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Performance analysis of opportunistic CSMA schemes in cognitive radio networks

Bang Chul Jung[1] · **Woongsup Lee**[2]

Abstract In this paper, we consider *underlay* cognitive radio (CR) networks where an amount of interference caused by secondary stations (STAs) has to be kept below a predefined level, which is called interference temperature. We propose *opportunistic* p-persistent carrier sense multiple access schemes for the CR networks, which opportunistically exploit wireless channel conditions in transmitting data to the secondary access point. We also devise an adaptive interference-level control technique to further improve quality-of-service of a primary network by limiting the excessive interference due to collisions among STAs. The performances of the proposed schemes are mathematically analyzed, and they are validated with extensive computer simulations. The simulation results show that the proposed schemes achieve near optimal throughput of the secondary network while they are backward-compatible to the conventional p-persistent CSMA scheme.

Keywords Cognitive radio network · Spectrum sharing · Random access · CSMA · Interference temperature

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✉ Woongsup Lee
wslee@gnu.ac.kr

Bang Chul Jung
bcjung@cnu.ac.kr

[1] Department of Electronics Engineering, Chungnam National University, Daejeon, Republic of Korea

[2] Department of Information and Communication Engineering, Gyeongsang National University, Tongyeong, Republic of Korea

1 Introduction

Recently, cognitive radio (CR) technology [3, 4] has been considered as an attractive solution for utilizing scarce radio resource in an efficient way. In the CR technology, the secondary (unlicensed) users, coexisting with primary (licensed) users, are allowed to utilize the spectrum of the primary users (PUs) as long as the amount of interference caused by secondary transmitters to a primary receiver (PR) is below the predefined threshold[1] [5–7].

The study of CR technology was initially inspired by an interference temperature model, which was proposed by the Federal Communication Commission (FCC) in 2003 as a means of regulating the received interference temperature at a PR [8]. Although the study item of the interference temperature model was terminated in 2007 [9], many recent academic studies have been conducted regarding CR technology afterwards, especially, in the area of scheduling and resource allocation in CR systems [6, 7, 10–18].

1.1 Recent research on CR systems and decentralized scheduling in CR systems

The fundamental capacity of a CR system was studied in [14] and [15] under additive white Gaussian noise (AWGN) and fading channel environments, respectively. Later, research in [6] studied the capacity limit of a CR system with multiple secondary users (SUs). Specifically, the authors in [6] proposed a centralized resource management for the SU network, which performs an efficient resource allocation, while the allowable interference constraint at the PR is not violated. However, in order to

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[1] This interference constraint guarantees that the PR can accept only predetermined degradation of its quality of service (QoS).

perform the optimal scheduling proposed in [6], all SUs must exchange full or partial information on the interference channel between secondary transmitter and the PR, which can result in huge signaling overhead, especially when the number of users in the secondary network increases. This kind of centralized schemes for CR systems has limited applications in practice due to high signaling overhead. Accordingly, a decentralized schemes with low signaling overhead will be preferable[2].

In the light of its necessity, decentralized scheduling schemes, i.e., medium access control (MAC) protocols, for CR systems have been investigated extensively [17, 18, 21–29]. In [21], the authors assumed that primary and secondary systems share the same frame structure. Based on the partially-observed Markov decision process (POMDP) framework, the access strategies for the secondary system to exploit spectrum holes between bursty transmissions of a PU were proposed. The CSMA based practical and heuristic decentralized MAC protocols were proposed in [22, 23]. Decentralized maximum weight scheduling for CR systems using queue length was proposed in [18]. Moreover, the bandwidth and delay of CSMA based MAC for CR systems were investigated in [17]. Futhermore, in [24], the authors considered the decentralized MAC protocol for heterogeneous CR network, where unfairness problems caused by uncoordinated PU detection ability and uncoordinated spectrum unit size were taken into account.

The joint optimization of spectrum access and other aspects of system was also investigated [25, 26]. To be more specific, cooperative power and contention control MAC was proposed in [25], where both multichannel hidden terminal problem and exposed terminal problem were taken into account. Moreover, the authors of [26] proposed a decentralized cognitive MAC which jointly optimizes spectrum sensing and spectrum access. Furthermore, in [27], the decentralized MAC protocol for an ad hoc CR network was proposed where historical prediction method was utilized to predict the arrival of PUs, and the utilization of channel negotiation window by CR network was also considered. In addition, the use of full-duplex transmission to solve the problem related to collision among SUs was considered in [28], in which the collision ratio, spectrum usage ratio and optimal contention window size were analytically derived. Finally, the testbed for validating decentralized multichannel cognitive MAC protocol was implemented using Universal Software Radio Peripheral (USRP) in [29].

One common drawback of decentralized MAC protocols is that it is unable to efficiently exploit time-varying channel condition, i.e., opportunistic scheduling, unlike centralized MAC protocols [30, 31], due to the lack of global instantaneous channel condition. In other words, the achievable throughput of decentralized MAC protocol is lower compared to that of a centralized approach. Aforementioned works did not consider this problem in the decentralized MAC protocol. Recently, the authors of [32] and [33] proposed a novel way to use opportunistic scheduling in the decentralized MAC. Especially in [33], instantaneous local channel condition was used to prioritize users waiting to send packets to a common access point where the upper bound of throughput which can be achieved with the use of a centralized scheduler, can be obtained in a distributed scheme. It should be noted that the opportunistic scheduling proposed in [33] is easy to implement because each node adjusts its transmission by comparing its channel condition with given thresholds. Although the use of opportunistic scheduling in decentralized CR MAC is beneficial, to the best of our knowledge, the use of opportunistic scheduling in decentralized CR MAC has not been properly taken into account in the literature [1, 17, 18, 21–29].

1.2 Main contributions

We herein propose *cognitive opportunistic p*-persistent CSMA (COpCSMA) schemes as decentralized MAC protocols for CR systems. The contributions of this paper are as follows:

- Novel decentralized opportunistic random access schemes for CR networks, which we denote as COpCSMA schemes, are devised. The proposed COpCSMA schemes efficiently exploit the opportunity in the channel between the secondary stations (STAs) and the secondary access point (SAP), i.e., signal channel, and also the channel between the STAs and the PR, i.e., interference channel, such that the optimal throughput can be achieved in a decentralized scheme where the global instantaneous channel condition is not needed. The use of opportunistic scheduling is the main difference of our work compared with our previous work [1] and previous works on decentralized MAC protocols for CR systems [17, 18, 21–29]. The proposed COpCSMA schemes are fast-to-market because they are backward compatible to the conventional CSMA schemes. We also propose an adaptive interference-level control scheme to further improve

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[2] Most emerging wireless applications, such as vehicle-to-vehicle (V2V) communications, vehicle-to-infrastructure (V2I) communications, or millimeter wave communications, operate in a decentralized manner. For instance, the IEEE 802.11p system [19, 20], which is also called the wireless access in vehicular environments (WAVE) protocol, is based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol which is one of the most popular distributed scheduling algorithm.

the QoS of the primary network, which has not been proposed in neither our previous work[3] [1] or previous works on decentralized MAC protocols for CR systems [17, 18, 21–29].
- We provide a rigorous mathematical analysis on the throughput of the proposed COpCSMA schemes. Moreover, through numerical results, we also verify the correctness of our analysis and evaluate the performance of the proposed COpCSMA schemes. Furthermore from numerical results, we find that the nearly optimal throughput can be achieved using our proposed scheme while assuring the QoS of the primary users.

The rest of the paper is organized as follows. In Sect. 2, the system model considered in this paper is described. The conventional p-persistent CSMA scheme and the transmit power control scheme considering the CR environment are provided in Sect. 3. The proposed COpCSMA schemes are depicted and the performance of proposed schemes are mathematically analyzed in Sect. 4. An adaptive interference-level control scheme for improving the QoS of the primary network is given in Sect. 5. Our numerical results are given in Sects. 6 and 7 concludes the paper.

2 System model

Figure 1 shows a system model with a single SAP, multiple STAs, and a single PR utilizing the same spectrum band. We assume that each STA accesses the channel and transmits its data in a decentralized and randomized manner. Given that the primary network has the priority for the band, the secondary network, i.e., SAP and STAs, is required to control its transmission such that the QoS constraints imposed by the PR is not violated.

