Performance Analysis of Unslotted CSMA Scheme for SUs in Heterogeneous Wireless Network

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Keywords: Heterogeneous wireless network. CSMA. Throughput. Packet loss probability.

Abstract. The spectrum access scheme for secondary users (SUs) in heterogeneous wireless network was studied. We propose a \( p \)-selective Carrier Sense Multiple Access (CSMA) scheme of SUs in cognitive radio network under the environment of heterogeneous network, and analyze the system performance by queueing analytic method. Numerical results show that the probability that SUs select different network has a large impact on the performance of SUs in heterogeneous wireless network.

1. Introduction

Advances in wireless communication systems and development of new services had significantly increased the demands for more frequency bands. Cognitive radio network is one of the methods to solve the contradiction between supply and demand of the spectrum. Cognitive radio network improves the spectrum efficiencies by enabling SUs to opportunistically access the channels unused by primary users (PUs). With the rapid development of wireless communication industry, the coexistence and integration of heterogeneous wireless networks is one of the most important features of the next generation communication networks. So, how to share spectrum resources for SUs in the environment of heterogeneous wireless network is one of important problems which should be resolved in the cognitive radio network.

There had been many studies on the opportunistic spectrum access for cognitive radio network. We classify the opportunistic spectrum access as the centralized (e.g., [1,2,3]) and decentralized (e.g., [4,5,6,7,8,9]) cognitive medium access control (MAC) protocols. The decentralized cognitive MAC protocols can be further classified as slotted structure (e.g., [4,5,6]) and unslotted structure (e.g., [7,8,9]). Shunfu Jin et al. [3] analyzed the performance of the novel centralized spectrum allocation scheme in cognitive radio networks. S. Huang et al. [7] proposed three random access schemes for SUs, namely, VX, VAC, and KS schemes. D. B. Zhu et al. [8] proposed and analyzed the performance of the random \( m \)-sensing scheme in unslotted cognitive radio network based on the VAC scheme. H. Q. Fang et al. [9] proposed and analyzed the performance of the grouped sensing scheme in cognitive radio network. These literatures only considered spectrum sharing strategy in homogeneous cognitive radio network, do not considered that in the heterogeneous wireless network. This is the motivation of our work. In this paper, we propose and analyze the \( p \)-selective CSMA scheme in cognitive radio network under the environment of heterogeneous network.

The rest of paper is organized as follows: In section 2, the \( p \)-selective CSMA scheme for SUs in heterogeneous wireless network is described in details. The performance of \( p \)-selective CSMA scheme was analyzed in section 3 by continuous time Markov process. Numerical examples are presented in section 4 and summary is given in section 5.

2. The \( p \)-selective CSMA scheme in heterogeneous wireless network

For convenience, let us assume that there are two different networks \( A \) and \( B \) in heterogeneous wireless network. Each SU always has packet to transmit. All SUs sense the channels before its packet transmission. We assume that each SU performs perfect sensing (i.e., no false alarm and no
mis detection) and the sensing period of channels is negligible. We also assume that each SU will vacate the channel when a PU returns to the channel before the SU finishes its packet transmission on the channel. We do not assume time synchronization among PUs and SUs.

The $p$-selective CSMA scheme in heterogeneous wireless network is operated as follows:

Step 1) Each SU senses the channels of the network ($A$ or $B$) before its packet transmission. Since there are two different networks, the SU randomly selects one from $A$ and $B$ networks with probability $p$ for $A$ and $1-p$ for $B$, then senses the channels in the selected network.

Step 2) If a SU finds idle channels, it selects one idle channel randomly and transmit a packet, then the SU goes to back-off state in order to prevent the channel being exclusively used by one SU. If the SU does not find any idle channels, then it goes to back-off state immediately.

Step 3) When a PU returns to the channel before the SU finishes its packet transmission on the channel, then the SU will vacate the channel to the PU and sense all channels in the selected network immediately. If the SU finds idle channels, then the SU continues to transmit its current packet on one of the idle channels, otherwise, the SU goes to back-off state and the transmission of current packet is regarded as unsuccessful and lost in the system.

