COGNITIVE FEMTOCELL NETWORKS: AN OPPORTUNISTIC SPECTRUM ACCESS FOR FUTURE INDOOR WIRELESS COVERAGE

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ABSTRACT

Femtocells have emerged as a promising solution to provide wireless broadband access coverage in cellular dead zones and indoor environments. Compared with other techniques for indoor coverage, femtocells achieve better user experience with less capital expenditure and maintenance cost. However, co-channel deployments of closed subscriber group femtocells cause coverage holes in macrocells due to co-channel interference. To address this problem, cognitive radio technology has been integrated with femtocells. CR-enabled femtocells can actively sense their environment and exploit the network side information obtained from sensing to adaptively mitigate interference. We investigate three CR-enabled interference mitigation techniques, including opportunistic interference avoidance, interference cancellation, and interference alignment. Macrocell activities can be obtained without significant overhead in femtocells. In this article, we present a joint opportunistic interference avoidance scheme with Gale-Shapley spectrum sharing (GSOIA) based on the interweave paradigm to mitigate both tier interferences in macro/femto heterogeneous networks. In this scheme, cognitive femtocells opportunistically communicate over available spectrum with minimal interference to macrocells; different femtocells are assigned orthogonal spectrum resources with a one-to-one matching policy to avoid intra-tier interference. Our simulations show considerable performance improvement of the GSOIA scheme and validate the potential benefits of CR-enabled femtocells for in-home coverage.

INTRODUCTION

Mobile Internet service has spurred exponential growth in cellular network usage, such as video sharing, game playing, and movie downloading. The explosion of data traffic volume has been further fueled by smartphones and various portable devices. To enhance mobile broadband access, the Third Generation Partnership Project (3GPP) Long Term Evolution Advanced (LTE-Advanced) standard has been developed to support higher throughput and better user experience. Moreover, it is predicted that in the near future a large amount of traffic (about 60 percent of voice traffic and 90 percent of data traffic) will originate from indoor environments (e.g., residential home and office) [1]. However, mobile cellular networks have a reputation for poor indoor coverage due to the penetration losses of walls. The attenuation is more prominent at higher frequency in LTE-Advanced. The traditional cell splitting with denser base station (BS) deployments cannot improve network capacity and coverage much. This is because the cell splitting gains are severely reduced by high intercell interference. Furthermore, dense macro BS deployments cause high capital expenditure and operational cost. Hence, it is important to find an alternative strategy to improve indoor coverage.

Femtocells offer a promising solution for indoor communications. A femtocell access point (FAP) is a low-power, low-cost, short-range, plug-and-play cellular BS deployed in a residential area or small office. FAPs enhance system capacity and coverage via improving link quality and enabling spectral reuse. In femtocells, higher data rates and better coverage are achieved by shorter communication distance and less penetration loss. Furthermore, high cellular capacity is reached by efficient spatial spectrum reuse in a smaller cell size. Femtocells not only provide better quality of service (QoS) to indoor users, but also diminish site expenditure, maintenance cost, and power consumption of base stations [2]. Nowadays femtocells have attracted a lot of attention from both academia and industry.

The channel deployment of femtocells in a two-tier heterogeneous network has three options: dedicated-channel deployment, partial-channel-sharing deployment, and co-channel deployment. Co-channel deployment is more attractive to operators due to low cost and backward compatibility. However, co-channel deployments of closed subscriber group (CSG) femtocells create coverage holes in macrocells. In order to solve this problem, cognitive femtocells are developed to sense their surroundings

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Specifications	Femtocell	Picocell	DAS	Relay	Wi-Fi
Typical power	10–100 mW	Outdoor: 250 mW–2W, indoor: < 100 mW		Outdoor: 250 mW–2W, indoor: < 100 mW	100–200 mW
Coverage range	20–50 m	150 m	Coverage extension of macro	Coverage extension of macro	100–200 m
Services	Real-time voice and data	Real-time voice and data	Real-time voice and data	Real-time voice and data	Primarily data and VOIP
Deployment scenarios	In-home/office	Hot spot/office	Indoor extension	Hot spot/office/ tunnel, high-speed train	In-home/hot spot
Access mode	Closed/open/hybrid	Open access	Open access	Open access	Closed/open access
Backhaul	DSL/cable/optical fiber	X2 interface	Optical fiber or RF links to macrocell	Wireless in-band or out-of-band	DSL/cable/optical fiber
Peak data rate	LTE-Advanced (3GPP R10): 1G b/s (DL) 300M b/s(UL)				600 Mb/s (802.11n)

Table 1. *Comparison of various indoor wireless access technologies.*

and flexibly adapt their operations to minimize interference. In the cognitive paradigm, interference mitigation approaches can be classified as opportunistic interference avoidance, interference cancellation, and interference alignment.

