DEPLOYING COGNITIVE CELLULAR NETWORKS UNDER DYNAMIC RESOURCE MANAGEMENT

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ABSTRACT

Smartphone fever along with roaring mobile traffic pose great challenges for cellular networks to provide seamless wireless access to end users. Operators and vendors realize that new techniques are required to improve spectrum efficiency to meet the ever increasing user demand. In this article, we exploit the great opportunities provided by cognitive radio technology in conventional cellular networks. Specifically, we first present challenging issues including interference management, network coordination, and interworking between access networks in a tiered cognitive cellular network with both macrocells and small cells. Taking into consideration the different network characteristics of macrocells and small cells, we then propose an adaptive resource management framework to improve spectrum utilization efficiency and mitigate the co-channel interference between macrocell and small cell users. A game-theory-based approach to efficient power control has also been provided.

INTRODUCTION

The fast development of cellular communications corroborates the success of the mobile Internet, which penetrates our daily lives by connecting end-user devices to the Internet with diverse quality of service (QoS). Thanks to the powerful computation and communication hardware platforms on mobile devices, individual users generate more data than ever before. For example, a smartphone user generates as much as 35 times the data of a voice-only cell phone. The global mobile data traffic has doubled for the past four years in a row [1].

To improve network capacity and meet the explosively growing data demand, more frequency bands have been assigned for fourth generation (4G) cellular networks. Meanwhile, efficient communications techniques, such as multiple-input multiple-output (MIMO) and smart antennas, have been applied, working with scheduling schemes designed for multidimensional resource allocation, such as orthogonal frequency-division multiple access (OFDMA) systems, to effectively improve network performance. Furthermore, to accommodate more users in a serving area, frequency reuse and network splitting are also introduced with interference management. However, these evolutional efforts cannot fully solve the bandwidth shortage. Besides, in today's ecosystem of cellular networks, which comprise both operators and users, end users are more actively participating in the networking and resource allocation to ensure their perceived QoS. For example, to improve the communication quality in an indoor environment, end users could deploy femtocells that operate in the licensed spectrum [2]. With the launch of new mobile services, such as e-health and personal financial services, critical QoS, security, and privacy issues are arising for both operators and end users [3].

Therefore, revisiting the network deployment and resource management issues in radio access networks and the backhaul is necessary for both operators and end users. To improve the overall system performance, the operators should not only optimize the resource utilization within the traditional domain of radio access, but also steer the usage patterns of end users. Some new opportunities are emerging, such as offloading traffic from macrocells to user deployed femtocells [2] or to operator deployed WiFi networks [4]. However, under such heterogeneous network deployment, spectrum sharing becomes complicated as multiple users attached through different network access portals generate mutual interference. Dynamic spectrum access in cognitive radio study has shown the potential to further enlarge the pool of available resources for users while reducing the access cost (e.g., sensing delay). In a layered network structure with prioritized spectrum access, users with lower priority trace the temporal and spatial distribution of spectrum access opportunities and adapt their transmissions to the activities of a prioritized user group [5]. A significant gain is expected by applying cognitive spectrum sharing in femtocells with efficient coordination between the femtocells and the macrocells for resource allocation. Until now, only a few works have addressed this critical issue, and the specifications of network deployment and operation are still open issues. In this article, we propose a new framework of cognitive cellular networks that applies cognitive radio techniques in resource management and network coordination of cellular networks. We first study

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the trends in current cellular networks that greatly shape the challenges and exhibit the design potential in improving network capacity and transmission quality. Specifically, the tiered network structure, energy awareness, and security issues are identified as the main trends. Next, we treat the arising challenges in the trends by introducing cognitive radio techniques on the aspects of network coexistence, dynamic spectrum access, and coordination mechanism design under limited bandwidth. Therefore, we propose a new framework of cognitive cellular networks in which we list three major research issues: interference management in the tiered network structure, mitigation of network bottlenecks, and coordination in resource management. For each research issue, we specify the features, compare the candidate solutions, and verify the impact on system performance. With a case study of cognitive cellular networks, we further discuss the design of interference management in femtocell deployment where we apply the game theory to model the operations with heterogeneous network entities and limited internetwork coordination capability.

