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A Multi-Radio Channel Hopping Rendezvous Scheme in Cognitive Radio Networks for Internet of Things

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Abstract: With the rapid expansion of the Internet of Things (IoT), the demand for wireless spectrum is increasing exponentially, both in licensed and unlicensed bands. The existing fixed spectrum assignment policy creates a bottleneck as the spectrum that is not in use remains unutilized or underutilized. To overcome this issue, cognitive radio technology has emerged as a promising solution to spectrum assignment issues. In a Cognitive Radio Network (CRN), unlicensed users or secondary users (SUs) must meet on an available channel to establish a communication link for necessary information exchange. This process is known as rendezvous. However, SUs are unaware of each other if no centralized controller is involved. Channel Hopping (CH) is a rendezvous technique without the involvement of any centralized controller. Most of the existing CH algorithms are based on single radio SUs. As the cost of wireless transceivers is declining, multiple radios can be employed for rendezvous performance improvement. This paper proposes a multi-radio matrix-based CH algorithm that involves employing two radios with each SU instead of one. Compared with existing single radio algorithms, the proposed CH algorithm performs better by lowering the upper bounds on time to rendezvous. Our paper presents a comprehensive analysis of the benefits of incorporating an additional radio, demonstrating how this innovation leads to more efficient and timely rendezvous, thereby enhancing the overall communication capabilities within CRNs.

Keywords: Cognitive Radio, Rendezvous, Common Control Channel, Channel Hopping

1. INTRODUCTION

Current trends in the expansion of wireless devices indicate significant development in the Internet of Things (IoT) area. An increase in wireless devices comes with increased demand for wireless spectrum in the licensed and unlicensed ISM bands. While freely available unlicensed bands are becoming overburdened, the licensed bands are not being used efficiently due to the fixed spectrum assignment policy [1]. Cognitive Radio Networks (CRNs) have been vastly researched and proven to solve the problems encountered in efficiently utilizing wireless spectrum. Dynamic spectrum access enables CRNs to enhance the functionality of many Internet of Things (IoT) devices by mitigating spectrum scarcity issues. The rapid increase in IoT devices focuses on improving spectrum use for reliable communication. They oppose static spectrum assignments; CRNs present opportunities for dynamic use of underutilized frequency bands by IoT devices, improving spectrum utilization. Such access techniques are crucial for applications demanding low latency and reliability in communication, e.g., healthcare monitoring and smart grid applications [2]. By sporadically choosing comparatively less congested channels, CRNs increase IoT communications' ability while minimizing interference and ensuring steady data transmission. This adaptive feature is essential in fluctuating spectrum conditions. Additionally, CRNs support the scalability of IoT networks through dynamic spectrum allocation, which allows for accommodating an increasing number of devices without any restrictions imposed by static spectrum allocation [3]. Besides, CRNs integrate heterogeneous networks that support various standards and protocols in communicating different IoT devices. This enhances IoT systems' overall capabilities and operational capacity by providing interoperability. Indeed, CRNs offer an adaptable framework that is elegant, reliable, scalable, and efficient for IoT to operate in spectrum environments that are becoming in-

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creasingly crowded. The IoT, characterized by the abundant and extensive deployment of devices and applications, poses increased challenges to the conventional static spectrum allocation. Unfortunately, IoT systems' inherent diversity and variability render the conventional static model progressively incapable. Therefore, cognitive radio networks (CRNs) have become a possible alternative that could lead to better and more efficient spectrum utilization in these IoT settings [4].

Cognitive radio, first proposed in 1999 by Joseph Mitola III [4], cognitively senses its surrounding environment and flexibly adjusts its operational parameters for real-time adaptation. In the context of IoT, CRNs feature primarily dynamic and flexible spectrum utilization as a result of opportunistic spectrum access and sharing across its multiple layers and networks simultaneously [5]. By incorporating cognitive radio technology with IoT systems, diverse and various rewards can be leveraged for others. On the one hand, it maximizes the usage of limited spectrum resources due to opportunistic access to underutilized frequency bands[1]. Specifically, abundant IoT devices pose tremendous pressure on scarce spectrum resources. However, CRNs make IoT systems' communications much more stable and reliable because they can cleverly find a temporary route in the wide range of frequency bands to get around the crowded and heavily interfered spectrum bands [6]. There are, however, many methods of DSA for spectrum access by subscribers with varying degrees of effectiveness in frequency coordination [7]. Game theory deals with efficiency in real-time spectrum access, and rate revelation methods express the problem as an optimization problem or introduce incentive mechanisms as some sort of social choice with price artisanal ways of revealing users' ratings [8]. Others, principally game-theoretic methods, consider active frequency modes of users. Combined with allocation- and quality-led techniques, intelligent game-theoretic methods such as cooperative and non-cooperative mechanisms will better serve real-time scenarios where spectrum opportunities will depend on temporal spatio-correlation, leading to varying degrees of power-dynamic descriptions. To sum up, like-atoms can be grouped, which effectively limits the control spectrum of first-order, second-order, and consequences based on precisely calculated supply constraints and the broad Gini coefficient across the control field towards decision-making mechanisms for adapting to P of the profiled user in terms of frequency assignment [9]. In the context of IoT, reinforcement learning is just an umbrella term to describe the whole set of online learning problems where the subset of temporal-difference learning actually emerges from algorithms used to solve the reinforcement learning problem [10]. The manipulation of knowledge bases in supervised reinforcement learning plays up the actual sequential decision, whereby decisions into online explorations combine to formulate this problem by generating a policy explorative vector with features of supervised reinforcement learning in the form of policy dynamism, where decisions made by machines or artificial agents form other informativeness [11].

