Credit-Based Spectrum Sharing for Cognitive Mobile Multihop Relay Networks

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Abstract—In cognitive mobile multihop relay (CMMR) network, the mobile user as the primary user is allocated with the channel for transmitting data. Relay station as the secondary user can help primary user to relay transmitted data while in return primary user grants channel access to secondary user. In this paper, credit-based spectrum sharing for primary and secondary user in CMMR network is proposed. With this sharing scheme, the credit is given to the secondary user when primary user requests relay transmission. Primary user can then later allow secondary user to access the allocated channel in return given available credit. An optimization model based on Markov decision process is formulated and solved to obtain optimal policy for primary user in this credit-based spectrum sharing. Knowing that the primary user will adopt optimal policy to grant channel access, the secondary user can optimize the relay transmit power such that the cost is minimized. The performance evaluation shows that the credit-based spectrum sharing can benefit both primary user to gain better QoS performance and secondary user to minimize the cost due to QoS degradation and relay transmit power.

Keywords—Cognitive radio, relay transmission, Markov chain.

I. INTRODUCTION

Mobile multihop relay (MMR) network has been introduced as the promising technology to improve the performance of wireless transmission. In MMR network, the data transmission of mobile user is based on the relay signal (e.g., using cooperative diversity techniques) from relay station. Traditionally, mobile user pays the service charge to receive this relay transmission from relay station. Alternatively, with the introduction of cognitive radio paradigm to improve spectrum utilization and quality-of-service (QoS) of data transmission, mobile user as the primary user can use relay transmission from relay station. In exchange, this relay station as the secondary user can access the primary user’s allocated channel for its own transmission [1]. This scenario can be referred to as the cognitive MMR (CMMR) network which can be adopted in the recent standard (e.g., IEEE 802.16j). However, to achieve the best performance of this CMMR network, the radio resource management (i.e., spectrum sharing scheme) will be important. Therefore, given the benefit of primary user and the cost of secondary user, their relay transmission and spectrum sharing actions have to be optimized.

In this paper, credit-based spectrum sharing for CMMR network is proposed. In this spectrum sharing scheme, the credit is given to the secondary user (i.e., relay station) when primary user (i.e., mobile user) uses relay transmission, e.g., when the burst packet arrival occurs and data queue of primary user is congested. With available credit, primary user grants the channel access to secondary user, e.g., when the packet arrival is light and data queue is empty. To obtain the optimal policy of primary user for this credit-based spectrum sharing, an optimization model based on Markov decision process (MDP) is formulated to maximize the QoS performance. Then, the queueing model for secondary user is developed. With this queueing model, secondary user can optimize the relay transmit power so that the cost is minimized. This interaction between primary and secondary users can be considered as the spectrum sharing game. The secondary user knows that primary user will always optimize the policy given the relay transmit power. Therefore, the secondary user can optimize relay transmit power to minimize the cost. The optimal solution of this game is known as the Stackelberg equilibrium.

The rest of this paper is organized as follows. The related work are reviewed in Section II. Section III describes the system model and assumptions. The optimization model for primary user is presented in Section IV. Queueing model and optimization model of secondary user are proposed in Section V. Section VI presents the performance evaluation results. The summary is given in Section VII.

II. RELATED WORK

The cognitive radio with relay transmission (e.g., cooperative diversity) has been studied in the literature. For example, the secondary user can relay data transmission from primary user and primary user allocates portion of spectrum for secondary user [1]. In [2], relay-assisted discontiguous OFDM (D-OFDM) transmission scheme was proposed. In this scheme, the relay node is selected to relay the data from primary user. The problem of relay selection and spectrum allocation were addressed using the centralized heuristic solution. In [3], the priority queueing system model based on M/G/1 was developed for the cognitive radio with relay transmission. The delay and throughput were analyzed. The concept of using credit for channel access in cognitive radio was first proposed in [4]. The protocol to facilitate the spectrum renting based on the credit was proposed. In [5], the auction mechanism was applied to determine the secondary user to obtain the credit token to access the spectrum. In [6], the game model was formulated and solved for the power allocation problem in cognitive radio with relay transmission. In this game model, the secondary users compete for relay transmission and channel access. In [7], the similar problem was considered in which the Bayesian potential game was formulated with incomplete information of channel gain. However, none of the works in literature considered the optimization of primary user to maximize QoS performance and secondary user to minimize cost of relay transmission in the CMMR networks. Also, the queueing performances were ignored.
III. SYSTEM MODEL AND ASSUMPTIONS

