A Decentralized MAC Protocol for Cognitive Radio Networks

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Abstract—One of the most challenging issues in cognitive radio networks is efficient channel sensing and channel accessing. In this paper, an analytical queueing model is used to derive the probability of successful transmission, channel sensing time, and transmission quota, for each data channel. Each CR node records the derived statistics in a channel preference matrix. A CR pair selects a data channel for sensing and accessing based on the successful transmission probability. According to the derivations, we design a media access control protocol, which utilizes the powerful computation capability of cloud servers to estimate the behavior of PUs, for infrastructure-based cognitive radio networks. We validate the analytical model with simulation results. Besides, the proposed MAC protocol is compared with other approaches via simulation. The simulation results showed that our protocol performs well in both utilization of channel idle time and the average tries of channel search.

Keywords— cognitive radio network; channel sensing; channel access

I. INTRODUCTION

With rapid increase of the wireless applications and products, unlicensed bands such as Industrial, Scientific and Medical (ISM) has become over-crowded. Cognitive Radio (CR) [1], as a promising solution to efficiently utilize the unused spectrum, has become an attractive research topic nowadays. The concept of the CR technique is that cognitive radio nodes (CR nodes) can temporarily borrow unoccupied channels from primary users (PUs) without interfering with PUs.

To utilize available spectrum efficiently, a media access control (MAC) protocol is of great importance to CR nodes. Existing CR MAC protocols can be classified into two categories: single rendezvous [2-3] or parallel rendezvous [4-5]. The former utilizes a common channel for CR nodes to exchange control messages; in the latter, contrarily, control messages are delivered on data channels.

The major advantage of single rendezvous protocols is the avoidance of collision and meaningless channel hops. This control channel, however, does become a bottleneck. Therefore, how to design a MAC protocol with a control channel efficiently is big challenge.

In [2], CR nodes perform negotiations on a common control channel. Besides, a CR pair can only transmit one packet on the temporarily occupied data channel (or on the control channel). In this mechanism, all CR nodes need to achieve global synchronization. However, this global synchronization significantly decreases the utilization of channel idle time. In [3], a CR pair can exchange at most "*TXQ*" frames once they discover an idle data channel. "*TXQ*" parameter efficiently reduces the average channel sensing time. However, how to properly set "*TXQ*" parameter is not addressed.

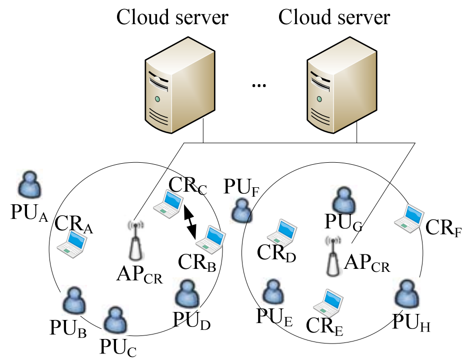


Figure 1. A simple network topology of infrastructure-based cognitive radio networks

On the other hand, the basic idea of parallel rendezvous protocols [4-5] is that nodes hop among different data channels according to their own sequences, and control messages are exchanged when a CR pair meets each other on a data channel. However, synchronization problem and hopping sequence generating function are still opened problems.

In this paper, we propose a cloud server-assisted MAC protocol for infrastructure-based cognitive radio networks (CRN), as in [6]. CR nodes cooperatively and periodically report channel qualities and positions to CR access points (denoted as AP_{CR}). AP_{CR}s further deliver collected information to cloud servers. One characteristic of cloud computing is the provided powerful computation capability. Cloud servers derive the distribution of PUs' arrival rate and channel idle time for each CR node and this information is forwarded by AP_{CR}s. This information helps on a CR node to estimate how much time it should spend on sensing a specific data channel, how many data frames it can deliver, and what the success probability is. CR nodes sense channels in decreasing order of successful probability.

The rest of this paper is organized as follows. Network model and problem description are presented in Section II. The designed cloud server-assisted MAC protocol is described in Section III. Section IV presents and discusses the simulation results, while Section V concludes the paper.

