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ASAA: Multi-Hop and Multi-User Channel Hopping Protocols for Cognitive Radio Enabled Internet of Things

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***Abstract*—The devices of Internet of Things (IoT) are integrated and interconnected by using the traditional wireless communication technology. Unavailability of spectrum sharing occurs in traditional wireless communication due to the presence of a massive number of IoT devices. Thus, Cognitive Radio Network (CRN) is introduced as a promising technology to utilize the spectrum efficiently. Channel Hopping Sequence (CHS) is used to establish communication among CRN users. However, the majority of CHS mechanisms only focus on multi-user single-hop scenarios, which can lead to bottleneck and throughput degradation problems. It is also found that few existing CHS mechanisms still have a low percentage of rendezvous that can cause difficulties for the Secondary Users (SUs) to communicate. Thus, it is a challenge to design efficient CHS for establishing fast communication among SUs under multi-user, multi-hop scenarios and asymmetric asynchronous environments. In this paper, Asymmetric Synchronous and Asymmetric Asynchronous (ASAA) Channel Hopping (CH) algorithms are designed for the multi-user CRN-enabled IoT devices to share the unused spectrum in the multi-hop scenario. The Multi-User Asymmetric Synchronous (MUAS) and Multi-User Asymmetric Asynchronous (MUAA) protocols are designed in the proposed ASAA channel hopping mechanism. The simulation results show that the proposed ASAA CHS algorithms outperform the existing CHS mechanisms in terms of throughput, Channel Loading (CL), Channel Utilization (CU), Maximum Time To Rendezvous (MTTR), Average Time to Rendezvous (ATTR) and Maximum Inter Rendezvous Interval (MIRI).**

***Index Terms*—Internet of Things, Cognitive Radio Networks, Channel Hopping, Multi-User, Multi-Hop, Asymmetric, Synchronous, Asynchronous**

I. Introduction

Internet of Things (IoT) generally refers to the devices connected through the internet and have communication and computational abilities to generate and exchange data among applications. These IoT devices are heterogeneous [1] and interconnected, and therefore can be integrated and implemented in various sectors such as smart healthcare [2], smart transportation [3], smart industry [4], etc. For instance, in smart transportation several traffic sensors are installed and connected wirelessly to control and monitor the traffic. CISCO [5] has predicted that data generated by IoT devices can be increased exponentially up to 49 Exabytes by 2021. With the rapid growth of IoT users and devices, the high demand for spectrum availability is inevitable. Conversely, spectrum resources are limited and precious as natural resources. Moreover, if no action is taken to utilize the wireless spectrum wisely, the spectrum scarcity problem [6] will be a global issue.

Cognitive Radio Network (CRN) has been introduced as a solution for the spectrum scarcity problem by enabling dynamic spectrum allocation. The main goal of CRN is to maximize the utilization of under-utilized licensed spectrum. CRN has the ability to sense and share the unused licensed spectrum. In CRN, the unlicensed Secondary Users (SUs) can sense and use the licensed spectrum in absence of the licensed Primary Users (PUs). Hence, spectrum utilization and spectrum scarcity can be improved by using cognitive radios. Thus, IoT devices need to be CRN-enabled to sense and utilize the unused spectrum in any emergency situation. Broadly speaking, the emergence of CRN-IoT has advanced traditional wireless communication technology. Normally, the available spectrum resources below 6GHz is allocated to various traditional wireless communication technologies such as Wireless LAN (WLAN), Wireless Sensor Networks (WSNs), Wireless Personal Area Networks (WPANs), Low Power Wide Area Network (LPWAN) such as LoRa, SigFox, and cellular networks [7]. In fact, the allocated spectrum is overcrowded and even under-utilized [8]. Thus, it is important to utilize and allocate the spectrum efficiently.

Traditional wireless communication does not allow the licensed spectrum to be shared among IoT devices. Therefore, the merging of CRN and IoT is an important research area. For instance, by applying CRN in future 5G mobile networks [7], the spectrum can be utilized wisely without any overcrowding. Moreover, it is difficult or even impossible to allocate bandwidth with numerous IoT devices. The increased number of licensed users may cause trouble for unlicensed users. By facilitating the unlicensed users, CRN can enable the licensed spectrum to be shared with the unlicensed users without causing any interference among the licensed users. Furthermore, in case of short-range traditional wireless communication such as WLAN, Bluetooth, ZigBee, and WSNs and even long-range wireless communication such as Cellular

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Networks, CRN can be used to satisfy user's demands in terms of flexibility and mobility. Communication establishment in CRN can be established through the process of Rendezvous in which any pair of SUs meets at the same channel concurrently. Negotiation and data transmission are carried out after the rendezvous has occurred.

The rendezvous process can be achieved by performing the Common Control Channel (CCC) or Channel Hopping (CH) approach. In the CCC approach, SU needs to switch to the control channel in order to negotiate with other SUs. However, considering multi-channel, multi-user, and multi-hop scenarios, collision and control channel bottleneck are unavoidable in CCC approach. On the other hand, in the CH approach, SUs need to execute the Channel Hopping Sequence (CHS) mechanism to hop and establish communication. Several proposed CHS protocols have been designed for the single-hop taking the symmetric-synchronous as their CHS environments. In multi-user scenarios, authors have proposed three types of CHS for three different environments; for symmetric asynchronous, asymmetric synchronous, and ARCH asymmetric asynchronous [9]. Moreover, the authors have designed the CHS [10] to achieve and guarantee lower bounds of MTTR [11] considering the asymmetric-synchronous environment. In contrast, authors have designed CHS for fully distributed broadcast protocol in asymmetric and asynchronous environments [12] in multi-hop scenarios.

The authors in [13], [14] have designed CHS protocols for single radio and multi radio to achieve better performance of MTTR for asynchronous and asymmetric environments, respectively. Although the designed CHS can obtain better performance, the existing CHS protocols are mostly only limited to multi-user single-hop scenarios where any pair of SUs can rendezvous and exchange the data. However, considering the IoT environment, multi-hop scenarios mostly occur where generated CHS for multi-user cannot cope up with the scenario. For instance, any SU can be paired with more than one SU which can lead to bottleneck, collision, and throughput degradation problems. It also analyzed that the under-utilized channel problem is still inevitable although the multi-hop scenario is taken into account. Thus, it is required to design CHS which can work efficiently with complete scenarios and environments to tackle the multi-user multi-hop problem. Therefore, a complete multi-user and multi-hop scenario is considered in this paper to design the CHS protocols for the Asymmetric Synchronous and Asymmetric Asynchronous (ASAA) environments to share the spectrum among the cognitive radio-enabled IoT devices. Most importantly, CRN-IoT has become the main concern in our work. Throughout the paper, the network used for the spectrum sharing among the cognitive radio-enabled IoT devices is referred to as the CRN.

Nowadays, wireless communication is much preferable over wired communications in IoT. Consequently, it can lead to an increasing need for spectrum resources. Due to the diversity of IoT applications, spectrum resources have been allocated for specific applications or services. As a result, most of the spectrum is pre-assigned according to the usage such as for licensed and unlicensed users. On the other hand, numerous technologies and data traffic of IoT devices have tremendously grown. This massive growth has occurred due to the insatiable demand from IoT users. For instance, people cannot access their associated licensed spectrum in an emergency situation and therefore additional availability of spectrum is required. Due to limited and precious resources, creating a new spectrum is costly and requires a massive time scale. Therefore, the spectrum scarcity problem would be unavoidable in near future.

CRN has been introduced to solve the spectrum scarcity problem. However, designing the Channel Hopping Sequence (CHS) to establish communication among CRN users is a challenge considering the multi-user multi-hop scenarios. Under multi-user scenarios, CHS can be executed by a few SUs. It is possible that all SUs may meet in the same channel at the same time slot and therefore, the overcrowding problem cannot be avoided. In multi-hop scenarios, collision and interference can most likely occur and eventually degrade the data transmission's throughput. In multi-user multi-hop scenarios, performance degradation may occur in terms of channel loading, throughput, and channel utilization. Hence, it is highly crucial to design an efficient CHS that can accelerate communication and can achieve better performance in terms of channel loading, throughput, channel utilization, TTR, MTTR and ATTR.

The objective of this study is to design CHS protocols that can perform on Asymmetric Synchronous and Asynchronous scenarios considering multi-user and multi-hop environments. Accordingly, Multi-User Asymmetric Synchronous (MUAS) and Multi-User Asymmetric Asynchronous (MUAA) protocols are designed that can work in complex scenarios. Our proposed CHS protocols can guarantee the rendezvous between any pair of users in every time slot of the generated CHS cycle. Though role-based CHS is applied for the multi-hop multi-user CHS in most of the existing works, the generated CHS is common for any SUs in our proposed work. Hence, no assignment of the sender-receiver role is required in our proposed protocols. Besides, our protocol can work for any number of available channels.

Based on our motivations, the main contributions of this paper can be summarized as follows:

- *Multi-User Asymmetric Synchronous (MUAS) and Multi-User Asymmetric Asynchronous (MUAA) protocols are designed considering any number of available channels.*
- *Channel Loading in MUAS and MUAA is very low as compared to other related works, which is* $(\frac{2}{|CHS|})100\%$*, where* $|CHS|$ *is the total number of generated Channel Hopping Sequences.*
- *Our proposed MUAS and MUAA protocols can work efficiently with a high percentage of channel utilization.*
- *Our proposed protocols can achieve a smaller value of MTTR. MUAS achieves* $< |N| - 3$*, and MUAA achieves* $< 3(|N| + 1)$ *and* $2(|N| + 2)$ *for even and odd number of available channels* $|N|$*.*

The rest of the paper is organized as follows. Related work is given in Section II. The system model and problem formulation are described in Section III. The proposed ASAA Channel

Hopping algorithms, MUAS and MUAA are elucidated in Section IV and V, respectively. Performance evaluation of the protocols is presented in Section VI and concluding remarks are made in Section VII.

