Cooperative Cognitive Radio with Priority Queueing Analysis

Caoxie Zhang, Xinbing Wang, Jun Li
Department of Electronic Engineering, Shanghai Jiao Tong University, China

***Abstract*—In this paper, we model the hierarchical structures inherent in cognitive radio networks as the priority queueing system in which primary users interact with the highest priority and secondary users belong to the lowest priority class. In a M/G/1 system containing one primary user and multiple secondary users, we obtain analytical forms of delay and throughput for different users with the function of traffic and channel conditions. Based on the analysis, the secondary user is considered to act as a relaying terminal to assist the primary communication by adopting an amplify-and-forward TDMA protocol. Cooperative diversity gains are examined next and the benefits of the secondary: improvement of throughput, is discussed with respect of the primary traffic.**

I. INTRODUCTION

Cognitive radio networks has been a new technology in wireless communication that improves utilization of limited spectral resources as demand for wireless spectrum increases rapidly in recent years [1]. The primary users have the exclusive access to their primary channels and they can adjust to their demand and the physical channel condition. Secondary users should not interfere with the on-going primary transmission and should be ejected from the used channel when a primary user is asking for. The secondary users, on the other hand, should be able to exploit the under-utilized spectrum, vacated by idle primaries, as spectral opportunity (also known as spectral holes) opportunistically.

One important issue in cognitive radios is to model the traffics of the primary users and secondary users. Recent research, such as [2], [3], [10] assume that the service time or the packet length of the users is exponentially distributed, therefore ON/OFF Markov Chain can be used to model the system. [4] proposes a more general case of arbitrary distribution of busy periods for primary user, however the packet length for the secondary users is either exponentially distributed or fix length. [5] offers a general distribution of the service time for both the primary and secondary, and to the best of our knowledge, is the first to analyze cognitive radio networks in the priority queueing framework. However, the analysis obtain the final form of delay approximately. In this paper, we model one primary user and multiple secondary user competing for the same primary channel and model the traffic as a M/G/1 preemptive priority queue with channel conditions of physical transmission rates and packet error rates. The priority queue characterizes the inherent traffic structures in cognitive radio networks. One of the contributions in this paper is that we obtain exact analytical forms of delay and throughput for different users. In addition, the one primary user scenario is discussed to be easily extended to multiple primary in a multiaccess channel.

In order to enhance network performance, cooperative diversity in wireless communication has been proved to provide diversity gains in terms of outage probability, [7]. The relay terminal could improve the adversity of the fading source-to-destination link, and the outage probability or packet error rates would decay according to a second-order behavior. Spurred by this idea, we employ the secondary user as a relay terminal to assist primary communication. The primary traffic could be therefore relieved and more spectral holes would be possible for the secondary to exploit, therefore the secondary would benefit from the improvement of its own performance. [8] gives a cognitive strategy of a cooperating relay and characterizes the maximum stable throughput region and delay performance. The idea that combines cognitive and cooperative in a capacity view is presented by [9] which add relaying capability to the secondary transmitter and rely on stability (i.e., finiteness of all the queues in the system at all times) as the criterion of performance. However, [9] does not propose a practical protocol for relaying. In this paper, we contribute to the cooperative cognitive networks by: (1) focusing on an information-theoretic view of the outage probability and apply an amplify-and-forward TDMA relay protocol in [11] to cognitive radio networks, (2) investigating the delay and throughput of the secondary user instead of stability. In addition, we investigate the performance gains of the relaying technique with the primary channel quality and the primary traffic loads. The advantages and limits would be discussed with different conditions.

The complete system model is depicted in Fig.1. In this network model, the secondary user 1 is acting as a relaying terminal for assisting primary communication. When the primary queue is empty, all the secondary users would attempt to compete for the access to the channel. The rest of this paper is organized as follows. Section II describes our system model under consideration. Section III deals with performance analysis based on priority queueing analysis and information theory. Section IV presents numerical results, and Section V makes concluding remarks.