II. Network Model and Problem Description

A. Network Model

We consider an infrastructure-based CRN which consists of AP_{CR}s, and CR nodes, as shown in Fig. 1. Besides, cloud servers are used to support the computation overhead of PUs' locations and the distribution of arrival rate and channel idle time. We assume there are N orthogonal data channels and one control channel. CR nodes register to an AP_{CR} for joining the CRN. In this paper, we consider single-hop CR flows. That is, two CR nodes can exchange frames when both are within each other's transmission range.

Each CR node equips a GPS and has only one transceiver. CR nodes periodically report their positions and measured channel qualities to AP_{CR}. AP_{CR} further forwards the collected information to cloud servers. Accordingly, for each data channel, cloud servers can identify PUs' locations [7]. Upon knowing positions of PUs' and CR nodes', and taking hidden terminal problem into consideration, cloud servers provide each CR node the distribution of PU traffic arrival rate and idle time for each channel.

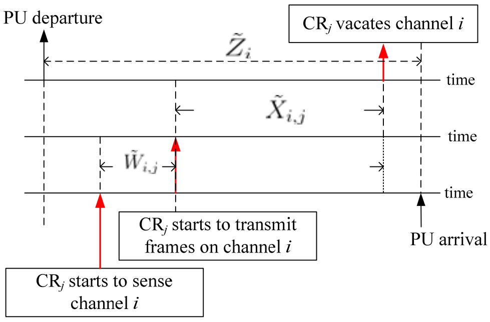
Communications between CR nodes and the AP_{CR} are on the control channel; while the AP_{CR} and the cloud server communicate through a backbone network. The control channel could be either a dedicated channel or an ISM-band channel.

B. Problem Description

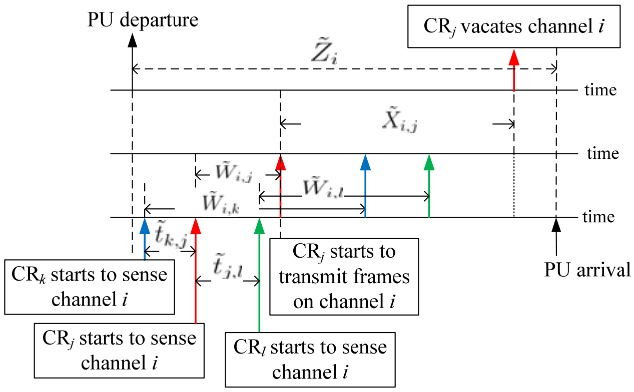
In this paper, we aim at increasing the successful transmission probability of a CR pair while avoiding interfering on PUs. Due to the support of cloud server, each CR node obtains channel and PUs' statistics without performing complex computation [7]. Our design concept is, for a CR node, to use the obtained statistics to estimate the successful transmission probability of each channel. Among all data channels, a CR pair exchanges frames on the data channel which has the highest successful probability. As a result, the major challenge is how to calculate this probability.

Specifically, frame transmission of a CR node is affected by both PUs and other CR nodes. Fig. 2(a) is an example to illustrate how PUs impact on CR transmission. For data channel i and CR node j (denoted as CR_j), let $\tilde{Z}_i$, $\tilde{W}_{i,j}$, and $\tilde{X}_{i,j}$ represent the channel idle time, channel sensing time, and data transmission time, respectively. To guarantee CR_j's successful transmission, $\tilde{W}_{i,j}+\tilde{X}_{i,j}\leq\tilde{Z}_i$. Therefore the probability that CR_j will successfully deliver frames on channel i without interfering PUs is $p_1=P(\tilde{W}_{i,j}+\tilde{X}_{i,j}\leq\tilde{Z}_i)$.

On the other hand, the impact from other CR nodes is shown in Fig. 2 (b). In Fig. 2 (b), CR_k starts to sense channel i before CR_j. Let $\tilde{t}_{k,j}$ be the difference of start-sensing time of CR_j and CR_k. If $\tilde{W}_{i,j}+\tilde{t}_{k,j}>\tilde{W}_{i,k}$, CR_j fails to transmits frames on channel i. We then consider another case that CR_l starts to sense channel i after CR_j. Similarly, if $\tilde{W}_{i,j}>\tilde{W}_{i,l}+\tilde{t}_{j,l}$, CR_j also fails to deliver frames on channel i. Therefore, the probability that CR_j transmits on channel i without forestalling by other CR nodes is $p_2=1-P(\tilde{W}_{i,j}+\tilde{t}_{k,j}>\tilde{W}_{i,k})-P(\tilde{W}_{i,j}>\tilde{W}_{i,l}+\tilde{t}_{j,l})$.



