Auction-Based Spectrum Management of Cognitive Radio Networks

Hung-Bin Chang, *Student Member, IEEE*, and Kwang-Cheng Chen, *Fellow, IEEE*

***Abstract*—Cognitive radio (CR) technology is considered to be an effective solution to enhance overall spectrum efficiency, whereas a primary radio network (PRN) typically does not fully utilize an available spectrum. However, to realize the CR concept, it is essential to provide enough incentives to PRNs and extra revenue to the service provider such that CR mobile stations (CR-MSs) may accordingly utilize PRN spectrum bands, which provides a new challenge for spectrum management. In this paper, we consider a PRN consisting of a primary system base station (PS-BS) and multiple primary system mobile stations (PS-MSs), and we, therefore, construct a CR network (CRN) consisting of a PRN with multiple CR-MSs. We propose a spectrum-management policy framework based on the Vickrey auction such that CR-MSs can compete for utilization of the PRN spectrum bands available for opportunistic transmission of CR-MSs. PRN users are granted incentives at a discounting factor to access spectrum bands and are being compensated for possible operating interference from CR-MSs, whereas the interference is constrained under a tolerance level without losing satisfaction for the PS-MSs. Once CR-MSs are granted spectrum bands, they can utilize the spectrum bands for a certain duration with no spectrum handoff. Consequently, in addition to incentives to the PRN, the overall spectrum utilization, the profit of the service provider, and the opportunity to access the spectrum for the CR-MSs are enhanced to achieve a co-win situation for every involved party in CRNs. Realistic simulations by incorporating pretty bad channel conditions into system operations show the robust operation of our proposed system, which enables the CR concept.**

***Index Terms*—Auction theory, blocking rate, cognitive radio network (CRN), dynamic spectrum access, network economy, queuing theory, spectrum management, spectrum utilization.**

I. Introduction

DUE to the dramatically increasing demand for a spectrum and underutilization of a spectrum, spectrum-efficient technology is highly necessary. The study supported by the Federal Communications Commission has shown that traditional fixed spectrum allocation policy is inadequate in addressing today's rapidly growing wireless communication [1]. It also shows many allocated spectrum blocks that are unused in certain geographical areas or idle most of the time [1]. These unused spectrum blocks are known as spectrum white space or spectrum holes. Dynamic spectrum access is proposed to resolve the challenge of insufficient spectrum utilization [2]–[5]. With a dynamic spectrum-sharing scheme, the spectrum hole or spectrum opportunity that is generated from the spectrum of licensed users (i.e., primary users) can be exploited to improve the utilization and, consequently, the revenue of a network operator.

Dynamic spectrum access/sharing is based on the technology of cognitive radios (CRs). CR technology is based on software-defined radio technology, which is proposed to enhance adaptability and flexibility of wireless transmission such that a CR has the ability to observe, learn, optimize, and change the transmission parameter according to the ambient radio environment [6]–[8]. Such capability of CRs enables dynamic spectrum access/sharing. CRs share the spectrum of a primary radio network (PRN) with license in an opportunistic way [9]–[13]. To facilitate dynamic spectrum sharing, spectrum management, together with an appropriate economic model, is required for all four involved parties in the CR network (CRN) scenario—the spectrum regulator (i.e., general public interests), the service provider (i.e., the operator), PRN users (i.e., licensed users or primary users), and CRs (i.e., unlicensed users or secondary users)—through spectrum pricing and radio-resource allocation. The spectrum regulator wishes to fully utilize spectrum bands; the service provider wishes to increase his or her profit (by increasing the revenue) with limited spectrum bands by allowing CRs to access the spectrum bands of PRNs; the PRN users wish to share the increasing profit of the service provider as incentives to allow CRs without losing quality of service (QoS) or with constrained QoS, and CRs wish to increase opportunity of accessing spectrum bands and be guaranteed a certain degree of QoS. Because CRs cannot induce any interference (or possible interference under some minimum service constraint) to primary system mobile stations (PS-MSs), CRs have some constraints to utilize the spectrum bands of PRNs. Therefore, CRs wish to utilize the spectrum bands of PRNs as secondary users while surely paying lesser (or no more) than the PRN users. There may be conflict or cooperation among the four involved parties so that the wishes of each party can be satisfied. Game theory is a fundamental technology that can solve conflict or cooperation problem among involved parties and has been considered as a useful technology for spectrum management in CRNs. Game theory has also been used for resource management (e.g., transmission rate control, admission control [14], and power control [14]–[17]) and can also be used to solve spectrum pricing. Auction theory is an extreme tool in game

Manuscript received May 27, 2009; revised September 29, 2009. First published February 8, 2010; current version published May 14, 2010. This work was supported by the National Science Council of Taiwan under Contract NSC 98-2219-E-002-018. This paper was presented in part at the 2009 IEEE Vehicular Technology Conference Spring. The review of this paper was coordinated by Prof. J. Mitola, III.

The authors are with the Graduate Institute of Communication Engineering and Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan (e-mail: r96942048@ntu.edu.tw; chenkc@cc.ee.ntu.edu.tw).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2010.2042474

0018-9545/$26.00 © 2010 IEEE

theory. It is a method that can determine the value of a community that is undetermined or the variable value price and is designed to allocate resources more efficiently. If we attempt to satisfy all involved four parties, spectrum pricing with an auction method must be considered.

In this paper, we propose a novel spectrum-management policy based on auction theory to construct the co-win situation that simultaneously satisfies all four parties. For a spectrum regulator, it takes care of general public interests and can significantly improve spectrum utilization. For the service provider, it can also increase its profit by allowing CRs to significantly compete in the spectrum bands of PRNs. For PRN users, they can have a discounting factor to access spectrum bands, as sharing the increasing profit of the service provider and the possible interference from CRs can be constrained under a certain level that PRN users can tolerate without losing satisfaction from PRN users. Furthermore, since PRN users suffered interference from CRs, they can be compensated for the interference. For CRs, they can gain new opportunity of accessing the spectrum bands of PRNs. Once they are granted the spectrum bands, each of them can be guaranteed a certain duration to utilize the spectrum bands with no spectrum handoff. Hence, the QoS of CRs can also be warranted to a certain degree. However, to constrain the interference to PRN users from CRs, the service provider only allows CRs to compete in the portion of the spectrum bands of PRNs per superframe basis, and the portion of the spectrum bands is determined from the constraint on the interference to PRN users. CRs that attempt to pay lesser (or no more) than the PRN users to utilize the spectrum bands of PRNs as secondary users can compete in the portion of the spectrum bands of PRNs with CRs by using the auction principle while surely paying less (or no more) to utilize the spectrum bands. For an auction, the price of accessing spectrum bands is determined from CRs (i.e., bidders). A class of auctions, i.e., the multiunit sealed-bid auction (i.e., the Vickrey auction), is suitable to execute in a determinable time with an acceptable signaling effort in comparison to the English (sequential) auction [18]–[20]. The Vickrey auction can also allocate unused spectrum bands to CRs faster, which is more efficient than the traditional English auction in limited duration and meets economic efficiency in which the spectrum bands can be allocated to the CRs valuing them most [18]. Thus, the Vickrey auction is adopted for CRs in our spectrum-management policy. In the end, a realistic simulation by incorporating high channel errors in system operations is considered to examine the robust operation of our proposed system. When channel errors occur, the CRs may fail to compete in utilizing the spectrum bands of PRNs during an auction process so that the profit of the service provider and spectrum utilization may decrease.

The major contributions of this paper are as follows.

1) We propose a novel spectrum-management policy that simultaneously considers and satisfies the four involved parties (i.e., the spectrum regulator, the service provider, PRN users, and CRs) such that co-win situation can warrant successful deployment of CR operation.
2) To the best of our knowledge, this is the first paper that not only considers how to avoid any inference to PRN users from CRs but also further considers the incentives of PRN users to allow CRs to utilize the spectrum bands of PRNs.
3) The Vickrey auction is a kind of multiunit sealed-bid auction and is used to implement a pricing model. It can efficiently allocate multiunits (i.e., multiple spectrum bands) to bidders (i.e., CRs) at a time and meet economic efficiency.
4) Extensive performance analysis and simulations are presented for the spectrum-management policy and give an insight into the spectrum-management challenge.

The rest of this paper is organized as follows. In Section II, we review and discuss the related works. The system model and assumptions are described in Section III. In Section IV, we propose a spectrum-management policy and formulate the policy. In Section V, the problem of spectrum-management policy is formulated and optimized. Section VI presents the performance evaluation results to verify the policy. In the end, conclusions are stated in Section VII.

