Design and Evaluation of IEEE 802.11ax Uplink Orthogonal Frequency Division Multiple Random Access in ns-3

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ABSTRACT

Wi-Fi networks have long relied on the Enhanced Distributed Channel Access (EDCA) mechanism, allowing stations to compete for transmission opportunities. However, as networks become denser and emerging applications demand lower latency and higher reliability, the limitations of EDCA — such as overhead due to contention and collisions — have become more pronounced. To address these challenges, Orthogonal Frequency Division Multiple Access (OFDMA) has been introduced in Wi-Fi, enabling more efficient channel utilization through scheduled resource allocation. Furthermore, Wi-Fi 6 defines Uplink Orthogonal Frequency Division Multiple Random Access (UORA), a hybrid mechanism that combines both scheduled and random access, balancing efficiency and responsiveness in resource allocation. Despite significant research on UORA, most studies rely on custom simulators that are not publicly available, limiting reproducibility and preventing validation of the presented results. The only known open-source UORA implementation in the ns-3 simulator exhibits key limitations, such as usage of the same trigger frame (TF) to schedule resources for buffer status reports and data transmissions, and lack of signaling for UORA configuration. In this paper, we present a fully standard-compliant and open source UORA implementation that is compatible with the latest ns-3 version, addressing these limitations to improve resource allocation efficiency and adaptability. This implementation enables more accurate and flexible evaluation of UORA, fostering future research on Wi-Fi resource allocation strategies.

CCS CONCEPTS

• **Network simulations**; • **Wireless local area networks**; • **Link-layer protocols**;

KEYWORDS

Wi-Fi, NS-3, simulation, channel access, OFDMA, UORA

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1 INTRODUCTION

For a long time, the channel access in Wi-Fi networks has been dominated by a random channel access mechanism called Enhanced Distributed Channel Access (EDCA). This mechanism allows multiple Wi-Fi stations to compete for the channel, with the possibility that multiple stations will transmit at the same time, leading to a *collision*, and consequent unsuccessful decoding of the data packets. In such cases, Wi-Fi stations will use the EDCA procedure again to gain access to the channel for retransmissions. With the evolution of Wi-Fi networks, multiple factors came into play. Firstly, networks have become denser, which leads to a higher number of devices competing for the channel and therefore more collisions. Secondly, new applications have emerged, such as Extended Reality (XR) and Industrial Automation, which require significantly lower delays with higher guarantees. Finally, the new Wi-Fi standards have significantly increased the amount of bandwidth, from 20 MHz in the early Wi-Fi standards to hundreds of MHz in the latest ones. As a consequence, the IEEE 802.11ax amendment, also known as Wi-Fi 6, introduced scheduled channel access called Orthogonal Frequency Division Multiple Access (OFDMA) to Wi-Fi networks [7]. Unlike earlier Wi-Fi standards, where a station occupies the entire channel bandwidth during transmission, OFDMA divides the available bandwidth into multiple Resource Units (RUs), which are assigned to different stations.

Using OFDMA, the access point (AP) can assign RUs to stations (STAs) associated with it. Wi-Fi supports both downlink (DL) and uplink (UL) OFDMA transmissions. The new channel access mechanism opens up many opportunities for efficient centralized resource management. Moreover, it significantly reduces the contention in uplink. Indeed, with UL OFDMA the STAs can stop competing for the channel, because the AP can now assign resources to them. This way, a significant part of the overhead related to back-off timers and retransmissions after collisions can be eliminated. To assign resources in uplink, the AP should be aware of the status of the buffers on the STAs. For that, the AP can also assign RUs for polling, i.e., for buffer status reports (BSRs) transmitted from STAs in uplink. With rising number of the STAs it becomes increasingly more complex for the AP to schedule RUs on time to avoid ineffective use of RUs, i.e., assignment of RUs to STAs with empty buffers while STAs with packets in their buffers are waiting for too long [2]. To overcome this issue, Wi-Fi 6 defines a hybrid approach called *Uplink Orthogonal Frequency Division Multiple Random Access (UORA)*, which shares the properties of both random and scheduled access mechanisms. Specifically, the AP divides the RUs into two types:

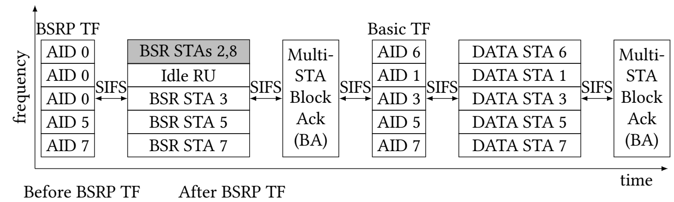
Scheduled Access (SA) RUs and Random Access (RA) RUs. Then the AP transmits a special frame called trigger frame (TF), which contains information about which RUs are assigned to which STAs. Upon receiving the TF, the scheduled STAs transmit using their assigned SA RUs in a contention-free manner. In contrast, all STAs can compete for RA RUs through a contention-based mechanism, which is described in detail in Section 2. Using UORA, the AP can maintain the balance between efficient scheduling of resources to the STAs with known buffer sizes and polling the STAs for information about new packets.

Multiple research papers [3–6, 8–11, 13, 15] have studied UORA from different perspectives. The majority of the papers propose various extensions to UORA for improvement in terms of resource utilization, number of collisions, and energy efficiency. Most of these papers rely on simulation for the performance evaluation of the proposed algorithms. However, the simulation results have been obtained in custom simulators, which are not publicly available for testing and validation. To the best of our knowledge, the only implementation of UORA in a major trustworthy open source network simulator was developed by Naik *et al.* [12]. The implementation makes use of the ns-3 simulator [14], and the results have been validated against a mathematical model. However, this implementation has several shortcomings. Firstly, due to its design, only one trigger frame (TF) is used in UL OFDMA transmission, meaning the same resources are allocated for buffer status reporting and data transmission, resulting in inefficient resource utilization. Secondly, the signaling required to configure the UORA parameter set on STAs has not been implemented, thereby restricting on-the-fly parameter configuration adjustments. In this paper, we present a fully standard-compliant implementation of UORA compatible with the newest ns-3 version, which incorporates a standalone scheduler designed to maximize the full potential of UORA by decoupling resource allocation for buffer status reports and data transmissions.

The remainder of the paper is organized as follows. In Section 2, we provide a detailed description of the UORA operation. We also give a brief overview of the state of the art of research related to UORA performance evaluation and optimization. In Section 3, we explain the key components of the proposed implementation in the ns-3 simulator. In Section 4, we show the results of our implementation's validation. Finally, in Section 5, we conclude the paper.

2 BACKGROUND

In this section, we describe the operation of UORA in detail. After the AP successfully gains channel access through contention, it initiates UL transmission by sending a Trigger Frame (TF). In this TF, the AP can designate each RU for either RA, allowing all STAs to use it, or SA, restricting its use to a single designated STA. There are two types of TF: Buffer Status Report Poll (BSRP) TF and Basic TF. The BSRP TF directs STAs to report their buffer status, while the Basic TF signals for UL data transmission. During the association stage, the AP sends the UORA parameter set, which includes the OFDMA Contention Window (OCW) range defined by $EOCW_{min}$ and $EOCW_{max}$. These parameters are transmitted in the beacon management frame, and their values can be adjusted as needed. After receiving these parameters, a STA uses them to set the value of



Before BSRP TF

STA	OBO
1	15
2	1
3	2
4	5
6	7
8	3

After BSRP TF

STA	OBO
1	12
2	0
3	0
4	2
6	4
8	0

Figure 1: Frame exchange sequence for OFDMA channel access with UORA. Tables in the bottom show the values of OFDMA back-off (OBO) for all STAs before and after BSRP TF is received. STAs whose OBO reaches 0 are framed with red.

