

# A Joint Sensing and Rendezvous Approach for Dynamic Cognitive Radio Networks

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**Abstract**—In cognitive radio networks (CRNs), the rendezvous problem—which entails creating a shared control channel among secondary users (SUs) in a distributed manner— continues to be a major challenge. In highly dynamic spectrum situations, traditional channel-hopping and blind rendezvous algorithms frequently have inefficiency, scalability problems, and excessive latency like Time to Rendezvous (TTR). This paper proposes a novel, joint sensing and rendezvous for efficient sharing of common channel within the practical constraints. In contrast to traditional sensing and rendezvous schemes, the joint sensing and rendezvous technique suggested in this research uses a partial number of channels for both sensing and rendezvous attempts. The challenge of finding vacant channels among the risk of occupancy is addressed by using the statistical distribution of unoccupied channels and rendezvous in terms of probability mass function and cumulative mass function. With the right statistical distribution, the proposed method shows a lower rendezvous time for a guaranteed rendezvous. Our simulation results show that the joint sensing and rendezvous model outperforms traditional distributed rendezvous strategies in terms of rendezvous time in the large-scale and dynamic CRNs.

**Index Terms**—Cognitive radio, multi-radio rendezvous, joint sensing and rendezvous, prime number theory, rendezvous statistical distribution, rendezvous probability.

## I. INTRODUCTION

In cognitive radio networks (CRNs), one of the primary responsibilities of cognitive radio users (CRUs) is to effectively identify open channels to avoid interfering with each other and with already-occupied channels. During data transmission, establishing a shared channel between the transmitter and receiver is a significant challenge because the blind rendezvous

mechanism must be used once unoccupied channels have been found. Since centralized networks are frequently unavailable in remote or real-world environments, this study emphasizes the necessity of distributed CRNs [1]. Spectrum sensing is an unavoidable component and prerequisite for rendezvous; that is, if the time for rendezvous and correct detection depend on the spectrum sensing. The design of every CR node in any distributed communication network system is therefore greatly impacted by the rendezvous's reliance on sensing stages for both time and energy consumption. The sensing and rendezvous are proposed as two distinct processes in all traditional techniques of research articles [2], [3] and the rendezvous is contingent on the status of all the channels identified by the sensing task.

C. Xin et al. proposed a lightweight, throughput-oriented algorithm utilizing sequential sequence generation to approach near-optimal rendezvous efficiency in dynamic spectrum access networks [4]. The optimization relies on an instantly determined and perfectly known available channel set, omitting the time cost and potential error incurred during necessary spectrum sensing. Focused on multi-destination rendezvous, T. Samak et al. [5] utilized a "sensing puzzle" mechanism to securely share channel availability results and prevent selfish data exploitation among secondary users. Moreover, D. Jin et al. [6] applied Reinforcement Learning (RL) to dynamically optimize channel hopping sequences for enhanced rendezvous efficiency in asymmetric CRNs. However, the RL policy refinement is built on state inputs (channel availability) whose reliability is highly susceptible to slow

or corrupted sensing data, a vulnerability not transparently modeled. The quinary coding and matrix structures are utilized to generate channel hopping sequences designed to mathematically guarantee blind rendezvous efficiency [7]. The guarantee of rendezvous success is purely structural, focusing on combinatorial alignment independent of physical channel conditions or the non-negligible time required for reliable spectrum sensing. A detailed and further rigorous statistical distribution analysis of the Sender-Jump Receiver-Wait (SJRW) rendezvous mechanism are illustrated, contributing to the analytical understanding of role-based systems [2], [8], [9]. J. Sheu et al. [3] introduced the seminal Jump-Stay (JS) rendezvous algorithm for tight bounds on the Maximum Time-to-Rendezvous (MTTR). These performance bounds are derived strictly from sequence overlap probabilities and timing synchronization, systematically excluding the time required for spectrum sensing necessary to confirm channel status before execution. For steady performance in static multi-radio multi-hop wireless networks, Lin et al. [10] suggested a coordinated channel-hopping and routing system. The SJRW algorithm is described as a straightforward, blind rendezvous method that relies on defined operating responsibilities [11]. The use of multiple radios as opposed to single radio was proposed to significantly reduce the Expected Time-to-Rendezvous (ETTR) by increasing the parallelism of channel searching [12]. While improving sequence speed, the design abstracts away the fact that each parallel search relies on independent sensing tasks whose cumulative energy cost and initial synchronization time are excluded from the calculated TTR reduction. The rendezvous attempts have a dramatic improvement for most of the aforementioned papers with the assumption that the sensing of all channels is done properly. However, sensing on the complete set of total channels and parts of the channels require to analysis due to different channel varying statistical behavior of the occupied channels in different times for any specific region of applications.