Trends in Cellular Networks

In cellular networks, two methods are usually used to meet the ever-increasing bandwidth demands of mobile users. The first method is to add more spectrum bands at the expense of billions of dollars. Since the spectrum resources are inherently limited and very expensive, the operators usually turn to the second method, deploying new physical and link layer techniques, such as MIMO, high-order modulation, and smart antennas, to further improve the spectrum utilization efficiency. However, these advanced techniques usually have high operational complexity and maintenance cost. To this end, a simple yet efficient solution is required to improve spectrum utilization and dimension future system design and management.

Heterogeneous Cells and Tiered Network Deployment

Compared to macrocell base stations, base stations of small cells have a smaller communication range with lower transmission power. Small cells are usually deployed as complements of macrocells with different purposes, such as to improve network capacity in hotspots, to compensate for long distance loss for users at network edges, and to provide coverage in the blind zone, as shown in Fig. 1. According to the working frequency and the deployment and control schemes, small cells can be roughly categorized into two types.

Out-of-band small cells: These small cells operate in the frequency bands other than the licensed frequency bands of macrocells, for example, WiFi cells in the unlicensed 2.4 GHz industrial, scientific, and medical (ISM) bands. Out-of-band small cells are usually deployed by end users. Nowadays, operators are interested in deploying WiFi access to offload mobile data from cellular cells to WiFi hotspots. Such operator-deployed WiFi networks are usually open to their own subscribers only.

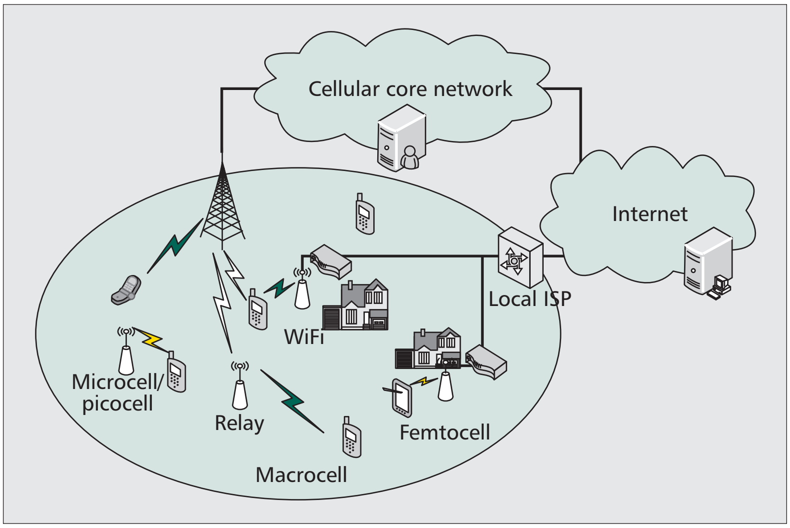

Figure 1. *Tiered framework of cognitive cellular networks.*

In-band small cells: These small cells operate in the same frequency bands as the macrocells, are usually deployed and managed by the operators, and are referred to as microcells and picocells. Recently, a new type of small cell, the femtocell, has been introduced to enhance the indoor cellular signal with a simplified cellular base station (BS) connected to the cellular core network via a third party Internet cable service [2]. Because these femtocells can be deployed by end users, operators only have limited control over them, which makes it challenging to mitigate the co-channel interference and manage the radio network resources.

A brief summary of the specifications of small cells is listed in Table 1. Compared to macrocells, small cells have advantages in some usage scenarios, such as capacity enhancement in hotspots, and coverage expansion into homes and workplaces. Basically, small cells allow for flexible BS deployment and simple transceiver design due to the limited communication coverage. As the radio environment becomes more and more complicated, using small cells is beneficial for operators to deal with localized coverage and link enhancement while offloading traffic from the macrocells to femtocells or WiFi [1].

