SABR: A Self-Adaptive Beamforming-Based Rendezvous Protocol for Cognitive Radio Networks with Dense Primary Users

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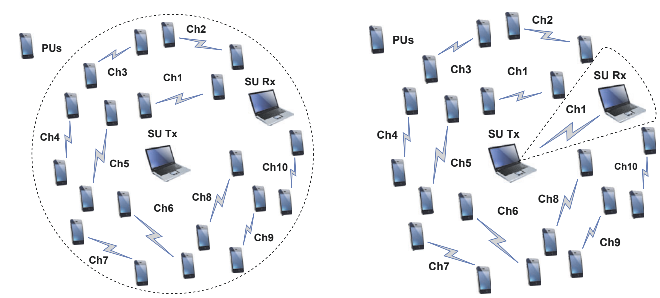
***Abstract*—Channel Rendezvous is a prerequisite and vital operation for two secondary users (SUs) to establish data communications in cognitive radio networks (CRNs). Channel hopping is a widely used method that can ensure two SUs meet on a common available channel within finite hops by following particularly designed hopping sequences. Most existing channel-hopping schemes are based on omnidirectional antennas. However, in a dense primary network, SUs with omnidirectional antennas can only use those channels that have no nearby PUs staying on. Such a limited number of available channels often leads to rendezvous failures. In this paper, we consider the utilization of directional antennas in the blind rendezvous process since more channels can be used due to the reduced interfering range. A novel joint design of sector hopping (beamforming) and channel hopping is proposed to guarantee the rendezvous. Furthermore, we identify a unique trade-off problem regarding the sector angle in these circumstances and derive an optimal solution that can adapt to different network conditions. Extensive simulation results demonstrate that the proposed framework significantly outperforms existing omnidirectional antenna-based rendezvous schemes under various dense primary networks.**

***Index Terms*—Cognitive radio networks, Directional antennas, Blind rendezvous, Beamforming**

I. Introduction

In order to fulfill the rising demand for high-speed data transmission and to better utilize the limited permitted spectrum, Cognitive radio networks (CRNs) has appeared as an enabling solution by providing access to secondary users (SUs) to use channels alongside primary users (PUs) [1], [2]. Since secondary users (SUs) can only use the channels which are not used by primary users (PUs), in order to communicate with each other, two SUs first need to search for a common available channel and build a connection between them. This action is called channel rendezvous [3]–[5]. Channel-hopping (CH) is the foremost method for the rendezvous algorithms model where expected time-to-rendezvous (ETTR) is defined as an important metric to evaluate CH algorithms. Achieving minimum ETTR in CRNs is the biggest challenge which depends on choosing various fundamental factors (e.g., protocol design, antenna type, sensing range, etc.).

There are many kinds of research available in the literature, which consider SUs with omni-directional antennas for channel rendezvous [6]–[8]. As omni-directional antennas radiates in all directions, interference occurred to all the PUs within the transmission range of a SU during transmission and receives data between SUs. In Figure 1(a), Omni directional antennas are used to communicate with each device which is shown its transmission range with a dashed circle. However, The goal of CRNs is that the SU sender will not create any interference to the PUs within its transmission range, consequently, only the channels which are unused by active PUs within range can be chosen [9]. Particularly, if the distance between two SUs lengthens, in order to maintain their active connection, the SUs expand their transmission power. Since the transmission range is large, causing interference proportionately to more PUs, two SUs under omni-directional antennas take more time to ensure the success of the channel rendezvous operation. Therefore, using Omni-directional antennas in CRNs encounters both PUs interference problem and power-consumption problem [10].



(a) Using Omnidirectional antennas. (b) Using Directional antennas.

Fig. 1. Two channel rendezvous scenarios with dense primary users.