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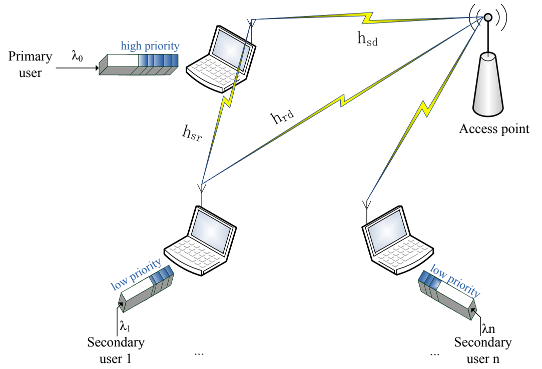

Fig. 1. Cooperative cognitive radio networks with priority queueing model.

II. SYSTEM MODEL OF THE COOPERATIVE COGNITIVE RADIO NETWORKS

A. A Non-cooperative Model Based on Priority Queueing System

We first consider a cognitive radio network model without relaying. We assume that the system is a packet-based system with one primary user and N secondary users accessing the same primary channel. There are two different priority classes: the primary user has the higher priority and all the secondary users belong to the lower priority class. Primary user is indexed by the subscript 0 and secondary users by the subscript p $(p = 1, 2, ..., N)$. Primary user is assumed to be able to preempt the transmission of the secondary users. Secondary users would sense the channel and time share the spectrum holes with the First-Come-First-Serve rule, [12]. When the transmission of the secondary user is preempted by the primary user, the rest of the secondary transmission would be taken up into the priority queue. Note that this discipline is called *preemptive resume*, [13]. We also assume that schemes of spectrum sensing and multiple access control are available for the secondary users to share the spectrum opportunities. Under these schemes, lower priority transmission would always wait in the queue for the transmission of higher priority class.

We consider the heterogeneous physical channel conditions for each user. The users operate with the physical transmission rates R_i, and packet error rates (also known as outage probability) P_i, $(i = 0, 1, 2, ..., N)$. In the case of cooperative diversity, the secondary user would help to relay the transmission from the primary user so that the primary packet error rates, P_0 would decrease and affect the entire traffic conditions of the system.

We model the traffic conditions of the systems by adopting an M/G/1 priority queueing model. The packets of each user arrive according to the Poisson process with the average arrival rate λ_i $(i = 0, 1, 2, ..., N)$. The length of the packet can be generally distributed so long as the mean packet length is known. This traffic model description is more general than the frequently used Markov ON/OFF channel model [2], which relies on exponential distribution of both the idle and busy periods. We denote L_i as the average packet length for user i, $(i = 0, 1, 2, ..., N)$. We assume that the failed packets would be retransmitted immediately under some Automatic Repeat Request protocol. We denote X_i $(i = 0, 1, 2, ..., N)$ as the transmission time in the physical channel for one packet from each user i. The first and second moment of the average service time are, as in [5]

$$E[X_i] = \frac{L_i + L_{oh}}{R_i(1 - P_i)} \quad i = 0, 1, 2, ..., N \qquad (1)$$

$$E[X_i^2] = \frac{(L_i^2 + L_{oh}^2)(1 + P_i)}{R_i^2(1 - P_i)^2} \quad i = 0, 1, 2, ..., N \qquad (2)$$

Here $R_i(1 - p_i)$ represents the effective transmission rate. R_i and P_i are the channel conditions dependent on the power allocations, the modulation, coding schemes or cooperative diversity. L_{oh} here denotes the equivalent control overhead including the time for protocol acknowledgement, information exchange, and channel sensing delay, etc [14]. Hence the first moment and second moment of the traffic load (also known as the utilization factor) for each user i is

$$\rho_i = \lambda_i E[X_i] \quad i = 0, 1, 2, ..., N \qquad (3)$$

$$\rho_i^2 = \lambda_i E[X_i^2] \quad i = 0, 1, 2, ..., N \qquad (4)$$

The utility function for each user is defined here as the effective throughput that can be achieved from the channel. We denote T_i $(i = 0, 1, 2, ..., N)$ as the end-to-end time for a packet from user i (the packet's arrival to its transmission finished). Thus the effective throughput is defined as

$$U_i = \frac{L_i}{E[T_i]} \quad i = 0, 1, 2, ..., N \qquad (5)$$

Note that T_i contains the waiting time in the queue and the transmission time in the channel. Section III.A deals with how to determine $E[T_i]$.

