EMERGING APPLICATIONS, SERVICES, AND
ENGINEERING FOR COGNITIVE CELLULAR SYSTEMS

Network Economics in Cognitive Networks

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ABSTRACT

Cellular networks are confronted with unprecedented pressure to accommodate the dramatically increasing demands of mobile Internet. This phenomenon is principally due to the restricted spectrum resource and low-efficiency spectrum management. Recently, cognitive radio technology has been corroborated to significantly improve spectrum utilization efficiency. In order to enhance the spectrum management efficiency in cellular networks, the concept of "cognitive cellular networks" was introduced. It has been realized that the network architecture, algorithms, and protocols cannot be simply designed without considering the socio-economic aspects involved. In this article, we consider the economic issues in cognitive cellular networks from the perspectives of game theoretic modeling and mechanism design. Specifically, both the simultaneous and sequential dynamic spectrum access games are investigated, respectively. The mechanism design related issues (i.e., spectrum auction, pricing, and contract) to ensure desired outcomes are introduced with detailed applications in cognitive cellular networks. The goal of this article is to provide an overview to understand the motivation, problem formulation, methodology, and solutions of the economic issues in cognitive cellular networks.

INTRODUCTION

The last decade has witnessed gigantic development in cellular communication networks, from third generation (3G) — wideband code-division multiple access (W-CDMA), time-division code-division multiple access (TD-CDMA) — 3.5G — Long Term Evolution (LTE), CDMA2000 — to 4G (LTE-Advanced) and ongoing 5G standardization. Meanwhile, mobile applications and mobile social networks have emerged with this trend, leading to a phenomenon of ubiquitous mobile Internet that has penetrated into our daily lives. The faster wireless cellular network access comes mainly at the expense of wider communication bands and more spectrum resource. Until recently, desired improvement of service quality and channel capacity in wireless networks has been severely limited by spectrum resource, which has triggered considerable research activities seeking new communications and networking paradigms.

To mitigate the problem of spectrum resource limitation, cognitive radio technology was proposed in a concept of dynamic spectrum access (DSA), where users can intelligently and efficiently share the spectrum resource [1]. The essence of DSA technology lies in the fact that devices with cognitive capability, called secondary users (SUs), can dynamically search and utilize the licensed spectrum resource not occupied by licensed users, usually called primary users (PUs). Recently, researchers have proposed to introduce DSA into traditional cellular networks, generating the concept of a cognitive cellular network (CCN). As shown in Fig. 1, there are generally two kinds of operation modes in a CCN. One is that the cognitive device-to-device (D2D) SUs or ad hoc SUs attempt to dynamically utilize the licensed spectrum of primary cellular networks, as shown on the left of Fig. 1, while the other is that secondary small cell (e.g., femtocell, picocell) networks dynamically share the licensed spectrum with primary cellular networks but with lower priority, as shown in the right of Fig. 1b.

Currently, most existing works about CCNs have focused on various technical issues, including spectrum sensing to identify the available spectrum resource, interference management between primary cellular networks and secondary small cell networks (e.g., power control, offloading), and dynamic resource allocation [2]. However, the economic issues in CCNs have not been well understood, which is essential when it comes to the practical deployment of CCNs. Past history has shown that implementations of successful technologies not only rely on good engineering solutions, but also need to take the socio-economic aspects into account, which is especially the case for CCNs. In this article, we aim to study the network economic issues in CCNs from the perspectives of game theoretic modeling and mechanism design, to reveal the fundamental problems and corresponding enabling techniques. In the following, we first study the SUs' interactions when they simultane-

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Bayesian game is characterized by the uncertain player's type, which embodies any information that is not common knowledge to all players and is relevant to the players' decision making. Although each player is unknown about the exact types of others, he/she has a belief that illustrates the distribution of other players' utility functions.