(a). An example to illustrate the impact of PUs on CR_j



(b) An example to illustrate the impact of other CR nodes on CR_j

Figure 2. An illustration of CR_j accessing channel i successfully

The objective of this paper is, for each CR node, to derive $p_1\times p_2$ value for all channels.

III. Cloud Server-Assisted MAC (CSA-MAC) Protocol for Cognitive Radio Networks

In this section, we describe the designed cloud server-assisted medium access control protocol, named CSA-MAC, in detail.

In CSA-MAC, each CR node, say CR_j, maintains/updates a channel preference matrix $\boldsymbol{H}_j=[\boldsymbol{P}_j\ \boldsymbol{W}_j\ \boldsymbol{Q}_j]$ when periodically receiving channel statistics from the AP_{CR}. $\boldsymbol{H_j}$ is an N×3 matrix, as shown in (1). Each row is for a specific data channel; the three elements of a row are successful transmission probability, sensing time, and transmission quota. Here $p_{i,j}$, $\tilde{W}_{i,j}$, and $q_{i,j}$ represent the successful transmission probability, channel sensing time, and transmission quota, of CR_j on channel i, respectively.

$$\boldsymbol{H_j}=[\boldsymbol{P_j}\quad \boldsymbol{W_j}\quad \boldsymbol{Q_j}]=\begin{bmatrix} p_{1,j} & \tilde{W}_{1,j} & q_{1,j} \\ p_{2,j} & \tilde{W}_{2,j} & q_{2,j} \\ \vdots & \ddots & \\ p_{N,j} & \tilde{W}_{N,j} & q_{N,j} \end{bmatrix} \tag{1}$$

In the following, we explain how to derive column vectors $\boldsymbol{W_j}$, $\boldsymbol{Q_j}$, and $\boldsymbol{P_j}$.

A. Derivations of $\boldsymbol{W_j}$ and $\boldsymbol{Q_j}$

Based on [8], the sensing time of CR_j on channel i, denoted as $\tilde{W}_{i,j}$, is

$$\tilde{W}_{i,j} = \frac{1}{B_i \gamma_{i,j}^2}\left[1.2 + 1.2(\gamma_{i,j}+1)\right]^2, \quad (2)$$

where B_i and $\gamma_{i,j}$ are channel capacity (in Hz) and measured signal-to-noise ratio (SNR) (in dB), respectively. Thus the sensing time of CR$_j$ on each channel is $\boldsymbol{W_j} = \left[\tilde{W}_{1,j}, \tilde{W}_{2,j}, \ldots, \tilde{W}_{N,j}\right]^T$.

Next, let $q_{i,j}$, t_x, and t_{ctl} indicate the transmission quota of CR$_j$ on channel i, frame transmission time, and control frame transmission time, accordingly. Given the idle time of channel i being r, i.e., $\tilde{Z}_i = r$, the time duration that CR$_j$ can utilize to transmit frames is $(\tilde{Z}_i - \tilde{W}_{i,j})$, which can accommodate $\left\lfloor \frac{\tilde{Z}_i - \tilde{W}_{i,j} - t_{ctl}}{t_x} \right\rfloor$ data frames. Thus the column matrix $\boldsymbol{Q_j}$ is

$$\boldsymbol{Q_j} = [q_{1,j}, \ldots, q_{N,j}]^T$$

$$= \left[\left\lfloor \frac{\tilde{Z}_1 - \tilde{W}_{1,j} - t_{ctl}}{t_x} \right\rfloor, \ldots, \left\lfloor \frac{\tilde{Z}_N - \tilde{W}_{N,j} - t_{ctl}}{t_x} \right\rfloor\right]^T \quad (3)$$

B. Derivation of $\boldsymbol{P_j}$

Both PUs and other CR nodes affect data transmission of CR$_j$ on channel i. Therefore our derivations consist of two parts: impact from PUs and impact from CR nodes.