The goal of this article is to study how cognitive radio (CR)-enabled femtocells mitigate both inter-tier and intra-tier interference to improve indoor coverage in a two-tier heterogeneous network. We first compare femtocells with other existing technologies for indoor coverage. Next, we investigate the problem of macrocell coverage holes caused by co-channel CSG femtocells. Then we study three CR-enabled interference mitigation approaches in co-channel deployment. A joint opportunistic interference avoidance scheme with Gale-Shapley spectrum sharing (GSOIA) is presented to mitigate both intra- and inter-tier interference. Finally, simulations are conducted to evaluate performance improvement of the proposed scheme on interference mitigation.

Indoor Coverage: Existing Technologies

Various technologies for indoor coverage are summarized in Table 1. In LTE-Advanced, femtocells, picocells, relays, and distributed antenna systems (DASs) are low-power nodes in a heterogeneous network [3]. Picocells are located inside hotspots like airports, shopping malls, and stadiums. Picocells work as simplified macrocells with low power and reduced cost. DASs comprise many separate antenna elements (AEs) connecting to macro BSs via dedicated fiber cables or radoi frequency (RF) links to extend macro coverage. A set of low-power distributed AEs replace high-power centralized antennas to cover the same cell area. Relays are installed in cellular dead zones without wired backhaul to compensate for the attenuation loss of barriers, such as buildings, tunnels, or high-speed trains. Although picocells/DASs/ relays are cost-effective alternatives to macrocells, they are still too expensive to be deployed in a house or small office. As an energy-saving, cost-efficient small cellular base station, FAP is suitable for a residential home that connects with the service provider's network via home broadband.

Wi-Fi is another popular wireless broadband access technology. A Wi-Fi router is also a plug-and-play access point without time-consuming network planning. Wireless LAN (WLAN) mainly provides data service and voice over IP (VoIP), while a femtocell realizes any call in real time. Although the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism in WLAN is a simple distributed coexistence solution, it is not robust due to the static resource allocation nature. Because of the selfish coexistence strategy, their mutual interference acutely increases with widespread deployments of WLAN. However, low-cost WLAN is still very attractive for free spectrum license on the industrial, scientific, and medical (ISM) band. In order to compete with Wi-Fi technology, FAP should improve performance at a reasonable price.

Femtocell Deployment and Technical Challenges

Femtocell Deployment Scenarios

Femtocells are overlaid within macrocells in a two-tier heterogeneous network. Allocating spectrum resources between femtocells and macrocells is a very important issue. There are three possible strategies for femtocell resource deployment: dedicated-channel deployment, partial-channel-sharing deployment, and co-channel deployment [3].

1) Dedicated-channel deployment: Femtocells are allocated a dedicated carrier frequency different from those of macrocells. This deployment is a simple solution to avoid mutual interference between the two tiers, but the spec-

Inter-tier interference (or cross-tier interference) and intra-tier interference coexist in this network. For inter-tier interference, the aggressor and the victim of interference belong to different tiers, while they belong to the same tier in intra-tier interference.

