCS has the role of providing the spectrum usage information to each of its served FAPs, along with additional information such as power level of neighboring femtocells and the location of M-BSs/M-UEs. Each FAP is characterized by a Spectrum Usage Decision Unit (SUDU) that exploits information received by both the FCS and MOSS to allocate spectrum for each transmission. Furthermore, the SUDU performs local spectrum measurements to detect the presence/absence of neighboring mobile terminals. Finally, end-user devices support a new air interface operating in noncontinuous channels across a multi-operator and multi-services broadband.

Kawade and Nekovee propose to use TV White Spaces (TVWS) in order to support home networking services [31]. The TVWS spectrum comprises large portions of the UHF/VHF spectrum that became available on a geographical basis for dynamic access as a result of the switchover from analog to digital TV.

The proposed investigation is carried out using a database approach: a centrally managed database containing the information of available TV channels is made available to femtocells. Based on the geolocation data and QoS requirements, FAPs query the central database for channel availability through the fixed-line connection. The database returns information about various operating parameters such as number of channels, centre frequencies and associated power levels for use in specific location. Simulation results show how TVWS can be an effective solution for low/medium rate services, while it should be used as a complementary interface for highly loaded traffic scenarios. Furthermore, the study underlines that, due to the lower propagation losses, operating in TVWS bands may result in a significant energy saving.

Similarly, Haines discusses advantages and drawbacks of implementing the CPC in the femtocell deployment scenarios [32]. The CPC is a dedicated logic channel, and is used to disseminate radio context information permitting terminals configuration and interference mitigation. Moreover, the distributed deployment of the CPC (DCPC) is under investigation [33] to improve the coexistence of heterogeneous systems in a shared band. In this scenario, several networks (such as WiFi and Bluetooth), which exploit different technologies and bands, may coexist in the femtocell coverage area. In each household a Smart Femto Cell Controller (SFC-C) is proposed as an interface with a centralized database managed by the cellular operator. The SFC-C is also able to collect and process the sensing outputs of different cognitive devices deployed in the area. Then, it sends interference management information to neighbouring terminals in order to coordinate the access to common spectral resources and avoid mutual interference. Furthermore, a peer to peer link is established to permit neighboring SFC-Cs, which coordinate different heterogeneous networks, to exchange local spectrum measurement and interference policies.

1.3 DYNAMIC RADIO RESOURCE MANAGEMENT

Static RRM algorithms allocate different parts of the available spectral resource between macrocell and femtocell tiers [34]. The goal of these techniques is to avoid in-band concurrent transmissions using full time/frequency orthogonalization of transmissions. However, these approaches are far from the SE targets of operators. The system performance can be enhanced by exploiting more flexible approaches.

Frequency Reuse (FR) schemes have been proposed to geographically reallocate to femtocells part of the spectral resources used by the macrocell (see, for instance [35]). However, due to the high number of expected interferers in dense femtocell deployments, FR schemes can be ineffective. A CR network, on the contrary, can exploit awareness on the spectrum usage and dynamic RRM algorithms to break the capacity limit of classic macrocell networks.

Li et al. propose a dynamic channel reuse scheduler that limits both *macro-to-femto interference* and *femto-to-femto interference* in the downlink scenario [36]. In this scheme, each femtocell exploits sensing outputs to construct a two-dimensional interference signature matrix. This model describes the local network environment in the time/frequency domains and attempts to avoid high peaks of interference. When there is a user to serve, the scheduler assigns the channel and power according to QoS and power constraints. First, it picks up the best available channel with respect to the user interference perception; then, the optimal transmission power is allocated in order to limit femtocell power consumption. Such a cognitive approach is further extended to the uplink scenario [37], where the presence of M-UEs in the household of the femtocell may cause a high level of macro-to-femto interference. This is a well-known issue, and it has been referred as the kitchen table problem [38]. In the above discussed scheme, the absence of coordination between neighboring femtocells results in high scalability and low complexity. However, nearby cognitive FAPs, which experience the same level of interference, may simultaneously access the same channels, thus interfering with each other. Furthermore, FAPs located at the macrocell edge may not be able to detect M-BS transmissions and subsequently cause strong cross-tier interference towards nearby M-UEs.

Wayan Mustika et al. propose a game-theoretic approach to deal with resource allocation in self-organizing closed access femtocells [39]. In the considered uplink interference scenario FAPs are affected by both co-tier and cross-tier interference. The resource allocation problem is modelled as a noncooperative potential game where F-UEs are represented by the set of players, the selected Resource Blocks (RBs) are the associated strategy, and the utility function takes into account both the perceived and generated interference. Hence, each F-UE iteratively acquires information about its environment and distributively selects the most appropriate set of RBs that improve its utility function. The authors demonstrate that the proposed approach converges to a Nash Equilibrium (NE). In such a state, no player gains any advantages from deviating from the selected strategy [40]. However, according to the simulation results the number of iterations necessary to meet the NE is quite high. Therefore, such a state may not be reached during the wireless channel coherence time and poor performance may be experienced during the *long* iterative process. Finally, the proposed approach requires knowledge of the link gains between F-UEs and nearby FAPs and M-BS, which is a hard task in the considered scenario.

Xiang et al. investigate a scenario in which cognitive femtocells access spectrum bands that are licensed to different legacy systems (such as macrocell and TVWS) to increase the aggregate network capacity [19]. Authors propose a joint channel allocation and power control scheme that aims to maximize the downlink femtocell capacity. The optimal allocation is found formulating a mixed integer nonlinear problem, which is decomposed [41] and distributively solved at each femtocell. F-UEs are allowed to use only the channels that are temporally not used by the primary system. Each FAP is equipped with two transceivers, with one dedicated to data transmission and the other used to continuously monitor the radio environment (i.e., sensing and transmission can be performed in parallel). Note that this approach ameliorates the protection of the legacy system, however, it also increases the cost of the devices and the complexity of the proposed approach. Whenever a FAP detects concurrent transmissions of the legacy system, it stops its activity and updates channel assignments accordingly. In order to increase spectral reuse and capacity, the proposed approach permits neighboring femtocells to access the same channels as long as generated interference is not harmful. Furthermore, neighboring FAPs share information about the presence of legacy transmissions in order to cooperatively improve the M-UEs' detection. However, this signaling exchange is realized on the cellular backhaul, thus the delay introduced by the Internet limits the benefits of the cooperative detection. Finally, as opposed to the classic cellular technologies, in the proposed scheme, each UEs can use only one channel, and the FAP is constrained to exploit a number of channels that is equal to the number of its served UEs.

As already mentioned, open access femtocells may limit harmful interference in two-tier networks. In fact, open access FAPs do not restrict access, and mobile users are allowed to connect to the closer femtocell in the vicinity. Hence, open access femtocell deployment results in higher macrocell offload and enhanced network capacity [42]. As drawbacks, network signalling and frequency of handover increase. Furthermore, security issues emerge in this type of access. Torregoza et al. consider a scenario in which both the M-BS and open access FAPs offer WiMAX services in their coverage areas [43]. Each femtocell has some private customers although public M-UEs, in order to improve their performance, can access both macro- and femtocells. In the presented model, a backhaul connection is introduced to permit communications between the M-BS and FAPs. A femtocell, which serves public M-UEs, receives a certain amount of the backhaul capacity as compensation for the poorer performance perceived by its private clients. Thus, a joint power control, base station assignment, and channel allocation scheme is proposed. This scheme improves the aggregate throughput while minimizing the need for femtocell compensation. In order to find the Pareto optimal solution for both downlink and uplink scenarios, two multi-objective problems are formulated and solved through a sum-weighted approach.

Jin and Li analyse further potential benefits of applying CR techniques in WiMAX-based two-tier networks [7]. In the investigated scenario, F-UEs connected to WiMAX femtocells via a dedicated channel experience guaranteed QoS. Oppositely, M-UEs are allowed to connect only to the M-BS with best effort services. However, this deployment scenario permits a high number of spatial reuse opportunities. Femtocells are characterized by small coverage areas, few UEs per cell, and low transmission power; hence, outdoor M-UEs can opportunistically reuse channels utilized by faraway femtocells. Therefore, in order to exploit the spatial diversity experienced by cognitive M-UEs, a two-hop cooperative transmission scheme is proposed (see Figure 1.5). In classical CR networks, sender and receiver periodically exchange their sets of available channels; then, in order to find a common available resource through which to communicate, a channel filtering procedure is realized [6]. In the considered scenario, when there are no channels free from interference, the presence of a relay introduces further possibilities to establish a reliable communication between the M-BS and indoor M-UEs. For instance, in Figure 1.5, the M-BS is allowed to communicate with M-UE 1 and M-UE 4 through relays M-UE 2 and M-UE 3, respectively. Furthermore, cooperative communication may permit reduction of the M-BS transmission power, which results in lower interference perceived at F-UEs and energy saving. Finally, the authors propose an RRM protocol that maximizes the aggregated throughput and includes routing strategies, power assignment, and channel allocation. Using stochastic optimization, nonlinear integer programming problems are formulated. At the best of our knowledge, the proposed cognitive framework is the only protocol that exploits the location dependency of spectrum opportunities to enhance the two-tier network performance. However, the high level of signaling and sensing overhead may result in low scalability.

