Capacity Improvement and Analysis of VoIP Service in a Cognitive Radio System

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***Abstract*—We herein analyze the capacity of voice over IP (VoIP) and propose a new method for finding the minimum detection and false-alarm probabilities to ensure the quality-of-service (QoS) requirement of VoIP users in a cognitive radio system. We propose a model for the system supporting the VoIP service as a 2-D discrete-time Markov chain (DTMC). The VoIP traffic and wireless channels in the cognitive radio system are described as a Markov-modulated Poisson process (MMPP) model and a Markov channel model, respectively. In addition, we introduce a simple spectrum-sensing model based on energy detection. By means of the DTMC approach, we demonstrate various analytical and simulation results under the constraint of imperfect spectrum sensing, such as the packet dropping probability, average throughput, and VoIP capacity.**

***Index Terms*—Cognitive radio, discrete-time Markov chain (DTMC), Markov-modulated Poisson process (MMPP), spectrum sensing, voice-over-IP (VoIP) service.**

I. Introduction

In FUTURE wireless communication systems, cognitive radio is a promising and challenging technology for maximizing radio resource utilization in recognition of the fact that conventional systems exploit the most available frequency bands for wireless communications but that these frequency bands are not generally fully utilized [1], [2]. The fundamental concept of the cognitive radio was first introduced by Mitola [3]. In a cognitive radio system, the cognitive user should be able to recognize the radio environment to accurately search spectrum holes that are not exploited by primary users. In this system, primary users should be sufficiently protected. Thus, spectrum sensing in the secondary network is one of the most important issues [2], [4]. In addition, the management of the spectrum channels found by the spectrum sensing is also very important in cognitive radio systems [5]–[7]. Apart from these research issues, there are many other problems to be solved in cognitive radio systems, such as spectrum sharing, dynamic spectrum access, spectrum mobility, cognitive medium-access control, and so on.

Furthermore, voice over IP (VoIP) will be an essential service in the future because, through VoIP technology, wireless users can more cheaply utilize voice services. Therefore, supporting as many voice users as possible while using limited radio resources is a very important issue that could be key to the success of future systems that include cognitive radio systems [8], [9]. Accordingly, we herein focus on the improvement and analysis of the VoIP capacity in a cognitive radio system under the constraints that the primary users are sufficiently protected and that the quality-of-service (QoS) requirements of the secondary VoIP users are guaranteed.

So proposed a discrete-time Markov chain (DTMC) framework based on a Markov-modulated Poisson process (MMPP) traffic model to analyze VoIP performance [10]. However, the author did not consider cognitive radio systems and showed the performance with respect to queue length, average throughput, and packet-dropping probability in the IEEE 802.16e orthogonal frequency-division multiple access system with in-band signaling. In [11], Bi *et al.* evaluated the VoIP capacity and delay performance of a 1xEV-DO revision A (DOrA) system using both analytical and simulation models. Here, they identified the challenges and investigated the feasibility of implementing the VoIP service using the DOrA system. Furthermore, by considering the sensing–throughput tradeoff, Liang *et al.* studied the problem of designing the sensing duration to maximize the achievable throughput of the cognitive system under the constraint that the primary users are sufficiently protected [12]. Here, they also addressed the relationship between the probability of detection and the probability of false alarm. In [13], Rashid *et al.* proposed a queuing framework of opportunistic spectrum access by secondary users in a cognitive radio system. They derived the queuing delay performance of the secondary users by considering the activity of primary users and the channel quality variation of the secondary users. On the other hand, we analyzed VoIP capacity in a cognitive radio system where spectrum-sensing errors do not occur [14]. However, to make our research more practical, we herein extend the scope of our prior research. That is, we take into account imperfect spectrum sensing.

In this paper, we analyze VoIP capacity in a cognitive radio system using a queuing model based on the MMPP traffic model and a Markov channel model where spectrum sensing errors occur. Here, the VoIP packets of the secondary users can be transmitted when the wireless channel is not utilized by a primary user/network. In addition, we propose a new method to find minimum target-detection and false-alarm probabilities for the spectrum sensing. To the best of our knowledge, the capacity analysis and improvement of VoIP services have yet to be studied for cognitive radio systems under the constraint of imperfect spectrum sensing.