Stimulated by the conditions to be met based on the conventional limitations of finding optimum result, in this paper we have presented the following primary improvements: (i) we analyze the statistical conditions of common channels with different channel occupancy; (ii) The analytical approach of problem formulation for maximizing rendezvous probability while minimizing time are identified (iii) based on the statistical distribution we have proposed a joint sensing and rendezvous technique where a part of channels are attempted for sensing followed by rendezvous on the parts of channels (iv) the guaranteed probability rendezvous time is ensured through the proposed system for the practical scenarios of applications.

## II. SYSTEM MODEL

### A. Network Model

In this article, the CR transmitter (CR-Tx) and the CR receiver (CR-Rx) are two users in a distributed CRN that attempt to communicate over a common frequency channel without the cooperation of any central or other nodes. Let  $C$  be the set

of all available channels, with cardinality  $|C| = N$ .  $N$  is the total number of channels that are the sum of the occupied and unoccupied channels for any CR user. We consider a collection of channel subsets,  $n_1, n_2, \dots, n_k$ , where each subset  $n_i$  is a proper subset of  $N$  ( $n_i \subset N$ ). The number of channels in each subset,  $|n_i|$ , is strictly less than the total number of channels, i.e.,  $|n_i| < N$  for all  $i$ . A rendezvous channel, denoted as  $R$ , is an element of this set ( $R \in C$ ). In our decentralized system with  $M$  channels, CR-Tx and CR-Rx do not know the available vacant channel for identification. The two CR nodes'  $M$  frequency channels are identified as  $\xi = \{\xi_1, \xi_2, \dots, \xi_M\}$ . With  $M_T = |\xi_T|$  number of Tx channels, we define the set of accessible channels at CR-Tx as  $\xi_T = \{\xi_1, \xi_2, \dots, \xi_{M_T}\}$ . In other words,  $\xi_T \subset \xi$ . The  $M_R = |\xi_R|$  Rx channel is contained in the  $\xi_R = \{\xi_1, \xi_2, \dots, \xi_{M_R}\}$  channel set of CR-Rx, where  $\xi_R \subset \xi$ . The number of common channels ( $\bar{M}$ ) equals  $\bar{M} = |\bar{\xi}|$  since the common channel is represented by  $\bar{\xi} = \xi_T \cap \xi_R$ . Both symmetric and asymmetric channels are possible between the transmitter and the receiver. Generally speaking,  $\bar{\xi} = \hat{\xi}_T \cap \hat{\xi}_R$  and  $M' = |\bar{\xi}|$  are the available unoccupied channels that are shared by both ends. Furthermore, the possible range of rendezvous initiation delay is taken into consideration by the system with range  $[0, \min(M_T, M_R)]$ . The start times of the CR-Tx and CR-Rx time slots match at random because we assume that the clock is randomly synced. However, there is a global time clock synchronization maintained of any CR nodes for the proper rendezvous attempt.

### B. Prime Number Theory based Rendezvous

In this part, we describe the two primary steps of the rendezvous attainment technique. First, the sequence is constructed with repetition using the channels that are accessible for both sides of CR-Tx and CR-Rx. After that, the prime number theory method is used to create each side, and the channel sequences are generated for both ends depending on the system.

