Cooperative Heterogeneous Framework for Spectrum Harvesting in Cognitive Cellular Network

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ABSTRACT

With the proliferation of mobile devices and emerging data-hungry applications, mobile data has been increasing dramatically. To accommodate massive mobile data, the cellular network has been straining to meet the need due to the scarcity of spectrum. As a promising technology, cognitive radio can be leveraged by the cellular network to harvest spectrum holes on demand. By employing cognitive radio, the cellular network becomes a cognitive cellular network. In this article, we first provide an overview of the cognitive cellular network, including the network architecture and main applications. Then existing spectrum harvesting approaches are reviewed, and the limitations are identified. To better explore spectrum access opportunities, three types of cooperation-based approaches are introduced for different scenarios, based on which an integrated cooperative framework is devised to fully harvest spectrum holes. Simulation results are provided to evaluate the performance of the proposed cooperative approaches.

INTRODUCTION

We have witnessed a boost in the growth of the cellular network, which continues to flourish worldwide. Billions of wireless devices are proliferating, and various wireless applications, such as mobile social networks, online gaming, and high-definition video streaming, are emerging. As a result, mobile traffic keeps increasing dramatically, which has overwhelmed the cellular network. In the future, mobile traffic is expected to skyrocket further. According to the Cisco Visual Networking Index (VNI) [1], mobile traffic is expected to grow at a compound annual growth rate (CAGR) of 61 percent from 2013 to 2018. It is predicted that mobile traffic will continuously grow up to 1000 times by 2020 from that in 2010. The massive number of mobile devices and ever increasing mobile traffic pose a great challenge for the cellular network to provide users with quality guaranteed services.

To accommodate the explosive growth in mobile traffic and devices, a large amount of wireless spectrum is needed. The spectrum demand for mobile systems is predicted to be around 1280–1720 MHz by 2020 [2], while the current mobile systems only own the spectrum around 230–430 MHz. To address the challenge, one way is to add more spectrum resource. The Federal Communications Commission (FCC) is trying to free up additional spectrum of 500 MHz for mobile networks, which still cannot bridge the gap. Another path is to improve spectrum efficiency by developing new physical and link layer techniques, which usually incurs high complexity, and the improvement is limited. Alternatively, spectrum harvesting could harvest unused spectrum bands to meet the ever growing spectrum demand [3], considering that a large portion of spectrum is underutilized temporally and spatially. Spectrum harvesting can be enabled by cognitive radio (CR), which is able to acquire information from surroundings through sensing and adapt to environments by adjusting the operating parameters [4, 5]. By employing CR technology, the cellular network can harvest and operate over the unused spectrum/spectrum holes from other systems, such as TV white space (TVWS). The cellular network equipped with CR technology is also referred to as the cognitive cellular network (CCN) [6].

In the CCN, through spectrum harvesting, additional spectrum can be utilized for traffic offloading or capacity relief. Furthermore, the harvested spectrum may present different propagation or penetration features, which can be exploited to support diverse applications with various quality of service (QoS) requirements. For instance, if the communication distance is long, a low frequency band can be exploited, while a high and wide frequency band is selected if high throughput is preferred. Besides spectrum harvesting, the CCN can also support many promising applications. For instance, CR can be utilized to mitigate intercell interference among the macrocell and small cells, which are expected to be deployed densely and underlay the macrocell in the cellular network. With CR, small cell base stations (BSs) can perform spectrum sensing before accessing the spectrum bands to mitigate interference [7]. In addition, users can adjust the transmission parameters to achieve different objectives (e.g., energy efficiency or high transmission rate) based on its operating context.

As the key enabling technology, spectrum sensing plays a vital role to identify unused spectrum bands for spectrum harvesting. Cognitive cellular users (CCUs) can access the spectrum band from other systems only when it is detected idle. Otherwise, the normal operation of the primary users, or PUs (the licensed users in other systems), will experience interference. However, due to fading and shadowing, spectrum sensing of individual users is not perfect, and sensing errors are inevitable, which adversely affect the performance of both CCUs and PUs [8]. In this article, we introduce user cooperation to overcome the limitations of individual spectrum sensing and better harvest unused spectrum for the CCN. We first present an overview of the CCN, including the network architecture and main applications. Then the existing spectrum harvesting approaches for exploiting additional spectrum are reviewed, and the limitations are discussed accordingly. To overcome the limitations, cooperation-based spectrum harvesting approaches for various scenarios are introduced; for example, cooperative spectrum sensing can be utilized to better detect unused spectrum, and cooperative relaying can be leveraged to explore access opportunities even though the PUs are active. Then an integrated cooperative framework is devised to combine these cooperation-based schemes, aiming to fully explore spectrum access opportunities. Simulation results are provided to evaluate the performance of the proposed cooperation schemes.