II. Related Works

There are excellent efforts that solve spectrum pricing and try to satisfy all involved parties via game theory or auction theory in CRNs. Reference [21] mainly focuses on developing solutions for wireless secondary users to successfully compete with each other in the limited and time-varying spectrum opportunities based on auction, given the experienced dynamics in the wireless network. Reference [22] considers the problem of spectrum sharing among a primary user and multiple secondary users, formulates this problem as an oligopoly market competition, and uses a noncooperative game to execute the spectrum allocation for secondary users. Reference [23] considers a key challenge in operating CRs in a self-organizing (ad hoc) network to adaptively and efficiently allocate transmission power and spectrum among CRs (i.e., secondary users), according to ambient surroundings without disturbing primary users. Reference [24] proposes a pricing-based collusion-resistant dynamic spectrum-allocation approach not only to optimize overall spectrum efficiency but also to combat the collusion among selfish secondary users. The collusion behavior among secondary users may seriously deteriorate the efficiency for wireless networks. Reference [25] investigates three different pricing models (i.e., market-equilibrium, competitive, and cooperative) via game theory among service providers and secondary users. Reference [26] considers the interaction between primary users (or service providers) and secondary users who can adapt the spectrum-buying behavior by observing the variations in price and QoS offered by primary users (or service providers) via the evolutionary game. Reference [27] adopts a second-price auction mechanism to solve spectrum pricing among an auctioneer (i.e., the service provider) and secondary users and looks into the problem of maximizing the revenue of the service provider while satisfying the QoS of secondary users. Reference [28] proposes an efficient mechanism for multiwinner spectrum auction, which is a novel concept and can efficiently improve spectrum utilization with collusion-resistant pricing strategies between the service provider and secondary users. The collusion behavior among secondary users may decrease the revenue of service providers. Reference [29] addresses the problem of spectrum pricing in a CRN where multiple service providers compete with each other to offer spectrum-access opportunities to secondary users under the QoS constraint for primary users. Therefore, these excellent explorations still lack a complete study of the satisfactions of all involved parties. In this paper, we propose a spectrum management policy based on auction to simultaneously consider and satisfy the four involved parties (i.e., the spectrum regulator, the service provider, primary users, and secondary users) in CRNs. It is important to consider or satisfy all four involved parties such that CR deployment can come true.

To realize the CR concept, it is essential to provide enough incentives to PRNs and extra profit to the service provider so that CR mobile stations (CR-MSs) may accordingly utilize the PRN spectrum. The incentive to the PRN is, therefore, provided by compensating the PRN with the portion of extra profit for the interference from CR-MSs to allow CR-MSs to access the spectrum. These CR-MSs compete in the unused spectrum bands of the PRN with CR-MSs by using the Vickrey auction principle. However, the QoS of PRN users to allow operation of CR-MSs is another essential factor of spectrum management but is not included in the mechanism in [30], although co-win among four parties has been discussed. In this paper, we, therefore, consider the QoS of PRN users through the blocking rate of PS-MSs to ensure a more complete and realistic study. We further allow PRN users to access spectrum bands at a discount rate as one sort of their incentives and can, therefore, derive optimal solution to satisfy all involved parties, while [30] could not explicitly reach this result. Furthermore, we conduct a more-realistic system verification to show the robust operation of our proposed spectrum-management policy in realistic channels.

III. System Model

We first summarize the important notations that are used in this paper in Table I. In the following, these notations are presented and explained in detail.

A. Network Topology

The network topology of the CRN is shown in Fig. 1. We consider an infrastructure CRN as defined in [9] and shown in Fig. 1. Fig. 1 consists of a service provider, a primary system base station (PS-BS), several PS-MSs (i.e., PRN users or primary users), and CR-MSs (i.e., CRs or secondary users) in the CRN. We construct a new superframe to synchronize the behavior of PS-MSs and CR-MSs. The service provider provides spectrum bands to all users (i.e., PS-MSs and CR-MSs) via the PS-BS and possesses a total of K spectrum bands. The numbers of PS-MSs and CR-MSs are time variant. Each spectrum band can only be utilized by one PS-MS or CR-MS at a time. Each user can only access one spectrum band at a time, cannot construct any connection to another user, and can only communicate with the service provider via the PS-BS.

TABLE I
Important Notations Used in This Paper

notation	description
λ_P	The arrival rate of PS-MSs
N_C	The number of CR-MSs attempting to compete in spectrum bands per superframe duration
T_S	A superframe duration, $T_S = T_C + DT_D$
D	Number of data frames in a superframe
α	Discounting factor for PS-MSs to utilize spectrum bands
β	The constrained blocking rate for PS-MSs
Q_{PS}	Price rate to utilize spectrum bands per control or data frame duration for PS-MSs
Q_{CR}	Price rate to utilize spectrum bands per data frame duration for CR-MSs
R_P	The revenue from PS-MSs
R_C	The revenue from CR-MSs
$f(\cdot)$	Function of private value of CR-MSs
$C(\cdot)$	Compensating function for PS-MSs
I	The index of frames in a superframe
B	Blocked numbers of PS-MSs per control frame or data frame duration
P_B	Blocking rate for PS-MSs per control frame or data frame duration
η_{PS}	Spectrum utilization of PRN only
η_{CR}	Spectrum utilization of CRN
K	Number of spectrum bands of the service provider
K_l	Number of spectrum bands allocated to CR-MSs
K_l^M	The maximum number of spectrum bands allocated to CR-MSs
K_l^*	The optimal number of spectrum bands allocated to CR-MSs
P_e	Packet error rate (PER)

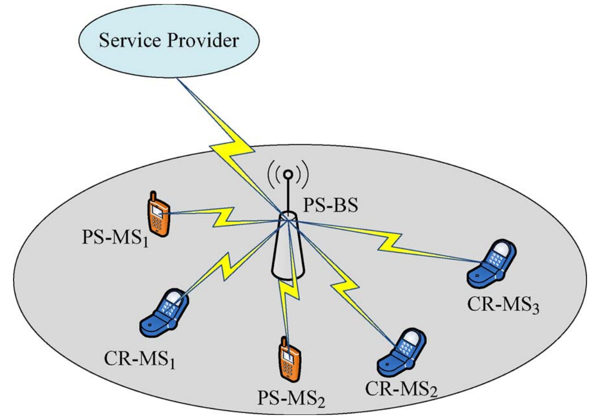


Fig. 1. Network topology of the CRN.

B. Superframe Structure

The superframe illustrated in Fig. 2 consists of one control frame and D data frames. The control frame consists of T_C time slots, and each data frame consists of T_D time slots. For simplicity, we assume that T_C is equal to T_D in our system model. The frames in a superframe are indexed by I, $I = 1, \ldots, D + 1$. The control frame is indexed by $I = 1$. The first data frame is indexed by $I = 2$, the second frame is indexed by $I = 3$, and so on. We assume that every superframe in each spectrum band starts simultaneously. Every superframe duration is set as T_S (i.e., $T_S = T_C + DT_D$).

C. Traffic Model

For two different kinds of users (i.e., PS-MSs and CR-MSs), two different traffic models have been considered for them.

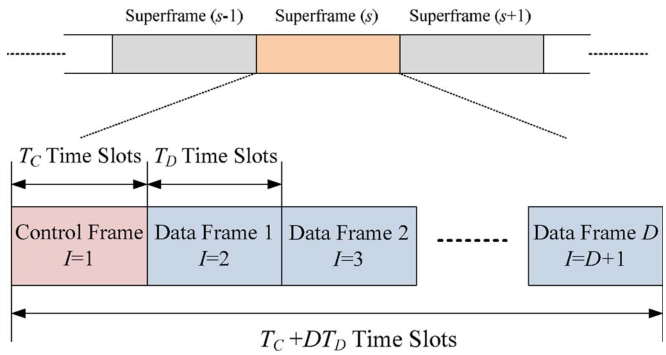


Fig. 2. Structure of a superframe.

1) PS-MS: If any spectrum band of the service provider is free, PS-MSs can access one of them in any control or data frame. The arrival of PS-MSs is a Poisson arrival with arrival rate λ_P. The service time of PS-MSs is T_C (i.e., one control frame) or T_D (i.e., one data frame). It depends on what kind of frames they access. Once a PS-MS accesses any spectrum band, the service of the PS-MS starts at the beginning of the next control frame or data-frame duration.

2) CR-MS: CR-MSs are only allowed to compete in the spectrum bands of the PRN in one control-frame duration and can utilize the spectrum bands with D data-frame duration without any spectrum handoff. Therefore, the service time of CR-MSs is DT_D (i.e., D data frames). In one control-frame duration, the service provider determines which CR-MSs can access spectrum bands via the Vickrey auction, and then, the CR-MSs determined by the service provider can access the following D data frames with no spectrum handoff. We assume that each CR-MS has the same constant arrival rate and that there are N_C CR-MSs attempting to compete in the portion of the spectrum bands of the PRN that can be allocated to CR-MSs without losing satisfaction for PS-MSs in every control frame. In the general case, N_C is larger than the number of spectrum bands of the service provider. Thus, in this paper, we consider the critical case that N_C is larger or equal to the total number of spectrum bands of the service provider K. The service of CR-MSs would start at the beginning of the first data-frame duration (i.e., $I = 2$).

D. Compensating Mechanism Model

The operating interference that CR-MSs induce to the PS-MS may result in outage to block PS-MS traffic. Assuming a cellular-type system, the service provider can measure the interference by using the number of blocked data frames that PS-MSs suffer (denoted as B) due to the occupation of the CR-MSs. The blocking rate for PS-MSs (denoted as P_B) is defined as the probability that PS-MSs attempting to utilize spectrum bands are blocked. The service provider depends on the measurement of the blocked numbers (i.e., B) to pay $C(B)$ to the PS-MSs as the compensation per data frame, where $C(B)$ is a compensating function and depends on B. We constrain the interference (i.e., the blocking rate for PS-MSs P_B) under a tolerance level (denoted as β) that the PS-MSs can tolerate without losing satisfaction for the PS-MSs. The compensation $C(B)$ is considered as an incentive for PS-MSs to allow CR-MSs. Hence, the compensation is the cost of the service provider.

Because we attempt to constrain the blocking rate for PS-MSs (i.e., P_B) under a certain tolerance level β, the general approach is to reverse some spectrum bands for PS-MSs such that P_B can be constrained under β [31]. We must calculate the number of the portions of spectrum bands (denoted as K_l) that can be allocated to CR-MSs without violating the constraint (i.e., $P_B \leq \beta$). To determine K_l, we first formulate the probability mass function of the number of PS-MSs arriving in one control-frame or one data-frame duration. It is given by

$$P(M = m) = \frac{e^{-\lambda_P T_D} (\lambda_P T_D)^m}{m!} \tag{1}$$

where M is the random variable of the number of PS-MSs arriving in one control-frame or one data-frame duration.

