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Carrier Sensing based Multiple Access Protocols for Cognitive Radio Networks

Shao-Yu Lien, Chih-Cheng Tseng, and Kwang-Cheng Chen

***Abstract*—Cognitive radio (CR) dynamically accessing inactive radio spectrum of the primary system (PS) at link level has attracted a lot of research interests. The cognitive radio network (CRN) organized by multiple CRs has been considered as an emerging wireless communication technology. In order to efficiently utilize the radio spectrum, the multiple access schemes of the CRN shall be considered together with physical layer (PHY) transmission schemes. In this paper, we propose a novel class of carrier sense multiple access (CSMA) based MAC protocols for the CRN while the PS is also operating with widely-applied carrier sensing protocols. Different from conventional CR either to transmit packets or not, our protocols with a feasible adaptive PHY transmission scheme allow possible transmission(s) for a CR even when the PS is actively transmitting. We analyze the proposed class of CSMA based MAC protocols and further propose the transmission strategy for each CR to improve the throughput of the CRN. Numerical results show that our proposed scheme improves the throughput of the CRN more than 36% and 100% as compared with the conventional CSMA and conventional CR operations, respectively.**

***Index Terms*—cognitive radio network (CRN), carrier sense multiple access (CSMA) based protocols, rate-distance nature.**

I. Introduction

TO EFFICIENTLY utilize the precious radio spectrum, the cognitive radio (CR) has been considered as a key technology toward future wireless communications by accommodating secondary system(s) [1]-[3]. Recently, the subjects of CR functionalities at the link level for the point-to-point communications have received significant research interests [4]-[6]. However, operations of CRs shall not be limited to the link level. After possible PHY transmissions of packets, multiple CRs can further form the cognitive radio network (CRN) and an effective multiple access scheme is critical. Therefore, the ideas of the CRN operations are germinating [7]-[10]. Existing works only consider CR operations either from the view point of the PHY or the MAC layer. Since it is critical to increase the throughput of the CRN via the MAC, we introduce a multiple access scheme together with adaptive communications for the CRN.

We note that an important feature of the wireless communications is that the received signal strength (and thus the signal to interference and noise ratio, SINR) decades as the link distance increases. Communications with a low SINR (and thus a long distance link) result in a low date rate and thus a low spectrum throughput. Therefore, the PS does not fully utilize the spectrum resources at long distance links. Therefore, a CRN coexisting with the PS can utilize the spectrum resources more efficiently. The key concept is that CRs transmit packets simultaneously during the transmission of the MS of the PS when interference to and from the MS of the PS are acceptable.

We recall the listen-before-transmission nature of carrier sensing protocols preventing simultaneous transmission for MSs of the PS and CRs. It is thus particularly suitable as the MAC protocol of the CRN when the PS is also with a carrier sensing protocols. Conventional CSMA family protocols operations only allow the packet transmission(s) when the channel is idle. In this paper, we propose a novel class of CSMA based MAC protocols for the CRN. With a feasible adaptive transmission power and rate adapting scheme to control the interference to and from the MS of the PS, the proposed class of CSMA based MAC protocols allow the CR simultaneously transmit the packet during the transmission of the MS of the PS. Thus the radio spectrum can be utilized more effectively. On the contrary, MSs of the PS consider the channel as busy and thus no packet transmissions when a CR is transmitting the packet. Under this circumstance, the interference from MSs of the PS to the CR is avoided.

For a general development of this paper, we first describe the operation of the proposed class of CSMA based MAC protocols for the CRN. Then, we analyze the performance of our class of protocols. A two-dimensional finite state Markov chain (2-D FSMC) model is established to analyze the throughput and the average packet delays of the CRN that consists of CRs with different data rates. The communication strategy for each CR is further proposed. By comparing with the conventional carrier sensing protocol without the simultaneous transmission capability and the conventional CR operation, numerical results show that our proposed scheme has a significant throughput improvement of the CRN.

The rest of this paper is organized as follows: In Section II, the rate-distance nature of wireless communications is introduced. A novel class of CSMA based MAC protocols and its performance analyses are in Section III. A power and rate adaptation scheme is proposed in Section IV. Numerical results and the communication strategy for each CRs are in Section V. Conclusions are given in Section VI.

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II. THE RATE-DISTANCE NATURE OF WIRELESS COMMUNICATIONS

A very important and fundamental nature of state-of-the-art wireless communications is the rate-distance nature [11]. Since most modern wireless communication systems widely apply adaptive modulation and coding (AMC), the system automatically adjusts the PHY transmission power, modulation and coding scheme and the data rate based on the received signal strength or quality. Here, "distance" is a measure of the received signal power, rather than just Euclidean distance. Therefore, communications with the long distance neighbors (i.e. with low received signal strength) select a low data rate but high interference resistible transmission scheme (e.g. QPSK). On the contrary, communications with the long distance neighbors (i.e. with high received signal strength) select a high data rate but low interference resistible transmission scheme (e.g. 64-QAM). Such a manner is referred to the rate-distance nature of wireless communications.

