Contention Window-Based Deadlock-Free MAC for Blind Rendezvous in Cognitive Radio Ad Hoc Networks

Xingya Liu and Jiang Xie
Department of Electrical and Computer Engineering
The University of North Carolina at Charlotte
Email: {xliu33, Linda.Xie}@uncc.edu

***Abstract*—Cognitive radio (CR) technology is a promising solution to the spectrum scarcity problem. Due to the spectrum varying nature of CR networks, unlicensed users are required to perform channel hopping to realize blind rendezvous. However, blind rendezvous can easily cause deadlock in the network. Moreover, due to the nature of blind rendezvous, a deadlock cannot be detected by either the suffering users or other users. Consequently, a deadlock will eventually cause the whole network stuck and prohibit the network throughput. In this paper, the challenge of deadlock-free blind rendezvous in CR networks is addressed for the first time. By analyzing the deadlock issues in both two-user and multi-user scenarios, we propose a novel MAC protocol with an optimal contention window size which can avoid deadlock and provide high network throughput. In addition, we also propose a probabilistic model for analyzing the network performance with our MAC. Simulation results validate our analytical model and demonstrate that our proposed protocol outperforms other possible attempts.**

I. INTRODUCTION

In a cognitive radio ad hoc network (CRAHN), secondary users (SUs) are equipped with cognitive radios which can dynamically configure their operating parameters to seek “spectrum holes”, or, available channels, and communicate with each other on these channels without causing harmful interference to primary users (PUs). However, the available channels of different SUs vary with time and location due to different PU activities. Hence, unlike traditional wireless networks, a control channel that is commonly available to all SUs in a CRAHN may not exist or cannot last for a long time. It is also impractical for a SU to obtain other SUs’ channel information using such a common control channel (CCC). Therefore, two SUs meeting each other on a common channel is a basic step before their data transmission. This process is called blind rendezvous.

Channel hopping (CH) is a state-of-the-art technique that can guide SUs to achieve blind rendezvous. A fully-distributed CH scheme, programmed in each SU in a network, divides time evenly into time slots, and tunes the radio to a chosen available channel in each time slot. A source SU broadcasts a Request-to-Send (RTS) message in each time slot on the chosen available channel until a Clear-to-Send (CTS) message is received. The number of hopped slots before the source SU meets its destination SU on a common available channel is called time to rendezvous (TTR).

Existing CH efforts [1]–[3] focus on designing the CH sequence to shorten the expected/average TTR (ETTR). Analytical models [4], [5] show that these CH schemes perform well when the role of each SU is predefined: for a given time, a source/destination SU will always be a source/destination SU, or, SUs are always in the same pairs and the pairing information is known. However, in a more practical scenario, the role of a SU is not fixed: a source SU may be a destination SU of other SUs, and a destination SU may be a source SU at the same time if it has data to send. In addition, a SU’s pairing SU may change with time. One main problem under such cases is the *rendezvous deadlock*. As illustrated in Fig. 1, SU$_1$ can rendezvous with its destination user SU$_2$ on channel 2 if SU$_2$ acts as an idle listening user. However, when SU$_2$ is also a source SU to another SU, it cannot hear from SU$_1$ even on their rendezvous channel. We call this case the *both-shouting* scenario. Among all both-shouting cases, the worst one is that SU$_2$’s destination user is SU$_1$ coincidentally, which is a rendezvous deadlock. The number of SUs in a deadlock can be more than two (as shown in the next section in Fig. 3(a)).

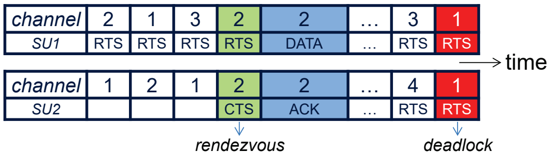


Fig. 1. The deadlock during blind rendezvous without role pre-assignment.

The rendezvous deadlock is a **unique** phenomenon in CRAHNs without CCC. In existing multi-channel MACs [6]–[8] for CRNs, the status/role of other users can be informed by the CCC. Thus, deadlock will not happen with the existence of a CCC. Meanwhile, in single-channel networks, since all users operate on the same channel, one can infer the RTS collision if no corresponding CTS is received. Hence, a deadlock can be easily detected and will not last for a long time. However, in CRAHNs, on one hand, before rendezvous, a SU is ignorant of other SUs’ role. As a result, there is always a chance to generate the deadlock. On the other hand, since the pair of deadlock users are blind of each other’s current operating channel, the deadlock cannot be noticed by the suffering SUs. For example, in Fig. 1, after SU$_1$ sends a RTS message on one channel, the expected CTS may not show up due to several reasons. One is the absence of the destination SU on the current channel, such as in SU$_1$’s first three time slots. Another reason is the both-shouting issue, as what happens in the last time slot in Fig. 1. Therefore, even if SU$_1$ and SU$_2$ are a deadlock pair, they have no clear evidence to confirm the situation and have to keep CH.