A. Cognitive Mobile Multihop Relay Network

We consider cognitive mobile multihop relay (CMMR) network with one relay station (Fig. 1). The mobile user is considered to be the primary user which is allocated to access the channel (e.g., subchannel in IEEE 802.16j). The transmission can be direct between primary user’s transmitter and receiver. Alternatively, the primary user can request the relay station to relay the data. This relay station is considered to be the secondary user. Later, primary user grants the channel access to the secondary user in return for relay transmission. At the primary and secondary users, radio link level queues are used to buffer incoming packets. The size of these queues are $X_{pri}$ and $B_{sec}$ for primary and secondary users, respectively.

![System model of cognitive mobile multihop relay network.](image)

B. Transmission Burst and Credit-Based Spectrum Sharing

The transmission burst (i.e., uplink or downlink in the frame) is divided into two parts. While the first part is always for the transmission by primary user, the use of second part depends on the action of primary user. Three types of transmission bursts corresponds to the action of primary user (Fig. 1), i.e., direct transmission, relay transmission, and transmission of secondary user.

1) If the primary user decides to use direct transmission without help from secondary user, the second part of transmission burst will be also the transmission of primary user.

2) If primary user decides to request relay transmission, both the receiver of primary and secondary users will receive the data transmitted by the transmitter of primary user in the first part of transmission burst. Then, the second part will be the transmission of received data by secondary user to the receiver of primary user.

3) If the primary user decide to grant the channel access to the secondary user, the second parts of transmission burst will be the transmission of the secondary user itself.

While primary user gains benefit of higher transmission rate from relay transmission, secondary user can gain benefit of channel access granted by the primary user. To exchange these benefits, the credit-based spectrum sharing is introduced. Without loss of generality, when the primary user requests secondary user to relay the data, credit for spectrum access for secondary user is generated. This credit is added into the credit queue (Fig. 1), if the credit queue with capacity $C$ is not full. Otherwise, the secondary user will refuse the request from primary user. When primary user grants the channel access to the secondary user, one credit is taken from the credit queue. In this way, the primary user can request the help from secondary user when the data queue becomes congested. Then later, primary user yields the channel access back to the secondary user once the backlog is clear. We assume that the state of credit queue is observable by both primary and secondary users. The optimization model to obtain the action of primary user in this credit-based spectrum sharing will be presented later in this paper.

C. Relay Transmission

For the relay transmission, the cooperative diversity as in [8] is used. The relay transmission is based on cooperative-space-time coding in the form of Alamouti scheme [9]. The same adaptive modulation and coding (AMC) mode is used for the transmissions of primary user’s transmitter and secondary user. We assume that the secondary user always receive the correct data from the transmitter of primary user. At the end of transmission burst, the receiver of primary user decodes the received signals in which the post-processing instantaneous SNR achieved after space time coding is obtained from

$$\gamma_{post} = 2\gamma_{sd} + \gamma_{rd}$$ (1)

where $\gamma_{sd}$ and $\gamma_{rd}$ are the instantaneous SNR from the transmitter of primary user and from the secondary user to the receiver, respectively. With Rayleigh fading channels, the cumulative distribution function (CDF) of post-processing SNR can be obtained from

$$F(\gamma) = 1 - \frac{\tau_{rd} \exp(-\gamma/\tau_{rd}) - 2\tau_{sd} \exp(-\gamma/2\tau_{sd})}{\tau_{rd} - \tau_{sd}}$$ (2)

where $\tau_{sd}$ and $\tau_{rd}$ are corresponding average SNR. Given the available AMC modes and their minimum required SNR thresholds $\Gamma_r$, the probability of using transmission rate $r$ can be obtained from $P_r(\tau_{sd}, \tau_{rd}) = F(\Gamma_{r+1}) - F(\Gamma_r)$ where $\Gamma_0 = 0, \Gamma_{R+1} = \infty$, and $R$ is the total number of AMC modes.