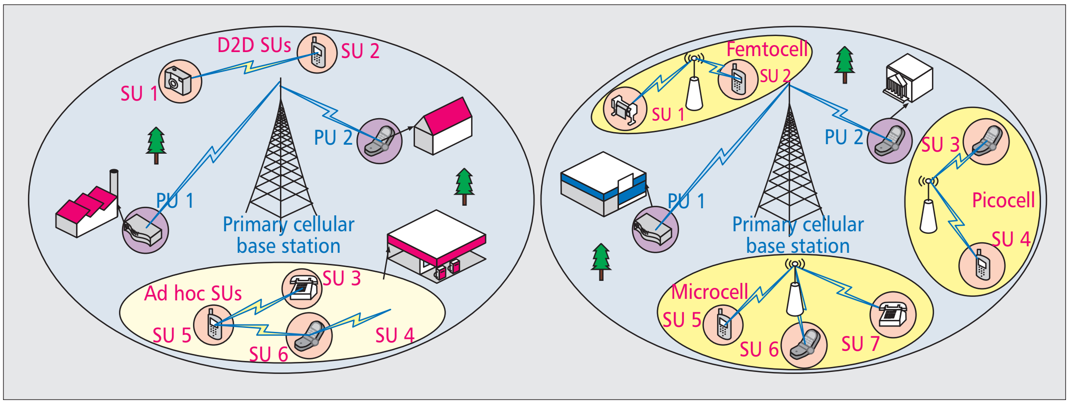

Figure 1. Two kinds of operation modes in CCNs.

ously access the primary cellular spectrum. Five simultaneous game models, including Bayesian, repeated, bargaining, coalition, and evolutionary games, are introduced with corresponding scenarios in CCNs. Then we further discuss the sequential DSA games considering two sequential decision structures in CCNs: sequential decision making between PUs and SUs, and sequential decision making among SUs. For the mechanism design issues, spectrum contract, auction, and pricing are introduced, respectively. Overall, this article provides a set of general models and methods for users' socio-economic behaviors and interactions analysis in CCNs.

SIMULTANEOUS DYNAMIC SPECTRUM ACCESS GAMES IN CCNs

Most existing licensed cellular networks (e.g., LTE, TD-CDMA, WiMAX) are both time/frequency-division-based systems, where all the devices are synchronized with the base station and coordinated through time slots. In such a case, if the SUs, whether ad hoc secondary devices or secondary small cells, intend to dynamically utilize the spectrum of primary cellular networks, they are required to synchronize with the network time slots in order to better control interference. A common operating mode is that the SUs perform spectrum sensing at the beginning of each time slot, and vacate the occupied spectrum at the end of the slot. Under such conditions, the SUs access the primary spectrum simultaneously, which leads to a practical problem of how an SU competes or cooperates with others. Meanwhile, one SU usually has no knowledge of other SUs' private information, such as channel state information and transmission power control policy, making the problem even more challenging.

A simultaneous game is an ideal tool to solve the aforementioned simultaneous spectrum access problem. It refers to a game where all players make a decision simultaneously without knowledge of the actions chosen by other players. In the literature, simultaneous game models have been extensively applied to SUs' spectrum access in CCNs, including Bayesian game [1], repeated game [3], evolutionary game [4], Nash bargaining [5], coalition game [1], and so on. Among those models, the first three are noncooperative game models, while the last two are cooperative. The Bayesian game is characterized by an uncertain player type, which embodies any information that is not common knowledge to all players and is relevant to the players' decision making. Although each player does not know about the exact types of others, he/she has a belief that illustrates the distribution of other players' utility functions. The authors in [1] summarized cognitive radio jamming games under uncertainty, where the transmitter was uninformed of the jammer's exact activities and had to make an expectation over all possibilities. Unlike the one-shot game model, Zhou *et al.* studied the long-run repeated interactions among SUs in a CCN using a repeated game [3]. This game is featured by a repeated decision making and punishment stage, which ensures that all players cannot deviate from the designed Nash equilibrium (NE). In [3], the transmission power level was considered as an SU's strategy, while the utility function was defined as an SU's long-term summation payoff discounted over time. Moreover, a reinforcement learning-based power control algorithm was designed for SUs to converge to the desired NE.