In this work, the channel rendezvous strategy is created using the provided local channel set and a particular system for CR-Tx and CR-Rx, respectively. In contrast to the conventional method of employing a single prime sequence with the entire channel series, we investigated the usage of many unique channels of each prime length [13]. The scanning space is minimized by a number of independent channels, and the early convergence of rendezvous is determined by the ratio of common to total channels with a prime length. Channel layout is guaranteed by the prime number principle [2], which entails selecting any initial channel (also known as initial channel selection) and selecting the channels at predefined intervals (also known as jumping rate) until the full sequence length is achieved. According to prime number theory, the first channel selection and jumping techniques provide a high likelihood of meeting in a random channel environment [14], [15]. The modular clock technique with jumping rates  $\alpha, \beta$  and  $\rho = M_R = M_T$  will cause two radios to rendezvous within  $\rho$  time slots [16]. It is assumed, without generalization, that CR-Tx and CR-Rx follow the same length and employ the same

approach with their respective channels. Any channel in the transmitter for the  $i$ 'th sequence for the  $n$ th time slot can be written as follows using the prime number technique:

$$\xi_t^i[\eta + 1] = \text{mod}\{\xi_t^i[\eta] + \alpha; \bar{M}_T\} \quad (1)$$

The receiver channel becomes:

$$\xi_r^i[\eta + 1] = \text{mod}\{\xi_r^i[\eta] + \beta; \bar{M}_R\} \quad (2)$$

where  $\alpha$  and  $\beta$  are the jumping rate of the channel for Tx and Rx, respectively;  $1 \leq \alpha \leq \bar{M}_T - 1$ ;  $1 \leq \beta \leq \bar{M}_R - 1$  and  $\bar{M}_T = \bar{M}_R = \arg \min_{\rho} \{\rho \geq M\}$ ;  $\rho$  is the prime number; and  $\text{mod}$  indicates the modulus operation.

### III. THE PROPOSED SOLUTION: A JOINT SENSING RENDEZVOUS APPROACH

#### A. The statistical distribution for Joint sensing, vacant channel and rendezvous

In this section, we have illustrated the conventional and proposed sensing and rendezvous technique. The conventional system Fig.1 senses all the available channels in the range of frequencies and then attempt rendezvous on the vacant channels. Also mentionable that the number of vacant channels for both transmitter and receiver may not be same due to imperfect channel and sensing. Therefore, after sensing all the channels in a range, the system requires to stay on the long range of channels that becomes complex in term of energy consumption, time consumption and sorting of the channels. The proposed system has assumed that the global time synchronization are maintained for all CR which is possible to share prior to any predefined session or any other global time sharing method. Therefore, instead of sensing all the channels in a range, every CR targets on a predefined range of frequencies for sensing and rendezvous which is less than  $N$  total channel, in the Fig.1. It is needless to mention that, among  $n_1, n_2..$  channels both vacant and occupied channels are exist. However, the question arises that the lower number of total channels have guarantee that at least one vacant channel available or not. For addressing this problem, in this paper the statistical distribution for total number of channels, vacant channels and probability of at least one common channel are analyzed which clarify the surety of getting the vacant channel for a successful rendezvous. After that the probability distribution of rendezvous among the vacant channels are shown for a transparent rendezvous systes. The statistical distribution of each time slot needed for the sender and receiver to meet is shown. The PMF and CMF are measured from the available channel sequence. To determine the maximum time to rendezvous (MTTR) and the overall rendezvous probability, a probabilistic analysis of the suggested approach is conducted.

1) *The probability distribution for total, occupied channels and channel vacancy:* This section provides a theoretical foundation and outlines the parameters for calculating the probability of successful rendezvous in a Cognitive Radio (CR) network. Successful rendezvous is defined here as finding

at least one common vacant channel when selecting a subset of channels ( $r$ ). The scenario involves selecting channels without replacement from a finite, fixed population of total channels ( $N$ ), which are divided into two distinct states: Vacant ( $M$ ) and Occupied ( $O$ ). The statistical analysis of this selection process is modeled accurately using the hypergeometric distribution.