In the system model, STAs communicate with the SAP through quasi-static fading channels such that the fading remains unchanged until the transmission of a packet is finished and it changes at the beginning of a new random access process. When the STA$_i$ accesses the channel, the received signal of the SAP, y, is given by

$$y = h_i x_i + n_i, \tag{1}$$

where h_i indicates a channel coefficient between the STA$_i$ and the SAP, which follows a Rayleigh distribution with the parameter $\sqrt{\frac{\mu_H}{2}}$. In (1), x_i is the transmitted signal of STA$_i$ whose power is P_i and n_i is the thermal noise which is modeled as AWGN. Herein, the power density of noise is assumed to be 1 and the maximum transmit power of a STA is assumed to be $\overline{P}$. Furthermore, we let g_i be the channel coefficient between the STA$_i$ and the PR[4], which is also modeled as a Rayleigh distributed random variable with the parameter $\sqrt{\frac{\mu_G}{2}}$. In addition, both h_i and g_i are assumed to be independent and identically-distributed (i.i.d.).

For a simpler expression, we define $\eta_i \triangleq |h_i|^2$ and $\gamma_i \triangleq |g_i|^2$. Note that both η_i and γ_i follow an exponential distribution. Therefore, the probability density function (PDF) of η_i and γ_i, which we denote as $f_\eta(x)$ and $f_\gamma(y)$, can be written as follows.

$$f_\eta(x) = \frac{1}{\mu_H} e^{-\frac{x}{\mu_H}}$$
$$f_\gamma(y) = \frac{1}{\mu_G} e^{-\frac{y}{\mu_G}}.$$

It is worth noting that η_i can be obtained by measuring the signal strength of the received packet from the SAP. Similarly, γ_i can be obtained by overhearing the preamble transmitted by the PR when the PR operates as a transmitter.

Herein, we assume that the achievable rate of STAs can be specified by the Shannon formula, i.e., the rate of STA$_i$ becomes $\log_2(1 + P_i\eta_i)$. When STA$_i$ transmits its data, the PR is affected by the undesired interference with the power $\gamma_i P_i$. In order to guarantee the QoS of the PR, an *allowable interference-level* Q can be used[5]. Based on the value of Q, the STAs can control their transmit power appropriately not to disturb the PR, i.e., STA$_i$ adjusts its transmit power to satisfy the following inequality.

$$\gamma_i P_i \leq Q. \tag{2}$$

It should be noted that when more than one STA transmit data, the amount of total interference can exceed Q. This case will be taken into account in Sect. 5.

3 p-Persistent CSMA with transmit power control

3.1 Conventional p-persistent CSMA

The CSMA protocols have been widely used in modern wireless communication systems such as WLAN due to their flexibility. Especially, p-persistent CSMA (pCSMA) in which a node transmits with probability p and defers with the probability $(1-p)$ when the shared medium is

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[3] In addition to this difference, we have also considered more sophisticated transmit power control scheme in our work compared with our previous work [1].

[4] In this paper, we assume that the number of PR is one. However, when multiple PRs coexist, g_i can be selected by referring the channel condition of the PR whose channel gain is largest, i.e., μ_G is highest.

[5] The proper value of Q can be notified by the PR or the SAP.

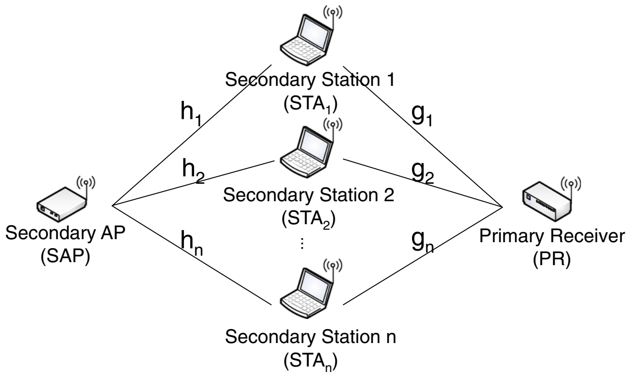


Fig. 1 System model

idle [34], is one of the most popular schemes, e.g., the MAC protocol of the IEEE 802.11 system can be approximated by the pCSMA [35].

The operational procedure of the conventional pCSMA is depicted in Fig. 2. In the pCSMA protocol, the system operates in time-slotted manner whose slot size is set to a in this paper, and all transmissions start at the beginning of a slot. We assume that the length of a transmission period (TP) is 1 for all transmissions. If one STA transmits a packet at time $t = 0$, all the other STAs have to wait until $t = 1 + a$ such that ongoing transmission is terminated. Packets from STAs can be modeled as a Poisson process with offered load G, which is related to the average number of active STAs in the system [33]. Given that multiple STAs can contend for the shared medium at the beginning of slot, the TP of STA can be started after random delay which we denote as the initial random transmission delay (IRTD).

For the conventional pCSMA, the number of successfully transmitted bits per unit time, $S_c(G,p,a)$, can be calculated as follows [33].

$$S_c(G,p,a) = \frac{(1-e^{-aG})R_c}{(1-e^{-aG})[a\overline{t'}\pi_0 + a\bar{t}(1-\pi_0)+1+a]+a\pi_0}, \quad (3)$$

where $\bar{t}$ and $\overline{t'}$ denote the average length of the IRTD before the first and the other TPs, respectively [34]. Furthermore, π_n is defined as

$$\pi_n = e^{[-(1+a)G]}\frac{[(1+a)G]^n}{n!}. \quad (4)$$

In addition, R_c represents the expected sum rate over the channel fading statistics and is given in a closed-form as

$$R_c = R_0 \sum\nolimits_{n=0}^{\infty} \pi_n p_s(n). \quad (5)$$

In (5), $p_s(n)$, which is given as $\frac{np(1-p)^{n-1}}{1-(1-p)^n}$, represents the probability that a packet is successfully transmitted without any collision in the presence of n STAs. Note that R_0 is the ergodic capacity of a single transmission and it can be given as follows.

$$\begin{aligned} R_0 &= \int_0^\infty f_\eta(\eta)\log_2(1+\eta)d\eta \\ &= \frac{e^{\frac{1}{\mu_H}}}{\ln 2}E_1\left(\frac{1}{\mu_H}\right), \end{aligned} \quad (6)$$

where $f_\eta(\eta)$ is the PDF of the signal channel gain η and $E_1(x)$ represents an exponential integral [36], which can be defined as follows.

$$E_1(x) = \int_x^\infty \frac{e^{-u}du}{u}. \quad (7)$$

3.2 Transmit power control considering CR networks

The conventional pCSMA was designed without considering the CR environment in which interference constraint exists such that it cannot be directly applicable to the CR networks, i.e., the amount of interference caused to the PR can exceed the maximum allowable level, Q.

To overcome this problem, a p-persistent CSMA with transmit power control (pCSMA-TPC) can be devised. Specifically, in the pCSMA-TPC, the transmit power of the STA$_i$, $P_i(\gamma)$, is controlled according to the channel gain γ_i, in order to satisfy the QoS of the primary network, i.e., the interference constraint (2). Accordingly, $P_i(\gamma)$ can be derived as

$$P_i(\gamma_i) = \begin{cases} \overline{P}, & \gamma_i \le Q/\overline{P} \\ Q/\gamma_i, & \gamma_i > Q/\overline{P} \end{cases}, \quad (8)$$

where $\overline{P}$ is the maximum transmit power.

Then, the expected sum rate of the pCSMA-TPC scheme is written as

$$R_p = R_{p,1}\sum_{n=0}^{\infty}\pi_n p_s(n). \quad (9)$$

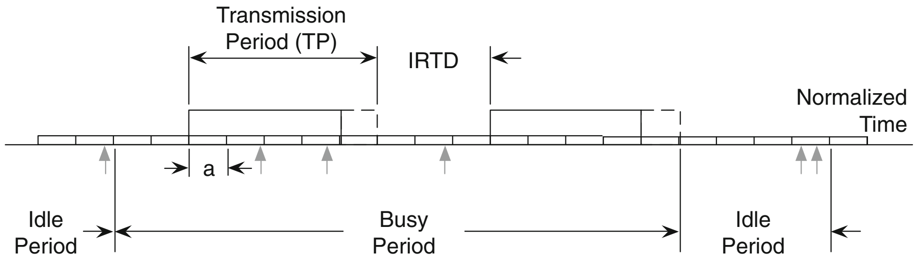
In (9), $R_{p,1}$ is the expected value of achievable capacity for successful transmission without collision, which can be given by

$$R_{p,1} = \int_0^\infty \int_0^\infty f_\Gamma(\gamma) f_\eta(\eta)\log_2(1+P_i(\gamma)\eta)d\eta d\gamma, \quad (10)$$

where $f_\Gamma(\gamma)$ is the PDF of the interference channel gain γ.