All possible K_l can be obtained by

$$P_B = \sum_{m=K-K_l+1}^{\infty} P(M = m) \leq \beta. \tag{2}$$

We set K_l^M as the maximum number of all possible K_l such that P_B would not violate the constraint (i.e., $P_B \leq \beta$). Thus, K_l can be from 0 to K_l^M.

E. Pricing Model

The service provider also has two different pricing models for them.

1) PS-MSs: Current wireless networks adopt a fixed pricing strategy that mobile users are charged with a flat rate or based on the volume (the time or the number of packets) of traffic. The major advantage of this strategy is that the billing and accounting process is simple [31]. Thus, the service provider charges the price of the PS-MSs that utilize spectrum bands at a flat rate $(1 - \alpha)Q_{PS}$ per data-frame duration or per control-frame duration, where α is the discounting factor that the service provider shares its extra profit with PS-MSs for collecting incentives to allow CR-MSs. We denote the revenue from PS-MSs as R_P.

2) CR-MSs: The service provider charges the price of the CR-MSs that utilize spectrum bands at a dynamic rate Q_{CR} per data-frame duration. The service provider needs a spectrum allocating method to allocate the portion of the spectrum bands of the PRN (i.e., K_l spectrum bands) to the right CR-MSs 1) at the earliest time and 2) with the highest offer(s) in auction. The Vickrey auction methodology satisfies the above requirements. Therefore, Q_{CR} is based on the auction method. We first introduce the basic auction model and then obtain the pricing model for CR-MSs.

Suppose that there are N_C CR-MSs attempting to compete in the K_l spectrum bands that can be allocated to them with a constraint on the blocking rate for PS-MSs (i.e., P_B) under β for PS-MSs, where $N_C \geq K$, and $K_l \leq K$. The ith CR-MS (i.e., the ith bidder) assigns a private value (i.e., the maximum amount a CR-MS is willing to pay) X_i for a spectrum band, $i = 1, 2, \ldots, N_C$. We assume that all CR-MSs are risk neutral (i.e., they attempt to seek to maximize their expected profit). For simplicity, we assume that each private value of CR-MSs is independent identically distributed with a probability density function (pdf) f. The pdf f depends on $(1-\alpha)Q_{PS}$, T_S, K_l, and so on. We can rewrite f as $f(x|(1-\alpha)Q_{PS}, T_S, K_l, \ldots)$. Because each CR-MS wishes to utilize the spectrum bands while paying lesser (or no more) than the PRN users, X_i has an up-bound value $(1-\alpha)Q_{PS}$ for $i = 1, \ldots, N_C$. Let $Y_1, Y_2, \ldots, Y_{N_C}$ be a rearrangement of $X_1, X_2, \ldots, X_{N_C}$ such that $Y_1 \geq Y_2 \geq \cdots \geq Y_{N_C}$. The K_l of N_C CR-MSs that have higher bids are granted to utilize the K_l spectrum bands. For the K_l CR-MSs, the service provider charges them with Y_{K_l+1} (i.e., $Q_{CR} = Y_{K_l+1}$). We can obtain the revenue from CR-MSs based on Q_{CR} and denote it as R_C.

From Sections III-D and E, we can obtain the profit of the service provider P_{ro} (i.e., $P_{ro} = R_P + R_C - C(B)$).

IV. Spectrum-Management Policy and Formulation

We propose a spectrum management policy algorithm to meet the co-win situation among the four involved parties. We refer to our proposed spectrum-management policy for the CRN as SMP, and the policy operates as follows.

A. SMP

1) To constrain the blocking rate for PS-MSs (i.e., P_B) under the certain tolerance level β. The service provider first determines the number of spectrum bands (i.e., K_l) that can be allocated to CR-MSs such that P_B is constrained under β, and K_l can be obtained from (2), where $K_l \leq K_l^M$.
2) At the beginning of the control frame (i.e., the first frame in a superframe), there are $N_P(D+1)$ PS-MSs that come from the $(D+1)$th frame duration in a superframe (i.e., $I = D+1$ or the Dth data frame) and attempt to utilize the spectrum bands.
   a) If $N_P(D+1) \geq K$, K spectrum bands are first allocated to the K of the $N_P(D+1)$ PS-MSs based on the first-come–first-serve (FCFS) principle.
   b) If $N_P(D+1) < K$, $N_P(D+1)$ spectrum bands are allocated to the $N_P(D+1)$ PS-MSs.
   c) The service provider allocates K_l spectrum bands to CR-MSs in the following D data frames via the PS-BS.
3) If $K_l > 0$, the PS-BS announces an auction process to all CR-MSs that are located in the communication region of the PS-BS. We reasonably assume that the auction process can be finished in one control-frame duration. The auction process consists of three processes: announcing, bidding, and permitting.
   a) Announcing: The PS-BS informs that there are K_l spectrum bands to be allocated to all CR-MSs within the communication range of the PS-BS.
   b) Bidding: When all CR-MSs correctly receive the announcing information and N_C of the CR-MSs attempt to utilize the K_l spectrum bands, each CR-MS would submit a bid to the PS-BS.
   c) Permitting: If the PS-BS correctly receives the bids from the N_C CR-MSs, it would permit K_l of the N_C CR-MSs with higher submitted bids to utilize the spectrum bands for D data frames with no spectrum handoff. We assume that the N_C CR-MSs would fully utilize the D data frames at a time in each auction process.
4) At the beginning of the Ith frame, $N_P(I-1)$ PS-MSs that come from the $(I-1)$th frame duration and attempt to utilize spectrum bands can utilize $K - K_l$ spectrum bands for $I = 2, 3, \ldots, D+1$ (i.e., data frames). However, K_l spectrum bands have been allocated to CR-MSs for D data-frame duration without any spectrum handoff. Therefore, the following hold.
   a) If $N_P(I-1) \leq K - K_l$, the CR-MSs that utilize the K_l spectrum bands would not interfere with PS-MSs (i.e., blocking PS-MSs).
   b) Otherwise, the CR-MSs would block the $N_P(I-1) - (K - K_l)$ of $N_P(I-1)$ PS-MSs. In this case, the service provider compensates the $N_P(I-1) - (K - K_l)$ PS-MSs for the interference.
5) The remaining procedure is repeated from steps 1 to 4.

From the spectrum-management policy algorithm, we attempt to know whether the service provider can gain extra profit and the spectrum utilization can be increased. In Section IV-B, we study the profit of the service provider and the utilization of spectrum bands per superframe duration by examining the behaviors of PS-MSs and CR-MSs.

B. Complexity of the SMP

Here, we analyze the complexity of our proposed SMP. Via detailed observation, the service provider needs $O(K)$ arithmetic operations to find whether P_B exceeds β when the service provider allocates K_l spectrum bands to CR-MSs from (2) in step 1. Therefore, the service provider needs $O(K^2)$ arithmetic operations to find all possible K_l in step 1. In step 3c (i.e., permitting process in the auction process), the service provider needs to sort all submitted N_C bids and then choose K_l of N_C based on the values of these bids. In this permitting process, if the service provider adopts a binary tree sort algorithm to sort the N_C bids, $O(N_C \log N_C)$ arithmetic operations are needed [32]. From the discussion above, the service provider needs $O(K^2 N_C \log N_C)$ arithmetic operations to execute the SMP. We consider a benchmark algorithm in [33] that also considers a CRN that secondary users share a set of channels with a primary network, and the complexity of the algorithm is $O(K{N_C}^2)$. In general, the number of spectrum bands in a cellular network is limited (i.e., K is finite) and is not significantly large. ${N_C}^2$ dominates the complexity. Therefore, our proposed SMP enjoys advantage in complexity.

C. Formulation of the SMP

Based on the number of spectrum bands that can be allocated to CR-MSs with a constraint on the blocking rate for PS-MSs under β for PS-MSs (i.e., K_l), we formulate the expected revenue from PS-MSs per superframe duration, the

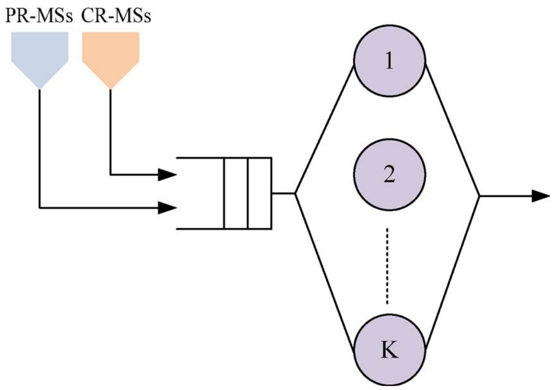


Fig. 3. Queuing model of the user's behavior.

expected revenue from CR-MSs per superframe duration, and the expected cost from the compensation per superframe duration to determine the expected profit of the service provider per superframe duration. Furthermore, here, we could also determine the average utilization of spectrum bands per superframe duration.