When all SUs in a CCN are fully selfish and uncooperative, NE sometimes becomes extremely inefficient. For a simple instance, in the power control game, all SUs adopting the highest transmission power is an NE [3]. Under such a circumstance, cooperation among SUs in a CCN can improve the system efficiency to a large extent, while the practical problem is how to encourage/stimulate them to be cooperative. A cooperative game can solve this problem well by bargaining or forming coalition among players. In [5], the Nash bargaining solution (NBS) was applied to analyze the cooperation between the PUs (licensed cellular network) and unlicensed ad hoc SUs in a CCN. The NBS can simultaneously satisfy *Pareto optimality, symmetry, fairness, independence of irrelevance alternative,* and *independence of linear transformations*. The authors in [4] derived the NBS by maximizing the product of PUs' utility minus its acceptable minimal utility and SUs' utility minus its minimal utility, where the utility was defined as the achievable throughput. Another typical kind of cooperative game is a coalition game, which focuses on how

Game models	Coop?	Equilibrium	Key features	App in CCN
Bayesian game	No	Bayesian NE	• Players' types • Bayesian expected utility	[1]
Repeated game	No	Repeated NE	• Long-term expected utility • Punishment stage	[3]
Bargaining game	Yes	Nash bargaining solution	• Pareto optimality, fairness • Utility production maximization	[5]
Coalition game	Yes	Nash stable coalitions	Coalition formation algorithm	[1]
Evolutionary game	No	Evolutionarily stable strategy	Replicator dynamics	[4]

Table 1. Comparison of different simultaneous game models.

In the dynamic Chinese restaurant game model, the SUs are assumed to arrive at the primary cellular network by Bernoulli process with certain probability. They sequentially sense and estimate the primary spectrum in a Bayesian manner, and sequentially access the available spectrum based on a multidimensional Markov decision process.

to formulate stable coalitions among a group of players. It has been applied to resource allocation in secure cognitive femtocells [1], where the utility function was defined as the gain in terms of secrecy rate minus the cost of information exchange. A distributed coalition formation algorithm was designed to find stable secure coalitions, and the convergence analysis was also conducted. In Table 1, we summarize and compare all the simultaneous game models.

The NE derived by the aforementioned models can only prevent one SU's deviation, while it is possible that multiple SUs deviate from the NE in order to selfishly attain more utility. When it comes to a small group of SUs' deviations, evolutionary game theory (EGT) can address this problem well. Different from the traditional game models that focus on the property of static NE, EGT emphasizes the evolutionary dynamics and stability of the whole population's strategies, which is called an evolutionarily stable strategy (ESS). In [4], we studied the joint spectrum sensing and access problem in CCNs using EGT. On one hand, when only a few SUs contribute to spectrum sensing, the false alarm probability is relatively high, resulting in a high interference probability and low throughput. On the other hand, when many SUs access the primary channel, the channel becomes very crowded, and little throughput can be obtained by an individual SU. Through analyzing the dynamics of SUs' sensing and access strategies, we derived the ESS from which no one can deviate, as well as a distributed learning algorithm for the SUs to converge to the ESS. From the simulation results in Fig. 2, we can see that the SUs with the designed learning algorithm can quickly abandon the initial undesired strategy, that is, only 10 percent SUs sense, while 90 percent access the spectrum. The system finally converges to different ESSs under different settings of the reward to the SUs who only contribute to sense the spectrum but not access, as shown on the top and in the middle of Fig. 2. In a practical network, the reward can be the credit of the SUs, or a period of network access time free of charge. It can be seen that a higher reward can attract more SUs to participate in spectrum sensing. In addition, the bottom of Fig. 2 shows that when a small group of SUs deviate from the ESS, the system can return back to the ESS quickly after the perturbation.