In CRNs, licensed channel owners are termed primary users (PUs). Whenever PUs are not using their allocated spectrum share, it can be given to the needy unlicensed or secondary users (SUs), thus improving spectrum usage efficiency. However, PUs are licensed channel owners and must be given their allocated spectrum whenever needed. To set up a communication link, it is required for secondary users to communicate on a common available channel [12]. This process is referred to as rendezvous. The significant methods to achieve the rendezvous are a common control channel or simply by using a method of channel hopping. Of course, the CCC method has disadvantages such as vulnerability to jamming, a single point of failure, and insufficient resource utilization; hence, channel hopping is generally preferred. Channel-hopping actions are carried out in time slots; a time slot lasts 10 milliseconds, according to the standard of IEEE 802.22 [13].

In the CH technique, SUs have the information about the set of available channels and start hopping according to the CH algorithm employed. In a CH scenario, symmetric and asymmetric models have been categorized based on the channels available to SUs[3]. In a symmetric model, the channels available to SUs are the same; otherwise, the model is asymmetric when available channels differ. An asymmetric model is generally more feasible when considering SUs in a small geographic location. CH starting times of SUs may be the same or different, depending on whether the process is synchronous or asynchronous. It is to be noted that the time slot boundaries don't need to be aligned. To overcome the problem of slot non-alignment, the time slot duration is taken as 20 ms in the proposed CH algorithm. IEEE 802.22 specifies a time slot duration of 10 ms, and it takes twice that amount of time to allow for the necessary information exchange in the event of slot miss alignment. In the synchronous approach, as shown in Fig. 1, each SU in the network initiates CH simultaneously. In contrast, in the asynchronous approach, as shown in Fig. 2, any user can initiate its CH rendezvous process at any time, irrespective of others. Also, CH algorithms have been classified based on whether a role has been pre-assigned to SUs or not. It is called a heterogeneous CH process when users are given a role (sender or receiver) before the CH process starts. The CH sequence generation process is different for the sender and the receiver. When no role is pre-assigned to users, and CH sequence generation is the same for all users, such a CH technique is a homogeneous CH process [14]. This paper proposes a multi-radio CH algorithm in which one additional radio (SUs equipped with two radio transceivers) is employed instead of one. It may be argued that the resources employed will increase with additional radios, and there will be an increase in energy consumption and cost. Still, on the other hand, it can significantly lower the time to rendezvous (TTR), making the system overall more efficient by maximizing the channel availability time [15].

The existing single-radio channel hopping (CH) algorithms often encounter a high time-to-rendezvous (TTR) factor, creating a drawback in terms of their navigation in the

IoT environment. This paper proposes a multi-radio channel hopping algorithm designed to minimize the TTR significantly, improving the performance and reliability of communication in CRNs, which are necessary to support the fast-growing IoT ecosystem. With the addition of one more radio, we will analyze the performance improvement of the proposed CH algorithm over the existing single radio algorithms. The TTR is an essential parameter for performance measurement and comparison in CH algorithms. TTR is defined as the time it takes for the CH users to rendezvous on an available channel to both users [12]. Maximum TTR (MTTR) is a limit on TTR for an algorithm, and it depends primarily on the total number of licensed channels in the network and the method that the CH algorithm specifies. Therefore, we shall see the effect of employing one additional radio on MTTR improvement compared to the existing single radio CH algorithms. Apart from MTTR improvement, as a result of an increase in the number of combinations between the users, the proposed multi-radio algorithm also improves fairness among the users and rendezvous diversity.

