# Enhancing UORA for IEEE802.11be

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**Abstract.** Currently, wireless networks have been tools commonly used in our daily lives. Users frequently connect multiple devices, especially IoT devices, to wireless networks to enjoy network services, no matter whether they are at home, in libraries, or in coffee shops. Also, different kinds of real-time applications which increase huge demands of high-speed transmission have been proposed. But, these applications pose challenges to the real-time transmission performance of wireless networks. To address these issues, IEEE 802.11be incorporates the Uplink OFDMA Random Access transmission method previously developed for by IEEE 802.11ax. However, when a large number of users need to transmit data, UORA suffers from long transmission delays and low transmission throughputs, which fail to meet the requirements of real-time applications. To fulfill the low-latency demands of real-time applications, this research proposes a transmission mechanism, named Priority-based OCW (POCW for short), to adjust the OCW range for IEEE802.11be stations based on priorities of data streams. This mechanism allows higher-priority STAs to transmit data before lower-priority STAs. Our simulations show that the POCW offers lower transmission delays for time-sensitive data streams and provides better throughputs in densely populated STA environments.

**Keywords:** IEEE 802.11be · UORA · RTA

## 1 Introduction

In recent years, due to rapid advancements of wireless technology, the unprecedented demands for real-time applications (RTAs) [1] have been dramatically increased. These applications as an integral part of our modern lives include diverse domains, such as online meetings [2], multimedia streaming [3], remote education [4], and smart homes [5]. To address the increasing demand of these applications, the IEEE 802.11be Task Group (TGbe) has introduced an innovative wireless network technology, called IEEE 802.11be (Wi-Fi 7), also named Extreme High Throughput (EHT) wireless communication, which provides wireless network services required by users and ensures low latency, fast transmission speed, and high throughputs of data transmission.

In fact, IEEE 802.11ax (also known as Wi-Fi 6) [6] introduced the Uplink OFDMA Random Access (UORA) technology [7], allowing multiple users to

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access the network simultaneously and transmit uplink data efficiently. Besides the improvements, as the number of users grew, UORA encountered a new problem, i.e., high data transmission collision, which conducts to significant network delays. However, the latest IEEE 802.11be draft continues to incorporate UORA technology [8].

To support real-time sensitive network applications for the IEEE802.11be standard on UORA, in this study, we propose a novel data-transmission control scheme called Priority-based OCW (POCW for short). The primary objectives are twofold: Prioritize different data streams based on their respective categories, especially focusing on highly time-sensitive streams. Enhance the utilization of transmission opportunities by reducing the number of idle RUs, thereby enhancing the overall Quality of Service (QoS) of a wireless network.

The purposes are improvement of resource allocation efficiency, reduction of collision probabilities during data transmission, and the provision of efficient and reliable transmission services, particularly in a dense-user environment. Our previous research results can be found in [9].

The article is organized as follows. Section 2 presents the UORA transmission mechanism and explore the factors contributing to its suboptimal network performance. Section 3 analyzes performance of the existing UORA schemes. Section 4 explains the practice and structure of POCW. The simulations of the POCW and their results are, respectively, evaluated and discussed in Sect. 5. Section 6 concludes this study and addresses our future studies.

## 2 UORA and Related Studies

### 2.1 UORA Operations

The working principles of the UORA mechanism are as follows. During a UORA transmission opportunity (TXOP) [10], the AP initially broadcasts a Trigger Frame (TF) to all the STAs in the network. The TF conveys essential channel information, such as the number of available RUs, the size of the OFDMA contention window (OCW) [11], and the association identifiers (AIDs) [12] of the STAs eligible to contend for the RUs. Upon receiving the TF, an STA intending to transmit data starts its backoff mechanism. The AP configures the OCW size, i.e.,, which is carried in TF sent to STAs. The and, used by STAi either for an initial transmission or successful transmission (retransmission), are calculated based on Eqs. (1) and (2) [13]:

$$OCW^i_{min} = 2^{EOCW_{min}} - 1 \tag{1}$$

$$OCW^i_{max} = 2^{EOCW_{max}} - 1 \tag{2}$$

in which $1 \leq i \leq n$, where $n$ is the number STAs now under the concerned AP; *EOCW* standing for Extended OFDMA Contention Window is specified by two parameters: $EOCW_{min}$ and $EOCW_{max}$, which as a part of the Random Access Parameter Set (RAPS) elements [14] presented in the TF, respectively, define the lower and upper bounds of the extended contention window range that the STAs must follow. $EOCW$ is utilized to dynamically increase the OCW size to adjust the backoff stage when needed, i.e., when there is a collision on an RU, then the OCW of concerned STA, e.g., STA$_i$ will be enlarged to reduce the probability of the following data-transmission collision. If STA$_i$ does not receive TF from AP, the default value of are set to 7 and 31, respectively.

When a STA intends to contend for RUs, it initiates the backoff process by randomly selecting a value from the range, shown in Eq. (3):

$$initialOBO = [0, OCW_{min}] \tag{3}$$

This value then serves as the initial OFDMA backoff counter (OBO) [15]. Upon receiving the TF, the STA decreases the OBO following Eq. (4):

$$OBO = OBO - (numberofavailable) \tag{4}$$

in which the item in the parenthesis is the number of available RU conveyed in underlying TF.

When the backoff stage ends, STA has three situations, i.e., no transmission, successful transmission, and transmission failure. The first situation is the case in which $OBO > 0$. Then, this STA must wait for its $OBO \leq 0$ in the following TXOPs. The second situation occurs, when the STA's $OBO \leq 0$. STA randomly selects an RU and successfully transmits data without collision. After that, the STA re-selects a new OBO value from the same $(0, OCW_{min})$ for the next TXOP, i.e., if the initial transmission is successful, the next OCW range is still from $(0, OCW_{min})$. But when the STA's $OBO \leq 0$, and collision occurs on data transmission, this is the third case in which new $OCW_{new} = min\,(2 * OCW_{min}, OCW_{max})$ and the STA randomly select a new OBO from the new OCW range, i.e., $(0, OCW_{new})$, for the next TXOP.

After the data transmission phase, the AP sends Multi-User Block Acknowledgment (MU-BACK) frames [16] as a confirmation of successful data transmission to those STAs successfully transmitting their data. On the other hand, STAs that fail to receive MU-BACK (maybe due to transmission error or fail to receive MU-BACK) will renew their OCW values, with the method described above and continue its backoff to wait for the next TXOP. The UORA process is represented in Fig. 1.

## 3 Related Studies

In the IEEE 802.11ax standard, the transmission efficiency of the UORA mechanism is only 37% [18] which can be attributed to two factors. First, when multiple STAs choose the same RU, collisions occur on that RU. Second, during data transmission, some RUs remain idle due to without being chosen by any STA for transmission.

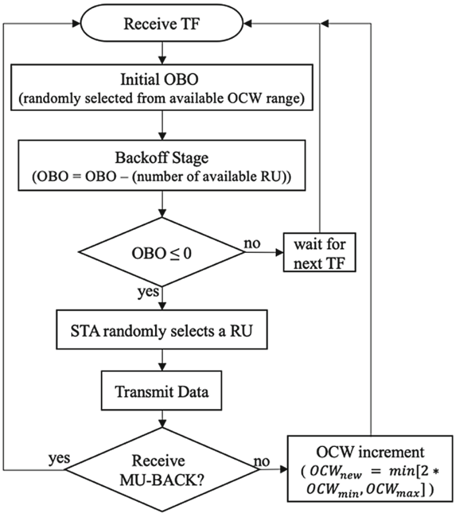


**Fig. 1.** The UORA Process.

To enhance the transmission efficiency of UORA, research results have been proposed [18–21]. Lanante *et al.* [19] employed a two-dimensional Markov-chain model to analyze the transmission efficiencies and throughputs of various numbers of STAs in the UORA mechanism.