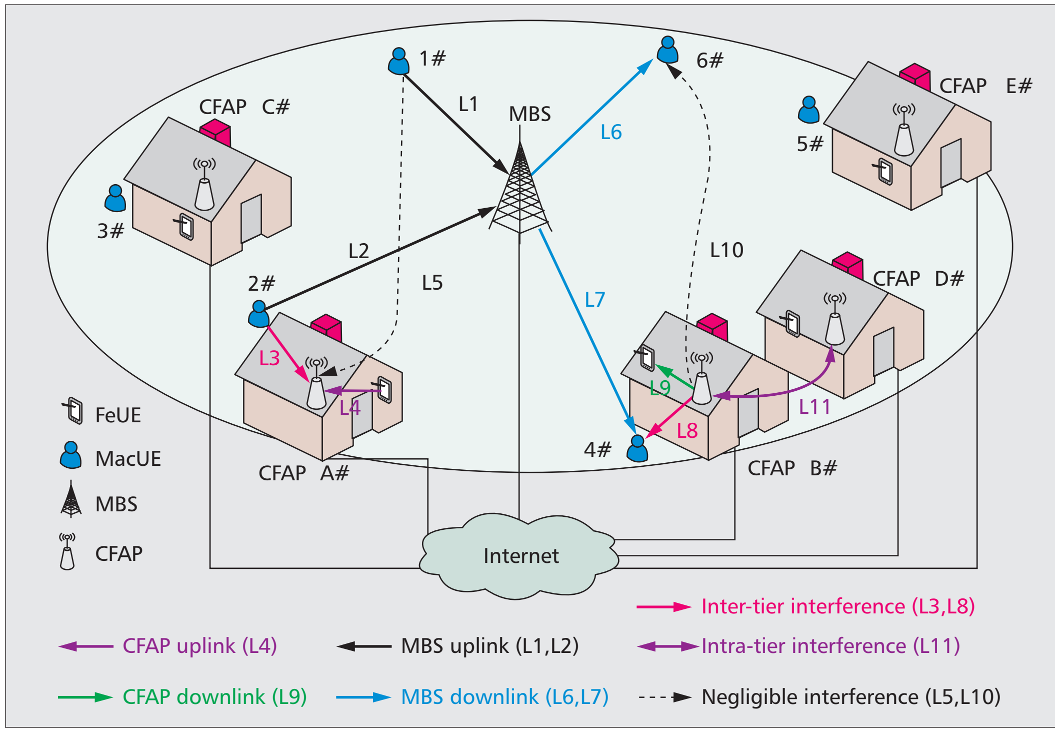


Figure 1. *Interference scenarios related to femtocells in co-channel CSG deployment.*

tral usage is inefficient due to bandwidth segmentation.

2) Partial-channel-sharing deployment: The overall bandwidth is segmented into two parts. One part is exclusively assigned to macro users, and the other part is shared by macrocells and femtocells. Macro users benefit from ubiquitous coverage on exclusive carrier frequency and partial coverage (outside the femtocell coverage) on sharing carrier frequency. This deployment is efficient without causing much bandwidth loss and mutual interference, but a portion of spectrum and high-cost carrier-aggregation-capable terminals are required.

3) Co-channel deployment: In this deployment, spectral usage is high because femtocells are deployed in the same carrier frequency as macrocells without bandwidth segmentation. This low-cost and backward-compatible strategy does not rely on high spectrum availability and carrier aggregation support at terminals. Co-channel deployment is especially attractive for operators in crowded spectrum. Nevertheless, co-channel deployments of CSG femtocells create coverage holes in macrocells due to the inter-tier interference. The details are given below.

Macro Layer Coverage Holes

Interference in macro/femto heterogeneous networks is more complicated than that of macrocells. Inter-tier interference (or cross-tier interference) and intra-tier interference coexist in this network. For inter-tier interference, the aggressor and the victim of interference belong to different tiers, while they belong to the same tier in intra-tier interference.

Coverage holes in macrocells are caused by co-channel interference (CCI) in CSG deployments of femtocells. Figure 1 illustrates various interference scenarios in a heterogeneous network. When a macro base station (MBS) is transmitting to macro user equipment (MacUE) 4# and 6# in the macro downlink (DL), the downlink of unregistered MacUE 4# (L7) is interfered by nearby closed CFAP B# (L8). Strong interference (L8) possibly causes communication outage of MacUE 4#. On the other hand, interference (L10) from CFAP B# to MacUE 6# is negligible due to the long distance between them. Hence, DL resource blocks (RBs or channels) of MacUE 6# can be reused by CFAP B#. Similarly, interference from MacUE 2# to CFAP A# (L3) is strong, while interference from MacUE 1# to CFAP A# (L5) is weak in the macro uplink (UL). Since interference between remote macro users and CFAP is negligible, RBs of macro users can be reused by a distant CFAP. More spectrum holes can be explored by sensing locations of macro users.

Unique features of femtocells pose challenges to interference management in a two-tier heterogeneous network. The ad hoc nature of femtocells makes centralized network planning infeasible. Moreover, intercell interference coordination (ICIC) cannot be implemented due to the lack of a direct X2 interface in LTE-Advanced. The delay of information exchange via wired backhaul (S1 interface) is too long to allow for efficient coordination. A static operation, administration, and maintenance (OAM) based solution in co-channel CSG deployment is just "time-of-day" adaptation, which is unable to adapt to the instantaneous characteristics of actual network traffic. As an intelligent wireless technology, cognitive radio provides an adaptive solution to mitigate interference in dynamic environments.

INTERFERENCE MITIGATION IN COGNITIVE FEMTOCELL

COGNITIVE FEMTOCELL

Cognitive radio technology holds great hope to break spectrum gridlock through advanced radio techniques and novel coexistence protocols. In order to meet stringent requirements of the LTE-Advanced standard, cognitive radio is integrated with femtocells to eliminate interference. Cognitive capability and self-configured capability are the main characteristics of cognitive femtocells [4]. Awareness of the radio scene is essential for CFAPs to obtain available spectrum opportunities in macrocell networks. Spectrum opportunities exist in various domains: frequency, time, geographical space, code, antenna spatiality [5]. Self-configuration capability helps CFAPs to coexist in a two-tier network without impact on existing cellular networks.

