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Research Article

Cognitive-Empowered Femtocells: An Intelligent Paradigm for Femtocell Networks

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Deploying femtocells has been taken as an effective solution for removing coverage holes and improving wireless service performance in 3G-beyond wireless networks such as WiMAX and Long Term Evolution (LTE). This article investigates a novel framework of dynamic spectrum management for femtocell networks, called cognitive-empowered femtocells (CEF), aiming at mitigating both cross-tier and intratier interferences with minimum modifications required on the corresponding macrocell network. With the proposed framework, each CEF base station (BS) and the femtocell users can utilize spatiotemporally available radio resources for the access traffic. We conclude that the proposed CEF framework can effectively complement the existing femtocell design and serve as a value-added feature to the state-of-the-art femtocell technologies, while achieving high scalability and interoperability by minimizing the required modifications on the macrocell protocol design.

1. Introduction

With a wide deployment of 3G and/or 3G-beyond wireless network infrastructure, ubiquitous communications and heterogeneous service provisioning can be achieved by an integrated macrocellular networking strategy that supports all the users in a single stage no matter they are mobile or fixed, indoor or outdoor, and for data or voice services [1]. A lesson learned from early experiences in developing macrocellular networks is that it is expensive to support both line-of-sight and non-line-of-sight communications in a typical range of a few tens of kilometers, and it becomes less economically viable to build infrastructures with increasing data rates. Besides, quality of service (QoS) could be noticeably degraded by the path loss, shadowing, and multipath fading effects due to wall penetration, which result in low data rates and poor voice quality inside the buildings.

One of the recent advances for overcoming indoor communication barriers without taking much infrastructure expenditure is the use of femtocells, which can achieve high data rate and manageable QoS for both users of macrocell and indoor femtocells. A femtocell is a small cellular area covering homes or offices, while a femtocell base station (BS) is simple, low-cost, and miniature access point designed for indoor wireless service coverage of the corresponding macrocell. As such, femtocell networks are end-user deployed hotspots that underlay the planned macrocell networks of mobile operators. Instead of using wireless transmissions like relays, a femtocell BS is connected with the macrocell BS via wired lines, such as coaxial cables. A femtocell provisions services as a whole with the corresponding macrocell BS, where a femtocell user could consume the femtocell resources at this moment yet switch to the macrocell and become a macrocell user in the next moment due to mobility, possibly by using different sets of radio resources and vice versa. Thus, a two-tier architecture is formed with the macrocell BS in the first/top tier and the femtocell BSs in the second/below tier.

1.1. Interference Resolution in Femtocell Networks. According to the most recent development in the 3GPP LTE/LTE-Advanced standardization progress, femtocells have the following three deployment modes [2–4]:

(i) Dedicated channel deployment: the femtocell and the macrocell utilize radio spectrum orthogonal to each other.

(ii) Cochannel deployment: the femtocell and the macrocell utilize a common set of radio subbands.

(iii) Partial cochannel deployment: some parts of radio spectrum utilized by the femtocell are orthogonal to that of the macrocell, while other parts of radio spectrum utilized by the femtocell overlap with that of the macrocell.

Although the dedicated channel deployment can avoid cross-tier interferences, the limited bandwidth of both femtocells and macrocell could seriously impair the performance. It is particularly not feasible under dense deployment of femtocells since each femtocell can only access very limited bandwidth. In the cochannel and partial cochannel deployment, on the other hand, a global scheduling scheme is needed for channel allocation; otherwise both the femtocells and the macrocell may suffer from terrible interference with each other. This becomes a major challenge in adopting these schemes.

A number of interference management approaches for femtocell networks have been reported, including a power control strategy for femtocell users [5], time hopped CDMA (TH-CDMA) combined with sectorized antenna [6], signal-to-interference-plus-noise based component carrier selection [7], and a centralized scheduling scheme that considers the mutual interference of both femtocell and macrocell users [8]. However, due to the design requirement for simplicity with minimum modifications on the macrocell protocols running at the BS, these interference management approaches may not be efficient and scalable. Note that the coverage of a macrocell could be over thousands of femtocells. Therefore, it is not a scalable solution in jointly considering those femtocell users in the design of macrocell resource allocation and scheduling schemes.

