A game-theoretic approach for opportunistic transmission scheme in cognitive radio networks with incomplete information

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***Abstract*—One of the key issues in cognitive transmission is for secondary users to dynamically acquire spare spectrum from the primary user and then select appropriate transmission schemes. The existing spectrum sharing scheme adopts a deterministic Cournot game to formulate this problem, of which the solution is Nash equilibrium. This formulation implicitly assumes that each secondary user is willing to fully exchange transmission parameters with all other users and hence knows the complete information of all others. However, this assumption may not be true in general. To remedy this, the present paper considers a more realistic assumption of *incomplete information*, i.e., each secondary user may choose to conceal its private information for achieving higher transmission benefit. Following this assumption, we adopt a probabilistic Cournot game to propose an opportunistic transmission scheme to maximize the transmission benefit of all secondary users. Bayesian equilibrium is considered as the solution of this game. Moreover, we rigorously prove that a secondary user can improve its expected transmission benefit by actively hiding its private transmission parameters and increasing the variance of its allocated spectrum.**

***Index Terms*—cognitive radio, Nash equilibrium, Bayesian equilibrium, game theory, opportunistic transmission.**

I. Introduction

As the scarcest resource for wireless communications, frequency spectrum may be overcrowded in the future to allow rapidly increasing users as well as various new applications. Cognitive radio (CR) networks [1] have been invented as one of the most promising solutions for the scarcity of frequency resource. Equipped with various flexible abilities, including channel sensing and spectrum sharing, CR technology improves intelligence, adaptability and flexibility of wireless transmission and increases network performance. The present paper considers the key intelligence in CR transmission for maximizing the overall benefit of the whole CR system.

One of the key issues in cognitive transmission is for multiple secondary users to dynamically acquire spare spectrum from the primary user and then select appropriate transmission schemes, i.e., modulation schemes and transmission rates, for the optimal utilization of the acquired spectrums. When primary and secondary users are belonging to different service providers, the secondary users have to pay the primary user for spectrum sharing. Such payment can be regarded as the cost of a secondary user who transmits data signals over the acquired spectrum. On the other hand, all secondary users gain benefits from data transmission via spectrum sharing. Thus the amount of shared bandwidth and pricing, as well as the selection of transmission schemes, should be determined such that the profit/utility of the secondary users is maximized while their requirements for quality of service (QoS) are satisfied.

Previously game theory has also been applied for multiplayer optimization to achieve individual equilibrium optimal solution. In [2], a game-theoretic adaptive channel allocation scheme was proposed to capture the selfish and cooperative behaviors of wireless users, of which the solution converges to the deterministic Nash equilibrium strategy. Recently, a game-theoretic spectrum sharing scheme was formulated by [3] and [4] as an oligopoly market competition. This scheme adopts a deterministic Cournot game [5] to obtain the spectrum allocation for secondary users, of which the solution is the Nash equilibrium of the game. The main objective of this Cournot game formulation is to maximize the profit or utility of all secondary users based on the equilibrium spectrum acquired by all secondary users. The formulation is based on the assumption of *complete information*, that is, each secondary user is willing to fully exchange its private transmission parameters with other secondary users and hence knows the complete information of all others, even though various constraints of radio transmission may obstruct such information exchange. Following this assumption, a static Cournot game is formulated in [5] to determine the strategy of each secondary user when radio environment allows full information exchanging, and a dynamic Cournot game in [4] for the case when radio environment does not.

However, the assumption of complete information in [3] and [4] may not be true in general. Since the competition among secondary users is non-cooperative, a more realistic situation is that a secondary user may be willing to conceal its private profit parameters for possible benefit. Thus, even if the radio environment supports full information exchange, a secondary user may still have *incomplete information* of others. This makes it more complicated for a user to select appropriate transmission scheme so as to maximize its transmission benefit. The main contribution of the present paper then is to formulate a probabilistic Cournot game under the assumption of incomplete information. In this game, the strategy of each secondary user is determined solely based on the prior proba-

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bilistic profit information of all other users, which is observed and broadcasted by the primary user. Bayesian equilibrium is considered as the solution of this game. Based on this solution, we further propose an opportunistic transmission scheme for a secondary user to maximize its expected transmission benefit. Moreover, we prove that a secondary user can increase its expected transmission benefit by hiding its private profit information and increasing the variance of its allocated spectrum.

