IEIE Transactions on Smart Processing and Computing, vol. 3, no. 4, August 2014
http://dx.doi.org/10.5573/IEIESPC.2014.3.4.173

IEIE Transactions on Smart Processing and Computing

Throughput Analysis of CSMA/CA-based Cognitive Radio Networks in Idle Periods

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Received December 20, 2013; Revised February 27, 2013; Accepted May 12, 2014; Published August 31, 2014

** Regular Paper*

** Review Paper: This paper reviews the recent progress possibly including previous works in a particular research topic, and has been accepted by the editorial board through the regular reviewing process*

Abstract: Random access protocols feature inherent sensing functionality and distributed coordination, making them suitable for cognitive radio communication environments, where secondary users must detect the white space of the primary spectrum and utilize the idle primary spectrum efficiently without centralized control. These characteristics have led to the adoption of carrier-sensing-multiple-access/collision-avoidance (CSMA/CA) in cognitive radio. This paper proposes a new analytical framework for evaluating the performance of a CSMA/CA protocol that considers the characteristics of idle periods based on the primary traffic behavior in cognitive radio systems. In particular, the CSMA/CA-based secondary network was analyzed in the terms of idle period utilization, which is the average effective data transmission time portion in an idle period. The use of the idle period was maximized by taking its statistical features into consideration.

Keywords: Cognitive radios, Random access, Multiple access, Throughput analysis

1. Introduction

Since it was reported that a considerable amount of the licensed-spectra is under-utilized, cognitive radio has been researched as a key technology for the efficient utilization of the unused spectrum on a secondary basis [1]. Cognitive radio can detect and utilize opportunistically a licensed spectrum that is not being used by adjusting the radio parameters based on the radio environment awareness of the primary communication system.

An idle period is a continuous time duration that a primary communication system is inactive in a licensed frequency resource. Secondary users can transmit signals only in idle periods without causing harmful interference to the primary communication system. Accordingly, the idle period is the most important radio resource to secondary users in cognitive radio. Conventional studies have focused primarily on how to reliably sense an idle period [2-4]. On the other hand, these studies did not address the issue of how multiple secondary users might be able to utilize the idle period. In this paper, Carrier Sense Multiple Access (CSMA/CA) was adopted for efficient coordination among secondary communications in idle periods. The inherent sensing functionality and distributed coordination feature of CSMA/CA allows heterogeneous secondary systems to be organized efficiently without a control signaling overhead with effective interference management.

CSMA/CA-based cognitive radio networks have been investigated [5-7]. Huang et al. proposed an adaptive MAC protocol that switches multiple access schemes between CSMA/CA and TDMA [5]. Ahuja et al. examined how to best apply the 802.11a MAC protocol to the UHF TV band white space (TVWS) and performed physical experiments [6]. Lien et al. evaluated the performance of CSMA/CA-based cognitive radio networks [7]. These studies [5-7], however, commonly overlooked the effects of the duration of the idle period on the throughput performance of CSMA/CA. The duration of the idle period is unpredictable due to the random departure and arrival of primary traffic. Therefore, the throughput performance of a CSMA/CA must come under the influence of the statistical characteristics of primary traffic.

In the present study, an analytical model for CSMA/CA-based cognitive radio networks that evaluates the idle period utilization (IPU) in exponentially-distributed idle periods (EDIP) was developed. As an environmental assumption, EDIP practically models the duration of the idle period when the primary traffic is generated by voice or UDP internet services [8-11]. IPU is a key performance metric to measure the average effective data transmission time portion in EDIP. By analyzing the IPU in EDIP, this paper will reveal the impact of the payload length on the throughput of CSMA/CA. A payload that is too short could waste the time resource available for the contention process because it precedes every secondary payload transmission. On the other hand, the last payload transmitted during an idle period must be dropped when a collision with newly arrived primary traffic occurs. Therefore, a secondary user payload length that is too long might degrade the secondary user throughput due to the dropped payload. The IPU that reflects such a tradeoff relationship can be maximized by controlling the payload length. This tradeoff cannot be analyzed under conventional analytical frameworks [12, 13].