The one-primary multi-secondary model could be extended to multi-primary multi-secondary by considering all the primary users as an equivalent primary user. This is because (1) summation of Poisson processes is still a Poisson process with the arrival rates being the sum of individual primary arrival rate, and (2) the new distribution of the transmission time can be devised to count for all the distributions of the primary transmissions due to general distribution. However, detail in primary model is not the major concern of this paper and we focus on the secondary interactions. Therefore, this paper remains to one-primary multi-secondary scenario for later analysis.

B. Applying Cooperative Diversity to Cognitive Radio Networks

Fading in wireless channel causes random fluctuation in signal level and one of the results could be packet error rates. Cooperative diversity has been introduced to realize spatial diversity gain. In this paper, we consider a simple scenario of one primary user, one secondary user and one access point. The primary user, the secondary user, and the access point in this single-relay model act as the source terminal, relay terminal and destination terminal respectively, denoted by the subscript S, R and D. When the primary user is to communicate with its link, the secondary user senses the channel and would use the relay protocol to amplify-and-forward (AF) or decode-and-forward (DF) the signal received from the primary user to the access point. Whatever the protocol it adopts, the error rates decay according to a second-order diversity behavior. For practical reasons, we here adopt a TDMA-based transmission protocol in AF mode from [11], known as AF-Based Protocol I. We assume that all terminals work in half-duplex with the same transmitting power and one transmission is divided into two time slots. In the first time slot, the source terminal communicates with the relay and destination terminals. In the second time slot, both the relay and source terminals communicate with the destination terminal. This protocol maximizes the degree-of-freedom and is superior than other AF-based protocols. The input and output signal of the channel $i \to j$ is modeled as

$$y = \sqrt{E_{ij}} h_{ij} x + n_j \tag{6}$$

E_{ij} $(i, j \in S, R, D)$ is the average signal energy received at the j terminal over one symbol period through the $i \to j$ link, having accounted for path loss and shadowing effects, and h_{ij} $(i, j \in S, R, D)$ are the random, complex-valued, unit-power channel gain between the $i \to j$ link. h_{ij} are assumed to be independent $\mathcal{CN}(0, 1)$, which corresponds to Rayleigh fading on the link and $n_j \sim \mathcal{CN}(0, N_0)$ is additive white noise.

We denote I as the maximum mutual information between the source input and the destination output for our cooperative protocol and η is the required spectral efficiency. The outage probability, or packet error rates, is then given

$$P_0 = P(I < \eta) \tag{7}$$

III. PERFORMANCE ANALYSIS OF THE SYSTEM MODEL

A. Delay and Throughput Analysis in Priority Cognitive Radio Networks

The primary concern, $E[T_i]$, can be expressed in the fundamental relationship between $E[X_i]$ and $E[W_i]$, which is the packet waiting time in the queue from user i.

$$E[T_i] = E[W_i] + E[X_i] \quad i = 0, 1, 2, ..., N \tag{8}$$

Thus, we need to determine the analytical results of the mean waiting time $E[W_i]$. We apply a similar method in Kleinrock's book[6]. Research [5] uses the method of mean value analysis (MVA) in [12] but achieves with approximate results. Here we would derive the *exact* analytical formulations with an elegant method.

We first derive the packet's mean waiting time, or delay, $E[W_i]$ for each secondary user i $(i = 1, 2, ..., N)$. The packet delay should be decomposed into three parts:

1) Delay due to the packet in transmission upon arrival, denoted as $E[W_i^{(1)}]$;
2) Delay due to the packets in the queue upon arrival, denoted as $E[W_i^{(2)}]$;
3) Delay due to primary packets arrive after arrival, denoted as $E[W_i^{(3)}]$.

