A Versatile Shuffle Resource Units Recomputation Algorithm for Uplink OFDMA Random Access

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***Abstract*—IEEE 802.11ax introduces Uplink Orthogonal Frequency Division Multiple Access (OFDMA)-based Random Access (UORA), a novel feature for facilitating random channel access in Wireless Local Area Networks (WLANs). Similar to the conventional random access scheme in WLANs, UORA employs the OFDMA backoff (OBO) procedure to access the channel's Resource Units (RUs) and selects a random OBO counter within the OFDMA contention window (OCW) range. The Access Point (AP) can determine and communicate this OCW range to each station (STA). Multiple STAs accessing RUs result in transmission failure due to RU collisions, which occur when specific RUs remain unassessed by any STA, leading to wastage. Efforts to optimize channel efficiency require minimizing both collisions and idle RU despite the challenges arising from UORA's distributed and random nature. The Fisher-Yates shuffle algorithm introduces a random uniform distribution strategy for managing RU allocations among STAs. The results demonstrate that this approach enables STAs to access RUs in a distributed manner, effectively reducing idle and wasted RUs, especially in scenarios involving a limited number of STAs. Furthermore, this approach effectively mitigates collisions among STAs, even in scenarios with a more significant number of STAs.**

Keywords—IEEE 802.11ax; OFDMA; UORA; random access; backoff; resource units allocation; multi-user

I. INTRODUCTION

Developing MAC (Medium Access Control) protocols that can support large-scale networks with low-power devices elevate the growing number of Internet of Things (IoT) devices; hence, secure communication is essential. OFDMA is a wireless communication technique that allows multiple users to transmit data simultaneously over the same frequency band [1, 2]. Utilizing OFDMA allows sending (e.g., power) to utilize only a fraction of the bandwidth, facilitating simultaneous transmissions, minimizing MAC congestion and reducing overhead, enhancing data transmission efficiency over dense networks, and reducing time wastage.

OFDMA functions in two distinct modes: scheduled access (SA) and random access (RA) [3]. While random access methods like Distributed Coordination Function (DCF) or Enhanced Distributed Channel Access (EDCA) were employed to manage or distribute radio resources in previous WLAN standards, they do not apply to the OFDMA system [1]. UORA is a new feature for random channel access introduced in IEEE 802.11ax.

The channel split into sub-carrier groups known as Resource Units (RUs) in the UORA process. These comprise the minimum OFDMA RUs that STAs need to reach the channel and transmit a frame. With various RUs, multiple STAs can send data packets simultaneously. Each STA chooses a random OBO counter from the OCW value and reduces it by the number of RUs available for UORA to send a particular control frame called a trigger frame (TF). The TF carries information such as the identity information of each STA that may take part in the UL multi-user transmission, the transmission duration, the RUs allocation for each STA, and other helpful information. If the decreased OBO counter drops to zero or less, the STA can send the TF with any available RU. UORA can flexibly control the OCW range based on the number of contending STAs, unlike DCF and EDCA, where the range of contention window (CW) is predetermined.

OCW range is crucial to the UORA performance and primarily depends on the number of contending STAs, but it is challenging for the AP to accurately and quickly estimate or keep track of the number of contending STAs without a specific signaling mechanism.

The Wi-Fi standard random access protocol seldom enables the advantages of reducing network congestion and channel access delay because of the severe frame collision brought by the crowded network conditions to initiate the OFDMA uplink broadcasts. Most studies consider saturation network throughput, but 802.11ax nodes' access delay needs careful examination due to their dependency on AP schedules. In short, the operation of UORA is based on the OCW range and OBO counter values, showing that the random modes of operation make the STAs compete to access the RUs in order to send their UL request during the random selection of one of the 26-RU [4, 5].

The organization of the remaining sections of this article is as follows. Section II delves into the discussion of related open issues concerning UORA. Section III presents the problem formulation. The proposed algorithm is presented in Section IV. The performance evaluation and discussion are in Section V. The conclusion is provided in Section VI.

II. RELATED OPEN ISSUES IN UORA

Numerous strategies have been put forth in the literature to enhance UORA effectiveness, such as grouping, joint, and clustering [6-12]. By aiming to give high channel efficiency, [6, 7] developed an adaptive grouping scheme on UORA. The study [6] consider a target wake time (TWT) to reduce transmission collision. At the same time, [7] proposed a Buffer State Report (BSR)-based Two-stage Mechanism-based adaptive STA grouping scheme (BTM) that analyses the relationship between group size and the RU efficiency in an ultra-dense wireless network, mainly when RUs properties are not identical. The proposed spatial clustering group division-based OFDMA (SCGD-OFDMA) by [8] allows the head STA and multiple STAs to compete for the channel resource where the number of STAs is up to 200 when used for random access. The AP in the Grouping-based UORA (G-UORA) method by [9] divides users based on the utility and distributes resources accordingly using the utility prediction model and matching the utility-based resource allocation algorithm. (OFDMA)-based joint reservation and cooperation MAC (OJRC-MAC) protocol proposed in [10] combines channel reservation and cooperation to reduce access collisions and increase transmission dependability, outperforming the basic UORA. Another protocol outperforms the basic UORA by [11] splitting network STAs into spatial groups based on neighbor channel sensing capacity. Designing an information collection system utilizes a probability-based two-level buffer state report, where intra-group STAs transmit data with minimal power consumption. Simultaneously, the AP strategically organizes two spatial groups to prevent interference. The modification by [12] from the 2019 IEEE 802.11be Wi-Fi standard combined with a novel resource allocation algorithm provides effective real-time communications for the uplink OFDMA feature.