The remainder of this paper is organized as follows. Section 2 describes the system model of a CSMA/CA-based cognitive radio network. In Section 3, the throughput of the CSMA/CA-based cognitive radio network is maximized. Section 4 reports the numerical results, and the conclusions are given in the last section.

2. System Model

In cognitive radio communications, secondary users can transmit the signals in the white space of a licensed spectrum that is temporarily unoccupied by the primary users, who own the spectrum. This idle period is generally defined as the time during, which the primary spectrum is continuously in an unoccupied state between two consecutive primary traffic periods [14]. During the idle period, secondary users attempt to transmit their data signals over a common spectrum using some distributed multiple access approaches. This study adopts the CSMA/CA [13] as the multiple access technique. CSMA/CA is the most popular random access technique. Its *distributed coordination function* (DCF) enables multiple secondary users to communicate efficiently in an idle period without any coordination between them.

As shown in Fig. 1, secondary communication using CSMA/CA begins at the end of the preceding primary traffic session. The end of the primary traffic can be detected using sensing techniques[1] that are essential for secondary users [2-4]. To transmit a secondary user's payload, a contention period must be processed to avoid collisions between secondary users. In each contention slot, a secondary user attempts to access the primary spectrum, where the probability depends on the predetermined minimum contention window size and the maximum number of backoff stages, which was analyzed previously [15]. In [15], for example, the minimum contention window size was 16 and the maximum number of backoff stages is six. The CSMA/CA protocol finishes the contention period only if one or more secondary user begins to transmit payload in a contention slot for the first time in the idle period. If only one user transmits a signal in the contention slot, the transmitted signal is delivered successfully to the corresponding receiver. On the other hand, if multiple secondary users simultaneously transmit signals in the contention slot, a collision occurs between the users, and the payloads involved in the collision are dropped[2].

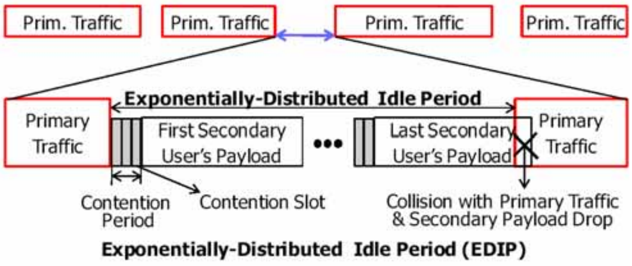

Fig. 1. CSMA/CA in the cognitive radio in EDIP.

In this paper, the existence of a CSMA/CA-operated secondary network with N secondary users was assumed. To investigate the maximized throughput of the secondary network using CSMA/CA, it is assumed that the traffic of each secondary user is saturated. Secondary users may belong to heterogeneous systems in cognitive radio environments. No priority between the secondary users is considered. Therefore, each secondary user has the same contention slot length, T_C, and a payload length, T_P. The CSMA/CA performance in EDIP is analyzed using the operation parameters defined in this section.

3. Performance Analysis in EDIP

This section considers the EDIP case, in which the durations of the idle periods are limited but vary with the arrival of primary traffic. Accordingly, the IPU, which can be achieved via CSMA/CA in cognitive radios, was first analyzed. The IPU is a newly defined performance metric that measures the effectively utilized time duration for successful secondary payload transmissions in an idle period. The IPU can provide relevant information on the CSMA/CA transmission performance in cognitive radios because, in the EDIP case, the secondary network can be stopped temporarily by the primary system.

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[1] Recently, a variety of sensing techniques, such as energy detection, feature detection, or matched filter detection, have been proposed. The detection accuracy can vary depending on which sensing technique is adopted. On the other hand, given that the main focus of this paper was to analyze the throughput of the secondary networks using CSMA/CA, discussions of sensing technique performance was omitted.