The probability of obtaining exactly  $k$  vacant channels (successes) in a random sample of size  $r$  is defined by the probability mass function,  $P(X = k)$ . The probability calculation utilizes the following key notations, ( $N$ ) representing the total number of available channels; successes in cahnnel ( $M$ ), which is the total number of vacant channels; failures in obtaining channel ( $O$ ), defined as the number of occupied channels  $O = N - M$ ; sample size ( $r$ ), the number of channels randomly selected; and successes in sample ( $k$ ), which is the number of selected vacant channels. The probability is given by:

$$P(X = k) = \frac{\binom{M}{k} \binom{N-M}{r-k}}{\binom{N}{r}} \quad (3)$$

where the binomial coefficient  $\binom{n}{k}$  is defined as:

$$\binom{N}{k} = \frac{N!}{k!(N-k)!} \quad (4)$$

The primary objective of any CR nodes is to obtain minimum one vacant channel to share data between sender and receiver. So it is required to determine the probability of selecting at least one vacant channel,  $P(X \geq 1)$ . This is most easily calculated using the complement rule, which defines this probability from the probability of selecting *zero* vacant channels ( $P(X = 0)$ ):

$$P(X \geq 1) = 1 - P(X = 0) \quad (5)$$

The probability of selecting zero vacant channels ( $P(X=0)$ ) is found by setting  $k=0$  in Equation (3):

$$P(X = 0) = \frac{\binom{M}{0} \binom{N-M}{r-0}}{\binom{N}{r}} = \frac{\binom{N-M}{r}}{\binom{N}{r}} \quad (6)$$

Substituting Equation (6) into Equation (5), the final probability for a successful rendezvous is:

$$P(X \geq 1) = 1 - \frac{\binom{N-M}{r}}{\binom{N}{r}} \quad (7)$$

2) *The probability distribution for vacant channels and rendezvous:* For the asymmetric channel condition,  $\rho - B$  channels are chosen from previous channel order of  $\rho$  channels before forming prime number sequence. Thus, there is no certainty of same channels with order between CR-Tx and CR-Rx. For this asymmetric context, the rendezvous probability is calculated based on the number of common channels along with repetition of each channel. For total  $\rho$  channels, the rendezvous probability is measured from the permutation of  $\rho$  length with the help of derangement [8], [9], [17]. Every cycle has the same channels but with different channel arrangements

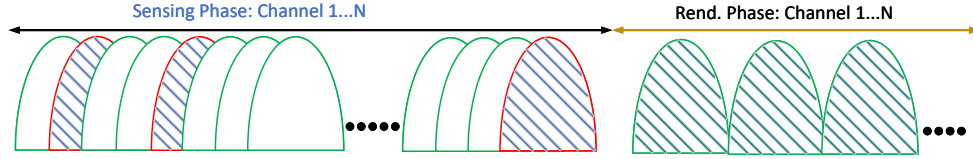


Figure.A: Conventional Sensing and Rendezvous

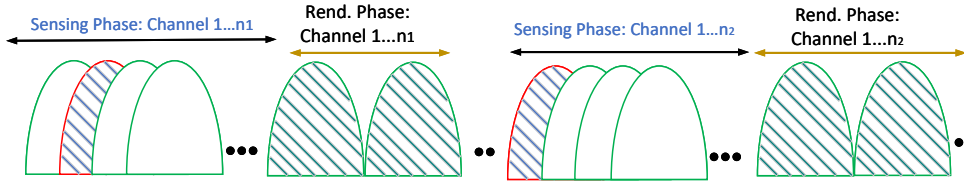


Figure.B: Proposed Sensing and Rendezvous

Fig. 1. The conventional and proposed sensing and rendezvous approach

as compared with other cycle. Hence, the rendezvous probability of any cycle is dependent on the prior cycle in the whole sequence. Before showing PMF for any time slot, it is necessary to clarify the constant nature of PMF for first cycle and so on for next cycles with total  $v$  repetition rate. For the first  $\rho$  time slot, the PMF is denoted by  $p_{\tau}^1(\tau)$ :

