TPO-MAC: Traffic-Priority-based Opportunistic MAC Protocol for Multi-Channel Cognitive Radio Networks

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Abstract. Opportunistic medium access control (MAC) protocol design is a challenging issue for multi-channel cognitive radio networks (CRN). This paper provides a novel traffic-priority-based opportunistic MAC (TPO-MAC) protocol in multi-channel CRN. An important mechanism in TPO-MAC is that whether the primary users (PUs) can access the licensed channels immediately depends on their traffic priority, which alleviates the collision between secondary users (SUs) and PUs. In order to investigate the performance of TPO-MAC, a Markov chain model is further proposed to derive the saturation throughput of TPO-MAC. We validate our model by extensive simulations and compare the performance of TPO-MAC with the results from other literature. The results show that TPO-MAC performs better than the existing opportunistic MAC protocols.

1. Introduction

In the past decade, the demand for spectrum has increased dramatically due to the wildly application of wireless networks and the electronic devices. However, according to the studies conducted by Federal Communication Commission (FCC), the utilization of spectrum is extremely uneven. The unlicensed portion of the spectrum (2.4-GHz and 5-GHz bands) is nearly exhausted while the licensed portion of the spectrum is only utilized between 15% and 85%. Cognitive radio networks (CRN) as an effective way to improve the utilization of licensed spectrum have attracted significant attention in recent years. In CRN, the unlicensed users (or secondary users, SUs) opportunistically use the licensed spectrum which is unused by licensed users (or primary users, PUs). The key problem in CRN is to allocate the resources (spectrum) among the users. Thus, spectrum allocation strategy, i.e., medium access control (MAC) protocol design becomes an essential problem in CRN.

Within this context, researchers have proposed plenty of MAC protocols for CRN. Zikria et al. [1] and Dappuri et al. [2] designed an opportunistic MAC protocol based on 802.11 DCF under the condition of multi-channel scenario and proposed an analytical model to analyse the performance of their proposed MAC protocols, respectively. Thilina et al. [3] proposed a dynamic common-control-channel-based MAC protocol which eliminates the requirement of a dedicated channel for information exchange. However, all of them assume that the SUs have to vacate the licensed channel whenever the PUs return while the traffic priority of PUs is not always high.

In this paper, we propose a traffic-priority-based opportunistic MAC (TPO-MAC) protocol for multi-channel CRN. There are two types of PUs’ traffic priority in TPO-MAC: high and low.
biggest difference between our protocol and others is that if the traffic priority is low, PUs sense the channel state first before their transmission and delay their transmission when the channel is occupied by SUs. Meanwhile, we further put forward a two-dimensional Markov chain model with pseudo state for saturation throughput analysis of TPO-MAC. Simulated results validate the accuracy of our model. We also compare the throughput obtained by TPO-MAC with other existing protocols for CRN and the results show that TPO-MAC performs better than the existing ones.

2. TPO-MAC protocol for CRN

2.1. Model assumptions
Consider there are \( N \) SUs and \( M \) licensed channels in a cognitive radio networks whose range is limited to a wireless local area network (WLAN). On one hand, the SUs contend to use the vacant licensed channels which are not occupied by PUs. An unlicensed channel is used as the common control channel (CCC) for contention and information exchange. On the other hand, the traffic priority of PUs can be divided into two kinds of high and low, and the proportions of them are \( p_h \) and \( p_l \), respectively. If the traffic priority of PUs is high, the PUs can occupy the licensed channels at any time, irrespective of the SUs’ transmission. However, if the traffic priority of PUs is low, they need to sense the channel state first before their transmission and delay their transmission when the channel has been occupied by SUs.

The PUs use the licensed channel in a slot-by-slot way with a fixed length \( T_p \), and each slot is further divided into several mini-slots for SUs opportunistically access the vacant channel unoccupied by PUs. The SUs have two independent transceivers [4] and they can work simultaneously. One is used for the contention of licensed channel over the CCC while the other is worked for tuning, sensing and transmitting over any one of the licensed channel.

2.2. Details of TPO-MAC
Assume that SUs work in saturated condition, i.e., SUs always have a packet available for transmission. Each SU attempts to access the channel on the basis of carrier sense multiple access with collision avoidance (CSMA/CA). Similar to IEEE 802.11, TPO-MAC also adopts the binary exponential backoff (BEB) scheme to avoid collision. As shown in figure 1, each SU needs to wait a random number of backoff slots which is uniformly chosen in the range [0, \( CW-1 \)] before their transmission. The value of \( CW \) is called contention window size and it is initialized to a constant value \( CW_{\text{min}} \). Once collisions occur, the contention window size is doubled unless \( CW_{\text{max}} \) is reached. Slot time (\( \delta \)) is the unit time of the contention window, it accounts for the propagation delay, and the time needed to switch from receiving to transmitting state. If the CCC is idle for a distributed interframe space (DIFS) time, then the backoff time counter decreases as long as the CCC is sensed idle, freezes when the CCC is sensed busy, and restarts when the CCC is sensed idle for a DIFS time again.