Lee [20] proposed a trigger frame and the carrier sensing-based H-UORA (Hybrid Uplink OFDMA Random Access) mechanism, which incorporates a two-stage OBO backoff mechanism. Next, each STA generates a random number $X_u$. If $X_u < \rho_u$, the STA senses the channels where $\rho_u$ is the OBO probability. When there are $n$ idle channels (i.e., idle RUs), $n \geq 1$, the STA randomly selects one to transmit data. If $X_u \geq \rho_u$, the STA waits for the next round of backoff, called the second backoff. The approach enables idle RUs to have a chance of being selected by STAs during the second backoff, thereby reducing the number of idle RUs and increasing the overall transmission efficiencies and throughputs.

Kim *et al.* [18] proposed a Collision Reduction and Utilization Improvement (CRUI) mechanism to address data-transmission collisions on RUs by Extra Backoff Stage (EBO) and Opportunistic RU Hopping (ORH). The CRUI enhancements aim to improve fairness for STAs needing to transmit data by providing a second chance for STAs, aiming to select, i.e., hopping to, another RU to avoid collisions. Further, the CRUI follows the IEEE 802.11ax rule of simultaneous start of data transmission and end of transmission. However, the EBO stage occupies transmission time, and the ORH increases the possibility of transmission collisions due to hopping.

Kim *et al.* [21] introduced a solution to enhance the IEEE 802.11ax standard by conducting control over the STA's OBO counter. Instead of using a fixed OBO value, each STA dynamically determines an OBO value based on the case whether its previous transmission succeeds or not. By controlling the OBO counter, the UORA mechanism can intelligently select a suitable OBO value based on each STA's transmission status. This approach indirectly influences the likelihood of RU collisions and the availability of free-time slots for data transmissions. For instance, when a small number of STAs competing for RUs, the OBO control allows STAs to produce smaller OBO values, making them easier to successfully compete for RUs. However, when the number of competing STAs increases, the potential collisions still exist.

To face this challenge, the POCW classifies the data streams to support delay-sensitive [17] and high-data-flow applications, such as voice and video, particularly for 5G/6G network uRLLC (ultra-Reliable Low Latency communication), thus improving the overall network performance. Besides, it minimizes data-transmission collisions, and improves throughput in a dense-user environment.

## 4 Proposed Scheme

In this study, we use the IEEE802.11e's data classification method to divide data streams into two types, including delay-sensitive data and delay-insensitive data. The former (latter) consists of AC_VO and AC_VI (AC_BE and AC_BK).

### 4.1 OBO Range

In this research, as receiving $EOCW_{min}$ and $EOCW_{max}$ carried in TF, we calculate $OCW_{min}$ and $OCW_{max}$ by using Eqs.(1) and (2), respectively. STA's OBO value is chosen from the range $[x, OCW]$ where represents the lower limit of the OCW size for a specific TXOP, i.e., the STA randomly selects an OBO value from $[0, OCW_{min}]$ for its initial selection, where, i.e., $x = 0$ and $OCW = OCW_{min}$. After a TXOP, STAs that did not obtain a transmission opportunity, i.e., $OBO > 0$, will wait for the next TXOP. STAs that successfully transmit their data will choose a new OBO value from the same $[x, OCW]$ range without changing the values of $x$ and $OCW$. A STA that does not transmit data successfully will double its $OCW$, and the new OBO will be randomly chosen from a revised new range as indicated in Eq. (5):

$$[x, OCW] = [X_{new}, OCW_{new}] \tag{5}$$

where $X_{new} = OCW$ and $OCW_{new} = min\,[OCW * 2, OCW_{max}]$. Then, STA's OBO is selected from the new range $[X, OCW]$ in order to reduce the chance of STA collisions and improve data-stream priority.