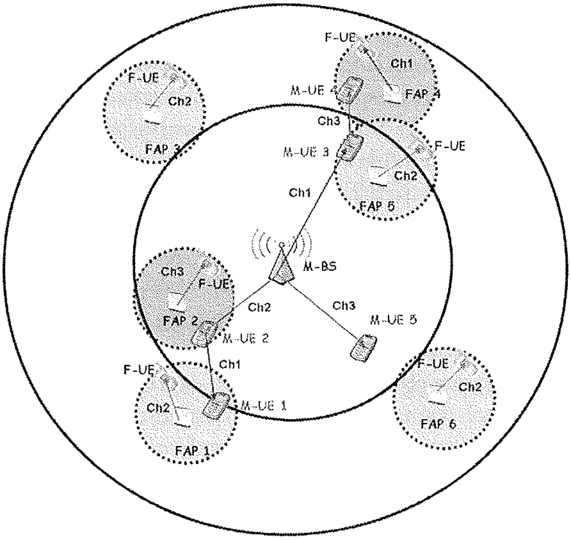

Figure 1.5 Two-hop cooperative transmission scheme for two-tier cellular networks [7]: the M-BS is allowed to communicate with M-UE 1 and M-UE 4 through relays M-UE 2 and M-UE 3, respectively. Furthermore, due to the cooperative communication scheme, neighboring FAPs are not interfered with by macrocell transmissions.

1.4 DYNAMIC SPECTRUM SHARING

Spectrum sharing functionalities aim to improve the coexistence of heterogeneous users accessing the radio resource. Three different cognitive transmission access paradigms are currently investigated in literature [44]: *underlay*, *overlay*, and *interweave*. In underlay transmissions, cognitive users are allowed to operate in the band of the primary system while generated interference stays below a given threshold (see Figure 1.6).

In overlay transmissions, cognitive devices exploit some specific information to either cancel or mitigate perceived/generated interference on concurrent transmissions (see Figure 1.7).

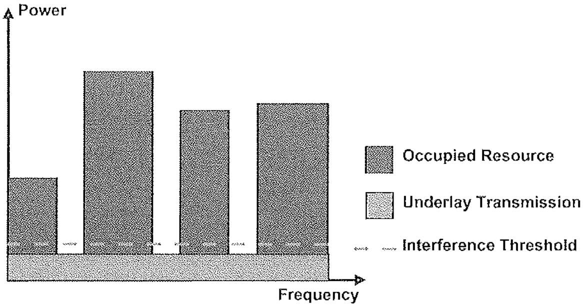

Figure 1.6 Underlay transmission scheme [44].

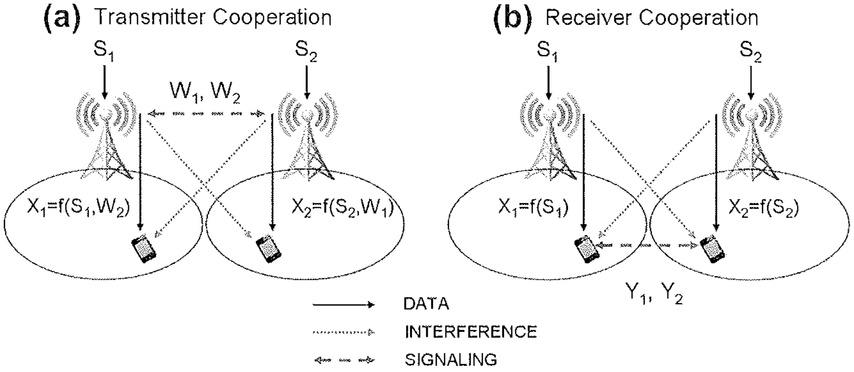

Figure 1.7 Overlay transmission scheme in transmitter/receiver cooperation scenarios [44](a) Overlay transmission scheme in transmitter cooperation scenario: the two BSs exchange information in order to acquire a priori knowledge about the concurrent transmissions. Such information is then exploited to either cancel or mitigate mutual interference [44]. (b) Overlay transmission scheme in receiver cooperation scenario: the two UEs jointly process received signals to correctly decode desired information.

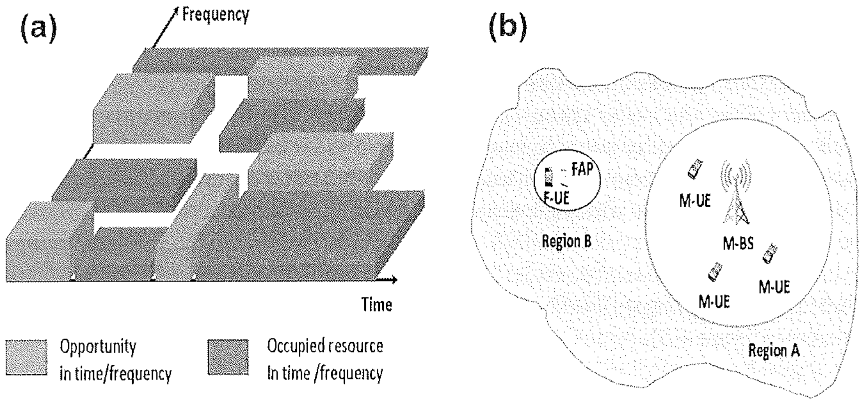

Figure 1.8 **(a) Interweave transmission approach in time/frequency domain: FAPs are not allowed to transmit while M-BS is transmitting. (b) Interweave transmission approach in space domain: some area around the M-BS (i.e., Region A) cannot be reused by FAP transmissions; however Region B can be used without interfering M-UEs.**

In interweave transmissions, opportunistic users transmit only in spectrum holes; if during in-band sensing a cognitive user detects a primary one, it vacates its channel to avoid harmful interference (see Figure 1.8).

In order to improve the coexistence between macrocells and femtocells, these schemes have been implemented also in cognitive-based two-tier networks.

Cheng et al. investigate the theoretical downlink capacity of a two-tier network, for each of the above-mentioned approaches [45]. The authors conclude that underlay and overlay schemes can result in better spectral reuse than the interweave scheme. However, former mechanisms require a better awareness of the network state and higher level information (such as the position of neighbouring interfered users, generated interference, scheduling information, and channel gains).

1.4.1 Underlay Spectrum Access

Galindo-Serrano et al. propose an algorithm that controls the aggregated *femto-to-macro interference* [46] by using a distributed Q-learning based mechanism [47]. Femtocells find the optimal policy by exploiting sensing outputs and periodic reports transmitted by the M-BS. However, the successful implementation of the proposed mechanism in a broadband cellular network can be constrained by the length of the learning process (see also the discussion related to the work of Mustika et al. in Section 1.3). Hence, the authors propose a novel cognitive concept, named *docition*, which permits FAPs to exchange their knowledge and experience. Femtocells are able to identify the most appropriate *teachers*. In fact, it is fundamental that cognitive terminals learn from *experts* that are in the same radio environment. This cooperative process increases convergence speed and accuracy. Depending on the degree of cooperation, two docitive schemes are investigated: in *Startup Docition*, cognitive femtocells share their policies only when a new node joins the network; in *IQ-Driven Docition*, cognitive femtocells periodically share their knowledge. The docitive approach may significantly reduce the sensing period resulting in energy saving and higher throughput. However, in the proposed scheme, additional overhead and complexity are introduced by coordination between femtocells and M-BSs, which periodically feedback the interference perceived at their associated M-UEs.

Chandrasekhar et al. consider a different approach to limit the femto-to-macro interference [48]. The authors first investigate the consequences of the near-far effect, which may result in excessive cross-tier interference in two-tier cellular networks (see Figure 1.9). Simulation results show that, due to mutual interference, achieving high SINR in one tier constricts the achievable SINR in the other tier. In order to deal with this issue, a closed loop power control is implemented at femtocells. The proposed algorithm iteratively reduces the F-UE uplink power until the SINR target at M-BSs is met. The authors propose that each F-UE distributively adapts its power in order to maximize a utility function, which results in lower complexity and overhead. This function is made up of two components: a reward and a penalty. The reward describes the gain achieved by the F-UE as a function of the difference between the experienced link quality and the minimum SINR target. The penalty represents the cost that femto transmission implies for the macrocell network as a function of the interference perceived at the M-BS. The proposed power adaptation mechanism does not require explicit cooperation between macrocell and femtocell networks. Nevertheless, in order to evaluate the generated interference at the M-BS, each F-UE needs to estimate the channel gain characterizing its link to the M-BS. However, the proposed power control scheme may not be sufficient to guarantee reliability of macrocell transmissions. In such cases, cross-tier coordination is introduced, and based on periodic M-BS reports, stronger femto interferers iteratively decrease their SINR target until the generated interference is adequately lowered.

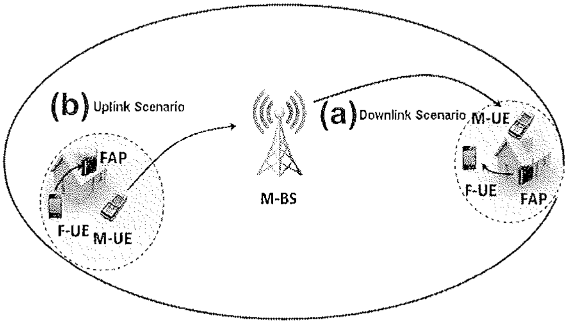

Figure 1.9 Near-far scenarios in two-tier cellular networks: (a) Downlink Scenario: FAP transmits to its F-UE and creates a dead zone for the cell edge M-UE. (b) Uplink Scenario: cell edge M-UE transmits with high power to its serving M-BS and creates a dead zone for the nearby FAP.