1) Expected Profit of the Service Provider per Superframe Duration:

a) Behavior of PS-MSs and CR-MSs: We model the behavior of PS-MSs and CR-MSs via a queuing model consisting of a PS-BS with K servers (i.e., K spectrum bands) in Fig. 3. This queuing model has two classes of users (i.e., PS-MSs and CR-MSs). For PS-MSs, the queuing model of the PS-BS is $M/D/K/FCFS$, that is, Poisson arrival, deterministic service, and K spectrum bands with the FCFS principle; the aggregate interarrival rate of PS-MSs is λ_P. For CR-MSs, the queuing model is $D^{[K_l]}/D/K_l/PR-A$, that is, deterministic bulk arrival, deterministic service time, K_l servers (i.e., a total of K_l spectrum bands can be allocated to CR-MSs) with a priority principle based on the auction process (denoted as PR-A), and the interarrival time is a superframe duration T_S. We assume that the service time utilized by each PS-MS is T_D or T_C (i.e., one data-frame or one control-frame duration), and the service time utilized by CR-MSs is DT_D (i.e., D data-frame duration). The service of PS-MSs starts at the beginning of one control-frame duration or one data-frame duration. The service of CR-MSs starts in the beginning of the first data-frame duration.

b) Expected revenue from PS-MSs per superframe duration: Because PS-MSs can have a discounting factor to utilize spectrum bands as an incentive to allow CR-MSs to compete in the spectrum bands of the PRN, the service provider charges the price of the PS-MSs that utilize spectrum bands at a flat rate $(1-\alpha)Q_{PS}$ per control-frame or data-frame duration, where α is the discount rate $(0 \le \alpha \le 1)$. Thus, the expected revenue from the PS-MSs per superframe duration is given by

$$\begin{aligned}E[R_P] = &\sum_{m=1}^{K}(1-\alpha)Q_{PS}mP(M=m)\\&+K\sum_{m=K+1}^{\infty}(1-\alpha)Q_{PS}P(M=m)\\&+D\Bigg[(1-\alpha)Q_{PS}\sum_{m=1}^{K-K_l}mP(M=m)\\&\quad+(1-\alpha)Q_{PS}(K-K_l)\\&\quad\times\sum_{m=K-K_l+1}^{\infty}P(M=m)\Bigg] \qquad (3)\end{aligned}$$

where M is a random variable of the number of PS-MSs arriving in a control-frame or a data-frame duration, and we set m as the value of M. The first two terms are the expected revenue in a control-frame duration. When the number of PS-MSs arriving in the $(D+1)$th frame duration (i.e., $m = N_P(D+1)$) is smaller than or equal to K (i.e., $m \le K$), the service provider can get $m(1-\alpha)Q_{PS}$ in a control-frame duration. Otherwise, the service provider can get $K(1-\alpha)Q_{PS}$. The last two terms are the expected revenue in D data frames. In a control-frame duration, the service provider allocates at most K_l spectrum bands to CR-MSs such that the blocking rate for PS-MSs (i.e., $P(B)$) is smaller than β. We assume that there are N_C CR-MSs that attempt to compete in the K_l spectrum bands in one control-frame duration, and N_C is always larger than K_l. Therefore, there are $K-K_l$ spectrum bands that PS-MSs can utilize. In the Ith frame duration, when $N_P(I-1) < (K-K_l)$ (i.e., $m < (K-K_l)$), the service provider can get $m(1-\alpha)Q_{PS}$, for $I = 2, 3, \ldots, D+1$. Otherwise, the service provider can get $(K-K_l)(1-\alpha)Q_{PS}$.

c) Expected revenue from CR-MSs per superframe duration: For simplification, we assume N_C to be a constant in each round of the auction process per superframe basis. The service provider uses the Vickrey auction to charge CR-MSs via the PS-BS. The PS-BS picks up K_l of the N_C CR-MSs according to the auction process. The CR-MSs with higher bids can be permitted to utilize the K_l spectrum bands with no spectrum handoff. According to the Vickrey auction [34], the revenue from the CR-MSs per superframe duration is $K_lDY_{K_l+1}$ (i.e., $Q_{CR} = Y_{K_l+1}$), where K_l is the total CR-MSs that are granted to utilize the K_l spectrum bands in a control frame duration, D is the number of data frames that CR-MSs can utilize in a superframe duration, and Y_{K_l+1} is the (K_l+1)th highest bid among the N_C CR-MSs.

Before obtaining the expected revenue from CR-MSs per superframe duration, we must know the cumulative distribution function of Y_{K_l+1}, which can be formulated from [34] and is given by

$$F_{Y_{K_l+1}}(y) = \sum_{i=N_C-K_l}^{N_C}\binom{N_C}{i}F(y)^i\left(1-F(y)\right)^{N_C-i} \qquad (4)$$

where $F(y)$ is the cumulative function of $f(y)$, which is the pdf of the private value of CR-MSs, and N_C is the number of CR-MSs that attempt to compete in the K_l spectrum bands. Thus, the pdf of Y_{K_l+1} can be obtained by deviating (5) and is given by

$$\begin{aligned}f_{Y_{Kl+1}}(y) = &\frac{N_C!}{K_l!(N_C-K_l-1)!}f(y)F(y)^{N_C-K_l-1}\\&\times\left(1-F(y)\right)^{K_l}. \qquad (5)\end{aligned}$$

The expected revenue from CR-MSs per superframe duration is obtained by integrating (5) with y and is given by

$$E[R_C] = K_l D \int_0^\infty y \frac{N_C!}{K_l!(N_C - K_l - 1)!} f(y) \times F(y)^{N_C - K_l - 1} (1 - F(y))^{K_l} \, dy. \quad (6)$$

d) Expected cost from the compensation per superframe duration: We derive the numbers of the blocked data frame for PS-MSs per superframe duration (CR-MSs only occupy data frames) and use our proposed compensation mechanism model to calculate the expected cost of the service provider per superframe duration. The expected number of blocked data frames per superframe duration is given by

$$E[B] = D \left\{ \sum_{m=K-K_l+1}^{K} [m - (K - K_l)] P(M = m) + K_l \sum_{m=K+1}^{\infty} P(M = m) \right\}. \quad (7)$$

CR-MSs have been granted to utilize K_l spectrum bands. If there are m PS-MSs arriving in each data-frame duration, and m is between $K - K_l + 1$ and K, then there are $m - (K - K_l)$ blocked data frames for PS-MSs. If m is larger than or equal to K, then there are at most K_l blocked data frames (CR-MSs only occupy K_l spectrum bands). The arrival of each PS-MS in one data-frame duration is a Poisson arrival and is independent of each other. Thus, PS-MSs have the same expected number of blocked data frames in each data frame. We can just multiply D of the numbers of blocked data frames per data-frame duration to stand for B. Thus, we obtain the expected cost per superframe duration $E[C(B)]$ as

$$E[C(B)] = D \left[\sum_{m=K-K_l+1}^{K} C(m - (K - K_l)) P(M = m) + C(K_l) \sum_{m=K+1}^{\infty} P(M = m) \right] \quad (8)$$

where $C(\cdot)$, depending on B, is the compensating function for the PS-MSs that are blocked by CR-MSs. The compensation mechanism is also considered as the sharing revenue of the service provider with PS-MSs by setting the compensating function such that the service provider can provide enough incentives for PS-MSs to allow CR-MSs to compete in the spectrum bands of the PRN.

e) Expected profit of the service provider per superframe duration: The expected profit of the service provider per superframe duration is given by

$$E[P_{ro}] = E[R_P] + E[R_C] - E[C(B)] \quad (9)$$

where $E[R_P]$, $E[R_C]$, and $E[C(B)]$ have been formulated in (3), (6), and (8), respectively.

In Section IV-C2, we formulate the average spectrum utilization per superframe duration and the improvement of spectrum utilization by allowing CR-MSs to compete in the spectrum bands of the PRN.

2) Average Spectrum Utilization per Superframe Duration: The average system utilization of the CRN per superframe duration is given by

$$\eta_{CR} = \frac{1}{K(DT_D + T_C)} \times \left\{ \left[\sum_{m=0}^{K} mP(M = m) + K \sum_{m=K+1}^{\infty} P(M = m) \right] T_C + D \left[\sum_{m=0}^{K-K_l} mP(M = m) + (K - K_l) \times \sum_{m=K-K_l+1}^{\infty} P(M = m) \right] T_D \right\} \quad (10)$$

where $K(DT_D + T_C)$ is a superframe duration for all K spectrum bands; the first two terms are utilized by PS-MSs in a control frame duration, and the third and fourth terms are the durations utilized by PS-MSs in D data-frame duration. When there are m PS-MSs arriving in the $(D+1)$th frame duration and $m \le K$, all m PS-MSs can utilize spectrum bands in the first frame duration (i.e., the control frame). Otherwise, a total of K spectrum bands are utilized by K of the m PS-MSs. When there are m PS-MSs arriving in the $(I-1)$th frame duration and $m \le K - K_l$, all m PS-MSs can utilize the spectrum bands in the Ith frame duration for $I = 2, 3, \ldots, D+1$. Otherwise, a total of $K - K_l$ spectrum bands are utilized by $K - K_l$ of the m PS-MSs in the Ith frame duration for $I = 2, 3, \ldots, D+1$.