Note that the system model of aforementioned CMMR network is applicable to multiple primary users. In this case, secondary user can relay the transmission from multiple primary users on different subchannels simultaneously. For credit-based spectrum sharing, the secondary user can also access multiple subchannels simultaneously.

IV. OPTIMIZATION OF CREDIT-BASED SPECTRUM SHARING

In this section, an optimization model based on Markov decision process (MDP) is presented to obtain optimal policy for the action of primary user with credit-based spectrum sharing.
A. State and Action Spaces

The state space of primary user is defined as follows \( \Omega = \{ (x, c) ; x \in \{0, 1, \ldots, X_{\text{pri}} \}, c \in \{0, 1, \ldots, C \} \} \) where \( x \) and \( c \) represent the number of packets in data queue and the number of credits in credit queue, respectively. \( X_{\text{pri}} \) and \( C \) are the maximum capacities of these queues.

The action of primary user is denoted as \( a \in \mathcal{A} \) where \( \mathcal{A} = \{0, 1, 3\} \) is the action space. Action \( a = 1 \) corresponds to the direct transmission by primary user. Action \( a = 2 \) is taken when the primary user requests relay transmission from secondary user, and action \( a = 3 \) is taken when primary user grants channel access to secondary user. The transmission is slotted. The state of data queue and credit queue is observed at the end of time slot, and the action is taken by primary user at the beginning of time slot (i.e., decision epoch).

B. Transition Probability Matrix

The transition probability matrix of MDP can be derived based on the action taken by primary user. First, the transition probability matrix of credit queue is considered. This matrix is denoted as \( C(a) \) whose element at row \( c \) and \( c' \) represents the probability that the number of credits is \( c \) in the current time slot and becomes \( c' \) in the next time slot. This matrix can be obtained as follows \( C(1) = I_{C+1} \) and

\[
C(2) = \begin{bmatrix}
0 & 1 \\
& \ddots \\
& & 1 \\
& & & 0
\end{bmatrix}, 
C(3) = \begin{bmatrix}
1 & 1 \\
& \ddots \\
& & 0
\end{bmatrix}
\]

where \( I_{C+1} \) is an identity matrix with size of \( C + 1 \times C + 1 \). The number of credits remains the same if the primary user decide to use direct transmission. The number of credits increases if the primary user requests for relay transmission from secondary user and the credit queue is not full. In contrast, the number of credits decreases if the primary user grants the channel access to secondary user and the credit queue is not empty.

Matrix \( D^{(d)}(a) \) represents the probability of \( d \) transmitted packets from data queue of primary user given action \( a \). The diagonal element of this matrix \( D^{(d)}(a) \) is denoted as \( D_{c,c}^{(d)}(a) \) and can be obtained as follows.

- \( D_{c,c}^{(d)}(a) = \sum_{(x,c') : x+v=d} \hat{P}_r \hat{P}_r \), if \( (a = 1) \) or \( ((a = 2) \text{ and } (c = C)) \) or \( ((a = 3) \text{ and } (c = 0)) \) for \( d = \{0, 1, \ldots, 2R\} \) where \( \hat{P}_r \) is the probability of using rate \( r \) with direct transmission of primary user.
- \( D_{c,c}^{(d)}(a) = P_d(\tau_{\text{del}}, \tau_{\text{rd}}) \), if \( ((a = 2) \text{ and } (c < C)) \).
- \( D_{c,c}^{(d)}(a) = \hat{P}_d \), if \( ((a = 3) \text{ and } (c > 0)) \).