Meanwhile, in the formulation of the proposed transmission scheme, we also refine the existing spectrum sharing scheme in [3] by clarifying the utility of a secondary user with more explicit physical meaning. More specifically, the revenue and cost of a secondary user, respectively, are reinterpreted as the total effective information bits that can be transmitted by this user and the primary user. Following this interpretation, the utility of all secondary users amounts to the surplus of the effective information bits transmitted by all secondary users over those by the primary user over the shared bandwidth.

The remaining of the present paper is organized as follows. Section II reviews the detail of the spectrum sharing scheme in [3] and [4]. Section III then refines the formulation of this scheme with more physical meanings. Based on this new formulation, Section IV then adopts a probabilistic Cournot game to formulate a new opportunistic transmission scheme under the assumption of incomplete information, which is simulated in Section V over a specific CR network. Our main contributions are finally summarized in Section VI.

II. The existing spectrum sharing scheme

This section reviews the spectrum sharing scheme ([3], [4]) for a class of CR networks, which consist of a primary user and multiple secondary users. In microeconomic literature, such a cognitive network can be regarded as an oligopoly competition market, where the players are all secondary users, and the Cournot model [5] in game theory is commonly applied to maximize the profit of players in this market, where the players compete in terms of quantity of spectrum/bandwidth sharing.

In this game, the primary user is willing to share some portion Q_i of its spare spectrum with secondary user i, where $1 \leq i \leq N$. Let $\mathbf{Q} = \{Q_1, Q_2, \ldots, Q_N\}$ denote the spectrum assignment to all users. Then the primary user is assumed to charge each user i at the price $P(\mathbf{Q}) = X + Y * (\sum_{k=1}^{N} Q_k)^\tau$ per unit bandwidth, where X, Y and τ are non-negative with $\tau \geq 1$. After allocation, all secondary users transmit in their obtained spectrum via adaptive modulation, i.e., uncoded Quadrature Amplitude Modulation (QAM), to enhance transmission performance. Then the bit error rate (BER) of uncoded QAM in a single-input-single-output Gaussian channel can be approximated by $BER \approx 0.2 * exp(-1.5 * \frac{\gamma}{2^k - 1})$, where γ is the signal-to-noise ratio (SNR) at the receiver of the channel and the spectrum transmission efficiency, as elaborated in [3].

To guarantee the quality of transmission, the BER should be constrained below the pre-assigned value, i.e., BER_i^{tar}. From [8], the transmission efficiency of secondary user i is $k_i = log_2(1 + K * \gamma_i)$, where $K = \frac{1.5}{ln(0.2/BER_i^{tar})}$ and γ_i, i.e., SNR at the receiver of the secondary user i, can be obtained by channel estimator. Given γ_i, target BER_i^{tar}, and the obtained bandwidth Q_i, the achieved transmission rate of the second user i is $Q_i * k_i = Q_i * log_2(1 + \gamma_i * \frac{1.5}{ln(0.2/BER_i^{tar})})$.

Assume that the revenue of secondary user i from unit transmission rate is r_i. Then the total revenue of this user can be expressed as $r_i * k_i * Q_i$. The profit of secondary user i then is equal to the difference of its revenue and its payment to primary user, that is, $U_i(\mathbf{Q}) = \theta_i * Q_i - Q_i * P(\mathbf{Q}) = r_i * k_i * Q_i - Q_i * P(\mathbf{Q})$, where $\theta_i = r_i * k_i$ is the revenue of secondary user i from unit bandwidth. When $P(\mathbf{Q})$ is chosen as the above, the profit of user i can be formulated by $U_i(\mathbf{Q}) = r_i * k_i * Q_i - Q_i * (X + Y * (\sum_{k=1}^{N} Q_k)^\tau)$. Differentiating this function with respect to Q_i, we obtain

$$\frac{\partial U_i(\mathbf{Q})}{\partial Q_i} = r_i k_i - \left(X + Y\left(\sum_{k=1}^{N} Q_k\right)^\tau\right) - Y Q_i \tau \left(\sum_{k=1}^{N} Q_k\right)^{\tau-1} = 0.$$