There are very few studies on both the harm of the rendezvous deadlock and the appropriate MAC protocols to avoid such deadlocks. Moreover, the rendezvous deadlock cannot

---

This work was supported in part by the US National Science Foundation (NSF) under Grant No. 0953644, 1218751, and 1343355.

978-1-4799-5952-5/15/$31.00 ©2015 IEEE

be well solved by existing MAC mechanisms. We cannot directly apply the existing CSMA/CA mechanism in IEEE 802.11, which theoretically requires the time slot for each hopping channel to be infinite long due to its retransmission mechanism. In [9], a cut-off rendezvous time is proposed for congestion control in CRNs, which may cut off those deadlock rendezvous pairs, but at the cost of packet-drop. A slot-asynchronous MAC for blind rendezvous in CRNs is proposed in [10]. Though it can avoid the deadlock issue, it generates the special handshake failure problem which decreases the throughput in asynchronous scenarios.

In this paper, first, we prove that rendezvous deadlocks can be easily formed in CRNs. Then, we demonstrate that the impact of the deadlock is not negligible. Instead, if no proper mechanism is taken, any deadlock can eventually cause the whole network shutdown. Then, we revise the CSMA/CA mechanism to adapt to the nature of CH schemes, which can be integrated into the time slotted system. In our MAC design, we keep the contention window (CW) concept but adding some new mechanisms to address deadlock scenarios. Since the rendezvous delay and network congestion caused by the deadlock will be eventually reflected on the network throughput, we define the normalized throughput of the network as our performance metric in this paper. In our design, the size of the CW is fixed in order to maintain the equal length of each time slot. The CW size is actually a tradeoff parameter. On one hand, a larger CW size increases the probability of both-shouting avoidance. On the other hand, a larger CW size increases the time slot length, and consequently, increases the rendezvous delay and reduces the network throughput. Since nearly all existing analytical models for blind rendezvous have the latent role-preassignment assumption, we develop a novel probabilistic model for deriving the optimal CW size in terms of maximizing the network throughput. Simulation results validate our analysis on the deadlock nature in CRAHNs as well as our analytical model. They also indicate that our proposed protocol outperforms other possible candidate MACs in [9] and [10]. To the best of our knowledge, this is the first MAC protocol that addresses the unique deadlock issue for blind rendezvous in CRNs.

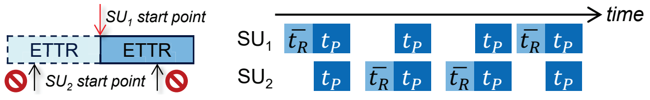
The rest of this paper is organized as follows. In Section II, we analyze the formation and the impact of the deadlock in CRNs. In Section III, a CW-based MAC protocol for deadlock-free blind rendezvous is proposed. The corresponding analytical model is given in Section IV. Simulation results are shown in Section V, followed by the conclusions in Section VI.

II. PROBLEM ANALYSIS

A. System Model

The system considered in this paper consists of finite number of PUs and SUs which can operate over N orthogonal channels. Without loss of generality, we assume that the packet arrivals of each SU follow the Poisson distribution. Each time when a SU has a new packet to transmit, it becomes a source SU and is randomly assigned a SU within its transmission range as its destination SU. We assume that each SU works in a half-duplex mode.

B. Deadlock in 2-SU CRNs



(a) deadlock prohibition (b) ideal scenario for network throughput

Fig. 2. Analysis of deadlock in 2-SU scenario.

First, consider a system of two SUs. As explained in Fig. 1, a deadlock forms as long as one SU turns to be a source SU while the other SU has already started rendezvous. In this case, without a proper MAC, both SUs will stay in the rendezvous state and cannot achieve a successful rendezvous. To achieve a successful rendezvous, one SU should not have traffic generated during the other's rendezvous time. As illustrated in Fig. 2(a), when SU_1 starts its rendezvous, if SU_2 also starts its rendezvous during the ETTR period either before or after the starting point of SU_1's rendezvous, this will lead to a deadlock.