We assume batch packet arrival in which the probability that \( v \) packets arrive in one time slot is denoted as \( \lambda_v \). The maximum size of batch is \( V \) packets. The transition probability matrix for state space \( \Omega \) of primary user is denoted as \( P(a) \) whose element is denoted as \( P_{x,x'}(a) \). This element represents the probability that the number of packets in data queue is \( x \) in the current time slot and becomes \( x' \) in the next time slot. This element can be obtained from

\[
P_{x,x'}(a) = \sum_{\{(v,d) : x+v-d=x'\}} \lambda_v D^{(d)}(a) C(a)
\]

C. Objective and Optimal Policy

Objective of primary user is to minimize the number of packets in data queue subject to packet delay and loss constraints. In this case, the packet delay and loss due to lack of buffer space must be maintained below thresholds \( D_{\text{max}} \) and \( L_{\text{max}} \), respectively. The long-term objective and constraints of primary user can be defined as follows:

Minimize:

\[
\mathcal{J}_X(\pi) = \lim_{i \to \infty} \sup_{t \to \infty} \frac{1}{t} \sum_{t'=1}^{t} E(\mathcal{X}(S_t', \mathcal{A}_t'))
\]

Subject to:

\[
\mathcal{J}_D(\pi) = \lim_{i \to \infty} \sup_{t \to \infty} \frac{1}{t} \sum_{t'=1}^{t} E(\mathcal{D}(S_t', \mathcal{A}_t')) \leq D_{\text{max}}
\]

\[
\mathcal{J}_L(\pi) = \lim_{i \to \infty} \sup_{t \to \infty} \frac{1}{t} \sum_{t'=1}^{t} E(\mathcal{L}(S_t', \mathcal{A}_t')) \leq L_{\text{max}}
\]

where \( \mathcal{J}_X(\pi) \) is the average number of packets in data queue, \( \mathcal{J}_D(\pi) \) is average packet delay, and \( \mathcal{J}_L(\pi) \) is packet loss probability. These objective and constraints are defined as the functions of policy \( \pi \) which is the mapping of state \( s \in \Omega \) to the action \( a \in \mathcal{A} \). \( E(\cdot) \) is expectation. \( \mathcal{X}(\cdot, \cdot) \), \( \mathcal{D}(\cdot, \cdot) \), and \( \mathcal{L}(\cdot, \cdot) \) are immediate number of packets in data queue, immediate packet delay, and immediate loss probability, respectively. These immediate performance measures are the functions of state \( S_t' \in \Omega \) and action \( \mathcal{A}_t' \in \mathcal{A} \) at time \( t' \).

The immediate number of packets in data queue is defined as follows \( \mathcal{X}(s, a) = x \) for composite state \( s = (x, c) \) where \( x \) is the number of packets in data queue and \( c \) is the number of credits in credit queue. The immediate packet delay is defined as follows \( \mathcal{D}(s, a) = \frac{x}{\lambda} \) where \( \lambda = \sum_{v=1}^{V} \lambda_v \) is the average packet arrival rate of primary user. The immediate loss probability is defined as follows:

\[
\mathcal{L}(s, a) = \frac{\sum_{v=x-x'+1}^{V} v \lambda_v}{\sum_{v=1}^{V} v \lambda_v}
\]

for \( x + V > X_{\text{pri}} \).

To obtain the optimal policy \( \pi^* \), the MDP formulation can be transformed into an equivalent linear programming (LP) problem [10]. We consider randomized policy in which the optimal probability of taking action \( a \) given state \( s \) is denoted as \( \psi_\pi^*(s, a) \). This probability can be obtained by solving equivalent LP problem whose optimal solution is denoted as \( \phi^*(s, a) \). The equivalent LP problem corresponding to the
MDP formulation can be expressed as as follows:

Minimize:  \[ \sum_{s \in \Omega} \sum_{a \in A} \phi(s, a) \mathcal{X}(s, a) \]  

Subject to:  \[ \sum_{s \in \Omega} \sum_{a \in A} \phi(s, a) \mathcal{D}(s, a) \leq D_{\text{max}} \]  
\[ \sum_{s \in \Omega} \sum_{a \in A} \phi(s, a) \mathcal{L}(s, a) \leq L_{\text{max}} \]  
\[ \sum_{a \in A} \phi(s', a) = \sum_{s \in \Omega} \sum_{a \in A} P(s'|s, a) \phi(s, a) \]  
\[ \sum_{a \in A} \phi(s, a) = 1, \quad \phi(s, a) \geq 0 \]  

for \( s' \in \Omega \), where \( P(s'|s, a) \) is an element of matrix \( P(a) \) representing the probability that the state of primary user changes from \( s \) to \( s' \) when action \( a \) is taken. The optimal randomized policy of MDP can be obtained from

\[ \psi_{\pi^*}(s, a) = \frac{\phi^*(s, a)}{\sum_{a' \in A} \phi^*(s, a')} \]  

where \( \phi^*(s, u) \) is optimal solution of equivalent LP problem.