1.4.2 Interweave Spectrum Access

In order to allow distributed intercell spectrum access, da Costa et al. propose a Game-based Resource Allocation in Cognitive Environment (GRACE) [49]. In the proposed approach spectrum access is autonomously managed at each femtocell. Hence intercell coordination is avoided, leading to better scalability and SE. The aggregate femtocell strategy is modelled as a game $\Gamma = \langle \Im, (\Sigma_i)_{i \in \Im}, (\Pi_i)_{i \in \Im} \rangle$, where $\Im$ is the set of femtocell players, Σ_i is the access strategy of the ith player, and Π_i is the utility function of the ith player. The utility function indicates the preferences of each player with respect to the possible access strategies. In GRACE, this function is constructed to jointly optimize capacity, load balance, and femto-to-femto interference. Simulation results show that GRACE achieves higher throughput than classic FR schemes especially at cell edge users. GRACE avoids inter-cell coordination, leading to high scalability and SE; however, this approach decreases the speed of the learning process and reduces the accuracy of the algorithm.

Garcia et al. propose a Self-Organizing Coalitions for Conflict Evaluation and Resolution (SOCCER) mechanism, which fairly distributes available resources between cognitive femtocells [50]. This approach is based on both graph and coalitional game theories and atempts to avoid harmful femto-to-femto interference. Soccer is composed of two main phases (see Figure 1.10): in the first phase, FAPs, which join the network or seek for more band, detect the presence of possible conflicts.

In particular, based on the RSRP measured at F-UEs, each FAP estimates which neighboring FAPs are currently strong interferers. In SOCCER, an interferer is strong whenever, due to the mutual interference, and an orthogonal access results to be more effective than a reused one's scheme. In the second phase, coalitions are formed and resources are distributed accordingly. The authors show through simulation that, even in high density deployment scenarios, the degree of interference (i.e., the number of neighbor interferers) of a FAP is rarely higher than three. Thus, in order to limit the algorithm complexity and the network overhead, SOCCER considers the case in which a new entrant BS sends a Coalition Formation Request (CFR) to at most two coalition candidates. After receiving the CFR message, coalition candidates fairly reorganize the available spectrum to avoid mutual interference. It is important to note that interference towards the legacy system is not considered in either the work of da Costa or Garcia, which may result in poor performance at M-UEs.

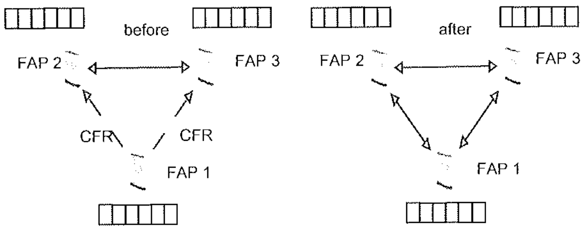

Figure 1.10 Dynamic spectrum sharing according to SOCCER [50].

On the contrary, Pantisano et al. propose a cooperative spectrum sharing approach, which may limit the effect of both cross-tier and co-tier interference [51]. In the proposed scheme, FAPs dynamically access the bandwidth used by the macrocell uplink transmissions, in order to avoid interference towards nearby M-UEs (see Figure 1.11). Furthermore, neighboring FAPs are able to form coalitions in which available frequency resources are cooperatively shared and femto-to-femto interference is limited. In fact, although isolated FAPs select their channels according to the perceived level of interference, FAPs in the same coalition use a Time Division Multiple Access (TDMA) scheme, which avoids having neighbouring FAPs simultaneously transmit on the same channel. However, co-tier interference is not fully eliminated because different coalitions generate mutual interference with one other. The proposed cooperation algorithm is divided into three main phases: neighbor discovery, recursive coalition formation, and coalition-level scheduling. During the first phase, each FAP uses a neighbor discovery technique to identify potential coalition partners. The second step is iteratively performed: First, each FAP finds coalitions characterized by an acceptable cost. This cost is related to power consumption due to the signaling exchange among the coalition members and depends on spatial distribution of the coalition members. Then, each FAP joins the coalition that ensures the maximum payoff. The coalition payoff is related to the achieved throughput and corresponding power consumption. Finally, the coalition formation ends when a stable partition is reached (i.e., FAPs have no incentive to leave the partition they blong to). In the third phase, FAPs within the same coalition first exchange information about their scheduling preferences on a defined in-band common control channel; then, a graph-coloring based resource allocation algorithm [52] is used in each coalition. The proposed approach may enable reliable co-channel deployment of femtocells and macrocells in the same geographic region. However, perfect sensing is supposed at FAPs, although missing detection of the M-UE transmission can result in harmful macro-to-femto interference.

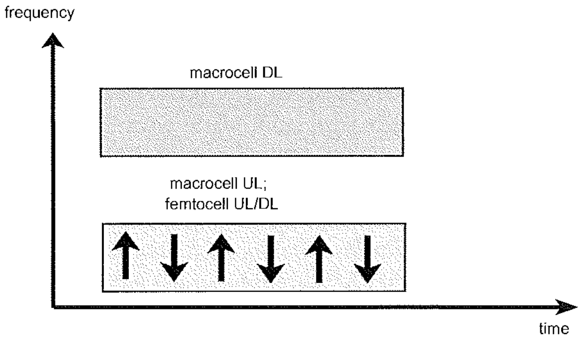

Figure 1.11 The TDD transmission scheme implemented in [51].

1.4.3 Overlay Spectrum Access

In suburban or low density urban deployment scenarios a femtocell generally operates in a very high SINR regime. However, we can identify two scenarios in which macro-to-femto interference may affect transmission reliability. In the first case, harmful downlink interference is experienced at F-UEs when the femtocell is very close to an M-BS. In the second case, an indoor M-UE that is far from its serving BS adapts it transmission power using fractional power control [53]. This mechanism may generate harmful interference at neighbouring FAPs (see Figure 1.9). However, in both cases, the harmful transmission is generally characterized by both high power and low rate. Thus, with high probability, the receiver (either a FAP or a F-UE) can process and cancel the perceived interference and subsequently correctly decode the useful message (a more detailed discussion on Interference Cancellation (IC) theory can be found in [54]). The general assumption of overlay transmission schemes is that the cognitive network possesses the necessary information (such as the channel gain related to the interferer transmission) to either cancel or mitigate interference.

The amount of signaling and coordination classically required in overlay access schemes may result in excessive complexity and overhead. Therefore, Rangan proposes an overlay approach that limits cross-tier cooperation [55]. The proposed method assumes Fractional Frequency Reuse (FFR) at macrocells. The overall band is divided in four contiguous bands (f_0, f_1, f_2, and f_3) as shown in Figure 1.12.

Each cell site is three way sectorized, and each of this sectors is referred to as a cell. Each cell is further divided in two regions, an inner region and an outer region. Subband f_0 is reused in all cells and it is allotted to M-UEs that are closer to the M-BS. However, remaining bands are used in only one cell per site and are allocated to cell edge M-UEs. Although this scheme reduces the system SE, it limits both the macro-to-macro and the femto-to-macro interference. The subband partitioning permits femtocells, regardless of their positions, to access a part of the spectrum where the generated cross-tier interference is minimal. In order to effectively reduce femto-to-macro interference, joint femtocell channel selection and power allocation is based on a *load spillage* power control method.This method avoids the operaion

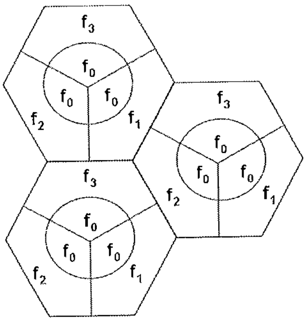

Figure 1.12 A FFR scheme for two-tier cellular networks [55].

of femtocells in bands either where the operating macro receiver is close or high load traffic is transmitted. However, signaling between macro and femto networks is required to allow each femtocell to be aware of the macro load factors. Furthermore, to successfully implement the load spillage power control, femto transmitters need to estimate channel gains that characterize the femto-to-macro links. Nevertheless, this scheme does not reduce the macro-to-femto interference experienced at F-UEs close to the M-BS. Thus, the author proposes implementation of the above-mentioned IC technique to jointly decode and cancel undesired signals. However, femto-to-femto interference is not mitigated by the proposed approach; on the contrary, due to the geographic based frequency partition, this interference can strongly affect femtocell performance especially in a dense deployment scenario.

Zubin et al. propose a dynamic resource partitioning scheme between femto and macrocells that does not rely on IC [26]. In this scheme, M-UEs identify the cell IDs of interferers by listening to the BCH of neighbor FAPs. Then, based on the corresponding RSRP, each M-UE identifies the most interfering femtocells and feedbacks this information to its serving M-BS. Hence, the M-BS indicates to interfering FAPs the channels that they should refrain from allocating in order to avoid *cross-tier interference*. This coordination message can be disseminated via X2 and S1 interfaces [56]. However, whenever the macrocell scheduling pattern changes, the M-BS should transmit new information to each interferer that is located in its region. The length of the scheduling period in modern cellular systems is related to the wireless channel coherence time. Hence, in medium/high density deployment scenarios, this scheme may result in excessive overhead.