Recognizing the differences between macrocells and small cells, it is necessary to revisit the network planning and management issues in a tiered network integrating both macrocells and small cells. First, different cells may have different capabilities to serve users. Small cells can provide higher throughput for local users, while macrocells provide mobile services with reduced link capacity for remote users. Second, it is critical to determine the cell size and number of cells to achieve the maximum network capacity in the serving area. Users can select the best access cell among multiple visible cells to achieve a high diversity gain; however, more visible cells will cause more burden on the network coordination and energy management [6]. Last but not the least, implementation encounters more challenges. For in-band small cells, severe co-channel interference from and into the macrocells may degrade the performance of the whole cel-

To address the challenges brought by the trends emerging in cellular networks, we should revisit the research issues in network deployment and resource management from multiple aspects.

	Macrocell	Microcell	Picocell	Femtocell	WiFi
Transmit power	50 W	A few watts	> 200 mW	10~100 mW	100~200 mW
Range	1~5 km	300~1000 m	< 200 m	20~30 m	100~200 m
Deployment	Operator	Operator	Operator	User	User
Operating bands	Operator's	Operator's	Operator's	Operator's	Unlicensed
Coverage	Outdoor/indoor	Outdoor	Outdoor/indoor	Indoor	Indoor

Table 1. *Specifications of different cells.*

lular network. For out-of-band small cells operating independent of macrocells, operators may not be able to rely on a centralized control architecture to help schedule traffic offloading from macrocells to small cells. Distributed traffic offloading remains an open research issue.

Green Cellular Networks and Sustainable Communications

Green radio communication networks have attracted great attention recently as the information and communication society realized the necessity of achieving energy efficiency and being environmental friendly. Operators and users are resorting to efficient power management solutions to reduce the energy consumption of BSs and extend the battery life of mobile devices.

Although cellular networks are widely deployed to provide ubiquitous wireless access worldwide, some users in developing countries have very restricted access, especially when they roam in off-grid suburban areas where power supplies rely on transported fuels such as diesel, which are very expensive. To reduce the cost of off-grid BS deployment, researchers and engineers are working on the development of green BSs, that is, BSs that are powered by sustainable power supplies such as solar, wind, and tides [7]. Unlike traditional electricity power supply, renewable power supply is inherently variable in its availability and capacity, which poses great challenges in network resource management. Considering the dynamic characteristics of sustainable energy sources in a green cellular network powered by renewable energy, the fundamental design criterion and main performance metric should shift from energy efficiency to energy sustainability [8]. Under such a new green network paradigm, network planning and resource management issues should be thoroughly revisited.

Secure Communications and User Privacy

In a tiered network, users can set up small cells for offloading data that will traverse the cellular core network to the Internet. This opens a door for malicious attackers who can easily set up a femtocell and eavesdrop or even change the information traversed over the cell. Although there are some existing attack models and analysis in general computer networks, these models do not accurately capture the openness and flexibility in the spectrum access of femtocells. How to ensure secure data transmission and preserve user privacy in the new tiered network with secure macrocells and open femtocells is still an open issue.

Cognitive Cellular Networks

To address the challenges brought by the trends emerging in cellular networks, we should revisit the research issues in network deployment and resource management from multiple aspects. In general, it requires flexible network deployment methods over diverse spectral environments and dynamic resource management schemes in heterogeneous networks. We propose a new framework, called *cognitive cellular networks*, as shown in Fig. 2. We apply the cognitive radio techniques and investigate the following issues in cellular networks:

- Heterogeneous network coexistence
- Spectral diversity and opportunistic access
- Adaptive interworking with constrained network coordination

Specifically, a strong candidate solution in cognitive cellular networks should first allow and facilitate the coexistence of small cells of the same or different types (e.g., in-band and out-of-band) with macrocells under a spectrum access strategy. In cognitive radio networks, the coexistence problem is formulated between two independent user groups, primary users (PUs) and secondary users (SUs), respectively. SUs coexist with PUs under a predefined spectrum sharing method that specifies the visibility of nodes' intra- and inter- user groups, priority in spectrum access, and conflict resolution [5]. Usually, the spectrum sharing methods can be categorized as overlay, underlay, or interweave to agree with the requirements in different deployment scenarios. In overlay mode, for instance, PUs actively participate in the spectrum sharing and release some bandwidth in exchange for SUs' relay assistance during PUs' transmissions to mitigate the interference from SUs. While in interweave mode, spectrum sensing and the database of channel usage pattern are the primary solutions to deal with the coexistence issues since SUs are transparent to PUs.