**D. Performance Measures**

The performance measures of the primary user can be obtained analytically from the optimal policy and transition probability matrix. First, the stationary probability \( p_{\pi^*}(s) \) for the primary user to be at state \( s \in \Omega \) is obtained by solving the following set of equations \( P_{\pi^*}^T \pi_{\pi^*} = \tilde{P}_{\pi^*}^T \pi_{\pi^*} \) and \( \tilde{P}_{\pi^*}^T \tilde{\mathbf{I}} = 1 \), where \( \tilde{P}_{\pi^*} = [ \cdots \ n_{\pi^*}(s) \cdots ] \), and \( \tilde{\mathbf{I}} \) is a vector of ones. \( \pi_{\pi^*} \) is the transition probability matrix when the optimal policy \( \pi^* \) is applied.

The packet loss probability can be obtained from

\[ L = \sum_{s \in \Omega} \sum_{a \in A} \mathcal{L}(s, a)p_{\pi^*}(s)\psi_{\pi^*}(s, a). \]  

Average packet delay can be obtained from

\[ D = \frac{\sum_{s \in \Omega} x_{\pi^*}(s) \lambda}{(1 - L)}. \]  

The probability of primary user to request for relay transmission from secondary user is obtained from

\[ P_{\text{rel}} = \sum_{s \in \Omega} \sum_{a \in A} p_{\pi^*}(s)\psi_{\pi^*}(s, 2) \]  

and the probability of primary user to grant channel access to secondary user is obtained from

\[ P_{\text{gra}} = \sum_{s \in \Omega} \sum_{a \in A} p_{\pi^*}(s)\psi_{\pi^*}(s, 3) \]  

where in general \( P_{\text{rel}} = D_{\text{gra}} \).

**V. Secondary User Adaptation**

Given the optimal policy of the primary user, the performance of secondary user can be analyzed and optimized. In this section, the queueing model is formulated to obtain the performance measures of secondary user. Then, the optimization model of secondary user to adjust the relay transmit power is presented.

**A. Queueing Model of Secondary User**

The state space of secondary user can be extended from the state space of primary user \( \Omega \) as follows \( \Psi = \{ (X, C, B) : X \in \{0, 1, \ldots, X_{\text{pri}} \}, C \in \{0, 1, \ldots, C \}, B \in \{0, 1, \ldots, B_{\text{sec}} \} \} \) where \( B \) is the number of packets in data queue of secondary user, and \( B_{\text{sec}} \) is the maximum capacity of the data queue.

For secondary user, the packet departing from the queue depends not only the transmission but also the action of primary user (i.e., \( a = 3 \) when the channel is granted for secondary user to access). Let \( E^{(d)} \) denote the probability matrix for \( d \) departing packets of secondary user. This matrix has the same size as that of \( P(a) \) of the primary user. Let \( P_r \) denote the probability of using transmission rate \( r \) for secondary user. The diagonal element \( E_{k,k}^{(d)} \) at row and column \( k \in \{1, \ldots, (X_{\text{pri}}+1)(C+1)\} \) of matrix \( E^{(d)} \) can be obtained from

\[ E^{(d)}_{x(C+1)+c+1,x(C+1)+c+1} = P_d\psi_{\pi^*}(s, a = 3) \]  

for \( d = \{1, \ldots, R_{\text{sec}}\} \) and \( s = (x, c) \), where \( R_{\text{sec}} \) is the maximum transmission rate used by secondary user. For \( d = 0 \), we obtain \( E_{k,k}^{(0)} = 1 - \sum_{d=1}^{R_{\text{sec}}} E_{k,k}^{(d)} \).