By solving this equation for $i = 1, 2, \ldots, N$, the equilibrium spectrum assignment $\mathbf{Q}^* = \{Q_1^*, Q_2^*, \ldots, Q_N^*\}$ is obtained, which qualifies as a Nash equilibrium that maximizes the profit of all secondary users. Thus, every secondary user i has no motivation to deviate from its equilibrium bandwidth Q_i^*. The key assumption of this Nash equilibrium is that each secondary user has *complete information*, including the full knowledge on the strategies and payoffs, of all other secondary users.

III. Refinement of the existing spectrum sharing scheme

One flaw of the spectrum sharing scheme in Section II is that those parameters, i.e., r_i and $P(\mathbf{Q})$, lack a clear physical meaning, which may lead to an unclear definition of the user profits and thus obstruct its practical application. This section refines this scheme with more explicit physical meanings.

Assume that all CR channels are stable and all matched filters used by secondary users are ideal, which means additive noises in radio channels. Under this simplification, the SNR at the receiver of a radio channel forms a linear function of the SNR at the transmitter of this channel. Since the SNR at the receiver can be interpreted as the "fidelity" of the radio channel, i.e., the effective information rate that can be received at the receiver, it qualifies as a natural definition of the parameter r_i in Section II. Thus $r_i = SNR_R^i = \Delta_i * SNR_T^i = \Delta_i * \frac{E_b^i}{N_0^i}$, where Δ_i is the transmission coefficient of a radio channel, over which the secondary user i transmits signals, while SNR_R^i and $SNR_T^i (= \frac{E_b^i}{N_0^i})$ are the average SNRs at the receiver and transmitter of this channel, respectively.

The secondary user i can estimate channel parameters, including Δ_i, according to the quality of radio channel and the performance of demodulator. In every time when the channel transmitter has finished data transmission and received the feedback from the channel receiver, it can compare the old and new SNRs to estimate the optimal channel parameters for determining the optimal strategy for next transmission.

Meanwhile, under different channel assumptions, i.e., Gaussian or Rayleigh, and different modulation methods, SNR_T^i at the transmitter of a radio channel can be determined by the

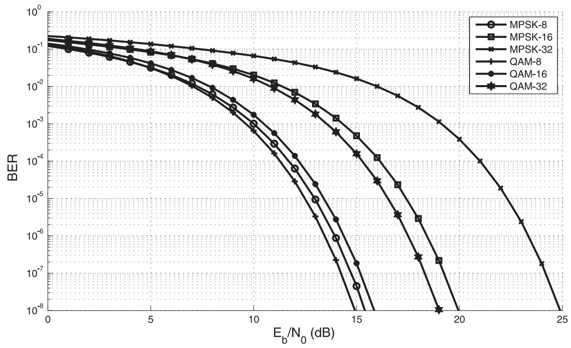

Fig. 1. Relationship between SNR and BER at the transmitter of a Gaussian Channel

target BER, i.e., BER_i^{tar}. For example, Figure 1 depicts the relationship between $SNR(=\frac{E_b}{N_0})$ and BER at the transmitter of a Gaussian Channel when it adopts QAMs or MPSKs with different transmission rates. Thus, given BER_i^{tar} and a specific modulation scheme, the transmitter, i.e., the secondary user i, can obtain its revenue parameter r_i.

Besides r_i, we also simplify the transmission efficiency k_i of secondary user i in Section II as its transmission rate $\eta = \frac{R_S}{B_T}(\frac{Baud}{Hz}) = \frac{R_b}{B_T}(\frac{Bps}{Hz})$ per unit bandwidth, where R_s is symbol rate, R_b is bit rate, and B_T is the bandwidth for signal transmission. Thus $r_i * \eta_i * Q_i$ means the total effective bits transmitted by the secondary user i.