(1) Impact from PUs

We assume the idle time of channel i is a random distribution $\tilde{Z}_i$ and for a specific period k its distribution is

$$f_{\tilde{Z}_{i_k}} = \frac{r f_{\tilde{Z}}(r)}{E[\tilde{Z}]} \quad (4)$$

Let $\tilde{S}_{i,j} = \tilde{W}_{i,j} + \tilde{X}_{i,j}$. According to the imbedded Markov chain [9], we can find the occupancy distribution of a CR node by applying z-transform on (4),

$$\begin{aligned} F^*_{\tilde{S}_{i,j}}(s) &= \frac{(1-z)(1-\rho)F^*_{\tilde{x}_{i,j}}(\lambda_c - \lambda_c z)}{F^*_{\tilde{x}_{i,j}}(\lambda_c - \lambda_c z) - z} \Big|_{z=\frac{\lambda_c - s}{\lambda_c}} \\ &= \frac{(1-\rho)F^*_{\tilde{x}_{i,j}}(s)}{1-\rho[1-F^*_{\tilde{x}_{i,j}}(s)]/(sE[\tilde{x}_{i,j}])}, \end{aligned} \quad (5)$$

where λ_c is the arrival rate of CR nodes, μ is channel service rate, and $\rho = \lambda_c/\mu$.

We use *M*/*M*/1 as an example to further explain how to derive $F^*_{\tilde{S}_{i,j}}(s)$. Assume $F^*_{\tilde{x}_{i,j}}(s) = \frac{\mu}{\mu+s}$, then

$$\begin{aligned} F^*_{\tilde{S}_{i,j}}(s) &= \frac{s(1-\rho)\frac{\mu}{\mu+s}}{s - \lambda_c + \lambda_c\frac{\mu}{\mu+s}} \\ &= \frac{\mu(1-\rho)}{s + \mu(1-\rho)} \end{aligned} \quad (6)$$

The probability density function of $\tilde{S}_{i,j}$ is $f_{\tilde{S}_{i,j}}(t) = \mu(1-\rho)e^{-\mu(1-\rho)t},\ t \geq 0$. Let λ_{p_i} be the PUs' arrival rate on channel i. The successful transmission probability of CR$_j$ on channel i without PU interruption is $P(\tilde{Z}_{i_k} \geq \tilde{S}_{i,j})$ and

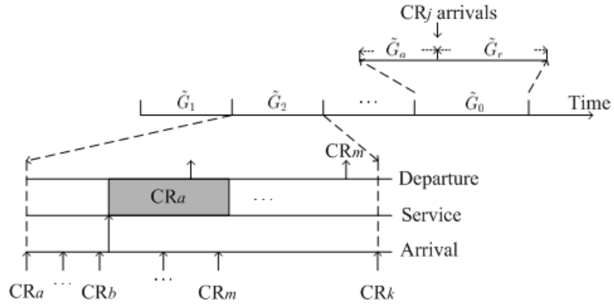


Figure 3. An example to illustrate the meanings of $\{\tilde{G}_\eta, \eta \geq 1\}$, aging time $\tilde{G}_a$, and residual time $\tilde{G}_r$

$$\begin{aligned} P(\tilde{Z}_{i_k} \geq \tilde{S}_{i,j}) &= \int_r^\infty P(\tilde{Z}_{i_k} \geq r | \tilde{S}_{i,j} = r) f_{\tilde{Z}_{i_k}(r)} dr \\ &= \int_r^\infty \int_0^r \mu(1-\rho)e^{-\mu(1-\rho)t} f_{\tilde{Z}_{i_k}}(r) dt dr \\ &= \int_r^\infty f_{\tilde{Z}_{i_k}}(r) dr - \int_r^\infty e^{-\mu(1-\rho)r} f_{\tilde{Z}_{i_k}}(r) dr \\ &= e^{-\lambda_{p_i} r} - \frac{\lambda_{p_i}}{\lambda_{p_i} + \mu - \lambda_c}\left(e^{-(\lambda_{p_i}+\mu-\lambda_c)r}\right) \end{aligned} \quad (7)$$

From (7), if $\tilde{Z}_{i_k} = r \geq \tilde{S}_{i,j}$, channel i has available capacity to serve CR$_j$ without interfering PUs. Further, if the channel idle time is exactly the sum of sensing time and frame transmission time, i.e., $r = \tilde{W}_{i,j} + \tilde{X}_{i,j},\ i = 1, 2, \ldots, N$, CR nodes maximally utilize the channel idle time.