Kaimaletu et al. extend the idea previously presented to the femto-to-femto interference scenario [57]. In this scheme, both M-BSs and FAPs schedule frequency resources by considering the potential interference generated towards each others' UEs. Each UE classifies interfering cells according to the strength of its RSRP. Therefore, it feedbacks this information to its serving cell, which reports to neighboring cells the number of victim UEs they create and the total number of UEs it serves. According to this information, macro/femtocells cooperatively block a subset of their frequency channels so that the victim UEs are protected. At the end of this iterative process, each cell uses a Proportional Fair (PF) scheduler [58] to serve its UE with a minimum amount of perceived/generated interference. In order to realize the proposed scheme, the authors assume perfect synchronization between all cells in the system both in time and frequency. In the proposed scheme, signaling exchange is not performed in small time scale; thus, it results in lower overhead with respect to Zubin's proposition [26]. However, in a dense deployment scenario, sources of interference can frequently change. This may increase the need for coordination, increasing overhead and reducing system scalability.

Pantisano et al. investigate a cooperative framework for uplink transmissions, where F-UEs act as a relay for neighboring M-UEs [59]. In this framework, each M-UE can autonomously decide to lease part of its allotted bandwidth to a cooperative F-UE. The latter split these channels into two parts: the first part of the band is used to forward the M-UE's message to its serving FAP; the second part of the

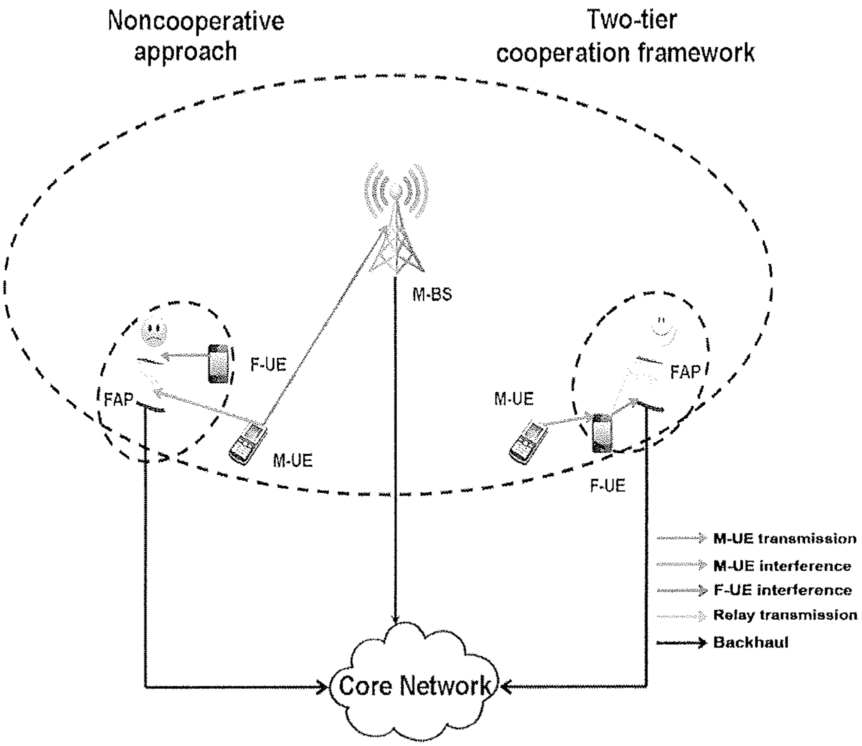

Figure 1.13 **Two-tier network cooperation framework [59].**

band represents a reward for the relaying F-UE, which can transmit its own traffic avoiding interference from the cooperative M-UE. Coordination can be beneficial for both M-UEs and FAPs, which may avoid excessive retransmissions (i.e., latency) and reduce the perceived cross-tier interference, respectively (see Figure 1.13). In fact, cell edge and indoor M-UEs likely experience poor performance due to penetration and propagation losses; hence, they are expected to transmit with relative high power to avoid excessive outage events. Therefore, M-UEs' transmissions result in strong interference at neighboring FAPs (see Figure 1.9). In order to ameliorate perceived performance, F-UEs can decide to cooperate with a group of M-UEs by forming a coalition, where transmissions are managed at the F-UE and separated in time in a TDMA fashion. Each member of the coalition receives a payoff that is measured as the ratio between the experienced capacity and related latency. Note that such a payoff depends on the amount of power/band that the F-UE uses to relay M-UEs messages and the remaining part that is used to transmit its own packets. To the best of our knowledge, this proposal is the first to consider device-to-device communication to enable cooperative transmission in a two-tier cellular network. However, two main challenges arise in such a work: first, this kind of cooperation results in security problems due to the exchange of data among coalition partners; second, relaying through the FAP introduces additional latency, due to transmission over the IP-based backhaul, that can results in poor performance at the M-UEs.

Cheng et al. propose a mixed transmission strategy that enhances the system SE by exploiting both interweave and overlay paradigms [60]. In fact, in such a strategy, F-UEs access idle RBs (as in the interweave approach) and further exploit transmission opportunities that arise during M-BS retransmissions. In particular, each FAP overhears communications originated at the M-BS so that during the retransmissions, F-UEs can transmit their data and FAPs are able to eliminate or mitigate the perceived interference. In order to be aware of retransmission events, it perfect synchronization is assumed between femtocells and the macrocell; hence, FAPs are able to detect the Automatic Repeat reQuest (ARQ) feedback sent by neighboring M-UEs. Moreover, the authors suppose that each F-UE knows the channel statistics of the links between M-BS and M-UE, between M-BS and itself, and between M-UE and itself. The process of interference mitigation is divided into two stages as illustrated in Figure 1.14. In stage S0, a FAP overhears the data transmitted by the M-BS while its F-UE is idle. When the M-UE does not correctly decode the received message, it sends a Negative ACKnowledgement (NACK) to the M-BS requiring a retransmission. This NACK is received also at the FAP, which schedules its F-UE in the next slot. Thus, in stage S1 the M-BS and the F-UE transmit simultaneously. Furthermore, the FAP exploits the message received at stage S0 to improve its decoding capability. Whenever it is able to correctly decode the M-BS message, the FAP completely eliminates the perceived interference; otherwise, it optimally combines data received in S0 and S1 to maximize the experienced SINR. Femtocells decide to access retransmission slots according to a given probability *p*. The optimal value of *p* is numerically computed to maximize the femtocell SE. Furthermore, in order to limit the femto-to-macro interference during retransmissions, the transmission power at the F-UE is constrained by a maximum value. This power is computed such that the outage probability constraint at the M-UE is satisfied. The proposed strategy strongly ameliorates the SE achieved with the classic interweave approach, however its efficacy is related to the precision of synchrony between the macrocell and femtocells and also to the channel statistics awareness at FAPs. These are complex tasks that require high overhead and may need signaling exchange between the M-BS and FAPs.

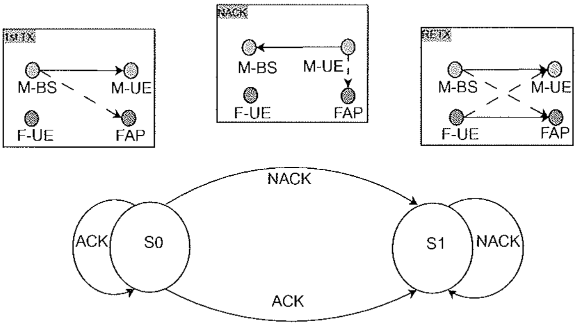

Figure 1.14 The overlay transmission scheme proposed in [60].

1.5 GREEN COGNITIVE FEMTOCELL NETWORKS

Femtocell networks have been proposed as an efficient and cost-effective approach to enhance cellular network capacity and coverage. Recent economic investigations claim that femtocell deployment might reduce both the OPEX and CAPital EXpenditure (CAPEX) for cellular operators [61]. A recent study [62] shows that expenses scale from \$60,000/year/macrocell to \$200/year/femtocell. However, according to the ABI Research [4], by the end of 2012 more than 36 million femtocells are expected to be sold worldwide with 150 million customers. Cellular network energy consumption might be drastically increased by the dense and unplanned deployment of additional BSs. The growth of energy consumption will cause an increase in global CO_2 emissions and impose more and more challenging operational costs.

In order to investigate the relationship between the BS load and its power consumption, the EARTH Energy Efficiency Evaluation Framework (E^3F) maps the radiated RF power to the power supply of a BS site [63]. Furthermore, the impact of the different components of the BS transceivers on the aggregate power consumption is analysed. Such a study in based on the analysis of the power consumption of various LTE BS types as of 2010. The effect of the various components of the BS transceivers is considered: antenna interface, power amplifier, the small-signal RF transceiver, baseband interface, DC-DC power supply, cooling, and AC-DC supply. Therefore, E^3F proposes a linear power consumption model that approximates the dependency of the BS power consumption to the cell load:

$$P^* = \begin{cases} P_0 + \Delta_{\mathrm{p}} P^{\mathrm{RF}}, & 0 < P^{\mathrm{RF}} \leqslant P_{\max}; \\ P_{\mathrm{sleep}}, & P_{\mathrm{out}} = 0. \end{cases} \tag{1.1}$$

where P^* is the BS input power required to generate the irradiated P^{RF} power, and Δ_{p} is the slope of the load dependent power consumption. Moreover, $P_{\max}$, P_0, and P_{sleep} indicate the RF output power at maximum load, minimum load, and in sleep mode, respectively.