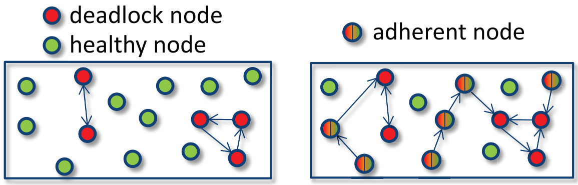
Suppose that the ETTR is known which is usually between $O(N) \sim O(N^2)$, where N is the number of channels in the network. Then, the average rendezvous time in seconds is

$$\overline{t_R} = ETTR \times t_{slot}, \tag{1}$$

where $t_{slot} = \frac{\text{(RTS+CTS) bits}}{\text{Bandwidth}}$. Since the number of packet arrivals k in a given time t follows the Poisson distribution, $P_k(t) = \frac{(\lambda t)^k}{k!} e^{-\lambda t}$, where λ is the average arrival rate, the probability that a source SU can have a deadlock-free rendezvous is approximately $P_0(2\overline{t_R}) = e^{-2\lambda \overline{t_R}}$.

A failure rendezvous is hard to be confirmed (especially in multi-user cases) and thus no corresponding retransmission scheme exists so far. Hence, once a deadlock occurs, no more throughput can be generated. In such a system, to have network throughput in the ideal scenario as shown in Fig. 2(b), the probability is $e^{-n\lambda \overline{t_R}}$, where t_P in the figure represents data transmission time between the two SUs and n is the number of consecutive rendezvous between the two SUs. In other words, even if λ and N are moderate, the probability of deadlock, $1 - e^{-n\lambda \overline{t_R}}$, exponentially increases with time.

C. Deadlock in Multi-SU CRNs

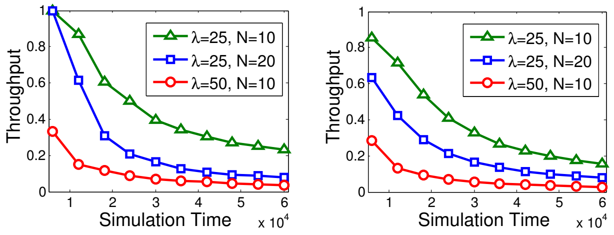


(a) formation (b) blackhole

Fig. 3. Deadlock formation and its influence.

When it comes to the multi-user CRN, more than one deadlock may be generated. In Fig. 3(a), 2-SU-deadlock and 3-SU-deadlock coexist, where SUs cannot contribute to the throughput. On the other hand, other SUs who want to communicate with any of these deadlock SUs will also get trapped into a both-shouting situation. It is just like a black hole in the network. At the beginning, there might be only two SUs in a deadlock. However, other SUs will be adhered to the deadlock as long as they want to communicate with any of the deadlock SUs, which causes the black hole becoming bigger, as illustrated in Fig. 3(b). The bigger the black hole, the higher probability that destination SUs of the rest SUs are in the black hole. Consequently, the growing speed of the black hole becomes faster and faster. Finally, the black hole devours the whole network.

It is difficult to have a precise probabilistic model for the deadlock in the multi-user scenario. However, from a macroscopic view, since all the packets generated from all SUs go to all the SUs in the network, we can treat the whole network as a 2-SU case. Therefore, the probability of the ideal network throughput in the multi-user case has the same form as that of the 2-user case. As illustrated in Fig 4, the simulation results on network throughput of both the 2-user and multi-user cases present the negative exponential form, which validates our analysis.



(a) 2-user case

(b) 50-user case

Fig. 4. Network throughput reflects the deadlock existence.

The simulation set-up for the above results is given in Section V. From the results, it is clear that no matter what network conditions are, the rendezvous deadlock is determined to happen in CRNs. In addition, the deadlock occurs earlier when other network parameters are high, such as the traffic rate in the secondary network, the number of channels in the primary network, and the number of SUs in the CRN. Based on such severe performance degradation, a deadlock-free MAC protocol for blind rendezvous in CRNs is highly desired.

III. PROPOSED MAC PROTOCOL

Based on the CSMA/CA mechanism in 802.11, we propose a contention window-based deadlock-free MAC protocol, CWDF-MAC, which is presented in Fig. 5. The definition of SIFS, RTS and CTS frames are the same as those in CSMA/CA in 802.11. However, according to the uniqueness of blind rendezvous in CRNs, CWDF-MAC has different features summarized as follows and in the corresponding protocol shown in Algorithm 1 (for convenience, the corresponding SIFS and propagation delay are not shown).