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The remainder of this paper is organized as follows. In Section II, we present the VoIP traffic model based on the MMPP and the Markov channel model for cognitive radio systems. In Section III, we propose a DTMC framework considering multiuser VoIP queuing and wireless channel-occupancy variations. Furthermore, we introduce a simple spectrum-sensing model and propose a new method to find the minimum target-detection and false-alarm probabilities under the assumption of satisfying the constraint of VoIP packet-dropping probability. In Section IV, we show various analytical and simulation results such as the packet-dropping probability, average throughput, and VoIP capacity. Finally, we draw some conclusions in Section V.

II. Modeling of Voice Over Internet Protocol Traffic and Cognitive Radio Channel

As a preliminary study, we introduce a VoIP traffic model and a cognitive radio channel model to analyze the performance of a cognitive radio system supporting VoIP services in this section.

A. *Modeling of VoIP Traffic*

The VoIP traffic of a single user can generally be formulated as a simple on–off model. The probability that the status of the users is inactive (= off) in the simple on–off model can be obtained by $p_{\text{off}} = \beta^{-1}/(\alpha^{-1} + \beta^{-1})$, and $p_{\text{on}} = 1 - p_{\text{off}}$. Here, $1/\alpha$ and $1/\beta$ are the mean values of the on and off periods, which are exponentially distributed. Furthermore, all the traffic generated by the VoIP users in the cell can be represented as a two-state MMPP model [15]. This MMPP model is highly suitable for formulating multiuser VoIP traffic because the MMPP captures the interframe dependence between consecutive voice frames. Here, the transition rate matrix ($\mathbf{R}$) and the Poisson arrival rate matrix ($\mathbf{\Lambda}$) of the MMPP can be expressed as follows:

$$\mathbf{R} = \begin{bmatrix} -r_1 & r_1 \\ r_2 & -r_2 \end{bmatrix}, \quad \mathbf{\Lambda} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}. \tag{1}$$

To exploit the MMPP model, we match the MMPP parameters (r_1, r_2, λ_1, and λ_2) in (1) with the parameters of the simple on–off model (α and β). We herein adopt the index of dispersion for counts (IDC) matching technique because it yields adequate results for the matching of parameters and has appropriate computation complexity compared with other matching techniques [10]. Then, r_1, r_2, λ_1, and λ_2 in (1) can be calculated by

$$r_1 = \frac{2(\lambda_2 - \lambda_{\text{avg}})(\lambda_{\text{avg}} - \lambda_1)^2}{(\lambda_2 - \lambda_1)\lambda_{\text{avg}}\,(\text{IDC}(\infty) - 1)} \tag{2}$$

$$r_2 = \frac{2(\lambda_2 - \lambda_{\text{avg}})^2(\lambda_{\text{avg}} - \lambda_1)}{(\lambda_2 - \lambda_1)\lambda_{\text{avg}}\,(\text{IDC}(\infty) - 1)} \tag{3}$$

$$\lambda_1 = A \cdot \frac{\sum_{i=0}^{N_{\text{act\_avg}}} i \cdot \pi_i}{\sum_{j=0}^{N_{\text{act\_avg}}} \pi_j}, \quad \lambda_2 = A \cdot \frac{\sum_{i=N_{\text{act\_avg}}+1}^{N} i \cdot \pi_i}{\sum_{j=N_{\text{act\_avg}}+1}^{N} \pi_j}. \tag{4}$$

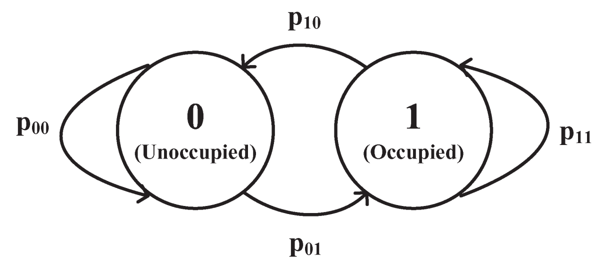

Fig. 1. Markov channel model for a cognitive radio system.