$$p_{\tau}^1(\tau) = \frac{v\hat{M}}{\rho^2} \quad (8)$$

The rendezvous probability for any independent (single) cycle with a sequence of  $\delta = 0$  and is given for a single radio as follows:

$$Pr(\tau \leq \rho) = \frac{\rho! - D_{\rho}}{\rho!}. \quad (9)$$

$D_{\rho}$  is the number of derangements. The derivation of (9) is given in [17]. Because the rendezvous per every cycle is independent, the total rendezvous probability ( $p_R$ ) for  $\delta = 0$  is given by:

$$p_R = \sum_{q=1}^{\Theta} Pr(\tau \leq \rho\sigma). \quad (10)$$

For our target rendezvous probability ( $\hat{p}_R$ ) with given  $\gamma$ , the minimum number of required channel cycles ( $\sigma_{min}$ ) is represented by (11) as follows:

$$\sigma_{min} = \arg \min_{\sigma} [p_R \geq \hat{p}_R] \quad (11)$$

Based on the system design, MTTR is measured on the maximum number of cycles for the  $\hat{p}_R$ :

$$MTTR = \rho\sigma_{min} \quad (12)$$

The average time to rendezvous (ATTR) is calculated as below:

$$ATTR = \sum_{\tau=1}^{MTTR} \tau p_{\tau}(\tau) \quad (13)$$

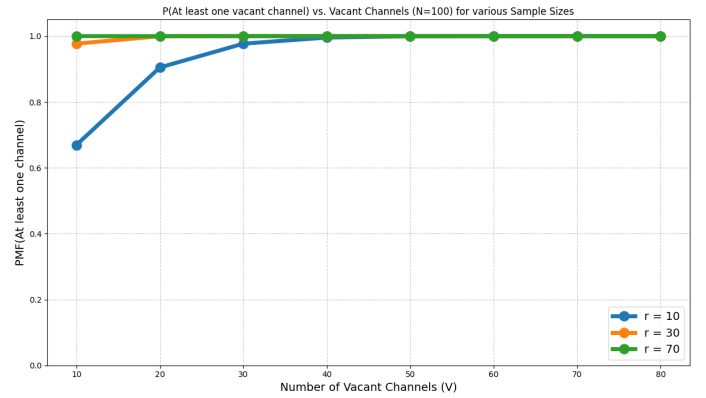


Fig. 2. Probability Mass Function (PMF) for sensing with  $N = 200$  channels

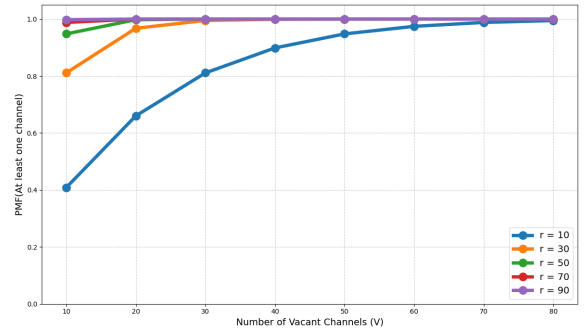


Fig. 3. PMF for sensing: channel selection variation with  $N = 100$  channels

#### IV. SIMULATION RESULT

In this section, we have demonstrated the rendezvous performances with statistical characteristics through MATLAB simulations for extracting the results with 100,000 to 1,000,000 runs for each simulation. The PMF of locating at least one empty channel ( $V$ ) with  $N = 100$  total channels is depicted in

