Fast Rendezvous for Cognitive Radios by Exploiting Power Leakage at Adjacent Channels

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***Abstract*—Cognitive radio is considered as a promising technology that enables dynamic spectrum access and improves spectrum utilization. To bootstrap the communication, rendezvous process is crucial for cognitive radio users to establish communication links among each other. Blind rendezvous is a representative technology for rendezvous purpose without relying on a common control channel. Existing works mainly focus on channel hopping (CH) sequence design to speed up or guarantee users meeting on the same channel, while largely ignored the MAC overhead and PHY layer characteristics. This paper proposes new blind rendezvous protocols that take into account the handshaking overhead and power leakage at adjacent channels. Our basic idea is that a cognitive radio user can infer the transmission at adjacent channels by exploiting adjacent channel power leakage, then it can launch a local channel search to find the other user even when they are not on the same channel initially, thus speeding up the rendezvous process. We analyze the time to rendezvous (TTR) of our protocols with two-user and multi-user settings, and identify the conditions under which our protocols outperform the existing ones. We have conducted extensive simulations to evaluate our protocols. Both analytical and simulation results show that our protocols can significantly decrease the time to rendezvous (TTR) by by 53.5% over the packets decoding based rendezvous.**

I. Introduction

In order to improve of spectrum utilization, cognitive radio technology was proposed as a mean for the unlicensed users to dynamically access the licensed bands on a non-interference basis. In cognitive radio networks (CRNs), the secondary users (SUs) opportunistically access the licensed bands when the primary users (PUs) are absent, but have to evacuate when PUs emerge [1], [2].

As in the majority of multi-channel wireless communication networks, setting up a control channel and exchanging control messages is the first step for the SUs to begin to communicate with each other [3]. The procedure of establishing the control channel and setting the common parameters for data communication between SUs is called *rendezvous* [2]. There are mainly two approaches to achieve spectrum rendezvous in cognitive radio networks: common control channel (CCC) and blind rendezvous. CCC-based rendezvous assumes there is a universal CCC for all the SUs [4]–[6]. Although CCC simplifies the process of rendezvous, it has several drawbacks: 1) a CCC may become congested under heavy load. 2) the uncertainty of the primary users' activity and dynamic change of the available spectrum make it infeasible to maintain a CCC in the unlicensed band for all the users. 3) a fixed CCC is vulnerable to jamming attack and easily creates a single point of failure.

In light of these limitations of CCC, blind rendezvous techniques for decentralized systems without using CCC have been attracting more attention in recent years [3], [7]–[11]. Channel hopping (CH) is a representative technique used to achieve blind rendezvous [3], [7], [10], [11]. The basic idea of CH is that each SU hops among its available channels in the hope of meeting other SUs on the same channel. Existing works mainly focused on CH sequence design to guarantee rendezvous, while largely ignored the MAC protocol design and PHY layer characteristics in the following aspects. First, handshake process is assumed to complete in one time slot regardless of the slot length or the number of SUs meeting on the same channel in the slot. Second, all the non-overlapping channels are simply assumed to be perfectly orthogonal. The first assumption tends to be violated in practice when there are multiple SUs meeting on the same channel trying to hand shake with each other. The second assumption may not hold either in practice, since power leakage at adjacent channels is inevitable due to imperfect design of transmitter and receiver spectrum masks [12]–[14].

In this paper, we propose new rendezvous protocols that take into account of the handshaking overhead and power leakage at adjacent channels. Instead of considering the power leakage at adjacent channels as interference, we exploit it to significantly speed up the rendezvous process. Our basic idea is that one cognitive radio user can infer the transmission at adjacent channels by exploiting adjacent channel power leakage, then it can launch a local channel search to find the other user even when they are not on the same channel initially, thus speeding up the rendezvous process.

The major contributions of this paper are summarized as follows.