II. Related Work

Recently, research on Channel Hopping (CH) for Cognitive Radio Networks (CRNs) has gained a lot of attention, notably, in solving the spectrum scarcity problem in Internet of Things (IoT). Considering the single-hop scenario, it is found that the authors [6] have discussed the importance of designing Channel Hopping Sequence (CHS) in solving the spectrum scarcity problem in IoT environments. The authors have designed algorithms to achieve the MTTR lower bound [11]. Similarly, authors have proposed CHS protocol for rendezvous guarantee and fair rendezvous by adopting the Hadamard matrix and hash function, respectively [15]. Minimizing the variance of pairwise rendezvous is also proven in this work [15]. Further, for any number of available channels, the authors have designed CHS for better performance in terms of the degree of rendezvous and MTTR for any pair [16]. In the same way, authors have proposed one symmetric-synchronous CHS out of three designed CHS algorithms using primitive root [14].

Using quorum and latin square, QLCH protocol has been designed by the authors [17]. On the other hand, considering symmetric-asynchronous, sequence and modular clock-based methods have been used to design the CHS and provide bounds of TTR [18]. Authors in [19] have designed two CHS protocols with role pre-assignment such as sender and receiver, and non-ID and unique ID [20]. Taking multi-user scenarios into consideration, the authors have proposed an asynchronous CH scheme called ARCH (Asynchronous Rendezvous Channel Hopping) [9]. In this work, two types of CHS are designed; alternative CHS for the sender and default CHS for a receiver. Although, the MTTR in this work is $2(|N|-1)$, and channel loading is $\frac{1}{|N|}$, it is also found that the percentage of channel utilization is low by considering the degree of rendezvous = $|N|$ and $|N|^2$ total time slots, $(\frac{|N|}{|N|^2}) \times 100\%$. It is also found that most of the existing CHS mechanisms are designed for the single-hop scenario, where channels are still under-utilized. Therefore, ASAA CHS protocol has been designed in this work to achieve maximal utilization of channels by considering multi-user and multi-hop scenarios. Concurrently, the proposed CHS protocol can reduce the collision by providing the high value of throughput and channel utilization compared to other works.

Furthermore, multi-user multi-hop scenarios have been considered in few works in designing CHS protocol. The authors have proposed BRACER [12] for multi-hop broadcast protocol. Two algorithms are designed for two roles; sender and receiver. In this work, collision avoidance can be achieved. Besides, all works are limited only to the symmetric environment [21], [22]. On the other hand, asymmetric asynchronous has been considered in these works [23]–[25]. By considering role pre-assignment, the authors [23], [24] have designed Sender-Jump and Receiver-Wait (SJ-RW) CHS. In this protocol, the value of MTTR and ATTR can be obtained such as $MTTR = (2M-1)D$ and $ATTR < \frac{M^2 D}{2}$, where M refers to number of available channels, D is the maximum total number of hops and the maximum total number of hop can be calculated by $D = m-1$, where m is the total number of SUs. In a similar way, Jump and Stay (JS) CHS is designed by the authors [25] and consists of two patterns such as Jump and Stay. In the Jump pattern, each SU jumps from one channel to another channel following their CHS, whereas, the stay pattern will be applied only for negotiation purposes. Although, JS can guarantee the rendezvous under an asymmetric asynchronous environment, the MTTR value is high, $MTTR = (3MP(P-G)+3P)D$ where, M is the total number of available channels, P is the smallest prime number, which is $> M$ and G refers to as the numbers of common available channels between two SUs.

Adjustable Multi-radios Channel Hopping (AMCH) generation protocol is proposed in [26] considering the multi-radio concept in which the proposed CHS can guarantee the rendezvous for any pair of SUs. Though rendezvous problem can be fixed in AMCH, the $MTTR = |S_i| \times |S_j|$ slots is still high, where $|S_i|$ and $|S_j|$ are the total number of slots of CHS of SU i and j, respectively. Similarly, Load Aware Anti-jamming (LAA) scheme CHS protocol is designed in [27] to guarantee the rendezvous under jamming attack. It has been reported that the LAA protocol has achieved less number of ATTR when the total number of common available channels is increased. However, the ATTR value is not reduced significantly in bottleneck topology when the number of common available channels is > 4. Besides, the probability of rendezvous in the LAA scheme is reduced when the total number of common channels is increased. Relay node with different number of buffer size concept in two-hop CRN scenario is studied in [28] by designing two-hop rendezvous model in which the MTTR with relay $MTTR_r = \frac{2N^3+3N^2-2N+1}{2N^2}$ is analyzed for any number of buffer size. In order to cope with the limitations of existing works on CHS, a CHS sequence with complete scenarios is proposed here including multi-user and multi-hop. Besides, asymmetric synchronous and asynchronous cases have been fully considered in the proposed ASAA protocols. Table I shows the summary of comparisons of CHS protocols considering asymmetric asynchronous scenarios.

III. Preliminary

To explain the proposed Channel Hopping Sequence (CHS) mechanisms, the system model is described here for the Cognitive Radio Networks (CRNs) environments. The detailed description of the existing PUs and SUs are elucidated and the considered metrics are presented in the problem formulations sub-section.

A. System Model

In Cognitive Radio Networks (CRNs), two types of users are present in the same communication range and they are the licensed users (PUs) annotated as $\{PU_1, PU_2, ..., PU_i\}$ and unlicensed users (SUs) annotated as $\{SU_1, SU_2, ..., SU_i\}$. Considering the multi-user scenario, the total numbers of

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TABLE I: The comparisons of CHS protocols considering asymmetric asynchronous scenario.

Ref	CL	CU	MTTR	ATTR	MIRI
[23]	-	-	M^2D	$\frac{M^2D}{2}$	-
[24]	-	-	M^2D	$\frac{M^2D}{2}$	-
[25]	-	-	$(3MP(P-G)+3P)D$	-	-
MUAA ($\lvert N\rvert = Even$)	$\frac{2}{\lvert CHS\rvert}$	$\frac{(\lvert N\rvert+(\lvert N\rvert+1)+\lvert M\rvert}{\lvert M\rvert\times\lvert L\rvert}$	$3(\lvert N\rvert+1)$	$\frac{3(\lvert N\rvert+1)+1}{2}$	$3(\lvert N\rvert-1)$
MUAA ($\lvert N\rvert = Odd$)	$\frac{2}{\lvert CHS\rvert}$	$\frac{(\lvert N\rvert+(\lvert N\rvert+1)+\lvert M\rvert}{\lvert M\rvert\times\lvert L\rvert}$	$2(\lvert N\rvert+2)$	$\frac{2(\lvert N\rvert+2)+1}{2}$	$3(\lvert N\rvert+1)$

Where:
M, $|N|$: Total number of available channels
CHS: Total number of Channel Hopping Sequences
D: Total number of hops
P: Smallest prime numbers, $P > M$
G: The number of commonly available channels between two users

heterogeneous SUs are considered as $|M|$, where $M \geq 3$. As shown in Figure 1, all SUs are connected and communicate in a multi-hop scenario. The total number of hops for $|M|$ can be determined by $T_h = |M| - 1$. For instance, $|M| = 4$, $\{SU_1, SU_2, SU_3, SU_4\}$, the total number of hops is $T_h = 4 - 1 = 3$, which is $SU_1 \rightarrow SU_2(Hop_1) \rightarrow SU_3(Hop_2) \rightarrow SU_4(Hop_3)$. Therefore, each SU needs to be equipped with one half-duplex cognitive radio transceiver that has the capacity to sense and access the licensed channels opportunistically in the absence of PUs. The total number of available channels can be considered as $|N|$, and the set N could be indexed as $\{c_0, c_1, ..., c_{|N|-1}\}$. Considering the asymmetric case, let $m = \{c_0, c_1, ..., c_{|N|-1}\}$ and $n = \{c_1, c_2, ..., c_{|N|-2}\}$ be the set of available channels for SU_1 and SU_2, respectively, where, $m, n \in N$ and $|m|, |n| \leq |N|$. In order to rendezvous the SUs successfully, there must be at least one common channels $|K|$ between any pair of SUs in any hop out of the total number of available channels, where $K = \{m \cap n\}$. The entire network is divided into multiple time slots, started from $T = \{t_1, t_2, ..., t_{|T|}\}$, where $|T|$ is defined as the total length of CHS. Based on the MUAS and MUAA protocols, total length is $|T| = |N|^2$ and $|T| = (|N| + 1)^2$, respectively. In addition, T is also divided into $|C|$ numbers of cycles in MUAS protocol, where each cycle C_1 comprises $|N|$ number of time slots. It is assumed that SUs can enter the network synchronously or asynchronously. In addition, the time slot boundaries are assumed to be aligned in both protocols.

B. Problem Formulation

In Channel Hopping (CH), several metrics are used to evaluate the performance of the CH algorithm as described below.

1) Channel loading (CL):
The maximum rendezvous proportion among all the Channel Hopping Sequence (CHS) is evaluated by using the Channel Loading (CL) parameter. It can be derived by determining the maximum occurrence of the channels (M), where rendezvous occurs and the total number of

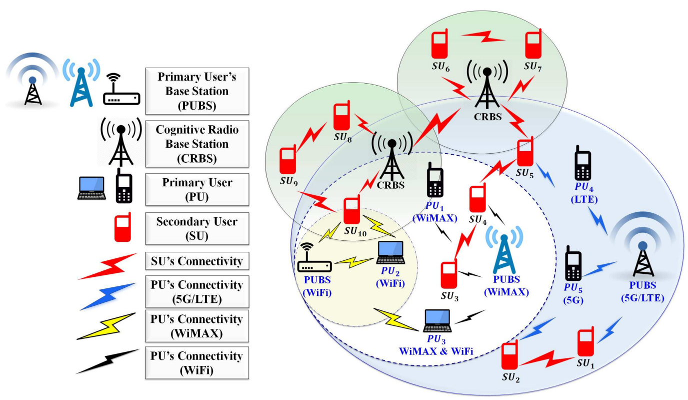

Fig. 1: System model.