One approach to solve the above crucial problem is using directional antennas instead of omni-directional [11]–[13]. With directional antennas, the SUs send messages in a specific direction at a certain angle. The area covered by the signals from a directional antenna is called a transmission sector, as shown in Figure 1(b). The transmission range is much smaller which can reduce the amount of interference to the PUs in the network when compared with the omni-directional antenna in Figure 1(a). As a result, it increases the number of available channels that can be utilized by the SUs in each of its transmission sectors. Hence, the probability of successful channel rendezvous can be significantly enhanced. When there are dense primary users, directional antennas provide a higher chance of a guaranteed rendezvous compared

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with omnidirectional antennas. The latter one may easily fail to rendezvous due to the absence of a common available channel.

Though the use of directional antennas for channel rendezvous in CRNs offers the above-mentioned amenities, it also confers some unique challenges. One of these challenges is the integration of sector rendezvous and channel rendezvous between the SU pair. Before establishing a connection between them, they should steer their antennas in specific directions so that their current transmission sectors can overlap with each other, which is called sector rendezvous. Only after sector rendezvous and channel rendezvous take place simultaneously, can the SU pair truly establish the connection. We name the entire time spent in this process the Total Rendezvous Time, T_{RT}. Though a few studies have focused on sector rendezvous in recent years [9], [14], they failed to reveal or explain the high T_{RT}, which sometimes is even longer than the omni case.

In addition, we identify that the angle of the transmission sector is a trade-off parameter in terms of the minimum T_{RT}. The smaller the angle is, the more available channels an SU can use, which increases the channel rendezvous probability. On the other hand, a smaller angle leads to a longer sector rendezvous delay. There are also other network parameters affecting its optimality. Further analysis is provided in Section II.C. However, so far there is no proper solution to address the optimal sector angle in existing efforts.

In this paper, we propose a self-adaptive beamforming-based rendezvous (SABR) protocol. We jointly design the sector hopping and channel hopping for SUs equipped with beamforming-enabled antennas. By dynamically addressing the sector angle trade-off problem, SABR can achieve fast and guaranteed rendezvous under various high-volume primary networks. The main contributions of this paper are summarized as follows:

- A more practical metric, T_{RT}, is proposed and derived for directional antenna-based rendezvous for the first time.
- To the best of our knowledge, SABR is the first protocol optimized the trade-off sector angle in the joint rendezvous (sector and channel) process.
- SABR can adapt with various network conditions in terms of the number of channels, the number of PUs, and the destination distance.

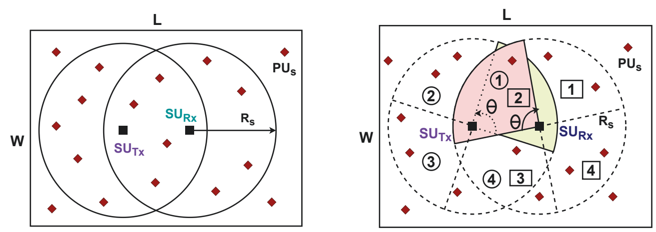
The rest of the paper is organized as follows: Section II provides the system model and problem formation. The trade-off parameter for SABR is analyzed and derived in Section III. The SABR protocol design is presented in Section IV. Performance evaluation is given in Section V, followed by the conclusions in Section VI.

II. Proposed System Model

In this section, we propose the system model and form the unique joint rendezvous problem..

A. Network Model

First, consider two types of CRNs shown in Figure 2: 1) CRNs-OMNI in which SUs are equipped with omni-directional antennas; 2) CRNs-Directional in which SUs are equipped with directional antennas. Related parameters are concluded in Table I. The system network consists of finite number (K) of PUs and a pair of SUs (SU_{T_x} and SU_{R_x}) in an $L \times W$ area. There are totally N primary channels which can be accessed opportunistically by the SUs in order to communicate with each other. For CRNs-Directional, Each SU_i is equipped with a directional antenna with beamwidth $\theta_i(0 < \theta_i < 360°)$. Accordingly, the $360°$ communication range of the SU_i is divided into $m_i = (360°/\theta_i)$ nonoverlapping transmission sectors that are indexed from 1 to m_i illustrated in the Figure 2(b). We assume that the directional antenna of each SU has same transmission sector angle θ and can adjust it according to the sophisticated beam-locking schemes.



(a) CRNs-OMNI (b) CRNs-Directional

Fig. 2. Network models of CRNs with different antennas.