- We propose new rendezvous protocols that take into account of the handshaking overhead and power leakage at adjacent channels that can significantly decrease the time to rendezvous (TTR) by 53.5% over the packets decoding based rendezvous.
- We analyze the expected value of the TTR of our protocols under multi-user settings.
- We conduct extensive simulations to evaluate our protocols.

A significant impact of our work is that the expected TTR is reduced to several tens of milliseconds which is fast enough for practical usage.

II. Related Work

Blind rendezvous techniques for decentralized systems without using CCC have been attracting more and more attention in recent years. A representative approach for blind rendezvous is to use CH technique, which has few restrictions and is highly adaptive to various conditions. CH technique is to adopt the hopping sequence generating (HSG) mechanism which guides

978-1-4673-2569-1/12/$31.00

different users in a network to hop on the same channel as soon as possible. Based on number theory, Theis et al. recently proposed an efficient HSG mechanism which is called modular clock algorithm (MC) and its modified version MMC in [8]. The main idea of MC and MMC is that each user picks a proper prime number and randomly selects a rate less than the prime number. Based on the prime number and the rate, the user generates its CH sequence via pre-defined modulo operations. However, MC cannot guarantee rendezvous if the selected rates of two users are the same.

Some other blind rendezvous systems are not based on the CH techniques. For instance, the authors of work [15] tried to set up an infrastructure by selecting a leader in the distributed network, which are responsible for discovering its neighboring users. In [16], some special signals such as cyclostationary signatures are employed to discover the neighbours.

Energy leakage from adjacent channels are found and measured in multiple works. In [12], the authors showed the power leakage from adjacent channels is $-22.04dB$, and the power leakage from next adjacent channels is $-39.67dB$ in 802.11a. For 802.15.4, the authors of [17] showed that the packet reception ratio on channel 24 drops from 100% to 60% if a jammer shows up on channel 22. Energy leakage from adjacent channels is usually considered harmful, since it will increase the noise and interfere the transmission. However, we found the power leakage from neighbouring channels is beneficial in the spectrum rendezvous problem, since spectrum rendezvous is basically a detection process not a data transmission process. To our knowledge, we are the first to utilize the power leakage phenomenon to speed up spectrum rendezvous.

III. System Model and Problem Definition

In this section, we will first describe the network model and the link model. The link model is based on the most recent discoveries on physical layer wireless transmission properties.

A. Network Model

We consider an OFDM network consisting of N secondary users (SU). The secondary users share a region with a group of primary users (PU), such as primary base stations, TV towers, and primary user equipments. The PUs form a licensed primary network whereas the SUs form a secondary network. We assume the SUs can access the primary spectrum when the PUs are idle. The network model is shown in Fig. 1.

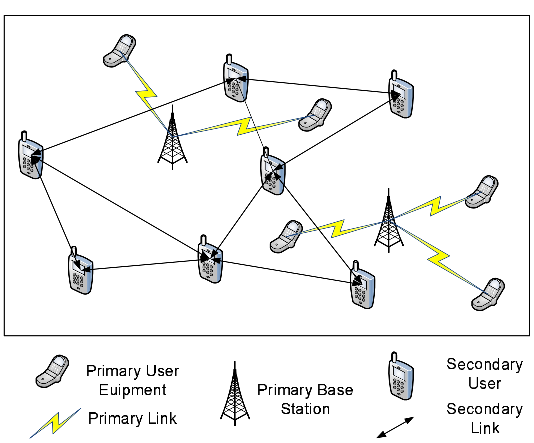

Fig. 1. System Model

B. Link Model

The available spectrum is divided into M non-overlapping orthogonal channels which are indexed uniquely as $1, 2, ..., M$. We assume the channel indices are well-known to all PUs and SUs. The whole set of available channels is denoted by $S = \{c_1, c_2, ..., c_M\}$, in which c_i denotes channel i. Each channel state is considered to be idle or busy from the point of view of the SUs [18], depending on the activities of the primary users. We assume each channel is able to support a data rate up to R.

