A Method for Ensuring QoS Requirement of VoIP in Cognitive Radio System

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Abstract

In this paper, we analyze a voice over IP (VoIP) capacity based on a two-dimensional discrete time Markov chain (DTMC) model and propose a new method to find a minimum detection and false alarm probabilities for the purpose of ensuring the quality of service (QoS) requirement of VoIP users in a cognitive radio system.

1. Introduction

Cognitive radio is a promising and challengeable technology for maximizing radio resource utilization in a future wireless communication system because conventional systems exploit most available frequency bands for wireless communications and these frequency bands are not always fully utilized in general. We here focus on the improvement and analysis of the VoIP capacity in the cognitive radio system under the constraints that the primary users are sufficiently protected and the quality of service (QoS) requirements of the secondary VoIP users are guaranteed. To the best of our knowledge, the capacity analysis and improvement for the VoIP service have not been studied yet in the cognitive radio system.

1.1. Channel Modeling in Cognitive Radio System

In the cognitive radio system, a wireless channel can be modeled as a two-state Markov process, as shown in Fig. 1 [1]. An occupied state means that the wireless channel is utilized by a primary user. Given that the channel status is ‘Occupied’, the cognitive user cannot use the channel. In this paper, we assume that there are ‘M’ wireless channels. Then, the transition probability \( P_{m,n} \) that there are \( m \) unoccupied channels \((x)\) in the current frame, and there will be \( n \) unoccupied channels in the next frame can be represented by

\[
P_{m,n} = \sum_{x' = \max(0, m-n)}^{\min(m, M-n)} \left( \frac{m}{x'} \right) p_{00}^{m-x'} p_{01}^{m-n-x'} \left( \frac{M-m}{y'} \right) p_{10}^{M-m-y'} p_{11}^{y'}.
\]

Here, \( y' = n - m + x' \), where \( x' \) and \( y' \) denote the numbers of channels whose status are altered from ‘Unoccupied’ to ‘Occupied’ and from ‘Occupied’ to ‘Unoccupied’, respectively.

1.2. Spectrum Sensing Modeling

In [2], Y.-D. Liang et al. presented the spectrum sensing model based on energy detection. Thus, we can represent the probability of channel detection \( p_d(\epsilon, \tau) \) and false alarm \( p_f(\epsilon, \tau) \) as follows.

\[
p_d(\epsilon, \tau) = \Pr(T(y) > \epsilon | H_1) = \int_{\epsilon}^{\infty} p_1(x)dx.
\]

\[
p_f(\epsilon, \tau) = \Pr(T(y) > \epsilon | H_0) = \int_{\epsilon}^{\infty} p_0(x)dx.
\]

In Eqn. (2) and (3), \( \epsilon \) is the detection threshold, \( \tau \) is the available sensing time, and \( H_0, H_1 \) denotes that the status of the primary user is inactive (active). Also, \( T(y) \) is the test statistic for the energy detector, and \( p_0(x) (p_1(x)) \) is the probability density function of the test statistic \( T(y) \) under hypotheses \( H_0 (H_1) \).

2. System Modeling

In this paper, we assume that one VoIP packet can be transmitted through one unoccupied wireless channel, and the packets transmitted through miss-detected channels are destroyed. Also, the number of sensing-users is sufficient for spectrum sensing, and the traffic generated by the VoIP users is modeled as a two-state Markov modulated Poisson process (MMPP) model [3].

We can formulate a multi-user queuing model for VoIP services in a cognitive radio system as a two-dimensional discrete-time Markov chain (DTMC). In our DTMC model, a transition probability \( B(i,m), (j,n) \) indicates the transitions between the number of unoccupied channels when the number of queuing packets is changed from \( i \) to \( j \). When the number of queuing packets is \( i \), given that \( k \) packets are scheduled, \( (j - \max(i - k, 0)) \) packets should arrive so that the number of packets becomes \( j \). Hence, \( B(i,m), (j,n) \) can be calculated by Eqn. (4). Here, \( P_s(k | x_c = m) \) is the probability that the BS serves \( k \) packets when the number of unoccupied channels is \( m \). Given that the number of real unoccupied channels is \( m \), the number of measured unoccupied channels \( m' \) by cognitive users is calculated as

\[
m' = m - m \times p_f() + (M - m) \times (1 - p_d()).
\]

In Eqn. (5), \( m \) \times p_f() channels are not reported by sensing-users as unoccupied channels due to the false alarms, and \((M - m) \times (1 - p_d())\) channels are reported as unoccupied channels due to the miss detections even though these channels are actually occupied. According to the reported sensing results by cognitive users, the BS schedules \( m' \) packets when the number of real unoccupied channels is \( m \). Namely, \( P_s(m' | x_c = m) = 1 \). As mentioned before, the packets
which are sent through miss-detected channels are destroyed by packet collisions. In addition, in Eqn. (4), $U$ and $D(m)$ are the transition probability matrix and the diagonal probability matrix of the DTMC model. Each element of $D(m)$ means the probability that $m$ VoIP packets arrive at the BS during the MAC frame duration ($T_f$) at each phase of the DTMC.