(2) Impact from other CR nodes

Let $\{\tilde{G}_\eta, \eta \geq 1\}$ denote a sequence of i.i.d. non-negative random variables with $P(\tilde{G}_\eta \geq 0), \forall \eta$. Here $\tilde{G}_\eta$ is the time interval which a CR user enters this channel which is unoccupied until the time which channel becomes unoccupied. An example is shown in Fig. 3. CR$_a$ starts to sense an idle channel during $\tilde{G}_2$, and there are other CR nodes hop to that channel to perform sensing. While all CR users finish their transmission or hop to other data channels pending $\tilde{G}_2$, we call the period $\tilde{G}_2$ is finished.

We assume that CR$_j$ starts to sense channel during $\tilde{G}_0$. Since the start-sensing time is randomly distributed within $\tilde{G}_0$, we divide $\tilde{G}_0$ into two parts: before CR$_j$'s start-sensing time (named aged time $\tilde{G}_a$), and after CR$_j$'s start-sensing time (named residual time $\tilde{G}_r$). We know $f_{\tilde{G}_0} = \frac{g f_{\tilde{G}}(g)}{E[\tilde{G}]}$. Therefore,

$$\begin{aligned} f_{\tilde{G}_r}(p) &= \int_{g=p}^\infty f_{\tilde{G}_r|\tilde{G}_0}(p|\tilde{G}_0 = g) dF_{\tilde{G}_0}(g) \\ &= \frac{1}{E[\tilde{G}]}\int_p^\infty f_{\tilde{G}}(g) dg \\ &= \frac{1 - F_{\tilde{G}}(p)}{E[\tilde{G}]} \end{aligned} \quad (8)$$

Again, in Fig. 2 (b), two criteria that CR_j can successfully transmit frames on that channel without forestalling other CR nodes' transmission are (1) $\tilde{t}_{k,j} \le \tilde{W}_{i,k} - \tilde{W}_{i,j}$, and (2) $\tilde{t}_{j,l} \ge \tilde{W}_{i,j} - \tilde{W}_{i,l}$. Let $x = \tilde{t}_{j,l} = \tilde{t}_{k,j}$, $\zeta_i = \tilde{W}_{i,j} - \tilde{W}_{i,l}$ and $\psi_i = \tilde{W}_{i,k} - \tilde{W}_{i,j}$, respectively, then the successful probability is

$$\begin{aligned} f_{\tilde{G}_a}(\zeta_i \le x \le \psi_i) &= \int_0^{\psi_i} f_{\tilde{G}_a}(x)dx - \int_0^{\zeta_i} f_{\tilde{G}_a}(x)dx \\ &= F_{\tilde{G}_a}(\psi_i) - F_{\tilde{G}_a}(\zeta_i) \end{aligned} \quad (9)$$

The column vector $\boldsymbol{P_j}$ is

$$\boldsymbol{P_j} = [p_{1,j}, p_{2,j}, ...p_{N,j}]^T$$

$$= \begin{bmatrix} (F_{\tilde{G}_a}(\psi_1) - F_{\tilde{G}_a}(\zeta_1))(e^{-\lambda_{p_1} r} - \frac{\lambda_{p_1}}{\lambda_{p_1}+\mu-\lambda_c}(e^{-(\lambda_{p_1}+\mu-\lambda_c)r}) \\ (F_{\tilde{G}_a}(\psi_2) - F_{\tilde{G}_a}(\zeta_2))(e^{-\lambda_{p_2} r} - \frac{\lambda_{p_2}}{\lambda_{p_2}+\mu-\lambda_c}(e^{-(\lambda_{p_2}+\mu-\lambda_c)r}) \\ \vdots \\ (F_{\tilde{G}_a}(\psi_i) - F_{\tilde{G}_a}(\zeta_i))(e^{-\lambda_{p_i} r} - \frac{\lambda_{p_i}}{\lambda_{p_i}+\mu-\lambda_c}(e^{-(\lambda_{p_i}+\mu-\lambda_c)r}) \\ \vdots \\ (F_{\tilde{G}_a}(\psi_N) - F_{\tilde{G}_a}(\zeta_N))(e^{-\lambda_{p_N} r} - \frac{\lambda_{p_N}}{\lambda_{p_N}+\mu-\lambda_c}(e^{-(\lambda_{p_N}+\mu-\lambda_c)r}) \end{bmatrix} \quad (10)$$