Overview of the Cognitive Cellular Network

Network Architecture

The future cellular network, that is, the fifth generation (5G) network, is envisioned to be a heterogeneous network [9]. Therefore, the CCN has a heterogeneous network architecture, as shown in Fig. 1, where different small cells underlay the macrocell: picocells, femtocells, and so on. The BSs of the macrocell and small cells, as well as the user equipments (UEs), are equipped with CR technology. For ease of presentation, all the network entities with CR are called cognitive cellular users (CCUs), including cognitive UEs and BSs. The BSs of macrocell and small cells are connected to the external spectrum trading market server, which facilitates the spectrum trading/leasing between the CCN and other systems with licensed spectrum bands. CCUs can harvest spectrum holes through either spectrum sensing or spectrum trading.

The operation of the CCN can be centralized, where the BS coordinates CCUs for spectrum harvesting and spectrum sharing. For instance, it can coordinate CCUs to perform spectrum sensing and then combine the sensing results to make a final decision [10]. With the harvested spectrum and the cellular bands, the BS performs resource allocation for CCUs based on their traffic types and QoS requirements. For example, when the signal reception for a CCU is very poor in an indoor environment, the BS can switch the CCU to other spectrum bands with better penetration features (e.g., TV bands).

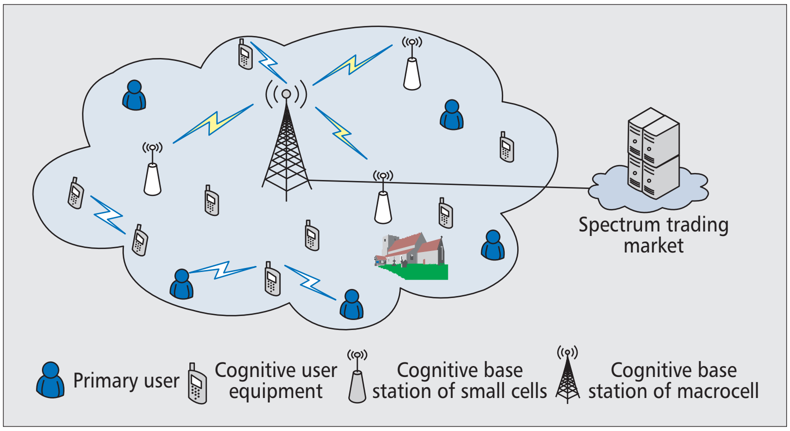

Figure 1. Network architecture.

The CCN can also operate in a decentralized fashion, where CCUs acquire available spectrum and access without a central controller. For instance, CCUs can sense the spectrum bands and select suitable spectrum bands based on their own needs. For instance, when the sender and receiver are far away, the low spectrum bands can be utilized due to the desirable propagation and penetration features. Moreover, different portions of unused spectrum band can be aggregated by the CCU to have a large spectrum band by means of spectrum bonding and aggregation.

Main Applications

Besides spectrum harvesting, CR also facilitates other applications.

Intercell Interference Mitigation: By deploying small cells densely, network capacity can be significantly improved. However, the main limiting factor for dense deployment of small cells is intercell interference among neighboring cells. One way to mitigate interference is spectrum splitting, which could lead to inefficient spectrum usage. With CR, small cells can sense the surroundings to detect the spectrum usage status and access the cellular spectrum bands only when they are not occupied. Moreover, small cells can also explore the unused spectrum bands owned by other systems, while the macrocell exclusively uses the cellular spectrum bands. By doing so, intercell interference can be mitigated, and different cells can coexist.

Transmission Adaption: The two main characteristics of CR are cognitive capability and reconfigurability. With cognitive capability, the CCU can get the information regarding the surrounding environments (the communication network, channel conditions, etc.). With