Again, batch packet arrival is assumed for secondary user. The probability that \( v \) packets arrive in one time slot is denoted as \( \alpha_v \). The transition probability matrix for the state space \( \Psi \) of the secondary user is denoted as \( Q \). The element \( Q_{b,b'} \) of this matrix represents the probability of the packets in the queue of secondary user changes from \( b \) in the current time slot to \( b' \) in the next time slot. This element can be obtained from

\[ Q_{b,b'} = \sum_{\{(v,d) : b + v - d = b'\}} \alpha_v E^{(d)} \pi_{\pi^*} \]  

for \( b' \leq B_{\text{sec}} \). For \( b' > B_{\text{sec}} \), \( b' \) will be truncated at \( B_{\text{sec}} \).

The stationary probability of secondary user is denoted as \( q(x, c, b) \) for \( x \) packets in data queue of primary user is \( x, c \) credits in queue, and \( b \) packets in data queue of secondary user. Again, this stationary probability can be obtained by solving the \( \tilde{q}^T Q = \tilde{q}^T \) and \( \tilde{q}^T \tilde{\mathbf{I}} = 1 \), where \( \tilde{q} = [ \cdots \ q(x, c, b) \cdots ]^T \). Given the stationary probability, the performance measures for secondary user (i.e., packet loss probability \( T_{\text{sec}} \) and average packet delay \( D_{\text{sec}} \)) can be obtained similarly to those of primary user (i.e., (11) and (12)).

Note that the approximated queueing model for the secondary user with multiple primary users can be formulated with assumption that the states of all primary users and secondary user are independent. For brevity of the paper, the detail of this queueing model is omitted.

**B. Optimal Relay Transmit Power**

Given optimal policy of spectrum sharing from primary user, secondary user can adjust the relay transmit power to achieve minimum cost. The cost is due to the QoS degradation (i.e., average packet delay) and relay transmit power. An optimization model for secondary user can be formulated as
and secondary users follow Poisson process with average rates. Also, given this optimal power, primary user will take action optimally (i.e., through optimal policy \( \pi^* \)) to request relay transmission and to grant channel access to secondary user. Therefore, the optimal relay transmit power \( p_{\text{rel}}^* \) and optimal policy \( \pi^* \) can be considered as the Stackelberg equilibrium. In this case, the secondary user is the leader which chooses relay transmit power \( p_{\text{rel}}^* \) before the primary user takes action according to optimal policy \( \pi^*(p_{\text{rel}}^*) \).

\[ \begin{align*}
\text{Minimize:} & \quad C_{\text{sec}}(p_{\text{rel}}) = \omega_1 D_{\text{sec}}(p_{\text{rel}}) + \omega_2 p_{\text{rel}}^* \\
\text{Subject to:} & \quad D_{\text{sec}}(p_{\text{rel}}) \leq D_{\text{sec, max}} \quad \text{(18)} \\
& \quad L_{\text{sec}}(p_{\text{rel}}) \leq L_{\text{sec, max}} \quad \text{(19)}
\end{align*} \]

where \( \omega_1 \) and \( \omega_2 \) are the cost weights due to average packet delay \( D_{\text{sec}}(p_{\text{rel}}) \) and relay transmit power \( p_{\text{rel}} \) of secondary user, respectively. \( D_{\text{sec, max}} \) and \( L_{\text{sec, max}} \) are the average packet delay and loss thresholds of secondary user, respectively. Note that the average SNR (to be used in (2)) of relay transmission by primary user can be obtained from \( \gamma_{\text{rd}} = g_{\text{rd}} \) where \( g_{\text{rd}} \) is the channel gain between secondary user to the receiver of primary user.

The solution of this optimization (i.e., optimal relay transmit power \( p_{\text{rel}}^* \)) ensures that the cost of secondary user is minimized. Also, given this optimal power, primary user will take action optimally (i.e., through optimal policy \( \pi^* \)) to request relay transmission and to grant channel access to secondary user.

