Performance Analysis of an Opportunistic CSMA Scheme in Cognitive Radio Networks

Min Suk Kang and Bang Chul Jung
Department of Information and Communication, College of Marine Science, Gyeongsang National University
Email: mindolm@gmail.com and bcjung@gnu.ac.kr

(Invited Paper)

***Abstract*— We consider a cognitive radio network where both primary and secondary networks share the same spectrum resources. The secondary network is assumed to operate via a random access and to be composed of multiple secondary stations (transmitters) and a single secondary access point (receiver). At a primary receiver, an allowable interference-level Q is predefined as an interference constraint. In this paper, we propose a cognitive opportunistic p-persistent carrier sense multiple access (COpCSMA) scheme for the spectrum sharing network. The proposed scheme efficiently exploits the channel opportunity existing in both primary and secondary networks and yields nearly the optimal performance of the secondary network. We mathematically analyze the performance of the proposed scheme and the numerical examples illustrate that the analytical results match well with the simulation results.**

I. Introduction and System Model

In this paper, we propose a *cognitive opportunistic* p-persistent CSMA (COpCSMA) scheme as a decentralized MAC protocol for spectrum sharing systems. The proposed COpCSMA scheme fully exploits the opportunity in wireless channels.

Our system model has a system model with a single secondary access point (SAP), multiple secondary stations (STAs), and a single primary receiver (PR) coexisting in the same spectrum. The secondary network is assumed to be a random access system. Since the primary network has the priority for the shared spectrum resource, the secondary network is required to satisfy the quality of service (QoS) constraints of the PR.

In the system model, STAs communicate with the SAP through quasi-static fading channels. Assuming that only one STA accesses the channel at time t, the received signal of the SAP at time t is given by $y(t) = h_i x_i(t) + n_i$, where h_i indicates a Rayleigh distributed wireless channel coefficient between the STA$_i$ and the SAP with the variance of μ_H, $x_i(t)$ represents the transmitted signal of STA$_i$, and n_i denotes an additive white Gaussian noise (AWGN) with the power density of N_0. The power of the transmitted signal $x_i(t)$ is assumed to be P_i and can be dynamically controlled. For simple mathematical analysis, N_0 is assumed to be 1 without loss of generality. Moreover, g_i indicates the wireless channel coefficient between STA$_i$ and the PR, which is also modeled as Rayleigh distributed with the variance of μ_G. Both wireless channels h_i's and g_i's are assumed to be independent and identically-distributed (i.i.d.) random variables. For simplicity, we denote the channel gain of h_i and g_i as follows; $\eta_i \triangleq |h_i|^2$ and $\gamma_i \triangleq |g_i|^2$.

When STA$_i$ transmits its data symbol of $x_i(t)$, the PR is affected by the undesired interference with the power of $\gamma_i P_i$. To guarantee the QoS of the primary network, we assume that the secondary network controls the transmit power. The PR predetermines an *allowable interference-level* Q, and STA$_i$ cognitively controls its transmit power to satisfy the constraint $\gamma_i P_i \leq Q$. The allowable interference-level Q is assumed to be broadcasted to the secondary STAs from the PR or the SAP.

Each STA can obtain its own signal channel gain η_i by measuring the signal strength of the received packet from the SAP. Moreover, the STA$_i$ can also obtain the interference channel gain γ_i by overhearing the preamble transmitted by the PR when the PR operates as a transmitter.

The p-persistent CSMA (pCSMA) is one of the most popular CSMA protocols. When the shared medium is idle, a node transmits with probability p and defers with the probability $(1-p)$ [1]. Since it has been shown that the MAC protocol of the IEEE 802.11 system can be well approximated by the pCSMA [2], we adopt the pCSMA protocol as a basic random access protocol for the secondary network.