On the other hand, if we reinterpret $P(\mathbf{Q})$ as the effective bits transmitted by the primary user per unit bandwidth, then the physical meaning of the profit of secondary user i would be the surplus of the effective bits transmitted by the secondary user i over those by the primary user over bandwidth Q_i,

$$U_i(\mathbf{Q}) = \theta_i * Q_i - Q_i * P(\mathbf{Q}) = r_i * \eta_i * Q_i - Q_i * P(\mathbf{Q}) \quad (1)$$

where $\theta_i = r_i * \eta_i$ is the effective bits transmitted by the user i per unit bandwidth. This formula will serve as the basis for a new opportunistic transmission scheme in the next section.

IV. A NEW OPPORTUNISTIC TRANSMISSION SCHEME UNDER INCOMPLETE INFORMATION

Recall from the end of Section II that the Nash equilibrium relies on the assumption that each secondary user has complete information of all other secondary users. In other words, all secondary users are assumed to be faithful, i.e., each secondary user i is willing to fully disclose its private parameters, such as r_i and η_i in (1), to the primary user and all other secondary users. Meanwhile, after the primary user receives all these parameters and then determines the spectrum assignment $\mathbf{Q}$ as well as the unit bandwidth price $P(\mathbf{Q})$, it can also broadcast all the above parameters to all secondary users. Thus these parameters are public information for all secondary users.

However, in a realistic CR network, the above process of information exchange may not be performed successfully. Because of various constraints imposed by wireless channels, a secondary user may not be able to obtain the parameters of all other secondary users directly. More importantly, because the competition among secondary users is non-cooperative, each secondary user i may possibly prefer to concealing its real parameters, i.e., r_i and η_i, so as to maximize its profit. In both cases, each secondary user may only have *incomplete information*, i.e., part of the strategies and payoff parameters, of other secondary users, which could make the existing spectrum sharing scheme in Section II ineffective.

To solve this problem, a reasonable approach is for the primary user to observe the probability distributions of the parameters r_i and η_i of each secondary user i via historic information exchange and then broadcast such distribution information to all secondary users. Through this way, each secondary user can obtain fairly reliable probabilities on the parameters of all other users and then form strategies based on such priori information. Following this approach, the remaining of this section formulates an opportunistic transmission scheme under the assumption of incomplete information.

Similar as Section II, we again consider a CR network of one primary user and N secondary users. However, part of secondary users i has their parameters r_i and η_i (or, equivalently, θ_i) being unknown for all others. Thus the N secondary users can be divided into two classes: every user i in class I has its parameter θ_i being a common knowledge of all other, while every user j in class II has its parameter θ_j being unknown for all others but the probability distribution of θ_j is a common knowledge. For the convenience of further discussion, we assume that there are N_1 users in class I, which are labeled by 1, 2, ..., N_1, and the rest $N_2(= N - N_1)$ users in class II, which are labeled by $N_1 + 1$, $N_1 + 2$, ..., N. Meanwhile, the price $P(\mathbf{Q})$, at which the primary user charges each secondary user, is same as that in Section II.

From (1), when a class-I secondary user i, $1 \leq i \leq N_1$, obtains bandwidth Q_i from the primary user, its profit is $U_i(Q_i) = Q_i\theta_i - Q_i(X + Y(Q_i + \sum_{k\neq i,k=1}^{N} Q_k)^\tau)$. Assume that, via communication with the primary user, each secondary user knows that θ_j of the class-II secondary user j has $M_j(\geq 1)$ possible values, that is, θ_{j1}, θ_{j2}, ..., θ_{jM_j}, and the probabilities for $\theta_j = \theta_{j1}$, $\theta_j = \theta_{j2}$, ..., $\theta_j = \theta_{jM_j}$ are $p_{j1}, p_{j2}, \ldots, p_{jM_j}$, respectively, with $\sum_{k=1}^{M_j} p_{jk} = 1$. Thus the expectation value of the unit bandwidth revenue of the class-II secondary user j is known as $E(\theta_j) = \sum_{k=1}^{M_j} p_{jk}\theta_{jk}$.