By referring the transmit power control rule in (8), $R_{p,1}$ can be further summarized as shown below.

Fig. 2 Operation of the conventional *p*-persistent CSMA



$$
\begin{aligned}
R_{p,1} &= \int_0^{Q/\overline{P}} \int_0^{\infty} f_{\Gamma}(\gamma) f_{\eta}(\eta) \log_2(1+\overline{P}\eta) d\eta d\gamma \\
&\quad + \int_{Q/\overline{P}}^{\infty} \int_0^{\infty} f_{\Gamma}(\gamma) f_{\eta}(\eta) \log_2\left(1+Q\frac{\eta}{\gamma}\right) d\eta d\gamma \\
&= \mathbb{E}_{\eta}\left[\log_2(1+\overline{P}\eta)\right] F_{\Gamma}\left(Q/\overline{P}\right) \\
&\quad + \int_{Q/\overline{P}}^{\infty} \int_0^{\infty} f_{\Gamma}(\gamma) f_{\eta}(\eta) \log_2\left(1+Q\frac{\eta}{\gamma}\right) d\eta d\gamma,
\end{aligned}
\tag{11}
$$

where $\mathbb{E}_{\eta}[\cdot]$ represents an expectation over the channel gain η_i and $F_{\Gamma}(\cdot)$ is a cumulative density function (CDF) of an interference channel gain γ_i.

Unfortunately, the closed-form of $R_{p,1}$ does not exist. Instead, we derive the lower bound of $R_{p,1}$ using Jensen's inequality based on the fact that the function $\log_2\left(1+\frac{1}{x}\right)$ is convex for $x > 0$. The lower bound can be derived as follows.

$$
\begin{aligned}
R_{p,1} &\geq \mathbb{E}_{\eta}\left[\log_2(1+\overline{P}\eta)\right] F_{\Gamma}\left(Q/\overline{P}\right) \\
&\quad + \int_0^{\infty} f_{\eta}(\eta) \log_2\left(1+\frac{Qe^{\frac{Q}{\overline{P}\mu_G}}}{\mu_G+\frac{Q}{\overline{P}}}\eta\right) d\eta \\
&= e^{\frac{1}{\overline{P}\mu_H}} E_1\left(\frac{1}{\overline{P}\mu_H}\right)\left(1-e^{-\frac{Q}{\overline{P}\mu_G}}\right) + e^{\left(\frac{\mu_G+\frac{Q}{\overline{P}}}{Qe^{\frac{Q}{\overline{P}\mu_G}}}\right)} E_1\left(\frac{\mu_G+\frac{Q}{\overline{P}}}{Qe^{\frac{Q}{\overline{P}\mu_G}}}\right).
\end{aligned}
\tag{12}
$$

4 Opportunistic *p*-persistent CSMA schemes for CR networks

In a pCSMA-TPC scheme, each STA accesses the medium with the fixed probability p while transmit power is adjusted according to the interference channel gain. However, there is no exploitation of the channel opportunity[6] in wireless channels, i.e., η_i and γ_i for the control of medium access. Therefore, in this section, we propose COpCSMA schemes by exploiting both η_i and γ_i in medium access. More specifically, in the COpCSMA schemes, each STA decides whether to access the medium by comparing η_i and/or γ_i with its predetermined threshold[7], which is determined using the statistics of the wireless channel. Given that both the signal and the interference channels have intrinsic randomness, the channel access will be performed in a random manner.

Herein, we first propose a COpCSMA-I scheme which only exploits the interference channel γ_i. With this scheme, a STA with smaller interference channel gain, i.e., γ_i is small, has the higher priority to access the medium, because the STA with small γ_i is likely to transmit with higher power which results in the improvement of system throughput. Secondly, a COpCSMA-II scheme is proposed where each STA accesses the medium in the order of higher channel gain, η_i. Finally, COpCSMA-III is devised using both interference and signal channel gain, i.e., γ_i and η_i. The detailed explanation on each scheme is given follows.

4.1 COpCSMA-I: Considering interference channel gain only

In a COpCSMA-I scheme, we only exploit channel opportunity in the interference channel, γ_i. More specifically, in the COpCSMA-I scheme, a set of thresholds related to the statistics of interference channel gain γ_i, is assigned to each STA. Given that the interference channel statistics for all STAs are the same, all STAs share a single set of thresholds, which we denote as $\{T_0, T_1, \ldots, T_k, \ldots\}$ where T_k's are designed in increasing order. When the STA$_i$ has not yet accessed the medium until the $(k-1)$-th

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[6] The exploitation of the channel opportunity means that the transmission of STAs is adjusted according to randomly varying channel conditions. For example, the STA with high signal channel gain can be selected in scheduling to achieve higher throughput.

[7] This technique of using statistics of the wireless channel for determining the threshold is motivated by [33], and we extend it to various CR scenarios in this paper. The proposed schemes differ from the scheme of [33] in the design of thresholds and medium access mechanism.

backoff slot, the STA$_i$ accesses the medium if the following inequality holds.

$$\gamma_i < T_k. \tag{13}$$

Note that the STA with smaller γ_i has higher chance to access the medium because the threshold T_k is increasing in order.

Then, the channel access probability of STA at backoff stage k is given by

$$P(\gamma_i < T_k | \gamma_i > T_{k-1}) = \frac{F_\Gamma(T_k) - F_\Gamma(T_{k-1})}{1 - F_\Gamma(T_{k-1})}. \tag{14}$$

In our COpCSMA schemes, we set the same probability p of channel access for all backoff stages, such that $P(\gamma_i < T_k | \gamma_i > T_{k-1}) = p, \forall k$, where $T_{-1} = -\infty$. By using the same access probability for all backoff states, the operation of the proposed COpCSMA schemes becomes almost the same with that of conventional pCSMA schemes, such that the proposed scheme will be backward compatible to the conventional pCSMA scheme, i.e., it is easy to be applied in current wireless systems. In this case, the threshold T_k can be determined as follows.

$$\begin{aligned} T_k &= F_\Gamma^{-1}\left(1 - (1-p)^{k+1}\right) \\ &= -\mu_G \ln\left((1-p)^{k+1}\right). \end{aligned} \tag{15}$$

Once a STA satisfies the channel access condition in (13), the transmit power can be adjusted according to (8). Then, the expected sum rate for COpCSMA-I, which we denote as R_{I}, is given as

$$R_{\mathrm{I}} = \pi_0 R_{\mathrm{I},1} + (1 - \pi_0) R_{\mathrm{I},2}, \tag{16}$$

where $R_{\mathrm{I},1} = R_{p,1}$ in (10), which is the achievable rate when a single STA contends for the medium. Moreover, $R_{\mathrm{I},2}$ is the expected sum rate when multiple STAs are considered, which is given as follows.

$$R_{\mathrm{I},2} = \sum_{n=1}^{\infty} \frac{\pi_n}{1 - \pi_n} p_s(n) \sum_{k=0}^{\infty} p_K(k) R_{\mathrm{I},0}(k), \tag{17}$$

where $p_K(k) = (1-p)^{kn}\left(1 - (1-p)^n\right)$, represents the probability that at least one STA transmits at the backoff slot k. Furthermore, $R_{\mathrm{I},0}(k)$ is the expected sum rate at the backoff slot k and it is given as follows.

$$\begin{aligned} R_{\mathrm{I},0}(k) &= \int_0^{Q/\overline{P}} \int_0^{\infty} f_\eta(\eta) f_\Gamma(\gamma | T_{k-1} \le \Gamma < T_k) \cdot \log_2\left(1 + \overline{P}\eta\right) d\eta d\gamma \\ &\quad + \int_{Q/\overline{P}}^{\infty} \int_0^{\infty} f_\eta(\eta) f_\Gamma(\gamma | T_{k-1} \le \Gamma < T_k) \cdot \log_2\left(1 + Q\frac{\eta}{\gamma}\right) d\eta d\gamma \\ &= \mathbb{E}_h\left[\log_2\left(1 + \overline{P}\eta\right)\right] \int_0^{Q/\overline{P}} f_\Gamma(\gamma | T_{k-1} \le \Gamma < T_k) d\gamma \\ &\quad + \int_{Q/\overline{P}}^{\infty} \int_0^{\infty} f_\eta(\eta) f_\Gamma(\gamma | T_{k-1} \le \Gamma < T_k) \cdot \log_2\left(1 + Q\frac{\eta}{\gamma}\right) d\eta d\gamma. \end{aligned} \tag{18}$$