TABLE I
List of Symbol Notations

K	Total number of PUs in the network
N	Total number of primary channels in the network
R_s	Radius of the SU transmission range
m	Total number of sectors in the SUs
Z	The total number of channels covered by R_s
C_{ach}	Total number of common available channels
U_{ch}	Total number of unavailable channels
$A_{cs}(SU)$	Available Channel Set
Pr_{ch}	Probability of rendezvous per channel hop
Pr_{sec}	Probability of rendezvous per sector hop

Each SU has a circular sensing range with a radius of R_s in CRNs-OMNI. The two considered SUs are located within the transmission range of each other, and they can implement the same channel rendezvous scheme which can guarantee a successful channel rendezvous within a bounded time. Accordingly, in CRNs-Directional, we assume that the transmission sectors are used as sensing sectors by which every SU can anticipate the appearance of the running PUs within them. If a PU is active in that time within the sensing range of a SU, the corresponding SU can detect its appearance, and the PU transmission can be interfered by the SU transmission. Without loss of generality, we consider a time slotted communication, where time is divided into discrete slots that have fixed and equal durations. In the course of each time slot, we presume that a SU can only transmit data in one sector over an individual channel.

B. Sector Rendezvous and Channel Rendezvous

For two SUs equipped with directional antennas (SU_{TX} and SU_{RX}) who want to communicate with each other, they need to steer their antennas toward each other, where their transmission sectors can cover each other. Assume that SU_{TX} is located in the sector $x \in [1, m]$ of SU_{RX} and SU_{RX} is situated in the sector $y \in [1, m]$ of SU_{TX}. The pair of the sectors (x, y) is called the sector rendezvous pair. For example, in Figure 2(b), the sector rendezvous pair is $(1, 2)$. Since a SU does not know the other's location before a successful rendezvous, both SUs should keep hovering over their sectors until they both hop onto the correct sector pair. This is the *sector hopping (SH) process*. If we denote the index of the sector a SU stays at time slot t as S_t, the sequence S_0, S_1, . . . , S_t, . . . is called a *sector hopping sequence*. A well-designed sector hopping algorithm should always generate sector-rendezvous guaranteed sequences for any two SUs despite the number of sectors or their hopping moments offset.

Another factor affects the final rendezvous is the channel that the SU currently uses. If SU_{TX} and SU_{RX} are using different channels. Even though they are at the correct sectors, they cannot hear each other. Therefore, the rendezvous must take place in both dimensions in this scenario, sector and channel. This can be achieved in a straightforward way: after an SU hopping onto each transmission sector, it performs a predetermined channel hopping (CH) scheme which can guarantee a successful channel rendezvous as long as the two SUs have at least one common available channel, and, in this case, are at each other's rendezvous sectors.

C. Problem Formation and Performance Metrics

ETTR (expected time to rendezvous) and MTTR (maximum time to rendezvous) are regarded as two crucial metrics in traditional CH design. However, in this paper, we defined a new metric called Total Rendezvous Time, T_{RT}, as the total required time (in number of time slots) for a pair of SUs to achieve sector and channel rendezvous simultaneously. Following the aforementioned process, we can derive it as:

$$T_{RT} = MTTR_{CH} \times (ETTR_{SH} - 1) + ETTR_{CH} \quad (1)$$

where $ETTR_{SH}$ is the average number of hops for sector rendezvous, $MTTR_{CH}$ and $ETTR_{CH}$ are the worst-case and average number of hops for channel rendezvous. In other words, an SU needs to wait $MTTR_{CH}$ times slots on each transmission sector for a possible channel rendezvous. If it doesn't happen, the SU knows that it is not tuning to the right direction and will try the next sector, and so on so forth until a channel rendezvous takes place.

The $MTTR_{CH}$ mainly depends on the number of channels in the network, N. The state-of-the-art CH design can achieve MTTR at the order of $O(N^2)$. The ETTR can be derived given the per-hop rendezvous probability (ρ):

$$\begin{aligned} ETTR &= P(1)1 + P(2)2 + P(3)3 + \cdots \\ &= \rho(1) + 2(1-\rho)\rho + 3(1-\rho)^2\rho + \cdots \\ &= \sum_{i=1}^{\infty} i(1-\rho)^{i-1}\rho = \frac{1}{\rho} \end{aligned} \quad (2)$$

where $P(i)$ is the probability of rendezvous in i hops.