1.2. Does Cognitive Radio Take a Role? The concept of Cognitive Radio (CR) [9] was introduced decades ago, and its goal is to utilize spatiotemporally unused spectrum resources of licensed radio spectrums in a secondary and opportunistic manner, without interfering with the licensed user signals. Therefore, the CR techniques have been considered as attractive solutions to the improvement of spectrum utilization and mitigation of spectrum resource starvation for ubiquitous wireless services. The first standard aimed at using the CR techniques is IEEE 802.22, of which the initial drafts specify that the CR enabling networks should operate in spectrum allocated to Ultra High Frequency/Very High Frequency (UHF/VHF) TV broadcast service with a Point-to-Multipoint (P2MP) centralized infrastructure [3, 4].

To solve the interference management problem without imposing additional complexity and deviation from the current macrocell network design, we turn to consider the approach of CR dynamic spectrum management, which has demonstrated a strong synergy with the femtocell interference management in terms of their design premises and principle missions.

1.3. Outline of CEF Framework. This article investigates a novel framework of cognitive-empowered femtocells (CEF) for achieving efficient management for both cross-tier and intratier interferences. The CR dynamic spectrum sensing technique is taken as a built-in feature of the CEF BSs and the femtocell user handsets and aims to serve as an effective complement to the existing femtocell technologies. Under the CEF framework, the radio resources that a femtocell user can use to communicate with the CEF BSs are not only the licensed spectrum of the macrocell, but also the spectrum allocated to UHF/VHF TV broadcast services. This is expected to achieve effective interference management by minimizing the cross-tier and intratier interference via an opportunistic manner with little modification required on the macrocell protocol design. Besides, the consideration on other licensed bands can further resolve the possible bandwidth thirsty and improve QoS in femtocell networking.

To effectively and dynamically identify spatiotemporally available spectrum under the CEF framework, we propose a novel sensing coordination scheme for initiating interference-free communications between a CEF BS and its femtocell users. We will show that the proposed scheme can perfectly fit to the unique features and design premises of femtocell networks while taking the best advantage of the conventional standalone sensing and cooperative sensing strategies [10].

2. Dynamic Spectrum Sensing under CEF

Dynamic spectrum sensing is a unique feature in CR networks, which concerns whether an efficient and interference-free spectrum reuse at a CR device can be achieved. This section provides an overview on the state-of-the-art spectrum sensing technologies and the recently reported dynamic spectrum sensing schemes.

2.1. Existing Spectrum Sensing Techniques. There have been many spectrum sensing techniques proposed for radio-scene analysis [11], such as energy detection, cyclostationary detection, pilot-based coherent detection, and covariance-based detection. Due to the low computational complexity and easy implementation, energy detection is a natural choice for wideband sensing in CR networks [12]. The underlying motivation for using wideband sensing for CR networks is the desire to obtain as much vacant spectrum resources as possible in a simultaneous manner. Much of the focus has been placed in wideband sensing techniques on the signal reconstruction and detection decision making process [13–15].

An approach for reliable power spectral density (PSD) estimation and subband identification serves as a basis in achieving efficient wideband sensing when dealing with the heterogeneity of subbands over the spectrum. This is essential to the proposed CEF framework that deals with a dynamic network environment with changing subband availabilities and noise fluctuation conditions, as well as a heterogeneous mix of different macrocell users with different spectrum resource requirements. In this article, a state-of-the-art wideband sensing technique in [16] is employed for this purpose. It is characterized by a strong ability of noise fluctuation-free PSD estimation for wideband sensing as well as automatic detection of subband information from the acquired radio frequency signal, which is considered perfectly for the CEF BSs design in the energy detection based proactive sensing process under the proposed framework.

2.2. Dynamic Spectrum Sensing Schemes. A spectrum sensing technique takes a suitable dynamic sensing scheme as the implementation approach in a particular system. Cooperative sensing and standalone sensing are two most popular dynamic spectrum sensing schemes that have been widely reported and employed. With cooperative sensing, a central controller (e.g., a base station, cluster head, or a data sink) exercises a complete control over when and which subbands each wireless node must sense and makes a final decision on the spectrum availability by fusing the sensing results obtained from all the wireless nodes. With standalone sensing, on the other hand, each secondary user individually controls over when and which subbands to sense, and spectrum availabilities are solely determined based on its own observations. The advantages and disadvantages associated with both strategies are provided in Table 1.