[2] For the sake of simplicity, this study will not consider the capture effect here.

3.1 Derivation of IPU in EDIP

To analyze the IPU of a cognitive radio network using CSMA/CA, the average number of transmitted payloads in an idle period with a random duration was first calculated. This begins with defining the transmission probability, denoted by P_t, which a secondary user will transmit in a randomly chosen contention slot [12, 13]. Accordingly, the *non-transmission probability*, in which no N secondary users will transmit in a contention slot, can be calculated as follows:

$$P_{nt} = (1-P_t)^N. \qquad (1)$$

According to the CSMA/CA protocol, the contention period continues until one or more secondary users accesses the primary spectrum at a randomly chosen contention slot. The probability that the number of consumed contention slots for a payload transmission is x can be calculated as follows:

$$f_X(x) = P_{nt}^x(1-P_{nt}), x = 0,1,\ldots,\infty, \qquad (2)$$

where the capital letter X denotes the random variable of the number of consumed contention slots for a payload transmission, which depends on P_{nt}.

The idle period has a random time duration. Therefore, it may be possible to transmit one or more payloads, depending on the length of the idle period. If the idle period is too short, no payload transmission is available. To transmit k payloads during an idle period, the number of consumed contention slots, Y_k, during k contention periods can be defined as the summation of k independent random variables of X:

$$Y_k = \underbrace{X_1 + X_2 + \cdots + X_k}_{k\ i.i.d.\ Random\ Variables}. \qquad (3)$$

The probability density function (PDF) of (3) can be calculated by the convolution integral using (2), as reported elsewhere [16]:

$$f_{Y_k}(y) = \left[\frac{1}{(k-1)!}\prod_{i=1}^{k-1}(y+i)\right]P_{nt}^y(1-P_{nt})^k, \qquad (4)$$
$$y = 0,1,\ldots,\infty.$$

At this point, the normalized payload length, L, can be introduced as

$$L = \frac{T_P}{T_C}, \{L > 0\} \in \mathbb{R}. \qquad (5)$$

where T_C is the contention slot length and T_P is a payload length. This normalization process can be used to determine the trade-off between the payload length and the contention slot length related directly to the contention period.

Using (5), the probability that k payloads are transmitted in a T second idle period was formulated as follows:

$$P_k = \Pr\left[k\cdot L + Y_k \le T < (k+1)\cdot L + Y_k + X\right]. \qquad (6)$$

Eq. (6) is related to three random variables: Y_k, X and T. For example, when the idle period, T, is assumed to be $5L$, the maximum number of payloads transmitted in the idle period is five if a secondary user accesses the first contention slot in every contention period. On the other hand, such a case seldom occurs. In normal situations, less than five payloads are generally transmitted in the idle period depending on the contention processes. In the worst case, no payload can be transmitted if the secondary users rarely access the white spectrum and almost all idle periods are consumed for the first contention process. Those cases are reflected by random variables, Y_k and X, and their PDFs in (2) and (4).

The random variable, T, models the duration of white space depending on the primary traffic characteristics, which, according to recent investigations of white space duration in [8-11], can be modeled well using an exponential random variable. Accordingly, when the CSMA/CA payload length is L, the PDF of the exponential random variable with the normalized mean value, $\lambda_C = \lambda / T_C$, where λ is the mean time duration of an idle period, is applied to (6), which can be rewritten as:

$$\begin{aligned} P_k\left(L,\lambda_C,Y_k,X\right) &= \int_{k\cdot L+Y_k}^{(k+1)\cdot L+Y_k+X}\frac{1}{\lambda_C}e^{-\frac{T}{\lambda_C}}dT \\ &= e^{-\frac{k\cdot L+Y_k}{\lambda_C}}\left(1-e^{-\frac{L+X}{\lambda_C}}\right), \end{aligned} \qquad (7)$$