The average system utilization without CR-MSs per superframe duration can be obtained from (10) by setting K_l equal to zero and is given by

$$\eta_{PS} = \frac{1}{K(DT_D + T_C)} \times \left\{ \left[\sum_{m=0}^{K} mP(M = m) + K \sum_{m=K+1}^{\infty} P(M = m) \right] T_C + D \left[\sum_{m=0}^{K} mP(M = m) + K \sum_{m=K+1}^{\infty} P(M = m) \right] T_D \right\} \quad (11)$$

where $K(DT_D + T_C)$ is a superframe duration for all K spectrum bands, the first two terms are utilized by PS-MSs in a control frame duration, and the third and fourth terms are the duration utilized by PS-MSs in D data-frame duration. When there are m PS-MSs arriving in the $(D+1)$th frame duration and $m \le K$, all the m PS-MSs can utilize spectrum bands in the first frame duration. Otherwise, a total of K spectrum bands are utilized by K of the m PS-MSs. When there are m PS-MSs arriving in the $(I-1)$th frame duration and $m \le K$, all the m PS-MSs can utilize the spectrum bands in the Ith frame duration for $I = 2, 3, \ldots, D+1$. Otherwise, a total of

K spectrum bands are utilized by K of the m PS-MSs in the Ith frame duration for $I = 2, 3, \ldots, D + 1$.

V. Optimal Spectrum-Management Policy

Based on our system model and spectrum-management policy, due to the fact that the extra profit of the service provider is obtained by allowing CR-MSs to compete in the spectrum bands of the PRN, PRN users can share the extra profit of the service provider by allowing a discounting factor α. Since PRN users suffered interference from CR-MSs, they can be compensated for the interference based on a compensation function [i.e., $C(\cdot)$]. The service provider guarantees that once CR-MSs are granted the spectrum bands, each of them can be guaranteed a superframe duration (i.e., T_S) to utilize without any spectrum handoff. However, the service provider only allows CR-MSs to compete in the spectrum bands of the PRN per superframe basis, and CR-MSs cannot induce the blocking rate for PS-MSs to be more than β. Thus, CR-MSs attempt to pay lesser (or no more) than PRN users to utilize the spectrum as secondary users (i.e., $Q_{CR} \leq Q_{PS}$). We denote the spectrum utilization of the CRN as η_{CR} and the spectrum utilization of the PRN (i.e., without allowing CR-MSs to compete in spectrum bands) as η_{PS}. The spectrum regulator that cares about the spectrum utilization efficiently attempts to increase spectrum utilization (i.e., $\eta_{CR} \geq \eta_{PS}$). When the service provider satisfies the spectrum regulator, PRN users, and CR-MSs, the service provider attempts to maximize its profit by optimizing the number of spectrum bands that are allocated to CR-MSs (i.e., K_l) with a constraint on the blocking rate for PS-MSs from CR-MSs under a tolerance level β. From the optimal SMP [see (12)], the service provider can earn its profit gain by finding the optimal K_l^*. We formulate our problem as follows.

Given λ_P, T_S, K, D, β, $C(\cdot)$, $f(\cdot)$, α, and Q_{PS}, the parameters are described in Table I. Our problem formulation is as follows:

$$\begin{aligned}&\text{Maximize} \quad E[P_{ro}] = E[R_P] + E[R_C] - E[C(B)]\\ &\text{Subject to} \quad P_B \leq \beta, \quad \eta_{CR} \geq \eta_{PS}, \quad Q_{CR} \leq Q_{PS} \end{aligned} \qquad (12)$$

where $E[R_P]$, $E[R_C]$, and $E[C(B)]$ have been formulated in (3), (6), and (8), respectively. From (3), (6), and (8), we know that K_l is the factor of these equations when the above parameters are given. The complexity of our proposed policy has been discussed in Section IV-B and is given by $O(K^2 N_C \log N_C)$. Thus, we can use greedy search to find the optimal K_l^* that reaches the optimal SMP problem [i.e., (12)].

VI. Performance Evaluation

Here, a numerical example is considered to verify the performance of our spectrum management policy in Section VI-A, and performance evaluation results are shown in Section VI-B.

A. Simulation Parameter Setup

We consider a CRN consisting of one primary system network (PRN) with a PS-BS and several PS-MSs (i.e., primary users) and several CR-MSs (i.e., or secondary users), as in Fig. 1. The total number of spectrum bands that are available to the service provider is $K = 10$. The service provider allocates spectrum bands to all mobile users via the PS-BS. The time slots of the control frame and data frames in a superframe are normalized as $T_C = T_D = 1$. The usage of an allocated spectrum with utilization ranges from 15% to 85% [1]. However, when the spectrum utilization of the PRN is larger than 50%, the blocking rate for the PRN users is larger than β, which is set as 0.02, which is a value that mobile users can tolerate [35]. Therefore, we consider that the spectrum utilization of the PRN is 15%, 30%, and 45%, respectively, by setting λ_P as 1.5, 3.0, and 4.5, respectively, from (11). The number of CR-MSs attempting to compete in the spectrum bands of the PRN per superframe basis is $N_C = 15$. Each CR-MS utilizes D data frames at a time, and we consider $D = 1, 2, \ldots, 7$ in our evaluations. We would take a different value of D to verify our performance. The cost that the service provider charges PS-MSs is normalized as $Q_{PS} = 1$, and the discounting factor α for PS-MSs to utilize spectrum bands ranges from 0 to 1. We consider a simple pdf of f that is a private value function of CR-MSs to value spectrum bands and only depends on Q_{PS} and α. Because CR-MSs attempt to utilize spectrum bands as secondary users while paying lesser (or no more) than the PRN users, the private value of each CR-MSs has an upper bound $(1-\alpha)Q_{PS}$, and we set the lower bound as $\sigma(1-\alpha)Q_{PS}$. The common approach is to use a uniform distribution for f. Thus, f is given by

$$f(x) = \begin{cases} \frac{1-\sigma}{(1-\alpha)Q_{PS}}, & \text{for } \sigma(1-\alpha)Q_{PS} \leq x \leq (1-\alpha)Q_{PS} \\ 0, & \text{for otherwise} \end{cases} \qquad (13)$$

where $0 \leq \sigma \leq 1$, and σ is set as 0.5. We set a new random variable $U(u)$ as follows to normalize the random variable $X(x)$ in which the pdf is given by (13):

$$u = \frac{x - \sigma(1-\alpha)Q_{PS}}{1 - \sigma(1-\alpha)Q_{PS}}. \qquad (14)$$

Thus, the random variable of u follows a uniform distribution on the unit interval. The pdf of Y_{K_l+1} (5) can be reduced to

$$f_{Y_{Kl+1}}(u) = \frac{N_C!}{K_l!(N_C - K_l - 1)!} u^{N_C - K_l - 1}(1-u)^{K_l} \qquad (15)$$

which is a beta distribution with parameters $(N_C - K_l, K_l + 1)$ [36]. Thus, the expected revenue from CR-MSs ($E[R_C]$) is as follows:

$$E[R_C] = \left[\frac{N_C - K_l}{N_C + 1}(1-\sigma)(1-\alpha)Q_{PS} + \sigma(1-\alpha)Q_{PS}\right] DK_l. \qquad (16)$$

In our proposed compensation mechanism, if the PS-MSs are interfered with one data-frame duration by CR-MSs, they can be free to utilize one data-frame duration, and the PS-MSs have higher priority to utilize the spectrum bands in the next data-frame duration. Thus, a simple compensation function is given by

$$C(B) = B(1-\alpha)Q_{PS} \qquad (17)$$

The expected cost per superframe duration $E[C(B)]$ can be reduced from (8) as

$$E[C(B)] = D\Bigg\{\sum_{m=K-K_l+1}^{K}(1-\alpha)Q_{PS} \times [m-(K-K_l)]\,P(M=m) + (1-\alpha)Q_{PS}K_l\sum_{m=K+1}^{\infty}P(M=m)\Bigg\}. \quad (18)$$

Consequently, we obtain the expected profit for the service provider per superframe duration from (3), (16), and (18) in our example.

However, we assume that the channel is ideal in our derivations. Therefore, the packets of the auction process (i.e., announcing, bidding, and permitting packets) can be correctly transmitted between the PS-BS and CR-MSs. If we consider more realistic simulations by incorporating channel errors and interference in system operations, the channel errors could be categorized as a bit error rate (or a packet error rate) so that CR-MSs would miss the auction process and cannot compete in the spectrum bands of the PRN during the auction process. To ensure smooth system operation, it is required to examine the spectrum utilization and the profit of the service provider due to the CR-MSs missing the auction. More precisely, we include this more realistic simulation to examine the robust operation of the proposed system.

In our simulations, the packet error rate (denoted as P_e) is set as 10^{-1} or 10^{-2}, which is a pretty bad channel condition (i.e., a system pretty bad operating condition) from the PS-BS to CR-MSs (i.e., the auction downlink) or from CR-MSs to the PS-BS (i.e., the auction uplink).

B. Performance Enhancement for Four Parties

From our simulations, when P_e is 10^{-2}, the performance would be consistent with analytical results. When P_e is 10^{-1}, only the profit of the service provider is slightly lower than the analytical results. The more detailed results are shown in the following.