SEQUENTIAL DYNAMIC SPECTRUM ACCESS GAMES IN CCNS

In a CCN where ad hoc SUs sense and access the licensed cellular spectrum in a distributed manner, different SUs may arrive at or leave the network at different time slots. In such a case, one SU can observe the previous SUs' spectrum access behaviors as well as their released spectrum sensing results, which can be utilized to better understand the availability of the licensed cellular spectrum. Apparently, when considering multiple SUs' access in different time slots or their asynchronous access in one time slot, it becomes a sequential spectrum access problem. Apart from this sequential spectrum access among SUs, the sequential characteristic also exists between the PUs and SUs. In the CCN, the primary cellular networks always have highest priority as leaders, while the SUs, whether ad hoc secondary devices or secondary femtocells, are on the follower side. A common interaction mode is that the primary cellular network first determines its strategies (claiming the maximum tolerable interference level, announcing the amount of spectrum that can be utilized, etc.). Then, according to the PUs' actions, the SUs can make an optimal response on how to access the spectra. To summarize, the sequential dynamic spectrum access problems in CCN have two scenarios:

- PUs first propose the regulations of spectrum utilization, and then SUs decide how to access the spectrum according to the regulations.
- SUs sequentially determine how to sense and access the licensed cellular spectrum.

To address such a sequential spectrum access problems in CCNs, a sequential game is an effective tool to model and analyze the sequential decision making structure between PUs and SUs, and that among SUs. Sequential refers to games where one player makes his/her decision after the others, where an important feature is that later players have some information about the first users' strategies. Due to the sequential