its OCW. When a STA decides to participate in UORA (e.g., when it needs to transmit a new buffer status report), it initializes its OCW to $OCW_{MIN} = 2^{EOCW_{min}} - 1$ and randomly selects an initial OFDMA back-off (OBO) value within the range $[0, OCW]$. The maximum OCW value is determined as $OCW_{MAX} = 2^{EOCW_{max}} - 1$. Then upon receiving a new TF, it decreases its OBO counter by the number of RA RUs indicated in this TF. If the OBO counter is less than or equal to the number of RA RUs, the STA randomly selects one of advertised RA RUs in the TF and uses it to transmit. If the transmission is successful, the STA resets its OFDMA contention window (OCW) to OCW_{MIN}. In the event of a failed transmission, the OCW is doubled each time until it reaches an upper bound of OCW_{MAX}. The AP recognizes that the buffer status of STAs that experienced transmission failures remains unchanged. Consequently, it can account for this when allocating resources in subsequent transmissions.

Figure 1 illustrates the UORA frame exchange sequence. The AP initiates an UL OFDMA transmission by sending a BSRP TF, which includes three RA RUs (denoted by AID 0) and two SA RUs assigned to STAs 5 and 7. This BSRP TF prompts STAs to report their buffer status, enabling the AP to identify which STAs require resources. After one Short Interframe Space (SIFS), a STA transmits a BSR using either a randomly selected RA RU or an SA RU assigned to it. A STA is eligible to select an RA RU if its OBO value is less than or equal to the number of RA RUs advertised in the BSRP TF. STAs 2, 3, and 8 meet this criterion. Consequently, after a SIFS, they randomly select and transmit using one of the RA RUs. Specifically, STA 3 selects the third RA RU and successfully transmits, while STAs 2 and 8 transmit using the same RA RU, resulting in a collision (shown as the shaded area), leaving one unused RU. Following this, the AP acknowledges the transmission by sending a Multi-STA Block ACK after a SIFS. STA 3, which transmitted successfully, randomly selects a new OBO value from the range $[0, OCW = OCW_{MIN}]$, whereas STAs with unsuccessful transmissions choose their new OBO value from $[0, 2^{OCW} - 1]$, up to a maximum of OCW_{MAX}. After another SIFS, the AP allocates RUs to STAs that have reported having data to transmit (STAs 3, 5, and 7). The AP can also allocate

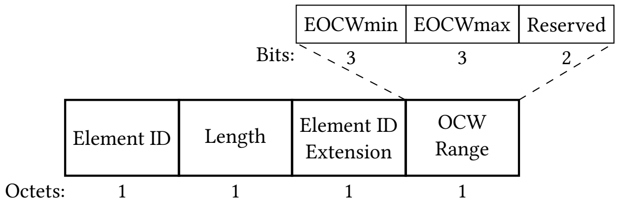


Figure 2: UORA Parameter Set element format

resources to STAs that have previously reported non-zero buffer statuses, or to STAs that it thinks might have data for transmission but failed to deliver their buffer statuses. For example, on the picture the AP also allocates resources to STAs 1 and 6. It is also allowed to assign some of the RUs for random access but the overhead due to collisions of the data packets is usually significantly higher than that for BSRs. Note that RUs can be of different sizes depending on the needs of the STAs, but for simplicity, they are considered the same. This allocation is communicated through the Basic TF. Following one more SIFS, these STAs transmit on their respective RUs. To ensure synchronized transmission, smaller payloads are padded to match the size of the largest payload. Finally, the AP sends a Multi-STA Block ACK after a SIFS, thereby concluding the UL OFDMA transmission with RA RUs.

Many studies proposed various modifications to UORA in order to improve its performance. In particular, modifications have been proposed for the selection of the OBO counter [9, 13], back-off countdown procedure [10, 11], and collision resolution [3]. Xie *et al.* [15] proposed to reduce collisions among stations contending for the same RU by applying busy tone arbitration. Multiple papers studied combining UORA with other mechanisms that emerged in new Wi-Fi standards, such as multi-link operation [8], and target wake time [6]. Furthermore, some papers [4, 5] proposed scheduling algorithms that leverage both random and scheduled access procedures.