$E[W_i^{(1)}]$ is also known as the residual life of a transmission time. The mean residual life of a transmission for each user k is $\frac{E[X_k^2]}{2E[X_k]}$ [6]. Since ρ_k $(k = 1, 2, ..., N)$ represents the utilization factor of the service under non-preemptive discipline, the conditional probability, that user$k$'s packet is being transmitted given that no primary packet is transmitted, is $\frac{\rho_k}{1-\rho_0}$. As for primary user, the probability of the utilization is simply ρ_0. These allow us to formulate $E[W_i^{(1)}]$ as

$$\begin{aligned} E[W_i^{(1)}] &= \rho_0 \frac{E[x_0^2]}{2E[x_0]} + \sum_{k=1}^{N} \frac{\rho_k}{1-\rho_0} \frac{E[x_k^2]}{2E[x_k]} \\ &= \frac{\rho_0^2}{2} + \frac{1}{1-\rho_0} \sum_{k=1}^{N} \frac{\rho_k^2}{2} \end{aligned} \tag{9}$$

Now consider the second delay, $E[W_i^{(1)}]$, which is due to other packets in the queue found by the new arrival. We denote $M_k^{(1)}$ as the number of packets in the queue upon the new arrival from user k. The average of this quantity, $E[M_k^{(1)}]$, can be obtained by Little's result, that $E[M_k^{(1)}] = \lambda_k E[W_k]$ $(k = 0, 1, 2, ..., N)$. Hence, the second part of the delay caused by these $\sum_{k=0}^{N} E[M_k^{(1)}]$ number of packets is

$$E[W_i^{(2)}] = \sum_{k=0}^{N} E[X_k] E[M_k^{(1)}] = \sum_{k=0}^{N} \rho_k E[W_k] \tag{10}$$

The third component of the delay can be similarly established. We define $M^{(2)}$ as the number of packets from the primary user which arrive after the new arrival. Since those primary packets would spend $E[W_i]$ time in the queue, by applying Little's result again, the mean value of $M^{(2)}$ is $E[M^{(2)}] = \lambda_0 E[W_i]$. Hence, the third part of the delay is simply related to the primary user, as

$$E[W_i^{(3)}] = E[X_0] E[M^{(2)}] = \rho_0 E[W_i] \tag{11}$$

By summing the three components of the delay from (9), (10) and (11), we establish the equation for the average packet delay from secondary user i

$$\begin{aligned} E[W_i] &= E[W_i^{(1)}] + E[W_i^{(2)}] + E[W_i^{(3)}] \\ &= \frac{\rho_0^2}{2} + \frac{1}{1-\rho_0} \sum_{k=1}^{N} \frac{\rho_k^2}{2} + \sum_{k=0}^{N} \rho_k E[W_k] + \rho_0 E[W_i] \end{aligned} \tag{12}$$

It is the same as

$$(1-\rho_0) E[W_i] = \frac{\rho_0^2}{2} + \frac{1}{1-\rho_0} \sum_{k=1}^{N} \frac{\rho_k^2}{2} + \sum_{k=0}^{N} \rho_k E[W_k] \tag{13}$$

Observe that $E[W_i]$ is the same for all secondary users. Solving (13) by substituting $E[W_i] = E[W_k]$ $(k \neq i)$, we have

$$E[W_i] = \frac{\frac{\rho_0^2}{2} + \frac{1}{1-\rho_0} \sum_{k=1}^{N} \frac{\rho_k^2}{2} + \rho_0 E[W_0]}{1 - \sum_{k=0}^{N} \rho_k} \tag{14}$$

For the primary user, we can obtain the mean waiting time of one packet $E[W_0]$ in a similar method

$$\begin{aligned} E[W_0] &= E[W_0^{(1)}] + E[W_0^{(2)}] \\ &= \frac{\rho_0^2}{2} + \rho_0 E[W_0] \end{aligned} \tag{15}$$

Note that we do not have $E[W_0^{(3)}]$ in (15) since the primary user will not be intercepted by any users. In (15), $E[W_0^{(1)}]$ and $E[W_0^{(2)}]$ are determined as $\frac{\rho_0^2}{2}$ and $\rho_0 E[W_0]$ respectively according to the similar definition for secondary users. Hence, we can solve $E[W_0]$ as

$$E[W_0] = \frac{\rho_0^2}{2(1-\rho_0)} \tag{16}$$

Substitute (16) into (14), we have the analytical form of the average packet waiting time for each secondary user i as

$$E[W_i] = \frac{\sum_{k=0}^{N} \rho_k^2}{2(1-\rho_0)(1-\sum_{k=0}^{N} \rho_k)} \tag{17}$$