Clearly, both sensing schemes are subject to limitations on the suitability for realizing the proposed CEF framework. For example, due to the nonnegligible heterogeneity in modern wireless networks which may accommodate devices of different vendors and wireless techniques, using a central controller to handle spectrum sensing, access and resource allocation processes may result in problems of low flexibility, poor scalability, and bad interoperability. In addition, the CEF BSs and femtocell users are simple devices, and it could be infeasible to implement a complicated distributed computing platform for cooperative sensing. Conversely, given that all the spectrum sensing and information processing are performed independently without any additional information and coordination, resolving the aforementioned problems could lead to significant performance degradation due to disorder accesses by secondary users, which then affect the sensing precision.

2.3. Sensing Coordination. The proposed CEF framework implements a coordinated spectrum sensing scheme, aiming to take the best of the two conventional spectrum sensing schemes, say cooperative sensing and standalone sensing, while avoiding the respective disadvantages, in order to satisfy the specific design requirements of the CEF networks. With coordinated sensing, when more radio resources are needed than that is available from the macrocell licensed bands, standalone sensing is performed under the coordination of associated CEF BS, which schedules the spectrum sensing process of all the surrounding femtocell users. Since the CEF BS simply instructs the sensing sequence and the range of spectrum for sensing instead of concluding the spectrum availability for each femtocell user, the master/slave relation between CEF BS and femtocell users is loosened when compared with cooperative sensing.

It is expected that integrating the sensing coordination scheme on top of the existing femtocell technologies allows for greater spectrum resource usage and efficient interference management, hence acting as a value-added complement to the femtocell network design. Its simplicity and efficiency, along with the high transparency to the existing protocols in the system, perfectly satisfies the desired features and original premises of modern femtocell systems.

3. The Proposed CEF Framework

The section first defines the functional modules of the CEF BSs, with a particular focus on the ones for dynamic spectrum sensing purposes, followed by the description of the proposed coordinated sensing scheme.

3.1. Functions of CEF BSs. The most distinguished feature of the CEF network is that a CEF BS can initiate communications with its femtocell users via both macrocell bands and unused TV bands in an opportunistic manner, so as to enlarge the system capacity while intelligently mitigating both cross-tier and intratier interference. Thus, in addition to the functions of existing femtocells, a CEF BS and its femtocell users explore both the macrocell's licensed bands as well as the licensed spectrum resources for UHF/VHF TV by periodically sensing the resource blocks via energy detection. The sensing at the CEF BS is to maintain real-time environmental and channel information related to the femtocell users. With the preliminary sensing results, the CEF BS schedules the femtocell users on when and which subbands to sense in a stochastic manner. It is clear that disorderly sensing among a group of femtocell users on a common set of available subbands could lead to incorrect sensing results and cause undesired interference [10]. Thus, under the coordination of the CEF BS, the femtocell users are instructed in terms of the range and priority of the possible channels to scan, and the coordination is expected to significantly improve the sensing accuracy at each femtocell user. Compared with cooperative sensing, the proposed coordinated sensing scheme has each femtocell user scan over a much smaller set of subbands with some certain sequence, which can effectively reduce the sensing delay and power consumption.

The CEF function is composed of two functional modules: *sensing coordination module* (SCM) installed at the CEF BS and *end-user modules* (EUM) equipped in the femtocell user handsets.

The operation at each SCM is comprised of three main processing phases: (i) proactive sensing, (ii) sensing coordination, and (iii) acknowledge (ACK) information adjustment. The operation of each EUM is comprised of two main processing phases: (i) knowledge-based estimation and (ii) sensing under reasoning.

The relations among the functional modules in SCM and EUM are shown in Figure 1. In the proactive sensing phase, the CEF BS periodically performs channel measurement to identify available resource blocks and collect real-time and immediate channel information. In each measurement period, the CEF BS performs sensing coordination by stochastically selecting likely available subbands and accordingly sharing the information with the EUM. This is to avoid cross-tier interferences.

With the shared information, the EUM estimate the sensing parameters such as the maximum number of sensing iterations and channel sequence for sensing and perform fine

Table 1: Comparison between cooperative and stand-alone sensing.

	Cooperative Sensing	Stand-alone Sensing
Density	Highly dependent on the density of sensing nodes. Highly dependent on independency of observation.	N/A
Heterogeneity Signals	May result in the situation where secondary users submit different sensing results and conclusions due to different perceptions of heterogeneity signals.	N/A
Communication Overhead	Heavier communication overhead.	N/A
Time Sensitivity	Introduce additional delay from collecting sensing results from sensing nodes to making the decision, resulting staled sensing results.	Able to promptly use available sub-bands once identifying the availabilities.
Spatial Diversity Gain	Achieve spatial diversity gain with certain densities and uncorrelated observations.	Not able to achieve.
Fading Signals	Higher detection sensitivity under proper density.	Able to achieve detection sensitivity by using feature detection techniques, such as cyclostationary detection, and covariance-based detection.
Coordination	Sensing and access are fully controlled by the central controller.	May result in disorderly accesses to the same available sub-bands like a swarm of bees.
Reliability	Highly depends on the data fusion scheme as well as the credibility of sensing nodes.	Highly depends on sensing techniques.

