Providing Statistical Quality-of-Service Guarantees in Cognitive Radio Networks with Cooperation

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Abstract—Cognitive radios (CRs) opportunistically sharing the wireless spectrum with the legacy primary system (PS) are promising to improve the spectrum utilization. However, this cognitive spectrum hole access makes the bandwidth of the cognitive radio network (CRN) formed by multiple CRs varies severely, which makes providing quality-of-service (QoS) guarantee over the CRN a very challenging task. Considering cooperative diversity with the merit of alleviating bandwidth variation, this paper proposes a cooperative scheduling algorithm for the CR in the CRN to select a relay path with the lowest packet dropping probability for packet transmissions. Under this scheme, the upper bounds of the mean packet dropping probability have been analytically derived and the corresponding admission control mechanism is further proposed. Analytical results show that the proposed scheme provides a better QoS guarantee than direct transmissions without cooperative relay for the CRN. Simulation results also confirm that traffic sources admitted into the system can absolutely meet their mean packet dropping probability requirements.

Index Terms—cognitive radio network, cooperative diversity, statistical QoS guarantee.

I. INTRODUCTION

Due to the intense demands of wireless spectrum for the increasing wireless high speed networks and the underutilization of licensed wireless spectrum [1], the cognitive radio (CR) opportunistically utilizing spectrum holes of the legacy primary system (PS) [2] has become a promising technology to improve the spectrum utilization. To further enable real-time multimedia applications over the cognitive radio network (CRN) formed by multiple cognitive radio CRs, providing QoS has become a critical issue and starts receiving considerable attentions. In [3], Hamdi et al proposed a proportional fair based scheduler and a modified largest weighted delay first based scheduler for the CRN. In [4], a cross-layer based medium access control protocol for the CRN is proposed to improve the delay provisioning. Attar et al proposed an optimum resource allocation strategy to support the minimum rate of the CRN in [5]. However, since the spectrum hole access of CRs makes bandwidth of the CRN varies opportunistically and significantly, to support the CRN on providing QoS guarantee faces fundamental intellectual challenges. Furthermore, due to the multipath fading, noise disturbance, and the co-channel interference from the PS, it is impracticable to provide deterministic QoS guarantees for the CRN even in the ordinary wireless networks [6]. Here, the deterministic QoS guarantee represents a zero probability of violating the QoS requirement. Therefore, to provide statistical QoS guarantee (i.e., the probability of violating the QoS requirement is bounded by a certain value) shall be a practical and ultimate goal for the CRN. For this purpose, one critical task is to decrease the bandwidth variation of the CRN.

To resolve this dilemma, cooperative diversity emerged as an alternative to combat fading in wireless channels [7], [8] and can be a promising technique to alleviate highly bandwidth variation of the CRN. Multiple CRs cooperating with each other to form the cooperative diversity, operating as a virtual antenna array, provide several relay paths (or links) for a CR to select the most competent one to transmit packets. A competent path can be a path (or links) with a low bit error rate (BER) [9], a low outage probability [10], or an acceptable interference to the PS [11]. Since packets those miss their QoS requirements are dropped, the packet dropping probability is used to represent the probability that packets violating their QoS requirements. This paper proposes a scheduling algorithm employing cooperative relay and the corresponding admission control mechanism to enable (statistical) QoS guarantee over the CRN. Consequently, all traffic sources can absolutely meet their mean packet dropping probability requirements.

This paper is organized as following: Section II describes the system model. The proposed cooperative scheduling algorithm, analytical upper bounds of the mean packet dropping probabilities, and the admission control mechanism are in Section III. Section IV evaluates the analytical results of the proposed scheme and the direct transmissions without cooperative relay and finally concluding the paper with Section V.