The second question is how to identify the available resources for transmissions with different priorities in order to improve spectrum utilization efficiency. In cellular networks, users are usually scheduled for data transmission in the time, frequency, code, and space domains by a central controller. In a tiered network with heterogeneous network environments, however, the centralized approach may not be available or will be costly from both the computational and communication aspects. In cognitive radio networks, the available spectrum resources have been finely identified at different locations and times. The transmission pairs select the spectrum access opportunities that can satisfy the required transmission qualities (e.g., length and/or bandwidth). Also, the traffic flows are routed according to the distribution of spectrum resources at the nodes [5]. Introducing adaptive resource management in cognitive cellular networks can improve the resource utilization efficiency via making opportunistic transmission decisions based on the local traffic and channel conditions.

It is also critical to design efficient interworking schemes for heterogeneous cells in cognitive cellular networks. In the tiered network architecture, the nodes have diverse capabilities in transmissions. The coordinations between end users and cells or inter-cell greatly affect network performance since mismatch of operations or inappropriate transmission settings would generate severe interference. When the coordination has constraints in the network topology and limited bandwidth for the control panel, the case becomes worse. For example, coordination between the femtocell and the macrocell is limited since the femtocell BS is indirectly connected to the cellular core network through a local Internet cable, which prohibits the operators performing integrated network operations. Distributed decision making has been shown as a promising solution in cognitive radio study [9]. Based on partial and/or delayed network information (e.g., channel gains), the distributed decision making process can be modeled to capture the interworking between the femtocells and the parent macrocell. To achieve efficient spectrum sharing among a large number of distributed users, a game theoretical approach is usually used for resource management of heterogeneous cells [10].

In cognitive cellular networks, the aforementioned issues are considered on the following aspects: interference management over the tiered network architecture, mitigating the network bottleneck for opportunistic and energy-efficient spectral access, and coordination schemes to optimize network utility. A good candidate solution to the dynamic resource management usually integrates the cognitive radio techniques to optimize the performance and concerning implementation issues, as shown in Fig. 2.

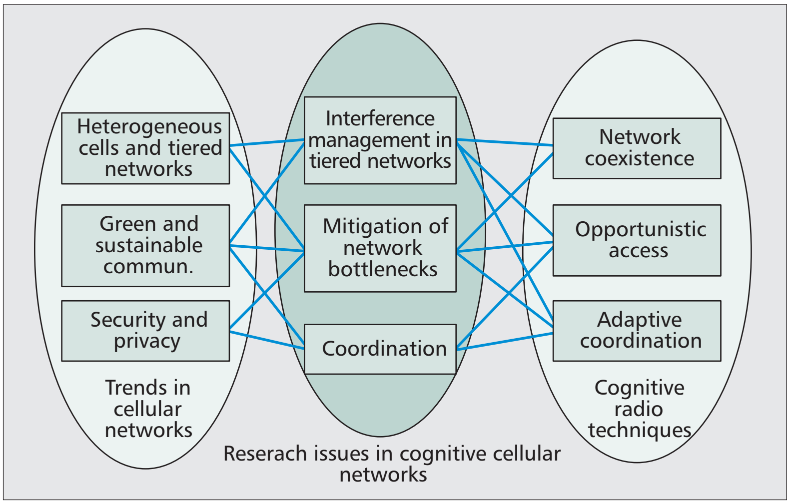

Figure 2. *The study framework of cognitive cellular networks.*

Interference Management in Tiered Networks

In cognitive cellular networks, small cells are employed to enhance the link quality and network capacity. As small cells operate in the same frequency as macrocells, severe co-interference exists among macrocell and small cell users. As shown in Fig. 1, mobile users served by macrocells may move to the edge of a cell, where they may experience strong signals from private femtocells. Similarly, the low-power transmissions in small cells are also likely to interfere with macrocell users. To mitigate the co-channel interference, some candidate approaches have been proposed.