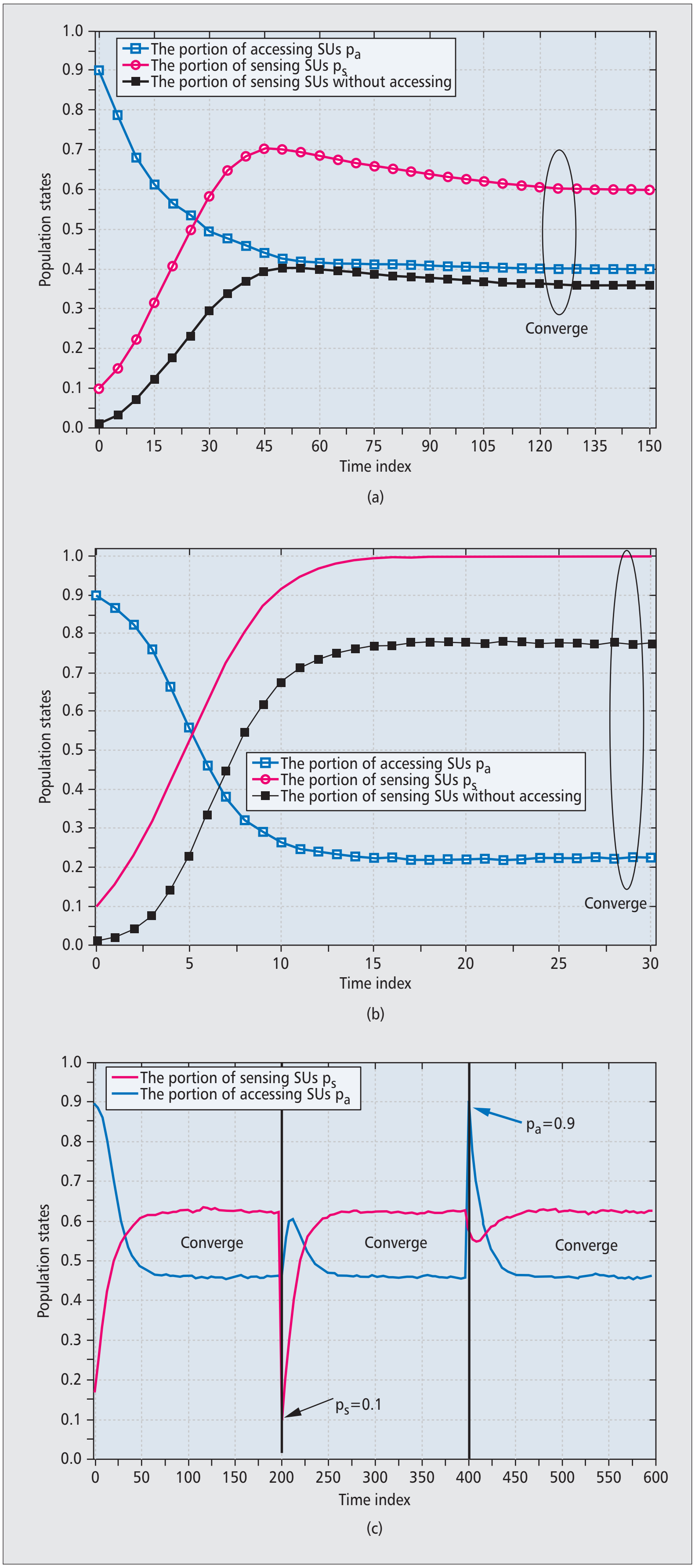

Figure 2. Evolutionarily stable strategy under different reward settings (the reward to the SUs who only contribute to sense the spectrum but not access). Top: reward = 40; middle: reward = 100; bottom: reward = 50.

characteristic, the game is usually represented by an extensive form or decision tree, and the corresponding NE can be found using a backward induction method. For the aforementioned first scenario (i.e., sequential decision making between PUs and SUs), the Stackelberg game has been widely employed to study the PUs' and SUs' best responses. The typical backward induction method to obtain the NE of such a Stackelberg game is first deriving the SUs' spectrum access decision, which is a function of the PUs' spectrum regulation policy, and then maximizing the PUs' utility to determine their optimal spectrum regulation policy, in turn the SUs' best spectrum access decision. In [6], the authors studied a scenario where the SUs act as the relay between the primary cellular base station and the PUs; meanwhile, in return, the base station allocates a portion of time in one time slot for the SUs. The primary base station first determines a fraction of one time slot for the SUs, and then each SU can decide on the payment to the PUs, which can be either money or a period of relay service. When calculating the Stackelberg NE of this game, a backward procedural was analyzed, first maximizing the SUs' utility and then the PUs'.

For the aforementioned second scenario (i.e., the sequential decision making between SUs) similar backward induction method can be utilized for the NE analysis. We studied such a sequential decision making problem in CCN using sequential dynamic Chinese restaurant game in [7], where the spectrum sensing and access analysis were integrated. This game model has two dimensions, one dimension is the ad-hoc SUs sequentially construct its belief on the availability of the primary cellular spectrum by using its spectrum sensing results, as well as the previous SUs' beliefs, which is a social learning perspective. The other dimension is the SUs sequentially access the spectrum according to one's own belief, as well as other SUs' spectrum access decisions. More importantly, the two dimensions are coupled together, since one SU's spectrum access decision is not only determined by its own belief, which is influenced by the previous SUs' belief, but also other SUs' spectrum access decisions due to the negative network externality; that is, the more SUs share a same part of spectrum resource, the less throughput each SU can obtain.

In the dynamic Chinese restaurant game model, the SUs are assumed to arrive at the primary cellular network by a Bernoulli process with certain probability. They sequentially sense and estimate the primary spectrum in a Bayesian manner, and sequentially access the available spectrum based on a multidimensional Markov decision process (M-MDP). A modified value iteration algorithm was also proposed to find the NE of the dynamic sequential spectrum access game. Figure 3 shows the performance evaluation of the proposed game strategy, where the centralized strategy is obtained by exhaustively searching all possible strategy profiles to maximize the social welfare. The myopic strategy is to maximize the immediate utility, that is, to choose the spectrum with the largest immediate reward, and the random strategy is to randomly