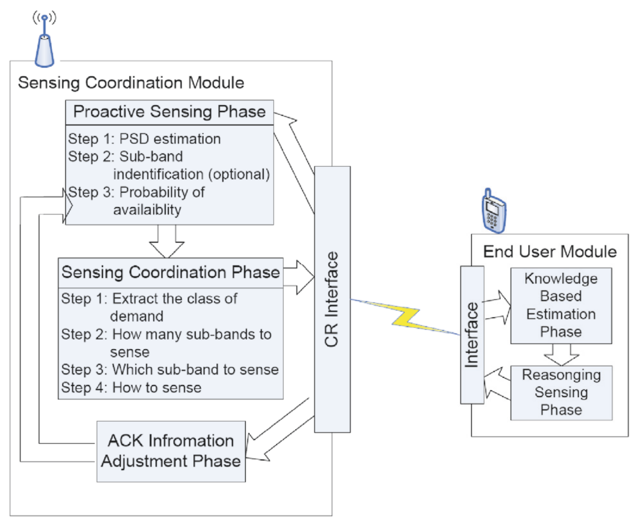

Figure 1: An overview of sensing coordination in CEF framework. It consists of the sensing coordination module (SCM) module on the left and the end-user module (EUM) on the right. SCM consists of two phases, i.e., proactive sensing phase and sensing coordination phase. EUM consists of two phases, i.e., knowledge-based estimation phase and reasoning sensing phase.

sensing on the suggested subbands via a reasoning process, in order to minimize the intratier interferences. Once a femtocell user accesses the subbands, the femtocell user will acknowledge the CEF BS regarding the usage of the subbands. Such ACK information assists the SCM to perform channel measurement on the corresponding spectrum to identify the macrocell user signals. Note that if any macrocell user signal is identified, the SCM will instruct the femtocell users to evacuate from those subbands immediately.

3.2. Sensing Coordination Modules (SCM). In brief, the SCM proactively performs wideband sensing for channel measurement to identify transmitting/receiving opportunities beyond legacy technologies, as well as maintaining and updating the proactive sensing results, so as to assist the femtocell users to determine their respective sensing parameters when they perform standalone spectrum sensing. The sensing parameters that will be estimated at each femtocell user handset will be introduced later.

In the following discussions, we consider the time and frequency under OFDMA/TDMA as network resources and use them as *resource blocks*. The periodic channel measurement process is illustrated in Figure 2 and summarized as follows:

(i) Proactive sensing phase: the SCM measures the Received Interference Power (RIP) on each resource block (i.e., each time slot of each subband). A measurement is performed during a complete subframe via wideband sensing upon all the time slots and subbands in the subframe, as shown in Figure 2.

(ii) Sensing coordination phase: the SCM extracts site-information of the macrocell from the wideband sensing and shares the information with the femtocell users.

(iii) ACK information adjustment phase: the CEF BS can adjust the original detection threshold to better estimate the activity of the associated macrocell users according to the ACKs information from its femtocell users.

Note that a resource block is considered as occupied by the macrocell if the RIP on that resource block exceeds a certain threshold. In any subframe not performing measurement, the CEF BS only schedules unoccupied resource blocks by the macrocell to its users. The SCM also obtains the channel availability information possibly on other licensed bands, such as that for TV.

The above three phases are performed in each channel measurement period of the SCM, which are detailed in the following subsections.

3.2.1. Proactive Sensing Phase

(i) **Step 1.** A fluctuation-free power spectral density (PSD) is obtained by using a constrained Bayesian estimation approach [16], where a weighted average of each frequency is computed across a tapering window. The weight assigned to each frequency within the tapering window is set based on a Gibbs-based likelihood function, where a low weight is assigned when the PSD deviation is high between that frequency and the frequency we wish to estimate. This likelihood function serves for two purposes: (i) frequencies with low PSD deviations (where the PSD deviations are due largely to noise fluctuations) have high contribution in smoothing out the noise fluctuations and (ii) frequencies with high PSD deviations (where the PSD deviations are due largely to the underlying PSD shape) have low contribution and as such have little effect on the overall PSD shape. Therefore, noise fluctuations are suppressed while the overall PSD shape is preserved.