The probability that k payloads will be transmitted in the exponentially-distributed idle period with the normalized mean value, λ_C, can be determined by averaging (7) over all cases of Y_k and X as follows:

$$\begin{aligned} P_k\left(L,\lambda_C\right) &= \sum_{x=0}^{\infty}\sum_{y=0}^{\infty}P_k\left(L,\lambda_C,y,x\right)\cdot f_X(x)\cdot f_{Y_k}(y) \\ &= \left(1-\frac{\left(1-P_{nt}\right)e^{-\frac{L}{\lambda_C}}}{1-P_{nt}\cdot e^{-\frac{1}{\lambda_C}}}\right)\cdot\left(\frac{\left(1-P_{nt}\right)e^{-\frac{L}{\lambda_C}}}{1-P_{nt}\cdot e^{-\frac{1}{\lambda_C}}}\right)^k \end{aligned} \qquad (8)$$

Using (8), the average IPU of a secondary network coordinated by CSMA/CA can be expressed as

$$\begin{aligned} C(L,\lambda_C) &= \frac{P_S}{\lambda_C}\sum_{k=0}^{\infty}k\cdot L\cdot P_k(L,\lambda_C) \\ &= \frac{L\cdot P_S(1-P_{nt})e^{\frac{1}{\lambda_C}}}{\lambda_C(e^{\frac{1+L}{\lambda_C}}+(P_{nt}-1)e^{\frac{1}{\lambda_C}}-P_{nt}e^{\frac{L}{\lambda_C}})}, \end{aligned} \qquad (9)$$

where P_S is the probability that a transmitted payload will be transmitted successfully without a collision between secondary users.

CSMA/CA has an inherent collision problem that cannot be resolved using the random backoff process [15]. A successful payload transmission can be made only if a secondary user from among N users accesses a contention slot. The corresponding successful transmission probability can be calculated easily as follows:

$$P_S = \frac{N \cdot P_t (1-P_t)^{N-1}}{1-(1-P_t)^N}. \tag{9}$$

3.2 Maximization of IPU in EDIP

In (9), the IPU is determined by three parameters, λ_C, L and P_{nt}. Of these three parameters, λ_C and P_{nt} are the pre-determined values depending on the primary traffic conditions and the CSMA/CA parameters, such as the minimum contention window size and the number of backoff stages, respectively. The only parameter that can be controlled by the secondary network is the secondary payload length, L. In addition, the contention slot length, which was resolved using the contention slot-normalized parameters λ_C and L, is a hidden but important parameter related to the IPU. Therefore, the focus of this section was to control the payload length, L, according to λ_C and P_{nt}.

Fig. 2 plots the mean IPU in (9). This figure suggests that the analytical results show very good agreement with the simulation results. In such a case, the transmission probability is determined by the number of secondary users $N = 8$, the minimum contention window size, $W_{min} = 15$, and the maximum backoff stage, $B_{max} = 6$ [15], which is a mandatory mode [18].

In general, the idle period in a primary spectrum accessed by multiple primary users with voice and data traffic is distributed exponentially with a mean value, λ, from tens to hundreds of milliseconds [9-11]. The contention slot duration, T_C, normally has a value ranging from 50 to 100 ms, even though it can vary depending on the physical transmission techniques adopted for the air interface in the CSMA/CA protocol. For these reasons, the values of λ_C were set to 500, 1000, 2000, and 3000 in Fig. 2. Fig. 2 shows that the average IPU increases initially, because the ratio of an effective payload transmission duration to the contention period improves with increasing normalized payload length. On the other hand, the normalized IPU begins to decrease above a certain normalized payload length because the idle period lost by the last secondary payload decreases due to the arrival of primary traffic, which becomes larger as the normalized payload length increases. This trade-off relationship generates the maximum normalized IPU at the optimal normalized payload length.