Each channel is defined by its central frequency and bandwidth. Without loss of generality, we assume each channel has equal bandwidth, and each channel's central frequency has a spacing of the bandwidth from the next/adjacent channel like 802.11a [19]. Ideally, these channels are non-overlapping. However, considering a non-perfect transmit spectrum mask in practice, the transmitted power on one channel can leak to adjacent channels [20]. The amount of energy leakage for non-overlapping adjacent channels in IEEE 802.11a is shown in Fig. 2. Similar phenomenon was also observed in 802.11g [19]. Due to the power leakage, the packet transmitted on one channel may be detected or even decoded on adjacent channels [19].

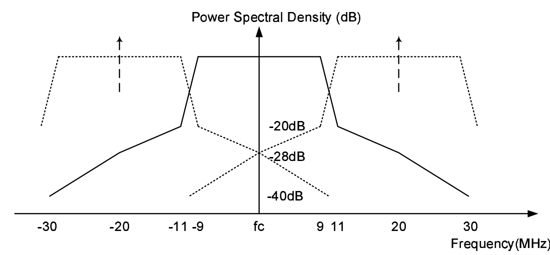

Fig. 2. Energy Leakage From Non-overlapping Adjacent Channels (802.11a) [14]

C. Problem Definition

The PUs are modelled in an ON/OFF manner depending on the traffic, where OFF is considered as spectral opportunity for SUs. For short-lasting idle periods, it is very difficult for the SUs to detect the existence of these opportunities before they disappear. Therefore we only focus on the long-lasting idle periods where the PUs remain OFF in the scale of several 10 seconds or longer [21].

Each SU is equipped with a cognitive radio transceiver which works in half-duplex manner. The SUs have to work in a distributed way and do not have any pre-load information about other SUs, e.g. locations and the total number of SUs in the network. Each SU applies feature sensing [22] individually to detect the available channels in its surrounding area. Let S_i denoted the set of available channels for the *ith* SU.

Since there is no common control channel, the SUs need to rendezvous with its neighbours at least once before any real data transmission. Obviously, quicker rendezvous enables the SUs to begin transmission earlier. In this paper, we focus on designing the rendezvous protocols which enable the SUs to achieve spectrum rendezvous in a short time-to-rendezvous TTR. The spectrum rendezvous problem is formally defined as following:

Definition 1: Given P primary users, N secondary users and M channels, the spectrum rendezvous problem seeks a mechanism which enables fast spectrum rendezvous for each SU.

Once a pair of SUs rendezvous, they can discuss next steps by exchange of short control messages. So TTR is the most important metric to evaluate the performance of the proposed protocols.

IV. Protocols To Facilitate Rendezvous

In this section, we first propose Decode Based Rendezvous (DBR) protocol to solve the collision problem which is common but not considered in many related works. Based on DBR, we further exploit power leakage from adjacent non-overlapping channels and design Preamble Detection Rendezvous (PDR) to speed up the rendezvous process. We also propose a Queuing Rendezvous protocol which specifies in solving blind rendezvous problem in high density cognitive radio networks. Since this paper mainly focus on spectrum rendezvous problem, we assume the spectrum sensing are perfectly done before the rendezvous process.

A. Handshake Process

In our study, the "attempt to rendezvous" process is a RTS/CTS based handshake process with collision avoidance. To differentiate from the 802.11 MAC, we call the "attempt to rendezvous" messages as Request To Rendezvous(RTR) and Clear To Rendezvous (CTR). The content of RTR and CTR messages will be discussed later in the rendezvous protocols.

Based on the RTR/CTR handshake model and the physical layer characterises shown in Fig. 2, we give a formal definition of successful rendezvous between a pair of SUs.

Definition 2: Successful Rendezvous: The rendezvous attempt between a pair of sender and receiver is considered successful if the RTR is correctly **detected** by the receiver and the CTR message is correctly **decoded** by the sender.