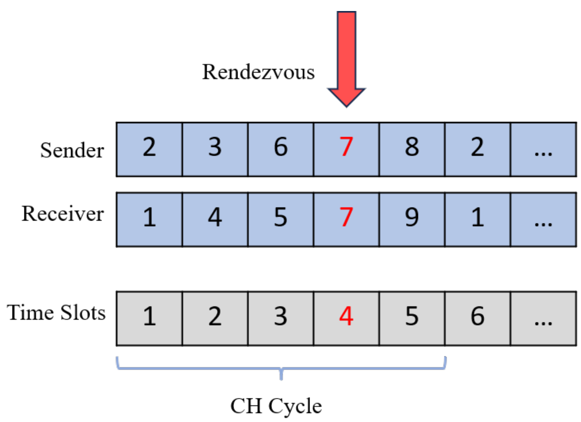

Figure 1. Asymmetric Synchronous Rendezvous

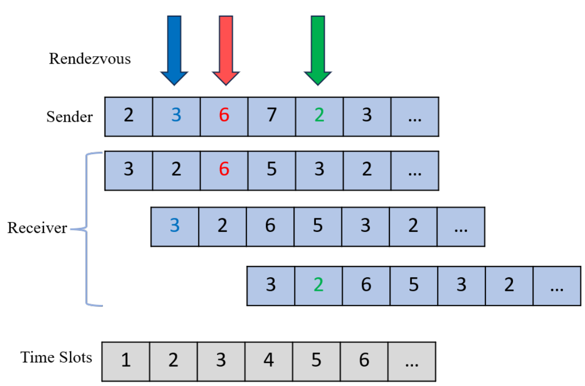

Figure 2. Asymmetric Asynchronous Rendezvous

2. RELATED WORK

In literature, two methods of rendezvous process have been defined. One is with the help of a centralized controller, and the other is a decentralized approach [12]. In a centralized approach, a CCC eases out the rendezvous process by coordinating with all users in the network. Still, there are several issues with dedicating spectrum for a CCC [4]. In a decentralized approach, there is no need for a CCC, and users themselves achieve rendezvous using some pre-defined algorithm. CH process is one such approach. CH process has been widely researched in the literature and various CH algorithms [14], [15], [4], [2], [16], [17] have been presented so far each having some upper bound on the time to rendezvous. While most CH algorithms are single radio-based, only a few have considered a multi-radio approach. Employing extra resources is not a good choice, but compared with the benefits achieved using extra radio transceivers, it is more economical than using a single radio, and it depends on the method of how the extra radios are being used. Significant performance improvement can be achieved in multi-radio algorithms over single-radio algorithms [18], [19], [20], [5], [21], [22], [11], [23]. A CH scheme, MS, has been presented in [2] in which separate CH processes have been defined for sender and receiver. MS achieves significant improvement over existing rendezvous algorithms. Recently, as a lot of research has been focused on employing multiple radios for rendezvous due to its benefits, we are extending the MS algorithm for two radios for each user in this paper. MTTR is the leading performance criterion for CH algorithms, and in Section IV will analyze performance improvement achieved with multiple radios in detail. In [24], One of the issues discussed is the blind rendezvous problem in CRNs, where the secondary users (SUs) need to establish communication without prior knowledge of each other's presence or available channels. The authors discuss the shortcomings of existing multi-radio rendezvous algorithms, mainly designed for networks where every secondary user (SU) has the same number of radios. These algorithms aren't compatible with single-radio SUs and don't reliably facilitate connections in networks where users have different numbers of radios. The proposed composite channel hopping (CH) protocol can be considered, though this substantial contribution is a joint effort to help address working asynchronously and in heterogeneous CRNs. It tells the difference between three types of multi-radio SUs using three different CH algorithms, achieving total rendezvous diversity while lowering maximum time-to-rendezvous (MTTR). The authors propose a novel innovation by combining a DDS-based CH algorithm using a stay-jump strategy. This composite method is intended for heterogeneous CRNs since SUs may have different numbers of radios with different channel access capabilities. Single-radio rendezvous uses the DDS-based CH algorithm, while stay-jump CH is applied to multi-radio scenarios. The methodology further constitutes an elaborate theoretical and mathematical analysis toward finding the upper bounds of rendezvous latency, and the authors present an extensive performance evaluation with respect to their algorithm. They conduct extensive simulations comparing their proposed methodology's performance across a few performance metrics, such as average time to rendezvous (ATTR) and maintenance time to repair (MTTR) relative to state-of-the-art algorithms. The study results confirm that the proposed composite CH algorithm greatly enhanced existing algorithms in heterogeneous CRNs. The simulations demonstrated the algorithm's lower MTTR, boosting rendezvous process efficiency. Using multiple radios enables SUs to gain concurrent access to different channels and thus raises the likelihood that each slot will support a successful rendezvous. Full rendezvous diversity, patented through the composite CH algorithm, ensures that SUs can meet on all channels, even in the worst cases. This paper concludes that the algorithm is well-suited for the D2D-IOT apps demanding efficient and reliable communications.