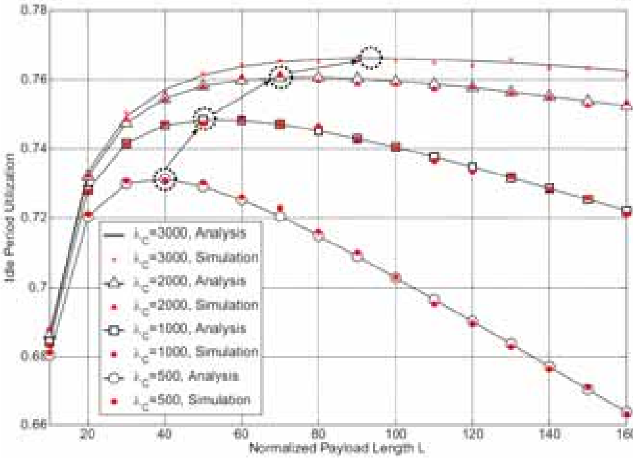

Fig. 2. Mean IPU: Maximized utilization point with respect to the normalized payload length exists due to trade-off between the payload length and contention period, and collided payload by primary traffic arrival.

$$\frac{\partial^2 C(L,\lambda_C)}{\partial L^2} = -\frac{Q \cdot e^{\frac{L}{\lambda_C}} \left(W \cdot (2\lambda_C + L) + e^{\frac{L}{\lambda_C}} (2\lambda_C - L)(e^{\frac{1}{\lambda_C}} - P_{nt}) \right) \left(e^{\frac{1}{\lambda_C}} - P_{nt} \right)}{\lambda_C^2 \left(W + e^{\frac{L}{\lambda_C}} (e^{\frac{1}{\lambda_C}} - P_{nt}) \right)^3} < 0. \tag{11}$$

Fig. 2 clearly shows that controlling the payload length maximizes the average IPU. Maximizing (9) by adjusting the value of L requires an examination of the concavity of the function with respect to L. For the variable, L, the second derivative of (9) can be proved to be a concave function when $Q = P_S(1-P_{nt})$ and $W = P_{nt} - 1$ in (11).

Generally, the payload length should not exceed the average idle period, λ_C, because the secondary payload might be too long to be transmitted successfully (i.e., due to a collision with primary traffic). Therefore, if a payload length value satisfying the condition $L \le 2\lambda_C$ is taken, and the second derivative of (9) has negative values, then (9) is concave with respect to L. (See the Appendix for detailed proof.) Therefore, the maximizer, L_{max}, of $C(\lambda_C, L)$ can be found using the first derivative of the function.

The first derivative of (9) with respect to L can be calculated as

$$\frac{\partial C(L,\lambda_C)}{\partial L} = \frac{Q \left(W \cdot \lambda_C + e^{\frac{L}{\lambda_C}} (\lambda_C - L)(e^{\frac{1}{\lambda_C}} - P_{nt}) \right)}{\lambda_C \left(W + e^{\frac{L}{\lambda_C}} (e^{\frac{1}{\lambda_C}} - P_{nt}) \right)^2}. \tag{12}$$

The maximizer, L_{max}, of $C(L,\lambda_C)$ can be obtained by solving the equation, $\partial C(\lambda_C, L)/\partial L = 0$ with respect to L. From the concavity of (11), the equation, $\partial C(\lambda_C, L)/\partial L = 0$, has a unique solution:

$$L_{max} = \lambda_C \left(1 + LW \left[\frac{-1 + P_{nt}}{e - e^{1 - \frac{1}{\lambda_C}} P_{nt}} \right] \right). \qquad (13)$$

where $LW(X)$ is the Lambert-W function. $Y = LW(X)$ is the solution to $Ye^Y = X$ [17]. The maximized IPU can be obtained by substituting the maximizer, L_{max}, into (9).