It is interesting to note that the rate-distance nature of wireless communications makes simultaneous transmission of the MS of the PS and the CR possible as shown in Fig. 1. The data rates between the base station and MSs of the PS are based on their effective distances (more precisely, received power levels). A high data rate is selected for communications of the MS near by the base station of the PS. On the contrary, a low data rate is selected for the MS far from the base station of the PS. However, within the coverage area of the PS, a CR communication can be established providing the interference levels to and from the PS is accepted. Under this circumstance, the transmission rate of the established communication is also determined by the interference levels from and to the PS.

III. A NOVEL CLASS OF CSMA BASED MAC PROTOCOLS FOR THE CRN

A. Preliminary

In this study, the PS and CRN are all carrier sensing based systems with four-way handshaking. We consider the CRN that is composed of a base station and multiple CRs that attempt to transmit packets to the base station.

Before transmitting, each MS of the PS shall sense the carrier for a period denoted by τ_p before transmission. If the channel is sensed as idle and the MS of the PS wants to transmit packets, it sends a request-to-send (RTS) message to the PS base station to contend the channel. Then, if a corresponding clear-to-send (CTS) message is successfully received, data packets can be transmitted followed by a responded acknowledgment (ACK) message. Otherwise, data packets are considered as backlogged and are postponed to the next sensed idle channel moment. On the contrary, when transmissions of a CR or other MSs are proceeding, the MS of the PS considers the channel as busy and thus no transmissions.

To develop our CSMA based MAC protocols, we describe features and operations of the proposed scheme as follows.

1) The influence caused by the CRN introduces considerable impacts on not only interference power to the MS of the PS but also the channel access priority when an idle channel is both sensed by CRs and MSs of the PS.

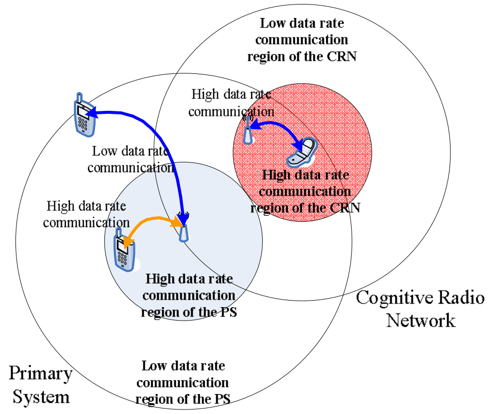

Fig. 1: The CRN and the PS are coexisted with the low-level interference to each other.

Therefore, MSs of the PS should have a higher channel access priority than CRs. We adopt that MSs of the PS have a shorter time and thus a higher priority to access the channel when the channel becomes idle. Therefore, CRs shall sense an idle channel for τ_s which is longer than the carrier sensing period, τ_p, of MSs of the PS to provide the priority.

2) The determination of the length of τ_s is related to the specific MAC protocol adopted by the PS. For instance, if CSMA/CA is adopted by the PS, τ_s should be long enough to reserve a reasonable number of backoff slots for the MSs of the PS to access the channel. However, τ_s should not be too large since τ_s is the overhead and it makes the performance of the CRN degraded.

3) Two statistical parameters are used to characterize the behaviors of MSs of the PS: the (aggregated) successful traffic transmission probability q_p of MSs of the PS during the carrier sensing duration of the CRN, and the remaining data transmission time τ_x after the end of CRs' carrier sensing period, which is shown in Fig. 2(a). Note that the MS of the PS can transmit more than one packet in the data transmission time, which is a common operation manner of the carrier sensing based protocol.

4) Different from traditional CSMA family protocols only consider the channel as either the busy or the idle state, our CSMA based MAC protocols consider the busy state of the channel (a MS of the PS is transmitting packets) as multiple *partial busy* states based on signal to noise and interference ratio (SINR) values. The packet of the CR is allowed to be transmitted when the channel is considered as partial busy states with a feasible adaptive power and rate adjusting that restricting the interference to MS of the PS.

5) A transmission opportunity means that the CR can find a feasible power and rate for the transmission to achieve:
   i) The interference to the MS of the PS can be maintained at an acceptable level.
   ii) The interference from the MS of the PS can be overcome. That is, the bit error rate (BER) of the CR is maintained.