![RTS-CTS mode](image1.png)

(a) RTS-CTS mode

![PTS-WTS mode](image2.png)

(b) PTS-WTS mode

Figure 1. Example of TPO-MAC

When the backoff time counter reaches zero, as shown in figure 1(a), the SU sends a control frame called request-to-send (RTS) if there is at least one vacant licensed channel available. When the receiver detects the RTS frame, it responds a clear-to-send (CTS) frame after a short interframe space (SIFS) time. With a successful RTS-CTS interaction, sender and receiver acknowledges the licensed
channel that will be used in the data transmission stage. If there is no available licensed channel when the backoff time counter reaches zero, as shown in figure (b), the SU sends a control frame called prepare-to-send (PTS) to reserve the priority of transmission. The receiver responds a wait-to-send (WTS) frame after a SIFS time. After the PTS-WTS interaction, all SUs suspend their backoff timer and sense the licensed channels state persistently. Once any one of the licensed channels is idle, the sender and receiver which have reserved the priority of transmission will restart the process of the RTS-CTS interaction. The rest of SUs resume the backoff timer till they receiver the CTS frame.

After a successful RTS-CTS interaction, the sender and receiver start data transmission stage on the appointed licensed channel. The receiver responds acknowledgement (ACK) upon successful reception of the packet. If there is any interference by PUs during data transmission stage, it is regarded as a failure transmission.

3. Performance analysis of TPO-MAC

3.1. Transmission probability

Consider a WLAN with \( N_s \) SUs, one control channel, \( M \) licensed channels and \( M \) PUs. We use a two-dimensional Markov chain \( \{s(t), b(t)\} \) to analyse the process of backoff of SUs, where \( t \) and \( t+1 \) correspond to the beginning of two consecutive backoff time slots. Let \( s(t) \) be the stochastic process representing the backoff stage \((0,\ldots,m)\) of SUs. Let \( b(t) \) be the stochastic process representing the backoff time counter. The value of \( b(t) \) is chosen in the range of \([0, w_i-1]\), where \( w_i = \min(2^{i}CW_{\text{min}}, CW_{\text{max}}) \) for \( i = (0,\ldots,m) \). The \( w_i \) will be reset to \( CW_{\text{min}} \) if a packet is still not successfully transmitted until the retransmission counter achieve its maximum value. In addition, the pseudo state \( S_i \) represents the transmission stage in licensed channel. In contrast to Bianchi’s model [5], other nodes which are not involved in the transmission will restart their backoff process after receiving the CTS frame in TPO-MAC. For the purpose of consistency of the model, we use a virtual backoff process \( \{S_i(t), c(t)\} \) to analyse the transmission stage of SUs. As shown in figure 3, \( S_i(t) \) represents the pseudo state of SUs at the backoff stage \( i \), and \( c(t) \) represents the virtual backoff time counter at time \( t \). The value range of \( c(t) \) is in \([0, T_i]\) wherein \( T_{i1} \) and \( T_{i2} \) represent the time of the successful transmission and the failed transmission, respectively.

We define the transition probability from state “a” to state “b” as \( P\{b|a\} \). Let \( p_c \) be the collision probability of SUs in control channel and \( p_d \) be the collision probability of SUs in data transmission stage. The non-null one-step transition probabilities of the model are

\[
\begin{align*}
P\{i, j | i, j + 1\} &= 1 \quad i \in [0,m] \quad j \in [0,W_i - 2] \\
P\{i, j | i-1, 0\} &= \frac{p_c}{W_i} \quad i \in [1,m] \quad j \in [0,W_i - 1] \\
P\{0, j | S_i\} &= \frac{1}{W_i} \quad i = 0, m \quad j \in [0,W_i - 1] \\
P\{0, j | S_i\} &= \frac{1 - p_d}{W_0} \quad i \in [1,m-1] \quad j \in [0,W_i - 1]. \quad (1) \\
P\{i, j | S_i\} &= \frac{p_d}{W_i} \quad i \in [1,m-1] \quad j \in [0,W_i - 1] \\
P\{S_i | i, 0\} &= 1 - p_c \quad i \in [0,m] \\
P\{0, j | m, 0\} &= \frac{p_c}{W_0} \quad j \in [0,W_0 - 1] 
\end{align*}
\]

Let \( b_{ij} = \lim_{t \to \infty} P\{s(t) = i, b(t) = j\} \), \( i \in [0,m], j \in [0,W_i-1] \) be the stationary distribution of the Markov chain. First, note that
\[ b_{i,W-1} = \frac{b_{i-1,0} p_C + b_{i,0} p_D}{W_i} \]

\[ = b_{i-1,0} p_C + b_{i,0} (1 - p_C) p_D \quad 0 < i \leq m. \]

\[ b_{i,0} = W_i b_{i-1,0} \]

\[ = W_i \frac{b_{i-1,0} p_C + b_{i,0} (1 - p_C) p_D}{W_i} \]

\[ = b_{i-1,0} p_C + b_{i,0} (1 - p_C) p_D. \]

