Optimal Queueing Control in Hybrid Overlay/Underlay Spectrum Access in Cognitive Radio Networks

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***Abstract*—Recently overlay/underlay framework in Cognitive Radio have been studied and it demonstrated the benefits such as spectrum efficiency and channel capacity maximization. Arising from these work, we suppose the secondary users can operate under overlay mode when the primary user is absent and operate under underlay mode when the primary user is present. In this paper, a hybrid overlay/underlay cognitive radio system is modeled as a M/M/1 queue where the rate of arrival and the service capacity are subject to Poisson alternations. Each packet (as a customer) arriving at the queue makes decision to join or balk the queue. Upon arrival, the individual decision of each packet is optimized based on his observation about the queue length and the state of system. We will present the individual strategy of each customer in detail in this paper.**

I. Introduction

Radio spectrum is one of the most scarce and valuable resources for wireless communications. Some surveys performing actual measurements have shown that most of the allocated spectrum is largely under-utilized [1]. Similar views on the under-utilization of allocated spectrum were reported by the Spectrum-Policy Task Force appointed by Federal Communications Commissions (FCC) [2]. Cognitive radio has been proposed as a way to improve spectrum efficiency by exploiting the unused spectrum in dynamically changing environments [3]. In a cognitive radio network, there are two types of users, namely, primary users and secondary users or cognitive users. In the cognitive radio concept, the transmission channel is licensed to the primary users while the secondary users opportunistically access the channel resources when it is not used by any primary users.

According to the access technology of the secondary users, spectrum sharing can be split into two groups: spectrum underlay and spectrum overlay [12], [13]. In spectrum underlay, the secondary users are permitted to transmit their data in the licensed spectrum band when the primary users are also transmitting. In order to protect the primary users, the interference temperature threshold is imposed on the secondary users' transmission power. However, due to the constraints on transmission power, the secondary users can not achieve the maximum throughput. On the other hand, the secondary users in spectrum overlay can only use the licensed spectrum when the primary users are not transmitting. Spectrum overlay is also referred to as opportunistic spectrum access. To avoid harmful interference to the primary users, the secondary users need to sense the licensed frequency band and detect the spectrum white space. In spectrum overlay, the secondary users can achieve the maximum throughput because there is no constraints on transmission power.

In recent years, overlay/underlay framework in cognitive radio have been studied. In [6], authors showed that the primary user networks are benefitted by the relaying capability of the infrastructure based cognitive radio network that operates in underlay/overlay(hybrid) transmission mode. And in [7], the outage performance of relay assisted hybrid overlay/underlay cognitive radio systems were presented. Authors in [8] used Markov chain to find exact strategy switching threshold between overlay and underlay/overlay(hybrid) transmission mode. The inspiration of this paper came from [12], [13] where novel overlay/underlay waveforms have been proposed to exploit not only unused spectrum bands but also under-used spectrum bands in cognitive radio.

In recent research, queueing theory has been employed in performance analysis of cognitive radio networks [5], [4]. Although some of recent work have studied in queueing analysis, only a few studies [11], [9] have been done for controlling the queues in cognitive radio networks. In this paper, we study a queue served by a hybrid overlay/underlay cognitive radio link by using M/M/1 queuing model where arrival and service rate are heterogeneous [14]. Each arrival packet, based on its observation of network such as queue length and system state, decides whether to join the queue or not. In [11], the author found the individually optimal strategy, from the viewpoint of each customer, in a cognitive radio system in which the server in cognitive radio suffers from service interruption(i.e. the cognitive radio system operates only under overlay framework). In contrast to [11], our study focuses on a hybrid overlay/underlay cognitive radio network in which the server in cognitive radio oscillates between two modes underlay and overlay. To the best of our knowledge, this is the first paper analyzing this kind of system.

The remainder of this paper is organized as follows. The system model is introduced in Section II. In Section III, the optimal individual strategy of the secondary users is analyzed. Then, numerical results are reported in Section IV. Finally, we draw conclusions in Section V.

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II. System Model

In this section, we will introduce the model of queueing system and the model of cognitive radio system.