If such a transmission opportunity can be found by CRs, the CR can transmit the packet during the transmission of the MS. When CRs want to transmit packets, RTS mes-

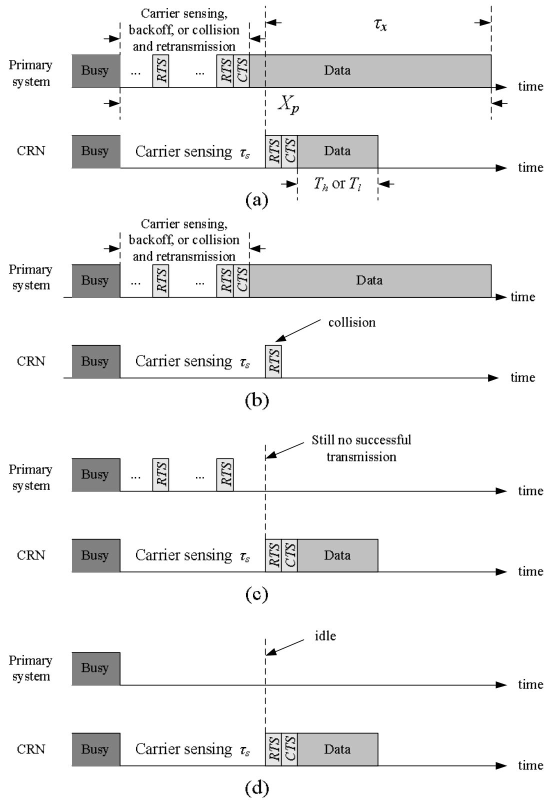

Fig. 2: CSMA based protocols with four-way handshaking procedure coexists with the PS (ACK messages are included at the end of each data transmission duration).

sages are sent to the CRN base station to contend the channel. If the channel contention is success, a packet transmission with feasible power and the data rate can be performed, which is shown in Fig. 2(a). If RTS messages are collided, which is shown in Fig. 2(b), CRs shall wait for the next idle channel or the next transmission opportunity. In this case, these data packets are considered as backlogged.

6) When an MS of the PS is transmitting and a RTS message is received by the CRN base station, the CRN base station computes the transmission power and rate. If a feasible transmission power and rate can be found (a transmission opportunity is found), they will be carried back to the CR transmitter through the responded CTS. If a transmission opportunity can not found, the CTS message is not sent back to the CR transmitter.

7) Although we propose a scheme with which each CR adaptively adjusts the transmission power and rate to prevent an unacceptable interference to the MS of the PS, a long simultaneously transmission time also increases the interference risk to MSs of the PS when CRs are under high mobile activities. Therefore, only one packet is allowed to be transmitted after each successful channel contention for each CR. Besides, there is at most one transmission opportunity for each CR during a data transmission duration of a MS of the PS.

8) The sizes of RTS and CTS messages are very small and a strong forward error correcting code (FEC) can be applied. Thus, we assume that RTS and CTS messages can be correctly received under the interference from the PS. The interference caused by RTS and CTS messages is ignored due to the small size of these messages.

9) If a successful packet transmission of the MS of the PS does not happen before the end of the CRN carrier sensing period, CRs can access the channel regardless of MSs of the PS. Under this circumstance, the MS of the PS considers the channel as busy and thus no packet transmissions until the next idle channel, which is shown in Fig. 2(c). RTS messages of CRs can be transmitted after sensing an idle channel for τ_s if all MSs of the PS do not have successful channel access before the end of CRs' carrier sensing period, which is shown in Fig. 2(d).

B. A Class of CSMA based MAC Protocols for the CRN

Based on the features and assumptions in the previous sub-section, the detailed operations of our CSMA based protocols are as follows.

Step 1: For each CR, if a CR wants to transmit a packet, it senses the channel for a duration τ_s after a busy channel.

a) If the channel is idle at the end of the sensing duration, the CR sends a RTS to the CRN base station to contend the channel.

b) If the channel is occupied by the MS of the PS at the end of the sensing duration, the CR also sends a RTS to contend the channel.

Step 2: If a RTS is received by the CR receiver and is not collided, the CR receiver computes the feasible transmission power and rate. If a feasible transmission power and rate can be obtained, they will be carried back to the CR transmitter through the responded CTS. Otherwise, the CTS is not responded.

Step 3: If the corresponding CTS is received, the CR transmitter transmits the data packet with the power and rate carried in the CTS. Otherwise, the CR transmitter shall wait for the end of next carrier sensing period to send another RTS.

Step 4: When the data packet is correctively received by the CRN receiver, an ACK is replied.

C. Analytical Model for the Proposed Class of CSMA based Protocols

We develop the analysis of the proposed class of CSMA based protocols for the CRN based on the following assumptions:

A1: Since proposed CSMA based MAC protocols support adaptive PHY, there are CRs with different data rates based on the received signal strength. Without loss of generality, two data rates, high and low, are considered.

A2: Based on the distance between the CR and the CRN base station, we assume that CRs near by and far from the CRN base station are with a high data rate and a low data rate, respectively.

A3: Let packets arrive at each of N_h high data rate CRs and each of N_l low data rate CRs are independent and are Poisson processes with mean arrival rates λ_h and λ_l, respectively.