### 4.2 Trigger Based Multi-Carrier CSMA

In this study, we utilize a function of the TB-MC-CSMA (Trigger Based Multi-Carrier CSMA) method [28], i.e., RU granular carrier sensing, to detect idle RUs during RU sensing (RS) slot time (see Fig. 2.) to reduce the number of idle RUs in underlying TXOPs. After backoff, STA 1's $OBO = 0$. It randomly selects RU 1 to transmit data. In the general UORA mechanism, STA 2 as its $OBO = 1$ must wait for the next TXOP. But after RU sensing, RU 2 will be found to be idle. Then STA 2 backs off again. Now, $OBO = 0$. STA 2 dynamically selects RU 2 to transmit data. Thus, the probability with which RU 2 is idle in this TXOP is lowered. https://www.overleaf.com/project/64daff6c4751f2b81202dba1

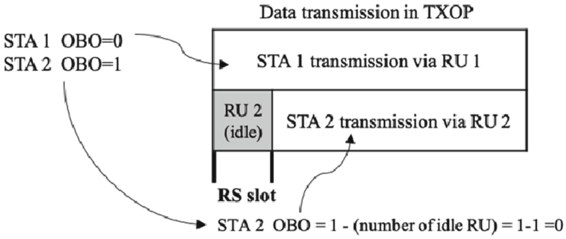


**Fig. 2.** TB-MC-CSMA architecture.

## 5 Simulations and Analyses

In this study, we simulated a BSS (Basic Service Set) [32] environment, including one AP and multiple STAs. Table 1 lists the experimental parameters. In addition, three schemes, including the UORA, H-UORA, and POCW without RS are also evaluated and compared with the POCW. POCW without RS is also known as POCW without RU sensing.

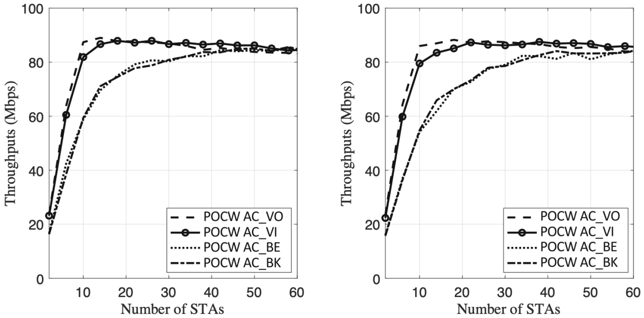
**Table 1.** Our experimental Parameters.

| Paremeter | Value |
|---|---|
| Number of subcarrier per RU | 26 tones |
| Number of STA | 1–100 |
| Packet Size | 100/2k/10k bytes |
| TF duration | 100 µs |
| SIFS duration | 16 µs |
| PIFS duration | 25 µs |
| MU-BACK duration | 68 µs |

In the following, a total of 3 experiments was performed. The first studied the throughputs and delays of the POCW. The former is defined as the number of bytes received per second at the receiving end, while delay is defined as the time that a packet travels from its sender to receiver. The second, and the third experiments were done by giving different numbers of RUs, packet sizes and bandwidths of an RU, respectively. Success probabilities, defined as the probabilities that a STA can successfully transmit its data in underlying TXOP, are also evaluated in these three experiments.

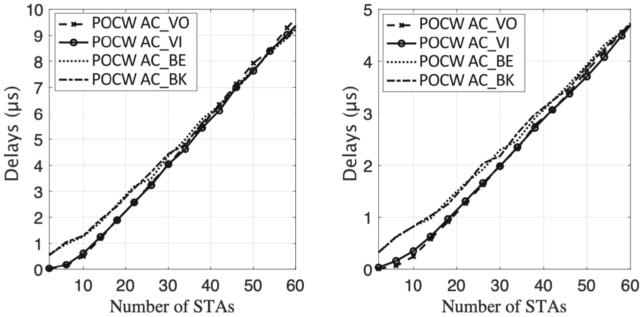
### 5.1 Experiment on Different Numbers of STAs for the POCW

The first experiment studied the POCW given 9 RUs and different numbers of STAs ranging from 1 to 60.



(a) Two non-overlapping segments (b) Two overlapping segments

**Fig. 3.** Throughputs of the POCW on two overlapping and non-overlapping segments given 9 RUs and different numbers of STAs ranging from 1 to 60.