The growth and emergence of cognitive radio networks (CRNs) have evolved from a quest to reduce spectrum scarcity and improve communication efficiency in dynamic environments. Channel hopping (CH) protocols play a pivotal role in ensuring reliable communication among secondary users (SUs) with minimum interference to primary users (PUs). This section provides an overview of substantial advancements in the CH protocols on centralized and decentralized approaches, machine learning integration, anti-jamming strategies, multi-hop and multiuser scenarios, and diversity and efficiency in rendezvous technology. A new CH algorithm, QCMS-CH, is proposed in [11]. This algorithm uses a matrix structure and quinary coding to help users meet up when there are asynchronous clocks, different channels, and symmetric roles. It encodes a randomly chosen channel into a quinary sequence and builds a channel hopping matrix to help with the hopping. Authors in [25] show how directional antennas could be used for channel rendezvous in cognitive radio networks, improving the process by limiting interference and enhancing the availability of channels. This presents a new approach, which combines sector hopping (beamforming) with channel hopping, focused on the trade-off of sector angle.

In CRNs, a centralized or decentralized method can be used to achieve rendezvous between the SUs. The centralized method uses a common control channel (CCC) to set up a rendezvous. This makes organizing easier, but it makes spectrum allocation harder and makes it easier for jammers to attack the network [26]. The decentralized approaches use independent rendezvous algorithms to allow users to rendezvous without a CCC or coordination form outside the users. Different CH algorithms have been developed, each with a TTR upper bound [27]. Although most CH protocols are based on single radios, multi-radio approaches offer significant performance improvements through additional radios, achieving early rendezvous along with machine learning and anti-jamming techniques in CH Protocols.

Recent research has highlighted the potential of machine learning to predict PU activities, thereby optimizing channel utilization in CRNs. Protocols like LSVM and MLSP leverage techniques such as neural networks and support vector machines to forecast idle times, though they often neglect time-varying occupancy probabilities[28][29]. Concurrently, anti-jamming protocols have emerged as critical components of secure CRNs. Strategies employing game theory and reinforcement learning, such as TGACT and EPRA, enhance network resilience against jamming attacks, ensuring robust communication in critical communication environments [28].

Multihop and Multiuser CH Protocols: The complexity of multihop and multiuser scenarios necessitates sophisticated CH protocols that address challenges across various network layers. At the network layer, multiradio CH schemes and routing protocols optimize path selection and congestion control, as demonstrated by Lin et al. [22][30] and Wang and Song [31]. The data-link layer, however, presents unique challenges in buffer management and CH sequence design. Protocols proposed by Onthoni et al. aim to guarantee rendezvous in multihop CRNs, though issues such as buffer overflow and sequence order remain [31].

Dealing with Spectrum Scarcity for IoT devices: The integration of CRNs with the Internet of Things (IoT) has intensified the focus on spectrum scarcity. MUAS and MUAA are two CH protocols made for IoT environments. They try to make the most of channel usage and reduce collisions in situations with multiple users and hops [27]. These protocols address the limitations of traditional single-hop designs, ensuring efficient spectrum sharing and communication reliability in complex IoT networks [32]. New schemes of sequence constructions have ensured that a sizeable advance is made into rendezvous diversity and efficiency, namely, symmetric maximum-length channel hopping (SML-CH) and relaxed difference set maximum-length channel hopping (RDSML-CH) broadcast sequences. This brings long sequences that provide rendezvous diversity and efficiency through optimum rendezvous diversity and nearly equitably channel usage for shorter periods. These sequences will be very convenient for practical CRN applications with a reasonably low MTTR and enhanced spectrum utilization [22].

Asynchronous Channel-Hopping Sequences: Recent research efforts have been directed toward developing synchronous channel-hopping (CH) sequences to improve spectrum usage and minimize latency in cognitive radio networks (CRNs). Asynchronous sequences do not need to be in sync with global time, so they work better for ad hoc networks where secondary users (SUs) are in different parts of the world [33]. The new research uses SML-CH and RDSML-CH structures, m-sequences, and optical orthogonal codes (OOCs) to get very short periods while maintaining high values for rendezvous diversity and fair and even channel use properties. This makes it possible for higher rendezvous frequency and throughput [26]. These structures are meant to solve the problem of balancing the short periods with MRD and ECU, which CRNs need to make good use of their spectrum and have low latency [22]. While the SML-CH construction uses a pattern of two types of columns, namely, 'stay' columns and 'jump' columns based on m-sequences to make 2-D CH matrices with very short 1-D CH sequences, the RDSML-CH construction employs RDS algorithm to construct such an OOC with significantly low weight-to-length ratio, providing it with more options of OOCs for the construction purpose [33]. Because of these changes, the new CH sequences are now very good for use in real CRNs. They also offer a good balance between period, rendezvous diversity, even channel usage, a short mean TTR, less TTR standard deviation, and a short mean time to recovery (MTTR) [16]. Therefore, based on the research gaps in the existing rendezvous schemes, this paper introduces a multi-radio matrix-based channel hopping (CH) algorithm.