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A4: If a packet arrives at a non-backlogged CR (that is, the CR without backlogged packet) in the carrier sensing period τ_s, a RTS message is transmitted to contend the channel. Thus, we use $q_{ah}=1-e^{-\lambda_h \tau_s}$ and $q_{al}=1-e^{-\lambda_l \tau_s}$ to represent the RTS transmission probabilities for each non-backlogged CR near by and far from the CRN base station, respectively.

A5: If a packet arrives at a non-backlogged CR while the channel is busy, this packet is considered as backlogged.

A6: No buffer is assumed in each CR, and thus, new packets arrive at backlogged CRs are dropped.

A7: Data packets of the CRN are with the same fixed size, and CRs near by and far from the CRN base station require T_h and T_l for a data packet transmission, respectively.

A8: The packet size of the CRN is small, and both T_h and T_l is less than the remaining data transmission duration τ_x of the MSs of the PS.

A9: A failure packet reception of the CR is only caused by packet collision, rather than channel fading or interference from MSs of the PS, since an adaptive communication scheme can overcome the channel fading and interference damage, and maintain the BER to an acceptable value such as 10^{-3} or 10^{-6}.

1) Throughput Analysis

To analyze the performance of the CRN, a 2-D FSMC is used as shown in Fig. 3. In this figure, the state index (n_{bh}, n_{bl}) represents the number of backlogged high and low data rate CRs. Backlogged packets shall wait for the end of next sensing duration and are retransmitted with probabilities q_{bh} and q_{bl} for high and low data rate CRs, respectively. When there are neither new packets nor backlogged packets of CRs attempted to be transmitted while MSs of the PS also has no successful transmissions, the state transits at the end of the CR carrier sensing duration. Otherwise, the state transits at the end of a (partial) busy channel period. We define the throughput as the packet departure rate (precisely, expected number of packet departures per state transition).

We denote τ_{RTS} and τ_{CTS} as the RTS and CTS message receiving times including the worst case packet propagation delay, respectively. Let $g_h(n_{bh}) = (N_h - n_{bh})\, q_{ah} + n_{bh} q_{bh}$ and $g_l(n_{bl}) = (N_l - n_{bl})\, q_{al} + n_{bl} q_{bl}$ be the aggregated packet transmission probabilities of high and low data rate CRs at the end of the carrier sensing period, respectively. If RTS messages are collided, CRs need τ_{CTS} (no corresponded CTS message is received) to recognize collisions. When MSs of the PS have no successful transmission in τ_s with probability $(1-q_p)$, there are four (one step) state transition periods in our 2-D Markov chain model.

i) τ_s (in the case of neither new packets nor retransmission packets and thus RTS messages of CRs are sent at the end of the carrier sensing period. This happens with probability $e^{-(g_h(n_{bh})+g_l(n_{bl}))}$.)

ii) $\tau_s + \overline{T}_h$ (in the case of a high data rate CR successful transmission, $\overline{T}_h = T_h + \tau_{RTS} + \tau_{CTS}$. This happens with probability $g_h(n_{bh})e^{-(g_h(n_{bh})+g_l(n_{bl}))}$).

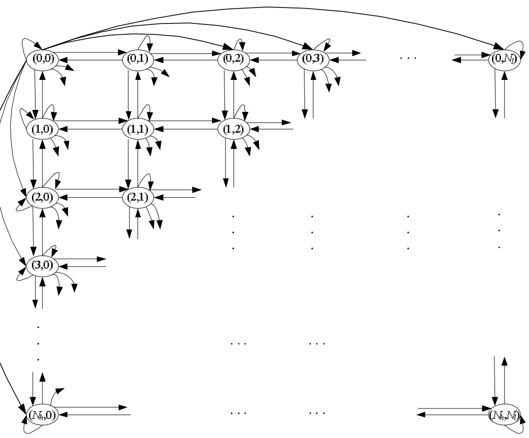

Fig. 3: 2-D finite state Markov chain using (n_{bh},n_{bl}) as the index of the state used to analyze the number of backlogged high and low data rate CRs.

iii) $\tau_s + \overline{T}_l$ (in the case of a low data rate CR successful transmission, $\overline{T}_l = T_l + \tau_{RTS} + \tau_{CTS}$. This happens with probability $g_l(n_{bl})e^{-(g_h(n_{bh})+g_l(n_{bl}))}$).

iv) $\tau_s + \beta$ (in the case of collisions between CRs, $\beta = \tau_{RTS} + \tau_{CTS}$. This happens with probability $1-e^{-(g_h(n_{bh})+g_l(n_{bl}))} - (g_h(n_{bh})+g_l(n_{bl}))e^{-(g_h(n_{bh})+g_l(n_{bl}))}$).

When a MS of the PS has a successful transmission during the carrier sensing period of CRs, τ_s, with probability q_p, the state transition period is X_p, $X_p = \tau_s + \tau_x$.