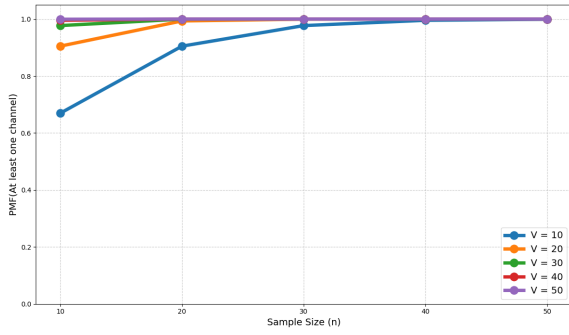


Fig. 4. PMF for sensing with  $N = 100$  channels for different vacancies

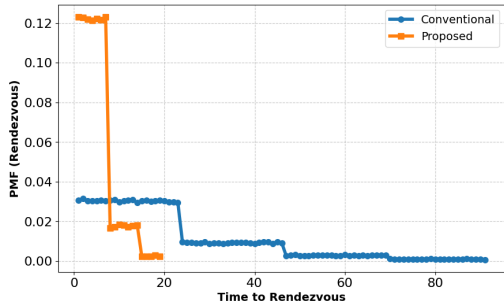


Fig. 5. PMF of single channel with different total channels

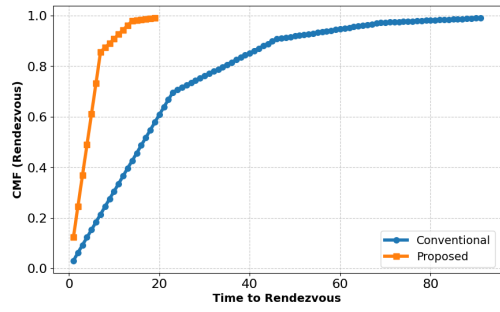


Fig. 6. Cumulative Mass Function for a rendezvous attempt

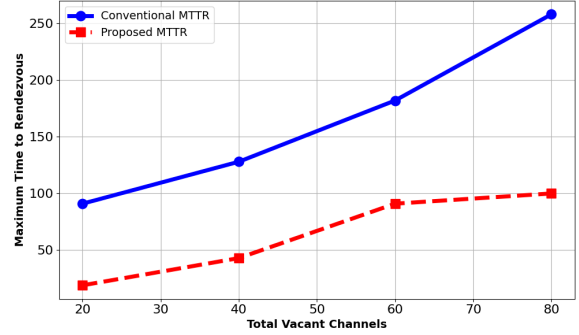


Fig. 7. Maximum time to rendezvous for total  $N = 100$  channels

the Fig.2. The likelihood of effective sensing is significantly increased by higher channel numbers ( $r$ ) selection at once from total  $N$  channels. In particular, with only  $V = 10$ ,  $r = 70$  yields  $PMF \approx 1$ , demonstrating the advantage of expanding the cooperative sensing sample size. Higher  $r$  values result in a more steeper PMF, showing that a higher number of channels is can guarantee a high likelihood of identifying at least one channel in bigger channel spaces ( $N$ ). This figure shows how the PMF of finding a vacant channel increases with sample size ( $n$ ) for  $V = 10$ . For a large channel vacancy ( $V = 50$ ), the PMF quickly saturates at 1.0 with  $n \approx 20$ . However, for low vacancy ( $V = 10$ ), a larger sample size ( $n \approx 40$ ) is required to achieve  $PMF \approx 0.95$ . For  $V = 20$  vacant channels, the PMF still demonstrates a positive correlation with sample size ( $n$ ). With  $V = 50$ ,  $PMF \approx 1.0$  is achieved by  $n = 10$ . For the sparse case ( $V = 10$ ), a sufficient sample size is essential to ensure a high sensing success probability.