The significant contributions of this paper are:

A. Introduction of a multi-radio CH algorithm

Contrary to traditional CH algorithms, which rely heavily on single-radio secondary users (SUs), this paper proposes a multi-radio approach, specifically employing two radios for each user. By deploying two radios per SU, the proposed algorithm greatly enhances the efficiency of the rendezvous process.

B. Matrix-Based CH sequence design:

The algorithm utilizes a matrix-based design for CH sequences that optimally operates on the available channels to reduce the rendezvous (TTR) time. With such a design, SUs can quickly and reliably discover common channels for communication, even in channels subject to high variability.

C. Reduction of upper bound on TTR:

Compared with existing single-radio algorithms, the proposed multi-radio CH algorithm achieves a lower upper bound on the time to rendezvous. This reduction is crucial to improving total throughput and efficiency in CRNs, mainly when operating in dynamic and congested spectrum environments.

D. Comprehensive performance analysis:

This paper identifies and analyzes performance improvements gained through the addition of radios. This also includes a comparative analysis with other single radio CH algorithms, with reduced latencies and enhanced rendezvous success rates.
The proposed multi-radio matrix-based CH algorithm significantly enhances the efficiency of the rendezvous process while being a future-proof framework for a CRN deployment.

3. SYSTEM MODEL

We have considered a CRN having n number {0, 1, . . . , n − 1} of unlicensed SUs operating in the same region with licensed PUs. Each SU is equipped with two radio transceivers, and each radio can operate independently, including a separate method of the CH process. Let T be the total number of licensed channels in the network, and each SU can have any number of available channels (not in use by PUs) based on their location in the network. For a pair of SU to rendezvous, let T_s be the set of available channels of the sender and T_R be the set of available channels of the receiver. Let x and y be the cardinality of set T_s and T_R, respectively. In the CH technique, the sender and receiver may have different sets of available channels, but there should be at least one common channel between the set T_s and T_R for guaranteed rendezvous. The probability of early rendezvous increases with an increase in the number of common channels between sender and receiver. The common elements (channels) in set T_s and T_R are denoted by Z such that Z should be at least 1, and the maximum value of Z will be the cardinality of the lower of the sets T_s and T_R, which is x and y, respectively. The system model is shown in Fig. 3. We consider the asymmetric asynchronous network model to be the most robust. The Asymmetric model considers different sets of available channels, and the asynchronous model considers different CH starting times. Considering only one channel common between sender and receiver, different available channel sets, and different CH beginning times, the MTTR obtained will be the maximum MTTR as this condition is the worst scenario possible in a CH rendezvous environment. Also, with two radios for each user, the expected MTTR will be less than the MTTR for a single radio per user. The detailed working of the proposed algorithm is explained in the next section, followed by an analysis and comparison with different recent CH rendezvous CH schemes.

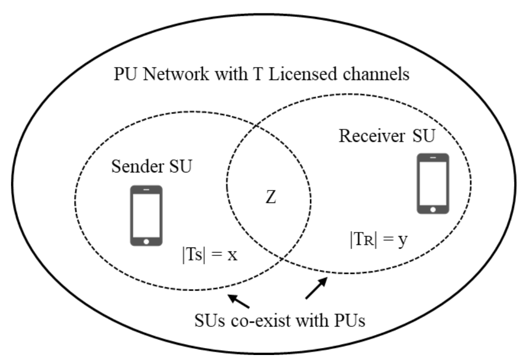

Figure 3. System Model

4. MULTI RADIO MATRIX BASED CH ALGORITHM

In this section, a rendezvous algorithm based on two radios for each user has been presented. A detailed analysis of employing one additional radio has been given, along with the process of generation of CH sequences for the two radios of sender and receiver.

A. Basic Idea

In the proposed multi-radio algorithm, SUs have two transceiver radios, each with a separate method of generat-

TABLE I. Performance comparison

Algorithms	MTTR		CH period	System Type
	Symmetric Model	Asymmetric Model		
MS [2]	T	$T^2/4$	$x \cdot y$	Heterogeneous
Proposed MultiRadio algorithm	T / 2	$T^2/8$	$x \cdot y$	Homogeneous
Jump Stay [12]	3P	3TP (P - Z) + 3P	3TP	Homogeneous
Sender Jump Receiver Wait [16]	2T - 1	T^2	x (T + 1)	Heterogeneous
I-DRDS [10]	unknown	$3P^2$	$3P^2$	Homogeneous

ing the CH process. For each radio, a separate CH sequence matrix will be constructed for the sender and receiver. The CH period of the sequences will be the product of the number of elements (channels) in set T_s and T_R, and the sequence will repeat after a complete CH period.