Therefore, the expected duration of a state transition period is

$$\Gamma_c(n_{bh}, n_{bl}) = (1-q_p)[\tau_s + \overline{T}_h g_h(n_{bh})e^{-(g_h(n_{bh})+g_l(n_{bl}))} + \overline{T}_l g_l(n_{bl})e^{-(g_h(n_{bh})+g_l(n_{bl}))} + (1-e^{-(g_h(n_{bh})+g_l(n_{bl}))} - (g_h(n_{bh})+g_l(n_{bl}))e^{-(g_h(n_{bh})+g_l(n_{bl}))})\beta] + q_p X_p \quad (1)$$

where the first term in the square bracket is the expected duration of carrier sensing period. The second term in the square bracket is the expected duration of a high data rate CR successful transmission. The third term in the square bracket is the expected duration of a low data rate CR successful transmission. The forth term in the square bracket is the expected duration of a collision.

The expected numbers of successful transmissions per state transition of high and low data rate CRs are $(g_h(n_{bh}))e^{-(g_h(n_{bh})+g_l(n_{bl}))}$ and $(g_l(n_{bl}))e^{-(g_h(n_{bh})+g_l(n_{bl}))}$, respectively. Since these two successful transmissions are disjointed, the throughput (or the packet departure rate) of the CRN can be expressed as

$$S_c(n_{bh}, n_{bl}) = \frac{(g_h(n_{bh})+g_l(n_{bl}))e^{-(g_h(n_{bh})+g_l(n_{bl}))}}{\left\{\begin{array}{l}(1-q_p)[\tau_s+(\overline{T}_h g_h(n_{bh})+\overline{T}_l g_l(n_{bl}))e^{-(g_h(n_{bh})+g_l(n_{bl}))}+(1- \\ e^{-(g_h(n_{bh})+g_l(n_{bl}))}-(g_h(n_{bh})+g_l(n_{bl}))e^{-(g_h(n_{bh})+g_l(n_{bl}))})\beta]+q_p X_p\end{array}\right\}} \quad (2)$$

where the numerator is the expected number of packet departures per state transition, and the denominator is the expected duration of a state transition period.

2) Average Packet Delay Analysis

The average packet delay analysis for the CRN can be obtained by modifying the average delay analysis in [12]. The average packet delays for high and low data rate CRs denoted by W_{high_rate} and W_{low_rate}, respectively, can be approximated as

$$W_{high\_rate} \approx \frac{[(1-q_p)(\frac{\overline{\lambda}_h(\tau_s+\overline{T}_h)}{\overline{\lambda}_h+\overline{\lambda}_l}+\frac{\overline{\lambda}_l(\tau_s+\overline{T}_l)}{\overline{\lambda}_h+\overline{\lambda}_l})+q_p X_p]^2+2[E[t]-(\tau_s+\overline{T}_h)]}{2(1-(\overline{\lambda}_h+\overline{\lambda}_l)E[t])} \quad (3)$$

$$W_{low\_rate} \approx \frac{[(1-q_p)(\frac{\overline{\lambda}_h(\tau_s+\overline{T}_h)}{\overline{\lambda}_h+\overline{\lambda}_l}+\frac{\overline{\lambda}_l(\tau_s+\overline{T}_l)}{\overline{\lambda}_h+\overline{\lambda}_l})+q_p X_p]^2+2[E[t]-(\tau_s+\overline{T}_l)]}{2(1-(\overline{\lambda}_h+\overline{\lambda}_l)E[t])} \quad (4)$$

where $E[t]$ is the reciprocal of the throughput and can be interpreted as the expected required time for each packet departure of the CRN, $\overline{\lambda}_h = (N_h - n_{bh})\lambda_h$ and $\overline{\lambda}_l = (N_l - n_{bl})\lambda_l$ are the aggregated arrival rates of high and low data rate CRs, respectively. The average packet delay in (3) and (4) are valid when $(\overline{\lambda}_h+\overline{\lambda}_l)E[t]<1$. That is, the overall arrival rate of the CRN is less than the throughput of the CRN.

3) Throughput and Average Packet Delays of the CRN under Different Data Rates

Values of each reference parameters we used are as follows: $T_h = 1$, $\tau_s = 0.12$, $\tau_{RTS} = \tau_{CTS} = 0.02$, $\lambda_h = \lambda_l = 0.1$, $N_h = N_l = 10$, $q_{bh} = q_{bl} = 0.04$, and $X_p = 10$. The throughput and the average packet delays of the CRN are shown in Fig. 4 and Fig. 5, respectively, under different packet transmission times of low data rate CRs, T_l. Please note that q_p is the successful transmission probability of the MS of the PS during the carrier sensing period of CRs, it is in practical. We select values of q_p in a feasible region from 0 to 0.01.

