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Finding an Individual Optimal Threshold of Queue Length in Hybrid Overlay/Underlay Spectrum Access in Cognitive Radio Networks*

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SUMMARY In this paper, a hybrid overlay/underlay cognitive radio system is modeled as an 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 a decision to join the queue or not. Upon arrival, the individual decision of each packet is optimized based on his observation about the queue length and the state of system. It is shown that the individually optimal strategy for joining the queue is characterized by a threshold of queue length. Thus, the individual optimal threshold of queue length is analyzed in detail in this work.

key words: *cognitive radio, hybrid overlay/underlay, queue theory, game theory*

1. Introduction

Radio spectrum is one of the most scarce and valuable resources for wireless communications. Cognitive radio has been proposed as a way to improve spectrum efficiency by exploiting the unused spectrum in dynamically changing environments [1]. According to the access technology of the secondary users, spectrum sharing can be split into two groups: spectrum underlay and spectrum overlay [2]. 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 are no constraints on transmission power.

In recent years, overlay/underlay frameworks in cognitive radio have been studied. In [3], the outage performance of relay assisted hybrid overlay/underlay cognitive radio systems were presented. Authors in [4] used Markov chains to find exact strategy switching threshold between overlay and underlay/overlay(hybrid) transmission mode. The inspiration of this paper came from [2] where novel overlay/underlay waveforms were proposed to exploit not only unused spectrum bands but also under-used spectrum bands in cognitive radio.

In recent research, although some of recent works have studied queueing analysis, only a few studies [5] have been done for controlling the queues in cognitive radio networks. In [6] the queuing control for the server with breakdown model under the observable queue case (i.e., customers observe the queue length when making a decision) was studied. 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 rates are heterogeneous [7]. Each arrival packet, based on its observation of network such as queue length and system state, decides whether to join the queue or not. This paper will analyze optimal strategies for maximizing the individual reward by finding an individual optimal threshold of queue length. 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 Sect. 2. In Sect. 3, the optimal individual strategy of the secondary users is analyzed. Numerical results are reported in Sect. 4. Finally, we draw conclusions in Sect. 5.

2. System Model

2.1 Cognitive Radio System Model

We consider a single-channel cognitive radio system accessed by multiple secondary users. The base station in the cognitive radio system have role as a server and each secondary users' data packet as a customer. The primary users have a license to use the band. And when the primary users

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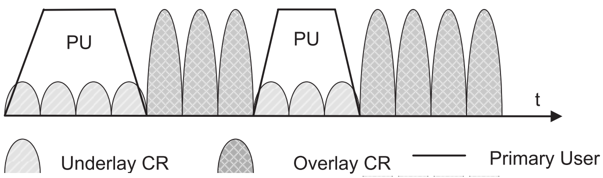

Fig. 1 Hybrid overlay/underlay spectrum access.

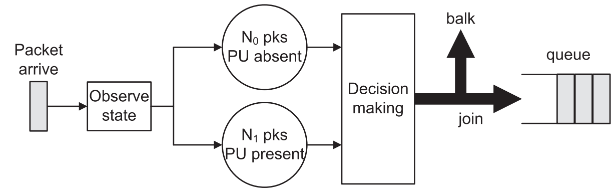

Fig. 2 Hybrid overlay/underlay decision making.

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.

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 primary users' 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 [8]. 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 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.

2.2 Queueing Model

Poisson process is used for packet arrivals so that the interarrival times are exponentially distributed. In general, we suppose the secondary user 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.

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. A first-in-first-out (FIFO) queue is used for the packets. Assuming that when the secondary user has an arrival packet and wants to send it to the base station, the secondary user would observe the state of the primary users' band by sensing process and get the current queue length information by receiving a broadcast message consisting of queue length information from the cognitive radio base station. Then, the secondary user makes a decision to send the packet to the base station or not. This packet would join the queue and be served by the base station. Once the secondary user's packets 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 [7]. The decision making process is illustrated in Fig. 2.

Throughout the paper, we will equalize the terms "customer" and "packet". Every customer receives a reward of R units for completing service. The reward R could be proposed by the secondary user to the cognitive radio base station. Some mechanisms can be designed to force them to send the true value of R. In this work, we consider a symmetric system model between the secondary users. Therefore, all secondary users have the same value of R. In the future works, the generic case of different Rs, which represent for different kinds of QoS application in networks, will be considered. For example, we can assume that there are N types of customers, each having one value of R. Then, one possible approach is to use N queues for different types of customers. 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 queue for T time slots and completes service successfully is derived as follows

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

Our queueing model is similar to the work in [5]. In this work 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. In contrast to these work, our study focuses on a hybrid overlay/underlay cognitive radio network in which the server in cognitive radio oscillates between two

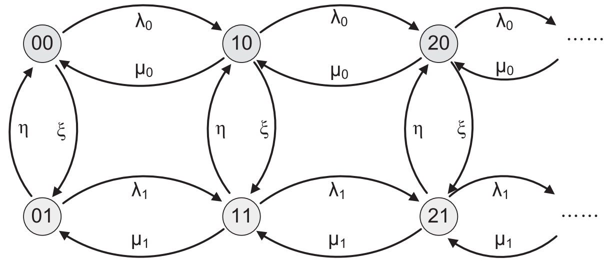

Fig. 3 Transition-rate diagram.

modes underlay and overlay. We consider the fully observable case where the secondary customers know the state of the primary users' band and the queue length. We can use the symmetric game to model the circumstance among the customers.