Through the transition matrix, we can obtain the steady-state probability matrix of our DTMC as follows: $\pi = [\pi(0) \; \pi(1) \; \pi(2) \; \cdots \; \pi(L_{max})]$ where $L_{max}$ is the maximum queue length. First, by using $\pi$, the average queuing-time ($L_{avg}$) and the average arrival rate ($\rho$) can be calculated by

$$L_{avg} = \sum_{i=0}^{L_{avg}} i \cdot \pi(k),$$

$$\rho = s \cdot \sum_{m=0}^{A_{max}} \pi(m) \cdot D(m) \cdot 1$$

where $A_{max}$ is the maximum number of packets that can arrive from one VoIP user during $T_f$. Moreover, the number of average serviced VoIP packets ($\kappa_{er}$) can be expressed by Eqn. (8). Here,

$$\frac{1-\pi_m}{\pi_m (M-i+1) - \pi_m i}$$

represents the ratio of the number of successfully transmitted packets to the total number of scheduled packets. By using $\kappa_{er}$, the average throughput and the packet dropping probability are represented as $S_{er} = \kappa_{er} \times (1-P_{DUD})$ and $P_{DUD} = 1 - \kappa_{er}/\rho$, respectively.

In VoIP services, the upper threshold of the packet dropping probability ($P_{limit}$) is generally smaller than 0.03 [3]. On the other hand, the threshold of the detection probability specified by the primary system ($P_{d,j,h,s}$) is not usually larger than $1 - P_{limit}$ in the cognitive radio system [4]. Therefore, if we use $P_{d,j,h,s}$ as the target detection probability for the spectrum sensing, we absolutely cannot ensure the QoS requirements of the VoIP services. In the following section, we will demonstrate the problem induced in the conventional cognitive radio system. Here, in order to resolve this problem, we propose a new method to find the minimum target detection and false alarm probabilities under the assumption of ensuring the QoS requirements of the VoIP services as follows: First, the BS finds the combinations of minimum detection and false alarm probabilities satisfying the constraint which will be utilized for the spectrum sensing as follows: $1 - \kappa_{er}/\rho \leq P_{limit}$. Second, the BS calculates the proper target detection probability and the number of required sensing users per channel satisfying the minimum detection and false alarm probabilities found in Step 1. Also, given that the target detection probability is fixed, we just find the number of required sensing-users per each channel.

3. Results and Discussion

We here set the target detection probability ($P_d$) utilized for the spectrum sensing in each user as 0.9 based on [4], and we assume that the upper threshold of the packet dropping probability of the VoIP service is 0.02. Then $1 - P_{limit} = 0.98$. Also, $M = 10$, $T_f = 5$ ms, $L_{max} = 50$, $A_{max} = 200$, $\gamma = -15$dB, $f_s = 6$MHz, and $\tau = 1$ms. We utilized the 4729B codec, and compressed upper-layer header size by payload header suppression is 16 bytes.

$$B_{i,m}(j,u) = \sum_{k=0}^{M} \left\{ U \cdot D(j - \max(i - k, 0)) \cdot P_e(k \mid x_e = m) \sum_{x'=\max(0, m - u)}^{\min(m, M-n)} \left( \begin{array}{c} m \\times' \end{array} \right) \frac{e^{-m} \cdot m^x'}{x'd!(m-x')!} \left( \begin{array}{c} M-m \\times'y' \end{array} \right) P_{01}^{y'} P_{11}^{M-m-y'} \right\}.$$ (4)

$$\kappa_{er} = \sum_{i=0}^{M} \sum_{j=0}^{L_{max}} \sum_{k=0}^{M} \left\{ \min(j, k) \cdot \pi(k) \cdot P_s(j \mid x_e = i) \cdot \tau \cdot \epsilon(i) \cdot \sum_{l=0}^{L_{max}} \left( \begin{array}{c} i-1 \cdot x_s(l) \end{array} \right) \frac{1}{(M-l)!(i-1-p_d(l))!} \right\}.$$ (8)

Fig. 2 shows that the QoS requirement of the VoIP service is ensured when the number of sensing users per channel is above 4. That is, the probability of detection should be larger than 0.9845, and the probability of false alarm should be smaller than 0.0236, in order to satisfy the packet dropping constraint. These values can be obtained from Eqns. (2) and (3) [2]. Here, if we utilize more sensing information than 4, the VoIP capacity slightly can be improved, as shown in Fig. 2. The maximum supportable number of VoIP users can be given in the case of error-free spectrum sensing when $M = 10$ and $p_{10} = p_{01} = 0.5$.

4. References