Based on the curves in Fig. 4 and Fig. 5, we indicate that reducing the packet transmission time of low data rate CRs, T_l, (and thus increasing the data rate) increases the throughput

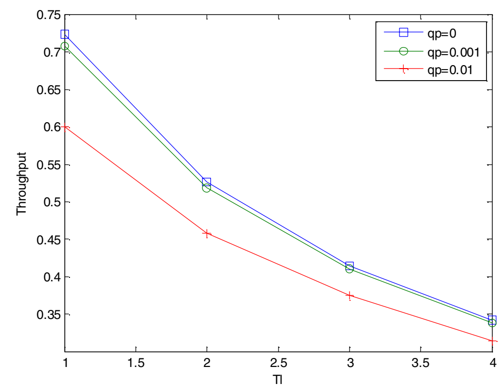

Fig. 4: Throughput of the CRN under different packet transmission time (T_l) of low data rate CRs.

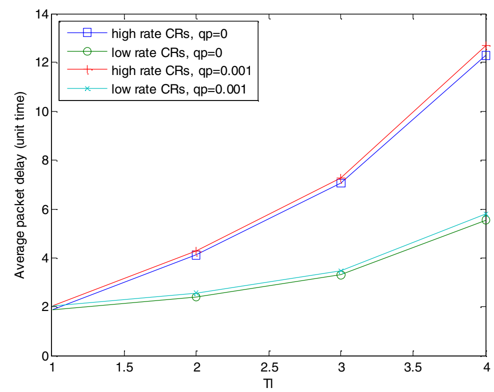

Fig. 5: Average packet delays under different packet transmission time (T_l) of low data rate CRs.

while the average packet delays of high and low data rate CRs decreases. In this analysis, the performance of the CRN both in the throughput and the average packet delays are improved as the data rate of low data rate CRs increases. However, a high data rate transmission relies on a high SINR, which also relies on a high transmission power. The data rate can not increase unlimitedly since CRs are required to prevent an unacceptable interference to the MS of the PS. Thus, we propose the transmission strategy for each CR to improve the throughput as follows.

When MS of the PS is transmitting, CR can use the maximal transmission power (or the maximal transmission data rate) which does not violet the interference constraint of MS of the PS to concurrently transmit packets.

This communication strategy for each CR can also be considered as to achieve the maximal spectral efficiency that does not violet the interference constraint of MS of the PS. This communication strategy is the guide to design the adaptive power and rate adjusting.

IV. Adaptive Power and Rate Communication Scheme

A. Modified Truncated Channel Inversion

We present an adaptive power and rate scheme as a pilot example for CRs rejecting an unacceptable interference to the PS. We modify the scheme in [13][14] for adaptive communication of each CR.

The suboptimal spectral efficiency of the modified truncated channel inversion adaptation scheme is

$$\frac{R}{B} = \max_{\gamma',\gamma' \geq \gamma_0} \log_2\left(1 + \frac{-1.5}{\ln(5\text{BER})\overline{[1/\gamma]}_{\gamma'}}\right) p(\gamma > \gamma') \quad (5)$$

where $p(\gamma)$ is the distribution of SINR under fading and interference, $p(\gamma > \gamma')$ is the probability that $\gamma > \gamma'$, and γ_0 is a threshold value, γ' is the cutoff SINR, R is the data rate, and B is the signal bandwidth. (5) is slightly different from the spectral efficiency in [13][14] where the spectral efficiency of the truncated channel inversion is maximized over all possible cutoff SINR values. However, a low SINR makes the CR need to use a larger transmission power to invert the channel. This large transmission power of CRs increases the interference to MSs of the PS. Since CRs shall maintain an acceptable interference MSs of the PS, the spectral efficiency in (5) is only maximized over the cutoff SINR values that exceed a particular threshold value γ_0. Otherwise, interference caused by CRs to MSs of the PS may exceed an acceptable value. We will show how to provide an acceptable interference guarantee to the MS of the PS in the following subsection, and γ_0 will also be derived.

B. Guarantee an Acceptable Interference to the MS of the PS.

We model the outage probability of the MS of the PS as the probability that interference power from the CR to the MS of the PS is larger than a pre-determined value I_{acc}. This outage probability should be less than p_{outage}, and can be expressed as

$$\Pr\{S(\gamma)_{rx} > I_{acc}\} < p_{outage} \quad (6)$$

where $S(\gamma)_{rx}$ is the received interference power from the CR to the MS of the PS. Based on (6), the maximal allowable transmission power of the CR transmitter denoted by Ψ can be represented as

$$\Psi = I_{acc}\left[10\alpha\log_{10}\left(\frac{d_{p_{outage}}}{d_0}\right) + q(\gamma)_{p_{outage}}\right] \quad (7)$$

where $d_{p_{outage}}$ is the distance value such that

$$\int_0^{d_{p_{outage}}} d(r)dr \leq p_{outage} \quad (8)$$

$d(r)$ is the Euclidean distance distribution between an arbitrary transmitter of the CR and the receiver MS of the PS, and can be obtained in [15], and $q(\gamma)_{p_{outage}}$ is the received SNR value of the MS of the PS such that

$$\int_0^{q(\gamma)_{p_{outage}}} q(\gamma)d\gamma \leq p_{outage} \quad (9)$$

$q(\gamma)$ is the fading distribution.