In OFDM RF receivers, three steps are performed sequentially to decode a received packet: RSSI estimation (energy detection), preamble detection and decode [19]. The estimated RSSI value of the received energy is calculated by subtracting the RSSI as measured at the Analog-to-Digital Converter, the overall amplification gain and the ambient noise [20]. Preamble detection is a complex procedure which includes ambient noise calibration, automatic gain control and receiver sensitivity configuration.

The time is slotted in the system. In each slot, the SUs may perform once or multiple times of handshake procedure. The length of each time slot depends on the protocols we are going to discuss. We assume there is a time synchronization mechanism to synchronize the starting time of each slot. The SUs periodically broadcast RTR beacons at selected channels if no collision is detected. The SUs that successfully detect the RTR beacons broadcast a CTR message to response to the rendezvous request if the request was not replied before.

B. Channel-hopping Algorithms

If we consider the case that each SU has multiple available channels and only one channel can be accessed in each time slot, an algorithm is needed to select a proper channel in each slot to perform the rendezvous attempt. In this study, we focus on designing spectrum rendezvous protocols which can work with ANY channel-hopping algorithm. Among various channel hopping algorithms, SSCH [23] algorithm and the jump-stay algorithm [10] guarantee rendezvous in bounded time. The SSCH algorithm was proposed for 802.11 networks in which the available channel set for each node is the same. In cognitive radio networks, the available channel sets of the SUs may be asymmetric. The jump-stay algorithm proposed in [10] also works in asymmetric available channel set model. To analyse the performance of the proposed protocols, we choose the jump-stay algorithm [10] for channel selection in each time slot.

The details of the jump-stay algorithm can be found in [10]. "Jump" is to switch to another channel, and "stay" is to stay at the current channel. Initially the SU randomly picks an initial channel $i0$ and a jumping step length $r0$. Then the SU "jumps" $r0$ for the next $2P$ time slots, then "stays" at $r0$ for P time slots, where P is the smallest prime bigger than M. The jump-stay algorithm requires $3P$ time slots in the worst case, and expected TTR is $5P/3 + 11/3 + 1/M$ time slots, where M is number of available channels and P is the smallest prime larger than M.

C. Decode Based Rendezvous

The first protocol we are going to propose is the Decode Based Rendezvous (DBR). As shown in Fig. 3, when a group of SUs happen to tune to the same channel for rendezvous, the RTR/CTR packets may collide. Because of collision, only the RTR sender and the CTR responder get rendezvous. The other SUs involved in the collision can either backoff and try again or switch to another channel to explore opportunities to rendezvous. Since the RTR sender does not know the existence of its neighbours before rendezvous, it is hard to choose a proper waiting period for the CTR message. It may waste time to wait for CTR replies which do not exist. To avoid the unlimited waiting time in the worst case and wasting time in waiting for non-exist CTR repliers, the DBR is a limited waiting mechanism. The flow chart is shown in Fig. 4.

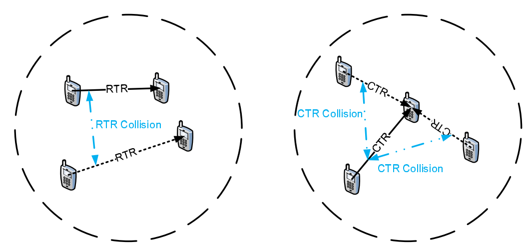

Fig. 3. Collision in the handshaking procedure

In each time slot, each SU applies jump-stay algorithm to select a channel in which it is going to try to rendezvous. If no collision is detected in the chosen channel, the SU sends out a RTR beacon, then waits for the CTR reply. The SU received the RTR beacon replies a CTR in the same channel. The RTR/CTR packets include the MAC address, the central frequency and the bandwidth of the RTR/CTR sender. If both the RTR and the CTR are received, these two SUs successfully rendezvous. Otherwise, the SU starts the same process again.