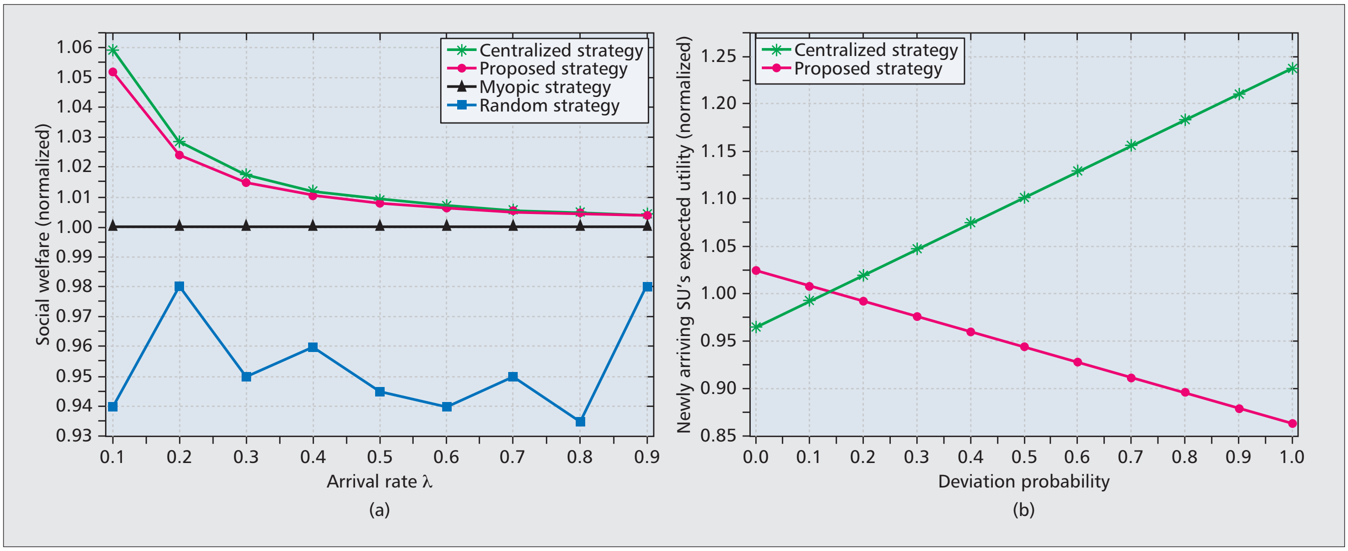

Figure 3. Left: social welfare comparison of different strategies; right: Nash equilibrium verification.

choose a part of primary spectrum to access. We can see that the proposed strategy performs better than both myopic and random ones, but slightly less than the centralized strategy. However, the centralized one cannot avoid the malicious SU's strategy deviation, as shown on the right of Fig. 3, and the complexity is extremely high, sometimes even computationally intractable.

MECHANISM DESIGN IN CCNS

In a CCN, the primary cellular networks own the licensed spectrum, while the SUs attempt to dynamically utilize the spectrum. In most cases, such dynamic occupation is not cost-free for the SUs. Instead, they have to pay something in return to the PUs (e.g., money or serving as PUs' relays). Thus, the spectrum becomes a special kind of commodity in a CCN, where the cellular network operator can lease the vacant spectrum to the SUs, and the latter purchase the spectrum on demand. Such a spectrum trading process involves many practical problems. On one hand, for the operators of cellular networks, their issues are to price the spectrum to maximize their own profit, and to offer appropriate contracts to attract more SUs. On the other hand, for the SUs, they need to consider how much spectrum to purchase from the primary operator, and how to respond to the offered contract. Meanwhile, how to design a trading mechanism that can ensure that both the primary operator and the SUs attend the spectrum trading rationally, actively, honestly, and efficiently is also an important issue. Apparently, all those practical problems during the spectrum trading process in CCNs are similar to those during a common commodity transaction in real-world economics. Therefore, they can be addressed using the analytical tools in economics.