Figure 2 shows cognitive radio technology in femtocells from the cross-layer perspective. The cognitive and self-configuration modules are synthesized by a cognitive engine. The cognitive module first senses the environment and collects specific information of all layers (e.g., spectrum holes, collision probability, and QoS requirement). Then the cognitive engine analyzes spectrum characteristics and estimates available resources. Finally, the self-configuration module exploits cognitive information in a spectrum state database to optimize parameters of all layers in dynamic surroundings.

The self-configuration module includes three components: spectrum mobility, spectrum sharing, and spectrum configuration. Spectrum mobility management enables femtocells to smoothly hand over, which minimizes their performance degradation as much as possible when macro channels are unavailable or current channel conditions become worse. Spectrum sharing management avoids co-channel collisions of multiple femtocells, like the medium access control (MAC) mechanism in many networks. The spectrum configuration module ensures that femtocells work in the best available channels. Configurable parameters in the physical layer include time-frequency resource blocks of orthogonal frequency-division multiplexing (OFDM), modulation and coding schemes, transmission power, and antenna angle.

The ognitive module provides femtocells with radio awareness capability, while the self-configuration module enables femtocells to adapt to a dynamic environment. Any change sensed by the cognitive module automatically triggers an adjustment. With learning and reasoning capabilities, cognitive femtocells keep track of variations and estimate spectrum state from historical data in a dynamic environment. Since CFAPs have potential to adaptively allocate radio resources and efficiently mitigate co-channel interference (CCI) in a two-tier network, it is promising to apply CR-enabled femtocells to break through the spatial reuse barrier of cellular systems.

COGNITIVE INTERFERENCE MITIGATION OVERVIEW

CR-enabled femtocells can exploit side information about their environment, including macrocell activities, channel gains, codebooks, and

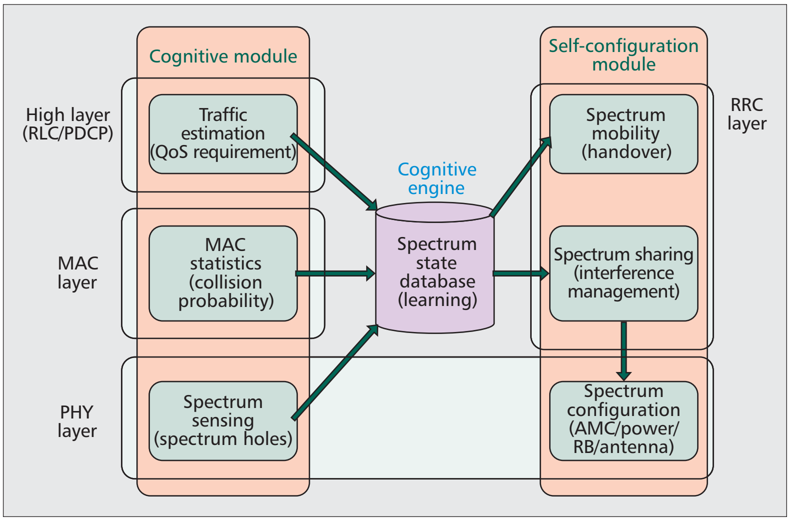


Figure 2. *Cognitive radio technology in femtocells.*

messages to mitigate interference in a two-tier cellular network [6]. In the cognitive paradigm, interference mitigation techniques include opportunistic interference avoidance, interference cancellation, and interference alignment. Table 2 compares the three techniques.

Opportunistic Interference Avoidance — Since femtocells are overlaid within macrocell networks, opportunistic spectral access can be exploited for the hierarchal overlay system to avoid inter-tier interference. After sensing macrocell activities that acquire available spectral resources, CFAPs exploit unoccupied spectrum holes or white spaces to minimally disrupt macrocell communications. Accurate macrocell activities are required for orthogonal resource allocation to avoid inter-tier interference. Opportunistic access improves overall spectral efficiency from a perspective of temporal, spectral and spatial reuse of RBs between macrocell and femtocells.

Interference Cancellation — This scheme is suitable for strong interference that is demodulated or decoded along with channel estimation to cancel received interference from desired signals. Interference cancellation requires knowledge of macrocell messages and codebooks. Dirty paper coding (DPC) or sphere decoding techniques may be used to cancel interference signals from the desired signal [7].

Interference Alignment — In this scheme, all interference is restricted into approximately half of the signal space at each receiver, leaving the other half interference-free space for the desired signal. The enabling premise for perfect interference alignment is that cognitive femtocells have knowledge of global channel state information. Although interference alignment achieves more degrees of freedom under a time-varying channel, global channel knowledge must be learned before its benefits translate into practice [8].