In the following section, we analyze a key parameter, θ, representing the angle of the transmission sector. It affects the ρ of $ETTR_{SH}$ and $ETTR_{CH}$ in two opposite directions. Therefore, we also address the following optimization problem in this paper:

$$\underset{\theta}{\text{Minimize}} \quad T_{RT}. \quad (3)$$

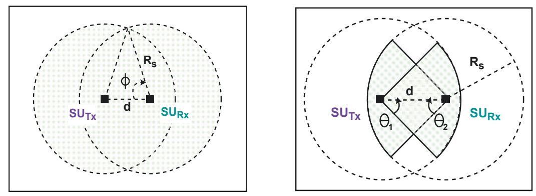
III. Parameters Analysis and Derivation

In this section, we will analyze parameters related to T_{RT} and derive T_{RT} in terms of θ step by step.

A. Number of Common Available Channels

From Figure 3, if the number of PU occupied channels in SUs' union transmission area (dotted portions) is denoted as Z, then the number of common available channels both SUs can use would be

$$C_{ach} = N - Z \quad (4)$$



(a) Coverage area with Omni-directional antennas.

(b) Coverage area with Directional antennas.

Fig. 3. The union transmission areas of the SU pair.

- From Figure 3(a) we can see for Omni-directional antennas, the distance between SUs is d and the angle between d and R_s, $\phi = arccos\frac{d}{2R_s}$.
  Then, the union area covered by two SUs' transmission range is:

$$\begin{aligned} A_{omni} =& S_{cir} + 2 * (S^{Rx}_{sec} - (S^{Tx}_{sec} - S_{tri})) \\ =& \pi R_s^2 + 2(\pi R_s^2 \times \frac{180^\circ - \phi}{360^\circ} - \\ & (\pi R_s^2 \times \frac{\phi}{360^\circ}) + \frac{dR_s sin\phi}{2}) \end{aligned} \quad (5)$$

  If the PU density in a unit area is k_{omni} then, the total number of occupied channels covered by R_s , Z_{omni} is

$$Z_{omni} = k_{omni} \times A_{omni}. \quad (6)$$

- For directional antennas, from Figure 3(b), the area of a sector is:

$$A_{sec} = \pi R_s^2 \times (\frac{\theta}{360^\circ}) \quad (7)$$

  where θ is the sector angle.
  In the inner quadrilateral, if the angle between d and lower sector side of SU_{TX} and SU_{RX} are θ_1 and θ_2. Accordingly, the area of the inner quadrilateral is:

$$\begin{aligned} A_{iq} = \frac{1}{2} \times d^2 \times (&\frac{(sin\frac{\theta-\theta_1}{2})^2}{sin(180^\circ - 2\theta + \theta_1 + \theta_2)} + \\ &\frac{(sin\frac{\theta_1}{2})^2}{sin(180^\circ - \theta_1 - \theta_2)}) \end{aligned} \quad (8)$$

  A_{iq} equals to zero when the SUs are at the edge of each other's sectors, i.e., when $\theta_1 = \theta$ and $\theta_2 = 0$, or the vice-versa case. To derive the optimal θ in the following analysis, we need to consider a more meaningful and common cases when the two SUs' sectors are directly facing each other, i.e., θ_1 and θ_2 are equally divided by d then we get the maximum A_{iq} from Eq. 8:

$$A_{iq}^{max} = d^2 \times (\frac{(sin\frac{\theta}{2})^2}{sin(180^\circ - \theta)}) \tag{9}$$

Then, the minimum union area covered by two SUs' transmission ranges with directional antennas is:

$$\begin{aligned} A_{dir}^{min} &= 2 \times A_{sec} - A_{iq}^{max} \\ &= 2 \times \pi R_s^2 \times (\frac{\theta}{360^\circ}) - d^2 \times (\frac{(sin\frac{\theta}{2})^2}{sin(180^\circ - \theta)}) \end{aligned} \tag{10}$$