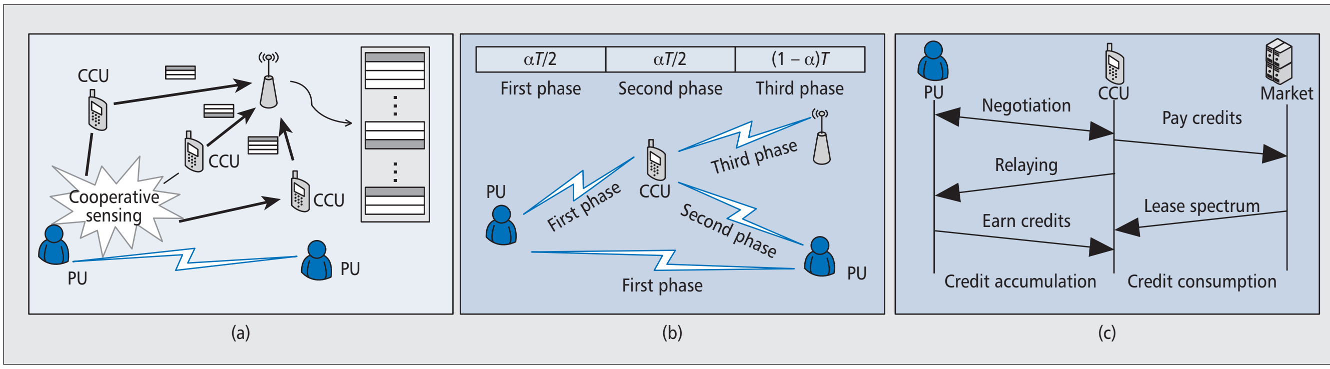

Figure 2. Cooperation-based spectrum harvesting.

reconfigurability, the CCU can dynamically and autonomously adjust the operating parameters to satisfy the QoS requirement in terms of throughput, reliability, delay, and so on, being aware of the operating environments. For the future cellular network, in order to achieve network access any time and anywhere, the CCU can detect the surrounding available network service and change the operating parameters for access.

Spectrum Harvesting Approaches and Challenges

The basic and main target of the CCN is to harvest spectrum holes to support mobile traffic growth. In this section, the existing spectrum harvesting approaches are reviewed.

Spectrum Harvesting Approaches

Geolocation database: Due to the transition from analog TV to digital TV, TVWS is considered to be allowed for free secondary access. Since TV programs are predetermined, the channel availability information can be provided by a geolocation database, which is governed by certified third parties [11]. The procedure for the geolocation database approach is as follows. The CCU sends a request to the geolocation database with location information. Then the database sends back the channel availability information for the given location.

In terms of implementation, Google and Microsoft have launched their geolocation database products, Google spectrum database and Microsoft spectrum observatory, respectively.

Spectrum sensing: Spectrum sensing is the key approach to spectrum harvesting. The CCUs perform spectrum sensing to detect spectrum holes and prevent interference to the PUs. The CCUs access the channel only when the channel is detected to be idle. Since spectrum holes can be in a specific time, frequency band, or spatial location, spectrum sensing can be performed in the time, frequency, and space domains. Spectrum sensing can also be used to acquire information regarding the carrier frequency, modulation schemes, bandwidth, and so on. Popular spectrum sensing methods include energy detection, matched filtering, and cyclostationary detection [8].

Spectrum trading: Spectrum trading allows the spectrum resource to be exchanged among different parties, on either a long- or short-term basis. The resources for trading can be the available frequency bands, the maximum allowable transmission power, and the time duration for access in the spectrum bands [12]. The CCUs can gain temporary exclusive rights to use the spectrum by paying a certain amount of money when PUs are willing to lease the spectrum for monetary rewards. During transmission, the CCUs will not be interrupted by the PUs, so their QoS can be guaranteed to some degree.

Limitations

Geolocation Database: To acquire channel availability, geolocation information is required, which is usually obtained from the global positioning system (GPS). However, some CCUs might not have GPS functions. Moreover, the geolocation information might be inaccurate due to poor GPS signals at some locations. In addition, there are two types of PUs in the TV spectrum band: TV broadcasters and microphones. Since it is difficult to predict the activities of microphones, they might be interfered with by CCUs using this approach. Last but not least, the database can only provide channel availability for TV bands [13].

Spectrum sensing: Spectrum sensing is considered as the main approach to harvesting spectrum holes. However, the detection performance of spectrum sensing is limited by several factors such as multipath fading and shadowing [8]. Specifically, when the CCU experiences multipath fading or shadowing, the reception of a PU's signal will be significantly degraded, which reduces the detection accuracy dramatically. In addition, for CCUs that are out of the transmission range of the primary transmitter, it is impossible to detect the PU's presence. Then the CCUs might start to transmit, causing harmful interference to the primary receiver. Moreover, once the PU reclaims the channel, the CCUs have to vacate the current channels and find other idle channels, resulting in intermittent transmission.