D. Preamble Detection Rendezvous

Due to the limitation of hardware, it is hard to render the spectrum mask exactly the same as a "gate" shape. Therefore the energy will leak to neighbouring channels. Multiple related works [17] [19] [20] verify this phenomenon. As discussed in Section. IV-A, the preamble detection is before the packet decoding process and requires lower RSSI threshold. The

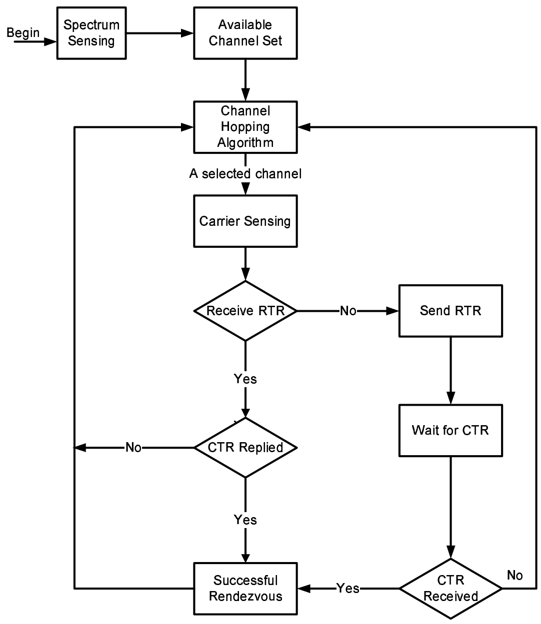

Fig. 4. Decode Based Rendezvous

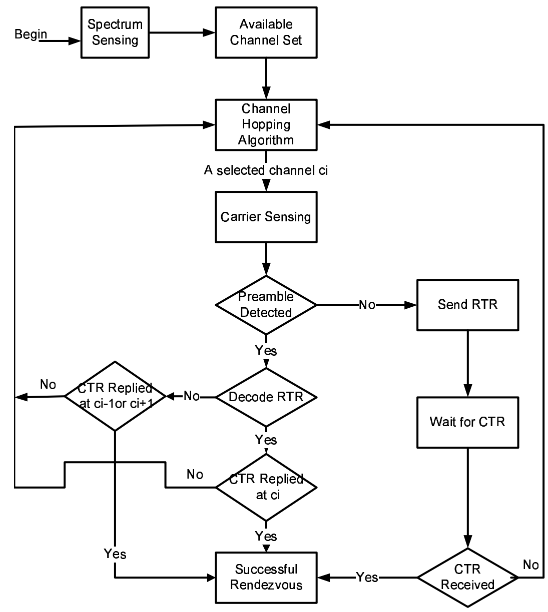

Fig. 5. Preamble Detection Rendezvous

probability to detect preamble from neighbouring channels is higher. If we follow the 802.11 RSSI threshold for preamble detection which equals to -82 dBm, the authors of [17] showed the preamble detection probability is over 60% if the sender and the receiver are on adjacent non-overlapping channels.

By exploiting energy leakage on adjacent channels, we propose the Preamble Detection Rendezvous (PDR) protocol to speed up the rendezvous process. Different from the Decode Based Rendezvous, the receiver has more choices to deal with the detected RTR. If the RTR is successfully decoded, then the receiver replies a CTR according to the channel information included in the RTR packet. Since the preamble detection can only detect the existence of RTR preambles from adjacent channels with certain probability but not able to decode the packet to know which side (lower frequency or higher frequency) the energy leakage is from, the receiver replies 2 CTRs sequentially, first at lower adjacent channel, then at higher adjacent channel. The basic flow chart is shown in Fig. 5. The RTR/CTR packets use the same format as DBR.