UORA introduces the OBO counter for the operation of multi-user transmission. An important observation is that the backoff procedure for UORA differs from that of DCF or EDCA. While DCF and EDCA perform backoff in the time domain to decide when to transmit, UORA's backoff procedure is two-dimensional, which simultaneously determines both the RUs to occupy in the frequency domain and the transmission time to produce high-efficiency results [1, 13, 14, 15, 16]. The research in [1] demonstrates a noteworthy increase in throughput through a straightforward modification to the OBO counter. However, implementing this suggested mechanism in real-world WLANs with practical settings becomes impractical due to the complexities associated with the OBO control rule. The CRUI (Collision Reduction and Utilization Improvement) method, introduced in [13], improves UORA performance by reducing transmission collisions. This enhancement involves increasing backoff times and utilizing opportunistic sub-channel hopping. Notably, the CRUI scheme ensures that it does not degrade the performance of UL transmissions and prioritizes distributed real-time STA transmissions. Retransmission number aware channel access (RNACA) increases throughput when there are more random access RUs than STAs and lowers packet latency [14]. By optimizing parameters like CWmin and CWmax, RNACA significantly increases the throughput of the maximum number of transmission trials (MNTTSTAs can conduct complementary transmission without backoff using the probability complementary transmission scheme (PCTS) described in [15]. However, it is essential to note that this scheme is applicable only in WLANs with lower mobile station numbers than random access RUs, as STAs must choose RUs based on OFDMA-based backoff counters, causing retransmission delays. In [16], developing a new uplink hybrid UORA (H-UORA) OFDMA access mechanism introduces an RU-sensing slot, enabling additional channel sensing to minimize transmission collisions further. However, H-UORA needs a much finer carrier sensing circuit for the current 802.11ax amendment.

The 802.11ax network throughput can be optimized through RU allocation strategies, as demonstrated in [17, 18, 19, 20, 21]. The research in [17] examined the effects of various RA RU and SA RU distributions on the MAC layer performance, while [18] created a new RU distribution scheduler for managing access that features a closed-loop feedback controller with proportional gain. In [19], the research algorithm achieves a delay of less than one millisecond with a remarkably high level of reliability. On the other hand, in [20], OFDMA transmissions ensure reliable and dependable communication, especially in the presence of interference. Both studies demonstrate the ability to support real-time applications. The study in [21] proposed a channel access scheme for next-generation vehicle-to-anything (V2X) systems that expands backward compatibility with IEEE 802.11-based extension.

Fair Allocation and Effective Utilisation of RUs (FAEU-RUs) protocol in [5] handles the OFDMA MU communications based on the two factors. First is the fairness criterion of ensuring that all STAs in UL reasonably access the RUs, and second is the practical criterion of ensuring that the RUs are optimally allocated and used. The suggested solution in [3] guarantees fairness in RU access and requires minimal overhead, producing results close to optimal. However, it does not effectively adapt to traffic needs.

UORA and RU allocation are a big area to discover because of the drawback of this access mode, which is the high rate of collisions due to competition. Researchers continuously refine advancements in RU allocation for OFDMA as indicated by ongoing research on related open issues. This research focuses on the RU allocation for UORA.

III. Problem Formulation

The IEEE 802.11ax standard [22] defines scheduled and random access as two distinct kinds of uplink multi-user (MU) OFDMA operations. In scheduled access, each STA uses BSR signaling to ask the AP for authorization to transmit while the STAs share the OFDMA RUs without causing any contention. The AP then transmits a TF carrying the scheduling data to allot a dedicated RU to a particular STA. On the other hand, in a random access mode, the STA acquires the RU by the UORA mechanism in a contention-based way.

Fig. 1 illustrates a multi-user wireless communication network model with a single AP and a plurality of STAs based on [4] invention. Table I presents device attributes, which are in Fig. 1. The AP represents the access points, while STA1, STA2, STA3, STA4, STA5, STA6, and STA7 represent various wireless communication devices or STAs.

The UORA method operated by the AP shows that every n^{th} TF for random access transmitted by the AP includes at least one RU for random access available to 20 MHz operating STAs, where N is a positive integer. In other words, every Nth TF for random access contains at least one RU for random access in the primary 20 MHz channel and is unrestricted from being used for 20 MHz operating STAs. A 20 MHz operating STA is allowed to reach the AP with the UORA mechanism when receiving TF for random access.

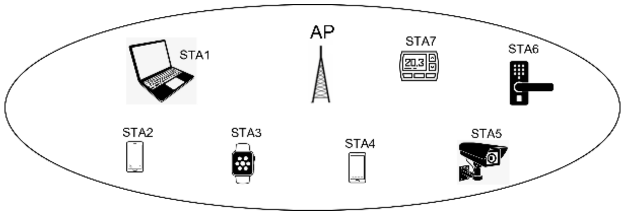


Fig. 1. Network model of a multi-user wireless communication network.