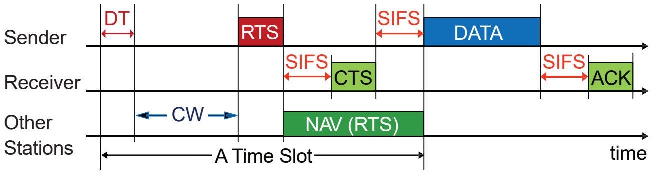


Fig. 5. The diagram of the CWDF-MAC.

At the beginning of each time slot on a new channel, a detection time (DT) is employed to help a SU ensure the status of the channel not changed. Since a full spectrum sensing is only done in a periodic manner, an available channel may become unusable during a sensing period due to new transmissions of PUs or SUs in the same channel. The optimal duration of DT can be determined based on [11]. We regard the length of DT as a mini-slot.

After the DT, if the channel is detected busy, a SU sets its network allocation vector (NAV) value to be the rest time of the current time slot and sleep. After the DT, if the channel is confirmed idle, a source SU chooses a random number between 0 and CW (in terms of mini-slots) as its backoff time to avoid potential contentions on the same channel. Unlike 802.11, the size of the CW is fixed to maintain the constant length of time slots. Similarly, the binary-exponential-backoff retransmission mechanism is not practical for a slotted system. Even the RTS retransmission in one time slot is not wise. For example, if the destination user is not on the same channel, the retransmitted RTS in the same time slot can only decrease other contenders' sending chance and lead to unnecessarily long time slots. Thus, CWDF-MAC only offers one attempt for RTS sending in one time slot.

A SU does not sleep during the backoff period. Instead, it keeps monitoring the channel. Then, even if one source SU's backoff timer is one unit ahead of another source SU's, the later SU can detect the signal and suspend its own timer (this is why we set DT as the basic unit of mini-slots).

If the detected signal finally turns out to be an RTS message, the decoding SU may face two possible cases. One is that the decoding SU itself is the destination SU of the RTS, which will lead to a deadlock without our MAC. As illustrated in the left part of Fig. 6, SU_C will buffer its own packet and send a CTS to rendezvous with SU_A. This action may help the network to have one more packet throughput and at the same time become less crowded because of one less source SU. Note that the data transmission can start immediately within the same time slot in order to increase the channel utilization before PUs' return.

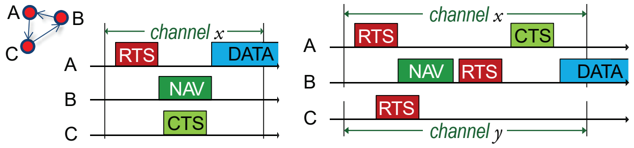


Fig. 6. An example of CWDF-MAC.

If the RTS is aiming at another SU, the decoding SU sets two SIFS time and one CTS time as its NAV value (see Fig. 5). This SU does not need to listen during the NAV period. On one hand, a CTS may or may not be sent depending on whether the destination SU is on the same channel. On the other hand, even if a CTS is sent, this SU may or may not hear this message depending on whether the destination SU is a hidden terminal of it. However, the SU can tell which case happens by sensing whether the channel is busy after the NAV period.

An RTS may not be decoded if there are multiple RTSs sent at the same time, or RTSs from hidden terminals collide. Under such circumstance, the decoding SU still sets the same NAV value.

After the NAV period, if the channel is still busy, it can be deferred that the RTS and CTS have been successfully exchanged and the corresponding source SU starts to transmit data, as shown in Fig. 5. Then, this SU has to keep silent till the end of this time slot. On the other hand, if the channel is idle after the NAV period, this means a failed CTS receiving. If the left time is still enough for an RTS/CTS exchange, this source SU can send its own RTS. As illustrated in the right case in Fig. 6, after a failure attempt of SU_A, SU_B still has the chance to rendezvous with SU_A, which avoid the deadlock in such scenarios.

Algorithm 1: The CWDF-MAC protocol for a source SU

```
Input: $t_{DT}$, $t_{RTS}$, $t_{CTS}$, and $t_{CW}$;
CH to a new channel. Set $t = 0,\ t_{NAV} = 0$;
if $t \le t_{DT}$ then
    if (detects channel busy) $t_{NAV} = t_{slot} - 1$;
    if (detects channel idle) $t_{backoff} = t_{DT} + rand(t_{CW})$;
if $t_{DT} < t \le t_{backoff}$ then
    if detects signal then
        keep listening for $t_{RTS}$;
        if right RTS then
            Buffer current packet;
            Send CTS; Prepare to receive data;
        else $t_{NAV} = t + t_{CTS}$;
if ($t_{NAV} \le t_{backoff} < t$) send RTS;
if $t_{backoff} \le t_{NAV} < t \le t_{DT} + t_{CW}$ then
    send RTS;
if all other situations then
    Set NAV until the end of current time slot;
```

IV. ANALYTICAL MODEL FOR OPTIMAL CW

Due to the CW-based design, the CW has to be incorporated in every time slot which is not the rendezvous slot during a CH cycle. Thus, a long CW design increases the t_{slot} in (1) and then decreases the network throughput. An optimal CW size is derived in this section.