II. SYSTEM MODEL

A. Network Model

A simplified network topology is showed in Fig. 1. The proposed system, composed of node A, node B, and node D, shares the same wireless spectrum (channel) with the legacy PS. There may be other secondary systems (SS’s) without the proposed mechanism also operating on the same channel. Node A has traffics to transmit to node D. Packets can be transmitted via the direct path composed of link $l_{A,D}$, or via the relay path composed of links $l_{A,B}$ and $l_{B,D}$. On each of $l_{A,D}$, $l_{A,B}$, or $l_{B,D}$, the proposed system will suspend
Packets are generated periodically every \( 1 \) is the maximum acceptable mean packet dropping probability. \( \epsilon \) is the maximum tolerable jitter (packet delay variation), and \( \delta \) is the maximum acceptable mean packet dropping probability. A VBR source regulated by a \((\sigma, \rho)\)-leaky bucket are stored in the RTT buffer. If the packet delivery violates its maximum tolerable delay, the packet is dropped. VBR sources with a smaller \( d \) have higher priority.

This paper focuses on the scheduling such that all admitted CBR and VBR sources meet their maximum acceptable mean packet dropping probability \( \epsilon \) and \( \xi \), respectively. It is assumed that all data packets in the system have the same size \( N \).

**D. Channel Model**

Under the assumption that the wireless channel is slow flat-fading, the fading statistics on each link is independent and identical distributed (i.i.d.) with Nakagami-\( m \) distribution. The channel varies frame by frame. Node A and node B adopt a fixed transmission power, thus adaptive modulation and coding (AMC) in the proposed system selects an appropriate transmission mode (i.e., the modulation and code pairs) to maximize the data rate while maintaining a prescribed PER, \( \eta_0 \). Adopting the signal to noise ratio (SNR) boundary points searching algorithm in [12], the channel can be modeled as a finite state Markov chain (FSCM). Each state of the FSMC corresponds to a transmission mode of AMC. By using the properties and methods in [12]–[14] to construct the state transition probability, the stationary distribution of the FSMC, denoted by \( \Pi \), can be obtained as

\[
\Pi = [\pi_0, \pi_1, \ldots, \pi_N]
\]

on each link, where \( N + 1 \) is the total number of transmission modes. The transmission mode 0 represents that there are no appropriate modulation and code pairs to maintain the PER. Thus the transmission is suspended.

**E. Medium Availability of the System**

The medium occupancy of the PS and other SSs can be modeled as a continuous-time Markov chain (CTMC) with available (the link is idle) and unavailable (the link is busy) states [15]. It is assumed that the transmissions of the PS and other SSs are not slotted. The channel holding times of the PS and other SSs are independent and exponentially distributed with aggregated parameter \( q_{x,y}^{-1} \) for the available state and \( u_{x,y}^{-1} \) for the unavailable state on link \( l_{x,y} \). Under this (CTMC) model, the stationary distribution of the available and unavailable states are given by [15] as

\[
\varphi^0_{x,y} = \frac{u_{x,y}}{q_{x,y} + u_{x,y}} \tag{2}
\]

\[
\varphi^1_{x,y} = \frac{q_{x,y}}{q_{x,y} + u_{x,y}} \tag{3}
\]
In contrast to the PS and other SSs, the proposed system employs the slotted scheme. Therefore, on each slot, the probabilities for availability and unavailability is \( \varphi^1_{x,y} \) and \( \varphi^0_{x,y} \), respectively.

### III. Cooperative Scheduling Scheme

In this section, we propose a cooperative scheduling algorithm in Section III-A and the upper bounds of the mean packet dropping probabilities are provided for CBR and VBR sources in Section III-B. The admission control mechanism is proposed in Section III-C.

#### A. Scheduling Algorithm

**Algorithm 1 (Cooperative Scheduling):**

1. At the beginning of each frame, Node D informs the transmission modes selected on \( l_{A,D} \) and \( l_{B,D} \) to node A and node B, respectively. Node B informs the transmission mode on \( l_{A,B} \) to node A.
2. At the end of a transmission, node A scans its RTT buffers for CBR sources according to a present priority.
   a. If a packet is found in the RTT buffer, node A transmits at most one packet from this RTT buffer through \( l_{A,D} \) if this path is with a lower packet dropping probability.
   b. Otherwise, the packet is transmitted through \( l_{A,B} \) to node B and node B relays this packet to node D.
3. If the link becomes busy before the packet is completely transmitted, the packet transmission is suspended.
4. When the link becomes idle, the packet is continuously transmitted. If the packet transmission misses its jitter requirement, the packet is dropped.
5. If the packet is completely received by node D, node D broadcasts a transmission complete (TC) message. Otherwise, node A broadcasts a packet dropped (PD) message to announce the end of a transmission.
6. If there are no packets found in the RTT buffers of CBR sources, node A scans its RTT buffers for VBR sources according to a present priority.
   a. When a packet is found, node A transmits a packet from its RTT buffer through \( l_{A,D} \) if this path is with a lower packet dropping probability.
   b. Otherwise, the packet is transmitted through \( l_{A,B} \) to node B and node B relays this packet to node D.
7. The remaining procedures are similar to Step 2(c)-(d).
8. If the packet is completely received by node D, node D broadcasts a TC message. Otherwise, node B broadcasts a PD message.