The three approaches differ in the nature of the side information obtained from sensing. Opportunistic interference avoidance requires femtocells to communicate using spectral holes,

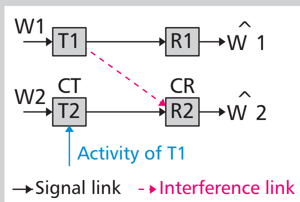
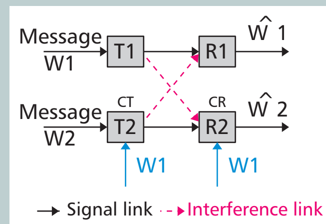
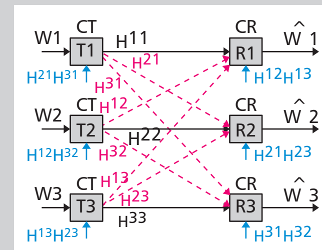
	Opportunistic interference avoidance	Interference cancellation	Interference alignment
Side information requirement	Activities of macrocells in multiple domains: time-frequency, space/location, antenna spatiality	Channel gains, codebooks, and messages of macrocells	Global channel state information
Interference mitigation approach	Exploit spectrum holes to avoid interference in the interweave paradigm.	Dirty paper coding (DPC) or sphere decoding in the overlay paradigm	Align all interference in half of the received signal space, and leave the other half interference-free for the desired signal.
Interference channel model			

Table 2. *Comparison of CR-enabled interference mitigation techniques.*

so ideally they cause no interference. In contrast, interference cancellation exploits strong interference through sophisticated coding strategies to facilitate communications for others. Interference alignment orthogonalizes all interfering signals and the desired signal to avoid interference. With different network side information, the three techniques achieve different network degrees of freedom. Because macrocell messages or channel knowledge must be acquired with more communication overhead in the interference cancellation and interference alignment approaches, an opportunistic interference avoidance scheme is desirable to mitigate both types of interference with less complexity.

The GSOIA Solution

In this article we present GSOIA to mitigate both tiers' interferences. We propose this interweave-paradigm-based scheme because macrocell activities can be obtained without significant overhead in femtocells. The goal is to opportunistically exploit spectrum holes to improve network spectral utilization. The key ideas are:

- With the opportunistic interference avoidance approach, CFAPs exploit orthogonal spectrum resources (idle time-frequency RBs of a macrocell) obtained from sensing to avoid inter-tier interference.
- GSOIA: A one-to-one policy to avoid multiuser collisions is utilized to mitigate intra-tier interference.

In the GSOIA scheme, macrocells and femtocells are modeled as primary users (PUs) and secondary users (SUs) in a CR network, respectively. Figure 3 shows the procedure of the GSOIA scheme. First, CFAPs independently sense radio surroundings to explore spectrum holes. Then spectrum sharing based on Gale-Shapley (G-S) theory provides a one-to-one matching policy to allocate available spectrum holes among multiple CFAPs in a distributed fashion. CFAPs periodically monitor resource occupancy state and exploit spectrum holes to communicate. Once macrocell users are present in these resources, CFAPs vacate spectrum holes immediately.

Opportunistic Interference Avoidance

The challenge of opportunistic interference avoidance is how to reliably detect spectrum holes in macrocell networks. It is noted that spectrum holes are not only blank macrocell RBs, but also interference-free RBs allocated to faraway macro users from femtocells. Instead of using a central database of spectrum usage lists in TV white space bands, CFAPs detect macrocells' activities via two methods: listening to scheduled information of a macro BS (MBS) or actively sensing their environment. A hybrid scheme combining two approaches is summarized below:

- A CFAP listens to scheduled information from MBS over the air. As MBS broadcasts scheduled information in a signaling channel with relatively high transmission power, any CFAP in the cell can get knowledge of resource maps. The "eavesdropping" mechanism is reasonable in practice because MBSs and CFAPs belong to the same operators.
- CFAP periodically senses spectrum to identify nearby MacUE. Various techniques of spectrum sensing are applied to identify macrocell activities, such as energy detection, cyclostationarity feature detection, waveform-based sensing, matched filtering, and radio identification. A simple method is to measure the interference power of each RB. In LTE-Advanced, the received interference power in DL/UL is adopted as a mandatory sensing quantity in BSs. Hence, our approach can be applied to LTE-Advanced without hardware modification.
- CFAP compares sensing outcomes with scheduled information to identify spectrum opportunities. The detailed signal processing procedure is discussed in [9]. CFAP updates a pool of unoccupied spectrum resources and only selects idle channels to communicate.

The hybrid sensing scheme improves reliability of spectrum detection in which scheduled information increases the accuracy of spectrum sensing, and spectrum sensing obtains more spectrum opportunities by identifying nearby macro users. After acquiring a pool of available spectrum resources, the subsequent challenge is how multiple CFAPs share spectral resources. Collisions happen when the same channel is simultaneously selected by neighboring CFAPs (collocated CFAPs). The Gale-Shapley spectrum sharing scheme is propounded to resolve this issue.