Here, N is the total number of VoIP users in the system, A is the emission rate in the ON-state ($A = 1/T_{\text{basic}}$), and T_{basic} is a frame duration of voice codec. Furthermore, the average arrival rate is $\lambda_{\text{avg}} = N \times A \times p_{\text{on}}$, the average number of active users is $N_{\text{act\_avg}} = \lfloor N \times p_{\text{on}} \rfloor$, and the steady-state probability of a 1-D Markov chain when considering N independent simple on–off voice users can be calculated by $\pi_i = {}_N C_i \cdot p_{\text{on}}^i \cdot (1 - p_{\text{on}})^{N-i}$. Moreover, IDC($\infty$) is given as [15]

$$\text{IDC}(\infty) = 1 + \frac{2(\lambda_1 - \lambda_2)^2 r_1 r_2}{(r_1 + r_2)^2(\lambda_1 r_2 - \lambda_2 r_2)}. \tag{5}$$

B. *Modeling of Cognitive Radio Channel*

A wireless channel can be modeled as a two-state Markov process in a cognitive radio system, as shown in Fig. 1 [14], [16]. 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_c) in the current frame and that there will be n unoccupied channels in the next frame can be represented by

$$P_{m,n} = \sum_{x'=\max(0,m-n)}^{\min(m,M-n)} \binom{m}{x'} p_{01}^{x'} p_{00}^{m-x'} \binom{M-m}{y'} p_{10}^{y'} p_{11}^{M-m-y'}. \tag{6}$$

In (6), $y' = n - m + x'$, where x' and y' denote the numbers of channels whose status are altered from "Unoccupied" to "Occupied" and from "Occupied" to "Unoccupied," respectively.

III. Voice Over Internet Protocol Capacity Analysis Under the Constraint of Imperfect Spectrum Sensing

We herein analyze the VoIP capacity of a cognitive radio system where spectrum-sensing errors arise. In this section, we release the typical assumption of perfect spectrum sensing to obtain more advanced and practical results. Namely, we consider imperfect spectrum sensing. Moreover, we propose a new method to find minimum target-detection and false-alarm probabilities to ensure QoS requirements of VoIP services.

Spectrum-Sensing Modeling: In [12], the spectrum-sensing model based on energy detection was presented. Thus, if we assume that the primary signal is complex phase-shift keying

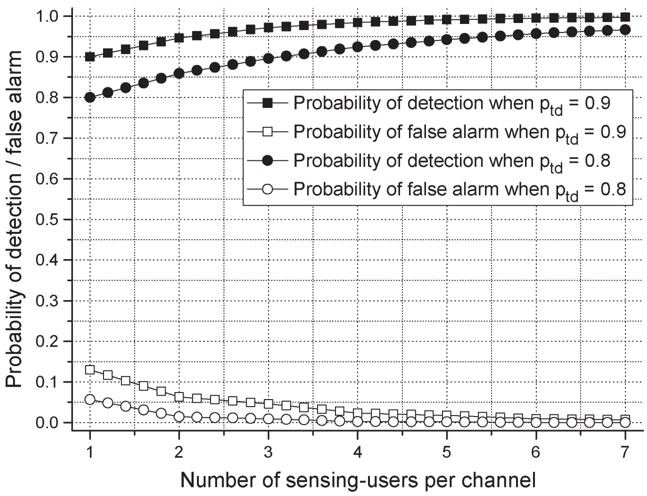

Fig. 2. Probability of detection and false alarm versus the number of sensing users per channel when $P_{\mathrm{td}} = 0.8$ and 0.9.

(PSK) modulated and the noise has a circularly symmetric complex Gaussian (CSCG) distribution, we can represent the probabilities of channel detection $(p_d(\epsilon, \tau))$ and false alarm $(p_f(\epsilon, \tau))$ as follows:

$$p_d(\epsilon, \tau) = \mathcal{Q}\left(\left(\frac{\epsilon}{{\sigma_u}^2} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{2\gamma + 1}}\right) \tag{7}$$

$$p_f(\epsilon, \tau) = \mathcal{Q}\left(\left(\frac{\epsilon}{{\sigma_u}^2} - 1\right)\sqrt{\tau f_s}\right) \tag{8}$$

where ϵ is the detection threshold, τ is the available sensing time, σ_u^2 is the variance of the Gaussian noise, f_s is the sampling frequency of the received signal, and γ is the received SNR of the primary user measured at the cognitive user under the hypothesis $\mathcal{H}_1$. Here, $\mathcal{H}_0$ denotes that the status of the primary user is inactive, and $\mathcal{H}_1$ represents that the status of the primary user is active. Furthermore, $\mathcal{Q}(\cdot)$ is the complementary distribution function of the standard Gaussian.