Channel Hopping Sequence is $|CHS|$. Therefore, the channel loading of the CRN can be defined as follows:

$$CL = \frac{M}{|CHS|} \times 100\% \tag{1}$$

2) Channel utilization (CU):
This metric is to evaluate the utilization of channels over the entire CHS. Channel utilization (CU) depends on the total number of rendezvous $|U|$, the total number of SUs $|M|$ and total length of the entire CHS $|T|$. Hence, the percentage of channel utilization can be derived as follows:

$$CU = (\frac{|U|}{|M| \times |T|}) \times 100\% \tag{2}$$

3) Maximum Time To Rendezvous (MTTR):
Time To Rendezvous (TTR) values need to be calculated, which is defined by the number of time slots an SU takes to rendezvous. Considering the set of TTRs values $TTR = \{r_1, r_2, ..., r_i\}$, the Maximum Time To Rendezvous (MTTR) $Max()$ can be derived as $Max(r_1, r_2, ..., r_i)$.

4) Average Time To Rendezvous (ATTR):
Average Time To Rendezvous (ATTR) determines the

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average time required for the SUs to rendezvous, which is calculated by the following equation:

$$ATTR = \frac{\sum_{i=1}^{r_i}(r_i)}{|TTR|} \quad (3)$$

Where $\sum_{i=1}^{r_i}(r_i)$ is defined as the summation of all TTR values and $|TTR|$ refers to the total numbers of TTR.

5) Maximum Inter Rendezvous Interval (MIRI): Initially, Inter Rendezvous Interval (IRI) value needs to be calculated in order to determine the Maximum IRI (MIRI). Subtraction operation is used to calculate IRI value between two consecutive rendezvous and is derived based on the following equation.

$$IRI_i = t_{i+1} - t_i \quad (4)$$

For instance, if the first and second rendezvous occur at time slot t_i = 5 and t_{i+1} = 15, respectively, the IRI = 15 - 5 = 10, which implies both SUs need to wait for 10 slots of time for the next rendezvous. Considering the asynchronous scenario, the IRIs value may vary based on the entry time of each SU. Thus, the MIRI $Max()$ can be determined from the set of IRIs, $IRI = \{i_1, i_2, ..., I\}$, where I is the total number of IRI values. High value of MIRI can lead to longer waiting time and degrade communication among SUs. Therefore, MIRI should be minimized in order to achieve a high degree of rendezvous and rapid communication establishment.

IV. Multi-User Asymmetric Synchronous (MUAS)

Few techniques have been used to generate the Multi-User Asymmetric Synchronous (MUAS) protocol and our proposed MUAS protocol is described in this section. The protocol is mainly focused on designing the Channel Hopping Sequence (CHS) in the first cycle C_1. For the next cycle C_2 until $|N|$ cycle, Left Circular Shift (LCS) is applied. Based on the system model as depicted in Figure 1, the generation of CHS depends on the commonly available channel sets of two connected SUs in multi-user multi-hop environments. Initially, the total number of available channels of the SUs need to be normalized, where it must be equal to the total number of available channels, $|p| == |N|$. The normalization procedure requires K set of common available channels for any connected pair of SUs. The normalized sets could be used further for generating the first C_1 cycles of the CHS. The generation of CHS involves a set of operations such as relative complement, multiplication and intersection operations. The purpose of these operations is to find the intersection value α, which could be used to calculate the hopping seed (H). Let, m and n, $m, n \in p$, be the set of available channels for SU_i and SU_{i+1}, respectively. Thus, the relative complement can be performed for each pair as follows: $R_{SU_i} = m - n$ and $R_{SU_{i+1}} = n - m$, where $|R_{SU_i}|$ and $|R_{SU_i}|$ are indexed as $\{1, ..., |R_{SU}\}$. Further, the multiplication operation can be calculated by the following equations.

$$\begin{aligned} X_{SU_i} &= \{(1 \times |R_{SU_i}|), ...(|R_{SU_j}| \times |R_{SU_i}|)\} \\ X_{SU_j} &= \{(1 \times |R_{SU_j}|), ...(|R_{SU_i}| \times |R_{SU_j}|)\} \end{aligned} \quad (5)$$

Algorithm 1: MUAS protocol.

Data:
$|N|$: Total number of available channels
p_{index}: The index of SU's available channels
p: The set of available channels for any connected pair of SUs
K: The set of common available channels
Result: CHS: Channel Hopping Sequences

Parameters: L: Queue, $L \subseteq K$, δ:$|K|$: Total number of common available channels
$|R_{SU_i}|$: The relative complement of SU_i with respect to SU_j
$|R_{SU_j}|$: The relative complement of SU_j with respect to SU_i
X_{SU_i}: Multiplication of $|R_{SU_i}|$ and $|R_{SU_j}|$
X_{SU_j}: Multiplication of $|R_{SU_j}|$ and $|R_{SU_j j}|$
α: The number of intersection, H: The hopping seed; $H \in [1, |N|]$
$C_{|N|}$: Total number of CH sequence cycles
$MSIC = |N|$
For each SU (Connected Pair) **Do**
if *(*$|p|! = |N|$*)* **then**
  $|L| = |N| - |p|$;
  $L \rightarrow p$
end
else
  Ignore
end
$|R_{SU_i}| = m - n$;
$|R_{SU_j}| = n - m$;
if *(*$|R_{SU_i}| = 0$ *or* $|R_{SU_j}| = 0$*)* **then**
  Mapped $0 \rightarrow 1$;
end
Calculate **Equation 5** ;
$\alpha = X^m_{SU_i} \cap X^n_{SU_j}$;
$H = \alpha + \delta$;
For Cycle 1 (C_1)
for $t = 1$ **to** $|N|$ **do**
  $t_i = (t_i + H) mod|N|$;
  Mapped $t_i \rightarrow p_{index} \rightarrow p$;
end
Rearrange Index Sequence $\forall t_i$ $\{MSIC, 1, 2, ..., |N| - 1\}$
for *CYCLE=* C_2 **to** $C_{|N|}$ **do**
  for $Index = MSIC$ **to** $|N| - 1$ **do**
    $NewIndex_i = (Index - 1) \mod |N|$;
  end
end
Return $CHS = C_{|N|}$

The intersection α can be derived by finding the intersection of $X_{SU_i} \cap X_{SU_j}$. Moreover, the hopping seed is calculated by adding up two values; intersection value α and the total number of common available channels δ. Furthermore, the CHS can be generated for the cycle C_1 that comprises $|N| - 1$ time slots, modulo operation with $|N|$ carried out in the first cycle.

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The rest CHS cycles are generated based on the first cycle sequence C_1 by using Left Circular Shift (LCS) permutation method. The complete procedure of MUAS protocol is given in Algorithm 1.

A. Rendezvous of Secondary Users in MUAS

The generated CHS by executing the MUAS protocol can be seen in Figure 2. As illustrated in Figure 3 and formally described in 1, the CHS generation in MUAS protocol can be elucidated as follows. Let us consider an example for $|N| = 5$ and $|M| = 4$, denoted as $\{SU_1, SU_2, SU_3, SU_4\}$. For simplicity, only SU_1 and $SU2$ are graphically explained in Figure 3. Considering the multi-user multi-hop pair for all SUs, let $|M|$ numbers of SUs be connected as: $SU_1 \rightarrow SU_2 \rightarrow SU_3 \rightarrow SU_4$. Each SU has its own set of available channels such as $SU_1 = \{0, 1, 3, 4\}$, $SU_2 = \{0, 2, 3\}$, $SU_3 = \{0, 1, 2, 3\}$ and $SU_4 = \{1, 2\}$. For instance, let us consider the generation of the first SU_1 by taking SU_2 as the pair. Let, $m = \{\mathbf{0}, 1, \mathbf{3}, 4\}$ and $n = \{0, 2, 3\}$ be the available channel sets for SU_1 and SU_2, respectively. Based on the pair, the total and set of commonly available channels can be derived as $|K| = 2$ and $K = \{0, 3\}$, respectively. As given in lines 10-12, the total number of available channels in the set $|m| = 4$ and $|n| = 3$ need to be compared with $|N| = 5$. As $4! = 5$ and $3! = 5$, normalization can be proceeded by performing the subtraction and modulo operations. For instance, considering the queue L, $L \subseteq K$, $|L| = 5 - 4 = 1$, $L = \{0\}$, and $|L| = 5 - 3 = 2$, $L = \{0, 3\}$. Next, L number of subsets can be added to the set of available channels, which belong to the respective SUs. For example, $m = \{0, 1, 3, 4, 0\}$ and $n = \{0, 2, 3, 0, 3\}$.

Furthermore, in lines 17-18, the relative complement for $SU_1(R_{SU_1})$ and SU_2 (R_{SU_1}) is calculated as follows: $R_{SU_1} = \{0, 1, 3, 4, 0\} - \{0, 2, 3, 0, 3\} = \{1, 4\}$ and $R_{SU_2} = \{0, 2, 3, 0, 3\} - \{0, 1, 3, 4, 0\} = \{2\}$. Thus, $|R_{SU_1}| = 2$ and $|R_{SU_2}| = 1$. Based on lines 22-23 and followed by Equation 5, the multiplication operation for SU_1 (X_{SU_1}) and SU_2 (X_{SU_2}) is calculated as follows: $X_{SU_1} = \{(1 \times 2)\} = \{2\}$ and $X_{SU_2} = \{(1 \times 1), (2 \times 1)\} = \{1, 2\}$. Next, intersection α needs to calculate as $\alpha = \{2\} \cap \{1, 2\} = 2$. Further, the deviation value δ can be calculated as $\delta = |K| - \alpha = 2 - 2 = 0$.

In line 24, the hopping seed (H) can be calculated as $H = \alpha + \delta$, $H = 2 + 0 = 2$, where $H \in [1, |N|]$. In line 25-29, from $t = 1$ until $t = |N|$, the first cycle C_1 CHS for SU_1 can be generated as: $t_1 = (1+2) \mod 5 = 3$, $t_2 = (2+2) \mod 5 = 4$, $t_3 = (3 + 2) \mod 5 = 0$, $t_4 = (4 + 2) \mod 5 = 1$, $t_5 = (5 + 2) \mod 5 = 2$. A mapping procedure is performed for generating the first cycle C_1, where $\{3, 4, 0, 1, 2\}$ is mapped to the p_{index} of m set of available channels for SU_1. The final CHS for SU_1 in the first cycle C_1 is $\{4, 0, 0, 1, 3\}$. In lines 30-36, as shown in deep blue, light blue, pink, red, and brown arrows, Left Circular Shift (LCS) is applied to each cycle. Finally, the complete CHS for the total number of SUs $|M|$ are $SU_1 = \{4, 0, 0, 1, 3, 0, 0, 1, 3, 4, 0, 1, 3, 4, 0, 1, 3, 4, 0, 0, 3, 4, 0, 0, 1\}$. In the same way, the rest of CHS for SU_2, SU_3, and SU_4 are generated as follows: $SU_2 = \{3, 0, 2, 3, 2, 0, 2, 3, 2, 3, 2, 3, 2, 3, 0, 3, 2, 3, 0, 2, 2, 3, 0, 2, 3\}$,

---

Algorithm 2: MUAA protocol.