Figures 5 and 6 present the PMF and CMF of the TTR distribution, offering a comprehensive statistical view that explains the low ATTR and bounded MTTR observed previously. The PMF (Fig. 3) shows that the proposed scheme has a high probability ( $\approx 0.12$ ) of instantaneous rendezvous within the first few time slots, before the probability quickly drops to zero by  $TTR \approx 20$ . In stark contrast, the conventional scheme scatters its probability across a much wider range, with low uniform probabilities ( $\approx 0.03$ ) extending up to  $TTR \approx 70$ . This is further confirmed by the CMF (Fig. 4), where the proposed scheme achieves a 100% rendezvous

probability by  $TTR \approx 20$ . The conventional scheme requires approximately  $TTR \approx 75$  to reach the same certainty. These distributions mathematically validate the superior efficiency and reliability of the proposed algorithm by demonstrating that it concentrates the probability mass in the shortest possible time, thus minimizing both average and maximum synchronization latency. Fig.7 presents the MTTR as a function of the total vacant channels, quantifying the statistical worst-case latency for both schemes. The proposed channel case has one third of the total channels are selected in the first phase. The conventional MTTR exhibits a rapid, near-linear increase, escalating from approximately 90 to over 250 time slots across the 20 to 80 channel range. This exponential

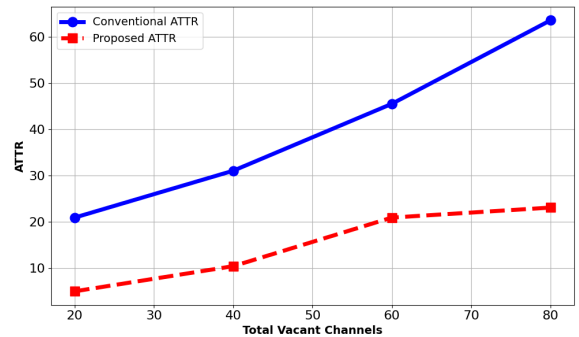


Fig. 8. Average time to rendezvous for total  $N = 100$  channels

rise severely impacts network reliability, as the maximum required synchronization time becomes prohibitively large in dense spectral environments. Conversely, the proposed MTTR scheme demonstrates superior stability. It maintains low latency, increasing gradually from  $\approx 20$  to  $\approx 100$  time slots. The Fig. 8 illustrates the comparative ATTR performance against the number of vacant channels, a key metric for rendezvous latency in blind synchronization. The conventional ATTR exhibits poor, near-linear scalability, increasing sharply from 21 to 63 time slots as the channel space expands. In sharp contrast, the proposed ATTR maintains robust efficiency with a significantly lower, sub-linear growth trend, rising moderately from  $\approx 5$  to  $\approx 23$  time slots. This superior statistical design confirms its efficacy in minimizing rendezvous latency, crucial for reliable CR network bootstrapping and improved QoS.

## V. CONCLUSION

In this research paper we have investigated the joint sensing and rendezvous approach for an efficient rendezvous. The surety of vacant channels for rendezvous is analyzed through statistical distributions for each time slot with the presence of occupied channels. The MATLAB-based simulation (with the Monte-Carlo method) was performed for verification of our results. The formulation of the problem focuses on guaranteed rendezvous through minimizing rendezvous time. In this research we have identified and demonstrated the rendezvous with minimum rendezvous time which leads to less energy consumption to achieve the desired outcomes across various practical scenarios. Moreover, this research paper opens a new horizon of joint sensing and rendezvous approach instead of the conventional separate sensing and rendezvous method. The optimization of time, energy and other resources are not included in this article which will be a scope for extended and comprehensive future research. The findings underscore the importance of optimizing time consumption, suggesting that the contributions of this study will facilitate advancements in resource-efficient communication strategies, ultimately reducing costs while enhancing performance in future low energy consumption networks such as LPWAN network applications. Future research will also extend this protocol to Industrial IoT scenarios where such low-latency performance is a prerequisite. Specifically, this protocol could serve as the time-critical communication backbone for monitoring Floating Photovoltaic (FPV) systems, which operate in harsh aquatic environments and require robust, distributed sensor networks to ensure structural integrity [18] [19]. Furthermore, by ensuring reliable and efficient channel access, this joint sensing approach provides the necessary throughput to support data-intensive operations, such as the real-time transmission required for Deep Learning-based power quality models in next-generation renewable energy grids [20].

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