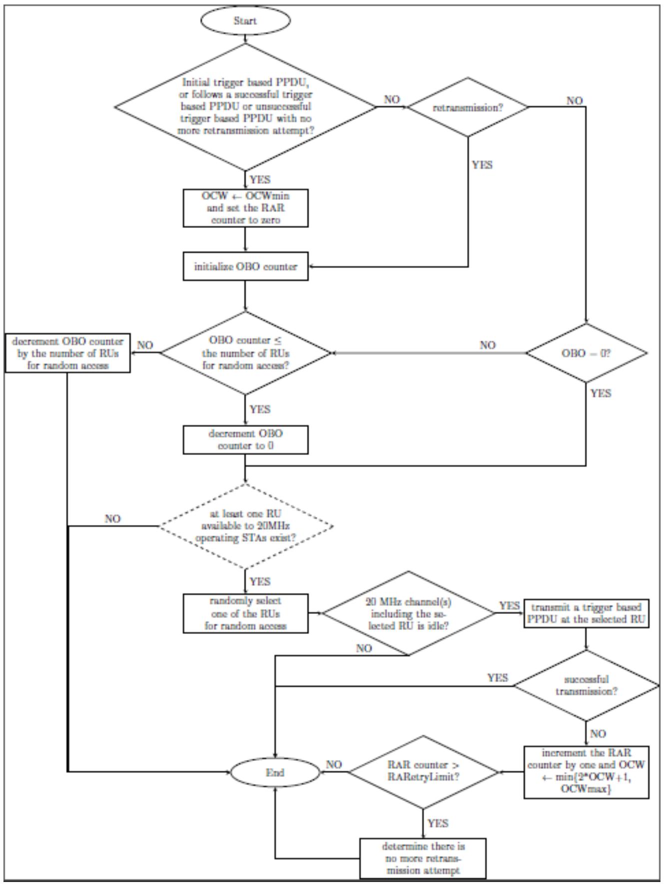


Fig. 2. UORA method operated by a 20MHz station.

The flow chart in Fig. 2 shows an example UORA method operated by a 20 MHz operating station with a detailed explanation in Table II. We assume this scenario occurs between the AP and any available STA capable of operating with a 20 MHz channel width, particularly STA3, STA6, and STA7, as indicated in Table I, since these STAs can only operate using this channel width.

TABLE I. DEVICES ATTRIBUTES

	STA1	STA5	STA2	STA4	STA3	STA6	STA7
Device type	laptop	CCTV	smartphone		smartwatch	Door lock	Thermostat
QoS requirement	high				low		
Power management	Low power saving		Concern about power consumption		Compassionate power consumption		
Channel width (MHz)	20, 40, 80, 80+80, 160		20, 40, 80		20		

TABLE II. DETAILING ON STEPS ACCORDING TO THE FLOW CHART IN FIG. 2

Step	Event
1	20 MHz operating STA receives a TF for random access from the AP.
2	20 MHz operating STA determines its UL transmission as an initial trigger-based PPDU transmission, follows a successful trigger-based PPDU transmission, or follows an unsuccessful trigger-based PPDU transmission for which there is no more retransmission attempt.
2.1	If 20 MHz operating STA UL transmission fulfils Step 2, the STA sets OCW value to OCWmin value and the Random Access Retry (RAR) counter to zero.
2.2	If 20 MHz operating STA UL transmission is unfit, Step 2, 20 MHz operating STA, continues to check if its UL transmission is a retransmission of an unsuccessful trigger-based PPDU transmission.
2.2.1	If 20 MHz operating STA UL transmission is retransmission, the UORA method proceeds to Step 3
2.2.2	If 20 MHz operating STA UL transmission is not retransmission, 20 MHz operating STA determines if the OBO counter is equal to value zero.
2.2.2.1	If the 20 MHz operating STA OBO counter equals zero, the UORA method proceeds to Step 5, implying that the 20 MHz operating STA won the contention but did not transmit a trigger-based PPDU in the previously selected RU in Step 1 since one or more 20 MHz channels containing the previously selected RU are considered busy.
2.2.2.2	If the 20 MHz operating STA OBO counter is not equal to zero, the UORA method proceeds to Step 4. This situation implies that the 20 MHz operating STA did not win the contention to access the RUs for random access in the previous TF in Step 1.
3	20 MHz operating STA initializes its OBO counter to a random value in the range of zero and OCW.
4	20 MHz operating STA checks that its OBO counter is smaller or equal to the number of RUs for random access in the previous TF in Step 1.
4.1	If the OBO counter is smaller or equal, 20 MHz operating STA decreases its OBO counter to zero. This situation implies that 20 MHz operating STA wins the random access contention, which proceeds to Step 5.
4.2	If the OBO counter is higher than 0, 20 MHz operating STA decrement its OBO counter by the number of RUs for random access in the received TF in Step 1, which proceeds in Step 11.
5	20 MHz operating STA determines if at least one RU for random access available to 20 MHz operating STA exists in the received TF.
5.1	If 20 MHz operating STA fulfills Step 5, the UORA method proceeds to Step 6.
5.2	If 20 MHz operating STA is unfit in Step 5, proceed to Step 11.
6	20 MHz operating STA randomly selects one of the RUs for random access in the previous TF in Step 1.
7	20 MHz operating STA checks if each of one or more 20 MHz channels, including the selected RU, is idle due to physical and virtual carrier sensing.
7.1	If the selected RU is idle, 20 MHz operating STA transmits a trigger-based PPDU at the selected RU.
7.2	If the selected RU is not idle, proceed with Step 11.
8	The STA operating at 20 MHz determines the successful transmission of the trigger-based PPDU on the selected RU.
8.1	In the event of a successful transmission, proceed to Step 11.
8.2	If an immediate response is not received as solicited by Step 8, consider the transmission unsuccessful and proceed to Step 9.
9	20 MHz operating STA increments the RAR counter by one and sets the OCW value to the minimum of a sum of double the current OCW value plus one and a value of OCWmax.
10	20 MHz operating STA determines if the RAR counter is more significant than a RARetryLimit threshold, indicating the maximum