Consider two source SUs on the same channel in the same time slot. Under CWDF-MAC, each of them should generate a random number between 0 and CW. Each SU has equal probability to get a shorter backoff time than the other, excluding those cases when they generate a same number. Then, the probability that a chosen SU finishes backoff prior than the other SU is

$$P(\text{first send}) = \frac{CW^2 - CW}{2CW^2} = \frac{CW-1}{2CW}. \tag{2}$$

Next, we derive the ETTR of CH under CWDF-MAC. The ETTR of different CH algorithms under the role-preassigned assumption is derived in existing papers [12], [13]. Since we focus on the analysis of the MAC design, we employ a simple yet effective random CH (RCH) algorithm for our analysis. The successful rendezvous probability in each time slot under the RCH algorithm is $P_0 = \frac{1}{N}$ [10], [13]. Let P_s and P_l be the probabilities that the destination SU is a source SU or a listening SU on the rendezvous channel, respectively. Thus, under CWDF-MAC, the probability that a chosen source SU can successfully rendezvous in a time slot without role-preassignment is

$$P_0' = P_0 P_s P(\text{first send}) + P_0 P_l = \frac{P_s(CW-1)}{2N \cdot CW} + \frac{P_l}{N}. \tag{3}$$

Then, the ETTR in our protocol, denoted as $\overline{X}$, can be derived as

$$\overline{X} = \sum_{i=1}^{\infty}(1-P_0')^{i-1}P_0' = \frac{2N \cdot CW}{(P_s + 2P_l)CW - P_s}. \tag{4}$$

We then get the ETTR in terms of seconds with our new t_{slot}. As shown in Fig. 5, we have

$$t_{slot} = \frac{\text{(DT+CW+RTS+CTS+2SIFS) bits}}{\text{Bandwidth}} + 2\alpha, \tag{5}$$

where α is the propagation delay. For the convenience in the following analysis, we ignore SIFS and α which are negligible as compared with other time durations. Meanwhile, assume that the size of an RTS and CTS is k times longer than that of the DT. Then t_{slot} can be expressed as $t_{slot} = (CW+k+1)t_m$, where t_m is the length of a mini slot in seconds. According to (1),

$$\overline{t_R} = \frac{2N \cdot CW(CW+k+1)t_m}{(P_s + 2P_l)CW - P_s}. \tag{6}$$

From (6), when $CW = 1$ ithout our(w MAC), $\overline{t_R} = \frac{N(k+2)t_m}{P_l}$. When a deadlock occurs or in a saturated network, $P_l = 0$ leads to endless CH time, which agrees with our analysis in Section II. However, when $P_l = 0$ with our MAC ($CW > 1$), $\overline{t_R}$ has a finite value once a CW is selected. Let t_P be the packet transmission time. We treat $\overline{t_R} + t_P$ as the average service time of each packet. Then, each SU can be considered as a $M/D/1$ system based on queuing theory [14]. Thus, a SU under our protocol can still have a steady normalized throughput even in a saturated CRN, denoted as Γ_{th}, which is the lower bound of the network throughput. Since the size of CW is a predefined parameter in our protocol, we aim to find its optimal value in terms of maximizing Γ_{th}.

A. Throughput in 2-SU CRNs

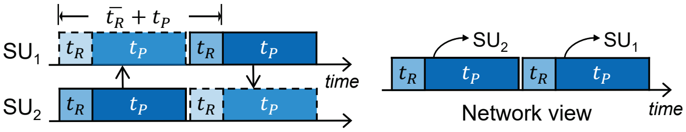


Fig. 7. The analytical model for 2-SU CRNs.

In a saturated 2-SU scenario, a SU is either in a rendezvous state or in a packet transmission/receiving state. Since there are only two SUs in the network, they must be in the same state at the same time. As shown in Fig. 7, when each of them rendezvous, the other one must also be in the rendezvous state. Thus, $P_s(\text{2-user}) = 1$.