3. Secondary User Strategy

3.1 Expected Mean Sojourn Time Analysis

In this section we firstly analyze the expected mean sojourn time of a customer given that he observes the system at state $(N(t), I(t))$ just before his arrival where $N(t)$ denotes the number of customers in the queue and $I(t)$ denotes the mode of the cognitive radio base station (1: underlay, 0: overlay) which corresponds to the state of the primary users' band respectively. Figure 3 shows the Markov process corresponding to the system evolution. We derive the expression of the expected mean sojourn time $T(n, i)$ of the customer when he finds the system at state (n, i) as follows

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

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

$$T(n,0) = \frac{1}{\mu_0+\xi} + \frac{\mu_0}{\mu_0+\xi}T(n-1,0) + \frac{\xi}{\mu_0+\xi}T(n,1), \quad n = 1,2,3,... \quad (4)$$

$$T(n,1) = \frac{1}{\mu_1+\eta} + \frac{\mu_1}{\mu_1+\eta}T(n-1,1) + \frac{\eta}{\mu_1+\eta}T(n,0), \quad n = 1,2,3,... \quad (5)$$

Based on the expression in [6], three terms in Eq. (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 [6]. We derived Eq. (5) in the similar way. From Eqs. (4) and (5) we can rewrite $T(n, i)$ as

$$\mu_0(T(n,0)-T(n-1,0)) + \xi(T(n,0)-T(n,1)) = 1 \quad (6)$$

$$\mu_1(T(n,1)-T(n-1,1)) - \eta(T(n,0)-T(n,1)) = 1 \quad (7)$$

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:

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

And we rewrite Eqs. (6), (7) as

$$\mu_0 x_n + \xi y_n = 1 \quad (9)$$

$$\mu_1 z_n - \eta y_n = 1 \quad (10)$$

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

$$y_n = My_{n-1} - N, n = 1,2,3,... \quad (11)$$

where $M = \frac{\mu_0\mu_1}{\mu_1\xi+\mu_0\eta+\mu_0\mu_1}$ and $N = \frac{\mu_0-\mu_1}{\mu_1\xi+\mu_0\eta+\mu_0\mu_1}$. By solving the system of (2) and (3) we obtain

$$T(0,0) = \frac{\mu_1+\eta+\xi}{\mu_0\mu_1+\mu_0\eta+\mu_1\xi} \quad (12)$$

$$T(0,1) = \frac{\mu_0+\eta+\xi}{\mu_0\mu_1+\mu_0\eta+\mu_1\xi} \quad (13)$$

Therefore, we obtain

$$y_0 = T(0,0) - T(0,1) = \frac{\mu_1-\mu_0}{\mu_0\mu_1+\mu_0\eta+\mu_1\xi} = -N \quad (14)$$

By substituting (14) in Eq. (11) then we have the general expression of y_n as

$$y_n = -(M^n + M^{n-1} + ... + M + 1)N, n = 1,2,3,... \quad (15)$$

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

$$T(n,0) = (T(n,0) - T(n-1,0)) + ... \\ ... + (T(1,0) - T(0,0)) + T(0,0), n = 1,2,3,... \quad (16)$$

then we obtain

$$T(n,0) = \sum_{i=1}^{n} x_i + T(0,0) \\ = \frac{n - \xi\sum_{i=1}^{n} y_i}{\mu_0} + T(0,0), n = 1,2,3,... \quad (17)$$

By similar approach, we get

$$T(n,1) = \frac{n + \eta\sum_{i=1}^{n} y_i}{\mu_1} + T(0,1), n = 1,2,3,... \quad (18)$$

3.2 Optimal Individual Strategy

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:

$$S(n,i) = R - CT(n,i), \quad (19)$$

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' [6].

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

$$-\frac{1}{1-M}N < -\frac{1-M^n}{1-M}N = y_n < 0, n = 0, 1, 2, 3, ... \quad (20)$$

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

4. Simulation Results

The parameters are given as follow: $\xi = 5; \eta = 2; \mu_0 = 10; \mu_1 = 2; C = 1; N_{max} = 1000$. It can be seen in Fig. 4, when the reward R increases, the queue length threshold also goes up. Figure 4 shows that the threshold $n(0)$ is always larger than $n(1)$. It means that the queue length threshold with absence of primary users is longer than that with presence of primary users. The reason is that when the primary user does not occupy the licensed band the arriving packet has the expected waiting time $T(n, 0)$ less than the expected waiting time $T(n, 1)$ when the primary user occurs.

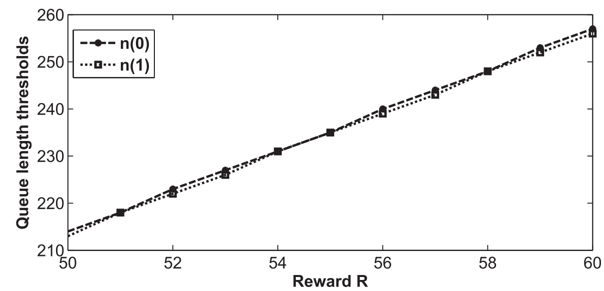

Fig. 4 Secondary user's threshold strategy.

5. Conclusion

In this paper, we have proposed a queueing control strategy in a hybrid overlay/underlay cognitive radio system by using heterogeneous arrivals and a service queueing model. The equilibrium strategy has complex analysis and expression. However, the individual optimal queue length threshold has been proved existed.

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