A problem caused by preamble detection is false alarm. If SU detects a preamble from adjacent channels, it will consider its own channel is not free and give up sending out its RTR. Fortunately, this will not affect the expected time-to-rendezvous of our protocol. Although the RTR is not sent out, the SU can rendezvous with the sender of the detected preamble. The expected TTR of all the proposed schemes are shown in Sec. V.

E. Queueing Rendezvous

When a specific SU broadcasts a RTR in a high density network, although more SUs are expected to receive the RTR, only one SU is able to reply the CTR due to collision. Therefore, all the other SUs have to completely give up the opportunity to rendezvous with this specific RTR sender in the current slot and wait for the next meeting time. In this section, we propose the Queueing Rendezvous (QR) protocol to make use of the rendezvous opportunity in the current slot to bring forward the next meeting time.

The basic idea works as follows. First we modify RTR packets to include the available channel set (S_i), the initial channel ($i0$), the initial step length ($r0$) and the starting time ($t0$) of the sender. When a SU SU_a receives a RTR but fails to reply a CTR due to collision, it inserts the RTR into a buffer B. Whenever SU_a becomes idle in the current time slot and B is not empty, SU_a looks into the buffer and tries to respond to the buffered RTRs. Since each SU follows the same jump-stay channel-hopping algorithm, it is easy for each SU to compute the channel which is used by the target SU by running jump-stay algorithm on the information inside the RTR packet. In other words, once the RTR is received, spectrum rendezvous is guaranteed. The flow chart of the QR is shown in Fig. 6.

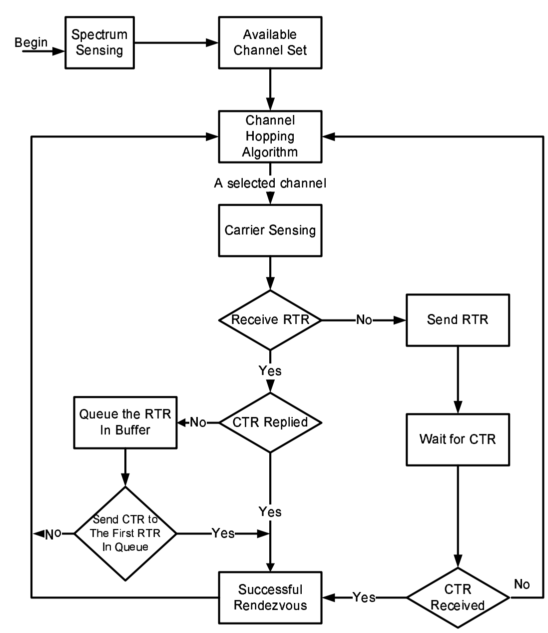

Fig. 6. Queuing Rendezvous

V. Performance Evaluation

In this section, we evaluate the proposed rendezvous protocols' performance by analysis and simulation. The notations are listed as below.

- L_{RTR}, L_{CTR}: the length of the RTR/CTR packets;
- L'_{RTR}:the length of the modified RTR packets used in QR;
- R: the data rate of each channel;
- p: the probability of successful preamble detection from adjacent channels;
- g_i: the number of SUs within SU_i's range;
- G_i: the number of SUs within SU_i's interference range;

A. Performance Analysis

Markov Chain models are used to analyse the performance of the proposed rendezvous protocols. Since each SU is independent and can be analysed in the same way, we consider the TTR that each SU_i needs to rendezvous with all neighboring SUs in its transmission range. Each state of the constructed Markove Chain corresponds to the number of SUs that SU_i has rendezvoused. Since in each time slot, at most 1 SU can rendezvous with SU_i. The state j of the constructed Markov Chain can only transfer to the state $j+1$. The SUs compete to send their RTRs and CTRs. We assume each SU holds the same opportunity in the competition, i.e. each with probability $1/h$ if h SUs are competing. Due to space limitation, we only describe how to derive the expected TTR for DBR. The results of PDR and QR are also listed.