Spectrum trading: CCUs can have exclusive spectrum access rights through spectrum trading so that the QoS can be guaranteed. Long-term spectrum trading still has the problem of spectrum waste because the CCUs might have no

Cooperation Schemes	Scenarios	Partners	Objective
Cooperative spectrum sensing	Have traffic and cellular bands are not sufficient	CCUs with CCUs	Detect idle bands where no active PUs are present
Cooperation with PUs for access	Have traffic and no sufficient bands even through sensing	CCUs with active PUs	Gain access time through cooperation with PUs
Cooperation with PUs for credits	No traffic now but may have in the future	CCUs with active PUs	Earn credits for future use

Table 1. Comparison among different cooperation schemes.

traffic at a specific time due to the bursty nature of the traffic. For short-term or even real-time spectrum trading, the spectrum utilization can be improved. However, from the perspective of the CCN or CCUs, besides the operational and maintenance costs, additional money has to be paid when purchasing the spectrum through the market. Over a long period the cost could be fairly high, resulting in a burden on the CCN or CCUs. From the viewpoint of PUs, they might not only pursue monetary benefits through spectrum trading. In some cases, the PUs also desire to improve the transmission performance (e.g., increase throughput whenever they have a large volume of traffic). The existing trading mechanism does not consider these types of PUs' needs.

Cooperation-Based Approaches

The geolocation database approach can be complemented by spectrum sensing to protect microphones and explore spectrum holes in other bands. However, the detection performance of individual spectrum sensing is limited, as mentioned before. To overcome these issues, user cooperation can be leveraged, mainly in two forms: cooperative spectrum sensing [10] and cognitive cooperative relaying [14]. For the former, cooperation is carried out among CCUs, where multiple CCUs cooperate with each other to enhance the sensing performance for better detecting spectrum holes, as shown in Fig. 2a. For the latter, cooperation is performed between CCUs and active PUs, where CCUs cooperate with PUs to improve the transmission performance of the PUs and gain spectrum access opportunities as a reward, as shown in Fig. 2b.

Cooperative spectrum sensing aims to harvest the spectrum holes where no active PUs are present, while cognitive cooperative relaying tries to explore spectrum access opportunities when PUs are active. In addition, CCUs can acquire exclusive spectrum rights through the spectrum trading market. To compensate for the cost in spectrum marketing, CCUs can cooperate with PUs to improve the PUs' transmission performance and request credits when they are idle. That is, through cooperation, idle CCUs can accumulate credits, and the PUs' performance can be enhanced. The earned credits can be used by CCUs in the spectrum trading market when needed in the future, as shown in Fig. 2c. The comparison among different cooperation schemes is provided in Table 1.

Cooperation-Based Spectrum Harvesting Approaches

In this section, the three cooperation-based spectrum harvesting approaches are introduced.

Cooperation for Spectrum Sensing

Cooperative spectrum sensing can improve the detection performance in terms of increasing the detection probability and reducing the false alarm probability by exploiting spatial diversity and multiuser diversity. In cooperative spectrum sensing, each CCU performs local sensing and then forwards the results to a fusion center (e.g., the BS) to make a final decision. The fusion rules to combine the sensing results include AND rule, OR rule, and so on. Through cooperation, the deficiency of individual observations can be mitigated. Since CCUs are usually in a multi-channel environment, the fundamental issue is how to coordinate CCUs for multi-channel sensing. In what follows, the cross-entropy (C-E) method is applied to schedule CCUs to sense different channels for better harvesting spectrum holes.

Suppose that there are K primary channels that N CCUs can explore for transmission. The states of the channels alternate between ON (busy) and OFF (idle), which are modeled by an ON-OFF model with different transition rates. To better harvest spectrum holes, the BS coordinates the CCUs to perform cooperative spectrum sensing. Specifically, each individual CCU adopts energy detection for spectrum sensing and reports the sensing results to the BS, which makes a combined decision. Considering the AND rule is adopted as the fusion rule, a channel is deemed busy when all the CCUs report the OFF state. The detection probability and false alarm probability[1] of CCU i to sense channel j are denoted by $p_d(i, j)$ and $p_f(i, j)$, respectively, which are functions of the associated channel conditions. The expected available time for a given channel j is $T^j_{off}p^j_{off}(1 - F^j_f)$, where T^j_{off} is the sojourn time of the OFF state, p^j_{off} is the associated probability, and F^j_f is the cooperative false alarm probability. Note that $F^j_f = \Pi_{i\in \mathbf{S}_j} p_f(i, j)$, where $\mathbf{S}_j$ is the set of CCUs selecting channel j for sensing.

The objective of the CCN is to maximize the expected available time of all the channels while sufficiently protecting the PUs. To this end, we define a channel selection matrix $\mathbf{I} = (I_{i,j})_{N\times K}$, where $I_{i,j} = \{0,1\}$ indicates whether or not CCU

[1] The detection probability and false alarm probability are the probabilities that the PU is detected to be present when it is actually present or absent, respectively.