(ii) **Step 2.** In the situation where the subbands are unknown (e.g., wireless devices from different manufacturers use different frequency bands), a first-order derivative filter is applied to the fluctuation-free PSD to identify significant PSD changes, which characterizes the boundaries of the individual subbands [16].

(iii) **Step 3.** Test statistics are computed from the fluctuation-free PSD within each subband and compared it with the detection threshold to determine the probability of availability. Furthermore, the threshold will be updated in the ACK information adjustment phase.

3.2.2. Sensing Coordination Phase. In the sensing coordination phase, the SCM instructs the femtocell users on which subbands and in what sequence to sense these subbands, in order to mitigate intratier interferences and improve the likelihood of obtaining usable bandwidth and meeting the tolerable delay due to the sensing process. On the other hand, it leaves the decision on transmission rate and modulation to

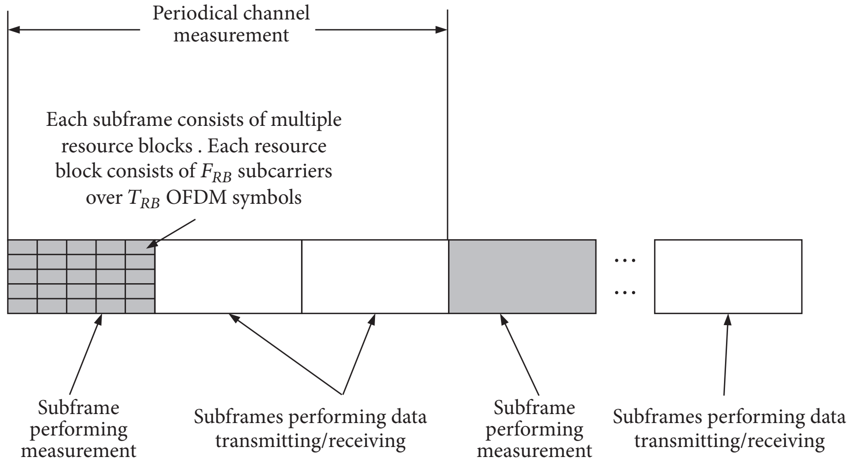

Figure 2: The femtocell BS performs periodical channel measurement to identify whether a resource block is occupied by the macrocell in a subframe.

the femtocell users, which are essential conditions to satisfy their QoS requirements.

Note that there could be a hidden terminal problem at the femtocell user side when a subband that is considered available at the CEF BS side is actually occupied by an adjacent CEF BS. This simply causes intratier interferences. Therefore, instead of completely following the instruction of the channel availability from the CEF BS, each user handset performs fine sensing via energy detection on the set of subbands instructed by the CEF BS through a reasoning approach.

(i) **Step 1.** Extract the service class c_m of demand.

(ii) **Step 2.** Stochastically determine the number of subbands, denoted as N_{c_m}, for the femtocell users to sense with a probability θ_{c_m} according to a distribution $f_{c_m}(\overline{N}_{c_m}, \sigma_{c_m})$ with mean $\overline{N}_{c_m}$ and standard deviation σ_{c_m}. Note that this can be a simple Gaussian distribution.

(iii) **Step 3.** Stochastically select a set of N_{c_m} subbands for the femtocell users to sense and access according to the probability of subband availability determined in the proactive sensing phase. As such, the femtocell users are instructed on the most likely available subbands.

(iv) **Step 4.** Among the set of selected subbands, instruct the femtocell users to perform only energy detection prior to access on the subbands associated with the sensing results within the channel detection time, denoted as τ, which is specified in IEEE 802.22. Energy detection is sufficient for these cases due to the freshness of the sensing results. If the recommended subbands are older than τ seconds, the femtocell users will be instructed to perform feature detection prior to access given the staleness of the sensing results.

Fairness is another important design goal other than interference mitigation, which can be effectively achieved by manipulating the number of subbands that a user is allowed to scan for each transmission. On the other hand, the optimal number of subbands for scanning at a femmtocell user can also help to mitigate intratier interference since the femtocell users, with a stochastic channel sensing strategy, do not likely select a common set of subbands and scan them in the same order. This will be examined in the simulations.