Let the class-II secondary user j obtain bandwidth Q_{jk} from the primary user when $\theta_j = \theta_{jk}$ for $1 \leq k \leq M_j$. Thus the expectation value of the bandwidth obtained by this user is

$$E(Q_j) = \sum_{k=1}^{M_j} p_{jk} Q_{jk} \quad (2)$$

Thus the equilibrium bandwidth obtained by a class-I secondary user i, $1 \leq i \leq N_j$, should satisfy $Q_i(\theta_i) \in \arg\max_{Q_i}\{Q_i\theta_i - Q_i(X + Y(Q_i + \sum_{k\neq i,k=1}^{N} Q_k)^\tau)\}$. Because this user does not know the exact values of the unit bandwidth revenue θ_k as well as the bandwidth Q_k obtained by each class-II user k, it has to adopt $E(Q_k)$ to replace Q_k for further derivation. Differentiating the function resulted by the replacement with respect to Q_i, we obtain:

$$\theta_i - (X + Y(Q_i + \sum_{k\neq i,k=1}^{N_1} Q_k + \sum_{k=N_1+1}^{N} E(Q_k))^{\tau}) -$$

$$\tau Y Q_i (Q_i + \sum_{k\neq i,k=1}^{N_1} Q_k + \sum_{k=N_1+1}^{N} E(Q_k))^{\tau-1} = 0 \quad (3)$$

Similarly, when a class-II secondary user j, $N_1 + 1 \leq j \leq N$, obtains bandwidth Q_j from the primary user, the equilibrium value of Q_j should satisfy $Q_j(\theta_j) \in \arg\max_{Q_j}\{Q_j\theta_j - Q_j(X + Y(Q_j + \sum_{k\neq j,k=1}^{N} Q_k)^{\tau})\}$. Since this user also does not know the exact value of θ_k as well as the bandwidth Q_k obtained by every class-II user k for $N_1 + 1 \leq j \neq k \leq N$, again it has to adopt $E(Q_k)$ to replace Q_k for further derivation. Differentiating the function resulted by the replacement with respect to Q_j, we obtain:

$$\theta_j - (X + Y(Q_j + \sum_{k=1}^{N_1} Q_k + \sum_{k\neq j,k=N_1+1}^{N} E(Q_k))^{\tau})$$

$$-\tau Y Q_j (Q_j + \sum_{k=1}^{N_1} Q_k + \sum_{k\neq j,k=N_1+1}^{N} E(Q_k))^{\tau-1} = 0 \quad (4)$$

By substituting $\theta_j = \theta_{j1}, \ldots, \theta_j = \theta_{jM_j}$ into (4) and combining the resulting equations with (2) and (3), we can obtain the equilibrium bandwidth sharing, i.e., Q_i^* of the class-I user i and Q_{jk}^* of the class-II user j, where $1 \leq i \leq N_1$, $N_1 + 1 \leq j \leq N$, and $1 \leq k \leq M_j$. This solution qualifies as the Bayesian equilibrium that maximizes the profit of all secondary users. Under this equilibrium, a secondary user determines its opportunistic transmission scheme as follows:

(IV.1) A class-I secondary user i obtains bandwidth Q_i^* from the primary user and adopts the modulation scheme and transmission rate, which yields θ_i, for data transmission.

(IV.2) With probability p_{jk}, each class-II secondary user j obtains bandwidth Q_{jk}^* from the primary user and adopts the modulation scheme and transmission rate, which yields θ_{jk}, for data transmission.

Theorem 1. If the bandwidth Q_i obtained by a class-I user i is equal to the expected bandwidth $E(Q_j)$ obtained by a class-II user j, then the expected profit of user j is larger than that of user i.

The detail proof of Theorem 1 is omitted here. A significant implication of Theorem 1 is that if the expected bandwidth obtained by a secondary user is constant, then it can obtain more expected profit by concealing its profit information for the opportunistic transmission scheme than by publicizing such information. In other words, to obtain more expected transmission benefit, a secondary user prefers a randomized transmission scheme to a deterministic transmission scheme.