It is well known that cooperative relaying can improve the transmission rate, save energy, enhance reliability, and so on. Leveraging cooperative relaying, CCUs can improve the PUs' performance by acting as relays to gain spectrum access opportunities as a reward.

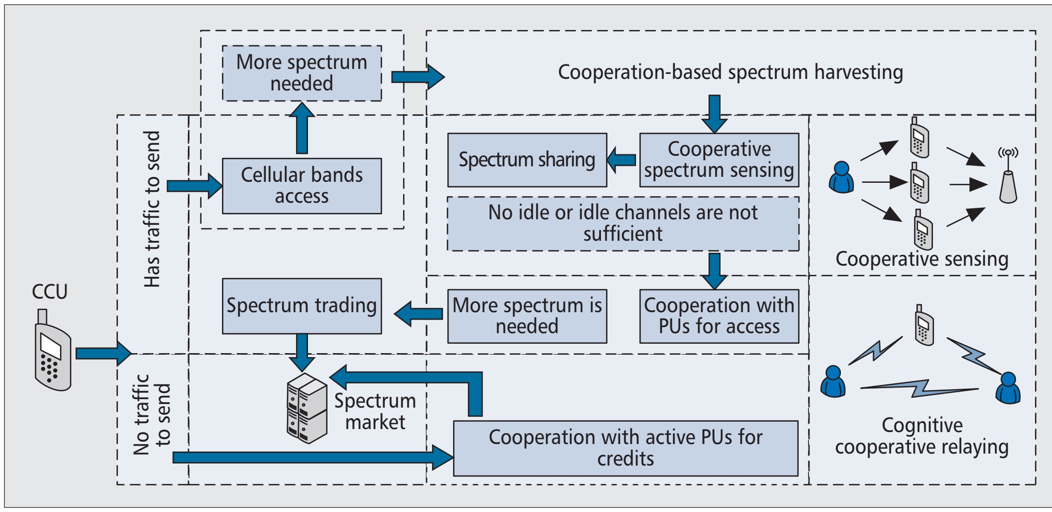

Figure 3. An integrated cooperative framework for spectrum harvesting.

i selects channel j for sensing. $\mathbf{I}$ can be determined by applying the C-E method of stochastic optimization [15] to maximize the average idle time. The main idea of the C-E method is as follows. In the initial phase, all the CCUs select the sensing channels following the uniform distribution. According to the distribution, a set of channel selection samples are generated, which are utilized to calculate the fitness (i.e., the total expected available time). Then, based on the outcome of all the samples, those channel selection samples with higher fitness will be utilized to update the distribution parameters to produce a "better" sample in the next iteration. By performing this procedure iteratively, it can converge to an optimal or near-optimal deterministic solution (i.e., the channel selection results).

Cooperation with PUs for Access

It is well known that cooperative relaying can improve the transmission rate, save energy, enhance reliability, and so on. Leveraging cooperative relaying, CCUs can improve the PUs' performance by acting as relays to gain spectrum access opportunities as a reward. As shown in Fig. 4b, cooperative communication can be performed in a three-phase manner. Specifically, the CCU acts as a relay to perform cooperative communication with the PU in the first two phases (i.e., αT) to improve the letter's transmission performance. Then the PU grants the third period of time with $(1 - \alpha)T$ to the CCU as a reward. Through cooperation, a "win-win" situation is created, where the PU's performance is improved while the CCU obtains spectrum access rights. For a multi-user scenario, how to perform cooperation between multiple PUs and CCUs needs to be studied.

Suppose that multiple PUs desire to improve their throughput through cooperation, each of which owns a time slot of T. The CCUs can cooperate with the PUs to gain spectrum access opportunities in a three-phase manner. Each PU selects a CCU for cooperation, and amplify-and-forward (AF) mode is adopted. Cooperation between a single PU and a generic CCU is modeled as a Stackelberg game, where the PU acts as the leader and the CCU acts as the follower. The PU's utility is defined as the achievable throughput through cooperation, while the CCU's utility is defined as the throughput achieved in rewarding time minus the energy cost. Note that the energy cost is given by $\lambda_1 P_C(1 - \alpha T/2)$, where λ_1 is the cost rate for transmission power and P_C is the transmission power of the CCU for cooperation. To maximize the utilities, the PU selects the time allocation coefficient α, while the CCU chooses the transmission power P_C. By analyzing the game, the best α and P_C can be determined, which are utilized in the multi-user cooperation scenario.