Data: $|N|$: Total number of available channels
m: Set of available channels of SU_i
K: Set of commonly available channels
Result: CHS: Channel Hopping Sequences
1 Parameters: $Index$: Index of SU's available, $\{0, 1, ..., |N| - 1\}$
2 L : Length of Common Channel Sequence (CCS)
3 $|K|$: Total number of Common Channel
4 CHS : Channel Hopping Sequence
5 **For** each SU_i **Do**
6 **Assign** $Index(x) \leftarrow m$ and **Assign** $Index(z) \leftarrow K$;
7 **for** *each column* $tc_i = 0$ **to** $|N| - 1$ **do**
8 $tc_i = \frac{(tc_i(tc_i+1))}{2}$;
9 **for** *each row* $tr_j = tc_i + 1$ **to** $|N|$ **do**
10 $tr_j = (tr_j + tc_i) \mod |N|$;
11 **if** *$(tr_j \geq |m|)$* **then**
12 $tr_j \mod tr_j$;
13 **end**
14 **Convert** $tr_j \rightarrow Index$ x $\rightarrow m$ (channel i) ;
15 **Assign** Channel $i \rightarrow TA(tc_i, tr_j)$;
16 **end**
17 **end**
18 **for** *each column* $tc_i = |N|$ **to** 0 **do**
19 $tc_i = \frac{(tc_i(tc_i+1))}{2}$;
20 **for** *each row* $tr_j = 0$ **to** $|N| - 1$ **do**
21 $tr_j = (tr_j + tc_i) \mod |N|$;
22 **if** *$(tr_j \geq |m|)$* **then**
23 $tr_j \mod tr_j$;
24 **end**
25 **Convert** $tr_j \rightarrow Index$ x ;
26 **Convert** $Index$ x $\rightarrow m$ (channel i) ;
27 **Assign** Channel $i \rightarrow TB(tc_i, tr_j)$;
28 **end**
29 **end**
30 **Define** $L = |N| + 1$
31 **for** *each* $CCS_i = 1$ **to** L **do**
32 $CCS_i = (CCS_i + |K|) \mod |N|$;
33 **if** *$(CCS_i \geq |K|)$* **then**
34 $CCS_i \mod CCS_i$;
35 **end**
36 **Convert** $CCS_i \rightarrow Index$ z ;
37 **Convert** $Index$ z $\rightarrow K$ (channel K) ;
38 **end**
39 **for** *each* $t = 1$ **to** $(|N| + 1)^2$ **do**
40 $CHS_{Qt} \leftarrow CCS_t$;
41 **for** *each row* $tr_j = 0$ **to** $|N| - 1$ **do**
42 $CHS_{Qt} \leftarrow TA((t - 1), tr_j)$;
43 **for** *each row* $tr_j = 0$ **to** $|N| - 1$ **do**
44 $CHS_{Qt} \leftarrow TB(t, tr_j)$;
45 **end**
46 **end**
47 **end**
48 **Return** CHS

$SU_3 = \{3, 1, 0, 1, 2, 1, 0, 1, 2, 3, 0, 1, 2, 3, 1, 1, 2, 3, 1, 0, 2, 3, 1, 0, 1\}$, and $SU_4 = \{2, 1, 1, 2, 1, 1, 1, 2, 1, 2, 1, 2, 1, 2, 1, 2, 1, 2, 1, 1, 1, 2, 1, 1, 2\}$.

B. Performance Analysis of MUAS

1) Channel Loading: The channel loading is analyzed by considering the first cycle C_1. Let us consider the same CH sequences for $|N|$ = 5, $|M|$ = 4, and difference set of available channels such as $SU_1 = \{0, 1, 3, 4\}$, $SU_2 = \{0, 2, 3\}$, $SU_3 = \{0, 1, 2, 3\}$ and $SU_4 = \{1, 2\}$. Upon performing the MUAS protocol, the first cycle C_1 CHS is generated, which is shown in Figure 4. It is analyzed that the maximum occurrences of channels (M) is 2, which can be seen respectively in channels 3, 0, 1, 2 at time slots t_1,t_2, and t_5. Hence, the channel loading in one cycle C_1 can be calculated as $\frac{The maximum occurrences of channels}{|CHS|} \times 100\% = \frac{2}{4} \times 100\% = 50\%$. Therefore, the channel loading of MUAS is $\frac{2}{|CHS|}$, $\leq 50\%$.

2) Channel Utilization: Channel utilization depends on the rendezvous between any pairs of SUs. Thus, the channel utilization can be calculated based on the following lemma:

Lemma 1. ***Percentage of channel utilization in MUAS is CU =*** $\frac{(|N|+1)\times|N|}{|M|\times|T|}$.

Proof. Let the number of available channels be $|N|$ = 5, and total number of SUs be $|M| = 4$. As shown in Figure 5, the total number of rendezvous among SUs is $|U|$ = 30. From the definition of channel utilization, $CU = (\frac{|U|}{|M|\times|T|}) \times 100\%$=$\frac{30}{4\times25} \times 100\% = 30\%$, where $|T|$ is the total length of the CHS. Therefore, the percentage of channel utilization is 30%. Considering the right-hand side, it could be calculated as $\frac{(|N|+1)\times|N|}{|M|\times|T|}$=$\frac{6\times5}{4\times25}$= $(\frac{30}{100})$= 30% and therefore the lemma is proved. □

It is to be noted that MUAS can work efficiently in the multi-user multi-hop scenario with a high percentage of channel utilization. As shown in cycles C_1 through C_5 of Figure 2, there are rendezvous among the multi-hop multi-users SU_1, SU_2, SU_3 and SU_4. For instance, in the first cycle C_1, if 4-users $SU_1 \to SU_2 \to SU_3 \to SU_4$ are considered, there are 3 hops among them. Users SU_1 & SU_2, SU_2 & SU_3, and SU_3 & SU_4 can rendezvous in channel 0 at time slot 2, in channel 3 at time slot 1, and in channel 1 at time slot 2, respectively. As rendezvous occurs among 4 nodes in 3 different channels (channels 0, 1 and 3) in cycle C_1, $|M| = 4$, $|N|$ = 3 and the length of the CHS $|T|$ in cycle C_1 is 5. Hence, channel utilization in cycle C_1 is $CU = \frac{(|N|+1)\times|N|}{|M|\times|T|}$=$\frac{4\times3}{4\times5}$= 60%. Similar patterns of rendezvous are also observed in the rest cycles among different users in different channels and time slots.

3) Average Time To Rendezvous and Maximum Time To Rendezvous: In order to analyze the MTTR, the TTR value needs to be analyzed first since MTTR is considered as the worst case of TTR. In our protocol, the value of TTR varies because of the asymmetric environment. Hence, the TTR value can be analyzed as follows:

Lemma 2. *The MTTR in MUAS is* $|N|-3$ *and ATTR is* $\frac{(|N|-2)}{(|N|-3)}$

Proof. Considering an example for $|N|$ = 5 and $|M|$ = 4, TTR, MTTR and ATTR can be analyzed and calculated as: $SU_1 = \{4, \mathbf{0}, 0, 1, 3, 0, 0, 1, 3, 4, 0, 1, 3, 4, 0, 1, 3, 4, 0, 0, 3, 4, 0, 0, 1\}$, $SU_2 = \{\mathbf{3}, \mathbf{0}, 2, 3, 2, 0, 2, 3, 2, 3, 2, 3, 2, 3, 0, 3, 2, 3, 0, 2, 2, 3, 0, 2, 3\}$, $SU_3 = \{\mathbf{3}, \mathbf{1}, 0, 1, 2, 1, 0, 1, 2, 3, 0, 1, 2, 3, 1, 1, 2, 3, 1, 0, 2, 3, 1, 0, 1\}$, $SU_4 = \{2, \mathbf{1}, 1, 2, 1, 1, 1, 2, 1, 2, 1, 2, 1, 2, 1, 2, 1, 2, 1, 1, 1, 2, 1, 1, 2\}$. Based on CHSs of SUs, the value of TTR can be 1 and 2 by considering $SU_2 \to SU_3$ and $SU_1 \to SU_2$, respectively. In general, the minimum and maximum of TTR is 1 and $|N|-3$, respectively. Hence, the ATTR can be calculated as $ATTR = \frac{1+(|N|-3)}{(|N|-3)}$ = $\frac{(|N|-2)}{(|N|-3)}$. The MTTR can be derived as $MTTR = Max(1, |N| - 3)) = |N| - 3$. □

V. Multi-User Asymmetric Asynchronous (MUAA)

In this section, the Multi-User Asymmetric Asynchronous (MUAA) protocol is described step by step. MUAA is generated without any global clock synchronization and with the availability of different channels. Initially, m is the set of SU's available channels and the K set of commonly available channels is annotated indexed from $\{0, 1, 2, |N| - 1\}$. The annotated numbers will be used further to map the results of TA, TB structures and Common Channel Sequence (CCS) generations. From Figure 6, TA and TB structures can be seen as triangular that comprises column i and row j. TA and TB sequences are generated consecutively using modulation operations with $|N|$. Similarly, modulation operation with $|N|$ and additional operation with $|K$ is used to generate the CCS by considering the set K common available channels from any pair of SUs in any hop. Besides, CCS is generated recursively $L = |N| + 1$ times. Moreover, all the derived values are mapped such as TA and TB are mapped from the index x to channel m from the set of SUs available channels, and CCS is mapped from z to channel K from a set of common channels. Finally, the complete CHS can be generated by merging recursively those three different sequences without sorting the channels. The merging can be performed in the following format: $CCS_1 \cup TA_{colum0} \cup TB_{colum1} \cup \cup CCS_L \cup TA_{colum|N|-1} \cup TB_{colum|N|}$. The formal description of MUAA protocol is given in Algorithm 2.