VI. PERFORMANCE EVALUATIONS

A. Parameter Setting

We consider primary and secondary users as shown in Fig. 1. The data queue sizes of primary and secondary users are \( X_{\text{pri}} = B_{\text{sec}} = 15 \) packets. The credit queue size of primary user is \( C = 8 \). The channel quality between the primary user’s transmitter and receiver is \( \gamma_{\text{rd}} = 3 \) dB. Four AMC modes with SNR thresholds \( \Gamma_1 = 6.4 \) dB, \( \Gamma_2 = 9.4 \) dB, \( \Gamma_3 = 11.2 \) dB, and \( \Gamma_4 = 16.4 \) dB are used. Average delay threshold of primary user is \( D_{\text{max}} = 30 \) time slot, and packet loss threshold is \( L_{\text{max}} = 0.1 \). Packet arrivals of both primary and secondary users follow Poisson process with average rates \( \lambda_{\text{pri}} = 0.8 \) and \( \lambda_{\text{sec}} = 0.1 \) packets/time slots, respectively. For the cost function of secondary user, the parameters are as follows \( \omega_1 = 1 \) and \( \omega_2 = 0.5 \).

B. Numerical Results

Fig. 2 shows the action of primary user to request relay transmission from secondary user given the number of packets in data queue and the number of credits in credit queue. We observe that primary user will request relay transmission when the number of packets is large, and the number of credits is small. With the relay transmission, the queueing performance of primary can be improved. In this case, the primary user grants the channel access to secondary user when the number of packets in queue is small or when the number of credits in queue is large. Note that observing from the stationary probability, the probability that the data queue of primary user will be full is small, and hence the proposed credit-based spectrum sharing can achieve better performance.

Fig. 3 shows the average packet delay of primary user given different relay transmit power from secondary user. The delay performance is compared among the transmissions of primary user with credit-based spectrum sharing (i.e., optimal policy from MDP), no spectrum share, and with full spectrum share with secondary user (i.e., similar to that in [1]). In no-share scheme, primary user relies on the direct transmission. On the other hand, in full-share scheme, primary user constantly requests relay transmission and grants the channel access to the secondary user immediately in the next time slot. As expected, the average packet delay from credit-based spectrum sharing is the lowest and decreases as the relay transmit power increases.

At low relay transmit power chosen by secondary user, it is not worth for primary user to use relay transmission. As a result, average packet delay from credit-based scheme is close to that from no-share scheme. As the relay transmit power increases, the delay transmission rate increases. Primary user prefers using relay transmission, and hence the average packet delay from credit-based scheme approaches that of full-share scheme.

Fig. 4 shows the average packet delay of secondary user under different relay transmit power for one primary user. Again, as the relay transmit power increases, primary user increases the channel access for secondary user. As a result, the average packet delay decreases. In this case, if the secondary user has the constraint to maintain average packet delay
The minimum relay transmit power can be determined (e.g., model based on Markov decision process has been formulated allocated to mobile user as in IEEE 802.16j). An optimization the spectrum licensed to the primary user (e.g., subchannel can request for relay transmission from the relay station. In multihop relay network. In this network, the primary user increases, the secondary user can achieve lower optimal relay transmit power per primary user. This is due to that fact the secondary user has more chance to transmit the data relay transmit power of both primary and secondary users, the solution in terms of Stackelberg equilibrium can be reached in which the secondary and primary users are respectively the leader and follower of the spectrum sharing game in cognitive mobile multihop relay network.

For the future work, the relay transmit power optimization with multiple primary users will be developed for secondary user. The mobility of primary users will be considered in the optimization model.

VII. SUMMARY

The credit-based spectrum sharing scheme for the primary and secondary users has been proposed for cognitive mobile multihop relay network. In this network, the primary user can request for relay transmission from the relay station. In return, this relay station as the secondary user can access the spectrum licensed to the primary user (e.g., subchannel allocated to mobile user as in IEEE 802.16j). An optimization model based on Markov decision process has been formulated to obtain the optimal policy of primary user to use direct transmission, relay transmission, and to grant channel access to the secondary user. For secondary user, a queueing model has been formulated to analyze the QoS performance given the optimal policy from primary user. The secondary user can optimize the cost due to QoS performance and relay transmit power for primary user. With an optimization model of both primary and secondary users, the solution in terms of Stackelberg equilibrium can be reached in which the secondary and primary users are respectively the leader and follower of the spectrum sharing game in cognitive mobile multihop relay network.

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