The result in (13) supports the motivation for this investigation on the CSMA/CA in cognitive radio, which is the effect of the primary traffic on the performance of the secondary network. As shown in (13), achieving the maximum IPU of a CSMA/CA-operated secondary network means considering not only the parameters related directly to the CSMA/CA protocol to control, P_{nt}, but also the statistical characteristics, such as the mean value, λ_C.

The maximum throughput of the secondary network can be obtained directly using the analytical result for the maximum IPU. Applying (13) to (9), the maximum throughput of the secondary network can be calculated as follows:

$$R(L_{\max}, \lambda_C, \mu_C) = \frac{\lambda_C}{\lambda_C + \mu_C} \cdot C\left(L_{max}, \lambda_C\right) \cdot B \cdot E \qquad (14)$$

where μ_C is the average primary user service period normalized by the contention slot, T_C, and B and E are the bandwidth of the primary spectrum and the spectral efficiency of a secondary link measured in bps/hz, respectively. This system depends only on the statistical characteristics of the idle periods. The statistical characteristics of the primary user service period are not relevant to this analysis. The first term, $\lambda_C / (\lambda_C + \mu_C)$, in (14) is denoted by κ_C, which is the portion of the idle period in the primary spectrum. For example, case $\kappa_C = 0$ means that the primary spectrum is fully utilized by the primary users. Inversely, if $\kappa_C = 1$, no primary user communications are occurring in the primary spectrum. The case, $\kappa_C = 0.8$, means the primary spectrum is in the idle state eighty percent of the time on average.

Owing to the maximum IPU analysis in EDIP, the maximum throughput of a secondary network using the CSMA/CA protocol can be achieved by controlling the payload size with (13), which reflects the average idle period duration. In addition, the secondary communication delay cannot be guaranteed in the EDIP case, where secondary communication can be halted at any time by the sudden arrival of primary traffic, and where the service duration of the arrived primary traffic is unknown to the secondary system. Therefore, EDIP supports only non-real-time applications, such as e-mail messaging, data transfer, or other applications, which are not urgent, provided the achievable throughput in (14) is sufficient.

On the other hand, wireless communication systems have been used to service a variety of real-time applications. If such real-time applications cannot be supported in the EDIP, then it is important to consider how else they might be supported using the CSMA/CA protocol in cognitive radio communications.

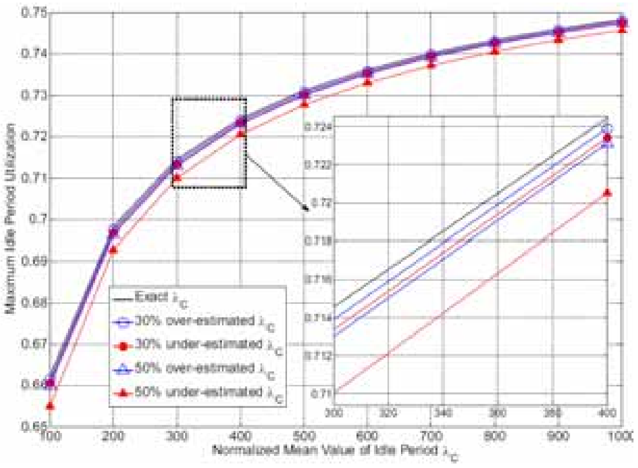

Fig. 3. Maximized IPU vs. normalized mean value of idle periods with an estimation error of λ_C: The maximized IPU can be achieved using the over-estimated values of normalized mean value of the idle periods even if the estimation error reaches 50 percentage.

In contrast to throughput analysis for non-real-time applications, investigations of real-time applications require a delay analysis as well as throughput analysis. In the next section, the analytical framework will be extended to an analysis of the delay performance of the CSMA/CA protocol.

4. Numerical Results

This section reports the numerical results based on the performance analysis of CSMA/CA in EDIP. For the EDIP, this section discusses the maximum IPU and throughput using (13) and (14).