By combing (3) and (4) into (16) and (17), we could achieve the mean waiting time for each user i. Thus $E[T_i]$ is finally obtained as in (8) and also the exact analytical throughput for each user i: U_i $i = 0, 1, 2, ..., N$ can be achieved from (5). The throughput for the primary user is

$$U_0 = \frac{L_0}{\frac{\rho_0^2}{2(1-\rho_0)} + \frac{L_0 + L_{oh}}{R_0(1-P_0)}} \tag{18}$$

and the throughput for secondary user i is

$$U_i = \frac{L_i}{\frac{\sum_{k=0}^{N} \rho_k^2}{2(1-\rho_0)(1-\sum_{k=0}^{N} \rho_k)} + \frac{L_i + L_{oh}}{R_i(1-P_i)}} \quad i = 1, 2, ..., N \tag{19}$$

Note that the throughput of the primary users, (18) is only related with its own condition because of the preemptive scheme.

B. Cooperative Diversity Analysis in Outage Probability

In an information-theoretic view, for direct transmission without relaying, we can easily obtain the exact outage probability

$$\begin{aligned} P(I_0 < \eta) &= P(\log(1 + \frac{E_{SD}|h_{SD}|^2}{N_0}) < \eta) \\ &= P(|h_{SD}|^2 \leq \frac{2^\eta - 1}{E_{SD}/N_0}) \\ &= 1 - e^{(-\frac{2^\eta - 1}{E_{SD}/N_0})} \end{aligned} \tag{20}$$

When the cooperative protocol is applied, the outage probability is upper-bounded to (18) in [11]

$$P(I < \eta) \leq P(|h_{SD}|^2 + |h_{SR}|^2 \leq \frac{2^{2\eta} - 1}{\beta}) \tag{21}$$

where

$$\begin{aligned} \beta &= \min\{(1 + \frac{1}{\omega^2})\frac{E_{SD}}{N_0}, \frac{1}{\omega^2}\frac{E_{SR}E_{RD}}{(E_{SR} + N_0)N_0}\} \\ \omega^2 &= 1 + \frac{E_{RD}}{E_{SR} + N_0} \end{aligned}$$

For β sufficiently large, recalling that $|h_{SD}|^2$ and $|h_{SR}|^2$ are exponentially distributed and according to the approximation $e^{-\frac{1}{x}} \approx 1 - \frac{1}{x}$ for sufficiently large x, we obtain

$$P(I < \eta) \leq (\frac{2^{2\eta} - 1}{\beta})^2 \tag{22}$$

which is the second-order decay to the effective SNR β achieved by our cooperative protocol.

IV. NUMERICAL RESULTS

We first consider a simple non-cooperative scenario of one primary user and one secondary user and present the numerical results of the throughput for the secondary user based on (19). The parameters are $R_0 = 1$ Mbps, $L_{oh} = 0$, $L_0 = 1K$ Bytes, $L_1 = 1K$ Bytes, $R_1 = 1$ Mbps, $p_1 = 0.1$, $\lambda_1 = 10$ Packets/sec. We examine how the throughput for the secondary user responses with the primary channel packet error rates $P_0 \in (0, 1)$, and the traffic load of primary user, setting $\lambda_0 E[X_0] \in (0, 1)$.

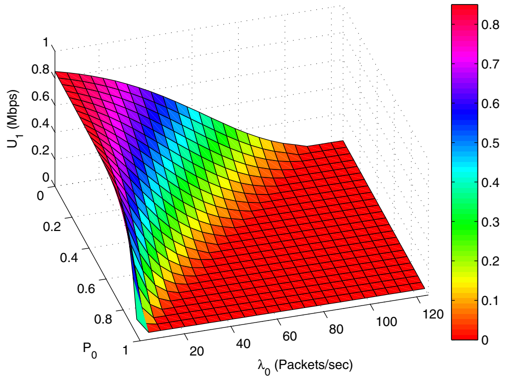

Fig. 2. Throughput of the secondary user with respect of the primary conditions: P_0 and λ_0 ($R_1 = R_0 = 1$ Mbps, $L_{oh} = 0$, $L_1 = L_0 = 1K$ Bytes, $p_1 = 0.1$).