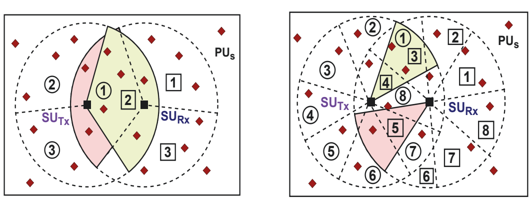
Similarly, if the PU density per unit area is k_{dir}, the minimum number of occupied channels covered by the union transmission area with directional antennas is:

$$Z_{dir}^{min} = k_{dir} \times A_{dir}^{min}. \tag{11}$$

By Eq. 4, we know the number of common available channels, C_{ach}, reaches the maximum under this scenario. Further, the smaller the θ is, the less area the A_{dir} has by Eq. 10. Consequently, the more C_{ach} they can use.

B. Analysis of the Section Angle

There exists a complex trade-off in designing the directional antenna sector angle shown in Figure 4. Here, We label the sector indexes of SU_{TX} and SU_{RX} with round and rectangular shapes accordingly.



(a) With large sector angle. (b) With small sector angle.

Fig. 4. Trade-off in designing Directional antenna's sector angle.

On one hand, if the sector angle is large (e.g., 3 sectors in Figure 4(a)), the transmission range of the SU is broad and relatively easy to steer their antennas to the proper direction of their communication partners. This means that the time needed for the sector hopping process is short. However, since the sector angle is large, the interference rate to nearby PUs within the transmission range is high and the common available channels between the SUs become fewer. This can also be derived by Eq. 10 and 11. On the other hand in Figure 4(b), if the sector angle is small (e.g., 8 sectors), the transmission range of the SU is narrow. It interferes with less PUs into the transmission range and the common available channel between the SUs increases, which accords the conclusion in the previous subsection. However, the time needed for the sector rendezvous, (4, 8), is long or may not even exist. The goal of this section is to mathematically derive the exact relationship between this tradeoff parameter and the total rendezvous time.

C. Derivation for T_{RT}-OMNI

From Eq. 4, 5, and 6, we know that the number of common available channels under omni-CRNs is only related with N, k, and d. In a high-dense primary network (a large k), the MTTR can easily go to infinity, i.e., no common available channel found, no rendezvous guaranteed. The following derivation supposes that C_{ach} is at least above zero.

Denote $A_{CS}(SU)$ as the number of available channels each individual SU can use, then $A_{CS}(SU) = N - k\pi R_s^2$. The per-hop rendezvous probability, ρ_{omni} under this case can be derived as:

$$\begin{aligned} \rho &= \frac{\binom{C_{ach}}{1}}{\binom{A_{CS}(SU)}{1}\binom{A_{CS}(SU)}{1}} \\ &= \frac{C_{ach}}{(N - k\pi R_s^2)^2} \end{aligned} \tag{12}$$

Since there is no SH involved in omni-cases, T_{RT} can be derived from Eq. 2:

$$T_{RT} = ETTR = \frac{(N - k\pi R_s^2)^2}{C_{ach}}. \tag{13}$$

D. Derivation for T_{RT}-Directional

Without loss of generality, we use the upper bound of MTTR in existing CH algorithms:

$$MTTR = N^2 \tag{14}$$

As the number of sectors in SUs is $m \approx \pi/\theta$, the per-hop sector rendezvous probability, ρ_{sec} can be derived as:

$$\rho_{sec} = \frac{1}{\binom{m}{1}}\frac{1}{\binom{m}{1}} = \frac{1}{m^2}. \tag{15}$$

By Eq. (2), $ETTR_{SH} = m^2 = (\pi/\theta)^2$.