The cutoff SINR threshold of CRs can be determined as

$$\gamma_0 = \frac{\bar{S}\sigma_0}{\Psi} \quad (10)$$

where σ_0 is the corresponding target SINR of the channel inversion and $\bar{S}$ is the average power constraint. Substituting (10) into (5), the suboptimal spectral efficiency that guarantees the acceptable interference power to the MS of the PS is obtained.

V. Numerical Results

The objective of this section is to show the throughput comparison of the proposed scheme with the carrier sensing protocol without simultaneously packet transmission capability and conventional CRs operations. All the contexts are under the presence of the PS.

In Fig. 6, we analyze the throughput-offer load characteristic of our protocols under different q_p values of the PS. The curve is of special interest when the PS is absent ($q_p = 0$) and the CRN is with a homogeneous rate ($T_l = 1$), which shows that our proposed protocols have a similar performance as the non-persistent CSMA with four-way handshaking shown in [16]. Thus, we verify that our proposed protocols also operate well when the PS is absent.

We also compare the throughput of the CRN with our proposed scheme with following two cases.

Case 1: Carrier sensing protocol without the simultaneously transmission capability (CSMA non-ST): In this case, we analyze the throughput of our proposed class of CSMA based protocol without the simultaneously transmission capability. All CRs in the CRN are with the same data rate.

Case 2: The conventional CRs operations (Conventional CR): In this case, with certain cognition mechanisms, CRs does not simultaneously transmit the packet during the transmission of the MS of the PS. We construct the throughput of this case by the following assumptions.

1) The slotted Aloha (s-Aloha) is adopted for the multiple access protocol. Since different data rates are used by CRs, each successful CR transmission occupies different number of successive slots.
2) Since the s-Aloha does not provide the channel access priority for MSs of the PS, if a CR accesses the channel at the beginning of an idle slot (which is the slot not occupied by other CRs or MSs of the PS), MSs of the PS consider the channel as busy and shall wait for the end of the CR's transmission. We refer these occupied successive slots to a burst.
3) Let the number of packets arrive at each non-backlogged CR near by and far from the CRN base station are independent and are Poisson process. Similar to the analysis method in the previous section, we use g_h and g_l for CRs near by and far from the CRN base station, respectively, to represent the attempted transmission probabilities at the beginning of an idle slot.
4) q_f is the probability that MSs of the PS does not have a successful transmission in an slot.
5) T_s is the slot length (since s-Aloha is adopted) of the CRN in this degenerated case.
6) We normalize the packet transmission time of CRs near the CRN base station, T_h, to T_s.

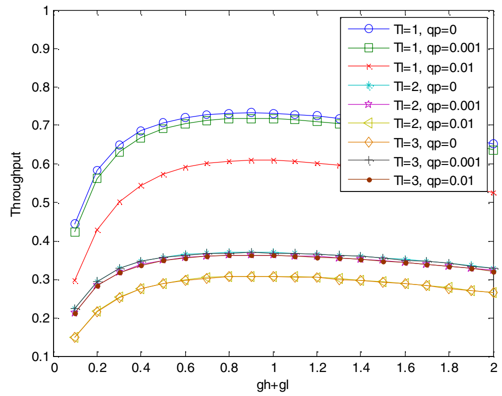

Fig. 6: Throughput-offer load characteristic of the CRN.

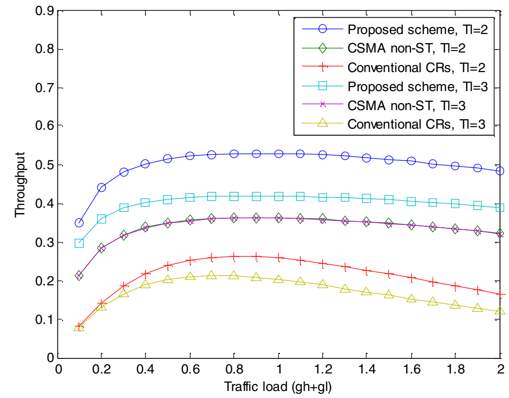

Fig. 7: Throughput comparisons of the CRN.

7) If a MS of the PS successfully contend the channel during an idle slot (it may not happen at the beginning of the slot since MSs of the PS have to sense the channel for a duration τ_p before transmission), the MS can transmit data for a duration τ_x not including this successful channel contention slot. Therefore, $X_p = \lceil \tau_x \rceil$ slots.

8) The rest of parameters are with the same definitions as in previous sections.