Let the transmission times of a TC, a PD, and an EOF message be one time slot. It is assumed that the interference to the PS caused by broadcasting one of these messages for one time slot is acceptable to the PS. To identify a path with a lower packet dropping probability in Step 2(a) and Step 4(a), the packet dropping probabilities on the direct transmission path and the relay path are provided in the following lemmas.

**Lemma 1** *(The packet dropping probability of the link \( l_{x,y} \)):* Let \( \Psi \) be the remaining time slots before the maximum tolerable delay or jitter is expired, the packet dropping probability when a packet is transmitted via \( l_{x,y} \) is given by

\[
\mu_{x,y}(\Psi, n) = \sum_{r = \Psi - S^0_{x,y} + 1}^{\Psi} \left( \frac{\Psi^1_{x,y}}{\Psi^0_{x,y}} \right)^r \psi_{x,y}^{-r} 
\]

where \( x \in \{A,B\}, y \in \{B,D\}, x \neq y \), \( S^0_{x,y} = \lceil N_p / (R_n N_a) \rceil \) is the number of time slots required for one packet transmission when the transmission mode \( n \) is chosen, \( N_a \) is the number of symbols per time slot, and \( R_n \) is the number of bits carried in a symbol.

**Proof:** The probability that there are \( r \) unavailable time slots in \( \Psi \) is

\[
\left( \frac{\Psi^1_{x,y}}{\Psi^0_{x,y}} \right)^r \psi_{x,y}^{-r}.
\]

Since it requires \( S^0_{x,y} \) slots for one packet transmission, the packet violates its QoS requirement if the number of unavailable slots exceeds \( \Psi - S^0_{x,y} \). By taking the summation of probabilities that there are \( \Psi - S^0_{x,y} + 1 \) to \( \Psi \) unavailable time slots, we can obtain (4).

**Lemma 2** *(The packet dropping probability of the relay path):* The packet dropping probability when a packet is transmitted via the relay path, \( l_{A,B} \) and \( l_{B,D} \), is given by (6), where \( n' \) and \( n'' \) are transmission modes selected on \( l_{A,B} \) and \( l_{B,D} \), respectively.

**Proof:** See Appendix A.

Considering the packet dropping probabilities in **Lemma 1** and **Lemma 2**, the path selection strategies for Step 2(a) and Step 4(a) are consequently proposed as follows.

**Proposition 1** *(For Step 2(a)):* For a packet of a CBR source, the packet is transmitted through \( l_{A,D} \) if

\[
\mu_{A,D}\left(1 + \frac{1}{\lambda} + t_{tc} - 1 - \delta - t, n \right) \leq \mu_{relay}\left(1 + \frac{1}{\lambda} + t_{tc} - 1 - \delta - t, n', n'' \right)
\]

where \( t \) represents the current time slot and \( t_{tc} \) is the transmission complete time of the previous packet of the CBR source.

**Proof:** Since the packet is transmitted via a path with a lower packet dropping probability, the path selection strategy stated above is intuitive. This proof focuses on showing \( \Psi = 1/\lambda + t_{tc} - 1 - \delta - t \) in **Lemma 1** and **Lemma 2**. Let \( t' \) be the transmission complete time of the packet. Since the jitter of the packet is \( 1/\lambda - (t' - t_{tc}) \leq \delta \), the packet meets its jitter requirement if \( 1/\lambda - (t' - t_{tc}) - 1 \leq \delta \), where subtracting one time slot is for the TC or PD message transmission. We focus on the case when the equality is valid. Rearrange above expression, \( t' = 1/\lambda + t_{tc} - 1 - \delta \) is obtained. Subtracting \( t \) on the both side of the equal sign, \( \Psi = t' - t = 1/\lambda + t_{tc} - 1 - \delta - t \) is obtained.
according to the priority without preemption, the jitter of the following lemmas.