Fig. 2 shows the probability of detection and false alarm versus the number of sensing users per channel when $P_{\mathrm{td}} = 0.8$ and 0.9, and this figure is obtained from (7) and (8). Here, P_{td} is a target detection probability, which is utilized in the spectrum sensing of each sensing user. To obtain $p_d(\cdot)$ and $p_f(\cdot)$, we first set P_{td} to a certain value; then, we can obtain ϵ from (7). After that, by using ϵ, we can calculate a false-alarm probability from (8). In the IEEE 802.22 Wireless Regional Area Network, a detection probability must be maintained below 0.9 [17]. Hence, we herein adopt this value $(P_{\mathrm{td}} = 0.9)$ as the target-detection probability. In this figure, we assume that $\gamma = -15$ dB, $f_s = 6$ MHz, and $\tau = 1$ ms. Since the base station (BS) could have a number of sensing results for each channel, we apply a majority rule to make a final decision [12]. As shown in Fig. 2, the false-alarm probability decreases with the increase in the number of sensing users because of the increment of sensing information for each primary channel. Moreover, the false-alarm probability when $P_{\mathrm{td}} = 0.9$ is larger than the probability when $P_{\mathrm{td}} = 0.8$ because we should set the ϵ at a lower value to satisfy the constraint of the target-detection probability.

Assumptions:

1) One VoIP packet can be transmitted through one unoccupied wireless channel. If all the channels are used by the primary users, the VoIP packets cannot be sent.
2) There are no packet retransmissions. That is, unreceived and destroyed packets are not sent again.
3) The primary signal is complex PSK modulated, and the additive noise has a zero-mean CSCG distribution.
4) The packets transmitted through miss-detected channels are destroyed.
5) The received SNRs for the primary user measured at the cognitive users are all the same.
6) The number of sensing users is sufficient for spectrum sensing.

System Modeling: We can formulate a multiuser queuing model for VoIP services in a cognitive radio system, such as a DTMC. In other words, we can analyze the behavior of queuing packets in the BS with this DTMC model. Then, the transition matrix $(\mathbf{P})$ can be defined as

$$\mathbf{P} = \begin{bmatrix} \mathbf{A}_{0,0} & \mathbf{A}_{0,1} & \cdots & \mathbf{A}_{0,L_{\max}} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{L_{\max},0} & \mathbf{A}_{L_{\max},1} & \cdots & \mathbf{A}_{L_{\max},L_{\max}} \end{bmatrix} \tag{9}$$

where $L_{\max}$ is maximum queue length, and submatrix $(\mathbf{A}_{i,j})$ is expressed as

$$\mathbf{A}_{i,j} = \begin{bmatrix} \mathbf{B}_{(i,0),(j,0)} & \mathbf{B}_{(i,0),(j,1)} & \cdots & \mathbf{B}_{(i,0),(j,M)} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{B}_{(i,M),(j,0)} & \mathbf{B}_{(i,M),(j,1)} & \cdots & \mathbf{B}_{(i,M),(j,M)} \end{bmatrix}. \tag{10}$$

In (10), $\mathbf{A}_{i,j}$ represents the variation in the number of queuing packets. That is, there are i packets in the current frame, and there will be j packets in the next frame. In $\mathbf{A}_{i,j}$, each element $(\mathbf{B}_{(i,m),(j,n)})$ indicates the transitions between the numbers of unoccupied channels when the number of queuing packets is changed from i to j. Furthermore, $\mathbf{B}_{(i,m),(j,n)}$ is a 2×2 matrix because our MMPP model has two phases, i.e., underloading and overloading. 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, $\mathbf{B}_{(i,m),(j,n)}$ can be calculated by

$$\mathbf{B}_{(i,M),(j,n)} = \sum_{k=0}^{M} \Bigg\{ \mathbf{U} \cdot \mathbf{D}(j - \max(i-k,0)) \cdot P_s(k|x_c = m) \cdot \sum_{x'=\max(0,m-n)}^{\min(m,M-n)} \binom{m}{x'} p_{01}^{x'} p_{00}^{m-x'} \binom{M-m}{y'} p_{10}^{y'} p_{11}^{M-m-y'} \Bigg\}. \tag{11}$$

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 one VoIP packet can be transmitted through one unoccupied wireless channel, $P_s(m|x_c = m) = 1$.