For the multi-user scenario, a secondary-centric cooperative scheme (SCC) is introduced to coordinate the users' cooperation to maximize the aggregate throughput of all cooperative CCUs. Note that the achievable throughput for a given CCU can be calculated when it cooperates with a certain PU using the cooperation parameters obtained before. For multiple CCUs and PUs, the problem is to select the suitable CCU for each PU to maximize the total throughput of CCUs, which can be represented as a maximum weight bipartite matching. In the bipartite graph, the weight on each edge represents the throughput of the CCU, if the corresponding CCU and PU (represented by vertices) cooperate with each other. Finding the best partner is equivalent to finding the maximum weight matching. To this end, the well-known Hungarian algorithm can be applied to determine the optimal matching (e.g., pairs of CCUs and PUs) such that the sum of weights is maximized [14].

Cooperation with PUs for Credits

When CCUs have no traffic, they can still harvest spectrum in the following way. The CCUs can cooperate with PUs to improve PUs' transmission performance and then request credits as compensation. The earned credits can be utilized by CCUs for spectrum trading in the future when they have traffic. In other words, the CCUs can earn credits through cooperation with PUs and consume credits in the spectrum trading market when needed, as shown in Fig. 4c.

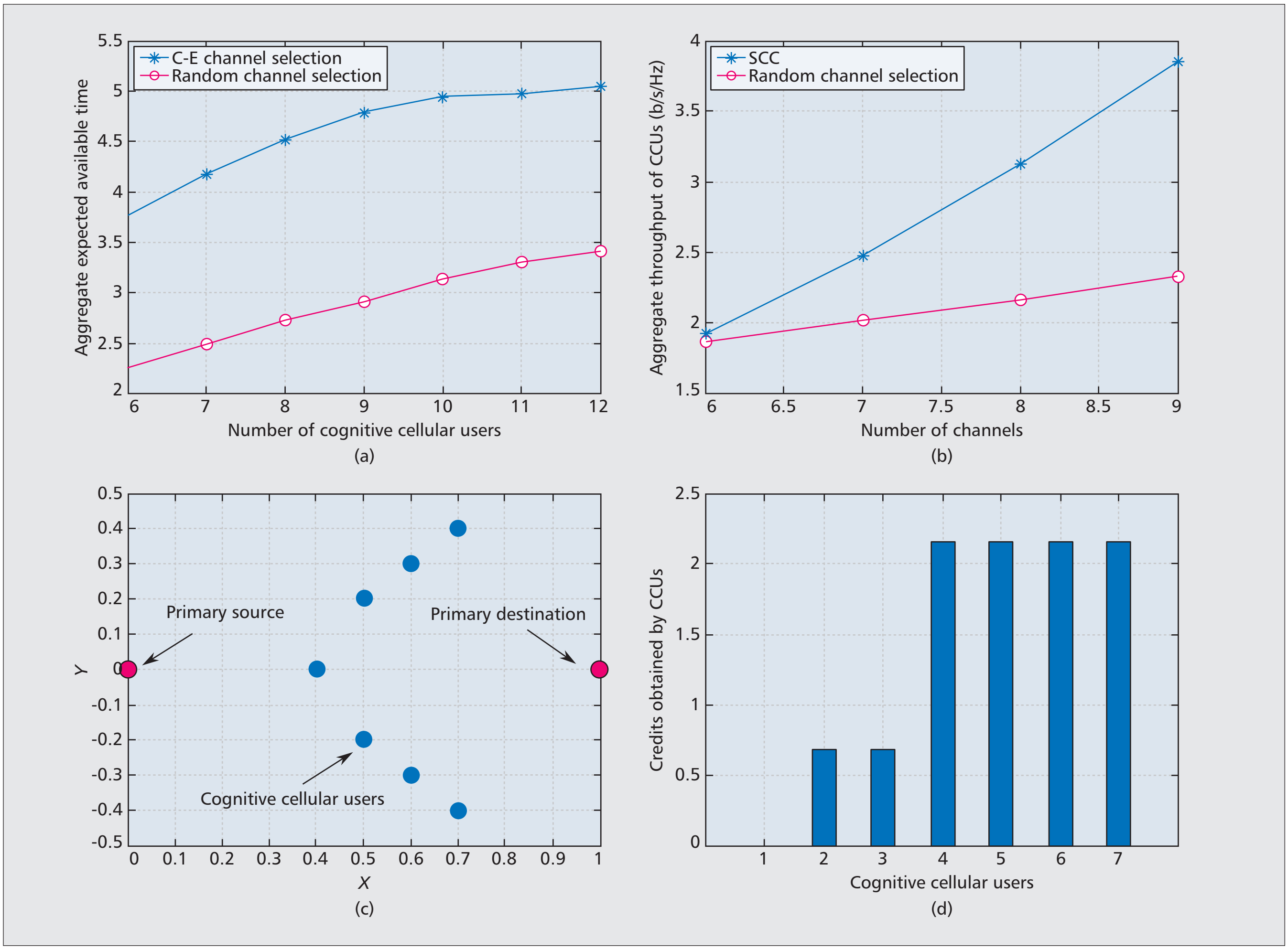

Figure 4. Performance of the cooperation based spectrum harvesting schemes: a) aggregate expected available time vs. number of CCUs; b) aggregate throughput vs. the number of channels; c) network scenario for simulation; d) credits earned by CCUs through cooperation.

Suppose a PU intends to increase its throughput, and a group of CCUs are interested in acting as cooperative relays. To compensate the cooperative CCUs, the PU selects an amount of credits to be shared by CCUs according to their contribution. Since the CCUs act as relays to increase the PUs' throughput, the contribution of CCU i can be approximately given by $P_C^i h_d^i$, where P_C^i is the transmission power of CCU i for cooperation, and h_d^i is the channel gain between CCU i and the primary receiver. Then the utility of the PU is given by $U_p = \lambda_2 R_p - R_m$, where R_p is the achievable throughput through cooperation, λ_2 is the profit per throughput, while R_m is the credits granted to the CCUs. The utility of CCU i is given by

$$U_i = \frac{P_C^i h_d^i}{\sum\limits_{j \subseteq \mathbb{C}} P_C^i h_d^j} R_m - \lambda_1 P_C^i,$$

where $\mathbb{C}$ is the set of cooperative CCUs.

To determine the parameters for cooperation (i.e., the payment of the PU and the transmission power of the CCUs), a two-layer game is used to analyze the negotiation procedure. At the top layer, a buyer-seller game is utilized to model the process by which the PU pays for the service provided by the CCUs. At the bottom layer, for a given payment, the CCUs determine their transmission powers to share the credits in a distributed way, which can be analyzed by a non-cooperative power selection game G. The game G is defined as $G = \{\mathbb{C}, \{\mathbb{S}_i\}, \{U_i\}\}$, where $\mathbb{C}$ is the set of players, U_i is the utility function, and $\mathbb{S}_i$ is the strategy set of CCU i (i.e., the transmission power CCU i can choose).