(a) Two non-overlapping segments (b) Two overlapping segments

**Fig. 4.** Delays of the POCW on two overlapping and non-overlapping segments given 9 RUs and different numbers of STAs ranging from 1 to 60.

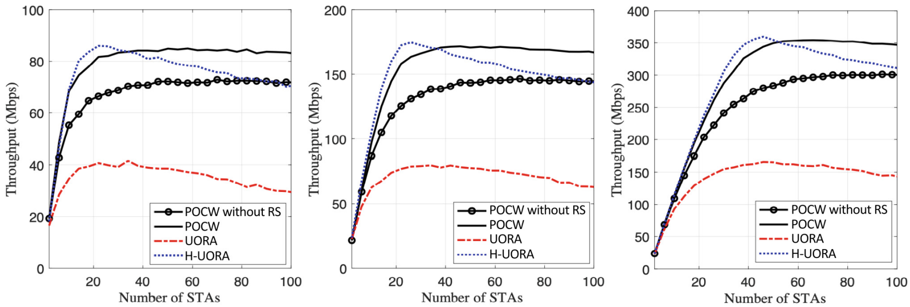
Figure 3 and 4 present throughputs and delays of the POCW, respectively. Figure 3 illustrates that when numbers of STAs are lower, throughputs of AC_VO and AC_VI are higher than those of AC_BE and AC_BK, no matter whether it is an overlapping or non-overlapping segment. This is because, when the number of STAs and the OCW range are both small, STAs that would like to deliver AC_VO or AC_VI have higher opportunities to transmit due to generating smaller OBO values (higher probabilities) to win contention. The system throughputs are saturated (see Fig. 3.) at 9 RUs because only 9 RUs are available. However, as the number of STAs increases, the throughputs of the non-overlapping-segments are not higher than those of the overlapping-segments. This is because the small OCW range of non-overlapping segments increases the probabilities of transmission collisions, which in turn leads to a decrease of throughputs.

Figure 4 illustrates that the delays of AC_VO and AC_VI are lower than those of AC_BE and AC_BK in both the overlapping and non-overlapping segments because their smaller OCW ranges (values in left-hand-side segment) contribute to win contention. However, as the number of STAs is higher, the smaller OCW range of AC_VO and AC_VI increases the chance of collisions. Also, the delays of AC_BE and AC_BK are longer because of the larger range of OCW, leading to bigger OBO values and a longer backoff time. Thus, it is not easy for them to win contention. It is clear that AC_VO and AC_VI outperform AC_BE and AC_BK. Comparing Fig. 4.(a) and Fig. 4.(b), the delays of AC_VO and AC_VI on non-overlapping segments are relatively higher than those of AC_VO and AC_VI on overlapping segments, particularly when number of STA is high (please refer to these two figures and the rows of AC_VO and AC_VI in Table 4 when No. of STAs is 30 and 50). Thus, we utilize non-overlapping segments to do the following experiments.