Spectrum splitting refers to resource allocation by assigning orthogonal resources (e.g., subcarriers) to transmission pairs that cause strong interference to each other. In the tiered network, the operator can split the spectrum into subbands and assign them to neighboring small cells to reduce the interference between neighboring cells. However, such static allocation may cause waste of spectrum and reduce the adaptation to the varying traffic demands.

Power control adjusts the transmit power of nodes in the network to secure the reception quality at the receivers. It is a good candidate to reduce interference in the network and encourage energy-efficient transmissions. However, the central controller needs to acquire actual channel conditions and nodes' operational parameters to optimize performance, which introduces heavy coordination cost, especially in the tiered architecture.

Offloading tries to reduce strong interference sources by arbitrarily handing these users over to cells with better link quality to mitigate their interference on neighbors. In this approach, both link quality and resource allocation need to be considered before the handover. The availability of such a cell is another issue when the targeted femtocell is closed access, for private use only.

Network Bottleneck Mitigation

In cognitive cellular networks, as small cells become more likely to be deployed by users, it is very difficult for operators to determine the available network resources in real-time operations. In addition, the capacity of access links (e.g., the links between the users and the femtocell BS) and backhaul links (e.g., the one between the femtocell BS and its parent macrocell BS) may vary. The cellular downlink throughput can achieve 100 Mb/s, while the backhaul of a femtocell has limited capacity provided by Internet service providers, normally up

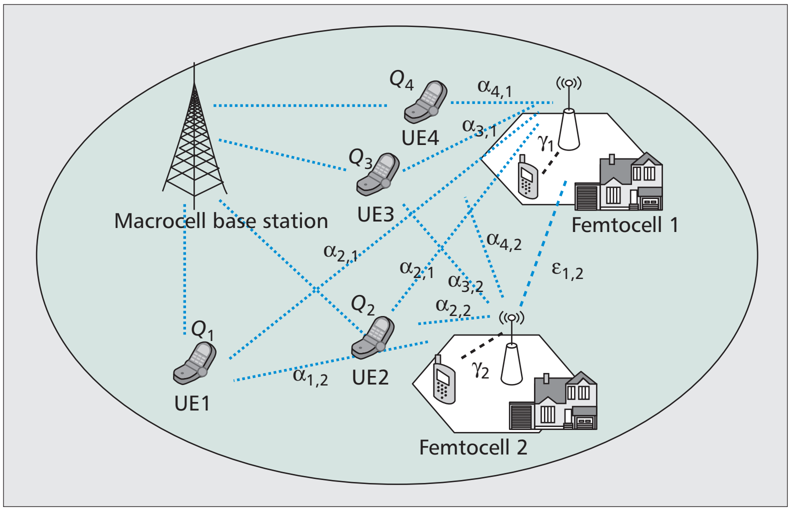

Figure 3. *Interference management in cognitive cellular networks.*

to 10 Mb/s according to the data plan by region and price. Therefore, the smaller bandwidth of the femtocell backhaul becomes a network bottleneck that limits the QoS of users. To tackle this problem, a possible solution is to allow multipath data transmissions through different network interfaces (e.g., using WiFi and cellular networks [4]) for the throughput aggregation at the end users.

In a communication network where the wireless backhaul is the bottleneck, opportunistic data forwarding is an efficient solution for cognitive cellular networks, jointly considering the forwarding capability of femtocell BSs and the traffic loads, as proposed in [5]. Specifically, the femtocell BS evaluates its forwarding capability based on the expected relay advancement in the forwarding direction as well as the interference in the transmission channels, which determines the order of relay candidates along the forwarding path. To fight against fading in wireless channels, the proposed forwarding scheme incorporates multiple nodes at each transmission so that the successful receiver, if there is any, can continue with the data forwarding if the nodes with higher forwarding capability fail. Such an opportunistic forwarding scheme adapts well to the dynamic channel conditions, and significantly reduces transmission failures in the backhaul.