4.1 Effect of the Estimation Error of Mean Idle Period

Consistent with the results in Fig. 2, the same values of P_t were used for the number of secondary users, $N = 8$. Figs. 3 and 4 plot the maximum IPU by the optimum value, L_{max}. The optimal payload length, L_{max}, can be obtained by applying P_{nt} and λ_C to Eq. (13).

To calculate P_{nt} as defined in (1), P_t and N must be estimated based on the minimum contention window size used in reference [15] and the number of secondary transmitter identifiers, such as the MAC addresses of the secondary users. An exact estimation of λ_C is not achieved easily, but it can be obtained by measuring the statistics of the idle period depending on the primary traffic [8, 9]. Therefore, this study evaluated the maximized IPU with the optimal payload length in (13) and considered the estimation errors of P_{nt} and λ_C.

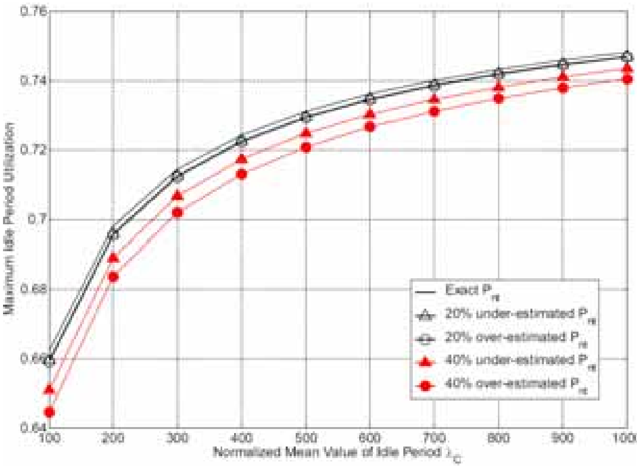

Fig. 4. Maximized IPU vs. normalized mean value of idle periods with estimation error of P_{nt} : The Maximized IPU can be nearly achieved with under-estimated values of non-transmission probability.

In Fig. 3, the exact maximized IPUs are plotted using the 30 and 50 % over- and under-estimated values of λ_C. L_{max} with a 30 % error causes the secondary network to have only a small amount of performance degradation. In particular, an over-estimated value of L_{max} causes less performance degradation for the secondary network than the under-estimated value. For L_{max} with a 50 percent error, the performance difference between the under- and over-estimated L_{max} values is more significant. Such behavior is caused by the slope of the normalized IPU function after the optimal value of L_{max}, which is less steep than before L_{max}, as shown in Fig. 2. Therefore, even if the value of L_{max} is over-estimated, the performance degradation due to an estimation error is not serious.

4.2 Effect of the Estimation Error of Number of Secondary Users

Fig. 4 shows the performance degradation due to the estimation error in P_{nt}. In this case, the under-estimated value of P_{nt} performs better than the over-estimated value. The maximum IPU loss is limited only from 1 to 4 % of the maximum IPU depending on the mean value of idle periods, even though the value of P_{nt} is 40 % over-estimated. Looking at (1), P_{nt} is a function of N, W_{min} and B_{max}. In practice, however, N solely determines P_{nt} because W_{min} and B_{max} are given values depending on the CSMA/CA protocols. Therefore, the estimation error of P_{nt} is due to that of N. On the other hand, there is no need to estimate N precisely. In Fig. 4, a 40 % over-estimated value of P_{nt} means that secondary users poorly estimate $N = 2, 10$ instead of the exact values $N = 10, 40$, respectively, because $P_{nt} = 0.792, 0.574, 0.410$ when $N = 2, 10, 40$, respectively. Therefore, near-optimal performance of the secondary network can be expected even if the secondary users cannot detect a few of the other users' MAC addresses because of the weak channel condition among them.