Theorem 2. Assume that the expected bandwidths of the two class-II users j and k are equal, i.e., $E(Q_j) = E(Q_k)$. If the variance of Q_j is larger than that of Q_k, then the expected profit of user j is larger than that of user k.

The detail proof of Theorem 2 is also omitted. Theorem 2 implies that, when the expected bandwidth obtained by a secondary user is constant, the larger the variance of the obtained bandwidth, the more expected profit. Equivalently, if a secondary user is able to adopt a randomized transmission scheme with larger bandwidth variance, then it will obtain more expected transmission benefit.

V. NUMERICAL SIMULATION

This section simulates the opportunistic transmission scheme proposed in Section IV. The simulation is performed over a special CR network, consisting of one primary user and three secondary users labeled by 1, 2, and 3. Thus $N = 3$. In order to compare the effects of complete information and incomplete information on the proposed scheme, we assume:

(V.1) $\theta_1 = \theta_2 = \theta_3 = 192$ in the case of complete information and $E(\theta_1) = E(\theta_2) = E(\theta_3) = 192$ in the case of incomplete information.

Moreover, we fix simulation parameters as follows:

(V.2) $BER_i^{tar} = 10^{-4}$ for $1 \leq i \leq 3$.

(V.3) Each radio channel is additively white Gaussian and has the transmission coefficient of 8.

(V.4) X = 0 and $Y = \tau = 1$ in (4).

Under the condition of complete information, each secondary user has full knowledge of the profit parameters of other two. Figure 2 depicts the utility (profit) function of each user i for $1 \leq i \leq 3$ in terms of the obtained bandwidth. The three utility functions are fully overlapped because $\theta_1 = \theta_2 = \theta_3$. When the bandwidth obtained by a secondary user is 48, its profit reaches the maximum value of 2304. As illustrated in Figure 3(a, b), the allocation of bandwidth 48 to each user qualifies as the unique Nash equilibrium.

Under (V.1) and (V.3), we have $\frac{E_b^i}{N_0^i} * \eta_i = \frac{\theta_i}{\Delta_i} = \frac{198}{8} = 24$. A possible modulation scheme for each user i then is QAM16 because the transmission rate of QAM16 is $2 (= \frac{1}{2} * log_2 16)$ and, according to Figure 1, the average SNR at a transmitter should be no less than 12 to satisfy the target $BER_i^{tar} = 10^{-4}$. In conclusion, an optimal strategy is to obtain bandwidth 48 from the primary user and adopt QAM16 for data transmission.

In the case of incomplete information, we further assume that user 1 is of class I and users 2 and 3 class II. Moreover, let the primary user broadcast the following priori information:

- $\theta_1 = 192$. With probability 9/13 or 4/13, respectively, the value of θ_2 is 144 or 300. With probability 2/3, 9/41 or 14/123, respectively, the value of θ_3 is 132, 256 or 420.

Thus this priori information satisfies (V.1). Given this priori information, Figure 2 depicts the utility function of users 1, 2, and 3 in terms of the obtained bandwidth. In this figure,

- When user 1 obtains bandwidth 48, its utility function U_1 reaches the maximum value of 2304;
- When user 2 obtains bandwidth 24 or 102 in the case of $\theta_2 = 144$ or 300, respectively, its utility function U_{21} or U_{22} reaches the maximum value of 576 or 10404;
- When user 3 obtains bandwidth 18, 80, or 162 in the case of $\theta_3 = 132$, 256, or 420, respectively, its utility

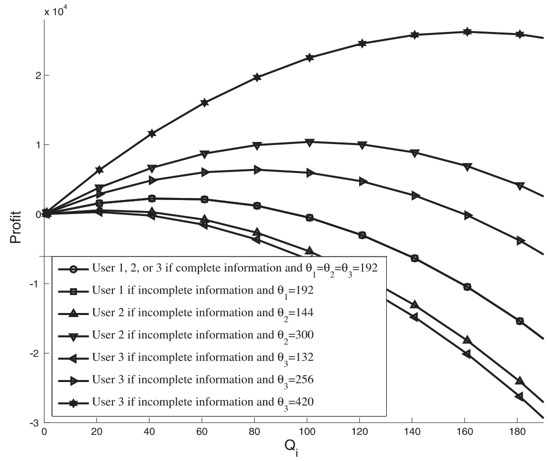

Fig. 2. The utility (profit) of user i, $1 \leq i \leq 3$, is depicted in terms of its obtained bandwidth Q_i in the case of complete or incomplete information.