Coordination in Cognitive Cellular Networks

In cognitive cellular networks, a user senses the channel conditions and makes the best strategy for its own utility. The egocentricity of individual operations may impair the whole network performance when effective coordination mechanisms are missing. Overall, resource management in cognitive cellular networks can be formulated as a network utility maximization problem. Specifically, under a transmission strategy, denoted by $\mathbf{a}$, which specifies the operation parameters of each node (cell selection, transmit power, etc.), the objective is to maximize the aggregated utility functions of all links in the network (i.e., $\max_{\mathbf{a}} \sum_{i \in C} \sum_{j \in C_i} U_{\mathbf{a}j}$), where C is the set of cells including all macrocells and small cells in the network, and C_i represents the set of active wireless access connections in cell i. Given the other nodes' transmissions, $\mathbf{a}_{-j}$, each node selects its transmission strategy, $\mathbf{a_j}$, to best respond to $\mathbf{a_{-j}}$ (i.e., $U_{\mathbf{aj},\mathbf{a-j}} \geq U_{\mathbf{a'_j},\mathbf{a-j}}, \forall\ \mathbf{a_j}, \mathbf{a'_j} \in \mathbf{a}, \mathbf{a'_j} \uparrow \mathbf{a_j}$). Furthermore, one candidate transmission strategy should not violate the network coexistence rules Γ, which determine the maximum allowable interference in the links (i.e., $\mathbf{I_a} \leq \Gamma$). The operators manipulate the decision making of individuals from the network aspect, such as load balance, interference management, and security. Candidate approaches include introducing incentive schemes [10], defining new utility functions for players [11], and so on.

Besides the competitions in the zero-sum game for radio resources, users and small cells can also cooperate for channel condition monitoring, handover management, and relay transmission. The cooperation can benefit the users who have limited capability to acquire the necessary network or channel conditions to make decisions. No matter whether competition or cooperation, the participating users require knowledge of all possible moves of other players or the required coordination information in cooperative communication. In cognitive cellular networks, the design of the coordination connections is critical, considering the overhead and performance.

Case Study: Dynamic Resource Allocation in Tiered Cellular Networks

We investigate the power management problem in a tiered network with both macrocells and femtocells. Self-deployed femtocells may cause severe interference with nearby macrocell users. As shown in Fig. 3, femtocell 2 is located at the edge of the macrocell. In the downlink, the leaked signal from femtocell 2 to the nearby macrocell user, UE2, may be stronger than UE2's received signal from the macrocell BS as UE2 is located at the edge of the macrocell. Therefore, femtocell 2 introduces significant interference on UE2's transmission. Many works on femtocells have addressed this problem [2]. However, existing solutions mainly focus on centralized resource management, which may not be suitable for a tiered cognitive cellular network where a robust distributed approach is more desirable due to the random deployment of femtocells.

In reality, the central controller of the macrocell can hardly fully control the affiliated femtocells, because these femtocells may not follow the scheduling information but prefer to aggressively compete for network resources to maximize their own utility. For example, femtocell BSs can increase their transmit power to achieve higher throughput while causing greater interference to neighboring users. In current cellular networks, the central controller may not be able to specify the violation behaviors of individual femtocells even when the neighboring macrocell users report the reception failure caused by such violation. In other words, the central controller cannot effectively eliminate the co-interference resulting from self-deployed femtocells.

To analyze the motivation and behavior of femtocells in violation of the centralized scheduling, we apply a game theory approach to study power management, which is widely used for resource allocation among PUs and SUs in cognitive radio networks [11]. We derive the downlink interference, and the uplink analysis can be obtained in a similar way.

As shown in Fig. 3, a group of closed access femtocells are located in the serving area of a macrocell, all cells operating in the same frequency band. In the macrocell, there are M active macrocell users in the downlink, denoted by $U = \{u_1, u_2, \ldots, u_M\}$. u_i has a threshold Q_i, which indicates the maximum tolerable interference level in the downlink. The macrocell users are scheduled to transmit in non-overlapping resource blocks so that there is no interference among macrocell users. The active femtocells in the downlink form a set $F = \{f_1, f_2, \ldots, f_N\}$ with size N. In a femtocell, the femto BS schedules one user for transmission at a time. Therefore, there is one active link in each femtocell at any time. The transmit power of femtocell f_j is denoted by P_j. We assume that the channel gains, $\alpha_{i,j}$ of the link between u_i and f_j, $\varepsilon_{j,k}$ of the link between f_j and f_k, and γ_j of the link within f_j are known to each femtocell as well as Q_i of each u_i, and the links are symmetrical.