From the view of the network as shown in Fig. 7, the rendezvous period and the transmission period alternately take place along the time line. Since the successful rendezvous probability is the same for both SUs (P(first send)), during each *network rendezvous period* t_R, either SU_1 successfully rendezvous or SU_2 does. Thus, $t_R = \frac{1}{2}\overline{t_R}$ ($\overline{t_R}$ is calculated from the SU's view). Meanwhile, SU_1 and SU_2 should have the same amount of throughput on average. Therefore, we have

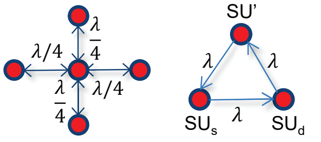
$$2\lambda\Gamma_{th}(t_R+t_P)=\lambda\Gamma_{th}(\overline{t_R}+2t_P)=1. \tag{7}$$

Then, the optimal CW value can be derived by solving the following optimization:

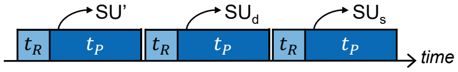
$$\begin{aligned}&\underset{CW}{\text{Maximize}} && \Gamma_{th}\\ &\text{subject to} && P_l=0, P_s=1, (6), \text{and } (7).\end{aligned} \tag{8}$$

B. Throughput in Multi-SU CRNs

1) The Optimal CW: It is difficult to precisely model the throughput in the multi-user scenario due to the topology changing in two dimensions independently (i.e., the pairing space and the channel space). However, for a chosen SU, we can classify its traffic into the inner traffic λ and the outside traffic λ'. Inner traffic includes the packets generated by a SU itself which need to be sent to other SUs and outside traffic includes the traffic received from other SUs. Since the destination SU of each packet is randomly assigned, the traffic to each neighboring SU is evenly distributed. In such a system, it is easy to infer that $\lambda=\lambda'$. As illustrated in Fig. 8(a), suppose that each node has 4 neighbors within its transmission range on average. The outer traffic of each node is $4\frac{\lambda}{4}=\lambda$. Then, for a given SU, it is equivalent to regard all the outer traffic generated from one SU, say, SU'.



(a) traffic pattern (b) traffic model



(c) network view

Fig. 8. The analytical model for multi-SU CRNs.

In this way, the pairing topology can be largely simplified. As shown in Fig. 8(b), let $\mathrm{SU_s}$ be the source SU and $\mathrm{SU_d}$ represent all destination SUs of $\mathrm{SU_s}$. Then, for $\mathrm{SU_s}$, its inner traffic goes to $\mathrm{SU_d}$ and its outer traffic comes from SU'. Similarly, for $\mathrm{SU_d}$, it also has inner traffic to SU' representing all its destination SUs and outer traffic from $\mathrm{SU_s}$. Then, the network throughput can be modeled as shown in Fig. 8(c).

Note that each SU has equal probability to rendezvous with its destination SU or be rendezvoused with its source SU, which is just like the 2-SU scenario. Thus, the rendezvous period t_R is also $\frac{1}{2}\overline{t_R}$. Therefore, the throughput of the whole network is

$$3\lambda\Gamma_{th}(t_R+t_P)=\lambda\Gamma_{th}(\frac{3}{2}\overline{t_R}+3t_P)=1. \tag{9}$$

Comparing (7) and (9), we can get

$$\Gamma_{th}(\text{multi-SU})=\frac{2}{3}\Gamma_{th}(\text{2-SU}). \tag{10}$$

Thus, the optimal CW of 2-SU CRNs also holds the optimality for multi-SU scenarios when other parameters are the same.

2) Impact of a larger CW: On the other hand, when the CW is large, P_0' differs. As explained in Fig. 6 in Section III, a SU still has the chance to send its own RTS even after selecting a larger backoff time than other source SUs on the same channel, as long as the left time in the current time slot is long enough for another RTS and CTS exchange, i.e., $CW+k+1\leq 2(k+1)$, or, $CW>k$.

Suppose the backoff time expiration moment of other source SUs is earlier than the chosen SU. This moment can be selected from CW-1 mini slots. Among these selections, only those moments early enough so that the CW still opens even after $t_{RTS+NAV}$ are considered, which requires the moment to be selected within $CW-k$. Suppose that the average number of neighbors of each SU is m. The $P(\text{first send})$ under this circumstance should be replaced with

$$P(\text{RTS send})=\frac{CW-1}{2CW}+\frac{CW-1}{2CW}\frac{CW-k}{CW-1}\frac{m-1}{m}, \tag{11}$$

where $\frac{m-1}{m}$ denotes the probability that the prior RTS is sent to SUs except the chosen SU.

Thus, if the CW size is allowed to be larger than $k+1$, its optimal value should be recalculated with condition (11) taken into (8).