As can be seen in Fig.2, for either severely poor primary channel or heavy primary traffic loads, the throughput of the secondary user decreases much sharply. We then consider the cooperative mode while secondary user is acting as a relay node to the primary. We set the receive power $E_{SR} = E_{RD} =$ 30 dB, spectral efficiency $\eta = 0.2$, $\lambda_0 = 30$ Packets/Sec and other parameters are the same as previous. The performance of secondary is to vary with E_{SD}/N_0, the SNR of the primary link. Note that the variation of E_{SD} can be variation of the channel quality, e.g. path loss or shadowing. As can be seen in Fig.3, the throughput performance of the secondary user indicates that throughput gains little when the quality of the primary channel turns better. It is intuitive that for good primary channel, there is no need to apply relaying technique although the outage probability is still outperformed.

We then further investigate a circumstance of poor primary link in which cooperative diversity could promise effective gains. We vary the primary traffic loads λ_0, such that $\lambda_0 E[X_0] \in (0, 1)$ and examine the throughput gains for

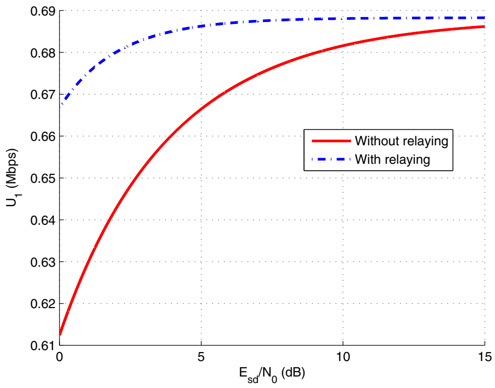

Fig. 3. Throughput of the secondary user with the function of E_{SD}/N_0 ($E_{SR} = E_{RD} = 30$ dB, $\eta = 0.2$, $\lambda_0 = 30$ Packets/Sec).

the secondary user by employing the relaying technique. The channel conditions are $E_{SD} = 0$ dB, $E_{RD} = E_{SR} = 10$ dB, other parameters are same as previous.

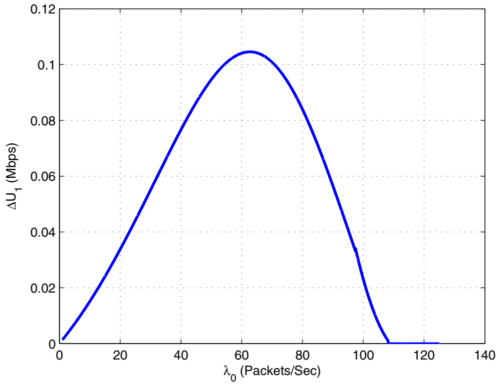

Fig. 4. Throughput gains of the secondary user with respect of the primary traffic loads. ($E_{SD} = 0$ dB, $E_{RD} = E_{SR} = 10$ dB)

As can be seen from Fig.4., for light and heavy primary traffic loads, the throughput of secondary dose not improve too much when adopting the relaying scheme. However, the maximum gain is obtained at the medium traffic, about $\lambda_0 = 63.58$ packets/sec. At low λ_0, the throughput without relaying is already high enough and relaying does not result in a good amount of spectrum opportunity. Also, at the heavy primary loads, relaying can help primary user to relieve its traffic but spectrum opportunity for the secondary user is still scarce and therefore achieve with little gain.

V. CONCLUSIONS

In this paper, we analyze the cognitive radio network based on a M/G/1 priority queueing system, with one primary user and multiple secondary users and obtain the analytical forms of delay and throughput for each user. Future work could extend to multiple primary users in the multiaccess channel by equalizing multiple primary users to one primary user in the M/G/1 framework. Then we propose to apply cooperative diversity into cognitive radio for a system of one primary and one secondary user. The secondary user employs an amplify-and-forward time-division relay protocol to assist the transmission of primary communication. Results show that the secondary user improves throughput a lot in poor primary channel. And the most throughput gain for the secondary user happens at medium traffic loads of the primary user. These results may shed some insights on how to make relay strategy for the secondary users.

VI. ACKNOWLEDGEMENT

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