A. Rendezvous of Secondary Users using MUAA Protocol

As shown in Figure 7, the Channel Hopping Sequences (CHSs) are generated by considering $|N| = 5$ and $|M| = 4$, where $M = \{SU1, SU2, SU3, SU4\}$. All SUs are connected through multi-hop scenario such as $SU_1 \to SU_2 \to SU_3 \to SU_4$. Each SU has its own set of available channels $SU1 = \{0, 2, \mathbf{3}, \mathbf{4}\}$, $SU2 = \{1, \mathbf{3}, \mathbf{4}\}$, $SU3 = \{1, 2, 3\}$ and $SU4 = \{0, 1, 2, 4\}$. For simplicity, let us consider the sequence generation for SU_1 by taking SU_2 as the pair, $SU1 \to SU2$. Accordingly, the total number of commonly available channels is $|K| = 2$, where $K = \{3, 4\}$. Let, $x = \{0, 1, 2, 3\}$, and $z = \{0, 1\}$ be indexed for $m = \{0, 2, 3, 4\}$, and $K = \{3, 4\}$, respectively. In lines 8-19, TA sequence

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	C_1					C_2					C_3					C_4					C_5				
Time Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
SU_1	4	0	0	1	3	0	0	1	3	4	0	1	3	4	0	1	3	4	0	0	3	4	0	0	1
SU_2	3	0	2	3	2	0	2	3	2	3	2	3	2	3	0	3	2	3	0	2	2	3	0	2	3
SU_3	3	1	0	1	2	1	0	1	2	3	0	1	2	3	1	1	2	3	1	0	2	3	1	0	1
SU_4	2	1	1	2	1	1	1	2	1	2	1	2	1	2	1	2	1	2	1	1	1	2	1	1	2

Fig. 2: Rendezvous for $|N| = 4$ and $|M| = 4$ by executing the MUAS protocol.

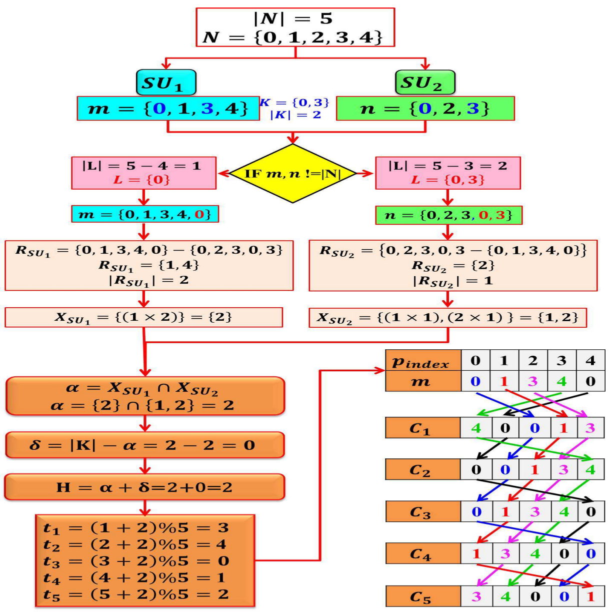


Fig. 3: MUAS protocol illustrations.

	C_1				
Time Slot	1	2	3	4	5
SU_1	4	0	0	1	3
SU_2	3	0	2	3	2
SU_3	3	1	0	1	2
SU_4	2	1	1	2	1

Fig. 4: Channel loading for $|N|$ = 5.

generation is performed in each column tc_i and row tr_j. Following the equation in line 9, each column is calculated as $tc_0 = \frac{0(0+1)}{2} = 0$. This value will be used further in calculating the row value tr_i. Starting from the first row tr_1, modulation operation with $|N|$ is used, which is $tr_1 = (1+0) \mod 5 = 1$, where $tr_1 = 1$ is referred to as the index number of x. In the next step, the mapping procedure is carried out from the index $x \rightarrow m$, $1 \rightarrow 2$. Channel number 2 is assigned in the respective column and row (tc_0, tr_1). In the same way, the rest of the sequences in TA structures are generated. Figure 6(a) shows an example of TA sequences.

Sequentially, in lines 20-30, TB sequences are generated. In contrast, column calculation is started from the $tc_{|N|}$, where $tc_5 = \frac{5(5+1)}{2} = 15$. Further, the row calculation can be derived as $tr_0 = (0+15) \mod 5 = 0$. Referring to the index x, $tr_0 = 0$ value is mapped to the m channel number $0 \rightarrow 0$. Therefore, the value of column and row $(tc_5, tr_0) = 0$. Furthermore, in lines 32-39, the generation of the Common Channel Sequence (CCS) is performed by using the addition operation with $|K|$ and modulation operation with $|N|$. For example, $CCS_1 = (1+2) \mod 5 = 3$. Continuously, the CCS sequence is generated as $CCS = \{3, 3, 3, 4, 3, 3\}$. Finally, as given in lines 41-50, the complete CHS for SU_1 can be produced by combining each component of CCS, TA, and TB. With $L = (|N|+1)^2 = (5+1)^2 = 36$, the length of CHS for SU_1 is $SU_1 = \{$3, 2, 3, 4, 0, 0, 2, 3, 4, 0, 0, 2, 4, 0, 3, 2, 3, 4, 2, 3, 4, 4, 0, 2, 0, 2, 3, 4, 3, 0, 0, 2, 3, 4, 0, 3$\}$. An example of the MUAA protocol is shown in Figure 8. According to MUAA protocol, the CHSs for $|M|$ number of SUs can be generated as follows:

1) $SU_1 = \{$3, 2, 3, 4, 0, 0, 2, 3, 4, 0, 0, 2, 4, 0, 3, 2, 3, 4, 2, 3, 4, 4, 0, 2, 0, 2, 3, 4, 3, 0, 0, 2, 3, 4, 0, 3$\}$.
2) $SU_2 = \{$3, 3, 4, 1, 1, 1, 3, 3, 1, 1, 1,3, 1, 1, 3, 3, 4, 1, 3, 4, 1, 4, 1, 3, 1, 3, 4, 1, 3, 1, 1, 3, 4,1,1, 3$\}$.
3) $SU_3 = \{$3, 3, 4, 1, 1, 1, 3, 3, 1, 1, 1,3, 1, 1, 3, 3, 4, 1, 3, 4, 1, 4, 1, 3, 1, 3, 4, 1, 3, 1, 1, 3, 4, 1, 1, 3$\}$.
4) $SU_4 = \{$4, 1, 2, 4, 0, 0, 1, 0, 4, 0, 0, 1, 4, 0, 0, 1, 2, 4, 1, 2, 4, 1, 0, 1, 0, 1, 2, 4, 2, 0, 0, 1, 2, 4, 0, 4$\}$.

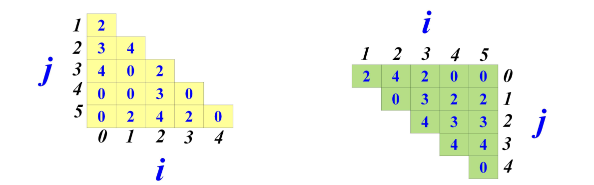
In addition, all SUs enter the network at different time instances. Let us consider $SU_1 = t_1$, $SU_2 = t_2$, $SU_3 = t_4$, and $SU_4 = t_3$. Hence, the complete CHS and rendezvous among all SUs can be shown in Figure 7.

B. Performance Analysis of MUAA Algorithm:

1) Channel Loading: Estimation of channel loading is a challenge in MUAA protocol due to variations in entering time instances by SUs. Considering $|N| = 5$ and $|M| = 4$, the CHSs are $SU_1 = \{$3, 2, **3**, 4, 0, 0, 2, **3**, 4, 0, 0, 2, 4, 0, 3, 2, **3**, 4, **2**, **3**, 4, 4, 0, 2, 0, 2, **3**, 4, 3, 0, 0, 2, **3**, 4, 0, **3**$\}$, $SU_2 = \{$ 3, **3**, 4, 1, 1, 1, **3**, 3, 1, 1, 1, 3, **1**, 1, 3, **3**, 4, 1, **3**, 4, 1, 4, 1, 3, 1, **3**, 4, 1, **3**, 1, 1, **3**, 4, 1, 1, 3 $\}$, $SU_3 = \{$ 1, 2, 3, 1, 1, 1, 2, 1, 1, 1, **1**, 2, 1, 1, 1, **2**, **3**, 1, 2, 3, 1, 2, 1, 2, 1, 2, **3**, 1, 3, 1, 1, 2, **3**, 1, 1, 1 $\}$, and $SU_4 = \{$4, 1, 2, 4, 0, 0, 1, 0, 4, 0, 0, **1**, 4, 0, 0, 1, **2**, 4, 1, 2, 4, 1, 0, 1, 0, 1, 2, 4, 2, 0, 0, 1, 2, 4, 0, 4$\}$. Let us assume that each SU has entered into the network at different instants of time slot index t_i. For example, $SU_1 = t_1$, $SU_2 = t_2$, $SU_3 = t_4$, and $SU_4 = t_3$. As shown in Figure 9, the maximum occurrence of channels 1, 2 and 3 is 3 times in time slots 14, 19 and 20, respectively. Therefore, the channel loading value for $|N| = 5$ is 75% for channel numbers

Time Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Channel 0		1&2	1&3			1&2	1&3				1&3				1&2				1&2	1&3			1&2	1&3	
Channel 1		3&4		1&3		3&4		1&3				1&3			3&4	1&3			3&4				3&4		1&3
Channel 2					2&3				2&3				2&3				2&3				2&3				
Channel 3	2&3									2&3				2&3				2&3				2&3			
Channel 4																									
(CU)	1	2	1	1	1	2	1	1	1	1	1	1	1	1	2	1	1	1	2	1	1	1	2	1	1
TOTAL													30												

Fig. 5: Channel utilization for $|N|$ = 5.



(a) An example of TA structure for |N|=5 (b) An example of TB structure for |N|=5

Fig. 6: An example of TA and TB structures for $|N|$ = 5.