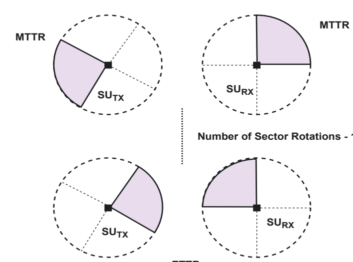


Fig. 5. Total Rendezvous Time for CRNs-Directional

On the other hand, the number of available channels for an individual SU is:

$$A_{CS}(SU) = N - k\pi R_s^2\theta. \tag{16}$$

Similar to Eq. 12, the per-hop channel rendezvous probability for directional cases , ρ_{ch}, can be derived as:

$$\rho_{ch} = \frac{C_{ach}}{(N - k\pi R_s^2\theta)^2} = \frac{N - Z_{dir}^{min}}{(N - k\pi R_s^2\theta)^2}. \tag{17}$$

We calculate $ETTR_{CH} = (N - k\pi R_s^2\theta)^2)/(N - Z_{dir}^{min})$ by Eq. (2), where ETTR is derived.

Next, we use $ETTR_{SH} - 1$ considering all the non-rendezvous sector hops before arriving at the correct sector pair, as in Figure 5. To calculate the T_{RT} in Eq. (1), we have

$$\begin{aligned} T_{RT} &= MTTR_{CH} \times (ETTR_{SH} - 1) + ETTR_{CH} \\ &= N^2 \times (\pi/\theta)^2 + \frac{(N - k\pi R_s^2 \theta)^2}{N - Z_{dir}^{min}}. \end{aligned} \tag{18}$$

IV. SABR Protocol Design

We established the SABR protocol with practical parameters that are either preknown, easy estimated by sensing, or derived in Section III. The pseudo-code of the SABR protocol is demonstrated in Algorithm 1. The rendezvous process for directional antenna-based rendezvous includes two phases, the sector hopping and the channel hopping. After hopping on to each sector, SUs wait for MTTR time slots for a potential channel rendezvous. If not rendezvous, it steers to another sector followed by a sector hopping algorithm which guarantees the sector rendezvous.

Algorithm 1: The SABR protocol for SUs

Input: R_s and N;

1: Sense PUs traffic on all channels in omni direction (running periodically);
2: Estimate the number of PUs, k, and use $d = R_s$ for the worse case;
3: Derive the optimal θ based on Eq. 9-11, and 18 ;
4: Label sectors in an anti-clockwise order;
5: **while** *no rendezvous* **do**
  Beamforming on a sector following any sector-rendezvous guaranteed sequence (e.g., [14]);
  Generate the available channel sets $A_{CS}(SU)$ for this sector;
  $t = 0$;
  while *no rendezvous* & $t \leq N^2$ *(time slots)* **do**
    $t = t + 1$;
    Hop onto a channel in $A_{CS}(SU)$ following any channel rendezvous guaranteed sequence (e.g., [3]);
    Handshake attempt;

V. Performance Evaluation

In this section, simulation environment is explained at first and then the proposed protocol is evaluated by comparing with CRNs-Omni in terms of Total Rendezvous Time and testing optimality under various primary networks.

TABLE II
Simulation Parameters

The side length of the network area	500 m
The side width of the network area	700 m
The radius of the SU sensing range	250 m
The distance between the two SUs	200 m
The total number of time slots in a simulation:T	5000

A. Simulation Environment

In this section, we evaluate the performance of our developed sector optimization scheme and compare with CRNs-Omni and CRNs-Directional networks in terms of different number of PUs and channels. We choose the sophisticated commercial software Matlab as the simulation tool. The network topology with random number of PUs and channels are deployed in an area of $700m \times 500m$. We evaluate our scheme in two categories: (i) when the number of PUs K are random and the number of channels N is fixed (ii) when the number of PUs K is fixed and the number of channels N is random. The SUs are considered in fixed position where the distance between the two SUs $200m$. During simulation, random channel hopping (RCH) scheme is adopted to find channel rendezvous. The parameters used in our simulation are listed in Table II.