The two-layer game can be solved by the backward induction method. First, for a given amount of credits, the non-cooperative power selection game is analyzed to get the solution, that is, the Nash equilibrium (NE). The NE strategies are the transmission powers selected by the CCUs. Then, based on the NE strategies, the PU can select the best payment to maximize its utility U_p in the buyer-seller game. After that, all the cooperation parameters can be determined (i.e., the payment and transmission power).

An Integrated Cooperative Framework

With the aforementioned cooperation schemes, an integrated cooperative spectrum harvesting framework is devised to better harvest spectrum

For our future work, we will develop security-aware cooperation-based spectrum harvesting since a partner may be an adversary and misbehave during cooperation. Moreover, how to jointly utilize cellular spectrum and harvested spectrum bands to optimize overall system performance will be investigated.

opportunities, as shown in Fig. 3. When the CCU has no traffic, it can accumulate credits through cooperation with active PUs. Once the CCU has traffic and the QoS requirement cannot be satisfied using only the cellular bands, such as when downloading a high volume of data, additional spectrum bands need to be explored. Then the CCUs can perform cooperative spectrum sensing to detect the unused spectrum for access. If no idle spectrum bands are detected or the idle spectrum bands are not sufficient for QoS requirements, the CCUs can seek spectrum access opportunities through cooperation with the active PUs or keep sensing after a period of time. Otherwise, the CCU can obtain some spectrum from the spectrum trading market by paying credits.

Performance Evaluation

In this section, simulation results are provided to evaluate the performance of the proposed cooperation schemes. In a 2 km × 2 km area, the PUs are randomly located inside the circle with 1 km radius, while the CCUs are randomly distributed outside the circle. The transmission power of PUs, the noise power, the path loss coefficient μ, and the minimum required false alarm probability are set to be 10 W, –80 dB, 3.5, and 10 percent, respectively. Figure 4a shows the aggregate expected available time of the CCN through cooperative spectrum sensing when the number of primary channels is set to 9. It can be seen that the C-E-based user scheduling can achieve a longer available time than the random channel selection algorithm whereby all the CCUs just randomly select a channel to perform spectrum sensing. This is because the C-E algorithm can adaptively adjust the channel selection stochastic policy to increase the aggregate expected available time.