1, 2 and 3. In contrast, the minimum occurrence 50% can be obtained considering channel number 3 at the time slots 3, 8, 17, 27, 30, 33, and 36. Hence, the channel loading percentage can be generalized as $\frac{M}{|CHS|} \times 100\% = \frac{2}{|CHS|}, \geq 50\%$.

2) Channel Utilization (CU): In our protocol, it is considered that the interval of entering the SUs into the network is dependent on total number of SUs $|M|$, for $1 < t_i \leq |M|$. Followed by all generated sequences for all $|M|$ number of SUs, the value of channel utilization can be calculated as given in the following lemma.

Lemma 3. *Percentage of channel utilization in MUAA is CU* $= \frac{|N|\times(|N+1|)+|M|}{|M|\times|T|}$.

Proof. Let the number of available channels be $|N| = 5$ and total number of SUs be $|M| = 4$. Accordingly, the number of rendezvous among the SUs in each time slot could be shown as in Figure 10. It is shown that the total number of rendezvous occurred is $|U| = 34$. Hence, channel utilization could be calculated as $CU = (\frac{|U|}{|M|\times|T|})\times 100\% = \frac{34}{4\times 36}\times 100\% = 23.61\%$, where $|T|$ is the total length of the CHS for all SUs. Therefore, the percentage of channel utilization for $|N| = 5$ and $|M| = 4$ is 23.61%. Considering the right hand side, it is also calculated as $\frac{|N|\times(|N+1|)+|M|}{|M|\times|T|} = \frac{(5\times 6)+4}{4\times 36} = \frac{34}{144} = 23.61\%$. □

As shown in Figure 7, the percentage of channel utilization could be analyzed for the multi-user multi-hop scenario of MUAA. Considering the interval of time slots from 1 to 9, it is observed that there are 7 distinct rendezvous among the multi-hop multi-users SU_1, SU_2, SU_3 and SU_4. For instance, if 4-users $SU_1 \rightarrow SU_2 \rightarrow SU_3 \rightarrow SU_4$ are considered, there are 3 hops among them and users SU_1 & SU_2, SU_2 & SU_3, and SU_3 & SU_4 can rendezvous in channel 3 at time slot 3, in channel 1 at time slot 7, and in channel 2 at time slot 5, respectively. Though rendezvous between any two nodes can occur multiple times in different channels and time slots, only one rendezvous for each pair of SUs is considered for simplicity. Accordingly, as rendezvous occurs among SU_1, SU_2, SU_3 and SU_4 in 3 different channels from time slots 1 through 9, $|M| = 4$, $|N| = 3$ and length of the CHS $|T| = 9$. Hence, the channel utilization is $CU = \frac{|N|\times(|N+1|)+|M|}{|M|\times|T|} = \frac{(3\times 4)+4}{4\times 9} = 44.44\%$. It is to be noted that similar patterns of rendezvous could be observed in each interval of 9 time slots among multiple users in the multi-hop scenario.

3) Average Time To Rendezvous and Maximum Time To Rendezvous (MTTR): Initially, the TTR value needs to be analyzed and the worst case of TTR is derived as the MTTR value. The MTTR can be analyzed by considering different entry time slot index in between interval $0 < t_i \leq |M|$, where $|M|$ is the number of SUs and t_i is the entry time slot index of each SU. Hence, MTTR in two cases is analyzed as follows:

Case-1: Even number of $|N|$ available channels

Lemma 4. *The MTTR in MUAA is* $3(|N|+1)$ *for* $|N| = even$.

Proof. Let us consider the number of available channel and total numbers of SUs are $|N|$ = 4 and $|M| = 4$. Each of SUs can start their CHS in any entry time slot index. For instance, $SU_1 = t_1$, $SU_2 = t_4$, $SU_3 = t_2$, and $SU_4 = t_3$. Based on Algorithm 2, the CHSs for all SUs are derived as follows:

1) $SU_1 = \{3, 2, 3, 4, 0, 0, 2, 3, 4, 0, 0, 2, 4, 0, 3, 2, 3, 4, 2, 3, 4, 4, 0, 2, 0, 2, 3, 4, 3, 0, 0, 2, 3, 4, 0, 3\}$.
2) $SU_2 = \{3, 3, 4, 1, 1, 1, 3, 3, 1, 1, 1{,}3, 1, 1, 3, 3, 4, 1, 3, 4, 1, 4, 1, 3, 1, 3, 4, 1, 3, 1, 1, 3, 4{,}1{,}1, 3\}$.
3) $SU_3 = \{3, 3, 4, 1, 1, 1, 3, 3, 1, 1, 1{,}3, 1, 1, 3, 3, 4, 1, 3, 4, 1, 4, 1, 3, 1, 3, 4, 1, 3, 1, 1, 3, 4, 1, 1, 3\}$.
4) $SU_4 = \{ 4, 1, 2, 4, 0, 0, 1, 0, 4, 0, 0, 1, 4, 0, 0, 1, 2, 4, 1, 2, 4, 1, 0, 1, 0, 1, 2, 4, 2, 0, 0, 1, 2, 4, 0, 4\}$.

The value of TTR can be obtained in any time slot index $t_i = \{2, 3, 4, ..., 3(|N|+1)\}$. Therefore, the ATTR can be calculated as $ATTR = \frac{1+2+...+3(|N|+1)}{3(|N|+1)} = \frac{\frac{(3(|N|+1))\times(3(|N|+1))+1}{2}}{3(|N|+1)} = \frac{3(|N|+1)+1}{2}$. Hence, by deriving from set of TTR, the MTTR can be determined as $Max(2, 3, 4, ..., 3(|N| + 1)) = 3(|N| + 1)$. □

Case-2: Odd number of $|N|$ available channels

Lemma 5. *The MTTR in MUAA is* $2(|N|+2)$ *for* $|N| = odd$.

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Time Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SU1	3	2	3	4	0	0	2	3	4	0	0	2	4	0	3	2	3	4
SU2		3	3	4	1	1	1	3	3	1	1	1	3	1	1	3	3	4
SU3				1	2	3	1	1	1	2	1	1	1	1	2	1	1	1
SU4			4	1	2	4	0	0	1	0	4	0	0	1	4	0	0	1

Time Slot	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
SU1	2	3	4	4	0	2	0	2	3	4	3	0	0	2	3	4	0	3
SU2	1	3	4	1	4	1	3	1	3	4	1	3	1	1	3	4	1	1
SU3	2	3	1	2	3	1	2	1	2	1	2	3	1	3	1	1	2	3
SU4	2	4	1	2	4	1	0	1	0	1	2	4	2	0	0	1	2	4

Fig. 7: Rendezvous among four SUs in MUAA.

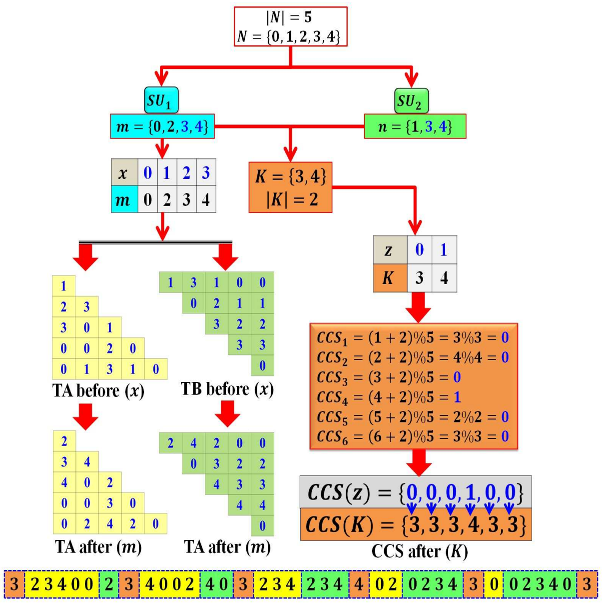

Fig. 8: MUAA protocol illustrations.

Proof. Let us consider the number of available channels $|N| = 5$ and the number of SUs $|M| = 4$. In this lemma we have analyzed the MTTR by considering the same CHSs, which have been mentioned for an even number of available channels. Moreover, it is assumed that the entry time slot index for each SU varies such as $SU_1 = t_1$, $SU_2 = t_4$, $SU_3 = t_2$, and $SU_4 = t_3$. Hence, the ATTR can be calculated as $ATTR = \frac{1+2+...+2(|N|+2)}{2(|N|+2)} = \frac{\frac{(2(|N|+2))\times(2(|N|+2))+1}{2}}{2(|N|+2)} = \frac{2(|N|+2)+1}{2}$. The MTTR can be defined as $Max(2, 3, 4, ..., 2(|N| + 2)) = 2(|N| + 2)$. □

4) Maximum Inter Rendezvous Interval (MIRI): The MIRI value can be calculated based on Equation 4. Based on the analysis of MTTR, it is found that total number of available channels $|N|$ can affect the MIRI values. Thus, MIRI value varies as $(3(|N|) - 1)$ and $(3(|N|) + 1)$ for $|N|$ is even and odd, respectively.

VI. Performance Evaluation

In order to evaluate the performance of the MUAS and MUAA CHS mechanism, the following simulation environment is considered. In this section, both protocols are evaluated in terms of channel utilization, throughout, and ATTR by considering different parameters such as the total number of SUs, number of channels and hops. The evaluation is also performed by comparing the proposed CHS mechanisms with the existing one.

A. Simulation Environment

In our simulation, OMNeT++ simulator IDE version 4.5 has been used to evaluate our Asymmetric Synchronous Asymmetric Asynchronous (ASAA) channel hopping protocol. The simulation has been conducted by considering an asymmetric environment, where an SU's available channels vary with at least one common channel of any pair of SUs, synchronously or asynchronously. Moreover, a total of 50 Primary Users (PUs) and 100 Secondary Users (SUs) have been considered to be within 1000m $\times$ 1000m communication area. The network time is divided into multiple time slots, where each time slot duration is equal to 0.02 second. During rendezvous, RTS needs to be sent by sender SU. After that, receiver SU has to respond by sending CTS to the sender SU. Upon successfully exchanging the RTS and CTS, data transmission between any pair of SU is carried out. By doing so, the size and rate of data packets such as 2000 bytes and 22.69 Mbps are considered. In addition, the Poisson process of arrival has been adopted for data packet generation, where multiple queues are maintained by each SUs. Various channel hopping protocols have been used to evaluate our proposed ASAA protocols such as JS [25], SARCH [9] and EJS [29], which are compared with MUAS, JS [25], FRCH [30] and EJS [29], which are compared with MUAA. Furthermore, taking different numbers of available channels, several metrics have been used to evaluate the performance of our protocols ATTR, channel utilization, and throughput, where the throughput is calculated as follows.

$$\frac{P_t \times P_i}{S_t} \tag{6}$$

where, P_t is the number of transmitted packets, P_i refers to the size of each packet i, and S_t is the simulation time period in seconds.

