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RESEARCH ARTICLE

Collision-Based Up-Link OFDMA Random Access Mechanism for Wi-Fi 6

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ABSTRACT The IEEE 802.11ax standard defines High-Efficiency WLAN (HEW), which is known as 6th Generation Wi-Fi (Wi-Fi 6) network. HEW uses an up-link OFDMA-based Random Access (UORA) mechanism for channel access in dense multi-user transmissions. Similar to legacy Wi-Fi networks, UORA recommends adopting a random OFDMA Back-Off (OBO) procedure within the OFDMA contention window (OCW) range to access the available channel resources randomly. IEEE 802.11ax follows a centralized channel resource allocation mechanism, in which an access point (AP) is responsible for calculating and configuring the OCW range and notifying the respective Random Access stations (RA-STAs). However, IEEE 802.11ax does not specify a method to determine reasonable OCW ranges based on the number of RA-STAs for uplink transmissions. In a centralized UORA approach, one of the major challenges for an AP is to accurately and quickly evaluate the exact number of RA-STAs to minimize collision probabilities without the aid of a specific signaling mechanism. The centralized approach in Wi-Fi 6 can significantly degrade the performance of the UORA owing to an inappropriate range of OCW, particularly when the number of random access stations changes dynamically. In this study, a Collision-based Distributed OBO control (CODOBO_CTRL) scheme is proposed where each RA-STA independently determines its OBO counter, instead of an AP-guided centralized mechanism. The motivation for CODOBO_CTRL is to improve the performance of UORA in highly dynamic networks using primitive network parameters. Considering the success or failure of recent UORA transmissions, in the CODOBO_CTRL scheme, each random access station actively adjusts the OBO counter using the relationship between realistic network parameters: channel bandwidth and a collision factor. The results of a simulation study validate that the achieved throughput of the proposed scheme is almost equal to that of the OPT_UORA scheme in a static network, and 11% higher specifically in highly dynamic scenarios. Furthermore, compared to the standard UORA and OBO_CTRL schemes, the CODOBO_CTRL scheme demonstrates improvements of up to 207% and 12%, respectively, in terms of throughput performance.

INDEX TERMS OFDMA, UORA, IEEE 802.11ax, future Wi-Fi.

I. INTRODUCTION

Wireless local area networks (WLANs), also termed Wi-Fi networks, are the first choice for providing end-user connectivity at a low cost with reliability and high data rate support. The evolution of WLANs into next-generation High-Efficiency WLANs (HEW) [1] is on the brink which demands support for even higher data rates in dense networks such as sports stadiums, airport lounges, residential buildings [2], video surveillance [3], health care [4], and intelligent transportation systems [5]. To enhance the spectrum efficiency of IEEE 802.11 for supporting highly dense networks and to meet future demands of aforementioned applications [6], IEEE 802.11ax was proposed in 2021.

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IEEE 802.11ax-based HEWs are also referred to as 6^{th} generation Wi-Fi (Wi-Fi 6) networks. Wi-Fi 6 is the successor to Wi-Fi 5 (IEEE 802.11 ac) network [7] in Wi-Fi technologies. The IEEE 802.11ax standard introduces several new technologies including (i) orthogonal frequency division multiple access (OFDMA), (ii) 1024-Quadrature Amplitude Modulation (QAM), (iii) Multi-User, Multiple-Input, Multiple-Output (MU-MIMO), (iv) Basic Service Set (BSS) coloring, and (v) Target Wake Time (TWT) to improve network capacity, user efficiency, and spectral efficiency in dense environments.

In legacy Wi-Fi networks, Random Access Stations (RA-STAs) randomly access the wireless medium using a Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) protocol which employs Distributed Coordinated Function (DCF) or Extended Distributed Coordinated Function (EDCF). The performance of DCF severely degrades in dense Wi-Fi network environments [8]. IEEE 802.11ax introduced Orthogonal Frequency Division Multiple Access (OFDMA) to support dense network requirements [9]. In addition, IEEE 802.11ax defines a set of rules for the Up-link OFDMA-based Random Access (UORA) schemes which are divided into sub-channels or RUs that can be allocated to end stations for data transmissions. The UORA scheme enables RA-STAs to operate concurrently to transmit control, management, and data frames using various RUs [9].

The significance of the UORA mechanism compared to legacy WLANs lies in its ability to (i) use the first OFDMA-based simultaneous uplink random access transmission approach in Wi-Fi networks, (ii) improve network capacity because the OFDMA spectrum is divided into RUs, and (iii) improve spectrum efficiency and user experience specifically in high-density environments. The IEEE 802.11ax standard recommends 9/18/37/74 RUs for 20/40/80/160MHz bandwidth channels for random and scheduled access transmissions. In IEEE 802.11ax UORA, channel resource allocation is centralized and governed by an access point (AP). The performance of the UORA depends on various factors including the number of RUs, number of RA-STAs, OFDMA Contention Window (OCW) ranges, OFDMA Back-Off (OBO), and Buffer Status Report (BSR). An AP determines the OCW range based on the number of RA-STAs, considering their BSR updates, and the number of RUs for each UORA Transmission Opportunity (TXOP). An AP explicitly requests a BSR from the RA-STAs using a BSR Pole (BSRP) query following a centralized UORA scheme. The OBO counter is randomly selected by each RA-STA within the range (0 to OCW) prior to accessing the RUs for BSR or data-frame transmissions [10].