C. CSA-MAC operations

In this paper, we propose two MAC protocols: CSA-MAC with handshaking and CSA-MAC without handshaking. For a CR pair, the sender (say CR_j) transmits an invitation to its intended receiver (say CR_k) on the control channel. If CR_k is idle and within CR_j's transmission range, it replies its channel preference matrix $\boldsymbol{H_k}$ to CR_j. CR_j is responsible to determine the channel preferences. How to determine the channel preferences is described below.

Upon receiving $\boldsymbol{H_k}$, for this CR flow, CR_j calculates the successful transmission probability of each channel, sensing time, and transmission quota, as in (11).

$$\begin{cases} p_i = p_{i,j} \times p_{i,k}, \\ \tilde{W}_i = max(\tilde{W}_{i,j}\ ,\ \tilde{W}_{i,k}), \quad i = 1, 2, ..., M \\ q_i = min(q_{i,j}\ ,\ q_{i,k}), \end{cases} \quad (11)$$

CR_j then sorts all data channels in decreasing order of p_i. This sorted channel sequence is exact the hopping sequence. CR_j informs CR_k the hopping sequence and the corresponding sensing time and transmission quota. Followed, both CR_j and CR_k hop to data channel(s) for channel sensing.

The major difference between CSA-MAC with handshaking and without handshaking is the exchanges of RTS_{CR} and CTS_{CR} on data channels. For CSA-MAC with handshaking, CR_j and CR_k will further exchange RTS_{CR} and CTS_{CR} when either side senses a data channel being idle; while CSA-MAC without handshaking does not perform RTS_{CR} and CTS_{CR} exchanges.

In the following, we use an example to illustrate CSA-MAC protocol. We consider two data channels (denoted as Ch1 and Ch2), and each is with 2MHz capacity with BPSK modulation scheme. CR_B wants to transmit frames to CR_C, as shown in Fig. 1. We assume 2048-byte frame size, and the frame transmission time is 8.4ms. The channel utilization of PUs of Ch1 and Ch2 are 0.4 and 0.5 individually.

Table I. The successful probability of derivation and simulation results in CRN.

N = 1	CR user = 1	Derivation result	0.8625
		Simulation result	0.8000
	CR user = 2	Derivation result	0.9472
		Simulation result	0.8791
N = 2	CR user = 1	Derivation result	0.7350
		Simulation result	0.7062
	CR user = 2	Derivation result	0.9058
		Simulation result	0.8136

The SNR values of Ch1 and Ch2 measured by CR_B are 0.0246 dB and 0.0231 dB individually. Thus the sensing times of Ch1 and Ch2 are $\tilde{W}_{1,B} = 1.3\text{ms}$, and $\tilde{W}_{2,B} = 1.4\text{ms}$. Assume that the observation time of Ch1 and Ch2 is 90ms and 86ms. According to (3), $q_{1,B} = \lfloor 0.6(90 - 1.3)/8.44 \rfloor = 6$, and $q_{2,B} = \lfloor 0.5(86 - 1.4)/8.44 \rfloor = 5$. Upon obtaining both transmission quota and sensing time, we can further calculate $\boldsymbol{r} = [1.3 + 6 \times 8.44, 1.4 + 5 \times 8.44]^T = [51.94, 48.6]^T$, and $q = [0.4707, 0.3316]^T$. Let $\tilde{G}_\eta$ be in lognormal distribution. By substituting all results into (9), the successful transmission probabilities that CR_B does not forestall other CR nodes' transmission on Ch1 and Ch2 are 0.1524 and 0.1241, respectively. Considering both impacts from PUs and other CR nodes, the successful transmission probability of CR_B is $\boldsymbol{p}_B = [0.07173, 0.07173]^T$. Finally, $\boldsymbol{H}_B = \begin{bmatrix} 0.07173 & 1.3 & 6 \\ 0.04115 & 1.4 & 5 \end{bmatrix}$.