B. Performance of MUAS

Impact of the number of channels on percentage of channel utilization is shown in Figure 11. Percentage of channel utilization is evaluated for different numbers of SUs. It is observed that our MUAS protocol has higher performance for $|M| = 6$ when compared to $|M| < 6$ numbers of SUs. It is proven theoretically that MUAS protocol can guarantee the rendezvous at the first cycle C_1 for $|N|$ number of slots. Similarly, the MUAS protocol has a higher percentage of CU in multi-hop scenarios when compared to the single-hop scenario. Figure 12 shows the performance of MUAS for multi-hop scenarios.

The impact of channel numbers on channel utilization is evaluated by comparing MUAS protocol with three different

Time Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SU_1	3	2	3	4	0	0	2	3	4	0	0	2	4	0	3	2	3	4
SU_2		3	3	4	1	1	1	3	3	1	1	1	3	1	1	3	3	4
SU_3				1	2	3	1	1	1	2	1	1	1	1	2	1	1	1
SU_4			4	1	2	4	0	0	1	0	4	0	0	1	4	0	0	1

Time Slot	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
SU_1	2	3	4	4	0	2	0	2	3	4	3	0	0	2	3	4	0	3
SU_2	1	3	4	1	4	1	3	1	3	4	1	3	1	1	3	4	1	1
SU_3	2	3	1	2	3	1	2	1	2	1	2	3	1	3	1	1	2	3
SU_4	2	4	1	2	4	1	0	1	0	1	2	4	2	0	0	1	2	4

Fig. 9: Channel loading for $|N|$ = 5.

Time Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Channel 0										3&4								
Channel 1				3&4			2&3		3&4		2&3	2&3		2&3&4				3&4
Channel 2					3&4													
Channel 3			1&2					1&2									1&2	
Channel 4				1&2														1&2
(U)	0	0	1	2	1	0	1	1	1	1	1	1	0	1	0	0	1	2

Time Slot	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Channel 0							1&4											
Channel 1			3&4			2&3&4		2&3&4		3&4			2&3			3&4		
Channel 2	1&3&4			3&4							3&4						3&4	
Channel 3		1&2&3							1&2			2&3			1&2			1&3
Channel 4			1&2		2&4					1&2						1&2		
(U)	1	1	2	1	1	1	1	1	1	2	1	1	1	0	1	2	1	1

TOTAL	34

Fig. 10: Channel utilization for $|N|$ = 5.

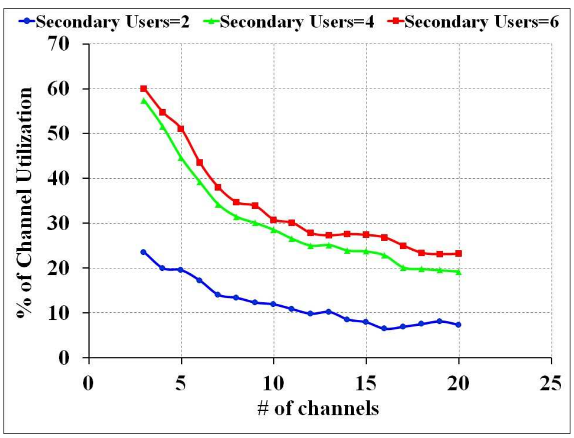

Fig. 11: Channel utilization performances for multi-user.

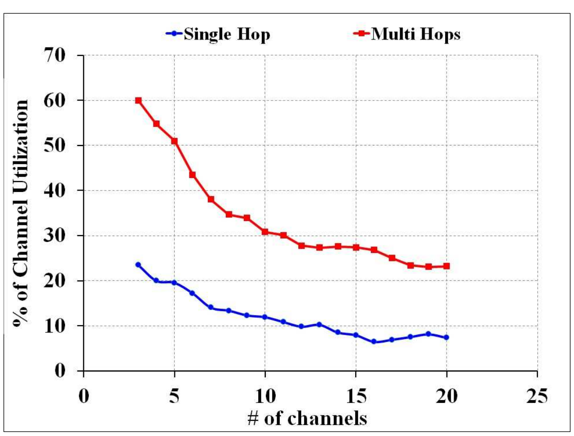

Fig. 12: Channel utilization performance for single-hop and multi-hop.

protocols such as JS, EJS and SARCH. Overall, our protocol outperforms others in terms of channel utilization percentages. Theoretically, $MTTR = |N| - 3$ can be obtained from MUAS. Thus, with a lower value of MTTR, communication can be rapidly established, and ultimately, the channel can be utilized up to the maximum level. In contrast, channel utilization percentage in EJS and JS is very low as the percentage of rendezvous is very less due to the random selection of the starting index i in jump pattern, and different channel number r in stay pattern. Similarly, in SARCH, the channel utilization percentage is low due to random selection of rotation seeds. These factors can affect the occurrence of rendezvous between the sender and receiver and ultimately affects channel utilization. Figure 13 shows the comparison of MUAS with other protocols. The impact of channel numbers on throughput is shown in Figure 14. From the impact of channel utilization percentage, it is clear that the throughput rate of EJS, JS and SARCH is very low as compared to our protocol MUAS.

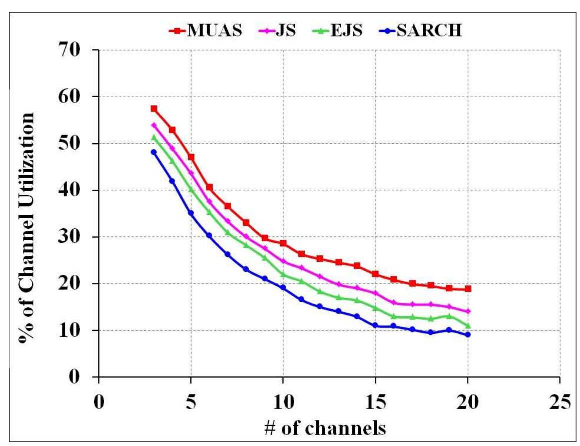

Fig. 13: Comparisons of channel utilization performance (%).

Figure 15 shows the impact of channel numbers on Average Time To Rendezvous (ATTR). In theoretical analysis, it is already shown that ATTR of MUAS under multi-hop in multi-user environment is $\frac{|N|-2}{|N|-3}$. Therefore, with a smaller value of

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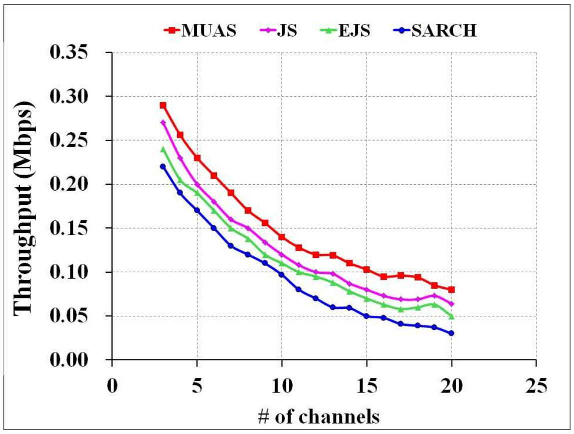

Fig. 14: Comparison of throughput performances.

ATTR, the longer waiting time to establish the communication can be avoided for any pair and hop of the SUs. This result can be supported by MTTR performance. As shown in Figure 16, MTTR of MUAS and SARCH is compared.

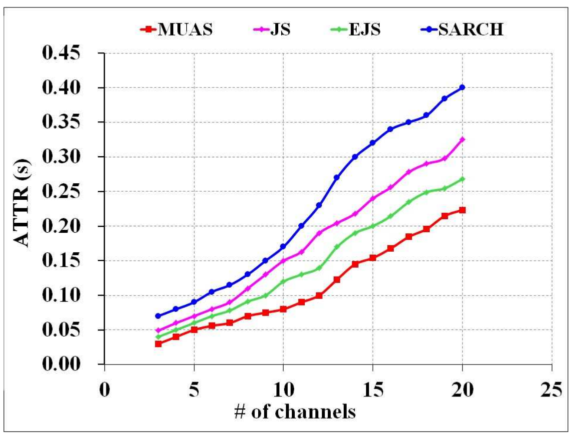

Fig. 15: Comparison of ATTR performances.

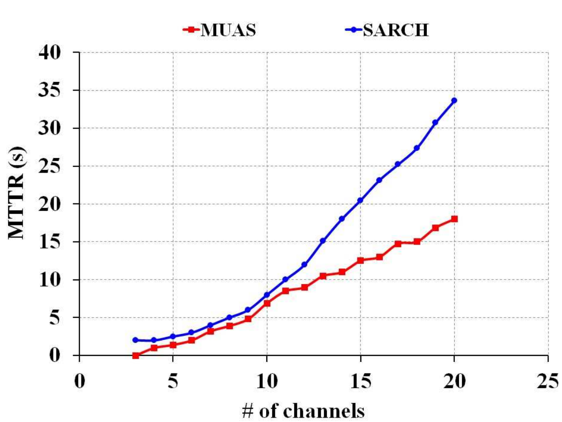

Fig. 16: Comparison of MTTR.

C. *Performance of MUAA*

Figure 17 shows the impact of channel numbers on channel utilization based on the number of SUs. Under an asymmetric asynchronous environment, channel utilization percentage in our protocol with a different number of SUs is evaluated. Based on the multi-hop environment, guaranteed rendezvous can be achieved in MUAA for any pair of SUs in any hops. It can be proved theoretically that the communication can be established rapidly with the achievement of MTTR=$3(|N|+1)$ and $2(|N|+2)$ for even and odd numbers of available channels, respectively. Therefore, along with the increase of any pairs and hops of SUs, the percentage of channel utilization is increased. Figure 18 shows a high percentage of channel utilization in multi-hop environments as compared to single-hop.