A. Cognitive radio system model

We consider a single-channel cognitive radio system accessed by multiple secondary users. The primary users have a license to use the band. And when the primary users wish to transmit, it is given a priority over the secondary users. This is implemented by having the secondary users perform spectrum sensing with perfect sensing assumed. If there is no signal of the primary users, the secondary users will operate under overlay framework. Otherwise if the band is occupied by the primary users, the secondary users will operate under underlay framework. The situation shown in Fig.1 can be interpreted to be an example of hybrid ovelay/underlay spectrum access framework.

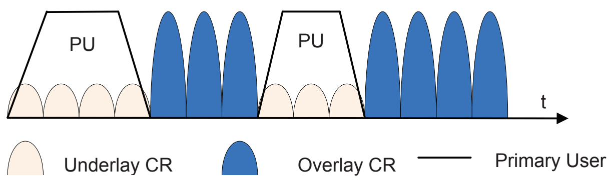

Fig. 1. Hybrid overlay/underlay spectrum access.

We assume that the primary users sojourn time(i.e., the amount of time that the primary users use the licensed band (or the time the primary users' band is in state ON) is random and exponentially distributed with mean $1/\eta$. And the amount of time that elapses between the end of a sojourn, and the starting of the next sojourn (i.e., the amount of time that the primary users' band is in state OFF) is random and exponential with parameter ξ.

The base station in the cognitive radio system, using the licensed band, is considered as a server and each secondary users' data packet as a customer. The primary users' band or licensed band can be considered as a server which oscillates between two feasible states ON/OFF (denoted by 1 and 0 respectively) which can be modeled by using Markov ON/OFF channel model [15]. Consequently, the cognitive radio base station operates also as a server that oscillates between two modes underlay and overlay which are denoted by 1 and 0 respectively. If the cognitive radio base station functions at state 0(i.e. overlay mode when the primary user is absent) then it tends to jump randomly to the alternative state 1(i.e. underlay mode when the primary user is present)with Poisson intensity ξ. And the reverse is also a Poisson process with intensity η. For both case, we assume that the secondary users' data packet are allowed to transmit with the service times which are exponentially distributed with rate μ_0 in overlay mode and μ_1 in underlay mode respectively. We assume that $\mu_0 > \mu_1$. Statistical independence between any two realizations is assumed.

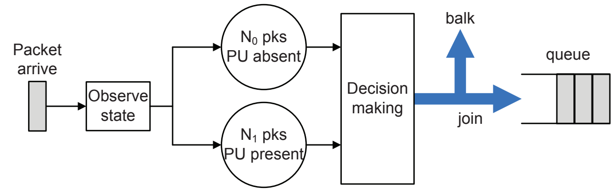

Fig. 2. Hybrid overlay/underlay decision making.

B. Queueing model

In this paper, we consider connections, sessions or data packets in cognitive radio networks as customers. We will study an arrival process of customers arriving at the cognitive base station which utilizes the primary user's band. Poisson process is used for customer arrivals so that the inter-arrival times are exponentially distributed. In general, we suppose customer arrival rate in two states are different, independent of previous history which is denoted by λ_0 when the primary user absent, and λ_1 when the primary user present. When each customer arrives, he can choose to join the queue according to first-in-first-out(FIFO) rule, or balk the queue. A FIFO rule can be implemented in the base station by letting each customer register its ID to the server when it arrives [11]. Throughout the paper, we will equalize the terms "customer" and "packet".

We assume that different packets are from different secondary users or even from the same user but each packet still have different individual interest. Each packet can be considered as a customer that want to maximize its own benefit. Assuming that when it arrives, a new secondary customer can observe the state of the primary users' band by sensing process and knows the current queue length by receiving a broadcast message consisting queue length information from the cognitive radio base station. Another way for customers to get the queue length information is to let the secondary user sends an inquiry. Upon arrival, each customer has to make a decision to join or balk the queue. Once customers have joined the queue, they are not marked state 0 or 1. Rather the service rendered to them possesses the instantaneous rate associated with the present state of the system. Therefore some basic properties of the queueing process (e.g., state probabilities, expected queue size, etc..) do not depend on the specification of the queue discipline [14]. The decision making process is illustrated in Fig. 2.

Every customer receives a reward of R units for completing service. Furthermore, there exists a waiting cost of C units per time unit that is continuously accumulated from the time that customer arrives the system till the time he leaves after being served. In practical systems, the cost C represents penalty for the delay or traffic congestion. We assume that the customers' decisions are made only at their arrival instants. And a decision to join is irrevocable and reneging is not allowed. Then, the net reward of a packet that stays in the system for T time slots and completes service successfully is derived as follows

$$S = R - CT \tag{1}$$

The net reward S can be negative if T is sufficient large. If the customer chooses not to joint the queue, he will get zero reward.