CR_C performs similar operations, while the viewed PU traffic loads and measured channel qualities on Ch1 and Ch2 are (0.3, 0.0231 dB) and (0.4, 0.0246 dB) individually. Thus its $\boldsymbol{H}_C = \begin{bmatrix} 0.07612 & 1.4 & 8 \\ 0.07173 & 1.3 & 6 \end{bmatrix}$. Furthermore, the successful transmission probabilities of Ch1 and Ch2 are 0.00546 and 0.00295, respectively. Note that in this example, both channels have the same sensing time (which is 1.4 ms) and transmission quota (which is 6). As a result, the hopping sequence of this CR pair is (Ch1, Ch2).

D. Model validation

We validate the derivation of successful transmission probability with simulation results. we assume CR nodes are always backlogged. In the simulation experiment, the mean and standard deviation of PUs' traffic load are 0.5 and 0.1, respectively. The comparison is summarized in Table I. There exists discrepancy between the derivation and simulation results, which is due to the setting of standard deviation. In our derivation, a CR node uses the mean traffic load value of PUs to estimate the corresponding successful transmission probability. However, in simulation experiment, channel idle time maybe cannot accommodate q_i frames, i=1, 2. In such a situation, PUs should wait for transmission completion. Those events are not counted in the calculation of the successful transmission probability. Thus the successful probability of simulation result is smaller than that of derivation. One significant achievement of our mechanism is that CR nodes utilize at least 70% of the channel idle time.

IV. PERFORMANCE EVALUATION

In this section, we develop a simulation program to compare the performance of the designed CACS mechanism with OSA-MAC [2], SSA-MAC [3], CH-MAC [4], and DRA-MAC [5].

In this experiment, there are one control channel, and five data channel. The PU traffic load on data channel i, $i = 1, 2, \ldots 5$, is poisson distribution with rate λ_{p_i}. Moreover, we set $\lambda_{p_1} = \lambda_{p_2} = 0.4$; $\lambda_{p_3} = 0.5$, and $\lambda_{p_4} = \lambda_{p_5} = 0.6$. CR nodes are always backlogged. The bandwidth of a data channel is 2 Mbps. Frame size is 2048 bytes. The transmission ranges of PUs, CR nodes, and CR APs are 150 meters, 100 meters, and 100 meters, respectively. The duration of DIFS and SIFS is 0.05 and 0.01 ms, accordingly. For SSA-MAC, the settings of TXQ and RTV are 4 and 1, respectively. The simulation time is 100 seconds. The observed performance metrics include "utilization of channel idle time", and "average tries of channel search".

We first investigate the utilization of channel idle time of various mechanisms, and the results are shown in Fig. 4. We found that CSA-MAC (with handshaking) performs better than other MAC protocols. The reasons have twofold: setting transmission quota according to PUs' traffic load; and adapting channel sensing time based on measured channel quality. As a result, CR nodes utilize channel idle time as much as possible. The performance gap between CSA-MAC with handshaking and without handshaking is caused by different dwell time when sensing a busy channel. Indeed, the dwell time for CSA-MAC with handshaking is $\widetilde{W}_i + t_{ctl}$, while it's $\widetilde{W}_i + \widetilde{X}_i$ for CSA-MAC without handshaking. The reason of low utilization for OSA-MAC is that a CR pair only exchanges one data frame when occupying a data channel. Moreover, the common drawback of DRA-MAC and CH-MAC is that if being aware of PU presence on the sensed data channel, CR nodes will stay at that channel for five slots, thus resulting in low utilization. SSA-MAC has a mechanism for PUs to interrupt CR transmission. Thus, SSA-MAC performs worse than CSA-MAC (with handshaking).

Next, the performance of the average tries of channel search for various mechanisms is in Fig. 5. It is common for all mechanisms that, when the number of CR pairs increases, the average tries of channel search also increases. Besides, CSA-MAC (with handshaking) outperforms CH-MAC and DRA-MAC. The reason is, in CH-MAC and DRA-MAC, a CR sender does not select channels according to PUs' traffic loads, and thus may frequently sense busy channels. Besides, comparing with random hopping sequence performed in SSA-MAC, our estimation of successful transmission probability makes a great impact when there are more than five CR pairs. In OSA-MAC, a CR sender only sense once during a fixed period. Thus, OSA-MAC has the least tries of channel search among all mechanisms, while its drawback is low utilization of channel idle time as previously discussed. Note that CSA (without handshaking) still performs better than most compared protocols. The reason is that a CR pair has to wait for $\widetilde{W}_i + \widetilde{X}_i$ when sensing a busy channel, which implies that CSA-MAC (without handshaking) has relative long sensing time.