1) Performance Versus K_l (the Number of Spectrum Bands That Are Allocated to CR-MSs): In Fig. 4, when K_l is smaller than 6, the expected profit $E[\text{Pro}]$ with $P_e = 10^{-1}$ in $\eta_{PS} = 45\%$ is larger than $E[\text{Pro}]$ with $P_e = 10^{-1}$ in $\eta_{PS} = 30\%$ or 15% due to the higher spectrum utilization. However, when K_l is larger than 6, $E[\text{Pro}]$ with $P_e = 10^{-1}$ in $\eta_{PS} = 45\%$ is smaller than $E[\text{Pro}]$ with $P_e = 10^{-1}$ in $\eta_{PS} = 15\%$ or 30% due to the high compensation cost from the higher blocking rate shown in Fig. 5. We define the incremental profit of the service provider (denoted as $E[\text{Pro}]_{\text{incre}}$) as follows:

$$E[\text{Pro}]_{\text{incre}} = \frac{E[\text{Pro}] - E[\text{Pro}]_{\text{noCR}}}{E[\text{Pro}]_{\text{noCR}}} \quad (19)$$

where $E[\text{Pro}]_{\text{noCR}}$ is the profit of the service provider without CR-MSs. The maximum gain of the incremental profit with $P_e = 10^{-1}$ can reach 197.79% (i.e., $E[\text{Pro}]_{\text{incre}} = 197.79\%$) in $\eta_{PS} = 15\%$, 72.69% in $\eta_{PS} = 30\%$, and 30.35% in $\eta_{PS} = 45\%$. However, the corresponding blocking rate is 0.1912, 0.1847, and 0.2971, respectively, in Fig. 5, which are larger than $\beta = 0.02$, and we resolve it later. From Figs. 4 and 6, we observe that CR-MSs can contribute the more profits to the service provider in the lower spectrum utilization. We also show the spectrum utilization of the CRN (i.e., η_{CR}) in Fig. 7. When K_l increases (i.e., the service provider allocates more spectrum bands to CR-MSs in one control frame), η_{CR} also increases. The spectrum utilization can be improved more than 80% when K_l is 10. In Fig. 5, we show that the blocking rate for PS-MSs (i.e., P_B) increases when K_l increases. When K_l is larger than 6, 3, and 1 in $\eta_{PS} = 15\%$, 30%, and 45%, respectively, the blocking rate P_B would be larger than β (i.e., 0.02). Although the spectrum utilization and the profit of the service provider can significantly increase in the high K_l, it would induce the blocking rate P_B larger than β (i.e., 0.02) in the nontolerance range.

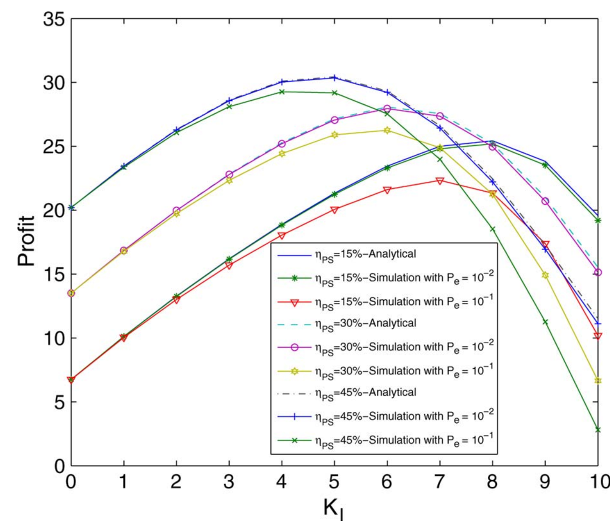


Fig. 4. Expected profit per superframe duration ($E[\text{Pro}]$) versus K_l (the number of spectrum bands of the PRN allocated to CR-MSs). Given D (the number of data frames in a superframe) is 4 and α (the discounting factor for PS-MSs to utilize spectrum bands) is 0.1.

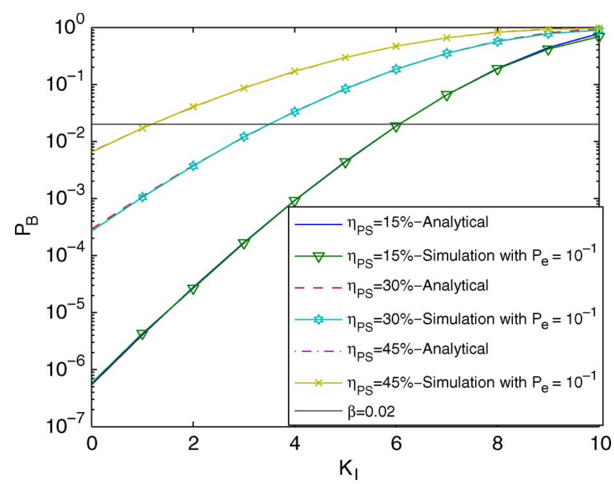


Fig. 5. Blocking rate P_B versus K_l (the number of the spectrum bands of the PRN allocated to CR-MSs). Given D (the number of data frames in a superframe) is 4, and α (the discounting factor for PS-MSs to utilize spectrum bands) is 0.1.

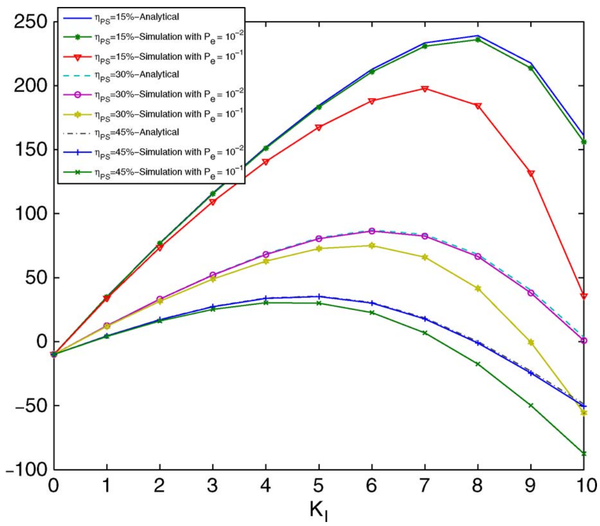


Fig. 6. Incremental profit ($E[\text{Pro}]_{\text{incre}} = E[\text{Pro}] - E[\text{Pro}]_{\text{noCR}}/E[\text{Pro}]_{\text{noCR}}$) versus K_l (the number of the spectrum bands of the PRN allocated to CR-MSs). Given D (the number of data frames in a superframe) is 4, and α (the discounting factor for PS-MSs to utilize spectrum bands) is 0.1.

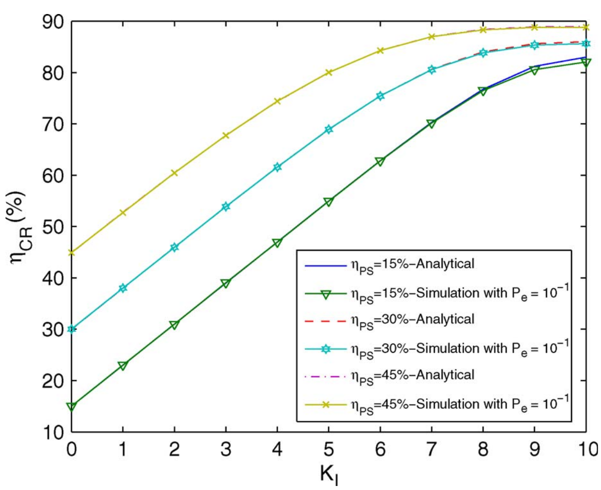


Fig. 7. Spectrum utilization of the CRN (η_{CR}) versus K_l (the number of the spectrum bands of the PRN allocated to CR-MSs). Given D (the number of data frames in a superframe) is 4, and α (the discounting factor for PS-MSs to utilize spectrum bands) is 0.1.

TABLE II
OPTIMAL SOLUTION FOR THE OPTIMAL SMP PROBLEM

	$\lambda_P = 1.5$	$\lambda_P = 3.0$	$\lambda_P = 4.5$
Optimal K_l (i.e., K_l^*) (Theo.)	6	3	1
Optimal K_l (i.e., K_l^*) with $P_e = 10^{-1}$ (Simu.)	6.0023	3.0015	0.9996
K	10	10	10
$E[Pro]$ (Theo.)	23.45	22.83	23.46
$E[Pro]$ with $P_e = 10^{-1}$ (Simu.)	21.6147	22.3355	23.3559
$E[Pro]_{incre}$ (Theo.)	212.68%	52.20%	4.49%
$E[Pro]_{incre}$ with $P_e = 10^{-1}$ (Simu.)	188.1970%	48.9225%	4.0406%
η_{CR} (Theo.)	62.81%	53.86%	52.76%
η_{CR} with $P_e = 10^{-1}$ (Simu.)	62.7916%	53.8873%	52.7114%
η_{PS}	15%	30%	45%
P_B (Theo.)	0.0186	0.0119	0.0171
P_B with $P_e = 10^{-1}$ (Simu.)	0.0185	0.0121	0.0170
β	0.02	0.02	0.02

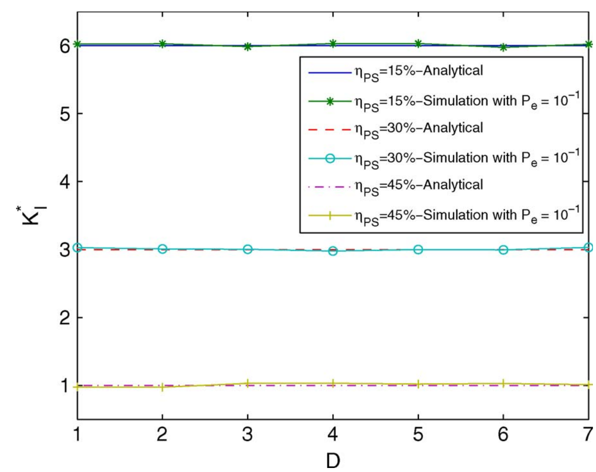


Fig. 8. K_l^* (the optimal number of the spectrum that can be allocated to CR-MSs) versus D (the number of data frames in a superframe). Given α (the discounting factor for PS-MSs to utilize spectrum bands) is 0.1.