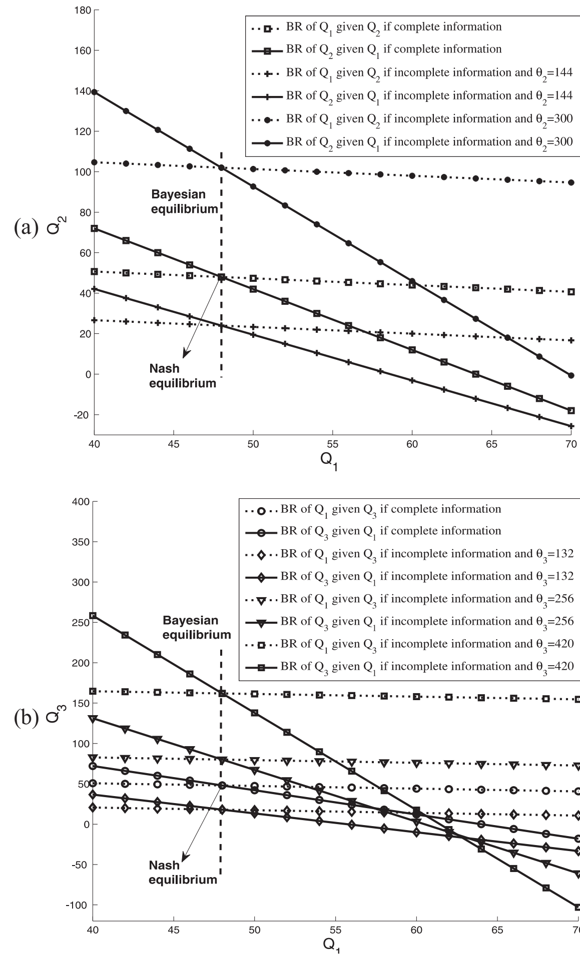

Fig. 3. In the case of incomplete or complete information and given the probability distributions of θ_2 and θ_3, the best response (BR) of Q_2 given Q_1 and the BR of Q_1 given Q_2 are depicted in (a), and the BR of Q_3 given Q_1 and the BR of Q_1 given Q_3 are depicted in (b).

function U_{31}, U_{32}, or U_{33} reaches the maximum value of 324, 6400, or 26244.

As illustrated in Figure 3, the above opportunistic bandwidth allocation qualifies as the unique Bayesian equilibrium.

Thus an optimal transmission scheme for user 1 is again QAM16; an optimal transmission scheme for user 2 is, with probability 9/13 or 4/13, respectively, to obtain bandwidth 24 or 102 from the primary user and adopt MPSK8 or QAM32 for data transmission; an optimal strategy for user 3 is, with probability 2/3, 9/41 or 14/123, respectively, to obtain bandwidth 18, 80, or 162 from the primary user and adopt QAM8, MPSK16 or MPSK32 for data transmission.

Note that the expected profit of secondary users 1, 2, and 3 are all 2304 under the assumption of complete information and are 2304, 3600, and 4608, respectively, under the assumption of incomplete information. This verifies Theorem 1. Moreover, since the variance of the bandwidth obtained by user 2 or 3 is 1296 or 2304, respectively, Theorem 2 is also verified.

VI. Conclusion

This paper proposes an opportunistic transmission scheme for secondary users in cognitive radio networks to maximize their transmission benefit. Different from the existing spectrum sharing scheme in [3] and [4], our scheme considers a more realistic assumption of *incomplete information*, i.e., a secondary user may be willing to conceal its private information for increasing its transmission benefit. We adopt a probabilistic Cournot game to formulate this problem and derive the Bayesian equilibrium of this game. Theorems 1 and 2 show that a secondary user can improve its expected transmission benefit by actively hiding its private parameters and increasing the variance of its allocated spectrum.

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