In DBR, the Markov Chain transfers from state j to state $j+1$ if one of the non-rendezvoused neighbours selected the same channel as SU_i and wins the spectrum resource competition. So the transfer probability from state j to state $j+1$ is:

$$p_{j,j+1} = \sum_{h=1}^{g-j} \frac{\binom{g-j}{h} p_k^h (1-p_k)^{g-j-h} h}{h + (G-h)p_k} \tag{1}$$

$$Let\ f(g, G, j, p_k) = p_{j,j+1} \tag{2}$$

where p_k is the probability two SUs meet at the same channel (for jump-stay CH algorithm, $p_k = \frac{1}{5P/3+11/3+1/M}$ [10]). h is the number of SUs which are in SU_i's interference range and selecting the same channel as SU_i. The state probability π_L that SU_i has rendezvoused with L SUs.

$$\pi_L = \pi_0 \cdot \prod_{j=1}^{L} f(j, g, G, p_k), (L >= 1) \tag{3}$$

$$\sum_{L=0}^{g} \pi_L = 1 \tag{4}$$

Then the state probability that SU_i has rendezvous with g SUs is

$$\pi_g = \frac{\prod_{j=1}^{g} f(j, g, G, p_k)}{1 + \sum_{L=1}^{g} (\prod_{j=1}^{L} f(j, g, G, p_k))}, (L >= 1) \tag{5}$$

By applying Little's Law, the expression for the expected TTR is:

$$ETTR_{DBR} = \frac{1 + \sum_{L=1}^{g} (\prod_{j=1}^{L} f(j, g, G, p_k))}{\prod_{j=1}^{g} f(j, g, G, p_k)} \tag{6}$$

$$\times \frac{L_{RTR} + L_{CTR}}{R} \tag{7}$$

The derivation for the PDR is similar to the DBR except $p_k = \frac{1+2p}{5P/3+11/3+1/M}$. The expected TTR is

$$ETTR_{DBR} = \frac{1 + \sum_{L=1}^{g} (\prod_{j=1}^{L} f(j, g, G, p_k))}{\prod_{j=1}^{g} f(j, g, G, p_k)} \tag{8}$$

$$\times \frac{L_{RTR} + 2L_{CTR}}{R} \tag{9}$$

In QR case, two SUs are considered rendezvoused, once the RTR packet is received. The same as the other two protocols, SU_i can only rendezvous with at most one SU in each time slot. So the transfer rate from state j to state j+1 is :

$$p_{j,j+1} = [1 - (1-p_k)^{g-j-1}]p_k \tag{10}$$

$$where\ p_k = \frac{1}{5P/3 + 11/3 + 1/M} \tag{11}$$

By calculating the state probabilities of the Markov Chain and applying the Little's Law, the expected TTR of QR protocol is:

$$ETTR_{QR} = \frac{p_k^g \prod_{l=1}^{g} [1 - (1-p_k)^{g-j-1}]}{1 + \sum_{j=1}^{g} p_k^j \prod_{l=1}^{j} [1 - (1-p_k)^{g-j-1}]} \tag{12}$$

$$\times \frac{L'_{RTR} + L_{CTR}}{R} \tag{13}$$

B. Protocol Simulation

Since power leakage phenomenon is revealed recently and is not implemented in popular simulation tools, e.g. OPNET and NS3, the proposed schemes are evaluated by simulations based on a detailed C++ implementation of both RTR/CTR collision and the jump-stay algorithm.

The PUs and the SUs are randomly placed in a $1000m \times 1000m$ rectangle area. There are 20 PUs, each of which occupies only one channel. The transmission range is set to be $150m$ and the interference range is set to be $300m$. Spectrum sensing are performed every 30 minutes [21]. The size of the RTR and CTR packets are set to be 20 bytes [2]. The size of the modified RTR in QR is set to be 40 bytes. The transmission data rate is $1Mbps$ for all the channels.