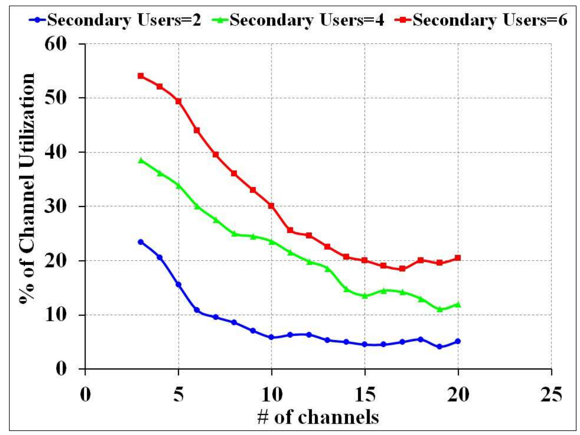

Fig. 17: Channel utilization performances for multi-user.

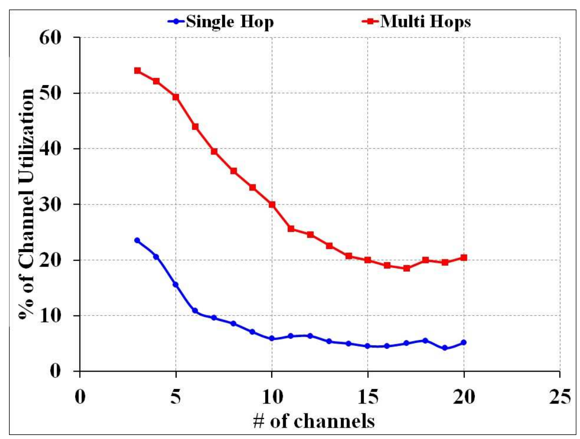

Fig. 18: Channel utilization performance for single-hop and multi-hop.

The impact of channel numbers on channel utilization has been evaluated to compare our protocols with other important existing works. In the Figure 19, the percentage of channel utilization in MUAA is higher than in other works. This can be proved theoretically, which is presented in Table I. Besides, taking any pair of SUs, MTTR in FRCH is $N(2N+1)$, which is high as compared to MUAA as MTTR=$3(|N|+1)$ and $2(|N|+2)$ for even and odd number of available channels, respectively. With a higher value of MTTR, any pair and hop of SUs need to wait longer to establish communication, which gradually decreases the percentage of channel utilization. As a result, a low percentage of channel utilization can affect the throughput of data transmission. Therefore, the throughput in EJS, JS and FRCH is decreased as shown in Figure 20. Considering the asynchronous environment in EJS and JS, the MTTR value for any pair is high, which is $> 4P$ and $> 3P$, respectively. Therefore, the opportunity to send the data is very low, which can decrease the throughput.

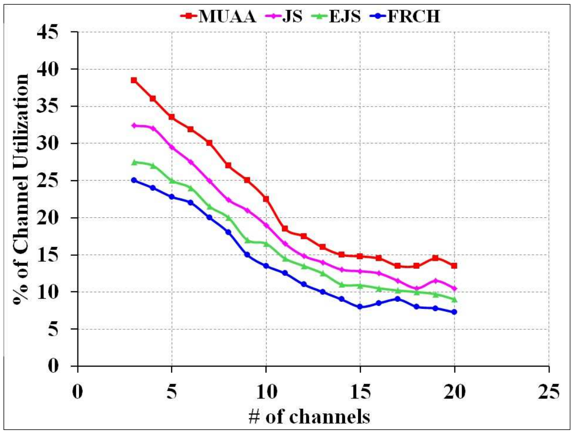

Fig. 19: Comparisons of channel utilization performance (%).

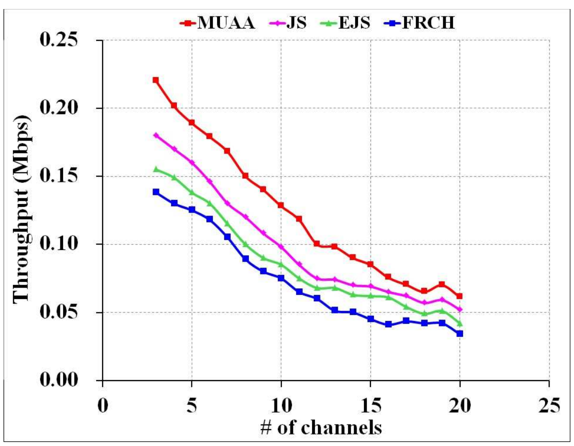

Fig. 20: Comparison of throughput performances.

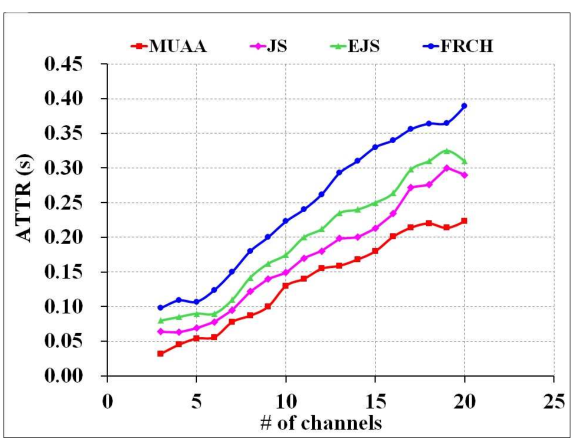

Fig. 21: Comparison of ATTR performances.

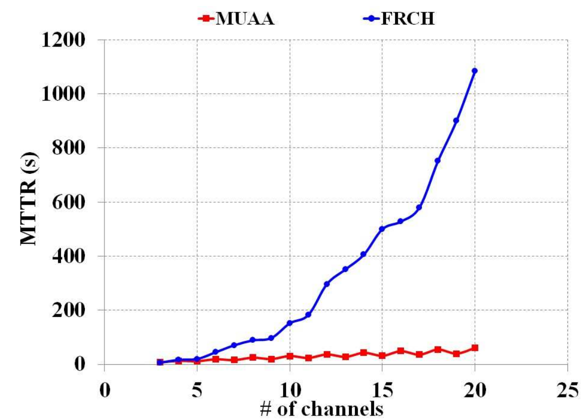

Fig. 22: Comparison of MTTR.

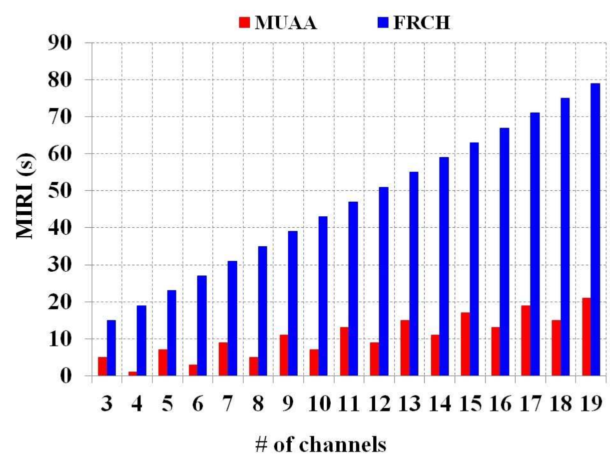

Fig. 23: Comparison of MIRI.

In theoretical analysis, it is already shown that MTTR of MUAA under multi-user multi-hop environment is $3(|N|+1)$ for $|N| = even$ and $2(|N|+2)$ for $|N| = odd$. It is also evaluated that the ATTR value is $\frac{3(|N|+1)+1}{2}$ for even and $\frac{2(|N|+2)+1}{2}$ for an odd number of available channels. Therefore, as shown in Figure 21, the ATTR value in MUAA is smaller as compared to other works, i.e., the MTTR of EJS $> 4P$, JS $> 3P$, and FRCH $N(2N+1)$. Figure 22 shows the comparison of our MUAA protocol with FRCH. It is proven that our protocol MTTR is lower even though the total number of channels is increasing. Moreover, considering MUAA and FRCH are asynchronous CHS algorithms, MIRI metrics are analyzed. Due to the high ATTR and MTTR of FRCH algorithms, as a result, the maximum inter rendezvous interval is high. As shown in Figure 23, it can be observed that the FRCH asynchronous CHS algorithm has a high MIRI metrics value along with the increase of available channels.

VII. Conclusion

In this paper, Asymmetric Synchronous and Asymmetric Asynchronous (ASAA) Channel Hopping (CH) protocol is proposed. The proposed protocol comprises Multi-User Asymmetric Synchronous (MUAS) and Multi-User Asymmetric Asynchronous (MUAA) Channel Hopping Sequence.

Both designed CHS algorithms can work for any number of available channels $|N| \geq 3$. Most importantly, considering multi-user multi-hop scenarios, rendezvous can be rapidly achieved in both proposed CHS algorithms. Taking asymmetric as a challenge to design the CHS, our designed CHS algorithms outperform JS, SARCH, EJS, and FRCH in terms of channel loading (CL), channel utilization (CU), Maximum Time To Rendezvous (MTTR), Average Time To Rendezvous (ATTR), and Maximum Inter Rendezvous Interval (MIRI). The performances have been analyzed and justified theoretically. Moreover, the performance of the CHS algorithms proposed in this paper has been evaluated and compared with other CHS protocols such as JS, EJS, SARCH, and FRCH. Based on the simulation results, the proposed MUAS and MUAA CHS algorithms perform better in terms of channel utilization, ATTR, and throughput. Evaluation of MUAS and MUAA under single-hop and multi-hop scenarios by simultaneously considering $|M|$ number of SUs and $|N|$ number of available channels has been carried out. The results of performance evaluations show that ASAA protocol can be beneficial in the IoT environment under multi-user multi-hop scenarios. In the future, the usage of ASAA protocol in CRN-IoT can enable reliable communication solutions with high throughput as demand for the IoT network is increasing. For instance, our proposed protocol can be utilized intelligently in any IoT devices during emergency situations including fire, natural disasters or accidents occur. By doing so, the IoT device can enable the CRN, sense the availability spectrum, and communicate with other IoT devices by executing the ASAA CHS protocol.

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