The performance of the conventional pCSMA is measured as the system throughput, which is a function of the offered load (G), the access probability (p), and normalized propagation delay (a). The system throughput of pCSMA is defined as the number of successfully transmitted bits per unit time [3] and is expressed as:

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

where $\bar{t}$ and $\overline{t'}$ denote the average length of the initial random transmission delay (IRTD) before the first and the other transmission periods (TPs), respectively [1], and π_n is defined as $\pi_n = e^{[-(1+a)G]}\frac{[(1+a)G]^n}{n!}$. The term R_c represents the expected sum-rate over the channel fading statistics and is given in a closed-form as $R_c = R_0 \sum_{n=0}^{\infty} \pi_n p_s(n)$, where $p_s(n)$ represents the probability that a packet is successfully sent without any collision in the presence of n STAs and is given as $\frac{npq^{n-1}}{1-q^n}$ for $n > 0$. The ergodic capacity R_0 of a single transmission with randomly selected h_i is given by

$$R_0 = \int_0^{\infty} f_{\mathrm{H}}(\eta)\log_2(1+P\eta)d\eta = \frac{e^{\frac{1}{\mu_H}}}{\ln 2}E_1\left(\frac{1}{\mu_H}\right), \quad (2)$$

where P indicates the transmit power of the STA. The term $f_{\mathrm{H}}(\eta)$ represents the probability density function (PDF) of the channel gain η_i and equals to $\frac{1}{\mu_H}e^{-\frac{\eta}{\mu_H}}$ and $E_1(x)$ represents an exponential integral.

II. Proposed Cognitive Opportunistic p-Persistent CSMA Scheme

In this section, we propose the cognitive opportunistic p-persistent CSMA scheme.

Each STA decides whether to access the medium by comparing its channel gain with its predetermined threshold. The threshold is determined by using the statistics of the wireless channel. Both the signal and the interference channels have intrinsic randomness, and thus the channel access is performed in a random manner. This technique of using statistics of the wireless channel for determining the threshold is motivated by [3], and we extend it to cognitive radio scenarios in this paper.

In COpCSMA, we propose the concept of *effective channel gain* f_i, which is defined as the signal channel gain η times

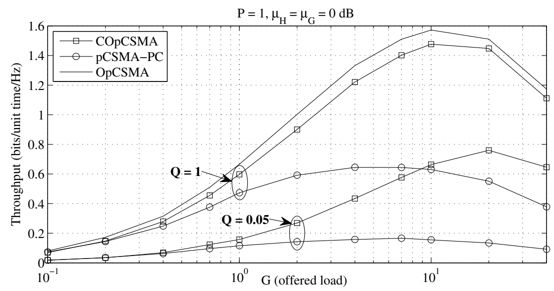

Fig. 1. Throughput of the proposed COpCSMA scheme and conventional schemes for different Q values.

transmit power $P_i(\gamma)$;

$$f_i \triangleq P_i(\gamma) \times \eta = \begin{cases} \overline{P}\eta, & \gamma \le Q/\overline{P} \\ \frac{Q\eta}{\gamma}, & \gamma > Q/\overline{P} \end{cases}. \quad (3)$$

The CDF of the effective channel gain is expressed as

$$F_F(x) = 1 - e^{-\frac{x}{\overline{P}\mu_H}} + \left(\frac{\mu_G x}{\mu_G x + \mu_H Q}\right) e^{-\left(\frac{x}{\overline{P}\mu_H} + \frac{Q}{\overline{P}\mu_G}\right)}, \quad (4)$$

where $\overline{P}$ indicates the maximum transmit power of each STA.

The COpCSMA scheme assigns each STA a set of thresholds related to the statistics of its effective channel gain f_i. We assume the identical channel statistics for all STAs and every STA shares a single set of thresholds, $\{T_0, T_1, \cdots, T_k, \cdots\}$, where T_k's are designed in decreasing order. Under the assumption that the STA$_i$ has not yet accessed the medium until the $(k-1)$-th backoff slot, the STA$_i$ accesses the medium if $f_i > T_k$.

The set of thresholds that maintains the medium access probability p for each step is determined as follows.

$$\Pr\{f_i > T_k | f_i < T_{k-1}\} = \frac{F_F(T_{k-1}) - F_F(T_k)}{F_F(T_{k-1})} = p \quad (5)$$

$$qF_F(T_{k-1}) = F_F(T_k) \quad (6)$$

$$T_k = F_F^{-1}(q^{k+1}). \quad (7)$$

Unfortunately, the closed form of the inverse function of the CDF in (4) does not exist,; thus, $\{T_k\}$ for the COpCSMA should be numerically calculated.