Mechanism design theory in economics can be applied to solve the aforementioned spectrum trading related problems. Different from the NE analysis under a given game rule, mechanism design is the "inverse" of traditional economic theory, which is typically devoted to a game structure design, as well as the analysis of the performance of a given mechanism. In the literature, some classical mechanism design methods have been adopted to analyze the spectrum trading problems, including contract design [8], auction design [9], and price design [10]. Contract theory studies how economic actors construct contractual arrangements, generally in the presence of asymmetric information; that is, they have little knowledge of the private information of the contract players. For example, in the labor market, employers generally do not completely know employees' private information before employment and need to offer employees a contract with incomplete information. This is quite similar to spectrum trading scenarios, where PUs offer a series of spectrum leasing contracts without SUs' preference information. Duan *et al.* investigated how the PUs should set up optimal/near-optimal contracts in [8], under complete, weakly complete, and strongly complete information of the SUs, respectively, where the information refers to the channel condition of each SU. The contract consists of a set of items representing combinations of the SUs' spectrum accessing time (i.e., reward) and relaying power (i.e., contribution). Through backward induction and maximizing the PUs' utility, that is, the average transmission rate during the entire time period, the author derived the optimal contracts from the perspective of primary cellular networks.

When it comes to the spectrum trading mechanism, auction is an ideal approach to organize the complex interaction between spectrum sellers and spectrum buyers. Generally, an auction mechanism is associated with a winning policy and a charging policy, the performance of which can be evaluated by four key properties:

- *Efficiency*: Resources are distributed to users that value them most.
- *Incentive compatibility*: A user cannot do better by unilaterally misreporting his/her value.

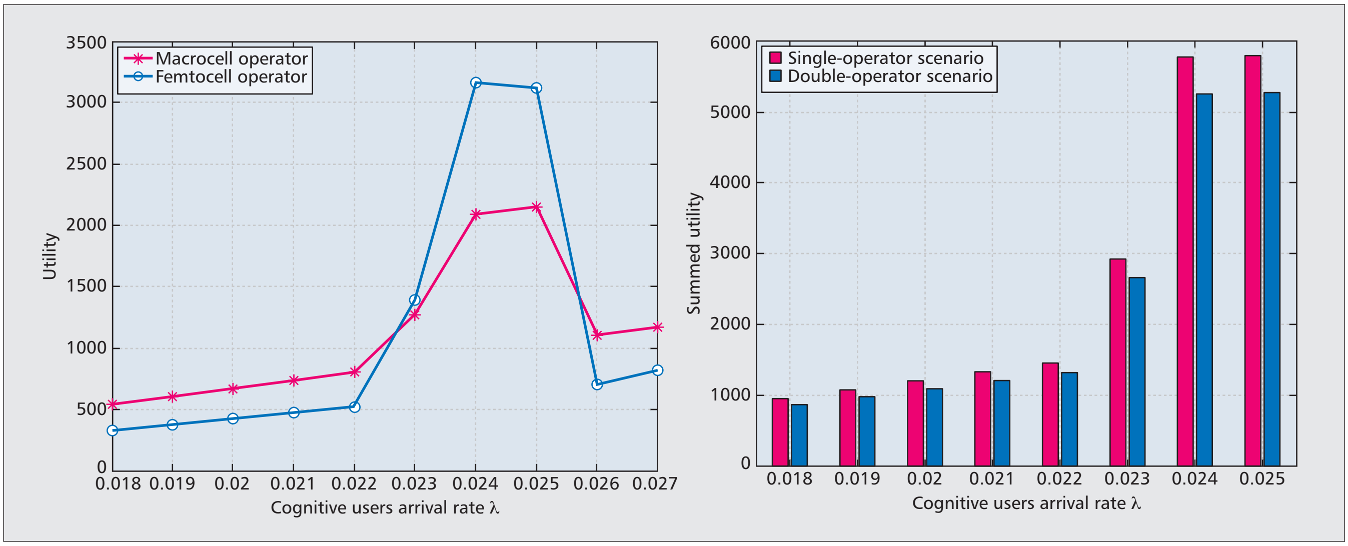

Figure 4. Left: utility comparison between macrocell and femtocell; right: utility comparison between single-operator and double-operator.

- *Individual rationality*: Users always expect non-negative value from the auction.
- *Budget balance*: Auctioneers do not lose money in the auction.