GALE-SHAPLEY SPECTRUM SHARING

Intuitively, a one-to-one matching policy between CFAPs and channels is a solution to multi-user collisions. The Gale-Shapley theorem can achieve a stable one-to-one matching by an iterative procedure. Hence, it is a feasible scheme to avoid interference among collocated CFAPs.

In the context of cognitive spectral allocation, the preference of a CFAP for a channel is denoted by channel utility in the Gale-Shapley theorem. Channel utility R is denoted by the normalized transmission rate of CFAP on a channel.

$$R = \left[\frac{T - T_s}{T}\right] \times I \times E(K) \times C \tag{1}$$

where T_s is the channel sensing and waiting time, I is the idle indication of the channel, $E(K)$ indicates multi-user collisions and is inversely proportional to the number K of competitive users, and C is the channel capability. A one-to-one matching function between the set of CFAPs and the set of available channels can be defined.

The essence of Gale-Shapley spectrum sharing is multichannel opportunistic sensing along with stable channel access control. It has been proven that a stable matching always exists in cognitive access control [10]. Lacking central control, backoff timers are triggered to implement distributed allocation. The Gale-Shapley spectrum sharing method is described as follows:

- Each CFAP first calculates the utility of every channel in a spectrum resource pool. Then the CFAP sets a backoff timer for every channel that is inversely proportional to channel utility.
- When a backoff timer expires, the CFAP detects the busy tone of the corresponding channel. If there is no busy tone over this channel, CFAP immediately selects it for communications. Otherwise, CFAP abandons this channel and waits for next backoff timer expiration.
- The process continues until each CFAP captures one channel or all channels are allocated.

To clearly explain this scheme, we give an example of the Gale-Shapley spectrum sharing method. In Table 3, there is a 3 × 5 utility matrix for three CFAPs and five channels. Each element is the utility of one user-channel pair, and the value in parentheses is the backoff time. Backoff time is inversely proportional to channel utility, which is calculated by measurement or by estimation from historical data. Table 4 shows the ping process. Figure 4 depicts channel allocation results in which each channel is selected by one CFAP without collisions according to channel utility order. It shows that Gale-Shapley spectrum sharing achieves a stable one-to-one channel selection in a distributed fashion.

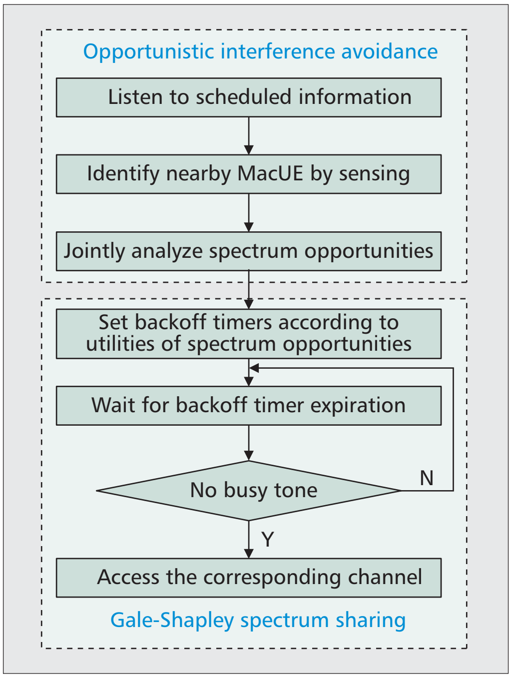


Figure 3. *The procedure of the GSOIA scheme.*

Because macrocell messages or channel knowledge must be acquired with more communication overhead in the interference cancellation and interference alignment approaches, an opportunistic interference avoidance scheme is desirable to mitigate both interferences with less complexity.

	CH1	CH2	CH3	CH4	CH5
User1	5(0.95)	11(0.89)	40(0.60)	22(0.78)	13(0.87)
User2	25(0.75)	30(0.70)	35(0.65)	14(0.86)	29(0.71)
User3	12(0.88)	28(0.72)	21(0.79)	4(0.96)	17(0.83)

Table 3. *Utility matrix.*

PERFORMANCE EVALUATIONS

We conduct simulation experiments to evaluate the performance improvement of the GSOIA scheme, and the simulation results are shown in Fig. 5 and Fig. 6. Femtocells are randomly deployed in the coverage area of a macrocell, and macro users are dispersed at random locations. Users are assumed to have continuous data flows to transmit. A group of collocated femtocells are considered instead of standalone femtocells that have no intra-tier interference. Perfect sensing and synchronization of all CFAPs are assumed for the GSOIA scheme. If multiple CFAPs access the same channel, only one transmits successfully. The achievable throughput of a femtocell in each available channel is normalized. A random access scheme is chosen as the benchmark. Figure 5 shows the throughput gain of femtocells for different macro-user locations, which is used to evaluate the benefit of opportunistic access. In Fig. 6, we compare the overall femtocells throughput of the GSOIA scheme with that of random access under different femtocell numbers to validate the performance of Gale-Shapley spectrum sharing.