Intuitively, the following parameters plays a key role in the system performance: the number of SUs N, the number of available channels M and the preamble detection probability p. We conducted our performance evaluation by varying these parameters to different values in different scenarios. The TTR is used as the performance evaluation metric. The corresponding results are presented in Fig. 7 to Fig. 9. Each point in the figures is an average value of 30 simulation runs.

We can make the following observation from the simulation results:

- Fig. 7 shows that the expected TTR is quite close to the simulated results. The difference between the expected TTR and the 30 runs average TTR is 10.2%, 7.7% and 8.4%, for DBR, PDR and QR respectively.
- In terms of TTR, PDR outperforms DBR and QR by 53.5% and 42.4% respectively. By using the same settings of [18], PDR decreases the TTR by 73.3% from [18].
- The probability of correct preamble detection of adjacent channels (p) is an important metric which directly affects the performance of PDR. When p is low, time is wasted in replying CTR to adjacent channels. Fig. 9 shows that the PDR can only outperform the other two protocols when p is relatively large (> 0.3).

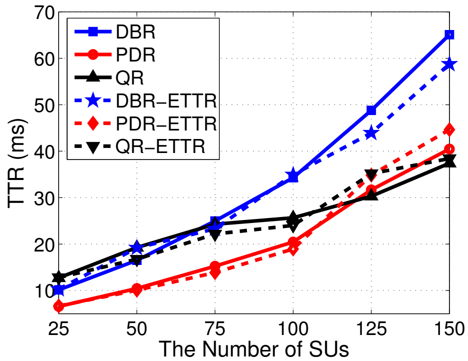

Fig. 7. M=60, P=0.5

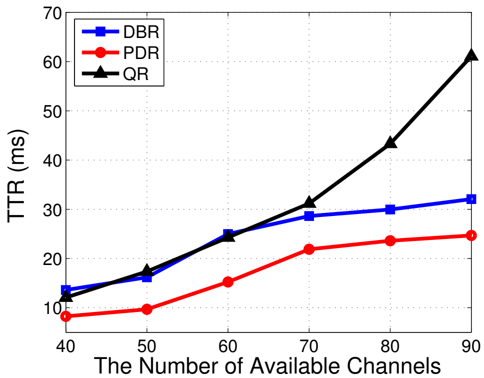

Fig. 8. N=75, P=0.5

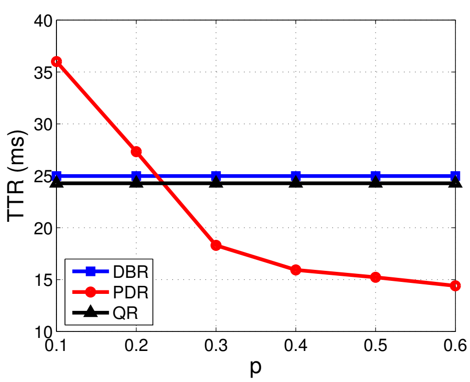

Fig. 9. M=60, N=75,, M=60, p is the probability of correct preamble detection in adjacent channels

- The QR only performs well in networks with high collision probability, since the extra content added to each RTR packet is relatively high. In networks with a low collision probability, the QR costs 35.5% more TTR than DBR. In high collision rate networks, the QR outperform the DBR and PDR by 22.8% and 8.4% respectively. One way to reduce the introduced overhead is to compress the data added into the RTR packets.

VI. Conclusion and Future Work

We proposed three spectrum rendezvous protocols for cognitive radio networks. By applying the non-waiting mechanism, we avoid the problem of wasting time for waiting for inexistent neighbours and simplify the MAC implementation. The preamble detection protocol is proposed to exploit the energy leakage from adjacent non-overlapping channels to increase the chance to rendezvous. For high collision probability networks, queuing rendezvous protocols is proposed to make use every rendezvous chance. The preamble detection protocols has the best overall performance.

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