Table 1.1 shows the classical values of $P_{\max}$, P_0, and Δ_p for M-BSs and FAPs. Note that the value of P_{sleep} depends on the hardware components that are deactivated during BS sleep intervals. However, more deactivated hardware components result in a slower reactivation process.

Figure 1.15 shows the operating power consumption of M-BSs (left) and FAPs (right) with respect to the traffic load.

Such representations evidence that:

Table 1.1 BS Power Model Parameters

BS type	$P_{\max}$ [W]	P_0 [W]	Δ_p
M-BS	40	712	14.5
FAP	0.01	10.1	15

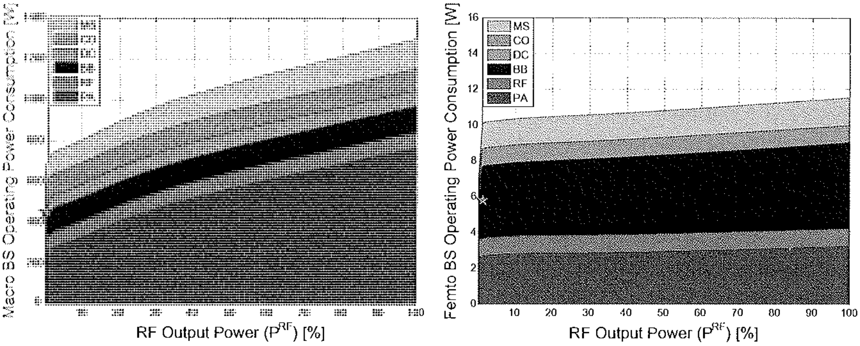

Figure 1.15 M-BS (left) and FAP (right) system power consumption dependency on relative output power [63]. Legend: PA=power amplifier, RF=small signal RF transceiver, BB=baseband processor, DC= DC–DC converters, CO=Cooling (only applicable to the M-BS), PS=AC/DC power supply; the red star mark indicates the BS power consumption in sleep mode.

- M-BS power consumption is strongly related to the load, thus, macro offloading via femtocell deployment can greatly enhance the overall cellular network EE;
- FAP power consumption does not vary much with the load, thus, the EE of femtocells is reduced in lightly loaded scenarios;
- Retransmissions have a higher impact on macrocell performance and slightly affect femto EE; therefore, retransmissions towards M-UEs should be performed by neighbouring small cells;
- Low cost power amplifiers designed to scale their power consumption with the load could improve the energy performance of femtocell networks;
- Dynamic cell switch-off techniques can adapt femtocell activity to the load in order to operate only in high EE state.

It is important to note that femtocells normally work in low load scenarios. Due to the limited number of UEs that can be simultaneously served by a FAP and the short distance between the AP and the user terminal, spectrum/power resources are often underutilized at FAPs. Furthermore, the femtocell density in urban scenarios is expected to be very high. A high number of low energy efficient FAPs can have a detrimental effect on the aggregate cellular network performance.

Although the E^3F model allows us to understand the trade-offs related to femtocell deployment, the relationships between EE, service constraints, and deployment efficiency are not straightforward and reducing the overall energy consumption while adapting the target of SE to the actual load of the system and QoS emerges as a new challenge in wireless cellular networks.

Furthermore, most of the literature aims to underline how much energy gain is achievable by deploying femtocells in the macrocell region (see for instance [64]), and few practical algorithms have been proposed to enhance the two-tier network EE.

A general classification of such energy-aware mechanisms can be realized according to the temporal scale in which they operate (cf. Figure 1.16). Deployment of additional femtocells, which offload the neighbouring macrocell and improve the network EE, is realized in a long-time scale (such as weeks). Due to the static characteristic of the indoor femtocell deployment scenarios, mechanisms that depend on the cell load, such as dynamic cell switch-off [65] and cell zooming [66] operate in mid-time scale (such as hours). Finally, energy-aware resource allocation schemes are implemented in short-time scale (e.g., the system scheduling period).

Ghost Femtocells is a short-time-scale algorithm that trades off transmission energy for frequency resources [67]. This RRM strategy profits from the inherent characteristics of co-channel femtocell deployment: due to the limited number of UEs that can be simultaneously served by a FAP (typically this number is less than four) and the short distance between the AP and the user terminal, spectrum resources are often underutilized at femtocells. The proposed algorithm is mainly composed by two steps: first, the femtocell scheduler attempts to serve as many UEs as possible according to their QoS constraints; second, further available resources are smartly exploited to spread the original message and lower the associated Modulation and Coding Scheme (MCS). Decreasing the MCS permits the subsequent strong limitation of the transmission power and enhancement of the transmission robustness. Simulation results show that the proposed approach limits both cross-tier and co-tier interference and increases the femtocell EE especially in low load traffic scenarios. However, this algorithm optimizes only the femtocell RF output power, which slightly impacts on the overall system power consumption.

López-Pérez et al. propose a similar approach, where self-organizing femtocells independently assign MCSs, RBs, and transmission power levels to UEs, while minimizing the cell RF output power and meeting QoS constraints [68]. In such a scenario, FAPs are aware of the spectrum usage at nearby femtocells

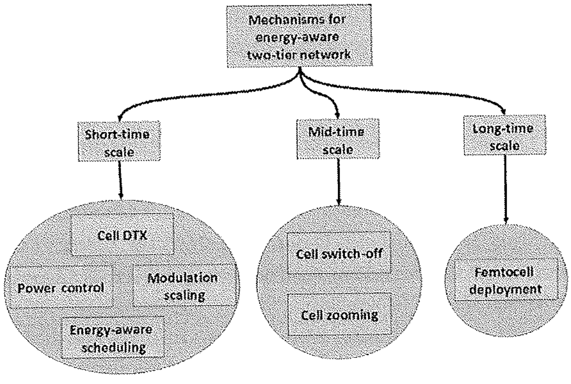

Figure 1.16 Time-scale chart of energy-aware mechanisms for two-tier cellular networks.

and tend to allocate less power to those UEs that are located in the proximity of the serving FAP or have low data-rate requirements. Subsequently, nearby FAPs allocate UEs with bad channel conditions or high data-rate constraints on those RBs characterized by low interference. Thus, in the proposed algorithm, neighboring femtocells dynamically control inter-cell interference without any coordination or static frequency planning. However, the authors do not investigate the impact of the proposed scheme in terms of femto-to-macro interference. M-UEs are affected by the aggregate interference produced by nearby FAPs. As showed in Figure 1.17, the discussed approach may create spikes of interference, which can corrupt macrocell transmissions, especially in high density femtocells scenarios.

Cheng et al. propose a more effective power optimization strategy [69]. The authors investigate a scenario in which femtocells and macrocells are deployed on orthogonal bands in order to avoid cross-tier interference. Furthermore, the spectral reuse between femtocells is limited to control the co-tier interference. System EE is measured through the *green factor*, which is defined as

$$\text{Green factor} = \frac{W(rT_\text{m} + (1-r)N_f r_f T_f)}{P_\text{system}^T}, \tag{1.2}$$

where W is the cellular bandwidth, r is the ratio between the number of channels dedicated at the macrocell and the total available channels, T_m is the macrocell downlink throughput, N_f is the number of deployed FAPs, r_f is the spectral reuse factor at femtocells, T_f is the femtocell downlink throughput, and P_system^T is the aggregate system power consumption of both macro and femtocells. Therefore, the proposed strategy aims to efficiently share the spectrum between M-BSs and FAPs in order to maximize the green factor while guaranteeing a certain SE at both M-UEs and F-UEs. However, although the proposed approach results in limited interference and

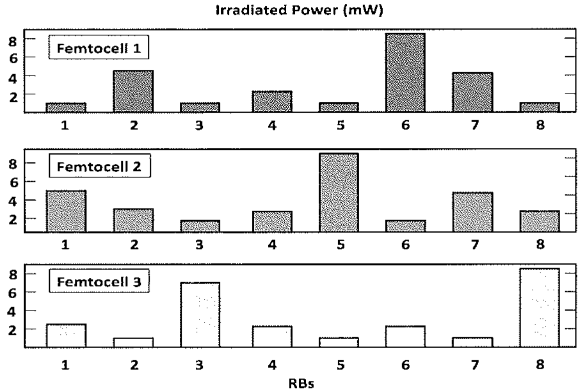

Figure 1.17 RB and power allocation of three neighbouring FAPs according to the scheme proposed in paper [68].

low complexity it may not be suitable in realistic scenarios, where SE constraints of different UEs can strongly vary. Furthermore, due to the orthogonal bandwidth deployment, it can result in low SE performance for both M-UEs and F-UEs, especially in deployment scenarios characterized by a high density of femtocells.

Higher EE can be achieved by dynamically switching off those FAPs that are not serving active users. Idle FAPs disable pilot transmissions and associated radio processing that represent the strongest contribution to the femtocell system power consumption. Dynamic femtocell switch-on/off is capturing the attention of both operators and researchers because it can introduce an important energy gain without seriously affecting UE performance. In fact, in this scenario, cellular coverage is guarantee by the active macrocell, while femtocells dynamically create high capacity zones adapting their activity status to the UE deployment.