V. PERFORMANCE EVALUATION

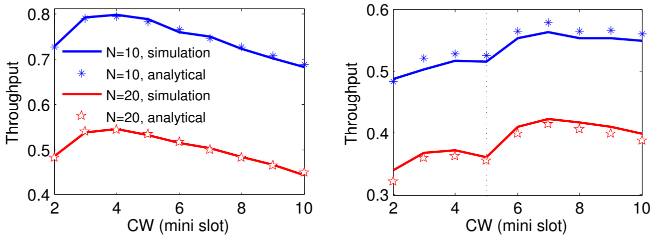
In this section, we evaluate the performance of our proposed MAC protocol under different scenarios by comparing simulation results with both the analytical values and other related protocols. Parameters used in our simulation are listed in Table I. In our simulation, each PU is randomly assigned a channel when a new packet needs to be transmitted.

TABLE I
SIMULATION PARAMETERS

Simulation area	5×5
Simulation time	60000 time slots
SU sensing range	1
The number of PUs	50
Bandwidth	2 Mbps
The size of (RTS+CTS)	$160+112$ bits (802.11b/g)
The size of DT	54 bits
PU/SU packet size	1700 / 850 bytes
Average packet arrival rate of each PU	50 pkt/s

Fig. 9 illustrates the normalized network throughput under different size of CW in two saturated CRNs ($\lambda=100$ pkt/s). The simulation results match the analytical results very well with a maximum difference of 3%. Fig. 9(a) shows that $CW=4$ is the optimal size of the CW in terms of the highest normalized network throughput in 2-SU CRNs. When CW is large, the improving space of $P(\text{first send})$ becomes smaller and smaller to approach its bound $\frac{1}{2}$. Instead, the impact of a larger time slot dominates the performance, which leads to the throughput decrease linearly.

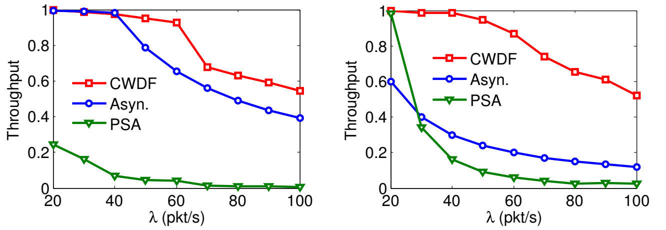
On the other hand, in Fig. 9(b), the throughput pattern before $CW=k$ ($k=5$ can be inferred from our simulation setting) is similar to that of the 2-SU scenario with a proportion about $\frac{2}{3}$, which agrees with the analysis in (10). When $CW>k$, $CW=7$ holds the optimality, which demonstrates the advantage of a larger CW in multi-user case in (11). Note that the performance patterns when $N=10$ and $N=20$ are very similar in both 2-SU and 50-SU CRNs, which reflects the number of channels, N, is only a gaining factor (see N in (6)).



(a) 2-SU CRN (b) 50-SU CRN

Fig. 9. Throughput vs. CW under different traffic conditions.

Fig. 10 compares the performance of our proposed CWDF-MAC with other related protocols PSA-MAC [9] and Asyn.-MAC [10] under different traffic conditions. The performance of CWDF-MAC shown in the figure is our proposed MAC with the optimal CW we already derived under saturated scenarios. From the figure we conclude that: 1) our protocol performs better than other MACs which has nearly 100% throughput under moderate traffic and at least 50% throughput under saturated traffic; 2) the network under our protocol can keep congestion-free (almost 100% throughput) under high traffic load. For example, the network congests when $\lambda = 70$ pkt/s in the 2-SU CRN under our protocol because the throughput begins to drop from 100%. Meanwhile, the network starts to saturate with low traffic load ($\lambda = 50$ pkt/s) under Asyn.-MAC and becomes saturated even easier in the multi-SU CRN ($\lambda = 20$ pkt/s); 3) when saturated, the throughput under our protocol linearly decreases with the increase of λ in both two networks, while exponentially decreases under other MAC in both networks; and 4) the Asyn.-MAC performs worse in the multi-SU scenario than in the 2-SU scenario, while CWDF-MAC can maintain its performance in a same level in multi-SU networks.



(a) 2-SU CRN, $N = 20$ pkt/s. (b) 50-SU CRN, $N = 10$ pkt/s.

Fig. 10. Comparison with other deadlock-free MACs in different scenarios.