### 5.2 Experiment on Different RUs

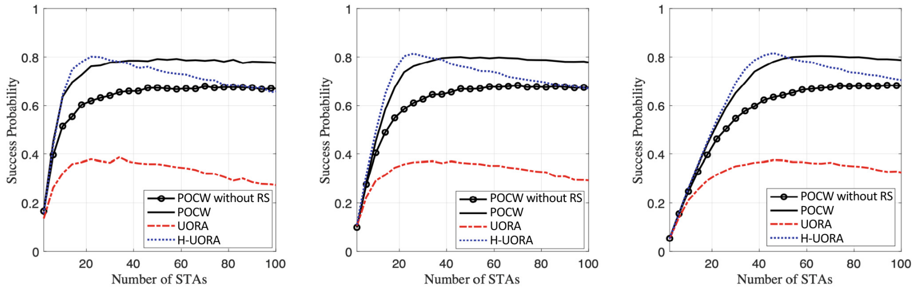
The second experiment was performed on different numbers of RUs, including 9, 18, 37 RUs. Figure 5, 6 and 7, respectively, illustrate the throughputs, success probabilities and delays of the four tested schemes. As shown in Fig. 5., the UORA exhibits the lowest throughputs regardless of the number of RUs, meaning that its function can be further enhanced. On 9 RUs and 18 STAs, the H-UORA achieves the highest throughputs of 86Mbps, surpassing the POCW by about 5Mbps. This is because in the POCW, the larger OCW of AC_BE and AC_BK results in lower throughputs due to the fact that their OBOs are often (not usually) larger than those of AC_VO and AC_VI. As the number of STAs increases, throughputs of the H-UORA are lower than those of the POCW because POCW optimizes the OCW range, thus maintaining its throughputs. If we check the Y-axes of Fig. 5.(a), 5.(b) and 5.(c), we can see that the throughputs of the 4 test schemes on 37 RUs at any specific number of STA, e.g., $k$ STAs, $10 \leq k \leq 100$, almost individually double those of 18 RUs also at $k$ STAs. Throughputs of 18 RUs also individually double those on 9 RUs at any $k$ STAs.

In addition, when there is no idle RU sensing and the number of STAs is small, the throughputs of the POCW are not better than those of the H-UORA. However, as the number of STAs is larger, its throughputs may be better than the H-UORA's. The POCW outperforms the POCW without RS since sensing idle



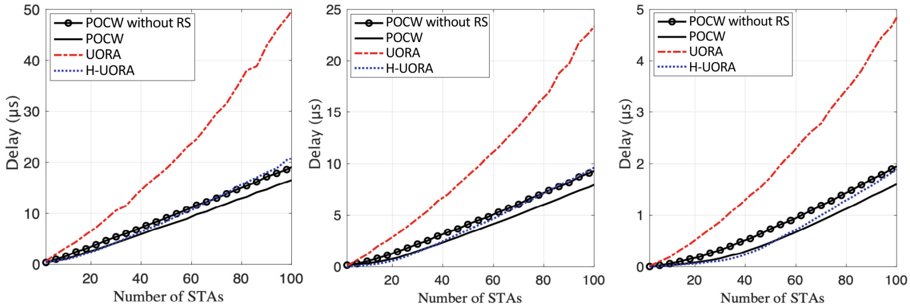
(a)No. of RUs = 9 (b) No. of RUs = 18 (c) No. of RUs = 37

**Fig. 5.** The system throughputs of the 4 test schemes on overlapping segments given different numbers of RUs, including 9, 18, and 37, and the number of STAs varies from 1 to 100.



(a) No. of RUs = 9 (b) No. of RUs = 18 (c) No. of RUs = 37

**Fig. 6.** The success probabilities of the 4 test schemes on overlapping segments given different numbers of RUs, including 9, 18, and 37, and the number of STAs varies from 1 to 100.



(a)No. of RUs = 9 (b) No. of RUs = 18 (c) No. of RUs = 37

**Fig. 7.** The delays of the 4 test schemes on overlapping segments given different numbers of RUs, including 9, 18, and 37, and the number of STAs varies from 1 to 100.

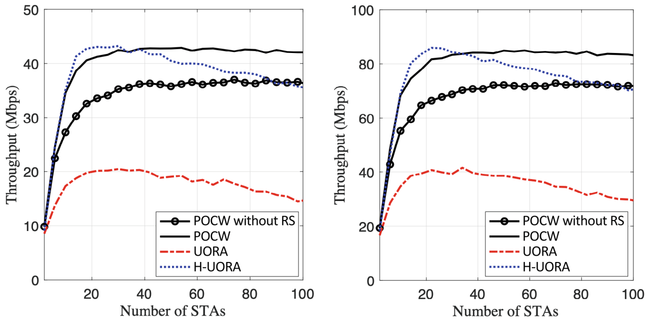
RUs during RS time slot actually reduces the probability of idle RUs. When the number of STAs is 100, in the 9-RU environment, the POCW exhibits throughput increases of 16%, 19% and 180% compared to those of POCW without RS, the H-UORA, and the UORA, respectively. Similarly, in an 18-RU environment, the POCW demonstrates a throughput improvements of 16%, 16% and 165% over the POCW without RS, the H-UORA, and the UORA, respectively. Further, in a 37-RU environment, the POCW achieves a throughput enhancements of 16%, 11%, and 139% higher than those of the POCW without RS, the H-UORA, and the UORA, respectively.