Ashraf et al. propose to equip FAPs with an energy detector that permits *sniffing* the presence of nearby M-UEs [65]. As previously discussed, an indoor UE, which is served by the M-BS, likely transmits with high power; hence it is easy to detect. The detection threshold is computed at a femtocell by estimating the path loss to the M-BS, such that UEs located at the femtocell edge can be correctly detected (see Figure 1.18). Henceforth, when an UE is detected, the FAP switches to active mode and if the UE has the right to access the femtocell, the handover process is initiated. Otherwise, the FAP reverts to the switch-off mode. Simulation results show the proposed approach can lead to high energy gain. However, in high density scenarios the aggregate energy received from different sources of interference can cause false alarm events that affect detection reliability.

In order to avoid additional hardware at FAPs, the authors extend the energy detector based proposal by introducing two novel algorithms that control femtocell activity [70]. In the first scheme, the femtocell status is managed by the core network that is in charge to transmit, via the backhaul, a specific message that controls FAP activation/deactivation. The core network exploits the knowledge about the UE position to find FAPs to which the UE is able to connect. Moreover, this solution has the

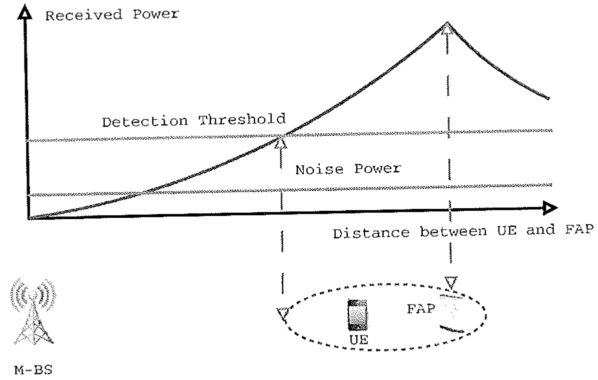

Figure 1.18 UE detection scheme in cell switch-off strategy [65].

advantage of distinguishing between registered UEs that can be served by closed access FAPs and unregistered UEs that can be served only by open/hybrid access femtocells. Furthermore, this approach also implements a centralized decision that considers global knowledge on the status of the netwok. In the second scheme, the femtocell activity is controlled directly by the UE. Two approaches are feasible: In the first case, a UE served by the M-BS periodically broadcasts a wake-up message to find idle FAPs in its range. In the second case, a reactive scheme is followed: a UE sends the wake-up message either when it experiences poor performance from the M-BS or when it requires higher data rate. In both the schemes FAPs are required to be able to detect the wake-up message during sleep mode. This message could include identification information such that closed access femtocells wake up only for registered UEs. The UE-controlled scheme suffers mainly from two drawbacks: First it increases UE battery consumption, especially in the proactive version. Furthermore, it requires the specification of a robust physical/logical wireless control channel where the UE can send the wake-up message.

An alternative solution is proposed by Telefonica [71] where the UE detection is based on the usage of a short range radio (SRR) interface, such as Bluetooth Low Power. In order to reduce power consumption, the SRR interface is maintained in standby as much as possible, and it is activated only when the UE is located nearby its serving FAP. In fact, UEs store a database, named the femto-overlapping macrocells list, that includes the IDs of M-BSs located in the serving FAP neighborhood. A UE camping in any of these M-BSs actives its SRR interface (shifting from standby mode to initiating mode) and starts searching for advertising packets broadcast by its FAP. Subsequently, if the UE is allowed to access the FAP, the two SRRs change in connect status, and after the connection is created, the FAP switches on its RF apparatus. This method is reliable because it is based on a point-to-point connection between the FAP and the UE, however, the main drawback is that currently there are no practical solutions to switch the FAPs from standby mode to advertising mode. Hence, FAPs should always keep their SRRs activated, decreasing the system EE and increasing interference in the already overcrowded ISM bands.

Dynamic cell switch-off mechanisms are inherent to FAPs that are not serving active UEs; however, cell zooming [66] and cell DTX [72, 73] have been recently proposed to enhance EE of lightly loaded systems. Cell zooming adaptively adjusts the cell size according to traffic load, user requirements, and channel conditions. Therefore, FAPs under light load self-deactivate to reduce network energy consumption; subsequently UEs located in coverage areas of such idle FAPs have to connect to the nearby M-BS. Alternatively, when open access femtocells are deployed, active FAPs may dynamically increase their irradiated power to guarantee service in the regions of neighboring idle FAPs. However, cell zooming can still create holes in the network coverage and strongly affect the system performance.

Cell DTX is implemented on a faster time scale and allows the FAP to immediately switch off cell specific signaling during subframes where there are no user data transmissions. Such a fast adaptation mechanism may allow for great energy savings especially in low traffic scenarios. However, depending on signals that are not transmitted, connectivity issues arise as UEs may not be able to detect a cell in DTX mode. Therefore, this mechanism may result in excessive handover latency and packet loss.

1.6 CONCLUSIONS AND FUTURE LINES OF RESEARCH

A comprehensive overview on cognitive strategies for two-tier cellular networks was presented. First, we critically discussed spectrum awareness, victim detection, resource allocation, and spectrum sharing techniques, which enable the effective coexistence of macrocells and femtocells in the same radio environment. Then, we examined the two-tier network in the EE perspective and we reviewed approaches proposed to achieve green communication through femtocell deployment.

Table 1.2 synthesizes the main features of the analyzed RRM schemes. The first column indicates the bibliography reference of such schemes and the second column describes the investigated interference scenario. The third and the fourth columns indicate the cellular technology and the transmission scenario (either uplink or downlink) in which the algorithm is implemented. The fifth and the sixth columns describe the FAP access type and the kind of cooperation that is exploited by the FAPs. A FAP can cooperate with the underlying M-BS as in [16], with neighboring FAPs as in [19], or both types of coordination can be implemented as in [46]. Obviously, cooperation has a direct impact on both the overhead and the system complexity, which are indicated in columns seven and eight, respectively. Note that in order to give a qualitative description of the algorithm complexity, we have taken into account also the number of transceivers required at the cognitive device, the type of information (location of the M-UE, scheduling, channel gain, etc.) needed, and the architecture (i.e., centralized or distributed) required.

Including cognitive principles in two-tier networks is producing great expectation. However, the design of efficient and robust cognitive-aware strategies for two-tier networks is still an open research field. With this chapter we aim to underline some of the major issues in the domain:

- In broadband mobile wireless scenarios, channel availability and quality change with space and time. When a licensed user is detected, to realize seamless transmission, a cognitive device vacates its channel and reconstructs a transmission link on a different channel. The procedure that permits this transition from a channel to another with minimum performance degradation is called *spectrum mobility*. While this functionality is fundamental in CR, to the best of our knowledge, it has not been investigated yet in cognitive femtocell scenarios. Specific solutions that reduce delay and loss during spectrum mobility are necessary. Furthermore, these algorithms should be aware of the running applications and adapt to QoS constraints. For instance, FTP traffic requires tight constraints on packet error rate: a retransmission protocol should be implemented to refrain from outage. Voice communication

Table 1.2 Characteristics of Analysed CR-Based RRM Schemes

Ref.	Interference	Technology	Scenario	Access	Cooperation	Overhead	Complexity
[7]	Cross-tier	WiMax	DL	Closed	No	High	High
[16]	Cross-tier	LTE	UL/DL	Closed	Macro	High	High
[19]	Co-tier	–	DL	Closed	Femto	Medium	High
[26]	Cross-tier	LTE	DL	Closed	Macro	High	High
[36, 37]	Cross-tier/ co-tier	LTE	UL/DL	Closed	No	Low	Low
[43]	Cross-tier/ co-tier	WiMax	UL/DL	Open	Macro	Average	High
[39]	Cross-tier/ co-tier	LTE	UL	Closed	No	Low	High
[46]	Cross-tier	–	DL	Closed	Macro/ femto	High	High
[48]	Cross-tier	–	UL	Closed	Macro	Medium	High
[49]	Co-tier	–	UL/DL	Closed	No	Low	Medium
[50]	Co-tier	LTE	UL/DL	Closed	Femto	Medium	Medium
[51]	Cross-tier/ co-tier	–	UL/DL	Closed	Femto	High	High
[55]	Cross-tier	LTE	UL/DL	Closed	Macro	Medium	High
[60]	Cross-tier	LTE	UL	Closed	Macro	Medium	High
[67]	Cross-tier/ co-tier	LTE	DL	Closed	Femto	Medium	Medium
[68]	Co-tier	LTE	DL	Closed	No	Low	Low
[69]	Cross-tier/ co-tier	LTE	DL	Closed	No	Low	Low
[59]	Cross-tier	–	UL	Closed	Macro	Medium	High

allows, however, a limited delay for the channel mobility to avoid call interruption.

- Backhaul connection between femtocells and the cellular network is a potential means for coordination between macro/femto cells. A cognitive control channel could be established over this fixed-line connection either to implement cooperative sensing techniques or coordinate the spectrum access. Moreover, cellular operators might broadcast information about the state of coexisting networks. Knowledge about users' traffic, location, and QoS constraints could greatly enhance the performance of cognitive two-tier networks. Nevertheless, increasing the amount of signalling augments the network overhead. Hence, to limit overhead, it is fundamental to exchange the most effective information, and also the frequency of these reports has to be limited. Furthermore, backhaul reliability and security should be considered.