	number of random access retransmission attempts.
10.1	If the RAR counter is lesser than RARetryLimit, proceed to Step 11.
10.2	If the RAR counter is enormous than RARetryLimit, 20 MHz operating STA determines there is no more retransmission attempt and then proceeds to Step 11
11	UORA method comes to an end or stops.

TF Info	STA 1 (unassociated)	STA 2 (associated)	STA 3 (associated)	STA 4 (associated)	STA 5 (associated)	STA 6 (associated)	STA 7 (associated)
Random initial OBO value	0	7	7	5	6	5	3
OBO counter	0 - 1 = -1	7 - 8 = -1	7 - 8 = -1	5 - 8 = -3	6 - 8 = -2	5 - 8 = -3	3 - 8 = -5
RU1 (0)	-						
RU2 (0)	-		Access			Access	
RU3 (0)	-						
RU4 (0)	-			Access			
RU5 (0)	-	Access					
RU6 (0)	-						Access
RU7 (0)	-				Access		
RU8 (0)	-						
RU9 (2045)	Access	-	-	-	-	-	-

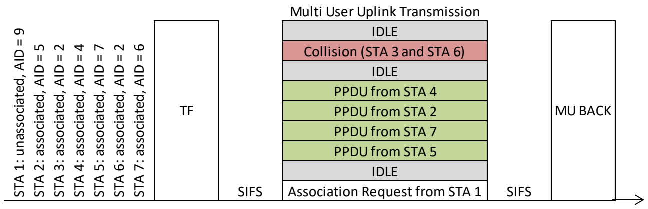


Fig. 3. An example of UORA operation in time and the OBO decrementation after TF reception based on [23].

The usage of the UORA mechanism in a contention-based manner, the STA acquires the RU, as shown in Fig. 3. The AP sends a TF to start the UORA process in the UORA mechanism. The TF includes various data bits, including the associated association identifiers and the eligible random access RUs (RA-RUs) (AIDs). The associated STAs can utilize RA-RUs with the AID number 0, while unassociated STAs can occupy RA-RUs with the AID number 2045 following the 802.11ax standard. The AP may assign some RUs to planned access and others to random access.

However, to concentrate on the efficiency of UORA, the assumption was made that all RUs are qualified for random access without taking scheduled access into account. To be more precise, one RU is assigned to have an AID of 2045 and the rest to have an AID of 0. According to the IEEE 802.11ax standard, the overall number of RUs depends on the channel bandwidth and the number of sub-carriers used for each RU.

Fig. 3 represents an example of the UORA operation. STA 1 is unassociated, and STAs 2-7 are associated. The channel bandwidth is 20 MHz, and 9 RA-RUs consist of eight RUs with AID 0 and one with AID 2045. On receiving the TF, STA 1 decreases its OBO counter by 1, and STAs 2-7 decrease the OBO counter by 8. In this example, the OBO counter for STAs 2-7 becomes ≤ 0, which means the OBO counter is not greater than the number of eligible RUs, and then the STAs sets its OBO counter to 0. Each time OBO = 0, the STAs select a random RA-RU among RU 1-8 to transmit a frame. If there are cases between the STAs where the OBO counter is > 0, the STA cannot access the channel and decreases its OBO counter, waiting for the next contention round upon receiving the next TF. This example also shows that RU can collide and remain idle. STA 3 and STA 6 access the came RU 2, so their transmission can fail due to collisions. Instead, STAs do not access specific RUs (1, 3, and 8), causing these RUs to become wasted. In case of an unsuccessful transmission, the STAs follow the retransmission procedure shown in Algorithm 1 as in the standard UORA. To ensure channel efficiency, one must minimize the number of collisions and wasted RUs. However, achieving this goal is challenging, given the distributed and random nature of UORA. The backoff procedure in UORA is two-dimensional because it determines which RU to occupy in the frequency domain and simultaneously establishes the transmission time, unlike DCF or EDCA, which performs the backoff procedure in the time domain to determine when to transmit.