Step 4) All SUs in back-off state will repeat Step 1) after its back-off time.

3. Performance Analysis

We assume that there are $N$ SUs in the system, network $A$ has $m_1$ channels and network $B$ has $m_2$ channels, $m_1+m_2=M$. The PU’s usage pattern of a channel in each network follows On/Off process and is independent with other’s channel usage patterns. An On-period is time duration which the PU occupies the channel, an Off-period is time duration which the channel can be opportunistically used by the SUs. It is assumed that the On-periods and Off-periods on the channel in each network have exponential distribution with mean $\alpha$ and $\beta$ respectively.

We assume the transmission time of SUs in network $A$ and network $B$ are exponentially distributed with mean $\mu_1$ and $\mu_2$, respectively. The back-off time of SUs in back-off state are exponentially distributed with mean $\nu$.

Let

$$N_{p_1}(t) = \text{the number of channels in network } A \text{ transmitting PU’s packet at time } t;$$

$$N_{p_2}(t) = \text{the number of channels in network } B \text{ transmitting PU’s packet at time } t;$$

$$N_{s1}(t) = \text{the number of channels in network } A \text{ transmitting SU’s packet at time } t;$$

$$N_{s2}(t) = \text{the number of channels in network } B \text{ transmitting SU’s packet at time } t.$$

Then $\{(N_{p_1}(t), N_{p_2}(t), N_{s1}(t), N_{s2}(t))|t \geq 0\}$ forms a numerical Markov process with state space

$$S = \{(i, j, k, l)|0 \leq i \leq m_1, 0 \leq j \leq m_2, 0 \leq k \leq m_1-i, 0 \leq l \leq m_2-j\}.$$ 

Since the process $\{(N_{p_1}(t), N_{p_2}(t), N_{s1}(t), N_{s2}(t))|t \geq 0\}$ is an irreducible Markov process with finite state space, it is always ergodic and exists the steady state probability. Let $\pi_{i,j,k,l}$ is the joint probability that the Markov process is in state $(i,j,k,l)$, then we can obtain the following balance equations:

1) If $k=0, l=0$,

$$[i+j]\alpha+(M-i-j)\beta+N\nu][\pi_{i,j,k,l} = (i+1)\alpha\pi_{i+1,j,k,l} + (m_1-i+1)\beta\pi_{i-1,j,k,l} + (j+1)\alpha\pi_{i,j+1,k,l} + (m_2-j+1)\beta\pi_{i,j-1,k,l} + \mu_1\pi_{i,j,k+1,l} + \mu_2\pi_{i,j,k,l+1} \tag{1}$$

2) If $0<k<m_1-i, 0<l<m_2-j$,

$$[i+j]\alpha+(M-i-j)\beta+k\mu_1 + l\mu_2 + (N-k-l)\nu][\pi_{i,j,k,l} = (i+1)\alpha\pi_{i+1,j,k,l} + (m_1-i+1)\beta\pi_{i-1,j,k,l} + (j+1)\alpha\pi_{i,j+1,k,l} + (m_2-j+1)\beta\pi_{i,j-1,k,l} + (k+1)\mu_1\pi_{i,j,k+1,l} + (l+1)\mu_2\pi_{i,j,k,l+1} + (N-k-l)\nu[p\pi_{i,j,k-1,l} + (1-p)\pi_{i,j,k,l}] \tag{2}$$

3) If $0<k< m_1-i, l=m_2-j$,

$$[i+j]\alpha+(M-i-j)\beta+k\mu_1 + l\mu_2 + p(N-k-l)\nu][\pi_{i,j,k,l} = (i+1)\alpha\pi_{i+1,j,k,l} + (m_1-i+1)\beta\pi_{i-1,j,k,l}$$