III. Secondary User Strategy

A. Expected mean sojourn time analysis

In this section we firstly analyze the expected mean sojourn time T of a customer given that he observes the system at state $(N(t), I(t))$ just before his arrival. We represent the state of the system at time t by a pair $(N(t), I(t))$, where $N(t)$ and $I(t)$ denote the number of customers in the queue and the mode of the cognitive radio base station (1 : underlay, 0 : overlay) which corresponds to the state of the primary users' band respectively. In other words, at time t we have $(N(t), I(t))$=(n, i). The process $(N(t), I(t))$ is a continuous time Markov chain with nonzero transition rates. Fig.3 shows the Markov process corresponding to the system evolution. We derive the expression of the expected mean sojourn time

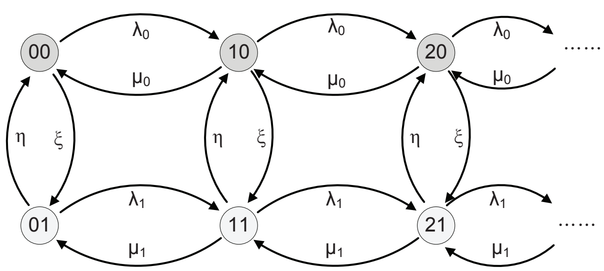

Fig. 3. Transition-rate diagram.

$T(n, i)$ of the customer when he finds the system at state (n, i) as follows

$$T(0,0) = \frac{\mu_0}{\mu_0+\xi}\frac{1}{\mu_0} + \frac{\xi}{\mu_0+\xi}T(0,1) \tag{2}$$

$$T(0,1) = \frac{\mu_1}{\mu_1+\eta}\frac{1}{\mu_1} + \frac{\eta}{\mu_1+\eta}T(0,0) \tag{3}$$

$$\begin{gathered} T(n,0) = \tfrac{1}{\mu_0+\xi} + \tfrac{\mu_0}{\mu_0+\xi}T(n-1,0) + \tfrac{\xi}{\mu_0+\xi}T(n,1) \\ n = 1,2,3,... \end{gathered} \tag{4}$$

$$\begin{gathered} T(n,1) = \tfrac{1}{\mu_1+\eta} + \tfrac{\mu_1}{\mu_1+\eta}T(n-1,1) + \tfrac{\eta}{\mu_1+\eta}T(n,0) \\ n = 1,2,3,... \end{gathered} \tag{5}$$

Based on the expression in [10], three terms in equation (4) are explained as follows: The first term is the mean value till the next event that is either a service completion or a failure (mean time of the minimum of two independent exponentials with rates μ_0 and ξ). This event corresponds to a service completion with probability $\frac{\mu_0}{\mu_0+\xi}$ in which case, $n-1$ customers will remain in the system and the server will be at state 0 (this case corresponds to the second term) or the event corresponds to a failure with probability $\frac{\xi}{\mu_0+\xi}$, in which case the number of customers remains the same, n, but the state of the server becomes 1 (this corresponds to the third term). Note that we do not consider arrivals in the formula, because future arrivals join the queue after the tagged customer and they do not influence him [10]. We derived the equation (5) in the similar way. From equation (4) and (5) we can rewrite $T(n, i)$ as

$$\mu_0 (T(n,0) - T(n-1,0)) + \xi (T(n,0) - T(n,1)) = 1 \tag{6}$$

$$\mu_1 (T(n,1) - T(n-1,1)) - \eta (T(n,0) - T(n,1)) = 1 \tag{7}$$

We denote $x_n = T(n,0) - T(n-1,0)$, $y_n = T(n,0) - T(n,1)$ and $z_n = T(n,1) - T(n-1,1)$. Then we have relation:

$$x_n - z_n = y_n - y_{n-1}, \ \ n = 1,2,3,... \tag{8}$$

And we rewrite equations (6), (7) as

$$\mu_0 x_n + \xi y_n = 1 \tag{9}$$

$$\mu_1 z_n - \eta y_n = 1 \tag{10}$$

By multiplying μ_0 with equation (10) and μ_1 with equation (9) then subtracting both sides and using relation (8), we have the expression of y_n as

$$\begin{gathered} y_n = \tfrac{\mu_0\mu_1}{\mu_1\xi+\mu_0\eta+\mu_0\mu_1} y_{n-1} - \tfrac{\mu_0-\mu_1}{\mu_1\xi+\mu_0\eta+\mu_0\mu_1}, \\ n = 1,2,3,... \end{gathered} \tag{11}$$