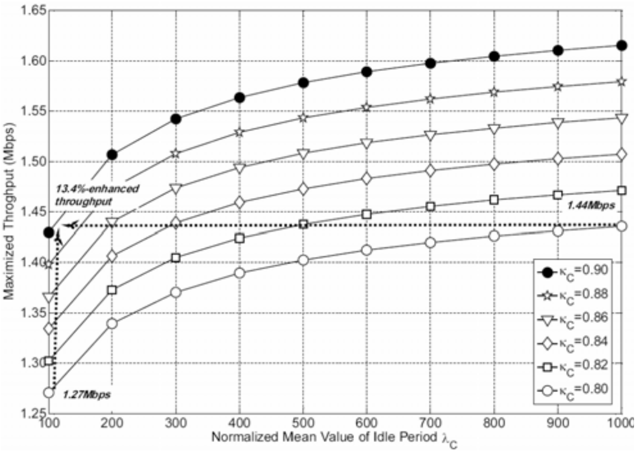

Fig. 5. Maximized throughput of the secondary network with four secondary users when a portion of the primary spectrum in the idle state κ_C is from 0.8 to 0.9: To achieve higher maximized throughput, both a larger portion of the primary spectrum in the idle state κ_C and a larger mean value of idle periods are needed.

Based on the results shown in Figs. 3 and 4, the maximized idle period utilization can almost be achieved without requiring precisely estimated parameters. Therefore, the analyzed average idle period utilization in (9) and its maximizer, L_{max}, in (13) can practically provide the design criteria for CSMA/CA-based secondary networks and evaluate them.

4.3 Effect of the Primary Users' Traffic Arrival

Fig. 5 plots the maximized throughput for the secondary network. The figure provides an interesting result concerning the effect of the absolute amount of idle periods and the length of idle periods on the maximized throughput of the CSMA/CA-operated secondary network. The secondary network can achieve 1.44 Mbps when $\kappa_C = 0.80$ and $\lambda_C = 1000$, which is larger than the maximized throughput when $\kappa_C = 0.90$ and $\lambda_C = 100$. A comparison of the two cases showed that although the latter case surely has more idle time than the former, the former case achieves a larger maximized throughput. Intuitively, the larger the number of idle periods, the higher the throughput of the secondary network. The result shows that the average idle period length is also an important factor if the secondary network is to achieve higher cognitive radio throughput. Therefore, regardless of the number of idle periods in a primary spectrum, if the average length of the idle periods is short due to the frequent arrival of primary traffic, the primary spectrum cannot be considered appropriate for a CSMA/CA-operated secondary network, where the goal is to achieve high throughput.

5. Concluding Remarks

This paper provided an analytical framework for evaluating the performance of the CSMA/CA-based cognitive radio networks in the EDIP. In the EDIP, the tradeoff relationship between the overhead for the contention periods and the collision loss due to primary traffic arrival was analyzed quantitatively with respect to the secondary payload length. Finally, this study determined the optimal payload length to maximize the IPU in EDIP that is both ideal and practically achievable. Overall, the CSMA/CA-based cognitive radio network can achieve the maximum throughput performance by adjusting the payload length in all situations where the statistical features of the primary traffic satisfy EDIP.

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Appendix

Proof of Concavity

When $Q = P_S(1-P_{nt})$ and $W = P_{nt} - 1$, the denominator of (11) always has a positive value according to the following relationship:

$$(e^{\frac{1}{\lambda_C}} - P_{nt})e^{\frac{L}{\lambda_C}} - (1-P_{nt}) \geq (1-P_{nt})(e^{\frac{L}{\lambda_C}} - 1) \geq 0,$$

where the equality is satisfied only when λ_C approaches infinity.

No secondary payload can be transmitted with a high probability if the payload length is larger than the duration of the idle period. To prevent such a case, L must not be larger than λ_C. Accordingly, $2\lambda_C > \lambda_C > L$ if $\lambda_C \neq 0$, so the numerator of (11) is also positive. Eq. (11) originally has a negative sign, so (11) is negative for any value of L that satisfies $2\lambda_C > L$.

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