Despite the considerable number of papers listed studying UORA, none of these papers provide a validated implementation of UORA in a trustworthy network simulation platform. To our knowledge, the only publicly available validated implementation has been developed by Naik et al. in [12]. However, in the implementation of Naik *et al.*, resource allocation occurs only at the beginning of each UL OFDMA transmission when polling STAs for their buffer status. As a result, collided or idle RUs during polling are not utilized for data transmission, leading to a decrease in the expected performance of UORA. Additionally, signaling of the UORA parameter set to STAs via beacon management frames has not been implemented. The signaling of parameters enhances flexibility and control over parameter configuration and adjustments. For example, in our implementation, OCW_{min} and OCW_{max} can be dynamically modified based on the traffic density of the deployment.

3 UORA IMPLEMENTATION IN NS-3

In this section, we provide a high-level overview of the classes of the Wi-Fi module that were created or modified to implement the UORA functionality, explaining their interactions in enabling this feature in both the AP and STAs. We conclude by highlighting the aspect of UORA usage that is yet to be supported.

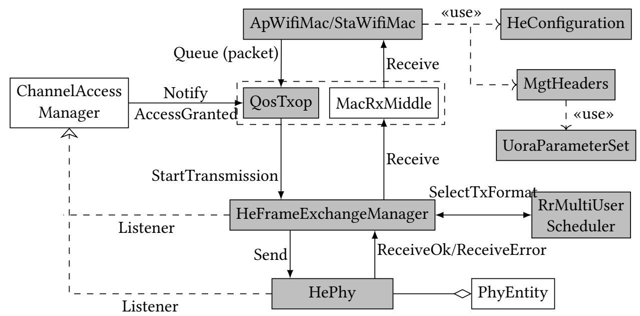


Figure 3: Abridged ns-3 802.11ax Wi-Fi models: components with a grey background represent modified or newly introduced classes in our Implementation

Our UORA implementation extends the ns-3 IEEE 802.11ax Wi-Fi models by adding new classes and modifying existing ones. Figure 3 depicts an abridged view of the ns-3 IEEE 802.11ax Wi-Fi models where components with a grey background indicate the modified and newly added classes. We introduce a new class, *UoraParameterSet*, that implements the UORA Parameter Set element. The UORA Parameter Set element consists of an octet for each of the element id, the length, the extension id and the *OCW* range, as illustrated in Figure 2. The first three bits of the most significant octet, *OCW* range, is $EOCWmin$ and the next three bits represent $EOCWmax$, with the final two bits reserved for future use. Additionally, we modified the *MgtHeaders* class to incorporate the UORA parameters in the beacons. The *HeConfiguration* class configures the $OCWmin$ and the $OCWmax$ values on the AP side.

The *ApWifiMac* and *StaWifiMac* classes manage beacon generation, probing, and association functionality in Wi-Fi. Consequently, these classes have been modified to incorporate UORA parameters into the management frames. Furthermore, the process of updating a STA's OCW value after a successful transmission on a randomly selected RU or a collision caused by multiple STAs transmitting on the same RU, along with selecting a new *OBO* value in either case, is implemented in *QosTxop*. The *HeFrameExchangeManager* is responsible for managing the frame exchange sequence of UORA, as illustrated in Figure 1, ensuring that each step in the sequence is executed at the appropriate time. For instance, it enforces that the AP sends a Multi-STA Block ACK after one SIFS when it receives a BSR from a STA on an RA RU. Additionally, it interacts with the *RrMultiUserScheduler* object to allocate RUs to STAs during scheduled access while reserving some RUs for RA. The *RrMultiUserScheduler* class prioritizes the rescheduling of unused RUs from the BSRP/BSR exchange, whether due to collisions or lack of selection by STAs, for packet transmission in the Basic TF, thus improving resource efficiency. However, it also accommodates scenarios where unused RUs from BSR transmission remain unscheduled in the Basic TF.

Unassociated STAs can send association requests in RA RUs, provided they receive a TF with the AID 2045 of an RA RU. However, this feature of UORA is not yet implemented. The code for this work is available at [1].