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(j + 1)\alpha_{i,j,k,l} + (m_z - j + 1)\beta_{i,j,k,l} + (k + 1)\mu_{i,j,k,l}
+ (N - k - l + 1)\nu(p_{i,j,k,l} + (1 - p)p_{i,j,k,l})
(3)

4) If \( k = m_z - i, 0 < l < m_z - j \),
\[
[(i + j)\alpha + (M - i - j)\beta + k\mu_z + l\mu_z + (1 - p)(N - k - l)\nu]_{i,j,k,l} = (i + 1)\alpha_{i,j+1,k,l} + (m_z - j + 1)\beta_{i,j+1,k,l} +
(m_z - j + 1)\beta_{i,j+1,k,l} + (m_z - j + 1)\beta_{i,j+1,k,l} +
(N - k - l + 1)\nu(p_{i,j,k,l} + (1 - p)p_{i,j,k,l})
(4)

5) If \( k = m_z - i, l = m_z - j \),
\[
[(i + j)\alpha + (M - i - j)\beta + k\mu_z + l\mu_z]_{i,j,k,l} = (i + 1)\alpha_{i,j+1,k,l} + (m_z - i + 1)\beta_{i,j+1,k,l} +
(m_z - i + 1)\beta_{i,j+1,k,l} + (m_z - i + 1)\beta_{i,j+1,k,l} +
(N - k - l + 1)\nu(p_{i,j,k,l} + (1 - p)p_{i,j,k,l})
(5)

By solving the linear equations (1)-(5), we can obtain the steady state probability \( \pi_{i,j,k,l} \).

The packet loss probability and throughput of SUs are the important system performance measures. The packet loss probability of SUs is defined as probability that a SU who transmits a packet is out of the channel because a PU reaturns to the channel and does not find idle channels by its sensing and so the packet of SU is forced to terminate.

To find packet loss probability, let \( \lambda_e \) be the effective packet arrival rate of SUs in the system and \( \tilde{\pi}_{i,j,k,l} \) be the arrival point probability that the SU finds the system in the state \((i,j,k,l)\) upon sensing after its vacation.

Let \( \tilde{\lambda}_e \) be the effective total packet arrival rate of SUs, then we have
\[
\tilde{\lambda}_e = \sum_{i=0}^{m_z} \sum_{j=0}^{m_z-1} \sum_{k=0}^{m_z-j} \sum_{l=0}^{m_z-i} (N - k - l)\nu \pi_{i,j,k,l}
(6)

Then, the arrival point probability \( \tilde{\pi}_{i,j,k,l} \) is given by
\[
\tilde{\pi}_{i,j,k,l} = \frac{(N - k - l)\nu \pi_{i,j,k,l}}{\tilde{\lambda}_e}
(6)

Let \( P_{b1} \) and \( P_{b2} \) be the probability that the SU’s packet is blocked due to no idle channels in the system upon sensing after its backoff time, then we have
\[
P_{b1} = \sum_{(i,j,k,l)\cap \{k=m_z\} \cap l=m_z} \tilde{\pi}_{i,j,k,l}, \quad P_{b2} = \sum_{(i,j,k,l)\cap l=m_z} \tilde{\pi}_{i,j,k,l}.

Let \( P_{f1} \) and \( P_{f2} \) be probability that the SU does not find any idle channels in network A and network B when the SU interrupted by a PU, then we have
\[
P_{f1} = \sum_{(i,j,k,l)\cap k=m_z} \tilde{\pi}_{i,j,k,l}, \quad P_{f2} = \sum_{(i,j,k,l)\cap j=m_z} \tilde{\pi}_{i,j,k,l}.