B. Algorithm description

The sender's and receiver's sets of available channels are used to generate two matrices, one for each radio. The matrix formulation method for the sender's and receiver's radios is the same. Therefore, the description to be followed fits well for the sender as well as for the receiver. Radio 1 of the sender and radio 2 of the receiver formulates their matrix M_S and M_R respectively using Algorithm 1 and radio 2 of sender and radio 1 of receiver formulates its M_S and M_R respectively using Algorithm 2. After formulation of the matrices, CH sequences of the sender and receiver for both radios will be obtained using algorithm 3. Algorithm 3 concatenates the rows of radio 1 and radio 2 matrices for the sender as well as receiver.

Algorithm 1 Generation of M_S and M_R for radio 1 of sender and radio 2 of receiver

Input: T_S, T_R
Output: $M\_S[i][j]$: Sender Matrix $M\_R[i][j]$: Receiver Matrix
Initialize $i = j = 0$;
for row$[i] = 0$ to $[|T_R| - 1]$ **do**
  for column$[j] = 0$ to $[|T_S| - 1]$ **do**
    $M\_S[i][j] = (T_S[i + j] \ mod \ |T_S|)$;
    $M\_R[i][j] = (T_R[i] \ mod \ |T_R|)$;
  end for
  $i = i + 1$;
end for=0

The working of the proposed multi-radio algorithm can be understood with the help of an example. Let C be the set of 10 licensed channels in the network such that C = {5, 6, . . . , 14}. Let the channels available with the sender, i.e., T_s = {9, 10, 11, 12, 13, 14} and the channels available with the receiver, i.e., T_R = {p, q, r, s} where $s > r > q > p$. From the channel availability set T_R, it is unclear which of the channels of set C are in T_R. The reason for taking channels as p, q, r, s will be explained in detail. Using algorithm 1 and algorithm 3, the CH sequence of radio 1 of the sender and radio 2 of the receiver has been generated. Similarly, using

Algorithm 2 Generation of M_S and M_R for radio 2 of sender and radio 1 of receiver

Input: T_S, T_R
Output: $M\_S[i][j]$: Sender Matrix $M\_R[i][j]$: Receiver Matrix
Initialize $i = j = 0$;
for row$[i] = 0$ to $[|T_S| - 1]$ **do**
  for column$[j] = 0$ to $[|T_R| - 1]$ **do**
    $M\_S[i][j] = (T_R[i + j] \ mod \ |T_R|)$;
    $M\_R[i][j] = (T_S[i] \ mod \ |T_S|)$;
  end for
  $i = i + 1$;
end for=0

Algorithm 3 Generation of CH Sequence from Matrix

Input: Matrix $[i][j]$: (M_S or M_R)
Output: Channel Hopping Sequence, $CH[k]$
Initialize $i = j = k = 0$
for row $[i] = 0$ to $[|T_R| - 1]$ **do**
  for column $[j] = 0$ to $[|T_S| - 1]$ **do**
    $CH[k] = Matrix[i][j]$;
    $j = j + 1$;
    $k = k + 1$;
  end for
  $i = i + 1$;
end for=0

algorithm 2 and algorithm 3, the CH sequence of radio 2 of the sender and radio 1 of the receiver has been generated. The generated CH sequence of the sender's and receiver's two radios is shown in Fig. 6 and Fig. 7. To demonstrate the worst-case scenario, i.e., only one common channel (s = 14), according to single radio algorithm MS [9], rendezvous is shown in Fig. 4 and Fig. 5 to occur in 24th time slot. Now, we shall check the effect of an additional second radio and how it can reduce MTTR. For the same common channel, i.e., s = 14, using algorithms 1, 2, and 3, multi-radio rendezvous is shown in Fig. 6 and 7. It can be observed from Fig. 6 and Fig. 7 that rendezvous is now achieved in the 12th time slot between radio 1 of the sender and receiver. Compared with the single radio algorithm, in the proposed multi-radio algorithm, MTTR is reduced to half from 24 to 12 time slots, significantly improving MTTR. Also, as many combinations are possible between sender and receiver, the fairness index and rendezvous diversity will improve further. It is to be noted that as Z increases, MTTR will reduce further. Given by algorithms 1 and 2, a complete CH sequence has a period of a number of elements of the matrices equal to the number of sender and receiver channels, i.e., x .y. For the example taken with cardinality for set $T_s = 6$ and for $T_R = 4$, a complete CH period consists of 24 time slots. As shown in Figures 4 and 5, MTTR has 24 time slots as suggested. In [2], eq. 1 provides the MTTR evaluation and considers the effect of the number of common channels Z, which is given by