Algorithm 1 Standard UORA

$OCW_{min} = 7$
$OCW_{max} = 31$
if first transmission, **then**
  $OCW = OCW_{min};$
  $OBO = \text{random integer}(0, OCW);$
else if retransmission, **then**
  $OCW = 2 \times OCW_{old} + 1;$
  if $OCW \geq OCW_{max}$ **then**
    $OCW = OCW_{max};$
  end if
  $OBO = \text{random integer}(0, OCW);$
end if
Station decrements OBO by number of RU and selects a random RU for transmission if $OBO = 0$

More examples are provided by [4] for different types of STA channel widths to perform the frequency scheduling for OFDMA multi-user transmission in 802.11ax. Frequency scheduling is generally performed based on RU that comprises a plurality of consecutive subcarriers. According to frequency scheduling, a radio communication AP adaptively assigns RUs to a plurality of STA based on the reception qualities of frequency bands of the STAs. The situation makes it possible to obtain a maximum multi-user diversity effect and efficiently perform communication.

While the techniques outlined in this disclosure apply to various wireless communication systems, it is essential to note that, for illustrative purposes, the subsequent descriptions in this disclosure pertain to an IEEE 802.11 WLAN system and its associated terminologies. However, this choice of example should not restrict the scope of this disclosure concerning alternative wireless communication systems. In IEEE 802.11-based WLANs, most networks operate in infrastructure mode, i.e., all or most of the traffic in the network must go through the AP. As such, any STA wishing to join the WLAN must first negotiate the network membership with the AP through association and authentication.

IV. Proposed Versatile Shuffle Recomputation RU Algorithm

We proposed to change the operation of standard UORA behaviors as in Algorithm 1 to improve its efficiency. To ensure the adaptability of STAs allocation based on the available RUs, we introduce the versatile shuffle recomputation RU (VSR-RUs) algorithm.

In VSR-RUs, The Fisher-Yates shuffle algorithm [24] shown in Algorithm 2, also known as the Knuth shuffle or the Durstenfeld shuffle, was applied for the RUs recomputation. The Fisher-Yates shuffle algorithm is employed to efficiently generate a random permutation of an array of elements by randomly shuffling them. This shuffle algorithm iterates the array in reverse order and swaps the current element at each step with a randomly chosen element that comes before it (including itself). This process ensures that every element in the original array has an equal chance of being placed in any position within the shuffled array, which means that when applied to UORA, it is the RUs allocation. Introducing randomness at each process step establishes a uniform likelihood of interchanging with any previous element. The algorithm has a time complexity of O(n), where n is the number of elements in the array. It is considered a highly efficient and unbiased method for shuffling arrays.

Algorithm 2 The Fisher-Yates shuffle algorithm

```
function fisherYatesShuffle(array)
    n = length(array);

    for i from n − 1 down to 1:
        j = random integer(0, i);
        swap(array[i], array[j]);
    OBO = random integer(0, OCW);

function randomInteger(min, max):
    return random(min, max);

function swap(a, b):
    temp = a;
    a = b;
    b = temp;
```

Table III shows the STAs RA-RUs allocation in standard OURA in Fig. 3 after applying the Fisher-Yates shuffle algorithm. Recomputing the allocation of RUs prevents collisions within RU 2 while distributing the available RUs among STAs ensures that each STA is guaranteed its allocation without sharing. However, RU 3 and RU 4 remain idle as the number of STAs is < the number of RUs. If an STA OBO counter is greater than 0 and cannot access the channel, it could be due to the STA not being allocated in any available RUs. In such cases, the STA must wait for the next contention round upon receiving the next TF.

Fig. 4 is an example of the Fisher-Yates shuffle mechanism using the RUs array [1, 2, 3, 4, 5, 6, 7, 8, 9]. The mechanism is performed in the following order;

1) *Randomly* select a number k from 1 to 9, and then swap the k^th^ and 9^th^ STA. So, if the random number is 4, swap the 4^th^ and 9^th^ STA in the list.

2) *Select* the following random number from 1 to 8 and swap the chosen STA with the 8th STA. If it is 6, for example, swap the 6^th^ and 8^th^ STA.

3) *If* the array contains multiple STAs, a random selection will determine which STAs are placed on the list.

4) *The* iteration continues until the permutation is completed, as illustrated in Fig. 4.

After shuffling, the last row of the shuffle displays the output on RUs. This process ensures that the original order of the array is completely randomized while maintaining a uniform distribution of possible outcomes.

TABLE III. THE STAS RUS SELECTION ON STANDARD UORA BEFORE AND AFTER APPLYING ALGORITHM 2

RU #	STAs allocation on RU #	
	Before	After
RU 1	[]	[Associated STA 5 (AID: 0)]
RU 2	[Associated STA 3 (AID: 0), Associated STA 6 (AID: 0)]	[Associated STA 3 (AID: 0)]
RU 3	[]	[]
RU 4	[Associated STA 4 (AID: 0)]	[]
RU 5	[Associated STA 2 (AID: 0)]	[Unassociated STA 1 (AID: 2045)]
RU 6	[Associated STA 7 (AID: 0)]	[Associated STA 6 (AID: 0)]
RU 7	[Associated STA 5 (AID: 0)]	[Associated STA 2 (AID: 0)]
RU 8	[]	[Associated STA 7 (AID: 0)]
RU 9	[Unassociated STA 1 (AID: 2045)]	[Associated STA 4 (AID: 0)]