The successful transmission rates of the 4 tests schemes are shown in Fig. 6. The UORA reaches only 37% of maximum throughputs as we mentioned before due to transmission collisions. When the number of STA increases, the POCW outperforms the H-UORA. The reason is described above. Actually, higher successful transmission rates will lead to higher throughputs. That is why the treads of Fig. 5.(a), 5.(b), and 5.(c) are similar to those of Fig. 6.(a), 6.(b), and 6.(c), respectively.

Figure 7 illustrates the delays of the 4 test schemes. When the number of STAs is higher, the delays' increasing rates of the H-UORA are higher than those of the POCW, and the delays' increasing rates of the POCW without RU sensing are not higher than those of the H-UORA because higher successful transmission probabilities lead to lower transmission delays. Further, when the number of STAs is the same, e.g., at STAs, the delay of 18 RUs is about one half of that of 37 RUs and the delay of 9 RUs is only about one half of that of 18 RUs. When the number of STAs is 100, in the 9-RU environment, the POCW improves delays about 11%, 20% and 67% compared to those of the POCW without RS, the H-UORA, and the UORA, respectively.

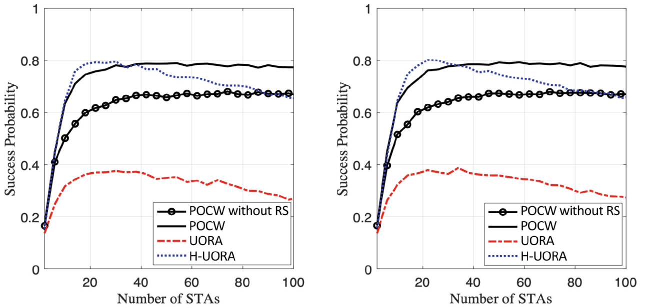
### 5.3 Experiment on Different Bandwidth of an RU

The third experiment was performed given different bandwidths to an RU, including 6.67 (Modulation and Coding Scheme 5) and 14.7 Mbps (Modulation and Coding Scheme 11) with the number of STAs ranging from 1 to 100. Figure 8, 9 and 10, respectively, show the throughputs, success probabilities and delays on packet size 2K bytes and 9 RUs. Comparing Fig. 8.(a) and 8.(b), Y-axis shows that the bandwidth of an RU greatly affect the throughputs. In Fig. 8.(a), the throughputs of the four schemes are individually about one half of those in Fig. 8.(b), no matter whether at any specific number of STAs. Further, when $|STAs| > 40$, the throughputs of the POCW are significantly higher than those of the H-UORA, which is similar to the cases in the previous experiments (see Fig. 5.). In addition, when $|STAs| > 90$, the throughputs of POCW without RU sensing are higher than those of the H-UORA, implying that in high-density user environments, the POCW outperforms the H-UORA. When $|STAs| = 100$, in 6.67Mbps-bandwidth-of-an-RU environment, the POCW exhibits throughput increases of 15%, 18% and 191% over to the POCW without RS, the H-UORA, and the UORA, respectively. Similarly, in 14.7Mbps-bandwidth-of-an-RU environment, the POCW demonstrates a throughput improvement of 16% over the



(a) Bandwidth of an RU=6.67Mbps (b) Bandwidth of an RU=14.7Mbps

**Fig. 8.** The system throughputs of the 4 test schemes on overlapping segments given different bandwidths to an RU, including 6.67 and 14.7 Mbps. The number of STAs varies from 1 to 100 and the packet size is 2kB.