The first term of (18) can be further derived as

$$\begin{aligned} &\mathbb{E}_\eta\left[\log_2\left(1 + \overline{P}\eta\right)\right] \int_0^{Q/\overline{P}} f_\Gamma(\gamma | T_{k-1} \le \Gamma < T_k) d\gamma \\ &\overset{(a)}{=} \begin{cases} 0, & Q/\overline{P} < T_{k-1} \\ \dfrac{F_\Gamma(Q/\overline{P}) - F_\Gamma(T_{k-1})}{F_\Gamma(T_k) - F_\Gamma(T_{k-1})} \dfrac{e^{\frac{1}{\overline{P}\mu_H}}}{\ln(2)} E_1\left(\dfrac{1}{\overline{P}\mu_H}\right), & T_{k-1} \le Q/\overline{P} < T_k \\ \dfrac{e^{\frac{1}{\overline{P}\mu_H}}}{\ln(2)} E_1\left(\dfrac{1}{\overline{P}\mu_H}\right), & T_k \le Q/\overline{P} \end{cases} \end{aligned} \tag{19}$$

where (a) holds due to the following equality.

$$f_\Gamma(\gamma | T_{k-1} \le G < T_k) = \begin{cases} \dfrac{f_\Gamma(\gamma)}{F_\Gamma(T_k) - F_\Gamma(T_{k-1})}, & T_{k-1} \le \gamma < T_k \\ 0 & \text{otherwise} \end{cases}. \tag{20}$$

Furthermore, the second term of (18) can be obtained as shown below.

$$
\begin{aligned}
&\int_{Q/\overline{P}}^{\infty}\int_{0}^{\infty} f_\eta(\eta) f_\Gamma(\gamma | T_{k-1} \leq \Gamma < T_k) \log_2\left(1 + Q\frac{\eta}{\gamma}\right) d\eta d\gamma \\
&= \begin{cases}
\dfrac{\int_{Q/\overline{P}}^{T_k}\int_0^\infty f_\eta(\eta) f_\Gamma(\gamma)\cdot \log_2\left(1+Q\frac{\eta}{\gamma}\right) d\eta d\gamma}{F_\Gamma(T_k) - F_\Gamma(T_{k-1})}, & T_{k-1} \leq Q/\overline{P} < T_k \\
\dfrac{\int_{T_{k-1}}^{T_k}\int_0^\infty f_\eta(\eta) f_\Gamma(\gamma)\cdot \log_2\left(1+Q\frac{\eta}{\gamma}\right) d\eta d\gamma}{F_\Gamma(T_k) - F_\Gamma(T_{k-1})}, & Q/\overline{P} < T_{k-1} \\
0, & T_k \leq Q/\overline{P}
\end{cases} \\
&\overset{(b)}{\geq} \begin{cases}
\exp\left(\dfrac{1}{e^{-\frac{Q/\overline{P}}{\mu_G}}[\mu_G + \frac{Q}{\overline{P}}] - e^{-T_k/\mu_G}[\mu_G + T_k]}\right) E_1\left(\dfrac{1}{e^{-\frac{Q/\overline{P}}{\mu_G}}[\mu_G + \frac{Q}{\overline{P}}] - e^{-T_k/\mu_G}[\mu_G + T_k]}\right) \\
\quad \times \dfrac{1}{\ln(2)(F_\Gamma(T_k) - F_\Gamma(T_{k-1}))}, T_{k-1} \leq Q/\overline{P} < T_k \\
\exp\left(\dfrac{1}{e^{-T_{k-1}/\mu_G}[\mu_G + T_{k-1}] - e^{-T_k/\mu_G}[\mu_G + T_k]}\right) \\
\quad \times E_1\left(\dfrac{1}{e^{-T_{k-1}/\mu_G}[\mu_G + T_{k-1}] - e^{-T_k/\mu_G}[\mu_G + T_k]}\right) \\
\quad \times \dfrac{1}{\ln(2)(F_\Gamma(T_k) - F_\Gamma(T_{k-1}))}, Q/\overline{P} < T_{k-1} \\
0, T_k \leq Q/\overline{P}
\end{cases}
\end{aligned}
\tag{21}
$$

where (b) holds due to the Jensen's inequality. Note that the lower bound of the expected sum rate for COpCSMA-I scheme can be obtained using the last inequality of (21).

4.2 COpCSMA-II: Considering signal channel gain only

In a COpCSMA-II scheme, only the signal channel gain, i.e., η_i, is exploited in the opportunistic medium access. The operation of medium access is almost the same as that of the COpCSMA-I scheme except η_i is used in determining when to access medium. In fact, the set of thresholds and its access process of the COpCSMA-II scheme can be derived by referring the opportunistic pCSMA (OpCSMA) proposed in [33]. Specifically, the set of thresholds for the COpCSMA-II scheme can be obtained using the following equation.

$$
\begin{aligned}
T_k &= f_\eta^{-1}((1-p)^{k+1}) \\
&= -\mu_H \ln\left(1 - (1-p)^{k+1}\right).
\end{aligned}
\tag{22}
$$

It should be noted that the difference between the COpCSMA-I scheme and the COpCSMA-II scheme is that the set of thresholds in the COpCSMA-II scheme are in decreasing order while the set of thresholds in the COpCSMA-I scheme are in increasing order.

At the backoff slot k, each STA accesses the medium if $\eta_i > T_k$. Accordingly, the expected sum rate of the COpCSMA-II scheme, which we denote as R_{II}, can be given as

$$
R_{\mathrm{II}} = \pi_0 R_{\mathrm{II},1} + (1-\pi_0) R_{\mathrm{II},2}. \tag{23}
$$

Same as in (16), $R_{\mathrm{II},1}$ in (23) is the achievable rate when only one STA contends for the medium such that $R_{\mathrm{II},1} = R_{p,1}$. Moreover, $R_{\mathrm{II},2}$ which corresponds to the achievable rate when multiple STAs are contending in medium access, can be obtained by replacing $R_{\mathrm{I},0}(k)$ in (17) with $R_{\mathrm{II},0}(k)$, where $R_{\mathrm{II},0}(k)$ is given by

$$
\begin{aligned}
R_{\mathrm{II},0}(k) =& \int_0^{Q/\overline{P}} \int_0^{\infty} f_\eta(\eta|T_{k-1} > \mathrm{H} \geq \mathrm{T_k}) f_\Gamma(\gamma) \cdot \log_2\big(1+\overline{P}\eta\big) d\eta d\gamma \\
&+ \int_{Q/\overline{P}}^{\infty} \int_0^{\infty} f_\eta(\eta|T_{k-1} > \mathrm{H} \geq \mathrm{T_k}) f_\Gamma(\gamma) \cdot \log_2\left(1+Q\frac{\eta}{\gamma}\right) d\eta d\gamma \\
=& \frac{(1-e^{-\frac{Q}{\overline{P}\mu_G}}) C_H(\overline{P}, T_k, T_{k-1})}{f_\eta(T_{k-1}) - f_\eta(T_k)} \\
&+ \frac{\int_{Q/\overline{P}}^{\infty} \int_{T_k}^{T_{k-1}} f_\eta(\eta) f_\Gamma(\gamma) \log_2(1+Q\frac{\eta}{\gamma}) d\eta d\gamma}{f_\eta(T_{k-1}) - f_\eta(T_k)} \\
\overset{(c)}{\geq}& \frac{(1-e^{-\frac{Q}{\overline{P}\mu_G}}) C_H(\overline{P}, T_k, T_{k-1})}{f_\eta(T_{k-1}) - f_\eta(T_k)} \\
&+ \frac{\int_{T_k}^{T_{k-1}} f_\eta(\eta) \log_2\left(1 + \frac{Qe^{\frac{Q}{\overline{P}\mu_G}}}{\mu_G + \frac{Q}{\overline{P}}} \eta\right) d\eta}{f_\eta(T_{k-1}) - f_\eta(T_k)} \\
=& \frac{(1-e^{-\frac{Q}{\overline{P}\mu_G}}) C_H(\overline{P}, T_k, T_{k-1})}{f_\eta(T_{k-1}) - f_\eta(T_k)} + \frac{C_H\left(\frac{Qe^{\frac{Q}{\overline{P}\mu_G}}}{\mu_G + \frac{Q}{\overline{P}}}, T_k, T_{k-1}\right)}{f_\eta(T_{k-1}) - f_\eta(T_k)},
\end{aligned}
\tag{24}
$$

where (c) holds due to the Jensen's inequality and $C_H(\overline{P}, a, b)$ can be denoted as follows.