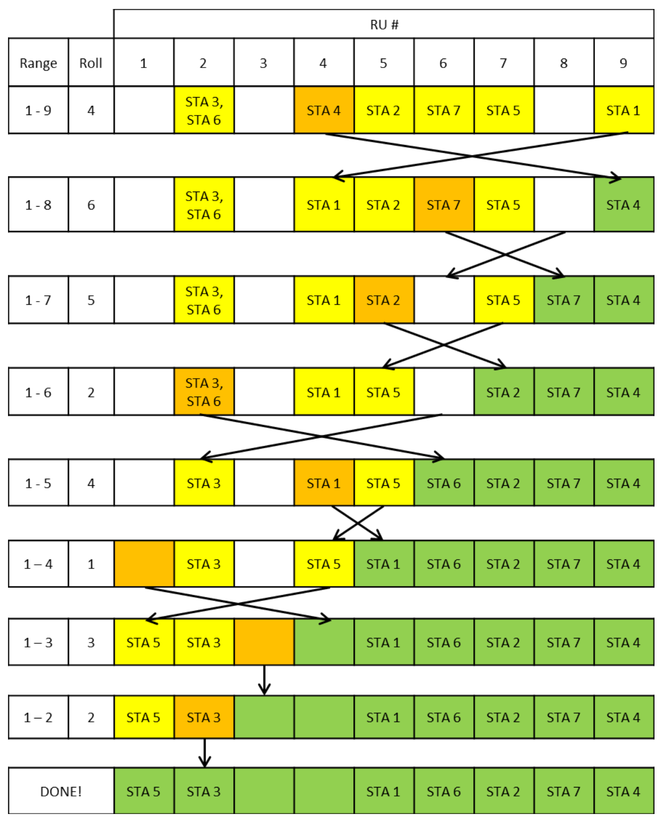


Fig. 4. Recomputation of array for RUs allocation by using Fisher-Yates shuffle.

V. Performance Evaluation and Discussion

This section concentrates on the implementation and evaluation of the performance of the proposed VSR-RUs algorithm. A comparison is made against the standard UORA [22]. These evaluations are used to assess the effectiveness of the VSR-RUs algorithm. The Java programming language develops the DES simulation using Eclipse IDE for Java Developers with Indigo Service Release 2 software.

Algorithm 3 Standard OURA pseudocode structure

```
for a := 1 to NumberofExperiment do
    initialization()
    for i := 1 to maxNoOfStation do
        event[i][j] = time assign;  //rand()%(OCW-1)
    end for
    while simulation run do
        if (simulationTime < 60) then
        scheduler()
        update simulationClock()
        if eventType = 1 then
            intendtoTransmit()
        else if eventType = 2 then
            packetGeneration()
        else if eventType = 3 then
            triggerFrame()
        else if eventType = 4 then
            acknowledgment()
        end if
    end if
end while
result()
end for
```

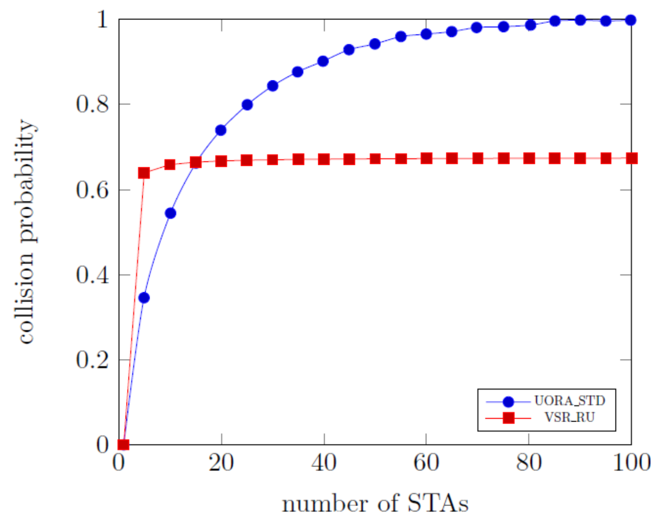
Algorithm 3 shows the pseudocode structure for the novel UORA. The pseudocode begins with the initialization of all the parameters involved. Table IV displays the parameters. Each STA has an event defined, and Table V illustrates these defined events. The Random() function from the mathematical Java library generates the random number, adhering to a uniform distribution. The larger the number generated, the smaller the access probability. During the simulation, as long as the simulation time remains under a minute, the scheduler function will execute, leading to an update of the simulation clock. Subsequently, the event will be chosen based on its type, and the simulation present the outcome afterwards.

TABLE IV. Simulation Parameters

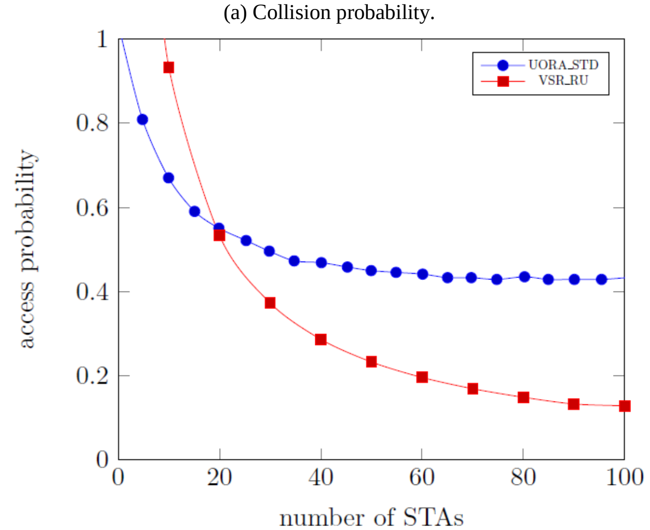
Parameter	Value
Simulation time	60 s
Channel bandwidth	20 MHz
Number of subcarriers RU	26
Number of RU AID = 0	8
Number of RU AID = 2045	1
Number of contending STAs	1~100
Data rate per RU	6.67 Mb/s
Trigger frame length	100µs