Denotes $M = \frac{\mu_0\mu_1}{\mu_1\xi+\mu_0\eta+\mu_0\mu_1}$ and $N = \frac{\mu_0-\mu_1}{\mu_1\xi+\mu_0\eta+\mu_0\mu_1}$ then we have

$$y_n = M y_{n-1} - N, n = 1,2,3,... \tag{12}$$

Solving the system of (2) and (3) we obtain

$$T(0,0) = \frac{\mu_1+\eta+\xi}{\mu_0\mu_1+\mu_0\eta+\mu_1\xi} \tag{13}$$

$$T(0,1) = \frac{\mu_0+\eta+\xi}{\mu_0\mu_1+\mu_0\eta+\mu_1\xi} \tag{14}$$

Therefore, we obtain

$$y_0 = T(0,0) - T(0,1) = \frac{\mu_1-\mu_0}{\mu_0\mu_1+\mu_0\eta+\mu_1\xi} = -N \tag{15}$$

By substituting (15) in equation (12) then we have the general expression of y_n as

$$y_n = -(M^n + M^{n-1} + ... + M + 1)N, n = 1,2,3,... \tag{16}$$

Based on the expression of $T(n, 0)$ as

$$\begin{gathered} T(n,0) = (T(n,0) - T(n-1,0)) + ... \\ ... + (T(1,0) - T(0,0)) + T(0,0), n = 1,2,3,... \end{gathered} \tag{17}$$

then we obtain

$$\begin{aligned} T(n,0) &= \textstyle\sum_{i=1}^{n} x_i + T(0,0) \\ &= \tfrac{n-\xi\sum_{i=1}^{n} y_i}{\mu_0} + T(0,0), n = 1,2,3,... \end{aligned} \tag{18}$$

By similar approach, we get

$$T(n,1) = \frac{n+\eta\sum_{i=1}^{n} y_i}{\mu_1} + T(0,1), n = 1,2,3,... \tag{19}$$

B. Optimal individual strategy

Because the customers are allowed to take their own decisions and therefore the system can be modeled as a game among the customers. Follow by the pioneering works of Naor [16], we will find the individually optimal strategy from the viewpoint of each customer. And the fundamental problem is to identify the Nash equilibria. From the point of view of game theory, a strategy is weakly dominant if it is a best response against any strategy. And a strategy is an equilibrium if it is a best response against itself.

Suppose that a customer arrives at the system and the expected net reward if he completes his service is:

$$S(n,i) = R - CT(n,i), \tag{20}$$

In the fully observable case, a pure threshold strategy is defined by a pair $(n(0), n(1))$ and has the expression 'While arriving at time t, observe the system state $(N(t), I(t))$; join the queue if $N(t) \leq n(I(t))$ and balk otherwise' [10].

Theorem 1: In the fully observable systems, there exists a pure threshold strategy $(n(0), n(1))$ such that the strategy 'Upon arrival at time t, observe $(N(t), I(t))$; join the queue if $N(t) \leq n(I(t))$ and balk otherwise' is a weakly dominant strategy.

Proof: We assume that $S(n,0) > 0, S(n,1) > 0$. With the assumption $\mu_0 - \mu_1 > 0$, we can easily prove that $M, N \in (0,1)$. And it's easy to prove that

$$-\frac{1}{1-M}N < -\frac{1-M^n}{1-M}N = y_n < 0, n = 0,1,2,3,... \tag{21}$$

Therefore, $\{T(0,0)$,$T(1,0)$,...,$T(n,0),...\}$ is the nondecreasing sequences. Then we conclude that $S(n,1) \geq 0$ if and only if $n \leq n(0)$ where the number n(0) satisfies that