$$
\begin{aligned}
C_H(\overline{P}, a, b) =& \int_a^b f_\eta(\eta) \log_2(1+\overline{P}\eta) d\eta \\
=& \frac{e^{-\frac{a+b}{\mu_H}}}{\ln(2)} \Bigg(e^{\frac{b}{\mu_H}} \ln(1+\overline{P}a) - e^{\frac{a}{\mu_H}} \ln(1+\overline{P}b) \\
&+ e^{\frac{1+\overline{P}a+\overline{P}b}{+\overline{P}\mu_H}} \left(E_1\left(\frac{1+\overline{P}a}{\overline{P}\mu_H}\right) - E_1\left(\frac{1+\overline{P}b}{\overline{P}\mu_H}\right)\right)\Bigg).
\end{aligned}
\tag{25}
$$

4.3 COpCSMA-III: Considering both signal and interference channel gain

In the COpCSMA-III scheme, we assume that the STA$_i$ utilizes both the instantaneous signal and interference channel gains, i.e., γ_i and η_i, in determining when to access the medium. To this end, we propose the *effective channel gain*, f_i, as follows.

$$
\begin{aligned}
f_i \triangleq & P_i(\gamma_i) \times \eta_i \\
=& \begin{cases} \overline{P}\eta_i, & \gamma_i \leq Q/\overline{P} \\ \dfrac{Q\eta}{\gamma_i}, & \gamma_i > Q/\overline{P} \end{cases}.
\end{aligned}
\tag{26}
$$

The CDF of the effective channel gain is found as

$$
F_F(x) = 1 - e^{-\frac{x}{\overline{P}\mu_H}} + \left(\frac{\mu_G x}{\mu_G x + \mu_H Q}\right) e^{-\left(\frac{x}{\overline{P}\mu_H} + \frac{Q}{\overline{P}\mu_G}\right)},
\tag{27}
$$

where the detailed derivation is given in Appendix.

Given that $\Pr\{f_i > T_k | f_i < T_{k-1}\} = \frac{F_F(T_{k-1}) - F_F(T_k)}{F_F(T_{k-1})}$, the set of thresholds that maintains the medium access probability p for each step can be determined as follows[8].

$$
T_k = F_F^{-1}\left((1-p)^{k+1}\right).
\tag{28}
$$

The expected sum rate of the COpCSMA-III scheme is obtained from that of the COpCSMA-I scheme by replacing $R_{\mathrm{I},0}$ in (17) with $R_{\mathrm{III},0}(k)$, which is given as follows.

$$
\begin{aligned}
R_{\mathrm{III},0}(k) =& \int_0^\infty f_{F|T_{k-1} > F \geq T_k}(f | T_{k-1} > F \geq T_k) \log_2(1+f) df \\
=& \frac{1}{F_F(T_{k-1}) - F_F(T_k)} \int_{T_k}^{T_{k-1}} f_F(f) \log_2(1+f) df.
\end{aligned}
\tag{29}
$$

Note that the closed form solution of (29) exists, but it is too complex and lengthy. And, it is hard to find meaningful intuitions from the solution. Therefore, we omit the closed form solution in this paper.

5 Adaptive interference-level control scheme for satisfying the QoS of the primary network

In this section, we further investigate the excessive interference problem of our proposed scheme. Specifically, under the assumption that multiple STAs cannot transmit simultaneously, the interference constraint of primary network in (2) will not be violated. However, due to collisions among the secondary STAs[9], more than one STA can transmit at the same time which possibly results in the violation of the interference constraint at the PR. For instance, when STA$_1$ and STA$_2$ are transmitting at the same time with their transmit powers of Q/γ_1 and Q/γ_2, respectively, the interference constraint is violated because $\frac{Q}{\gamma_1}\gamma_1 + \frac{Q}{\gamma_2}\gamma_2 = 2Q > Q$, even if the transmit power of each STA is adjusted.

To resolve the violation problem, we propose an *adaptive interference-level control scheme*. In the proposed scheme, we define the *broadcasted allowable interference-level*, i.e., Q_{bc}, which can be notified to all STAs, either by the PR or the SAP, and Q_{bc} is used instead of Q, in the transmit power control. The proper value of Q_{bc} can be determined based on the violation probability[10] in the

---

[8] Unfortunately, the closed form of the inverse function of $F_F(x)$ does not exist, such that $\{T_k\}$ for the COpCSMA-III should be numerically calculated.

[9] Given that the transmission is scheduled in distributed manner, the collision is inevitable.

[10] The violation probability is the probability that the interference constraint is violated.

Table 1 Medium access rules and thresholds for each proposed scheme

Types	Access rule	Thresholds
pCSMA-TPC	Random access with prob. p	N/A
COpCSMA-I	$\gamma_i < T_k$	$T_k = -\mu_G \ln((1-p)^{k+1})$
COpCSMA-II	$\eta_i \geq T_k$	$T_k = -\mu_H \ln(1-(1-p)^{k+1})$
COpCSMA-III	$f_i \geq T_k$	$T_k = F_F^{-1}((1-p)^{k+1})$

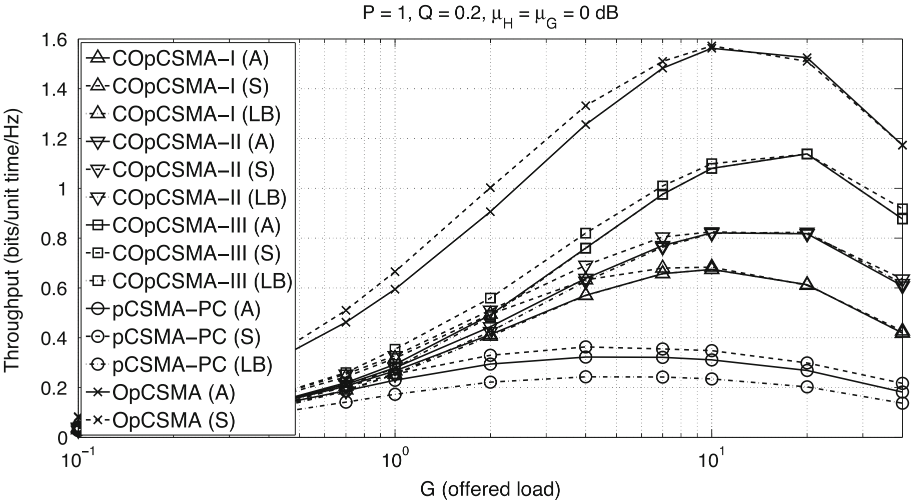


Fig. 3 Throughput of the proposed COpCSMA schemes and conventional schemes when $\mu_H = \mu_G = 0$ (dB) and $Q = 0.2$

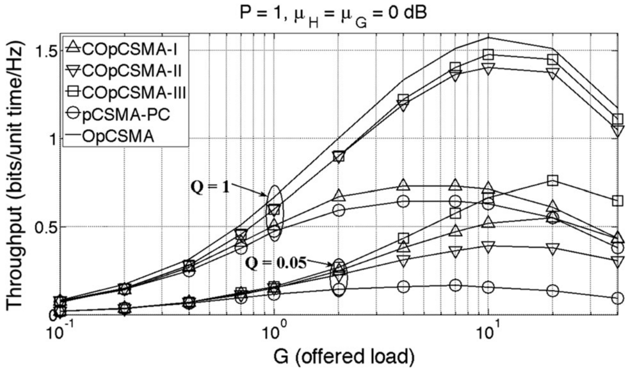


Fig. 4 Throughput of the proposed COpCSMA schemes and conventional schemes for different Q values

secondary network which is directly estimated from the offered load G of the secondary network. More specifically, $Q_{bc} = \frac{Q}{M}$, where M represents the allowable number of simultaneously transmitting STAs, e.g., $M = 2$ means that the simultaneous transmission of two STAs is allowable.

6 Numerical results

In this section, we evaluate the performance of the conventional pCSMA schemes and the proposed COpCSMA schemes through computer simulations in various environments. Moreover, the simulation results are compared with the results from the mathematical analysis. Furthermore, we also present the performance of the proposed adaptive interference-level control scheme introduced in Sect. 5 which reveals that by using our proposed scheme, the QoS of the primary network can be guaranteed with a reasonable performance loss of the secondary network.