TABLE V. Uplink OFDMA Event Define

No	Event	STA	Time Assign
1	Frame transmission intention	1	ev[1][1]
2	Generate random number	1	ev[1][2] = rand();
3	Trigger frame	1	ev[1][3] = transmit TF
4	Acknowledgment	1	ev[1][4] = transmit ACK
No	**Event**	**AP**	**Time Assign**
1	Frame transmission intention	1	evAP[1]
2	Trigger frame	1	evAP[2] = transmit TF
3	Acknowledgment	1	evAP[3] = transmit ACK



(a) Collision probability.



(b) Channel access probability.

Fig. 5. Performance comparison of collision probability and channel access probability between standard UORA and the proposed VSR_RU.

Fig. 5 compares the collision probability and channel access probability between the standard UORA and VSR_RU proposed algorithm. Fig. 5(a) shows that the number of collision probabilities for VSR-RUs is at steady state once the number of STAs approaches ten and increases. As the number of STAs increases, the RUs allocation is more uniformly distributed, thus contributing to the decrease in collision.

When examining Fig. 5(b), it becomes evident that with fewer STAs (1-20), the increased access probability of VSR_RUs has reduced the probability of having idle RUs. This reduction in idle RUs has the potential to enhance overall throughput. Conversely, employing lower access probabilities from VSR_RU could be a strategic choice for distributing resources among STAs or processes demanding a higher quality of service or performance. This approach would prioritize critical tasks appropriately.

The proposed VSR_RU algorithm improved the random distribution for allocating STAs to RUs, resulting in lower collisions among STAs. This strategy enables STAs to access RUs in a distributed fashion, which may cause fewer idle and wasted RUs, especially in scenarios with limited STAs. Besides, STA collisions are less when the number of STAs is higher.

VI. Conclusion

The VSR_RU algorithm, as proposed, employs a random uniform distribution approach using the Fisher-Yates shuffle algorithm for each STA to manage allocations in available RUs. This algorithm operates without requiring any prior information about the number of STAs. The key innovation lies in introducing a shuffled random distribution for assigning STAs to RUs, effectively minimizing collisions among STAs. This approach enables STAs to access RUs in a distributed manner, thereby reducing the occurrence of idle and wasted RUs, particularly in scenarios with a small number of STAs. Moreover, it also mitigates STA collisions in scenarios with many STAs. The adaptability incorporated into the proposed algorithm improves the standard IEEE 802.11ax UORA mechanism.

Further development could involve refining the OBO control rule through a more efficient UORA mechanism within the proposed algorithm. The limitation of the research is that shuffling can take a significant amount of time for massive arrays by applying the Fisher-Yates algorithms. Additionally, reinforcement learning technology can enhance UORA performance in real-world WLAN environments.

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References

[1] Y. Kim, L. Kwon, and E.-C. Park, "OFDMA Backoff Control Scheme for Improving Channel Efficiency in the Dynamic Network Environment of IEEE 802.11ax WLANs," Sensors, vol. 21, no. 15, 2021, doi: 10.3390/s21155111.

[2] C. Christopher, "Orthogonal Frequency Division Multiple Access, "In An Introduction to LTE LTE, LTE-Advanced, SAE, VoLTE and 4G Mobile Communications, pp. 67–85. John Wiley & Sons, Ltd, 2014, doi: 10.1002/9781118818046.ch4.

[3] K. Kosek-Szott, and K. Domino, "An Efficient Backoff Procedure for IEEE 802.11ax Uplink OFDMA-Based Random Access," IEEE Access, vol. 10, pp. 8855-8863, 2022, doi: 10.1109/ACCESS.2022.3140560.

[4] L. Huang, R. Chitrakar, Y. Urabe, I. Yoshii, "Orthogonal Frequency-Division Multiple Access Communication Apparatus and Communication Method," U.S.Patent 20210282184A1, 9 Sep. 2021.

[5] S. Brahmi, and M. Yazid, "Towards a Fair Allocation and Effective Utilization of Resource Units in Multi-User WLANs-based OFDMA technology," Computer Networks, vol. 224, pp. 109639, 2023, doi: 10.1016/j.comnet.2023.109639.

[6] J. Bai, H. Fang, J. Suh, O. Aboul-Magd, E. Au, and X. Wang, "Adaptive Uplink OFDMA Random Access Grouping Scheme for Ultra-Dense Networks in IEEE 802.11ax," 2018 IEEE/CIC International Conference on Communications in China (ICCC), Beijing, China, 2018, pp. 34-39, doi: 10.1109/ICCChina.2018.8641202.