$$S(0,0), S(1,0), ..., S(n(0),0) \geq 0 \, and \, S(n(0)+1,1) < 0 \tag{22}$$

In addition, $T(n,1) = T(n,0) - y_n > T(n,0)$ infers that $T(n,1) > T(n,0) > 0, \forall n$. It means $S(n,1) < S(n,0), \forall n$. Therefore, there must exist the number $n(1) \leq n(0)$ such that

$$S(0,1), S(1,1), ..., S(n(1),1) \geq 0 \, and \, S(n(1)+1,1) < 0 \tag{23}$$

A customer prefers to join the queue if his $S(n,i) > 0$ and he either joins nor balks if $S(n,i) = 0$, otherwise he balks. Therefore, we conclude that the arriving customer prefers to joint the queue if and only if $N(t) \leq n(I(t))$, where $(n(0), n(1))$ is given by finding the first negative term $(n(0)+1, n(1)+1)$ of ($S(n,0)$,S(n,1)). This strategy is preferable, regardless of what any other customers do, it means that it is a weakly dominant strategy.

■

Based on the proof of theorem 1 we can find the pure thresholds $(n(0)$,$n(1))$ by calculating the first negative term of $S(n,0)$ and $S(n,1)$. We assume that the cognitive radio base station has the maximum buffer size N_{max}, then we can use binary-search algorithm to calculate thresholds $n(0)$. Because $n(1) \leq n(0)$, the threshold $n(1)$ can be found by using exhausted search from 0 to $n(0)$.

IV. Simulation Results

The parameters are given as follow: $\xi = 5; \eta = 2; \mu_0 = 10; \mu_1 = 2; C = 1; N_{max} = 1000$. Fig.4 shows the delay time $T(n,1), T(n,0)$. It can be seen that $T(n,0) < T(n,1)$. In Fig.5 we vary the value of net reward R and the figure shows that the threshold $n(0)$ is always larger than $n(1)$. This is due to the fact that $T(n,0) < T(n,1)$. Furthermore, the difference ranges between 0 and 1 in most cases.

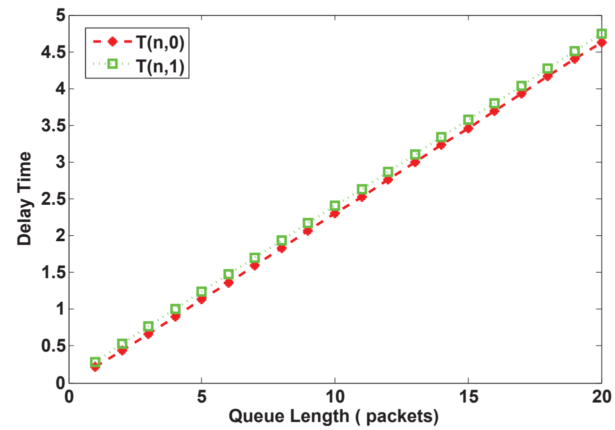

Fig. 4. Delay time of packets given by current queue length.

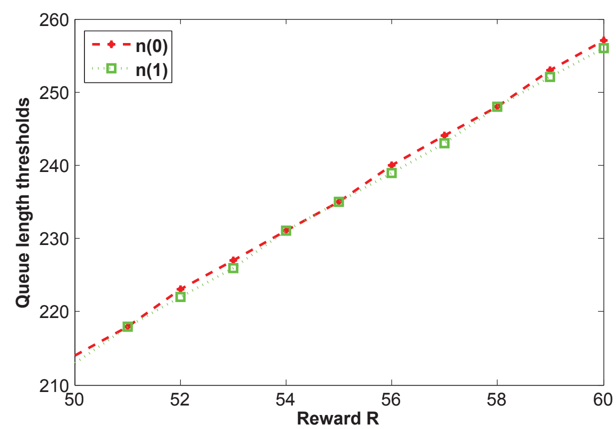

Fig. 5. Secondary user's threshold strategy.

V. Conclusion

In this paper, we have studied the queueing control in a hybrid overlay/underlay cognitive radio system by using heterogeneous arrivals and service queueing model. Because of heterogeneous arrivals and service, the system has complex analysis and expression of the equilibrium strategy in the fully observable case. Fortunately, we have proved the existence of the individually optimal strategy and can obtained it by simple algorithms. Simulation are used to validate the results, and simulation results demonstrate a high degree of accuracy for the derived expressions. In the future work, the socially optimal strategies will be studied.

VI. Acknowledgement

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