Time	User1	User2	User3
t=0	CH3	CH3	CH2
t=0.60	**CH3**	CH3	CH2
t=0.65		CH2	CH2
t=0.70		**CH2**	CH3
t=0.72			CH3
t=0.79			CH5
t=0.83			**CH5**

Table 4. *Gale-Shapley ping process.*

Figure 5 plots the overall femtocells throughput with and without sensing capability under different ratios of macrocell resource vacancies. Ten femtocells are deployed in the coverage area of a macrocell. The no-sensing scheme means that spectrum holes are obtained only by listening to scheduled information of MBS, while the sensing scheme denotes a hybrid scheme combining sensing with listening to scheduled information. The overall throughput improvement of femtocells by the sensing scheme is more significant than that of the no-sensing scheme. The reason is that femtocells can acquire additional interference-free spectrum opportunities of remote macro users. Spectrum opportunities are closely related to macrocell resource vacancies as well as the value of α. The parameter α denotes the percentage of macro users in the vicinity of femtocells. It is observed that as α increases from 50 to 75 percent, femtocells suffer higher inter-tier interference from ambient macro users and have fewer spectrum opportunities. When the macrocell resource vacancy is 30 percent, sensing capability can offer about 53 percent more gain than a no-sensing scheme (α = 50 percent), and the GSOIA scheme can provide an additional threefold performance improvement over a random access scheme in terms of overall femtocells throughput. Figure 5 shows that CR-enabled femtocells with sensing capability have potential to explore more spectrum holes, and the Gale-Shapley spectrum sharing approach greatly improves overall femtocells throughput.

Figure 6 shows performance gains of the GSOIA scheme over the random access scheme under different numbers of collocated femtocells. Twenty channels (RBs) are available to collocated femtocells, and 10 percent of macro users are located within the coverage areas of femtocells. Note that when the number of femtocells is more than 20 (the number of available RBs), the performance of the random access scheme gradually decreases due to more collisions with increasing femtocells. However, the performance of the GSOIA scheme is not impaired as it is a one-to-one matching policy. For example, when the number of femtocells and available RBs is the same (20), the GSOIA scheme can provide 170 percent throughput improvement over the random access scheme. The simulation result shows that the GSOIA scheme considerably outperforms the random access approach, especially in dense femtocell deployments.

Conclusion

In LTE-Advanced, femtocells are developed to support higher throughput and better user experience in homes and offices. Because of better link quality and efficient spectral reuse, femtocells not only improve indoor coverage and network capability, but also have less capital expenditure and maintenance cost than other low-power nodes in macrocell networks. With widespread deployments of femtocells, interference management is a challenge due to their unique features such as ad hoc mode, co-channel interference, and no direct coordination interface. To address the problem of macrocell coverage holes caused by co-channel interference, CR-enabled femtocells are studied to mitigate complicated interference in the two-tier heterogeneous network. In the cognitive paradigm, interference mitigation techniques include opportunistic interference avoidance, interference cancellation, and interference alignment. Different side information is required in these techniques to mitigate interference and increase