Figure 4b shows the aggregate throughput of the CCN achieved through cognitive cooperative relaying when the number of CCUs is 10. It can be seen that the SCC scheme can obtain a higher aggregate throughput, compared to the random channel selection algorithm whereby the CCUs just randomly select a channel to seek spectrum access opportunities. This is because the SCC scheme selects the best CCUs for each channel to maximize the total throughput.

Figure 4d shows the credits earned by the CCUs through cooperation with the PUs. The primary source and destination pair is placed at (0, 0) and (1 km, 0), respectively, while the location of a set of CCUs without traffic is shown in Fig. 4c. The maximum reward and λ_1 are set to be 20 and 10, respectively. It can be seen that six CCUs can obtain a ceratin amount of credits through relaying the PU's message. This means that the CCUs can accumulate credits through cooperation, which can be utilized for spectrum trading when needed.

Conclusion and Future Work

In this article, we have provided an overview of the cognitive cellular network. Three types of cooperation-based spectrum harvesting schemes have been introduced for different scenarios to better harvest spectrum opportunities. An integrated cooperation-based spectrum harvesting framework has been devised by considering the three cooperation-based schemes to fully explore the spectrum access opportunities. For our future work, we will develop security-aware cooperation-based spectrum harvesting since a partner may be an adversary, which misbehaves during cooperation. Moreover, how to jointly utilize cellular spectrum and harvested spectrum bands to optimize overall system performance will be investigated.

References

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast," White Paper, 2014.

[2] ITU-R Rep. M.2078, "Estimated Spectrum Bandwidth Requirements for the Future Development of IMT-2000 and IMT-Advanced," 2006.

[3] M. Pan *et al.*, "Spectrum Harvesting and Sharing in Multi-Hop CRNs Under Uncertain Spectrum Supply," *IEEE JSAC*, vol. 30, no. 2, 2012, pp. 369–78.

[4] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," *IEEE JSAC*, vol. 23, no. 2, 2005, pp. 201–20.

[5] N. Zhang *et al.*, "Dynamic Spectrum Access in Multi-Channel Cognitive Radio Networks," *IEEE JSAC*, vol. 32, no. 11, 2014, pp. 2053–64.

[6] Y. Liu *et al.*, "Deploying Cognitive Cellular Networks Under Dynamic Resource Management," *IEEE Wireless Commun.*, vol. 20, no. 2, 2013, pp. 82–88.

[7] W. Wang, G. Yu, and A. Huang, "Cognitive Radio Enhanced Interference Coordination for Femtocell Networks," *IEEE Commun. Mag.*, vol. 51, no. 6, 2013.

[8] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, "Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey," *Physical Commun.*, vol. 4, no. 1, 2011, pp. 40–62.

[9] M. Z. Shakir *et al.*, "Green Heterogeneous Small-Cell Networks: Toward Reducing the CO_2 Emissions of Mobile Communications Industry Using Uplink Power Adaptation," *IEEE Commun. Mag.*, vol. 51, no. 6, June 2013, pp. 52–61.

[10] M. Z. Shakir, A. Rao, and M.-S. Alouini, "Generalized Mean Detector for Collaborative Spectrum Sensing," *IEEE Trans. Commun.*, vol. 61, no. 4, 2013, pp. 1242–53.

[11] M. Fitch *et al.*, "Wireless Service Provision in TV White Space with Cognitive Radio Technology: A Telecom Operator's Perspective and Experience," *IEEE Commun. Mag.*, vol. 49, no. 3, 2011, pp. 64–73.

[12] L. Gao *et al.*, "Spectrum Trading in Cognitive Radio Networks: A Contract-Theoretic Modeling Approach," *IEEE JSAC*, vol. 29, no. 4, 2011, pp. 843–55.

[13] Y.-C. Liang *et al.*, "Cognitive Radio Networking and Communications: An Overview," *IEEE Trans. Vehic. Tech.*, vol. 60, no. 7, 2011, pp. 3386–3407.

[14] N. Zhang *et al.*, "Risk-Aware Cooperative Spectrum Access for Multi-Channel Cognitive Radio Networks," *IEEE JSAC*, vol. 32, no. 3, 2014, pp. 516–27.

[15] R. Y. Rubinstein and D. P. Kroese, *The Cross-Entropy Method: A Unified Approach to Combinatorial Optimization, Monte-Carlo SIMULation and Machine Learning*, Springer, 2004.

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