In this paper, since we assume that spectrum-sensing errors can occur, we should herein focus on two probabilities, namely, the detection probability and the false-alarm probability. The detection probability means that, under hypothesis $\mathcal{H}_1$, the cognitive user correctly detects the presence of the primary signal. In addition, the false-alarm probability represents that, under hypothesis $\mathcal{H}_0$, the cognitive user falsely detects the presence of the primary signal. In general, maximizing the detection probability while minimizing the false-alarm probability is a key issue in cognitive radio systems. In this paper, the BS performs packet scheduling based on the sensing results reported by each cognitive user. In other words, the information for miss-detected and false-alarm channels is unfortunately included in these reported results. Thus, packet collisions due to miss-detected channels and the waste of channel resources due to false-alarm channels can occur in the case of erroneous spectrum sensing.

Accordingly, when the number of real unoccupied channels is m, the number of measured unoccupied channels (m') by cognitive users is calculated as

$$m' = m - m \times p_f(\cdot) + (M - m) \times (1 - p_d(\cdot)). \qquad (12)$$

In (12), $m \times p_f(\cdot)$ channels are not reported by sensing users as unoccupied channels due to false alarms, and $(M - m) \times (1 - p_d(\cdot))$ channels are reported as unoccupied channels due to 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, in the case of erroneous spectrum sensing. Namely, $P_s(m'|x_c = m) = 1$. As mentioned before, the packets that are sent through miss-detected channels are destroyed by packet collisions. In addition, in (11), $\mathbf{U}$ and $\mathbf{D}(m)$ are the transition probability matrix and the diagonal probability matrix of the two-state MMPP model [10]. Each element of $\mathbf{D}(m)$ represents the probability that m VoIP packets arrive at the BS during the medium access control (MAC) frame duration (T_f) at each phase of the two-state MMPP.

Through the transition matrix $(\mathbf{P})$ in (9), we can obtain the steady-state probability matrix $(\boldsymbol{\pi}_p)$ for our DTMC model, which can be calculated by solving equations $\boldsymbol{\pi}_p \cdot \mathbf{P} = \boldsymbol{\pi}_p$ and $\boldsymbol{\pi}_p \cdot \mathbf{1} = 1$. Here, $\boldsymbol{\pi}_p$ is a "1" by "$2 \times (M + 1) \times (L_{\max} + 1)$" matrix. Therefore, the probability that k VoIP packets are queued in the BS can be expressed as

$$\pi(k) = \sum_{l=0}^{2(M+1)-1} \pi_p\left(2 \cdot (M+1) \cdot k + l\right). \qquad (13)$$

Using (13), the "1" by "$(L_{\max} + 1)$" steady-state probability matrix of the DTMC model can be obtained as follows:

$$\boldsymbol{\pi} = \left[\, \pi(0) \quad \pi(1) \quad \pi(2) \quad \cdots \quad \pi(L_{\max}) \,\right]. \qquad (14)$$

Therefore, by using this steady-state probability, we can present various analytical results such as the average number of arrived packets, the average queue length, the average number of serviced VoIP packets, the average VoIP throughput, and the packet-dropping probability. First, the average queue length (L_{avg}) and the average arrival rate (ρ) can be calculated by

$$L_{\text{avg}} = \sum_{i=0}^{L_{\max}} i \cdot \pi(k) \qquad (15)$$

$$\rho = \mathbf{s} \cdot \left\{ \sum_{m=0}^{N \times A_{\max}} m \cdot \mathbf{D}(m) \right\} \cdot \mathbf{1}. \qquad (16)$$

In (16), $\mathbf{s}$ is calculated by solving $\mathbf{s} \cdot \mathbf{U} = \mathbf{s}$, and $\mathbf{1}$ is a column matrix of ones. Furthermore, $A_{\max}$ is the maximum number of packets that can arrive from one VoIP user during T_f. Similar to the average arrival rate, the number of average serviced VoIP packets (κ_{er}) in the case of erroneous spectrum sensing may be expressed by

$$\kappa_{\text{er}} = \sum_{i=0}^{M} \sum_{j=0}^{M} \sum_{k=0}^{L_{\max}} \Bigg\{ \min(j,k) \cdot \pi(k) \cdot P_s(j|x_c = i) \cdot \pi_{\text{ch}}(i) \cdot \frac{i - i \times p_f(\cdot)}{i - i \times p_f(\cdot) + (M - i) \times (1 - p_d(\cdot))} \Bigg\}. \qquad (17)$$