To satisfy the constraint of β, we use greedy search to find the optimal K_l^* of the optimal SMP problem [i.e., (12)] satisfying the four involved parties at the same time. The result is summarized in Table II, and we observe that 1) the average spectrum utilization per superframe duration for which the spectrum regulator cares improves significantly (from η_{PS} to η_{CR}); 2) the expected profit per superframe duration (i.e., $E[\text{Pro}]$) for which the service provider cares greatly improves; 3) the blocking rate (i.e., P_B) for which PS-MSs care is constrained under a tolerance level (i.e., $\beta = 0.02$); and 4) the opportunity of accessing the spectrum bands for CR-MSs increases (such that they can share six of 10 PRN spectrum bands in $\eta_{PS} = 15\%$, three of 10 spectrum bands of the PRN in $\eta_{PS} = 30\%$, and one of 10 spectrum bands of the PRN in $\eta_{PS} = 45\%$, respectively) even when P_e is 10^{-1}.

2) Performance Versus D (the Number of Data Frames in a Superframe): We further discuss the effect of the number of data frames in a superframe. When CR-MSs can utilize more data frames at a time, the service provider can set the number of data frames in a superframe to be larger. From Fig. 8, the optimal K_l^* does not vary with D, even when P_e is 10^{-1}. Because the number of spectrum bands that are allocated to CR-MSs is decided in one control frame and fixed in the following data frame, the blocking rate (i.e., P_B) would not vary with D. Thus, the value of D does not affect the incentives of PRN users. The opportunity of accessing the spectrum bands of CR-MSs does not decrease with D, but CR-MSs can utilize more data frames at a time. From Fig. 9, when D increases, the incremental profit with $P_e = 10^{-1}$ also increases, particularly when the spectrum utilization of the PRN (i.e., η_{PS}) is low. From Fig. 10, when D increases, η_{CR} increases.

From the above discussions, if CR-MSs can utilize more data frames in one superframe, the satisfaction of PRN users are not affected, the service provider can collect more profits, and more spectrum utilization can be achieved, which satisfies all four parties.

3) Performance Versus α (the Discounting Factor for PS-MSs to Utilize Spectrum Bands): From Fig. 11, when the discounting factor α is smaller than 0.6, 0.3, and 0.1 for $\eta_{PS} = 15\%$, 30%, and 45%, respectively, the service provider can

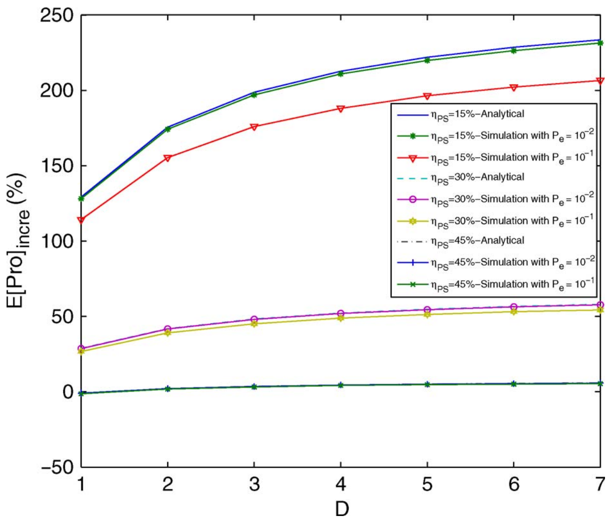


Fig. 9. Incremental profit $(E[\text{Pro}]_{\text{incre}} = E[\text{Pro}] - E[\text{Pro}]_{\text{noCR}}/E[\text{Pro}]_{\text{noCR}})$ versus D (the number of data frames in a superframe). Given α (the discounting factor for PS-MSs to utilize spectrum bands) is 0.1.

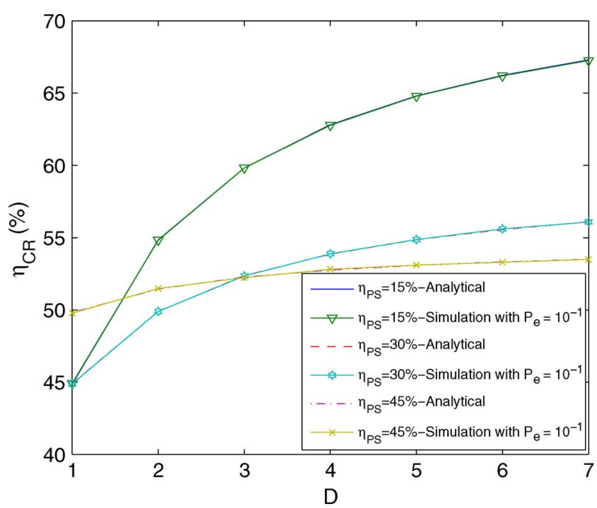


Fig. 10. Spectrum utilization of the CRN (η_{CR}) versus D (the number of data frames in a superframe). Given α (the discounting factor for PS-MSs to utilize spectrum bands) is 0.1.

increase its profit in $P_e = 10^{-1}$ (i.e., $E[\text{Pro}]_{\text{incre}}$ with $P_e = 10^{-1} > 0$). If the spectrum utilization of the PRN (i.e., η_{PS}) is larger and the service provider still can earn extra profit, the discounting factor is smaller. When η_{PS} reaches 50%, the discounting factor α is close to zero (i.e., the PRN users cannot share the extra profit of the service provider).

From our simulation results, we show that the four involved parties (the spectrum regulator, the service provider, PRN users, and CR-MSs) are satisfied at the optimal value K_l^*, and the simulation results are also close to the analytical results, even when P_e is 10^{-1}. For the spectrum regulator, the spectrum utilization increases significantly. For the service provider, the overall profit also increases significantly. For PRN users, they have a discounting factor to access spectrum bands; the blocking rate for PS-MSs (i.e., P_B) can also be constrained under a tolerance level β, which the PRN users can tolerate without losing satisfaction for the PS-MSs and can be compensated for any delay service from CR-MSs (if they are blocked one data

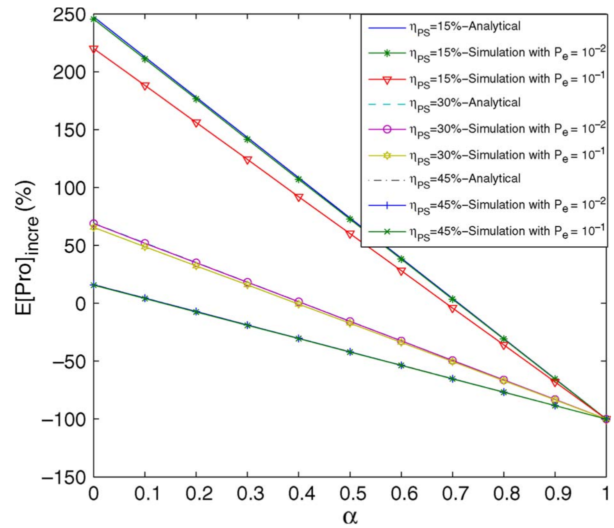


Fig. 11. Incremental profit $(E[\text{Pro}]_{\text{incre}} = E[\text{Pro}] - E[\text{Pro}]_{\text{noCR}}/E[\text{Pro}]_{\text{noCR}})$ versus α (the discounting factor for PS-MSs to utilize spectrum bands). Given D (the number of data frames in a superframe) is 4.

frame due to the occupation of CR-MSs, they can have free charge to utilize the next data frame). For CR-MSs, they gain the new opportunity of accessing spectrum bands by paying less (or no more) than the PRN users to utilize the spectrum bands as secondary users. The QoS of CR-MSs can also be warranted to a certain degree by granting certain duration (i.e., D data-frame duration) to utilize spectrum bands with no spectrum handoff. If CR-MSs can utilize more data frames at a time, the four involved parties can be more satisfied. Therefore, our proposed spectrum-management policy can construct a co-win situation among the four parties, particularly when the spectrum utilization of the PRN (i.e., η_{PS}) is low.

VII. Conclusion

We have considered an environment consisting of a primary system network (PRN) and several CR-MSs that attempt to compete in utilizing the spectrum bands of the PRN. We have presented a spectrum-management policy to obtain a co-win situation among the four involved parties (the spectrum regulator, the service provider, PRN users, and CR-MSs) in CRNs. The spectrum regulator significantly improves the overall spectrum utilization. The service provider greatly improves its profit by allowing CR-MSs (i.e., secondary users). The PRN users (i.e., PS-MSs or primary users) can share the increasing profit of the service provider by using a discounting factor to utilize spectrum bands. The PRN users may suffer the possible interference (i.e., blocking rate) from CR-MSs, which is also constrained under a certain tolerance β that the PS-MSs can tolerate without losing satisfaction for the PS-MSs. Since PS-MSs suffered interference from CR-MSs, PS-MSs can be compensated for the operating interference from CR-MSs by the service provider. CR-MSs gain new opportunities of accessing spectrum bands by sharing the portion of the spectrum bands of the PRN. Once the CR-MSs are granted to utilize the spectrum bands, the QoS of CR-MSs are warranted to a certain degree by being granted a certain duration (i.e., D data-frame duration) to utilize with no spectrum handoff. However, the service provider only allows CR-MSs to compete in the spectrum bands per superframe basis, and CR-MSs cannot induce the blocking rate for PS-MSs by more than β CR-MSs would attempt to pay less (or no more) than PS-MSs to utilize the spectrum bands as secondary users, and CR-MSs can pay less (or no more) by an auction process. To allocate the spectrum as fast as possible in one control-frame duration and meet economic efficiency, the Vickrey auction is proposed to price CR-MSs.