The aggregated interference at u_i should satisfy $P_1\alpha_{i,1} + P_2\alpha_{i,2} + \ldots + P_N\alpha_{i,N} \le Q_i$; otherwise, u_i is blocked. The capacity function c_j for femtocell f_j is defined as

$$c_j = \log_2\left(1 + \frac{P_j\gamma_j}{N_0 + \Sigma_{k \neq j} P_k \gamma_k}\right).$$

It is favorable for the femtocell BSs to use the maximal transmission power to achieve the highest link capacity. Therefore, femtocells may like to violate the power control strategy made by the central controller, which may cause co-channel interference with macrocell users. To address this issue, we apply the randomized silencing policy proposed in cognitive radio networks [10]. The policy is very straightforward: if any macrocell user u_i experiences interference greater than its limit Q_i, the central controller will randomly select one active femtocell from F and force it to turn off in the current transmission period. Such a silencing process continues for several rounds until no macrocell user reports the blocked case.[1]

Given a power allocation strategy of femtocells, $\mathbf{P} = \{P_1, P_2, \ldots, P_N\}$, once the interference requirement is met at each macrocell user, the utility of the macrocell is determined. The objective of resource allocation is to find the maximum aggregated utility of femtocells, which can be denoted as $\max_{\mathbf{P}} \Sigma_{j\in F} E[c_j \cdot \mathbf{1}_j]$, where the function $\mathbf{1}_j = 1$ if f_j is not shut down after the silencing process, and 0 otherwise. As each femtocell intends to maximize its utility by selecting the transmission power best responding to the transmission powers of other nodes, a candidate $\mathbf{P}$ would be a power allocation of the Nash equilibrium (NE).

Here, we present some preliminary results to explore the NEs for the optimal value. Using the theorems in [10], we can easily prove the orthogonal power allocation

$$P_{OR} = \begin{Bmatrix} \min_i \left\{\frac{Q_i}{\alpha_{i,1}}\right\}, \min_i \left\{\frac{Q_i}{\alpha_{i,2}}\right\}, \ldots, \\ \min_i \left\{\frac{Q_i}{\alpha_{i,N}}\right\} \end{Bmatrix}, i \in U$$

is an NE.

Moreover, we notice that a macrocell user causes significant interference when it is closer to some active femtocells than others. Therefore, the femtocell needs to avoid transmission in the resource block assigned to the nearby macrocell user if it is detected by the femtocell.[2] The femtocell can learn the allocation of resource blocks of each macrocell user by listening to the allocation message broadcasted by the macrocells at the beginning of each transmission period. In such case, we can also prove that the orthogonal power allocation

$$P_{OR} = \begin{Bmatrix} \min_{i\in U\backslash S_1} \left\{\frac{Q_i}{\alpha_{i,1}}\right\}, \min_{i\in U\backslash S_2} \left\{\frac{Q_i}{\alpha_{i,2}}\right\}, \ldots, \\ \min_{i\in U\backslash S_N} \left\{\frac{Q_i}{\alpha_{i,N}}\right\} \end{Bmatrix}$$

is an NE where S_j is the set of macrocell users near f_j with the channel gain ai,j greater than a predefined threshold.

To evaluate the performance of the proposed power allocation scheme, we simulate the network with Rayleigh fading channels where all $\alpha_{i,j}$ fade independently with average $\bar{\alpha}$, all $\varepsilon_{j,k}$ fade independently with average $\bar{\varepsilon}$, and all γ_j fade independently with average $\bar{\gamma}$ [10]. We set $M = 20$ and $N = 5$ in the macrocell, and $\bar{\alpha} = 1$ dB, $\bar{\varepsilon} = 1$ dB, and $\bar{\gamma}$ ranges from 1 to 50 dB. In each experiment, we randomly select two femtocells with a significant neighboring macrocell user, i.e, $\bar{\alpha} \approx \bar{\gamma}$. It can be seen in Fig. 4 that the recognition of the significant interference sources in femtocells can improve the interference management in cellular networks and achieve higher throughput for femtocells.