Table 1: List of simulation parameters

Parameter	Value
Carrier frequency	5 GHz
Bandwidth	20 MHz
Guard Interval	0.8 µs
MCS Index	8
Resource Unit Type	26-tone only
Transmit Opportunity	2080 µs
Beacon Interval	204 800 µs
OCW_{min}	31
OCW_{max}	127
Uplink Payload Size	1700 B
Traffic profile	Full buffer
Duration of Simulation	15 s

4 VALIDATION OF IMPLEMENTATION

To validate our UORA implementation, we run simulations in ns-3 and collect relevant performance metrics. The simulation results are then compared against the analytical model proposed by Naik et al. [12]. This comparison helps verify that our UORA model aligns with theoretical expectations.

4.1 Simulation Setup

In our simulation, we model a single Basic Service Set (BSS) consisting of multiple STAs and a single AP, both compliant with the IEEE 802.11ax standard. The STAs generate a constant bit rate (CBR) flow of UDP packets with the AP as destination. Downlink traffic generation is deliberately disabled, as this work focuses on UORA, which is suitable for only UL transmissions. Packet size is configured in such a way that the transmission always fits within the Transmit Opportunity (TXOP) allocated for data transmission. Furthermore, to maintain a continuous frame queue, the inter-packet generation interval is set to half of the TXOP duration, ensuring that packets are consistently available for transmission thus maximizing channel efficiency. EDCA is completely disabled during the experiment. This prevents STAs from transmitting packets using EDCA when the AP schedules resources with UL OFDMA. Additionally, the AP transmits management frames every 204 800 µs to minimize their impact on throughput.

We ensure that the probability of packet loss due to channel errors is negligible by transmitting at sufficiently high power, which guarantees that all STAs are within the AP's range. As a result, packet loss only occurs when two or more STAs simultaneously transmit in the same randomly chosen RU. Furthermore, we use the smallest RU type (i.e., 26-tones) to ensure an equitable distribution of resource among associated STAs and maximize the number of simultaneous transmissions. Table 1 lists the parameter values used in the experiments.

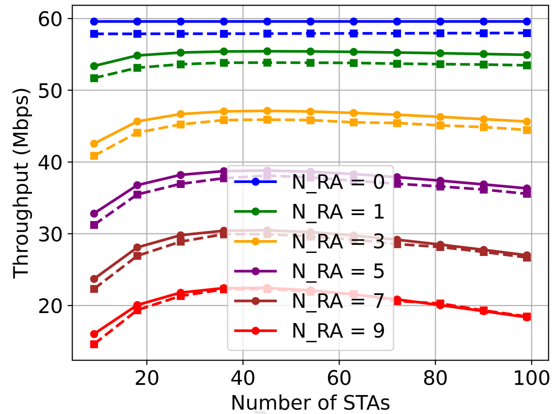


Figure 4: Validation of UORA implementation: throughput as a function of the number of STAs for different number of RA RUs. Solid lines depict the results from the analytical model [12] and the dashed lines represent the simulation results.

4.2 Discussion of Results

In this section, we compare the simulation results of our UORA implementation with those obtained from the analytical model proposed by Naik *et al.* [12], using the same parameters. The evaluation focuses on throughput as the key performance metric. Figure 4 depicts application-level throughput for different numbers of STAs, considering varying number of RA RUs (i.e., N_{RA}). The solid lines represent the analytical results, while the dashed lines correspond to the simulation results.

The simulation throughput, while closely following the trend of the mathematical model, is slightly lower, particularly in scenarios with few RA RUs. This discrepancy arises because the AP contends for channel access at the end of each TXOP, leading to wasted time resources. This aspect is not accounted for in the analytical model. Moreover, the inclusion of an additional TF (i.e., Basic TF) in the UL OFDMA transmission further reduces the achievable throughput.