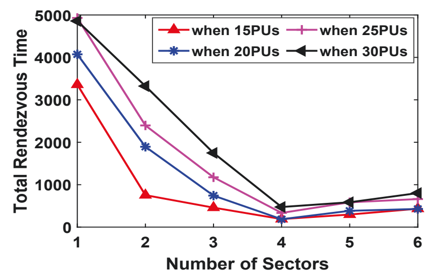
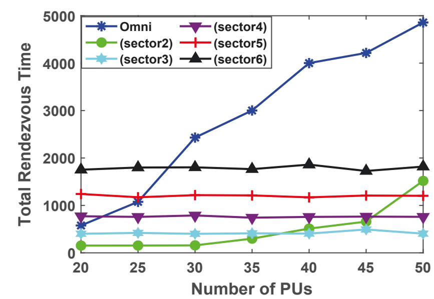
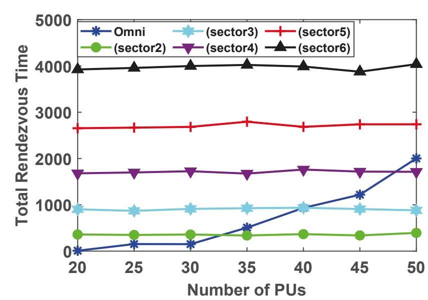


Fig. 6. T_{RT} vs. m ($N = 5$).



(a) T_{RT} vs K (when $N = 10$)



(b) T_{RT} vs K (when $N = 15$)

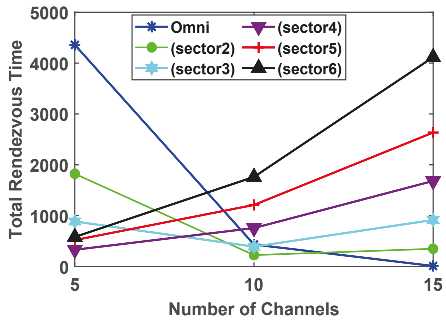
Fig. 7. T_{RT} vs K when N is fixed

B. When random K and fixed N

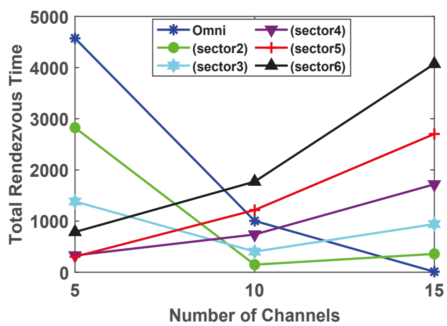
Fig. 6 highlights the impact of the number of PUs on the Total Rendezvous Time. It validates our proposed scheme that the optimal angle does exist (here $m = 4$) and can provide best and stable performance based on K and N. For CRNs-Omni (i.e., $m = 1$), T_{RT} climbed with the number of PUs increase. The results justify our research motivation of applying directional antennas with optimal beamforming angle as compared with omni-directional antennas in dense primary networks. After $m = 4$, with the increase of sectors, the T_{RT} increases due to the sector angle trade-off.

In Fig. 7, when the number of channels are 10 and 15, T_{RT} of CRNs-Omni are quickly boosted in both cases with the increasing density of PUs. In contrast, SU pairs with SH perform a stable output. It is also shown that the optimal m changes from 2 to 3 when the network gets denser, which supports the design of SABR to update m dynamically with the changing network conditions.

C. When random N and fixed K



(a) T_{RT} vs. N (when $K = 20$).



(b) T_{RT} vs. N (when $K = 25$).

Fig. 8. T_{RT} vs N when K is fixed.

TABLE III
T_{RT} VS. (N, K) USING SABR

$K \backslash N$	$N = 5$	$N = 10$	$N = 15$
$K = 20$	303.56 ($m = 4$)	148.01 ($m = 2$)	10.01 ($m = 1$)
$K = 25$	330.39 ($m = 5$)	391.45 ($m = 2$)	11.59 ($m = 1$)
$K = 30$	591.01 ($m = 6$)	300.93 ($m = 2$)	81.25 ($m = 1$)

From Figure 8, CRNs-Omni performed worse when channels are scarce and best when channels are sufficient. That's why directional antenna-based rendezvous should be mainly applied to saturated primary networks. In contrast, SABR always enjoys the lowest T_{RT} by adjusting m to the optimal value according to the environment. For example, in Figure 8(b), m shifts from 5 to 2 then to 1 when N increases from 5 to 10 then to 15.