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\( \Psi = \) the number of the CBR sources.
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in (12). By employing Markov inequality, we obtain
\[ Pr[\tau_d,i^\lambda_i,\sigma_i,1] \geq 1/\lambda_i - \sigma_i^* - 1 \]
\[ \leq \frac{E[\tau_d,i^\lambda_i,\sigma_i,1]}{1/\lambda_i - \sigma_i^* - 1} = \frac{\tau_d,i^\lambda_i,\sigma_i,1}{1/\lambda_i - \sigma_i^* - 1} \]
(15)

Further considering the stationary probability that the transmission mode 0 is selected such that the transmissions shall be suspended, the upper bound in Theorem 1 is obtained. ■

**Theorem 2:** The mean packet dropping probability of the jth VBR source is bounded above by \( \pi_0 + \tau_{d,j}^{\lambda_j,\sigma_j,1}/(d_h - \sigma_j^* - 1) \), where

\[ \hat{d}_j = \frac{\sum_{h=0}^{i} \delta_k + j - 1 + \sum_{k=0}^{i} (1 + \tau_{d,h}^{-\sigma_j,1}) \rho_h \sigma_j^*}{1 - \sum_{h=0}^{i} \rho_h} \]
(16)

\[ \hat{d}_0 = \sum_{i=1}^{c} (1 + \tau_{d,i}^{-\sigma_i,1}), \hat{\rho}_0 = \rho_0 \lambda_i, \hat{\sigma}_j = (1 + \tau_{d,j}^{-\sigma_j,1}) (\sigma_j + 1), \hat{\rho}_j = (1 + \tau_{d,j}^{-\sigma_j,1}) \rho_j, \] and \( \sum_{k=0}^{c} \hat{\rho}_k \leq 1 \) for \( j = 1, \ldots, n_v \).

**Proof:** The upper bound can be obtained similarly as in the proof of Theorem 1. ■

Since (12) and (16) are defined recursively, they are not easy to be obtained by the direct derivations. To compute the mean packet dropping probability bounds, the numerical approaches are proposed in the following algorithms.

**Algorithm 2** (The determination of \( \tau_{d,i}^{\lambda_i,\sigma_i,1}/(1/\lambda_i - \sigma_i^* - 1) \):

1) Set \( \sigma_i^* = 0 \).
2) Omit the first summation term in (12) and calculate \( \tau_{d,1}^{\lambda_1,\sigma_1,1} \) by (8), (9), and (7). Then, \( \tau_{d,1}^{\lambda_1,\sigma_1,1}/(1/\lambda_1 - 1) \) can be obtained.
3) Omit the first summation term in (12) and calculate \( \tau_{d,1}^{\lambda_1,\sigma_1,1} \) and \( \sigma_i^* \) by (7) and (12) for \( i = 2, \ldots, n_c \), respectively. Then, \( \tau_{d,i}^{\lambda_i,\sigma_i,1}/(1/\lambda_i - \sigma_i^* - 1) \) for \( i = 2, \ldots, n_c \) can be obtained.
4) Substituting \( \tau_{d,i}^{\lambda_i,\sigma_i,1}/(1/\lambda_i - \sigma_i^* - 1) \) into (12) to calculate new \( \sigma_i^* \) and \( \tau_{d,i}^{\lambda_i,\sigma_i,1}/(1/\lambda_i - \sigma_i^* - 1) \) for \( i = 1, \ldots, n_c \).
5) Repeat Step 4 until the stationary outputs can be obtained.

**Algorithm 3** (The determination of \( \tau_{d,j}^{\lambda_j,\sigma_j,1}/(d_h - \sigma_j^* - 1) \):

1) Substituting \( \tau_{d,i}^{\lambda_i,\sigma_i,1} \) for \( i = 1, \ldots, n_c \) into \( \tau_{d,j}^{\lambda_j,\sigma_j,1} \) of (16) to calculate \( \delta_j^* \) for \( j = 1, \ldots, n_v \).
2) Substituting \( \delta_j^* \) into (7) to calculate new \( \tau_{d,j}^{\lambda_j,\sigma_j,1} \).
3) Repeat Step 2 until stationary outputs can be obtained.