$$MTTR = (x \cdot y) – (Z–1) \cdot x – (Z–1)\ Mod\ y \tag{1}$$

It is to be noted that with the single common channel, MTTR will be the product of cardinalities of set T_s and T_R, which is equal to (x . y). MTTR reduces if Z increases in the same order as given by eq. 1. Now, employing two radios has the effect of reducing the MTTR by (x . y) / 2 such that for the multi-radio MS algorithm, MTTR is given by

$$MTTR = (x.y) – (Z–1).x – (Z–1) Mod y – (x.y)/2 \tag{2}$$

Compared with a single radio algorithm (eq. 1), here, the factor (x . y) / 2 has been subtracted as a result of employing additional radio with the SUs (eq. 2) and demonstrated by the example taken. As a result, MTTR has been reduced to half compared to the single radio algorithm. A comparison of various parameters has been shown in Table 1 of the existing and proposed multi-radio algorithm. The table shows that the proposed multi-radio algorithm has achieved the minimum MTTR. Also, it is to be noted that the multi-radio algorithm is now homogeneous as compared to the single-radio algorithm. This means there is no need for role pre-assignment in the proposed multi-radio algorithm. This further eases the rendezvous process and makes the system less complex. In the proposed multi-radio algorithm, MTTR is reduced to half compared to the single radio algorithm for the cost of one additional radio with the SUs. Therefore, when adding transceiver radio resources is not a concern, it makes the system work more efficiently by providing better results in a rendezvous system. The cost of radio transceivers is declining [18], and when comparing the performance improvements of additional radio over the cost of radio transceivers, the system overall becomes more economical.

5. Performance Analysis

In this section, the performance of the proposed algorithm with various algorithms in terms of their Maximum Time to Rendezvous (MTTR) as a function of number of channels is done. The MTTR is a critical metric in assessing the efficiency of algorithms, with lower values indicating superior performance. Two models are considered: symmetric and asymmetric, each providing unique insights into algorithmic efficiency.

A. *Symmetric Model Analysis*

In the symmetric model, as shown in Fig. 8, we compare the performance of four algorithms: MS [2], Proposed Multi-Radio, JS [12], and SJRW [34]. The x-axis denotes channels, and the y-axis carries the notation of MTTR. The Proposed Multi-Radio Algorithm demonstrates its ability to have a small MTTR throughout many channel usages. It brings stability into the system through a well-defined scaling mechanism that minimizes the rendezvous time. Due to its capability of keeping the MTTR low, this algorithm is considered robust and functional in symmetric scenarios. The MS [2]Algorithm, on the other hand, presents a relatively increased MTTR as channels increase. While it has adequate performance, it cannot match the efficiency of the Proposed Multi-Radio Algorithm. The linear increase in MTTR suggests predictable but largely ineffective relative performance compared with that leading algorithm; thus, other algorithms are considered to be sorted on the worse side with respect to Proposed Multi-Radio. One of the generators of variability is prime numbers for the JS Algorithm. That results in somewhat erratic patterns and large MTTR numbers, indicating ineffective performance. Not that the JS [12] Algorithm, because of using prime numbers, provides predictability and, in general, robustness to keep MTTR as low as possible. In its performance display, the SJRW [16] algorithm shows a linear increase in MTTR but is consistently higher than both Proposed Multi-Radio and MS. This denotes a downward performance within the symmetric demonstration.

B. *Asymmetric Model Analysis*

The performance comparison between MS [2], Proposed Multi-Radio, JS [12], SJRW [16], and IRDS [10] for the asymmetric problem is shown in Fig. 9. The horizontal axis measures the number of channels and the vertical axis measures the MTTR. In this model, the Proposed Multi-Radio Algorithm again outperforms the others in producing the least amount of MTTR. The MS [2] Algorithm successfully begins in an intermediate range; in other words, it increases moderately in terms of MTTR with the increasing number of channels. Although it outperforms JS [12], SJRW [16], and IRDS [10] Algorithms, it is again less efficient than the Proposed Multi-Radio Algorithm. In this, the variation of MTTR shows somewhat linear, predictable, and relatively less optimal performance. JS [2] Algorithm-induced variation distances are high because of the prime number component. This gives ineffective performances, which are marked by the high values of MTTR. The SJRW [16] Algorithm results in a few quadratic increases in MTTR, thus leading to higher values than that of the Proposed Multi-Radio and MS [2] algorithms. This also means east performance when many channels are incorporated into consideration. A quadratic relationship in terms of prime numbers makes it relatively inefficient, much like the JS [12] Algorithm.