3.2.3. ACK Information Adjustment Phase. In the ACK information adjustment phase, the ACK messages of the femtocell users bear the information on which subbands have been used by the femtocell users and the statistics of the channel conditions, such that the CEF BS can adjust the original detection threshold to better estimate the activity of the associated macrocell users.

3.3. End-User Modules (EUM). The EUM at femtocell user handsets take advantage of both extrinsic and intrinsic knowledge of the network environment to estimate the optimal number of channels in their standalone sensing process, which can use either energy detection or feature detection, according to the instructions from the SCM at the CEF BS. Moreover, the EUM dynamically refine the amount of sensing results to achieve the desired QoS requirements. The two phases are further elaborated in the following subsections.

3.3.1. Knowledge-Based Estimation Phase. Intuitively, scanning more channels will more likely obtain sufficient bandwidth to support the desired connections if sensing time is not a concern. However, sensing more subbands results in longer sensing delay that consequently decreases the throughput. Besides, a long sensing process increases the likelihood of unsuccessful transmissions and lost opportunities due to the dynamic nature of channel availability. Therefore, the cognitive EUM estimate the number of subbands to scan (denoted as n^*) using the knowledge instructed by the CEF BS, in order to achieve the best customer premise.

3.3.2. Reasoning Sensing Phase. Since EUM has to scan subbands one after the other, it is possible that an EUM identifies sufficient channels before scanning all the subbands recommended by the CEF BS. Therefore, a reasoning process is suggested to improve the sensing efficiency, where each EUM decides to proceed to scan the next subband only if the expected return in terms of throughput is positive, and the number of subbands has not reached n^*.

4. Performance Evaluation

Experiments were conducted to verify the performance of the proposed CEF framework. We simulated $50m \times 50m$ indoor network area with an average of 10 macrocell users and various number of femtocell users, which were allocated according to a Pareto distribution in three femtocells. Each femtocell user has a radio transmission range radius of $R = 30$. For each spectrum sensing event, a $400MHz$ spectrum is divided into 10 subbands with randomly generated bandwidth (which reflects the stochastic nature of wireless channels). For each transmission, a femtocell user is randomly chosen and then the intended receiver is the nearest CEF BS. We conducted the simulation for $t_{sim} = 5000s$ for each trial, where the performance of the proposed CEF framework was evaluated in terms of (1) the throughput upper bound in the proactive sensing phase, (2) the probability of intratier interference, and (3) the temporal usage rate. Note that we assume the wideband sensing in (1) can accurately identify the available resource blocks, such that the cross-tier interference can be completely removed.

4.1. Performance of Proactive Sensing via Periodic Channel Measurement. It is clear that the available channels provided by the CEF BS may or may not be free at the femtocell users, depending on the fine sensing results at the femtocell users which clarify the intratier interferences. Therefore, the throughput achieved by using available resource blocks identified in the proactive sensing phase can be simply taken as an upper bound on the real achievable throughput after considering the sensing results at the femtocell user side. This is illustrated in Figure 3, where the proposed scheme effectively achieves significant enhancement when compared with the scenario of "no measurement". Note that with "no measurement" the CEF BS randomizes the resource block allocation in each subframe, which is similar to the concept of interleaved resource block allocation to combat the block fading channel. The measurement period is counted by subframes.

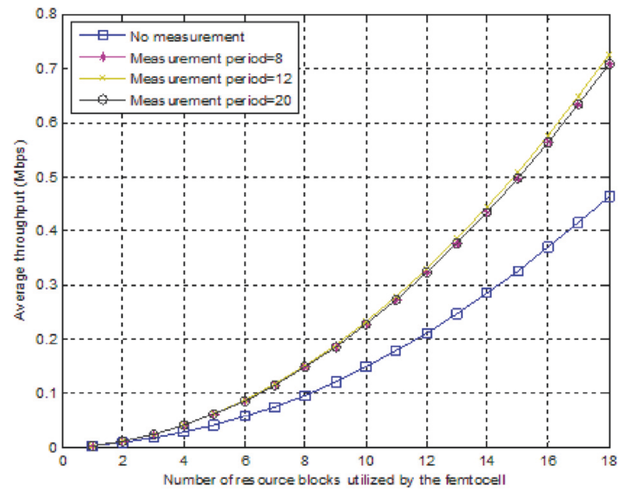

Figure 3: Simulation results of the average throughput of the femtocell.

4.2. Probability of Intratier Interference. This set of simulations evaluates the probability of intratier interference, which is the probability of more than one femtocell user identifying any common available subband. This causes intratier interference since competition for medium access could arise hereafter.