Here, $\pi_{\text{ch}}(i)$ is the steady-state probability that the number of unoccupied channels are i and can be expressed as

$$\pi_{\text{ch}}(i) = \binom{M}{i} \left(\frac{p_{10}}{p_{01} + p_{10}} \right)^{i} \cdot \left(\frac{p_{01}}{p_{01} + p_{10}} \right)^{M-i}. \qquad (18)$$

Furthermore, $(i - i \times p_f(\cdot))/(i - i \times p_f(\cdot) + (M - i) \times (1 - p_d(\cdot)))$ represents the ratio of the number of successfully transmitted packets to the total number of scheduled packets. By using κ_{er}, the average throughput (S_{er}) and the packet-dropping probability (P_{er}) in the case of the erroneous spectrum sensing are represented as

$$S_{\text{er}} = \kappa_{\text{er}} \times l_{\text{PDU}} \qquad (19)$$

$$P_{\text{er}} = 1 - \kappa_{\text{er}}/\rho. \qquad (20)$$

Here, l_{PDU} is the size of VoIP protocol data unit (PDU). In addition, the VoIP capacity in the case of erroneous spectrum sensing can be represented as follows:

$$C_{\text{er}} = \arg\max N \in \left\{ N \,\middle|\, 1 - \frac{\kappa_{\text{er}}}{\rho} \leq P_{\text{limit}} \right\} \qquad (21)$$

where P_{limit} is the upper threshold of the packet-dropping probability for VoIP services.

In VoIP services, the upper threshold of the packet-dropping probability (P_{limit}) for the VoIP packets is generally smaller than "0.03" [10], [11], [18]. However, the threshold of the detection probability specified by the primary system (P_{d_thr}) is not usually larger than $1 - P_{\text{limit}}$ in cognitive radio systems [17]. Therefore, if we use P_{d_thr} as the target-detection probability for the spectrum sensing, we cannot absolutely ensure the QoS requirements of the VoIP services because $P_{d\_\text{thr}} < 1 - P_{\text{limit}}$. In Section IV, we will demonstrate this problem in conventional cognitive radio systems. Furthermore, 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 requirement of the VoIP services as follows.

- **Step 1:** The BS finds the combinations of minimum detection and false-alarm probabilities satisfying the constraint that will be utilized for the spectrum sensing as follows: $1 - \kappa_{\rm er}/\rho \leq P_{\rm limit}$.
- **Step 2:** 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. Furthermore, given that the target-detection probability is fixed by a primary system, we find the number of required sensing users for each channel.
- **Step 3:** The BS informs the cognitive users of the target-detection probability that will be utilized for spectrum sensing in each user.
- **Step 4:** By using the target-detection probability, the cognitive user measures the presence of the primary signal and reports the sensing results to the BS.
- **Step 5:** According to the required number of reported sensing results per channel, the BS derives the final decision.

In the cognitive radio systems, since primary users should sufficiently be protected, the spectrum sensing in the secondary network is one of the most important issues. Furthermore, the spectrum sensing is in close relationship with the support for VoIP QoS requirements of cognitive users. Thus, finding the target-detection and false-alarm probabilities and the number of required sensing users per channel is a very important problem to ensure the VoIP QoS requirements. In our proposed method, we provide the analytical method for finding the minimum detection and false-alarm probabilities and the number of required sensing users per channel.

IV. Numerical and Simulation Results

We evaluated the VoIP performance of the cognitive radio system using MATLAB. We included all the essential factors required for performance evaluation, such as the round-robin scheduler, packet-size and packet-generation-period variations of VoIP codecs, and so on.

To obtain numerical and simulation results, we assumed that $M = 10$, $T_f = 5$ ms, $L_{\max} = 50$, and $A_{\max} = 200$. We utilized the G.729B codec where $T_{\rm basic}$ is 10 ms. This codec has two data rates (8 and 0 kb/s) and a voice-activity factor of 0.4. We assumed that the size of the RTP/UDP/IPv4 header compressed by payload header suppression is 16 B. Furthermore, the size of the MAC header is 6 B. In the simulation, we used an on–off source model for each VoIP user.