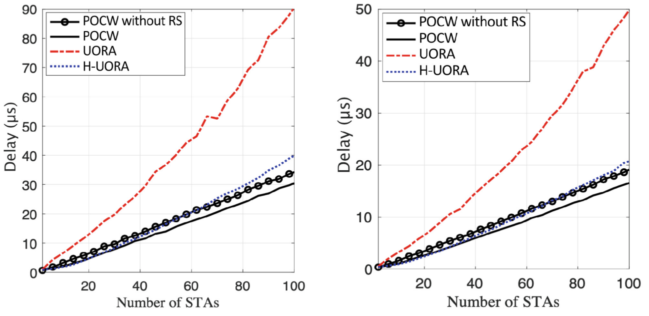


(a) Bandwidth of an RU=6.67Mbps (b) Bandwidth of an RU=14.7Mbps

**Fig. 9.** The success probabilities of the 4 test schemes on overlapping segments given different bandwidth of an RU, including 6.67 and 14.7 Mbps, and the number of STAs varies from 1 to 100.

POCW without RS, 19% increase over the H-UORA, and 180% increase over the UORA. This could be attributed to the POCW's optimization strategies, such as prioritizing data streams based on different access categories and efficient resource allocation, which effectively reduce data transmission collisions and providing higher success probability of data transmission. As $|STAs|$ is larger, the POCW can manage resources and win competition both in a more efficient method, resulting in relatively higher throughputs.

The successful transmission probabilities shown in Fig. 9 reflect the trends of the curves illustrated in Fig. 8. When $|STAs| = 100$, in the 6.67Mbps-bandwidth-of-an-RU environment, the POCW's success probabilities increase 15%, 18% and 196% over the POCW without RS, the H-UORA, and the UORA, respectively. Similarly, in the 14.7Mbps-bandwidth-of-an-RU environment, the improvements are, respectively, 15%, 18% and 185%.



(a) Bandwidth of an RU=6.67Mbps (b) Bandwidth of an RU=14.7Mbps

**Fig. 10.** The delays of the 4 test schemes on overlapping segments given different bandwidth of an RU, including 6.67 and 14.7 Mbps, and the number of STAs varies from 1 to 100.

Figure 10 confirms that the transmission delays of the POCW are lower than those of other three schemes. The POCW without RS has lower delays than the H-UORA when $|STAs|$ increases. In fact, at a specific number of STA, e.g., STAs, delays illustrated in Fig. 10.(a) are almost two times those shown in Fig. 10.(b). When $|STAs| = 100$, in the 6.67Mbps-bandwidth-of-an-RU environment, the POCW's delays decrease 12%, 24% and 66% compared to those of the POCW without RS, the H-UORA, and the UORA, respectively. Similarly, in the 14.7Mbps-bandwidth-of-an-RU environment, the delay improvements are, respectively, 11%, 20% and 67%.

## 6 Conclusions and Future Studies

In this study, we proposed an improved version of the POCW by calculated the appropriate optimal OCW size, adopting RS for RU sensing to reduce the number of idle RUs, and classified data streams, giving them different OCW ranges for priority contention.

Our simulation results showed that comparing with AC_BE and AC_BK, the POCW can provide higher throughputs and lower transmission delays for AC_VO and AC_VI. Our simulations also show that the POCW demonstrates better overall transmission performance, particularly when STAs are densely deployed.

Low-latency networks are crucial for real-time voice/video applications, such as video conferencing and virtual reality, where minimal delays and high reliabilities are essential. Recognizing these demands, IEEE 802.11be is specifically designed to meet the requirements. By offering a network with lower transmission delays, higher transmission rates, and better Quality of Service (QoS), IEEE 802.11be aims to enhance the overall user experience for delay-sensitive applications. To meet the requirements of different data streams and the delay-sensitive nature of IEEE 802.11be, future research will focus on selecting appropriate

OCW ranges in a more flexible and adaptive manner. It is hoped that such studies can provide optimal performance and transmission efficiency in different wireless networks under various network environments and conditions. We will also derive the reliability model and behavior model for the POCW so that user can realize their behaviors and reliabilities before using it. These constitute our future studies.

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