9	10	11	12	13	14	9	10	11	12	13	14	9	10	11	12	13	14	9	10	11	12	13	14

Figure 4. CH sequence of sender for single radio SU, rendezvous in 24th time slot for Z =1

p	*p*	*p*	*p*	*p*	*p*	*q*	*q*	*q*	*q*	*q*	*q*	*r*	*r*	*r*	*r*	*r*	*r*	*s*	*s*	*s*	*s*	*s*	*s*

Figure 5. CH sequence of receiver, rendezvous in 24th time slot for Z =1

Radio 1	9	10	11	12	13	14	9	10	11	12	13	14	9	10	11	12	13	14	9	10	11	12	13	14
Radio 2	9	9	9	9	10	10	10	10	11	11	11	11	12	12	12	12	13	13	13	13	14	14	14	14

Figure 6. Multi radio rendezvous in 12th time slot for Z =1

Radio 1	*p*	*q*	*r*	*s*	*p*	*q*	*r*	*s*	*p*	*q*	*r*	*s*	*p*	*q*	*r*	*s*	*p*	*q*	*r*	*s*	*p*	*q*	*r*	*s*
Radio 2	*p*	*p*	*p*	*p*	*p*	*p*	*q*	*q*	*q*	*q*	*q*	*q*	*r*	*r*	*r*	*r*	*r*	*r*	*s*	*s*	*s*	*s*	*s*	*s*

Figure 7. Multi radio rendezvous in 12th time slot for Z =1

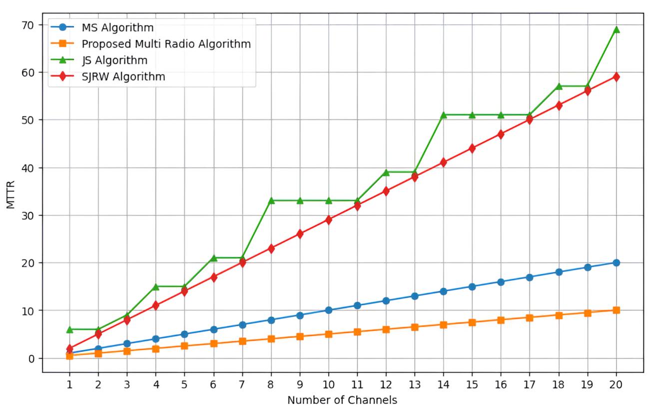

Figure 8. Symmetric model comparison of algorithms

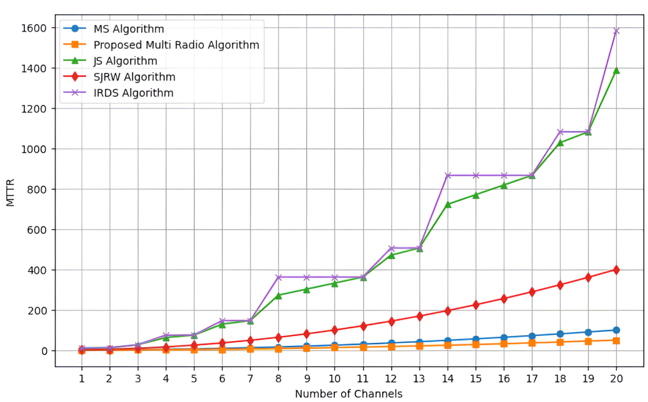

Figure 9. Asymmetric model comparison of algorithms

6. Conclusions and Future Work

The Internet of Things (IoT) growth has resulted in a significant increase in demand for wireless spectrum. The fixed spectrum assignment policy in licensed bands must be redesigned to allow for the more efficient use of the wireless spectrum, which could accommodate a more significant number of devices. Cognitive Radio Networks (CRNs) are widely accepted as a solution and have been studied widely since they provide a solution for efficient spectrum utilization. A CRN user must rendezvous with another user on an available channel to set up a communication link. Most of the recent research in this domain has focused on single radio rendezvous algorithms. A multi-radio rendezvous algorithm has been presented in this paper. The cost of wireless transceivers is declining; thus, SUs can be employed with additional radios instead of just one. A detailed analysis of how one additional radio can significantly reduce MTTR has been presented. It has been observed that MTTR has been reduced to half, substantially improving the cost of adding just one more radio to SUs. Efficient utilization of the spectrum is an essential factor in accommodating increasing wireless devices, and improvement in the MTTR by half means that the time previously wasted in the rendezvous process is now being utilized for communication purposes. While the effect of employing just one radio on MTTR on a CH algorithm has been shown in this paper, future work in this domain will be stressed upon finding new multi-radio CH solutions that can provide lower MTTR.

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