- Cooperative sensing may greatly enhance the effectiveness of M-UEs' detection wireless fading channels [74]. Collaborative detection is, however, affected by spatially correlated shadowing. For a given SNR, a larger number of correlated sensing nodes is needed to achieve the same detection probability of a few independent users. Future solutions should investigate the effectiveness of cooperative sensing in two-tier network deployment. Furthermore, correlation between different detectors has to be taken into account to develop more efficient sensing schemes.
- Classically, researchers have tried to develop spectrally efficient systems to enable heterogeneous networks to coexist within the same spectrum. Nevertheless, recent studies showed how spectrum scarcity is almost all due to static resource allocation strategies and that CR can notably improve the spectrum usage. However, femtocell deployment requires a new paradigm for two main reasons. First, F-UEs can benefit from a high quality downlink signal enabled by short range communications characterizing femtocell deployments. Second, only a few users locally compete for a large amount of the frequency resources in a femtocell. Therefore, a femtocell may benefit from a huge amount of available spectral/power resources. In this context, novel *green* cognitive approaches should be investigated in order to save power consumption, reduce interference, and improve the battery life of customer's devices.
- Cell discontinuous transmission (DTX) [72] is emerging as a means to greatly enhance the system EE especially in light load scenarios. Although DTX can be hard to implement at macrocells due to the need to continuously transmit the control channels, it can be more easily implemented at femtocells where the cellular coverage is always guaranteed by the nearby M-BS. However the implementation of this technique would completely change the characteristics of the perceived interference. Classical schemes to measure the quality of the wireless links may result in unreliable estimation. Cognitive techniques can be implemented to improve the awareness about interference behavior and permit reliable transmissions.
- Most of the CR literature for two-tier networks is based on the association secondary users to F-UEs and primary users to M-UEs. To the best of our knowledge only the authors of [7] have investigated a different approach. In our view, both macro and femto users should dynamically access the cellular spectrum; this deployment could result in more flexible and efficient systems.
- A multi-operator spectrum sharing approach might permit to the realization of novel and effective RRM techniques [30]. This strategy can potentially solve problems related to both co-tier and cross-tier interference and increase macrocell offloading. However, new business and pricing models are required

to implement scenarios in which competitors cooperate towards a more efficient usage of the aggregate resources.

- Amongst the discussed studies only the authors of [43] have considered the open access femtocell case. However, this is a very promising scenario in terms of both SE (due to the less perceived/generated interference) and EE (due to the increased macrocell offloading). Cognitive algorithms can represent a powerful instrument to deal with the problems inherent to this scenario such as the frequency of handover, femto-to-femto interference, etc.

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REFERENCES

[1] Mobile Broadband Access at Home, Informa Telecoms & Media, August 2008.
[2] V. Chandrasekhar, J. Andrews, A. Gatherer, Femtocell networks: a survey, IEEE Communications Magazine 46 (9) (2008) 59–67.
[3] Alcatel-Lucent, Metro cells: a cost-effective option for meeting growing capacity demands, 2011. <www.alcatel-lucent.com>.
[4] G. De La Roche, A. Valcarce, D. López-Pérez, J. Zhang, Access control mechanisms for femtocells, IEEE Communications Magazine 48 (1) (2010) 33–39.
[5] S. Carlaw, IPR and the Potential Effect on Femtocell Markets, FemtoCells Europe, ABIresearch, 2008.
[6] A. De Domenico, E. Calvanese Strinati, M.G. Di Benedetto, A survey on MAC strategies for cognitive radio networks, IEEE Communication Surveys and in press. Available at IEEExplore.
[7] J. Jin, B. Li, Cooperative resource management in cognitive WiMAX with femto cells, in: Proceedings of the 29th Conference on Information Communications (INFOCOM 2010), San Diego, CA, USA, March 2010, pp. 1–9.
[8] A. Attar, V. Krishnamurthy, O.N. Gharehshiran, Interference management using cognitive base-stations for UMTS LTE, IEEE Communications Magazine 49 (8) (2011) 152–159.
[9] J. Perez-Romero, O. Salient, R. Agusti, L. Giupponi, A novel on-demand cognitive pilot channel enabling dynamic spectrum allocation, in: Second IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007), Dublin, Ireland, April 2007, pp. 46–54.
[10] C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, W. Caldwell, IEEE 802.22: the first cognitive radio wireless regional area network standard, IEEE Communications Magazine 47 (1) (2009) 130–138.
[11] G. Gur, S. Bayhan, F. Alagoz, Cognitive femtocell networks: an overlay architecture for localized dynamic spectrum access dynamic spectrum management, IEEE Wireless Communications 17 (4) (2010) 62–70.

[12] S.M. Cheng, S.Y. Lien, F.S. Chu, K.C. Chen, On exploiting cognitive radio to mitigate interference in macro/femto heterogeneous networks, IEEE Wireless Communications 18 (3) (2011) 40–47.

[13] W. Ren, Q. Zhao, A. Swami, Power control in cognitive radio networks: how to cross a multi-lane highway, IEEE Journal on Selected Areas in Communications 27 (7) (2009) 1283–1296.

[14] A.C.V. Gummalla, J.O. Limb, Wireless medium access control protocols, IEEE Communications Surveys and Tutorials 3 (2) (2009) 2–15.

[15] H. Urkowitz, Energy detection of unknown deterministic signals, Proceedings of the IEEE 55 (1967), 523–531.

[16] M.E. Sahin, I. Guvenc, M.R. Jeong, H. Arslan, Handling CCI and ICI in OFDMA femtocell networks through frequency scheduling, IEEE Transactions on Consumer Electronics 55 (4) (2009) 1936–1944.

[17] T. Yücek, H. Arslan, A survey of spectrum sensing algorithms for cognitive radio applications, IEEE Communication Surveys and Tutorials 11 (1) (2009) 116–130.

[18] W.A. Gardner, Signal interception: a unifying theoretical framework for feature detection, IEEE Transactions on Communications 36 (1988) 897–906.

[19] J. Xiang, Y. Zhang, T. Skeie, L. Xie, Downlink spectrum sharing for cognitive radio femtocell networks, IEEE Systems Journal 4 (4) (2010) 524–534.

[20] S.Y. Lien, C.C. Tseng, K.C. Chen, C.W. Su, Cognitive radio resource management for QoS guarantees in autonomous femtocell networks, in: IEEE International Conference on Communications (ICC 2010), Cape Town, South Africa, May 2010, pp. 1–6.

[21] S. Barbarossa, S. Sardellitti, A. Carfagna, P. Vecchiarelli, Decentralized interference management in femtocells: a game-theoretic approach, in: Proceedings of the Fifth International Cognitive Radio Oriented Wireless Networks Communications (CROWNCOM 2010), Cannes, France, June 2010, pp. 1–5.

[22] 3GPP TSG-RAN1#62, R1-105082, Way forward on eICIC for non-CA based HetNets, August 2010.

[23] J. Lotze, S.A. Fahmy, B. Özgül, J. Noguera, L.E. Doyle, Spectrum sensing on LTE femtocells for GSM spectrum re-farming using Xilinx FPGAs, in: Software-Defined Radio Forum Technical Conference (SDR Forum), USA, December 2009.

[24] P.D. Sutton, J. Lotze, H. Lahlou, S.A. Fahmy, K.E. Nolan, B. Ozgul, T.W. Rondeau, J. Noguera, L.E. Doyle, Iris: an architecture for cognitive radio networking testbeds, IEEE Communications Magazine 48 (9) (2010) 114–122.

[25] 3GPP TSG-Ran4#52 and NTT DOCOMO, R4-093244, Downlink Interference Coordination Between eNodeB and Home eNodeB, 24–28 August 2009.

[26] B. Zubin, S. Andreas, A. Gunther, H. Harald, Dynamic resource partitioning for downlink femto-to-macro-cell interference avoidance, EURASIP Journal on Wireless Communications and Networking 2010 (2010).

[27] 3GPP TSG-Ran4 Ad hoc #2010-01, picoChip Design, and Kyocera, R4-100193 Victim UE Aware Downlink Interference Management, January 2010.

[28] 3GPP TSG-Ran Wg4 #51 and Qualcomm Europe, R4-091908, Partial Bandwidth Control Channel Performance.

[29] 3GPP TSG-Ran WG4 Meeting #52bis and picoChip Designs, R4-093668, Victim UE Aware Downlink Interference Management.

[30] M.M. Buddhikot, I. Kennedy, F. Mullany, H. Viswanathan, Ultra-broadband femtocells via opportunistic reuse of multi-operator and multi-service spectrum, Bell Labs Technical Journal 13 (4) (2009) 129–143.

[31] S. Kawade, M. Nekovee, Can cognitive radio access to TV white spaces support future home networks? in: IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN 2010), Singapore, April 2010, pp. 1–8.

[32] R.J. Haines, Cognitive pilot channels for femto-cell deployment, in: Seventh International Symposium on Wireless Communication Systems (ISWCS 2010), NewYork, UK, September 2010, pp. 631–635.

[33] M. Mueck, C. Rom, Wen Xu, A. Polydoros, N. Dimitriou, A.S. Diaz, R. Piesiewicz, H. Bogucka, S. Zeisberg, H. Jaekel, T. Renk, F. Jondral, P. Jung, Smart femto-cell controller based distributed cognitive pilot channel, in: Fourth International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM'09), Hannover, Germany, June 2009, pp. 1–5.