5 CONCLUSION

In this paper, we presented a standard-compliant implementation of UORA that is compatible with the latest version of the ns-3 simulator. By incorporating a standalone resource scheduler, our implementation provides a more accurate and flexible framework for evaluating UORA's performance in dense networks, where efficient UL scheduling is critical. We validate our implementation by comparing its results to those of an analytical model from literature. In our future research, we plan to design the mathematical model of the scheduler that decouples resource allocation for BSRs and data transmissions. We will use this implementation to validate this model.

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REFERENCES

[1] Douglas Dziedzorm Agbeve. 2025. WiFi UORA in NS-3. https://github.com/imec-idlab/WiFi_UORA_ns3

[2] Douglas Dziedzorm Agbeve, Andrey Belogaev, Wim Sandra, Carl Lylon, and Jeroen Famaey. 2025. A2P: A Scalable OFDMA Polling Algorithm for Time-Sensitive Wi-Fi Networks. In *Proc. of IEEE WCNC*.

[3] Evgeny Avdotin, Dmitry Bankov, Evgeny Khorov, and Andrey Lyakhov. 2019. Enabling Massive Real-Time Applications in IEEE 802.11be Networks. In *2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. IEEE, 1–6.

[4] Evgeny Avdotin, Dmitry Bankov, Evgeny Khorov, and Andrey Lyakhov. 2020. Resource allocation strategies for real-time applications in Wi-Fi 7. In *2020 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*. IEEE, 1–6.

[5] Sudeep Bhattarai, Gaurang Naik, and Jung-Min Jerry Park. 2019. Uplink Resource Allocation in IEEE 802.11ax. In *ICC 2019-2019 IEEE international conference on communications (ICC)*. IEEE, 1–6.

[6] Qinghua Chen and Yi-Hua Zhu. 2020. Scheduling Channel Access Based on Target Wake Time Mechanism in 802.11ax WLANs. *IEEE Transactions on Wireless Communications* 20, 3 (2020), 1529–1543.

[7] IEEE Std 802.11ax-2021. 2021. *Enhancements for High Efficiency WLAN.* Standard. IEEE.

[8] Minghao Jin, Jin Meng, Weimin Wu, and Yingzhuang Liu. 2024. Enhancing the Performance of Wi-Fi 7 Network via Investigation of Multi-link and UORA. *IEEE Communications Letters* (2024).

[9] Youngboo Kim, Lam Kwon, and Eun-Chan Park. 2021. OFDMA Backoff Control Scheme for Improving Channel Efficiency in the Dynamic Network Environment of IEEE 802.11ax WLANs. *Sensors* 21, 15 (2021), 5111.

[10] Katarzyna Kosek-Szott and Krzysztof Domino. 2022. An Efficient Backoff Procedure for IEEE 802.11ax Uplink OFDMA-based Random Access. *IEEE Access* 10 (2022), 8855–8863.

[11] Katarzyna Kosek-Szott, Szymon Szott, and Falko Dressler. 2022. Improving IEEE 802.11ax UORA Performance: Comparison of Reinforcement Learning and Heuristic Approaches. *IEEE Access* 10 (2022), 120285–120295.

[12] Gaurang Naik, Sudeep Bhattarai, and Jung-Min Park. 2018. Performance Analysis of Uplink Multi-User OFDMA in IEEE 802.11ax. In *Proc. of IEEE ICC*. 1–6. https://doi.org/10.1109/ICC.2018.8422692

[13] Abdul Rehman, Faisal Bashir Hussain, Rashid Ali, and Tahir Khurshaid. 2023. Collision-Based Up-Link OFDMA Random Access Mechanism for Wi-Fi 6. *IEEE Access* 11 (2023), 117094–117109.

[14] George F Riley and Thomas R Henderson. 2010. The ns-3 Network Simulator. In *Modeling and tools for network simulation*. Springer, 15–34.

[15] Dianhan Xie, Jiawei Zhang, Aimin Tang, and Xudong Wang. 2020. Multi-Dimensional Busy-Tone Arbitration for OFDMA Random Access in IEEE 802.11ax. *IEEE Transactions on Wireless Communications* 19, 6 (2020), 4080–4094.