Table III concludes the minimum T_{RT} SABR received over different network conditions. We can see that SABR maintained a relatively low and stable T_{RT} even under extreme cases. This makes SABR a promising approach for networks requiring reliable and efficient data transmission under diverse and challenging conditions. Omni and traditional (fixed) directional antenna based schemes will easily go above 1000 under the same condition, referred to Figure 8.

VI. CONCLUSION

In this paper, we jointly designed a protocol of sector and channel hopping to guarantee both rendezvous simultaneously. A novel metric (total rendezvous time) was proposed which integrated ETTR and MTTR of both SH and CH to evaluate the overall performance of directional antenna rendezvous comparing with the omni- results. Moreover, we established an analytical model to derive the optimal sector angle, which can be calculated with an SU's sensible information. SABR can dynamically beamform this angle to adapt with primary networks. Simulation validated our analysis and showed that SABR always enjoyed the minimum total rendezvous time especially under high dense primary users.

REFERENCES

[1] A. Ahmad, S. Ahmad, M. H. Rehmani, and N. U. Hassan, "A survey on radio resource allocation in cognitive radio sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 888–917, 2015.

[2] Q. Wang, H.-N. Dai, O. Georgiou, Z. Shi, and W. Zhang, "Connectivity of underlay cognitive radio networks with directional antennas," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 8, pp. 7003–7017, 2018.

[3] X. Liu and J. Xie, "SUBSET: A joint design of channel selection and channel hopping for fast blind rendezvous in cognitive radio ad hoc networks," in *12th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, pp. 426–434, 2015.

[4] F. Hu, B. Chen, and K. Zhu, "Full spectrum sharing in cognitive radio networks toward 5g: A survey," *IEEE Access*, vol. 6, pp. 15754–15776, 2018.

[5] X. Liu and J. Xie, "Contention window-based deadlock-free MAC for blind rendezvous in cognitive radio ad hoc networks," in *IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, 2015.

[6] H. Yazdani and A. Vosoughi, "On cognitive radio systems with directional antennas and imperfect spectrum sensing," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 3589–3593, 2017.

[7] H. B. Salameh and M. Al-Quraan, "Securing delay-sensitive CR-IoT networking under jamming attacks: Parallel transmission and batching perspective," *IEEE Internet of Things Journal*, vol. 7, no. 8, pp. 7529–7538, 2020.

[8] X. Liu and J. Xie, "A 2D heterogeneous rendezvous protocol for multi-wideband cognitive radio networks," in *IEEE Conference on Computer Communications INFOCOM*, pp. 1–9, IEEE, 2017.

[9] Y. Song and J. Xie, "Enhancing channel rendezvous in cognitive radio networks with directional antennas," in *IEEE International Conference on Communications (ICC)*, pp. 3702–3707, 2015.

[10] L. Hu, R. Shi, M. Mao, Z. Chen, H. Zhou, and W. Li, "Optimal energy-efficient transmission for hybrid spectrum sharing in cooperative cognitive radio networks," *China Communications*, vol. 16, no. 6, pp. 150–161, 2019.

[11] H. Yazdani and A. Vosoughi, "On optimal sensing and capacity trade-off in cognitive radio systems with directional antennas," in *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, pp. 1015–1019, 2018.

[12] A. M. Al-Mqdashi, A. Sali, N. K. Noordin, S. J. Hashim, and R. Nordin, "Combined sector and channel hopping schemes for efficient rendezvous in directional antenna cognitive radio networks," *Wireless Communications and Mobile Computing*, 2017.

[13] W. Na, J. Yoon, S. Cho, D. Griffith, and N. Golmie, "Centralized cooperative directional spectrum sensing for cognitive radio networks," *IEEE Transactions on Mobile Computing*, vol. 17, no. 6, pp. 1260–1274, 2017.

[14] J. Li and J. Xie, "Directional antenna based distributed blind rendezvous in cognitive radio ad-hoc networks," in *IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, 2015.