In the performance evaluation, we assume that $\overline{P} = 1$, $\mu_H = \mu_G = 0$ dB, and the data packets are generated according to the Poisson process with offered load G. The medium access rules and thresholds for the proposed schemes are summarized in Table 1. When more than one STA tries to access the medium simultaneously, a collision occurs and the transmitted packets will be failed to be delivered to the SAP. In our simulation, data is gathered from 10,000 samples for each simulation scenario.

Figure 3 shows the throughput of the secondary network when $Q = 0.2$. For all schemes, the plot with (A) represents the results from mathematical analysis, the plot with (S) represents the simulation result, and the plot with (LB) represents the results from lower bound analysis. We can find that the conventional pCSMA-TPC yields the lowest throughput among all schemes because it does not exploit the opportunity in the wireless channels. Furthermore, we can find that none of the proposed schemes can exceed the performance of the OpCSMA which is proposed in [33] because the interference constraint of the PR, i.e., (2), degrades the throughput. Note that the QoS of the PR can be severely degraded if the OpCSMA scheme is used.

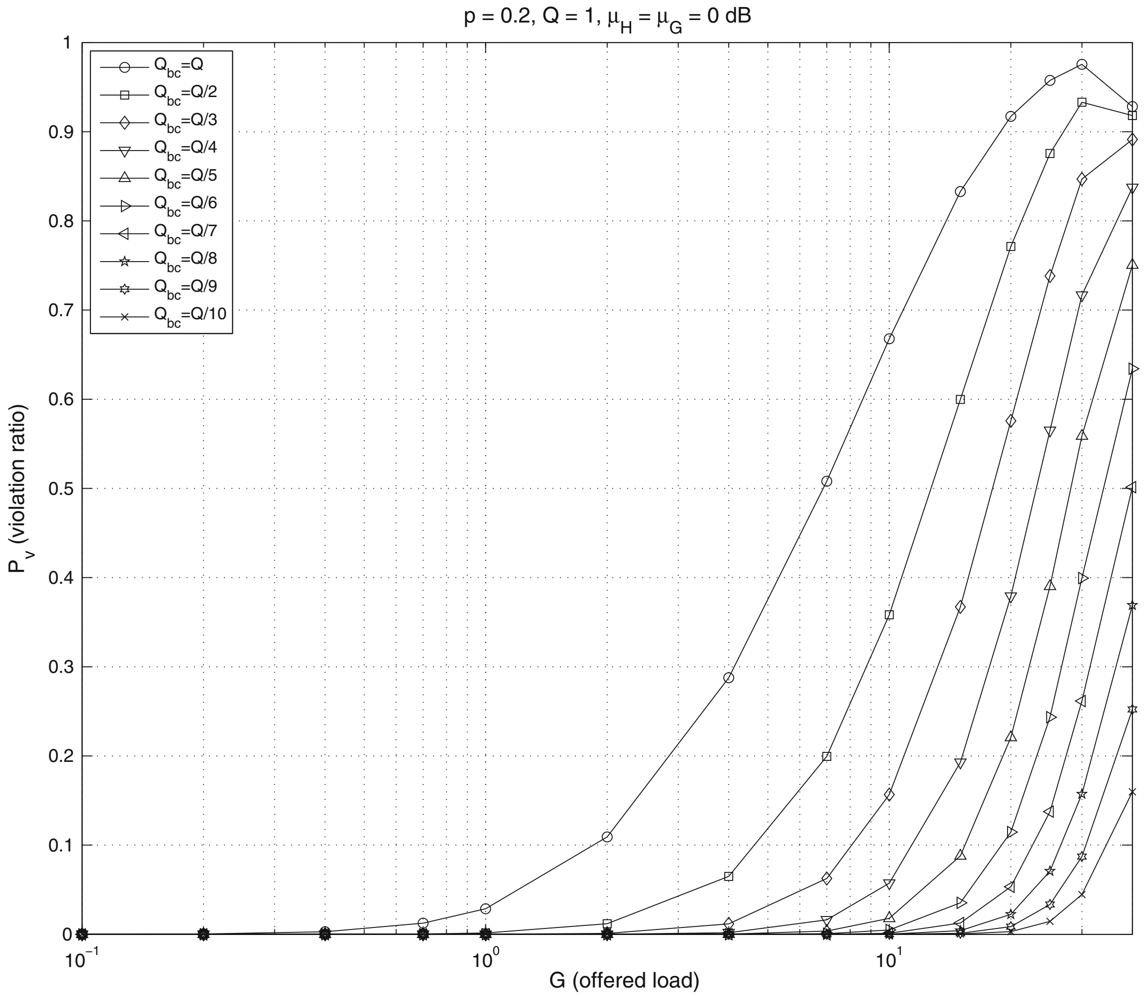


Fig. 5 Interference constraint violation ratio at the PR for different Q_{bc} values

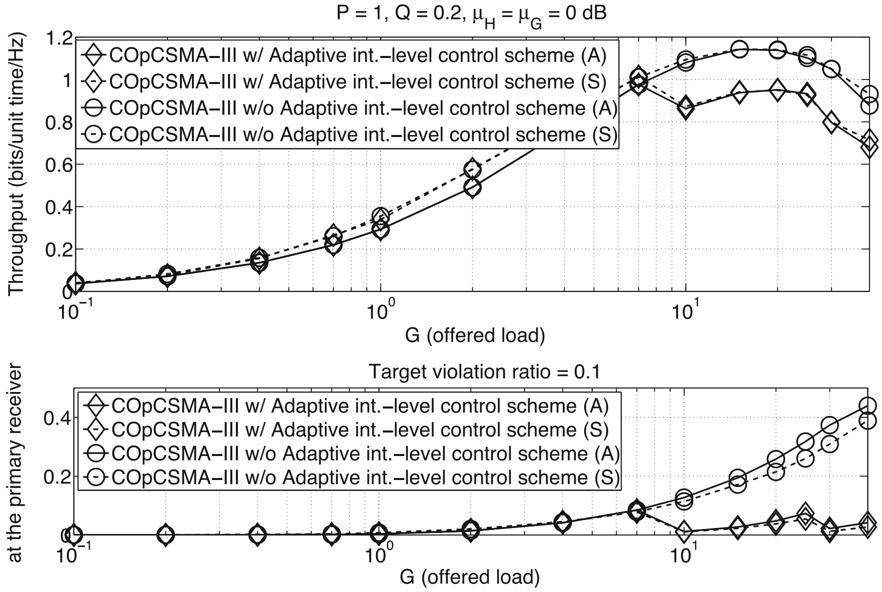
We can also find that the simulation results are well matched with the result from mathematical analysis. Moreover, the throughput of lower bound analysis is nearly the same with that of exact analysis models which shows that the derived lower bound is tight. Furthermore, we can see that the throughput of COpCSMA-III scheme is higher than other COpCSMA schemes because it exploits both η_i and γ_i while other schemes only exploit either η_i or γ_i.

The performance of the proposed schemes in different CR environments, i.e., different Q levels, is shown in Fig. 4. When the allowable interference-level is high, i.e., $Q = 1$, the throughput of COpCSMA-II and COpCSMA-III schemes is almost the same with that of OpCSMA. On the other hand, the COpCSMA-I scheme, which exploits interference channel only, performs almost the same as the pCSMA-TPC scheme. That is, at high Q, interference channel information may not be useful. However, when the allowable interference-level is low, i.e., $Q = 0.05$, all three COpCSMA schemes perform worse than the OpCSMA scheme in view of the throughput. Interestingly, when Q is low, the throughput of the COpCSMA-I scheme is higher than that of the COpCSMA-II scheme, because the effect of interference channel, γ_i, is more significant compared to that of data channel, η_i.

Through Figs. 3 and 4, we find that the COpCSMA-III scheme outperforms the COpCSMA-I and COpCSMA-II schemes. However, the COpCSMA-III scheme has the problem of high computational burden on STAs, because it needs to continuously monitor η_i and γ_i. As an alternative solution to the COpCSMA-III scheme, the COpCSMA-I and the COpCSMA-II schemes can be used. The COpCSMA-I scheme is suitable when Q is low, or equivalently, when μ_G is high, i.e., the STAs are very close to the PR. On the other hand, the COpCSMA-II scheme is applicable when Q is high or, equivalently, when μ_G is low, i.e., STAs are far away from the PR.