The expected sum-rate for the COpCSMA is obtained by $R_c = \pi_0 R_{p,1} + (1-\pi_0)R_2$. The term $R_{p,1}$ represents the average achievable capacity of a transmission where the transmission succeeds without collision and is given by

$$R_{p,1} = \int_0^\infty \int_0^\infty f_\Gamma(\gamma) f_\mathrm{H}(\eta) \log_2(1 + P_i(\gamma)\eta) d\eta d\gamma. \quad (8)$$

The term R_2 is given by

$$R_2 = \sum_{n=1}^{\infty} \frac{\pi_n}{1-\pi_n} p_s(n) \sum_{k=0}^{\infty} p_K(k) R_0(k), \quad (9)$$

where $p_K(k) = q^{kn}(1-q^n)$ and the term $R_0(k)$ represents the expected sum-rate when only one STA transmits at the backoff slot k and is given by

$$R_0(k) = \frac{1}{F_F(T_{k-1}) - F_F(T_k)} \int_{T_k}^{T_{k-1}} f_F(f) \log_2(1+f) df. \quad (10)$$

The closed form solution of (10) exists, but it is too complex and lengthy. Therefore, we omit the closed form solution in this paper.

III. Numerical Results

In this section, we evaluate the performance of the proposed COpCSMA scheme through computer simulations. Since we cannot directly compare the proposed scheme with the conventional pCSMA, we modify it to pCSMA-PC. In the pCSMA-PC, each STA accesses the channel exactly the same as in the conventional pCSMA, but it performs transmit power control just before its transmission to satisfy the interference constraint $\gamma_i P_i \le Q$.

We assume a virtual single source with an offered load G, instead of implementing multiple traffic sources (STAs). The traffic is generated according to the Poisson process with offered load G. Each packet generated by the Poisson process represents an STA waiting to transmit on the medium. Each STA determines whether to transmit or defer its packet according to the set of thresholds.

If more than one STA tries to access the medium at the same time t, a collision occurs and the multiple transmitted packets cannot be decoded at the SAP. If a single STA successfully transmits a packet, its instantaneous throughput follows Shannon capacity $\log_2(1 + P_i(\gamma)\eta)$.

To evaluate the performance of the proposed schemes in different cognitive radio environments, computer simulations were performed at different Q levels. In Fig. 1, at high allowable interference-level, $Q = 1$, the COpCSMA scheme nearly achieves the optimal performance of OpCSMA proposed in [3]. This implies that the interference constraint $\gamma_i P_i \le Q$ can be negligible in most transmissions of STAs and the interference channel information may not be useful. On the other hand, when the allowable interference-level is low, $Q = 0.05$, the COpCSMA scheme performs much lower than the OpCSMA scheme, but still achieves tremendous gain over the conventional pCSMA-PC scheme.

IV. Conclusions

We have proposed a cognitive opportunistic p-persistent carrier sense multiple access (COpCSMA) scheme for cognitive radio networks. The proposed COpCSMA scheme was proved to efficiently exploit the channel opportunity in signal and interference channels and achieve the optimal performance of the secondary network. We mathematically analyzed the performance of the conventional and the proposed schemes with the unified framework. The numerical examples illustrated that the analytical results in this paper match well with the simulation results.

Acknowledgements

This research was supported by Basic Science Research Project through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0011140).

References

[1] L. Kleinrock and F. A. Tobagi, “Packet Switching in Radio Channels: Part I - Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics,” *IEEE Trans. on Commun.*, vol. com-23, no. 12, pp. 1400 - 1416, Dec. 1975.

[2] F. Cali, M. Conti, and E. Gregori, “Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit,” *IEEE/ACM Trans. Networking*, vol. 8, no. 6, pp. 785 - 799, Dec. 2000.

[3] C.-S. Hwang, K. Seong, and J. M. Cioffi, “Throughput Maximization by Utilizing Multi-user Diversity in Slow-fading Random Access Channels,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 7. pp. 2526 - 2535, Jul. 2008.