[34] V. Chandrasekhar, J. Andrews, Spectrum allocation in tiered cellular networks, IEEE Transactions on Communications 57 (10) (2009) 3059–3068.

[35] I. Guvenc, M.R. Jeong, F. Watanabe, H. Inamura, A hybrid frequency assignment for femtocells and coverage area analysis for co-channel operation, IEEE Communications Letters 12 (12) (2008) 880–882.

[36] Y.Y. Li, M. Macuha, E.S. Sousa, T. Sato, M. Nanri, Cognitive interference management in 3G femtocells, in: IEEE International Symposium on Personal, Indoor and Mobile Radio Communications PIMRC'09, Tokyo, Japan, September 2009, pp. 1118–1122.

[37] Y.Y. Li, E.S. Sousa, Cognitive uplink interference management in 4G cellular femtocells, in: IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2010), Instanbul, Turkey, September 2010, pp. 1567–1571.

[38] Z. Shi, M.C. Reed, M. Zhao, On uplink interference scenarios in two-tier macro and femto co-existing UMTS networks, EURASIP Journal on Wireless Communications and Networking 2010 (2010).

[39] I. Wayan Mustika, Koji Yamamoto, Hidekazu Murata, Susumu Yoshida, Potential game approach for self-organized interference management in closed access femtocell networks, in: IEEE 73rd Vehicular Technology Conference (VTC Spring 2011), May 2011, pp. 1–5.

[40] K. Akkarajitsakul, E. Hossain, D. Niyato, D. Kim, Game theoretic approaches for multiple access in wireless networks: a survey, IEEE Communications Surveys Tutorials, (99) (2011), 1–24.

[41] D.P. Palomar, M. Chiang, A tutorial on decomposition methods for network utility maximization, IEEE Journal on Selected Areas in Communications 24 (8) (2006) 1439–1451.

[42] D. Calin, H. Claussen, H. Uzunalioglu, On femto deployment architectures and macrocell offloading benefits in joint macro-femto deployments, IEEE Communications Magazine 48 (1) (2010) 26–32.

[43] J.P.M. Torregoza, R. Enkhbat, W.J. Hwang, Joint power control, base station assignment, and channel assignment in cognitive femtocell networks, EURASIP Journal on Wireless Communications and Networking, 2010 (2010).

[44] A. Goldsmith, S.A. Jafar, I. Maric, S. Srinivasa, Breaking spectrum gridlock with cognitive radios: an information theoretic perspective, Proceedings of the IEEE 97 (5) (2009) 894–914.

[45] S.M. Cheng, W.C. Ao, K.C. Chen, Downlink capacity of two-tier cognitive femto networks, in: IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2010), Instanbul, Turkey, September 2010, pp. 1303–1308.

[46] A. Galindo-Serrano, L. Giupponi, M. Dohler, Cognition and docition in OFDMA-based femtocell networks, in: IEEE Global Telecommunications Conference (GLOBECOM 2010), Miami, FL, USA, December 2010, pp. 1–6.

[47] C.J.C.H. Watkins, P. Dayan, Q-learning, Machine Learning, 8 (3) (1992), 279–292.

[48] V. Chandrasekhar, J.G. Andrews, T. Muharemovic, Z. Shen, A. Gatherer, Power control in two-tier femtocell networks, IEEE Transactions on Wireless Communications 8 (8) (2009) 4316–4328.

[49] G.W.O. da Costa, A.F. Cattoni, I.Z. Kovacs, P.E. Mogensen, A scalable spectrum-sharing mechanism for local area network deployment, IEEE Transactions on Vehicular Technology 59 (4) (2010) 1630–1645.

[50] L.G.U. Garcia, G.W.O. Costa, A.F. Cattoni, K.I. Pedersen, P.E. Mogensen, Self-organizing coalitions for conflict evaluation and resolution in femtocells, in: IEEE Global Telecommunications Conference (GLOBECOM 2010), Miami, FL, USA, December 2010, pp. 1–6.

[51] F. Pantisano, M. Bennis, W. Saad, R. Verdone, M. Latva-aho, Coalition formation games for femtocell interference management: a recursive core approach, in: IEEE Wireless Communications and Networking Conference (WCNC 2011), March 2011, pp. 1161–1166.

[52] F. Pantisano, K. Ghaboosi, M. Bennis, M. Latva-Aho, Interference avoidance via resource scheduling in TDD underlay femtocells, in: IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops 2010), September 2010, pp. 175–179.

[53] C.U. Castellanos, D.L. Villa, C. Rosa, K.I. Pedersen, F.D. Calabrese, P.-H. Michaelsen, J. Michel, Performance of uplink fractional power control in UTRAN LTE, in: IEEE Vehicular Technology Conference (VTC Spring 2008), Calgary, Canada, May 2008, pp. 2517–2521.

[54] R.H. Etkin, D.N.C. Tse, Hua Wang, Gaussian interference channel capacity to within one bit, IEEE Transactions on Information Theory 54 (12) (2008) 5534–5562.

[55] S. Rangan, Femto-macro cellular interference control with subband scheduling and interference cancelation, in: IEEE GLOBECOM Workshops 2010, Miami, FL, 2010, pp. 695–700.

[56] I. Widjaja, H. La Roche, Sizing x2 bandwidth for inter-connected ENBS, in: IEEE 70th Vehicular Technology Conference Fall (VTC 2009-Fall), September 2009, pp. 1–5.

[57] S. Kaimaletu, R. Krishnan, S. Kalyani, N. Akhtar, B. Ramamurthi, Cognitive interference management in heterogeneous femto-macro cell networks, in: IEEE International Conference on Communications (ICC 2011), June 2011, pp. 1–6.

[58] K. Norlund, T. Ottosson, A. Brunstrom, Fairness measures for best effort traffic in wireless networks, in: 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2004), September 2004, vol. 4, pp. 2953–2957.

[59] F. Pantisano, M. Bennis, W. Saad, M. Debbah, Spectrum leasing as an incentive towards uplink macrocell and femtocell cooperation, IEEE JSAC Special Issue on Femtocell Networks, April 2012.

[60] S.M. Cheng, W.C. Ao, K.C. Chen, Efficiency of a cognitive radio link with opportunistic interference mitigation, IEEE Transactions on Wireless Communications 10 (6) (2011) 1715–1720.

[61] Airvana Inc, How femtocells change the economics of mobile service delivery, <http://www.airvana.com/>.

[62] M. Heath et al., Picocells and femtocells: will indoor base stations transform the telecoms industry? 2007. <http://research.analysys.com>.

[63] G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M.A. Imran, D. Sabella, M.J. Gonzalez, O. Blume, et al., How much energy is needed to run a wireless network? IEEE Wireless Communications 18 (5) (2011) 40–49.

[64] F. Cao, Z. Fan, The tradeoff between energy efficiency and system performance of femtocell deployment, in: IEEE seventh International Symposium on Wireless Communication Systems (ISWCS 2010), pp. 315–319.

[65] I. Ashraf, L.T.W. Ho, H. Claussen, Improving energy efficiency of femtocell base stations via user activity detection, in: IEEE Wireless Communications and Networking Conference, WCNC 2010, 2010, pp. 1–5.

[66] Z. Niu, Y. Wu, J. Gong, Z. Yang, Cell zooming for cost-efficient green cellular networks, IEEE Communications Magazine 48 (11) (2010) 74–79.

[67] E. Calvanese Strinati, A. De Domenico, A. Duda, Ghost femtocells: a novel radio resource management scheme for OFDMA based networks, in: IEEE Wireless Communications and Networking Conference (WCNC 2011), Cancun, Mexico, 2011.

[68] D. López-Pérez, X. Chu, A.V. Vasilakos, H. Claussen, Minimising cell transmit power: towards self-organized resource allocation in OFDMA femtocells, in: ACM SIGCOMM 2011, Toronto, Canada, August 2011.

[69] W. Cheng, H. Zhang, L. Zhao, Y. Li, Energy efficient spectrum allocation for green radio in two-tier cellular networks, in: IEEE Global Telecommunications Conference (GLOBECOM 2010), Miami, FL, USA, December 2010, pp. 1–5.

[70] I. Ashraf, F. Boccardi, L. Ho, Sleep mode techniques for small cell deployments, IEEE Communications Magazine 49 (8) (2011) 72–79.

[71] R3-110030, Dynamic H(e)NB Switching by Means of a Low Power Radio Interface for Energy Savings and Interference Reduction, 3GPP TSG RAN WG3 Meeting, Dublin, Ireland, January 2011.

[72] P. Frenger, P. Moberg, J. Malmodin, Y. Jading, I. Godor, Reducing energy consumption in LTE with cell DTX, in: IEEE 73rd Vehicular Technology Conference (VTC Spring 2011), May 2011, pp. 1–5.

[73] A. De Domenico, R. Gupta, E. Calvanese Strinati, Dynamic traffic management for green open access femtocell networks, in: IEEE 75th Vehicular Technology Conference Fall (VTC 2012-Spring), Yokohama, Japan, May 2012.

[74] A. Ghasemi, E.S. Sousa, Collaborative spectrum sensing for opportunistic access in fading environments, in: Proceedings of the Symposium on Dynamic Spectrum Access Networks (DySPAN'05), Baltimore, MD, USA, November 2005, pp. 131–136.