We can obtain the packet loss probability \( P_{l1} \) of SUs that occupy A network as follows:
\[
P_{l1} = \frac{\beta}{\beta + \mu_1} P_{f1} + \frac{\beta}{\beta + \mu_2} (1 - P_{f1}) P_{l1} \quad \text{i.e.,} \quad P_{l1} = \frac{\beta P_{f1}}{\mu_1 + \beta P_{f1}}.
(7)

Similarly, the packet loss probability \( P_{l2} \) of SUs that occupy B network is given by
\[
P_{l2} = \frac{\beta P_{f2}}{\mu_2 + \beta P_{f2}}.
(8)

The normalized throughput \( T_s \) of SUs per a channel is defined as the number of successfully transmitted packets on a channel per unit time, then we have
\[
T_s = \frac{(1 - P_{b1})(1 - P_{l1})\tilde{\lambda}_e \mu_1 + (1 - P_{b2})(1 - P_{l2})\tilde{\lambda}_e \mu_2}{M}
(9)

where \( \lambda_1 \) and \( \lambda_2 \) are given by

\[
\lambda_1 = \sum_{i=0}^{m_1} \sum_{j=0}^{m_2-m_1-j} \sum_{k=0}^{l_1} (N-k-l) \nu \pi_{i,j,k,l}, \quad \lambda_2 = \sum_{i=0}^{m_1} \sum_{j=0}^{m_2-m_1-j} \sum_{k=0}^{l_1} (N-k-l) \nu (1-p) \pi_{i,j,k,l}.
\]

4. Numerical Examples

In this section, we present numerical examples for the performance measures of SUs. We assume that network \( A \) has \( m_1=6 \) channels and network \( B \) has \( m_2=4 \) channels. Let the mean packet transmission time in network \( A \) and network \( B \) are \( \mu_1^{-1}=5 \text{ms} \) and \( \mu_2^{-1}=1 \text{ms} \), respectively. We assume that the mean Off-periods \( \beta_1^{-1}=0.65 \text{s} \) and mean back-off time of SUs \( \nu^{-1}=20 \text{ms} \).

Figure 1 depicts the throughput and packet loss probability of SUs in \( p \)-selective CSMA scheme as the probability \( p \) that SU selects network \( A \) increases and the number \( N \) of SUs is 30, 40 and 50. Fig. 1(a) shows that the SUs’ throughput of SUs in \( p \)-selective CSMA scheme increases at first then decreases as the probability \( p \) increases because the large number of SUs sensing network \( A \) leads to low channel utilization of SUs. Fig. 1(b) shows that the packet loss probability of SUs increases as the probability \( p \) increases.

![Figure 1. Performance of the system versus the probability of SU selects network A.](image-url)
Figure 2 depicts the throughput and packet loss probability of SUs in $p$-selective CSMA scheme as the back-off rate of SUs increases and the number $N$ of SUs is 30, 40 and 50. Fig. 2(a) shows that the SUs’ throughput of SUs in $p$-selective CSMA scheme increases as the back-off rate of SUs increases, because the large back-off rate of SUs leads to high channel utilization of SUs. Fig. 1(b) shows that the loss probability of SUs decreases as the back-off rate of SUs increases.

Figure 2. Performance of the system versus the back-off rate of SUs.
Figure 3. The optimal value of $p$ in different network environments.

Figure 3 depicts the optimal probability $p$ of SUs in $p$-selective CSMA scheme as the number of SUs and the mean packet transmission time of network $A$ increases. Fig. 3 shows that the optimal probability $p$ of SUs decreases as the number of SUs increases when the mean packet transmission time of network $A$ is fixed. In order to improve the throughput of SUs, need to increase the probability of sensing network $B$ because of the mean packet transmission time of network $B$ less than that of network $A$. Fig. 3 also shows that the optimal probability $p$ of SUs decreases mean packet transmission time of network $A$ increases when the number of SUs is fixed.

5. Summary

We have proposed a $p$-selective CSMA scheme for SUs in heterogeneous wireless network and analyzed the system by 4-dimensional continuous time Markov process. We obtain the steady state probability of the system and performance measures of SU such as the throughput of SUs and the packet loss probability of SUs. Numerical results showed that the probability of SUs select different network has an impact on throughput of SUs and the packet loss probability in heterogeneous cognitive radio network.

Acknowledgements

This work was financially supported by the Science and Technology Department of Jilin province science and technology development plan project (20170520165JH), Jilin, China.

References