In particular, here, we set the target-detection probability $(P_{\rm td})$ utilized for the spectrum sensing in each user as "0.9" based on [17], and we assume that the upper threshold of the packet dropping probability of the VoIP service is "0.02." Then, $1 - P_{\rm limit} = 0.98$. Table I shows the detection and false-alarm probabilities according to the increase in the number of sensing users per channel when $P_{\rm td} = 0.9$. These values can be obtained from Fig. 2. Based on this table, we can find

TABLE I
COMBINATION OF DETECTION AND FALSE-ALARM PROBABILITIES ACCORDING TO THE INCREASE IN THE NUMBER OF SENSING USERS PER CHANNEL

# of sens. users / ch. \ Pr.	Detection pr.	False alarm pr.
1	0.9	0.1297
2	0.9463	0.0633
3	0.972	0.0461
4	0.9845	0.0236
5	0.9914	0.0178
6	0.9952	0.0093

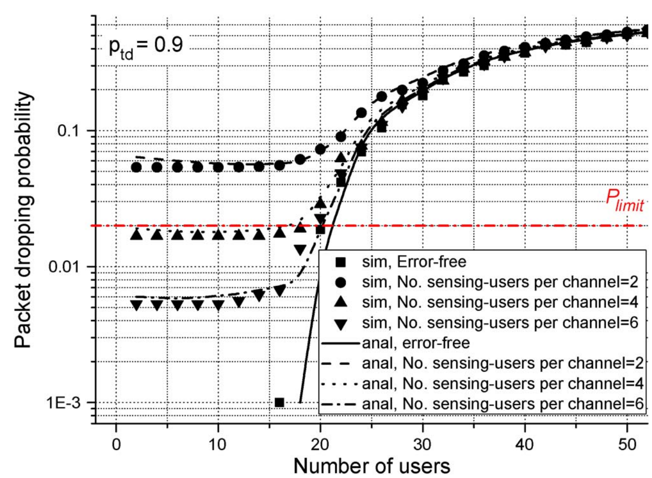

Fig. 3. Packet-dropping probability versus the number of users according to variation in the number of sensing users per channel in case of erroneous spectrum sensing when $M = 10$ and $p_{10} = p_{01} = 0.5$.

the combinations of the detection and false-alarm probabilities satisfying the QoS requirement of VoIP services.

We show the packet-dropping probability of VoIP packets versus the number of VoIP users according to the variation in the number of sensing users per each channel, as described in Fig. 3. This figure demonstrates that the QoS requirement of the VoIP services is ensured when the number of sensing users per channel is above four. That is, the probability of detection should be larger than 0.9845, and the probability of false alarm should be smaller than 0.0236 to satisfy the packet-dropping constraint. These values can be obtained from Table I. Here, if we utilize more sensing information, i.e., more than four sensing users per channel, the VoIP capacity may slightly be improved, as shown in Fig. 3. The maximum supportable number of VoIP users can be given in the case of error-free spectrum sensing when $M = 10$ and $p_{10} = p_{01} = 0.5$. Given that the number of sensing users per channel is smaller than three, since the constraint of packet-dropping probability for VoIP services is not guaranteed, we can declare that the VoIP capacity is zero based on our capacity definition. That is, if we do not adjust the detection and false-alarm probabilities in consideration of the constraint of the packet-dropping probability for VoIP services, we can never ensure the QoS requirement for VoIP services. Moreover, since the miss-detection probabilities are not zero, except the case of the error-free spectrum sensing, packet drops due to packet collisions always occur, even when the number of VoIP users is extremely small, as shown in Fig. 3.

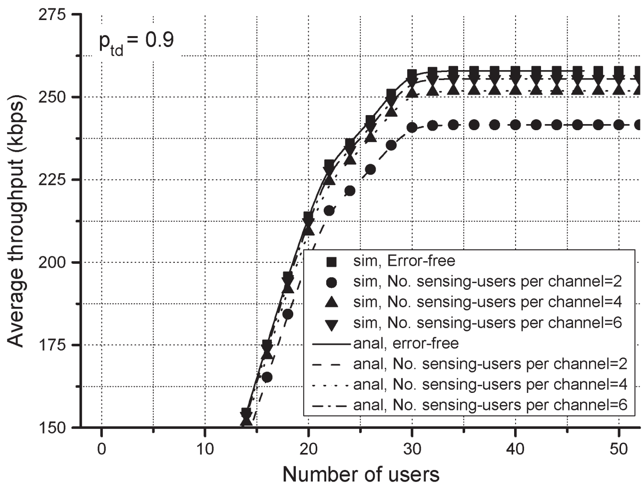

Fig. 4. Average throughput (in kilobits per second) versus the number of users according to variation in the number of sensing users per channel in case of erroneous spectrum sensing when $M = 10$ and $p_{10} = p_{01} = 0.5$.