Simplify equation (3), we get

\[ b_{i,0} = \frac{b_{i-1,0} p_C}{1 - (1 - p_C) p_D}. \]

For writing convenience, we define \( \lambda = p_c / (1 - (1 - p_C) p_D) \). Based on the recurrence relationship of the chain, we derive that

\[ \begin{cases} b_{i,0} = b_{0,0} \lambda^i & 0 < i \leq m. \\ b_{i,j} = \frac{W_i - j}{W_i} b_{0,0} \lambda^j & 0 \leq i \leq m, 0 \leq j \leq W_i - 1. \end{cases} \]

By imposing the normalization condition:
\[ 1 = \sum_{i=0}^{n} b_{i,0} + \sum_{j=1}^{n} \sum_{j=1}^{W_{j-1}} b_{i,j} + (1 - p_C) \left[ (1 - p_D) \sum_{j=0}^{m} s_{j,0} + p_D \sum_{j=0}^{m} s_{j,0} \right] \]

\[ = b_{0,0} \left\{ (1 - p_C) [T_{L,1} (1 - p_D) + T_{L,2} p_D] + 1 \right\} \left[ \frac{(1 - \lambda^{n+1})}{1 - \lambda} + \sum_{j=1}^{\infty} \frac{2^{W_0 - 1}}{2} \lambda^j \right], \]

\[ b_{0,0} \text{ is finally determined as} \]

\[ b_{0,0} = \left\{ (1 - p_C) [T_{L,1} (1 - p_D) + T_{L,2} p_D] + 1 \right\} \left[ \frac{(1 - \lambda^{n+1})}{1 - \lambda} + \sum_{j=1}^{\infty} \frac{2^{W_0 - 1}}{2} \lambda^j \right]^{-1} \]

where

\[ \begin{align*}
    p_C &= 1 - (1 - \tau_c)^{W_j - 1} \\
    p_D &= p_h \frac{T_s}{T_f}
\end{align*} \]

From (5) and (7), the probability \( \tau_c \) that a SU transmits in a random slot time in control channel can be written as

\[ \tau_c = \sum_{i=0}^{W_j} b_{i,0} = b_{0,0} \left[ 1 - \lambda^{n+1} \right] \left[ 1 - \lambda \right]. \]

3.2. Saturation throughput

Let \( S \) be the normalized system throughput, defined as the payload information transmitted per unit time. Let \( P_i \) denote the probability that the control channel is idle in a randomly given slot, which can be written as

\[ P_i = (1 - \tau_c)^{W_j}. \]

The probability of a successful RTS-CTS interaction in control channel can be written as

\[ P_s = N_s \tau_c (1 - \tau_c)^{W_j - 1}. \]

Now, we can express \( S \) as

\[ S = \frac{N_s \tau_c (1 - p_C)(1 - p_D)E[P]}{P_i \delta + P_i T_s + (1 - P_i - P_s) T_f}. \]

Here \( E[P] \) is average packet payload size, \( T_s \) is the average time that the control channel is occupied by SUs due to the RTS-CTS or PTS-CTS interaction, \( T_f \) is the average time that the control channel is sensed busy by a collision. Determining the value of \( T_s \) and \( T_f \) is not a difficult problem and we omit the detailed discussion of them.

4. Model validation and numerical results

In this section, we adopt the network simulator QualNet 4.5 to verify the proposed model. The values of the parameters we used in the simulations are listed in table 1.

| Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|
| Propagation model | Two-Ray | SIFS | 10μs |
| Transmission rate | 11Mbps | RTS | 20bits |
The simulation and numerical saturation throughput results of single SU against number of SUs for different number of licensed channels $M=1$, 2, 3 and 4 are compared in figure 4. On one hand, we find that the throughput of single SU is sensitive to the value of the number of SUs. It decreases when the number of SUs increases. The main reason accounts for this phenomenon is that the increasing of the number of SUs increases the collision due to contention among SUs. On the other hand, we observe that the more licensed channels, the better performance of throughput. It is easy to understand that more licensed channels bring more opportunities for transmitting.

Figure 4 Saturation throughput: numerical and versus simulation.

In figure 5, we compare the performance of TPO-MAC with the MAC protocols proposed in [6]. The number of licensed channels is fixed as 10. It can be seen that the throughput obtained by TPO-MAC performs better than MCASC, MCRA and MCGA. It benefits from the priority classification of PUs’ traffic in TPO-MAC. Whether the PUs can access the licensed channels immediately depends on the priority of their traffic. It alleviates the conflict between PUs and SUs. Thus, there is a marginal promotion of the saturation throughput in TPO-MAC compared to the existing ones.

5. Conclusions
In this paper, we have proposed a simple but effective traffic-priority-based opportunistic MAC protocol for multi-channel CRN. The traffic priority classification of PUs decreases the collision between PUs and SUs. Meanwhile, we further propose a two-dimensional Markov chain model to analyse the saturation throughput of TPO-MAC. The accuracy of our model is validated by extensive simulations. The results show that TPO-MAC performs better than other existing protocols for CRN.

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