Based on the discussion above, a good candidate solution is to integrate the considerations of the performance requirements and the corresponding techniques. Specifically, we treat the interference management problem as the major design objective by identifying the link interference conditions in the macrocell and femtocells. Meanwhile, we also take into consideration the performance requirements of limited interworking bandwidth and efficient coordination. On network bottleneck mitigation, regarding the limited bandwidth from the femtocell to the core network, we design the solution using game theory to analyze the nodal behavior in favor of its own utility. On coordination mechanism design, we develop the random shutdown scheme as the penalty for misbehavior that generates less control overhead while maintaining effective regulation.

A macrocell user causes significant interference when it is closer to some active femtocells than others. Therefore, the femtocell needs to avoid transmission in the resource block assigned to the nearby macrocell user if it is detected by the femtocell.

[1] The shutdown process is valid in cellular networks where macrocell users are protected with higher priority because they have been admitted into the serving macrocell. When the self deployed femtocells register at the cellular operator, they are required to yield to the priority of macrocells if confilicts occur.

[2] It is valid in cellular networks because the users measure the signal strength from visible cells, and the femtocell can detect such a nearby macrocell user through this process, although it may reject the user's access request if the user is not a private member.

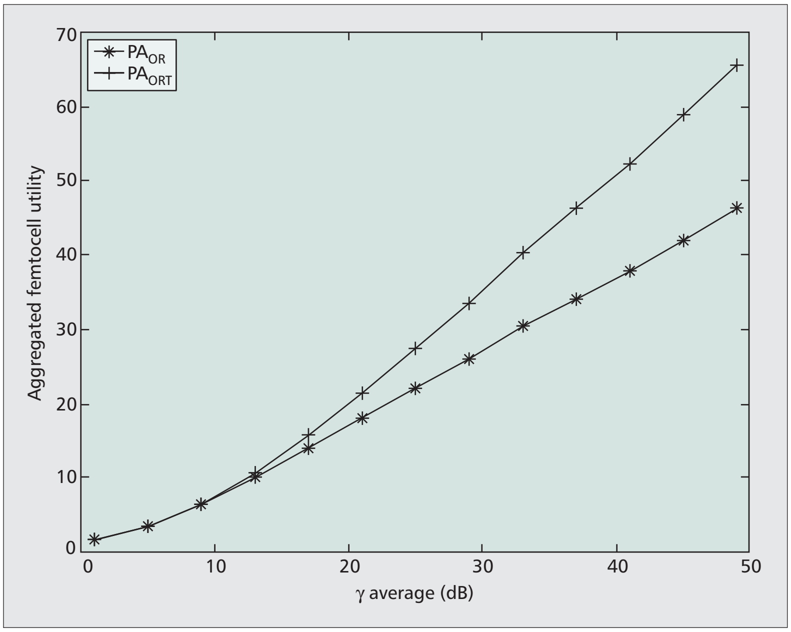

Figure 4. *Aggregated femtocell utility under intra-femtocell channel gains.*

Conclusion and Future Research

In this article, we have studied network deployment and resource management in a cognitive cellular network with both macrocells and small cells in a tiered architecture. We have discussed the main research trends and challenging research issues in cellular networks and proposed a framework of cognitive cellular network to address the challenges. A game-theory-based approach to efficient power control has also been provided for studying resource allocation in a cognitive cellular network where femtocells are deployed.

To further improve the performance of cognitive cellular networks, we can jointly consider power control and subcarrier allocation in a resource management framework. Some efforts on the standardization of cellular networks are needed to incorporate the new features, for example, direct coordination between the femtocell and macrocell base stations. Also, a cross-layer solution to improve the overall network efficiency and sustainability is an interesting yet challenging issue.

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