Figure 5 shows the violation probability which we denote as P_v, at the PR for different Q_{bc} values when the proposed adaptive interference-level control scheme is used. In the simulation, $\overline{P}$ and Q are set to 0.2 and 1,

Fig. 6 Performance evaluation of the proposed adaptive interference-level control scheme at $\mu_H = \mu_G = 0$ (dB) and $Q = 0.2$. *Upper* and *lower* plots represent throughput and violation ratio for varying offered load



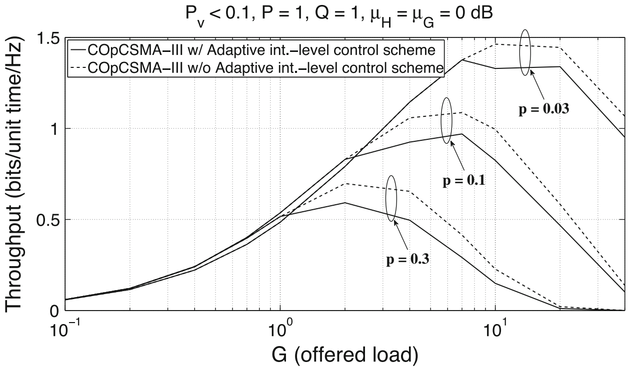


Fig. 7 Throughput of the proposed COpCSMA-III schemes with and without the adaptive interference-level control scheme for different *p* values

respectively. As can be seen from the figure, P_v decreases as G decreases or M increases because STAs will access the channel less frequently or they will use lower transmit power. By using these simulation results, the minimum value of M which guarantees P_v being less than the threshold can be determined for the given load level. For example, if the maximum allowable value of P_v is 0.2, the minimum M for the offered load $G = 2$ becomes 1. However, when $G = 20$, the minimum M will become 6, which implies that up to six simultaneous STA transmissions does not cause the violation of P_v. Note that the sum-capacity decreases as M increase, however, the QoS of the PR tends to be satisfied.

In Fig. 6, the performance of the proposed adaptive interference-level control scheme is depicted under the assumption of $Q = 0.2$. In this simulation, the target value of violation probability is set to 0.1, i.e., $P_v \leq 0.1$. Therefore, when the adaptive interference-level control scheme is used, Q_{bc} is varied according to its current P_v; if $P_v > 0.1$, it finds the lowest M which satisfies $P_v \leq 0.1$, and this M is used, i.e., $Q_{bc} = \frac{Q}{M}$ is broadcasted to neighboring STAs.

First, we can find that simulation results and the result from analysis models are well matched, which verifies the exactness of our analysis. We can also find that the COpCSMA-III schemes with static Q, i.e., the schemes without adaptive interference-level control scheme, have the same performance when $Q_{bc} = Q$. In Fig. 6, when $G < 10$, the PR sets $Q_{bc} = Q$. As a result, the performance of the COpCSMA-III schemes with and without the adaptive interference-level control scheme is the same. However, when G becomes larger than 10, P_v of the COpCSMA-III scheme with static Q is greater than 0.1. Specifically, when $10 \leq G \leq 25$, the M is set to 2, and correspondingly P_v is decreased below 0.1, because the transmit power of STAs is decreased which results in the decrease of throughput. In addition, when $G > 25$, M is increased to 3 in order to guarantee $P_v \leq 0.1$. Note that the throughput of the secondary network is degraded when $G \geq 10$, at the cost of ensuring the QoS of the primary network. However, the degradation of the throughput is only minor as illustrated in Fig. 6.

To see how well the adaptive interference-level control scheme works in the different CR environments, we evaluate the throughput of secondary network at different access probability, i.e., p, as shown in Fig. 7. When $p = 0.3$, too many collisions occur even at $G = 2$, which results in the increase of M, i.e., the throughput of secondary networks with the adaptive interference-level control scheme decreases. However, the performance degradation caused by the adaptive interference-level control is not significant. Therefore, we can conclude that the QoS of primary network can be guaranteed in our proposed scheme, with only minor performance degradation.

7 Conclusions

We have proposed three distributed COpCSMA schemes for CR systems in which the signal and interference channels are efficiently exploited using opportunistic scheduling, which has not been considered in previous works on decentralized CR MAC. We have also considered transmit power control and adaptive interference-level control to resolve the QoS degradation problem of primary network, which has also not been taken into account in previous works. The proposed schemes are backward compatible to the conventional pCSMA scheme such that it is easy to be applied to practical wireless systems. The throughput of proposed schemes is mathematically analyzed. Moreover, through simulations, we have justified the exactness of our analysis and shown that the throughput of CR network can be optimized without violating the QoS constraint of primary network. An interesting extension of this work might be the analysis of other aspects of system performance, e.g., packet success probability, service time, and fairness.

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Appendix

The CDF of the effective channel gain f_i

The CDF of f_i is, by definition, given as

$$\begin{aligned} F_F(x) &= \Pr\{f \le x\} \\ &= \Pr\{f \le x, \gamma_i \le Q/\overline{P}\} + \Pr\{f \le x, \gamma_i > Q/\overline{P}\} \\ &= \Pr\{\overline{P}\eta_i \le x, \gamma_i \le Q/\overline{P}\} + \Pr\left\{Q\frac{\eta_i}{\gamma_i} \le x, \gamma_i > Q/\overline{P}\right\} \\ &= \Pr\{\overline{P}\eta_i \le x\}\Pr\{\gamma_i \le Q/\overline{P}\} + \Pr\left\{Q\frac{\eta_i}{\gamma_i} \le x, \gamma_i > Q/\overline{P}\right\} \\ &= \left(1 - e^{-\frac{x}{\overline{P}\mu_H}}\right)\left(1 - e^{-\frac{Q}{\overline{P}\mu_G}}\right) + \Pr\left\{Q\frac{\eta_i}{\gamma_i} \le x, \gamma_i > Q/\overline{P}\right\}. \end{aligned} \tag{30}$$

$\Pr\left\{Q\frac{\eta_i}{\gamma_i} \le x, \gamma_i > Q/\overline{P}\right\}$ in (30) can be further derived as follows.

$$\begin{aligned} \Pr\left\{Q\frac{\eta_i}{\gamma_i} \le x, \gamma_i > Q/\overline{P}\right\} &= \int_{Q/\overline{P}}^{\infty} \Pr\left\{Q\frac{\eta_i}{t} \le x | \gamma_i = t\right\} f_\Gamma(t)dt \\ &= \int_{Q/\overline{P}}^{\infty} \Pr\left\{Q\frac{\eta_i}{t} \le x\right\}\left(\frac{1}{\mu_G}e^{-\frac{t}{\mu_G}}\right)dt \\ &= e^{-\frac{Q}{\overline{P}\mu_G}} - \left(\frac{\mu_H Q}{\mu_G x + \mu_H Q}\right)e^{-\left(\frac{x}{\overline{P}\mu_H} + \frac{Q}{\overline{P}\mu_G}\right)}. \end{aligned} \tag{31}$$

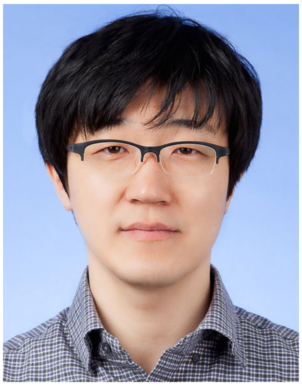
By substituting (31) into (30), we obtain the CDF of the effective secondary channel gain f_i given as

$$F_F(x) = 1 - e^{-\frac{x}{\overline{P}\mu_H}} + \left(\frac{\mu_G x}{\mu_G x + \mu_H Q}\right)e^{-\left(\frac{x}{\overline{P}\mu_H} + \frac{Q}{\overline{P}\mu_G}\right)}. \tag{32}$$