**C. Admission Control Mechanism**

Under the proposed cooperative scheduling scheme and the upper bounds of the mean packet dropping probabilities in the previous subsection, the admission control mechanisms for the CRN is proposed as follows.

**Proposition 3** (Admission Control for a VBR source): For a new VBR source, we calculate the upper bound of the mean packet dropping probability by the procedure described above. If \( \xi_j \leq \pi_0 + \tau_{d,j}^{-\sigma_j,1}/(d_h - \sigma_j^* - 1) \) for \( j = 1, \ldots, n_v \), the new VBR source is admitted.

**Proposition 4** (Admission Control for a CBR source): For a new CBR source, if both \( \varepsilon_i \leq \pi_0 + \tau_{d,i}^{-\sigma_i,1}/(1/\lambda_i - \sigma_i^* - 1) \) for \( i = 1, \ldots, n_c \) and \( \xi_j \leq \pi_0 + \tau_{d,j}^{-\sigma_j,1}/(d_h - \sigma_j^* - 1) \) for \( j = 1, \ldots, n_v \) are valid, the new CBR source is admitted.

**IV. Performance Evaluation**

In this section, the analytical results of the mean packet dropping probability upper bounds of the proposed scheme and the direct transmissions without cooperative relay are evaluated. The simulation is also performed to verify the proposed analytical bounds.

Let \( n_c = 4 \) and \( n_v = 2 \), the parameters on links \( l_{A,D}, l_{A,B}, l_{A,D} \), and \( l_{B,D} \) are i.i.d. and are listed in Table I. For the second column in Table I, the number of bits carried in a symbol on each transmission mode is adopted by [17]. In Fig. 3, the jitter and delay bounds in (12) and (16) are shown when the number of iterations increases. These bounds tend to stationary after 2 iterations. Thus the computational complexity is low. Furthermore, if \( 1/\lambda_i - \sigma_i^* - 1 \geq 0 \) at Step 2 in Algorithm 3 for CBR sources and \( d_h - \sigma_h^* - 1 \geq 0 \) at Step 1 in Algorithm 4 for VBR sources, the outputs converge to stationary values. The analytical upper bounds are shown in Table II. The upper bounds of the mean packet dropping probabilities for the direct transmissions without cooperative relay can be obtained by omitting the relay path portions of the provided upper bounds. It shows that the proposed cooperative scheduling scheme provides a lower mean packet dropping probability than direct transmissions. The simulation time is set to 20 seconds and the simulation is performed 100 times to obtain the average values. Simulation results also support the goal that the mean packet dropping probabilities are upper bounded.
packet dropping probability on the relay path can be obtained as
\(\mu_{\text{relay}}(\Psi, n', n'') = \mu_{A,B}(\Psi, n') + \mathbb{N}(1 - \mu_{A,B}(\Psi, n'))\).

**APPENDIX B**

**The Proof of Lemma 5**

To obtain the mean packet delivery time, following two cases shall be considered: 1) \(\mu_{A,D}(\Psi, n) \leq \mu_{\text{relay}}(\Psi, n', n'')\), and 2) \(\mu_{A,D}(\Psi, n) > \mu_{\text{relay}}(\Psi, n', n'')\). For the first case, it requires \(\Psi\) time slots if the packet is dropped. Otherwise, the packet delivery time is \(S^{d}_{A,D} + S^{m}_{B,D}\) and additional \(r\) unavailable time slots. For the second case, it requires \(\Psi\) time slots if the packet is dropped. Otherwise, the packet delivery time is \(S^{m}_{A,B} + S^{d}_{B,D}\) and additional \(r\) unavailable time slots. Finally, probabilities of the first and the second case depend on the transmission modes on \(l_{A,D}, l_{A,B}\), and \(l_{B,D}\). By taking expectation of the above expressions, we can obtain (7).

**REFERENCES**