After we obtain the throughput from our simulation, the network rendezvous time t_R can be derived using (7) or (9). To obtain the ETTR in the unit of slots, we divide $\overline{t_R}$ by its corresponding t_{slot}. For example, the network ETTR for the case where $N = 20$ in the 50-SU CRN is $0.0087/((7+6)*t_m) = 24.62$ slots. Then, the network ETTR under different scenarios is shown in Table II. It is shown that CWDF-MAC under practical scenarios can maintain the ETTR similar to the role-preassigned ETTR which is the theoretical ideal value. Therefore, our proposed MAC protocol does not affect the performance of the CH algorithm, but can eliminate the deadlock at the same time.

TABLE II
CWDF-MAC VS. ROLE-PREASSIGNED

CRN (N)	2 (10)	2 (20)	50 (10)	50 (20)
ETTR (CWDF-MAC)	10.48	20.92	13.85	24.62
ETTR (role-preassigned)	10	20	10	20

VI. CONCLUSION

In this paper, the impact of deadlock on blind rendezvous performance in CRAHNs is addressed for the first time. A contention window based deadlock-free rendezvous protocol without imposing the role-preassigned assumption is proposed which well adapts to the nature of CH systems. In addition, we developed the probabilistic model for throughput analysis in both 2-SU and multi-SU scenarios. By deriving the corresponding optimal size of the contention window, our proposed protocol can provide high throughput in both moderate and saturated networks. Additionally, our protocol does not affect the performance of the incorporated CH scheme in terms of ETTR.

REFERENCES

[1] Z. Lin, H. Liu, X. Chu, and Y.-W. Leung, "Enhanced jump-stay rendezvous algorithm for cognitive radio networks," *IEEE Communications Letters*, vol. 17, no. 9, pp. 1742–1745, 2013.

[2] H. Liu, Z. Lin, X. Chu, and Y.-W. Leung, "Ring-walk based channel-hopping algorithms with guaranteed rendezvous for cognitive radio networks," in *Proc. IEEE/ACM Int'l Conference on Cyber, Physical and Social Computing (CPSCom)*, 2010, pp. 755–760.

[3] I. Chuang, H. Wu, and Y. Kuo, "A fast blind rendezvous method by alternate hop-and-wait channel hopping in cognitive radio networks," *IEEE Transcations on Mobile Computing*, vol. 13, no. 10, pp. 2171–2184, October 2014.

[4] H. Su and X. Zhang, "Channel-hopping based single transceiver MAC for cognitive radio networks," in *Proc. Conference on Information Sciences and Systems (CISS)*, 2008, pp. 197–202.

[5] C. Xin, M. Song, L. Ma, and C.-C. Shen, "Performance analysis of a control-free dynamic spectrum access scheme," *IEEE Trans. Wireless Communications*, vol. 10, no. 12, pp. 4316–4323, 2011.

[6] B. Hamdaoui and K. Shin, "OS-MAC: An efficient MAC protocol for spectrum-agile wireless networks," *IEEE Trans. on Mobile Computing*, vol. 7, no. 8, pp. 915–930, 2008.

[7] S. Jha, U. Phuyal, M. Rashid, and V. Bhargava, "Design of OMC-MAC: An opportunistic multi-channel MAC with QoS provisioning for distributed cognitive radio networks," *IEEE Trans. on Wireless Communications*, vol. 10, no. 10, pp. 3414–3425, 2011.

[8] S. Debroy, S. De, and M. Chatterjee, "Contention based multichannel MAC protocol for distributed cognitive radio networks," *IEEE Trans. on Mobile Computing*, vol. 13, no. 12, pp. 2749–2762, 2014.

[9] X. Liu and J. Xie, "A practical self-adaptive rendezvous protocol in cognitive radio ad hoc networks," in *Proc. IEEE INFOCOM*, 2014, pp. 2085–2093.

[10] ——, "A slot-asynchronous MAC protocol design for blind rendezvous in cognitive radio networks," in *Proc. IEEE GLOBECOM*, 2014, pp. 4641–4646.

[11] P. Wang, L. Xiao, S. Zhou, and J. Wang, "Optimization of detection time for channel efficiency in cognitive radio systems," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, 2007, pp. 111–115.

[12] M. Barbeau, G. Cervera, J. Garcia-Alfaro, and E. Kranakis, "A new analysis of the cognitive radio jump-stay algorithm under the asymmetric model," in *Proc. IEEE International Conference on Communications (ICC)*, 2014, pp. 1590–1595.

[13] Y. Song, J. Xie, and X. Wang, "A novel unified analytical model for broadcast protocols in multi-hop cognitive radio ad hoc networks," *IEEE Trans. on Mobile Computing*, pp. 1653–1667, 2014.

[14] L. Kleinrock, *Queueing Systems Volume I: Theory*. New York: A Wiley-Interscience Publication, 1975.