The throughput of this case can be approximated as

$$S_{CR\_AC} \approx \frac{(g_h + g_l)e^{-(g_h+g_l)}}{\left\{ \begin{array}{l} (1-e^{-g_l})T_l + (1-e^{-g_h})e^{-g_l}T_h \\ +q_f T_s e^{-(g_h+g_l)} + e^{-(g_h+g_l)}(1-q_f)X_p \end{array} \right\}} \quad (11)$$

(11) can be approximated as the packet departure rate of this case.

Fig. 7 shows the throughputs under different data rates of CRs far from the CRN base station (which depends on different interference level to and from the MS of the PS and the channel condition, that is, the SINR level). Values of each reference parameters we used are as follows: $q_p = 0.001$, $X_p = 10$, $\tau_{RTS} = \tau_{CTS} = 0.02$ and $\tau_s = 0.12$, and $q_f = 0.99$. The CRN with our proposed class of CSMA based MAC protocols has more than 36% and more than 100% as compared with the throughputs of the carrier sensing protocol without simultaneously capability and the conventional CRs operations, respectively.

VI. CONCLUSIONS

In this paper, we proposed a carrier sensing based MAC protocols for CRN to coexist with the PS. With a feasible power and rate adjusting mechanism, our proposed scheme provide the simultaneous packet transmission capability for a CR during the transmission of the MS of the PS. Analytical expressions of the throughput and the average packet delays for the CRN are derived. Numerical results also showed that our proposed scheme significantly increases the throughput of the CRN as compared with that of the conventional carrier sensing protocol and the conventional CRs operations.

REFERENCES

[1] P. Kolodzy, "Spectrum Policy Task Force: Findings and Recommendations," in *International Symposium on Advanced Radio Technologies (ISART)*, March 2003.

[2] M. McHenry, "Report on Spectrum Occupancy Measurements," *Share Spectrum Company*, http://www.sharedspectrum.com/?section=nsf_summary.

[3] Cordeiro C., Challapali k., Birru D, Sai Shankar, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios," in *International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, Nov. 2005, pp. 328-337.

[4] S. H. Hung, S. Y. Hung, Eric H. K. Wu, and G. H. Chen "A Decentralized CR System Algorithm for Cognitive Borrowing Scheme from Primary Users," *IEEE International Symposium on PIMRC*, 2006.

[5] X. Zhu, L. Shen, and T. –S. Peter Yum, "Analysis of Cognitive Radio Spectrum Access with Optimal Channel Reservation," *IEEE Communications Letter*, Vol. 11, No. 4, pp. 304-306, Apr. 2007.

[6] O. Holland, A. Attar, N. Olaziregi, N. Sattari, A. H. Aghvami, "A Universal Resource Awareness Channel for Cognitive Radio," *IEEE International Symposium on PIMRC*, Sep. 2006.

[7] M. Thoppian, S. Venkatesan, S. Prakash, R. Chandrasekaran "MAC-layer scheduling in cognitive radio based multi-hop wireless networks," in *International Symposium on WoWMoM*, Jun. 26-29, 2006.

[8] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad-Hoc Networks: a POMDP framework," *IEEE Journal on Selected Areas in Communications*, Vol. 25, No. 3, pp. 589-600, Apr. 2007.

[9] A. C. –C. Hsu, D. S. L. Wei, and C. –C. Jay Kuo, "A Cognitive MAC Protocol Using Statistical Channel Allocation for Wireless Ad-hoc Networks," *IEEE WCNC*, 2007.

[10] L. –C. Wang, C. –W. Wang, Y. –C. Lu, and C. M. Liu, "A Concurrent Transmission MAC Protocol for Enhancing Throughput and Avoiding Spectrum Sensing in Cognitive Radio," *IEEE WCNC*, 2007.

[11] K. –C. Chen, L. –H. Kung, D. Shiung, R. Prasad, and S. Chen, "Self-Organizing Terminal Architecture for Cognitive Radio Networks," *The 10th International Symposium on Wireless Personal Multimedia Communications*, 2007.

[12] Dimitri Bertsekas, Robert Gallager, "Data Networks," Prentice Hall, second edition.

[13] A. J. Goldsmith, and S. –G. Chua, "Variable-Rate Variable-Power MQAM for Fading Channels," *IEEE Trans. Commun.* Vol. 45, No. 10, pp. 1218-1230, Oct. 1997.

[14] A. J. Goldsmith, and P. P. Varaiya, "Capacity of Fading Channels with Channel Side Information," *IEEE Trans. Inform. Theory*, Vol. 43. No. 6, pp. 1986-1992, Nov. 1997.

[15] C. –C. Tseng and K. –C. Chen, "Layerless Design of A Power-Efficient Clustering Algorithm for Wireless Ad Hoc Networks under Fading," *Wireless Personal Communications*.

[16] K. –C. Huang, and K. –C. Chen, "Interference analysis of nonpersistent CSMA with hidden terminals in multicell wireless data networks," *IEEE International Symposium on PIMRC*, 1995.