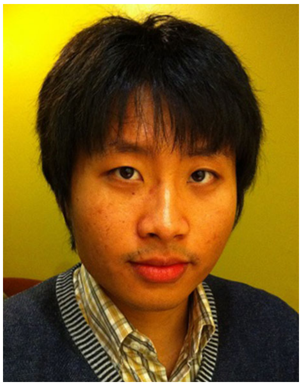
References

1. Kang, M. S., & Jung, B. C. (2010). A cognitive p-persistent CSMA scheme for spectrum sharing based cognitive radio networks. In *Proceedings of IEEE WCNC*.
2. Kang, M. S., & Jung, B. C. (2011). Performance analysis of an opportunistic CSMA scheme in cognitive radio networks. In *Proceedings of IEEE MTT-S IMWS*.
3. Mitola, J., & Maguire, G. Q. (1999). Cognitive radio: Making software radios more personal. *IEEE Personal Communications*, *6*(4), 13–18.
4. Haykin, S. (2005). Cognitive radio: Brain-empowered wireless communications. *IEEE Journal on Selected Areas in Communications*, *23*(2), 201–220.
5. Lee, W., & Cho, D.-H. (2011). Enhanced spectrum sensing scheme in cognitive radio systems with MIMO antennae. *IEEE Transactions on Vehicular Technology*, *60*(3), 1072–1085.
6. Ban, T. W., Choi, W., Jung, B. C., & Sung, D. K. (2009). Multi-user diversity in a spectrum sharing system. *IEEE Transactions on Wireless Communications*, *8*(1), 102–106.
7. Lee, W., & Cho, D.-H. (2013). Cooperation based new channel state acquisition scheme for ad hoc cognitive radio systems'. *IEEE Transactions on Vehicular Technology*, *62*(7), 3325–3338.
8. Federal Communications Commission, Spectrum policy task force report, (ET Docket No. 02-135), (2002). http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.
9. ET Docket No. 03-237; FCC 07-78, Interference Temperature Operation, site. http://www.gpo.gov/fdsys/pkg/FR-2007-05-30/pdf/E7-10337.
10. Ban, T. W., Choi, W., & Sung, D. K. (2009). Capacity and energy efficiency of multi-user spectrum sharing systems with opportunistic scheduling. *IEEE Transactions on Wireless Communications*, *8*(6), 2836–2841.
11. Zhang, L., Xin, Y., & Liang, Y.-C. (2009). Weighted sum rate optimization for cognitive radio MIMO broadcast channels. *IEEE Transactions on Wireless Communications*, *8*(6), 2950–2959.
12. Zhang, L., Liang, Y.-C., Xin, Y., & Poor, H. (2009). Robust cognitive beamforming with partial channel state information. *IEEE Transactions on Wireless Communications*, *8*(8), 4143–4153.
13. Guimaraes, F., da Costa, D., Tsiftsis, T., Cavalcante, C., & Karagiannidis, G. (2014). Multiuser and multirelay cognitive radio networks under spectrum-sharing constraints. *IEEE Transactions on Vehicular Technology*, *63*(1), 433–439.

14. Gastpar, M. (2007). On capacity under receive and spatial spectrum-sharing constraints. *IEEE Transactions on Information Theory*, *53*(2), 471–487.
15. Ghasemi, A., & Sousa, E. (2007). Fundamental limits of spectrum-sharing in fading environments. *IEEE Transactions on Wireless Communications*, *6*(2), 649–658.
16. Zhang, R., & Liang, Y.-C. (2008). Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks. *IEEE Journal on Selected Areas in Communications*, *2*(1), 88–102.
17. Shah, G. A., & Akan, O. B. (2014). Performance analysis of CSMA-based opportunistic medium access protocol in cognitive radio sensor networks. *Ad Hoc Networks*, *15*, 4–13.
18. Li, S., Ekici, E., & Shroff, N. (2015). Throughput-optimal queue length based CSMA/CA algorithm for cognitive radio networks. *IEEE Transactions on Mobile Computing*, *14*(5), 1098–1108.
19. Gozalvez, J., Sepulcre, M., & Bauza, R. (2012). IEEE 802.11p vehicle to infrastructure communications in urban environments. *IEEE Communications Magazine*, *50*(5), 176–183.
20. Pyun, S., Lee, W., & Cho, D. (2016). Resource allocation for Vehicle-to-Infrastructure communication using directional transmission. *IEEE Trans. Intell. Transp. Syst.*, *17*(4), 1183–1188.
21. Zhao, Q., Tong, L., Swami, A., & Chen, Y. (2007). Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework. *IEEE Journal on Selected Areas in Communications*, *25*(3), 589–600.
22. Zhang, Q., Fitzek, F., & Iversen, V. (2008). Cognitive radio MAC protocol for WLAN. In *Proceedings of PIMRC*.
23. Adamis, A., & Constantinou, P. (2007). Performance study of CSMA/CA over spectrum pooling environment for cognitive radios. In *Proceedings of WiMOB*.
24. Cheng, Y. C., Wu, E. H., & Chen, G. H. (2016). A decentralized MAC protocol for unfairness problems in coexistent heterogeneous cognitive radio networks scenarios with collision-based primary users. *IEEE Systems Journal*, *10*(1), 346–357.
25. Wu, C. M., & Su, H. K. (2014). Cooperative power and contention control mac protocol in multichannel cognitive radio ad hoc networks. In *Proceedings of IMIS*.
26. Banaei, A., Eslami, A., Georghiades, C. N., & Cui, S. (2014). Joint random spectrum sensing and access scheme for decentralized cognitive radio networks. In *Proceedings of ICC*.
27. Joshi, G. P., Nam, S. Y., & Kim, S. W. (2014). Decentralized predictive MAC protocol for ad hoc cognitive radio networks. *Wireless Personal Communications*, *74*(2), 803–821.
28. Liao, Y., Wang, T., Bian, K., Song, L., & Han, Z. (2015). Decentralized dynamic spectrum access in full-duplex cognitive radio networks. In *Proceedings of ICC*.
29. Wang, P., Ansari, J., Petrova, M., & Mhnen, P. (2014). Demo: CogMAC+-a decentralized multichannel MAC protocol for cognitive wireless networks. In *Proceedings of ACM SRIF*.
30. Knopp, R., & Humblet, P. (1995). Information capacity and power control in single-cell multiuser communications. In *Proceedings of ICC*.
31. Viswanath, P., Tse, D., & Laroia, R. (2002). Opportunistic beamforming using dumb antennas. *IEEE Transactions on Information Theory*, *48*(6), 1277–1294.
32. Qin, X., & Berry, R. (2003). Exploiting multiuser diversity for medium access control in wireless networks. In *Proceedings of INFOCOM*.
33. Hwang, C.-S., Seong, K., & Cioffi, J. (2008). Throughput maximization by utilizing multi-user diversity in slow-fading random access channels. *IEEE Transactions on Wireless Communications*, *7*(7), 2526–2535.
34. Kleinrock, L., & Tobagi, F. (1975). Packet switching in radio channels: Part I-carrier sense multiple-access modes and their throughput-delay characteristics. *IEEE Transactions on Communications*, *23*(12), 1400–1416.
35. Cali, F., Conti, M., & Gregori, E. (2000). Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit. *IEEE/ACM Transactions on Networking*, *8*(6), 785–799.
36. Gradshteyn, I. S., & Ryzhik, I. (2000). *Table of integrals, series, and products*. Cambridge: Academic Press.



Bang Chul Jung received the B.S. degree in electronics engineering from Ajou University, Suwon, South Korea, in 2002, and the M.S. and Ph.D. degrees in electrical and computer engineering from KAIST, Daejeon, Korea, in 2004 and 2008, respectively. He was a Senior Researcher/Research Professor with the KAIST Institute for Information Technology Convergence, Daejeon, Korea, from January 2009 to February 2010. From March 2010 to August 2015, he was a Faculty member with Gyeongsang National University, Tongyeong, Korea. He is currently an Associate Professor with the Department of Electronics Engineering, Chungnam National University, Daejeon, Korea. His research interests include 5G mobile communication systems, statistical signal processing, opportunistic communications, compressed sensing, interference management, interference alignment, random access, relaying techniques, device-to-device networks, in-network computation, and network coding. Dr. Jung was the recipient of the Fifth IEEE Communication Society AsiaPacific Outstanding Young Researcher Award in 2011. He was also the recipient of the Bronze Prize of Intel Student Paper Contest in 2005, the First Prize of KAIST's Invention Idea Contest in 2008, the Bronze Prize of Samsung Humantech Paper Contest in 2009. He has been selected as a winner of the Haedong Young Scholar Award in 2015, which is sponsored by the Haedong Foundation and given by the Korea Institute of Communications and Information Science (KICS).



Woongsup Lee received the B.S. degree and Ph.D. degree in electrical engineering from the KAIST, Daejeon, Republic of Korea, in 2006 and 2012, respectively. Since 2014, he has been an Assistant Professor in the Department of Information and Communication Engineering of Gyeongsang National University. His research interests include cognitive radio network, future wireless communication systems, smart grid system, and deep learning.