V. Conclusions

In this paper, we proposed a cloud server-assisted MAC protocol, named CSA-MAC, for infrastructure-based cognitive radio networks. In CSA-MAC, each CR nodes maintains a channel preference matrix, which records the successful transmission probability, sensing time, and transmission quota, of each data channel. The three parameters are derived through an analytical queueing model, and the support of powerful cloud servers. Two versions of CSA-MAC are presented and compared in this paper, with handshaking and without handshaking. The simulation results showed that CSA-MAC with handshaking performs better in the utilization of channel idle time, while CSA-MAC without handshaking diminishes the average tries of channel search. In the future, we will investigate the impact of different arrival rate of CR users and extend this work to multi-hop CR flows.

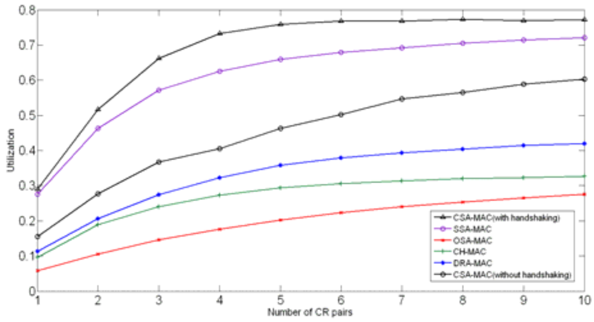


Figure 4. The utilization of channel idle time v.s. the number of CR pairs.

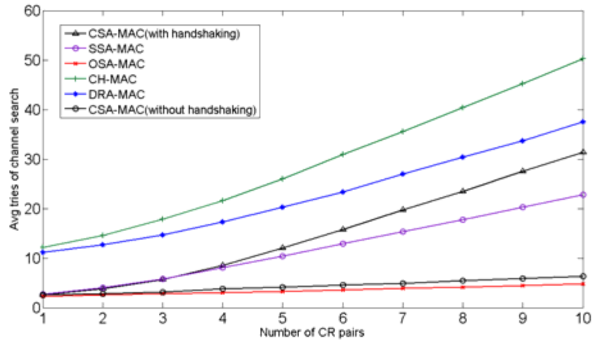


Figure 5. The average tries of channel search v.s. the number of CR pairs

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References

[1] FCC Spectrum Policy Task Force, "Report of the Spectrum Efficiency Working Group," FCC, Technical Report 02-155, 2002.

[2] L. Long and E. Hossain, "OSA-MAC: A MAC Protocol for Opportunistic Spectrum Access in Cognitive Radio Networks," in Proceedings of IEEE WCNC, 2008.

[3] T.C. Lou, H.L Chao, and T.J Tsai, "On Synchronized Channel Sensing and Accessing for Cognitive Radio Users in IEEE 802.11 Wireless Networks," in Proc of IEEE PIMRC, 2009.

[4] H. Su, and X. Zhang, "Channel-hopping Based Single Transceiver MAC for Cognitive Radio Networks," in Proc. of IEEE CISS, 2008.

[5] L. Jiao, and F.-Y. Li, "A Single Radio Based Channel Datarate-aware Parallel Rendezvous MAC Protocol for Cognitive Radio Networks," in Proc. of IEEE LCN, 2009.

[6] IEEE 802 LAN/MAN Standards Committee 802.22 WG on WRANs. http://www.ieee802.org/22.

[7] D-H. Huang, S.-H. Wu, and P.-H. Wang, "Cooperative Spectrum Sensing and Locationing: A Sparse Bayesian Learning Approach," in Proc. of IEEE GLOBECOM, 2010.

[8] W-Y Lee, and I.F. Akyildiz, "Optimal Spectrum Sensing Framework for Cognitive Radio Network," IEEE Wireless Communications, vol. 7, pp. 3845-3857, Oct. 2008.

[9] Kleinrock, L., "Queueing systems. Vol. II: Computer applications," John. Wiley & Sons, New York, 1976.