As shown in Fig. 4, the average throughput linearly grows according to the increment of the number of VoIP users up to the saturation point. Since channel resource saturation occurs at this point, the BS cannot assign channels to surplus users beyond the saturation point. Thus, even though the number of users increases, the average throughput cannot be enlarged without limit. In this figure, when the number of sensing users per each channel increases, since the sensing accuracy is gradually enhanced, the gap between the throughput for error-free sensing and the throughput for erroneous sensing is reduced in accordance with the increment of the sensing users per channel. Furthermore, from Figs. 3 and 4, it can be seen that the simulation results match the numerical results very well.

V. Conclusion

We have evaluated the performance of a VoIP service in a cognitive radio system. First, we have proposed a queuing framework to analyze the behavior of queuing packets in the BS based on the DTMC model. Under the constraint of imperfect spectrum sensing, we have shown various analytical and simulation results, such as the packet dropping probability, average throughput, and VoIP capacity. Furthermore, we have proposed a new method to find the minimum target-detection and false-alarm probabilities and have demonstrated that the QoS requirement of the VoIP users is well satisfied by using our proposed method.

References

[1] FCC Spectrum Policy Task Force, "FCC Report of the Spectrum Efficiency Working Group," Nov. 2002.

[2] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Comput. Netw.*, vol. 50, no. 13, pp. 2127–2159, Sep. 2006.

[3] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio," Ph.D. dissertation, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000.

[4] T. Yücek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Commun. Surveys Tuts.*, vol. 11, no. 1, pp. 116–130, First Quar., 2009.

[5] P. Papadimitratos, S. Sankaranarayanan, and A. Mishra, "A bandwidth sharing approach to improve licensed spectrum utilization," *IEEE Commun. Mag.*, vol. 43, no. 12, pp. S10–S14, Dec. 2005.

[6] V. Brik, E. Rozner, S. Banarjee, and P. Bahl, "DSAP: A protocol for coordinated spectrum access," in *Proc. IEEE DySPAN*, Nov. 2005, pp. 611–614.

[7] L. Ma, X. Han, and C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc network," in *Proc. IEEE DySPAN*, Nov. 2005, pp. 203–213.

[8] S. McBeath, J. Smith, L. Chen, and A. C. K. Soong, "VoIP support using group resource allocation based on the UMB system," *IEEE Commun. Mag.*, vol. 46, no. 1, pp. 114–120, Jan. 2008.

[9] F. Wang, A. Ghosh, C. Sankaran, P. Fleming, F. Hsieh, and S. J. Benes, "Mobile WiMAX systems: Performance and evolution," *IEEE Commun. Mag.*, vol. 46, no. 10, pp. 41–49, Oct. 2008.

[10] J.-W. So, "Performance analysis of VoIP services in the IEEE 802.16e OFDMA system with inband signaling," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1876–1886, May 2008.

[11] Q. Bi, P.-C. Chen, Y. Yang, and Q. Zhang, "An analysis of VoIP service using 1xEV-DO revision a system," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 1, pp. 36–44, Jan. 2006.

[12] Y.-C. Liang, Y. Zeng, E. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326–1337, Apr. 2008.

[13] M. M. Rashid, M. J. Hossain, E. Hossain, and V. K. Bhargava, "Opportunistic spectrum access in cognitive radio networks: A queueing analytic model and admission controller design," in *Proc. IEEE Globecom*, Nov. 2007, pp. 4647–4652.

[14] H. Lee and D.-H. Cho, "VoIP capacity analysis in cognitive radio system," *IEEE Commun. Lett.*, vol. 13, no. 6, pp. 393–395, Jun. 2009.

[15] H. Heffes and D. M. Lucantoni, "A Markov modulated characterization of packetized voice and data traffic and related statistical multiplexer performance," *IEEE J. Sel. Areas Commun.*, vol. SAC-4, no. 6, pp. 856–868, Sep. 1986.

[16] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 3, pp. 589–600, Apr. 2007.

[17] *Functional Requirements for the 802.22 WRAN Std., IEEE Std., 802.22-05/0007r47*, IEEE Std. 802.22 Wireless RAN, Jan. 2006.

[18] J. Hui and M. Devetsikiotis, "The use of metamodeling for VoIP over WiFi capacity evaluation," *IEEE Trans. Wireless Commun.*, vol. 7, no. 1, pp. 1–5, Jan. 2008.

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