The probability of intratier interference is a direct performance measure on the proposed framework, and it determines the feasibility and effectiveness of the proposed framework. In Figure 4, the probability of intratier interference in the proposed CEF framework, the standalone sensing scheme in [17], and the cooperative scheme is compared with the number of subbands being set to 5. As expected, the proposed framework yields a much lower probability of intratier interference than that by the standalone scheme and comparable with that of the cooperative scheme. The result demonstrates the potential benefits of integrating coordinated sensing into the CEF framework, where a spectrum sensing process with similar simplicity of standalone sensing yet the same efficiency as cooperative sensing can be achieved. Further, with more femtocell users, the proposed framework can better outperform than the standalone scheme in terms of the probability of intratier interference.

We noticed that with cooperative sensing the probability of intratier interference slightly decreases as the number of femtocell users increases. It is because the sensing accuracy of the proposed framework is highly dependent on the density of femtocell users and remains stable after reaching a certain number of femtocell users [18]. The results demonstrate the efficiency that can be achieved through the use of the proposed framework.

4.3. Temporal Usage Rate. To further evaluate the network-wide temporal efficiency, we investigated the temporal usage rate, which is defined as the percentage of time that an arbitrary subband is not used by any femtocell user. Our goal is to evaluate the impact of the femtocell user traffic on the underlay network-wide performance. By setting the communication traffic volume of each macrocell user as 10 packets/second, Figure 5 shows the temporal usage rate in the proposed framework with different femtocell user traffic volumes. It can be observed that the temporal usage rate is noticeably higher than that of the standalone sensing scheme due to the fact that the CEF BSs instruct the most likely available subbands for femtocell users based on both *a priori* subband information obtained from its energy detection and ACK information adjustment. Moreover, the proposed framework can achieve a similar level of network-wide temporal efficiency when compared with that of the conventional cooperative sensing scheme, while significantly

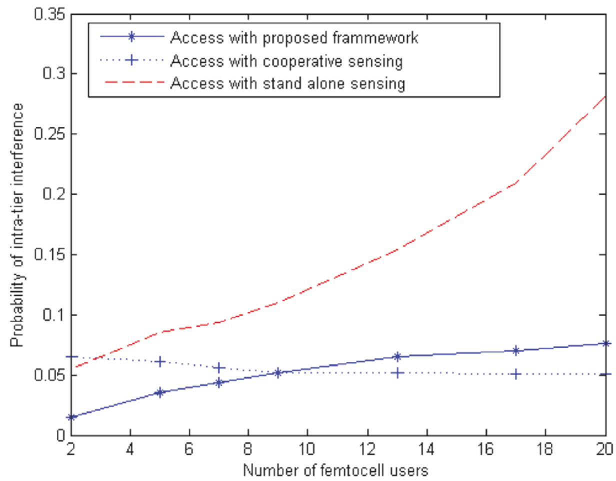

FIGURE 4: Probability of intratier interference versus the number of femtocell users, $N_{(2)}$.

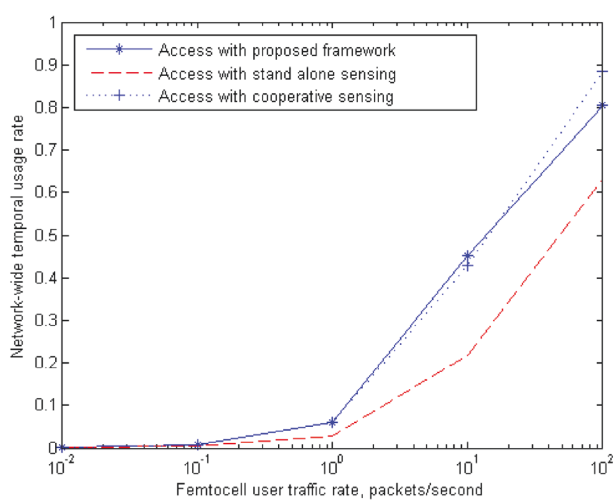

FIGURE 5: Temporal usage rate of the proposed framework with different femtocell user traffic arrival rate.

outperforming the cooperative sensing scheme in terms of overall efficiency and simplicity. This is a promising feature of the proposed framework with the effort of deploying simple, low cost, and custom-premised CEF BSs.