From performance evaluations, even under pretty bad channel conditions, the average spectrum utilization per superframe duration significantly increases, and the expected profit of the service provider per superframe duration also increases significantly; CR-MSs gain a new opportunity to access spectrum bands by sharing the portion of the spectrum bands of the PRN, particularly when the spectrum utilization of the PRN (i.e., η_{PS}) is not high. The blocking rate for PS-MSs remains constrained under β. Thus, our proposed spectrum-management policy can practically satisfy all four involved parties and is still robust under pretty bad existing channel conditions (i.e., the packet error rate is 10^{-1}) to enable the practical operation of CRs.

Acknowledgment

The authors would like to thank the constructive comments from anonymous reviewers that made the contents and the presentation of this paper more complete.

References

[1] First Report and Order, "Federal Communication Commission Std.," FCC 02-48, 2002.

[2] I. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Comput. Netw.*, vol. 50, no. 13, pp. 2127–2159, Sep. 2006.

[3] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 79–89, May 2007.

[4] Q. Zhao, L. Tong, and A. Swami, "Decentralized cognitive MAC for dynamic spectrum access," in *Proc. 1st IEEE Int. Symp. DySPAN*, Nov. 2005, pp. 224–232.

[5] Z. Ji and K. J. R. Liu, "Cognitive radios for dynamic spectrum access—Dynamic spectrum sharing: A game theoretical overview," *IEEE Commun. Mag.*, vol. 45, no. 5, pp. 88–94, May 2007.

[6] J. Mitola, III, "Software radio architecture: A mathematical perspective," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 4, pp. 514–538, Apr. 1999.

[7] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[8] S.-Y. Tu, K.-C. Chen, and R. Prasad, "Spectrum sensing of OFDMA systems for cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3410–3425, Sep. 2009.

[9] K.-C. Chen, Y.-J. Peng, N. R. Prasad, Y.-C. Liang, and S. Sun, "Cognitive radio network architecture: Part I—General structure," in *Proc. ACM ICUIMC*, Seoul, Korea, 2008, pp. 114–119.

[10] K.-C. Chen and R. Prasad, *Cognitive Radio Networks*. Hoboken, NJ: Wiley, 2009.

[11] C.-K. Yu and K.-C. Chen, "Radio resource tomography of cognitive radio networks," in *Proc. IEEE 69th VTC—Spring*, Apr. 26–29, 2009, pp. 1–5.

[12] S.-Y. Lien, N. R. Prasad, K.-C. Chen, and C.-W. Su, "Providing statistical quality-of-service guarantees in cognitive radio networks with cooperation," in *Proc. 2nd Int. Workshop Cognitive Radio Adv. Spectr. Manage.*, May 18–20, 2009, pp. 6–11.

[13] S.-Y. Lien, C.-C. Tseng, and K.-C. Chen, "Carrier sensing based multiple access protocols for cognitive radio networks," in *Proc. IEEE ICC*, May 19–23, 2008, pp. 3208–3214.

[14] L. Zhang, Y.-C. Liang, and Y. Xin, "Joint admission control and power allocation for cognitive radio networks," in *Proc. IEEE ICASSP*, Apr. 15–20, 2007, vol. 3, pp. III-673–III-676.

[15] D. Li, X. Dai, and H. Zhang, "Game theoretic analysis of joint rate and power control in cognitive radio networks," in *Proc. ICCCAS*, May 2008, pp. 319–322.

[16] P. Zhou, W. Yuan, W. Liu, and W. Cheng, "Joint power and rate control in cognitive radio networks: A game-theoretical approach," in *Proc. IEEE ICC*, May 2008, pp. 3296–3301.

[17] N. Hoven and A. Sahai, "Power scaling for cognitive radio," in *Proc. Int. Conf. Wireless Netw., Commun. Mobile Comput.*, 2005, vol. 1, pp. 250–255.

[18] O. Aftab, "Economic mechanisms for efficient wireless coexistence," Mass. Inst. Technol., Press, Cambridge, MA, MIT Tech. Rep. MIT-LCS-TR-876, Aug. 2002.

[19] C. Kloeck, H. Jaekel, and F. K. Jondral, "Dynamic and local combined pricing, allocation and billing system with cognitive radios," in *Proc. 1st IEEE Int. Symp. DySPAN*, Nov. 2005, vol. 2, no. 1, pp. 73–81.

[20] H. R. Varian and J. K. MacKie-Mason, Generalized Vickrey auctions, Univ. Michigan Press, Ann Arbor, MI. [Online]. Available: http://ssrn.com/abstract=975873

[21] F. Fu and M. van der Schaar, "Learning to compete for resources in wireless stochastic games," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1904–1919, May 2009.

[22] D. Niyato and E. Hossain, "Competitive spectrum sharing in cognitive radio networks: A dynamic game approach," *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2651–2660, Jul. 2008.

[23] F. Wang, M. Krunz, and S. Cui, "Price-based spectrum management in cognitive radio networks," *IEEE J. Sel. Topics Signal Process.*, vol. 2, no. 1, pp. 74–87, Feb. 2008.

[24] Z. Ji and K. J. R. Liu, "Multi-stage pricing game for collusion-resistant dynamic spectrum allocation," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 182–191, Jan. 2008.

[25] D. Niyato and E. Hossain, "Market-equilibrium, competitive, and cooperative pricing for spectrum sharing in cognitive radio networks: Analysis and comparison," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4273–4283, Nov. 2008.

[26] D. Niyato, E. Hossain, and Z. Han, "Dynamics of multiple-seller and multiple-buyer spectrum trading in cognitive radio networks: A game-theoretic modeling approach," *IEEE Trans. Mobile Comput.*, vol. 8, no. 8, pp. 1009–1022, Aug. 2009.

[27] B. Chen, H.-K. Wu, A. T. Hoang, and Y.-C. Liang, "Optimizing the second-price auction algorithm in a dynamic cognitive radio network," in *Proc. 11th IEEE ICCS*, Singapore, Nov. 2008, pp. 1514–1518.

[28] Y. Wu, B. Wang, K. J. R. Liu, and T. C. Clancy, "Collusion-resistant multi-winner spectrum auction for cognitive radio networks," in *Proc. IEEE GLOBECOM*, Nov. 2008, pp. 1–5.

[29] D. Niyato and E. Hossain, "Competitive pricing for spectrum sharing in cognitive radio networks: Dynamic game, inefficiency of Nash equilibrium, and collusion," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 192–202, Jan. 2008.

[30] H.-B. Chang, K.-C. Chen, N. Prasad, and C.-W. Su, "Auction based spectrum management of cognitive radio networks," in *Proc. IEEE 69th VTC—Spring*, Apr. 26–29, 2009, pp. 1–5.

[31] J. Hou, J. Yang, and S. Papavassiliou, "Integration of pricing with call admission control to meet QoS requirements in cellular networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 13, no. 9, pp. 898–910, Sep. 2002.

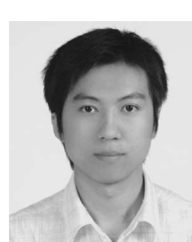
[32] K. Mehlhorn, *Data Structures and Algorithms I: Sorting and Searching*. Berlin, Germany: Springer-Verlag, 1984.

[33] A. Hoang, Y. Liang, and M. Islam, "Power control and channel allocation in cognitive radio networks with primary users' cooperation," *IEEE Trans. Mobile Comput.*, vol. 9, no. 3, pp. 348–360, Mar. 2010.

[34] V. Krishna, *Auction Theory*. New York: Academic, 2002.

[35] ITU. [Online]. Available: http://www.itu.int/net/home/index.aspx

[36] H. A. David and H. N. Nagaraja, *Order Statistics*, 3rd ed. Hoboken, NJ: Wiley, 2003.



Hung-Bin Chang (S'07) received the B.S. degree in electrical engineering and the M.S. degree in communication engineering from the National Taiwan University, Taipei, Taiwan, in 2007 and 2009, respectively.

He is currently with the Graduate Institute of Communication Engineering and Department of Electrical Engineering, National Taiwan University. His research interests include cognitive radio networks, queuing theory, and game theory.

Kwang-Cheng Chen (M'89–SM'93–F'07) received the B.S. degree from the National Taiwan University, Taipei, Taiwan, in 1983 and the M.S. and Ph.D degrees from the University of Maryland, College Park, in 1987 and 1989, all in electrical engineering.

From 1987 to 1998, he was with SSE, COMSAT, the IBM Thomas J. Watson Research Center, and National Tsing Hua University, working on mobile communications and networks. Since 1998, he has been with National Taiwan University, where he is the Distinguished Professor and Director for the Graduate Institute of Communication Engineering and Director for the Communication Research Center. His research interests include wireless communications, network science, and cognitive science.

Dr. Chen is actively involved in the technical organization of numerous leading IEEE conferences, including as the Technical Program Committee (TPC) Chair of the 1996 IEEE International Symposium on Personal Indoor Mobile Radio Communications, TPC co-chair for IEEE Globecom 2002, General Co-Chair for the 2007 IEEE Mobile WiMAX Symposium, Orlando, FL, the 2009 IEEE Mobile WiMAX Symposium, Napa Valley, CA, the IEEE 2010 Spring Vehicular Technology Conference, and the IEEE 2010 Workshop on Social Networks. He has served editorships with many IEEE and international journals and served in various positions with the IEEE. He also actively participates in various wireless international standards. He has authored and/or co-authored over 200 technical papers and has 18 granted U.S. patents. He co-edited (with R. DeMarca) the book *Mobile WiMAX* (Wiley, 2008), authored the book *Principles of Communications* (River, 2009), and co-authored (with R. Prasad) another book *Cognitive Radio Networks* (Wiley, 2009). He has received numerous awards and honors.