[7] J. Bai, H. Fang, J. Suh, O. Aboul-Magd, E. Au, and X. Wang, "An adaptive grouping scheme in ultra-dense IEEE 802.11ax network using buffer state report based two-stage mechanism," China Communications, vol. 16, no. 9, pp. 31-44, Sept. 2019, doi: 10.23919/JCC.2019.09.003.

[8] Y. Li, B. Li, M. Yang, and Z. Ya, "A spatial clustering group division-based OFDMA access protocol for the next generation WLAN," Wireless Networks, vol. 25, pp. 5083–5097, 2019, doi: 10.1007/s11276-019-02115-2.

[9] A. Yang, B. Li, M. Yang, Z. Yan, and Y. Xie, "Utility optimization of grouping-based uplink OFDMA random access for the next generation WLANs, "Wireless Networks, vol. 27, pp. 809–823, 2021, doi: 10.1007/s11276-020-02489-8.

[10] Y. Zhang, B. Li, M. Yang, Z. Yan, and X. Zuo, "An OFDMA-based joint reservation and cooperation MAC protocol for the next generation WLAN," Wireless Networks, vol. 25, pp. 471–485, 2019, doi: 10.1007/s11276-017-1567-1.

[11] M. Peng, B. Li, Z. Yan, and M. Yang, "A Spatial Group-Based Multi-User Full-Duplex OFDMA MAC Protocol for the Next-Generation WLAN," Sensors, vol. 20, no. 14, 2020, doi: 10.3390/s20143826.

[12] E. Avdotin, D. Bankov, E. Khorov, and A. Lyakhov, "Enabling Massive Real-Time Applications in IEEE 802.11be Networks," 2019 IEEE 30th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Istanbul, Turkey, 2019, pp. 1-6, doi: 10.1109/PIMRC.2019.8904271.

[13] J. Kim, H. Lee, and S. Bahk, "CRUI: Collision Reduction and Utilisation Improvement in OFDMA-Based 802.11ax Networks," 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 2019, pp. 1-6, doi: 10.1109/GLOBECOM38437.2019. 9013337.

[14] Y. Zheng, J. Wang, J., Q. Chen, and Y. Zhu, "Retransmission Number Aware Channel Access Scheme for IEEE 802.11ax Based WLAN", Chinese Journal of Electronics, vol. 29, no. 2, pp 351-360, 2020, doi: 10.1049/cje.2020.01.014.

[15] J. Wang, M. Wu, Q. Chen, Y. Zheng, and Y. -h. Zhu, "Probability Complementary Transmission Scheme for Uplink OFDMA-based Random Access in 802.11ax WLAN," 2019 IEEE Wireless Communications and Networking Conference (WCNC), Marrakesh, Morocco, 2019, pp. 1-7, doi: 10.1109/WCNC.2019.8885789

[16] L. Lanante, C. Ghosh, and S. Roy, "Hybrid OFDMA Random Access With Resource Unit Sensing for Next-Gen 802.11ax WLANs," IEEE Transactions on Mobile Computing, vol. 20, no. 12, pp. 3338-3350, 1 Dec. 2021, doi: 10.1109/TMC.2020.3000503

[17] S. Bhattarai, G. Naik, and J. -M. J. Park, "Uplink Resource Allocation in IEEE 802.11ax," ICC 2019 - 2019 IEEE International Conference on Communications (ICC), Shanghai, China, 2019, pp. 1-6, doi: 10.1109/ICC.2019.8761594.

[18] D. G. Filoso, R. Kubo, K. Hara, S. Tamaki, K. Minami, and K. Tsuji, "Proportional-based Resource Allocation Control with QoS Adaptation for IEEE 802.11ax," ICC 2020 - 2020 IEEE International Conference on Communications (ICC), Dublin, Ireland, 2020, pp. 1-6, doi: 10.1109/ICC40277.2020.9149111.

[19] E. Avdotin, D. Bankov, E. Khorov, and A. Lyakhov, "OFDMA Resource Allocation for Real-Time Applications in IEEE 802.11ax Networks," 2019 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), Sochi, Russia, 2019, pp. 1-3, doi: 10.1109/BlackSeaCom.2019.8812774.

[20] E. Avdotin, D. Bankov, E. Khorov, and A. Lyakhov, "Resource Allocation Strategies for Real-Time Applications in Wi-Fi 7," 2020 IEEE International Black Sea Conference on Communications and

Networking (BlackSeaCom), Odessa, Ukraine, 2020, pp. 1-6, doi: 10.1109/BlackSeaCom48709.2020.9234994.

[21] J. Ahn, Y. Y. Kim, R. Y. Kim, "A Novel WLAN Vehicle-To-Anything (V2X) Channel Access Scheme for IEEE 802.11p-Based Next-Generation Connected Car Networks," Applied Sciences, vol. 8, no. 11, 2018, doi: 10.3390/app8112112.

[22] "IEEE Draft Standard for Information Technology -- Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks -- Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment Enhancements for High Efficiency WLAN," IEEE P802.11ax/D4.0, February 2019, vol., no., pp.1-746, 12 Mar. 2019.

[23] "IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN," IEEE Std 802.11ax-2021 (Amendment to IEEE Std 802.11-2020), vol., no., pp.1-767,19 May 2021, doi: 10.1109/IEEESTD.2021.9442429.

[24] E. Manuel, "Fisher-Yates shuffle," Archive of Formal Proof, Nov. 2016.