5. Conclusions

In this article, we proposed a novel framework of interference management by way of channel measurement and dynamic spectrum sensing for femtocell networks, called cognitive-empowered femtocells (CEF), aiming at enhancing the femtocell capacity and mitigating both cross-tier and intratier interference in a single step. Under the proposed framework, the CEF BSs periodically perform channel measurement and sensing coordination with the corresponding femtocell users. With the dynamic spectrum sensing capabilities, the devices can utilize spatiotemporally available spectrum in an opportunistic manner. Simulation results demonstrated the potential of the proposed CEF framework with the effort of improving the overall network capacity via intelligent acquisition of spectrum opportunities with excellent scalability, flexibility, and transparency to the existing macrocell protocol design.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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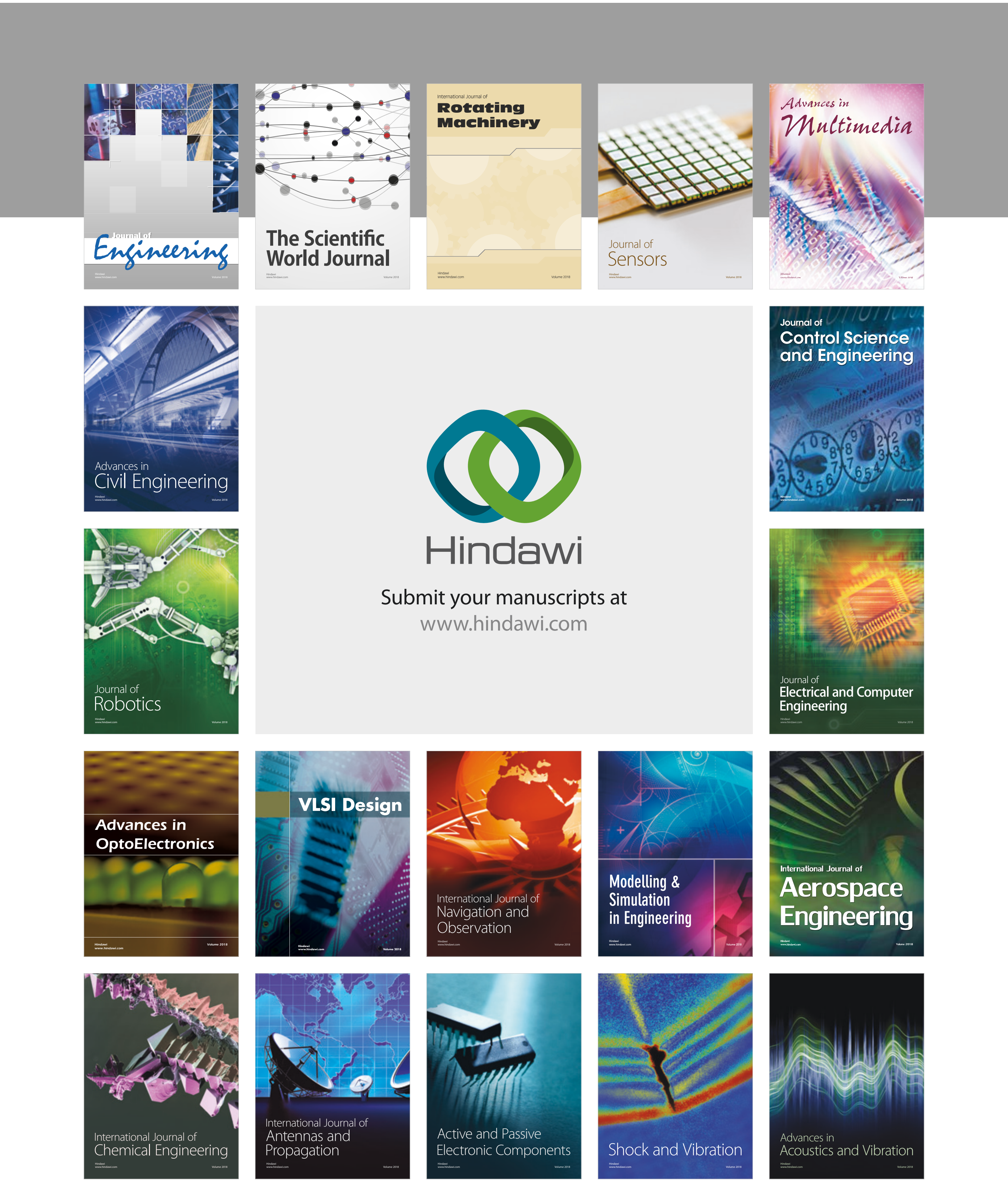
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