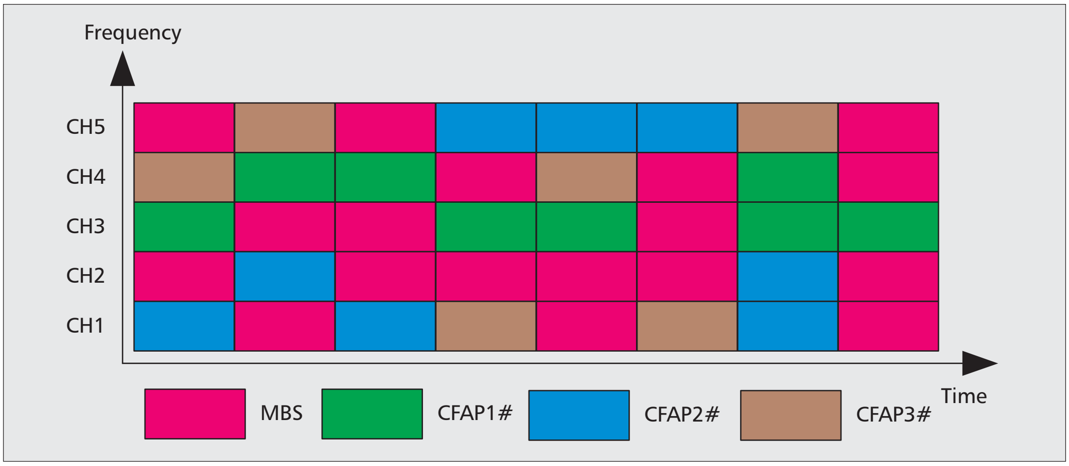


Figure 4. *Gale-Shapley spectrum sharing.*

the network degrees of freedom. Based on the fact that the side information of macrocell activities is available without significant overhead in femtocells, we propose a joint opportunistic interference avoidance scheme with Gale-Shapley spectrum sharing to mitigate both inter-tier and intra-tier interferences. With the opportunistic interference avoidance approach, CFAPs interweave their signals with those of macrocells without significantly impacting their communications. Gale-Shapley spectrum sharing provides a one-to-one matching policy to avoid collisions among multiple femtocells. Simulation results demonstrated considerable performance improvement of our scheme and showed that CR-enabled femtocells have good potential to break the spatial reuse barrier of cellular systems.

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Biographies

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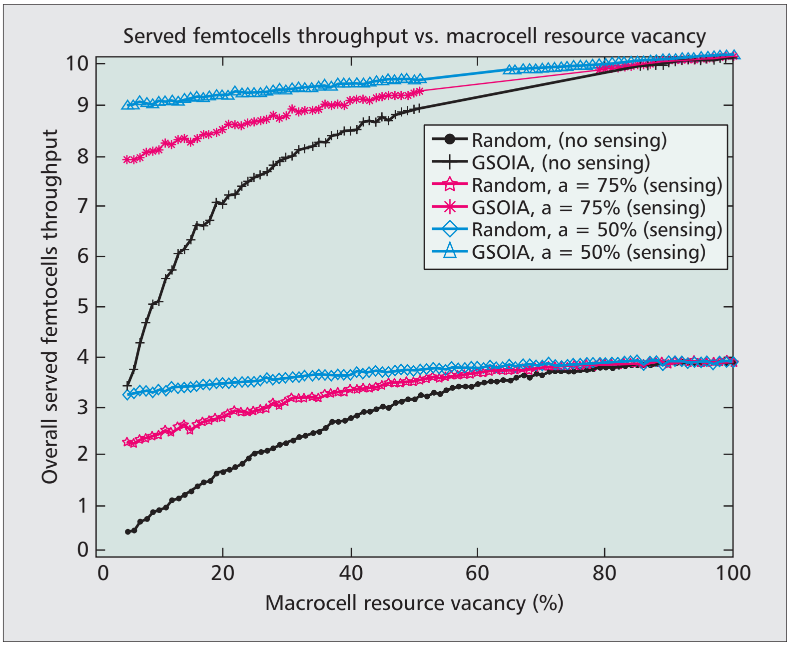

Figure 5. *Comparison of GSOIA vs. random spectrum sharing, scenario 1: different percentages of macrocell resource vacancies and macro users inside 10 co-channel CSG femtocells coverage.*

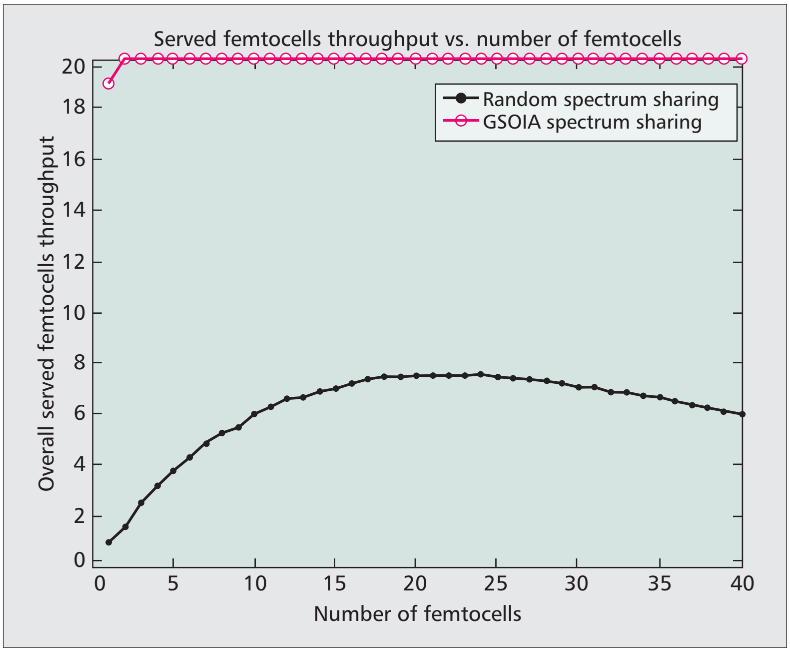

Figure 6. *Comparison of GSOIA vs. random spectrum sharing, scenario 2: different numbers of collocated femtocells share the same amount of spectrum resources (RBs = 20).*

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