The authors in [9] considered a spectrum double auction model, where the spectrum seller (the cellular network operator) may exaggerate the spectrum value to the auctioneer, while the spectrum buyers (the SUs) may report untruthful channel valuation as bids. The auctioneer collects the spectrum sellers' prices and the spectrum buyers' bids to determine the winners, where the prices and bids refer to the spectrum leasing prices at which sellers are willing to sell and buyers are willing to pay, respectively. A spectrum seller or buyer may submit a different price or bid from its true price or bid, as long as it believes that this is more beneficial. The authors formulated such a double-auction mechanism design problem as an optimization problem: maximizing the auction efficiency defined as the portion of winning buyers under the constraint of incentive compatibility, individual rationality, and budget balance. Meanwhile, the local market phenomenon was also taken into account; that is, a spectrum buyer can trade with any seller whose license area is centered within the same hexagonal cell of the buyer. Therefore, a colored graph representing the spectrum assignment result was also associated with the proposed spectrum double-auction mechanism to coordinate the interference among cells.

Spectrum pricing is another important economic issue in CCNs, where the cellular operator charges the SUs based on their interference level (underlay model) or utilization of vacant spectrum (overlay model). A common method to calculate the optimal price is backward induction, that is, first analyzing the SUs' behaviors given the price, and then maximizing the PUs' revenue to find the optimal pricing policy. In [10], we investigated the spectrum pricing scenario in a heterogenous network, where the secondary femtocells lease spectrum from the primary macrocells. Given the spectrum leasing price, macrocell and femtocell operators set the network access prices independently and noncooperatively. For the cognitive users, on one hand, accessing femtocells may obtain higher data rate but with higher payment due to additional spectrum leasing costs for the femtocell operator. On the other hand, accessing a macrocell network can lead to lower payment, but users may experience unsatisfactory data rate due to unfavorable locations. Therefore, rational cognitive users make their decisions (i.e., accessing a macrocell or femtocell network) by comparing the corresponding utilities. This pricing problem was formulated as a two-tier pricing model, and the NE prices were derived using the backward induction method under two models, static pricing and dynamic pricing, where "dynamic" means that the network access price is decreasing with the increasing number of users in the network; that is, negative network externality is considered.

The utility of macrocell and femtocell operators (the net profit under the proposed pricing mechanism) are shown on the left of Fig. 4 via simulation. When users' arrival rate is relatively small, the utility of a macrocell operator is larger than that of a femtocell operator, since accessing the uncrowded macrocell with a lower price is preferred by cognitive users. When the arrival rate is in the middle, a femtocell operator's utility becomes higher, which is because with the increasing number of users, accessing a femtocell network can achieve much higher throughput. When the arrival rate is relatively high, the macrocell operator's utility becomes higher again, since both networks become crowded, while the macrocell operator has additional spectrum leasing revenue. A comparison between our work and the scenario where both the macrocell and femtocell are operated by the same operator was also conducted. In such a single-operator scenario, the operator can globally optimize the network access prices of both macrocell and femtocell by maximizing their sum utilities. Apparently, as shown on the right of Fig. 4, the single-operator scenario can perform better than the double-operator scenario due to global optimization, but quite marginally. However, the single-operator scenario can only be applied to the monopoly-based market, which is rarely seen in the real-world market, while the double-operator scenario can be well applied in the competition-based market and provide an equilibrium point for the market, which is more common in the current practical scenario.

CONCLUSION

The network economics are the soul of CCNs; therefore, it is essential that they be carefully studied and planned for CCNs to thrive. In this article, the network economic issues in CCNs are discussed. We study both the simultaneous and sequential behaviors in CCNs with scenarios and examples to illustrate possible solutions. In addition, mechanism design issues to ensure desired outcomes are also introduced. This article offers an overview of the fundamental issues and key techniques regarding the network economic issues in CCNs, and also points out some possible research directions for future investigations.

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BIOGRAPHIES

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The authors formulated such a double-auction mechanism design problem as an optimization problem: maximizing the auction efficiency defined as proportion of winning buyers under the constraint of incentive compatibility, individually rationality and budget balance.