The UORA is a key feature in the Wi-Fi 6 network to improve the spectral efficiency specifically in dense and highly dynamic networks. The efficiency of STD_UORA and OPT_UORA is reduced in dynamic networks compared to static networks due to the rapid changes in network topology. The motivation for using UORA is to enable high data rate connectivity for high-density and dynamic users in Wi-Fi 6. It is infeasible for an AP to accurately determine the appropriate range of $OCW(OCW_{min}, OCW_{max})$ which is based on the number of RA-STAs owing to the presence of mobile devices [11]. Furthermore, as all RA-STAs respond to AP's BSR pole request, their BSR transmissions can collide with the AP. Consequently, channel access can be delayed. In IEEE 802.11ax, the aforementioned issues can significantly degrade the performance of centralized networks within dense networks [12]. Hence, centralized UORA channel resource allocation faces challenges because of (i) the need to collect BSR reports from each station before each TXOP, (ii) the low success rate of BSR report reception, with only 37% of reports received successfully, (iii) the control overhead incurred by the exchange of control frames, and (iv) the higher delay experienced in dense environments.

In [13], a detailed analytical analysis of the IEEE 802.11ax UORA was conducted, and it was concluded that the maximum achievable channel efficiency was 37% and referred to as the optimal UORA. Several centralized UORA studies have focused on achieving an optimal UORA performance in real network scenarios [14], [15], [16], and [17]. To address the limitations of centralized UORA, a recent research effort [18] proposed a decentralized approach in which stations determine their back-off counter value in a distributed manner. This research is inspired by the benefits of decentralized UORA [18] and aims to solve resource allocation issues in highly dense networks.

In this paper, we propose a collision-based distributed OFDMA back-off control (CODOBO_CTRL) scheme to improve the performance of Wi-Fi 6 networks. In the CODOBO_CTRL scheme, each random station scheme uses multiple network parameters such as the collision factor and channel bandwidth, to calculate the channel resource optimization index. Depending on the success or failure of the transmission, each RA-STA uses the aforementioned index to adjust its OBO using a distributed increase and decrease strategy. Furthermore, the CODOBO_CTRL scheme is analyzed against various performance evaluation metrics, including average network throughput, per-station throughput, RU analysis, channel access delay, and Jain's fairness index. Consequently, the results of CODOBO_CTRL were compared with those of existing studies regarding UORA schemes. The significant contributions of this study are as follows:

1) The proposed Collision-based Distributed OFDMA Back-Off Control (CODOBO_CTRL) scheme achieves higher network performance specifically under dynamic scenarios compared to the OBO_CTRL [18] and Optimal OCW (OPT_OCW) [13] scheme in Wi-Fi 6 networks.
2) The proposed scheme does require any signaling or control overhead messages between the AP and the RA-STAs. Furthermore, it is also compatible and can be easily implemented into standard UORA with minor changes.

3) Most of the existing studies on UORA, such as [12], [13], [14], [16], [17], [19], [20], and [21], primarily focus on static network scenarios. However, the CODOBO_CTRL scheme conducts a detailed analysis of the performance of the UORA under dynamic network loads with a high number of random access stations.

The remainder of the paper is organized as follows: Section II explains the channel access mechanism of the standard UORA scheme, Section III discusses the literature review, Section IV describes the proposed model, and Section V establishes the network simulation setup. Section VI concludes the paper and suggests directions for future research.

II. MU UP-LINK OFDMA RANDOM ACCESS (UORA) OPERATION

Figure 1 (b) and 1 (c) illustrate the working principle of the standard UORA for a transmission opportunity (TXOP) used in Wi-Fi 6 networks. In this mechanism, an AP configures a channel of 20 MHz divided into nine RUs consisting of eight RUs with an association identifier (AID) of 0 for associated RA-STAs and one RA-RU with an AID of 2045 for un-associating RA-STAs. Furthermore, the total number of RUs depends on the available channel bandwidth and the number of assigned sub-carries per RU [9]. The IEEE 802.11ax standard recommends a channel bandwidth (BW) of 20/40/80/160 MHz and allows up to 9, 18, 37, and 74 RA-STAs, respectively.

An AP utilizes a control frame called a Trigger Frame for random access (TF-R), in the downlink direction, carrying essential information such as the number of eligible RUs and OCW ranges. The UORA mechanism allows an AP to configure the OCW ranges (OCW_{min}, OCW_{max}). It periodically advertises it in several unicast or broadcast management frames, such as association response and fast initial link setup discovery beacons. Two 3-bit fields in these various management frames shared the values of $EOCW_{min}$ and $EOCW_{max}$. After receiving these frames, each RA-STA updates its OCW values to $OCW_{min} = 2^{EOCW_{min}} - 1$ and $OCW_{max} = 2^{EOCW_{max}} - 1$ to proceed with the UORA mechanism. If the RA-STA does not receive OCW-related management frames from the AP, it will use the default OCW range of (i.e., $OCW_{min} = 7$ and $OCW_{max} = 31$) to choose a random integer value of the OBO counter.

The UORA transmission collides if the OBO counter value of two or more stations reaches zero and two or more RA-STAs access the same RU. Finally, the AP sends back a multi-user (MU) block acknowledgment (BACK_ACK) frame (with a difference of a short period of Short Inter-Frame Space (SIFS)) to confirm whether either transmission has been accomplished or has collided. Initially, each RA-STA selects OCW as OCW_{min}, and OCW value is doubled ($2 \times OCW + 1$) (endure a longer delay for re-transmission), whenever the transmission collides until OCW, reaches to OCW_{max}. After consecutive failures, once $OCW = OCW_{max}$ up to m back-off stages, it remained unchanged. On the other hand, OCW is reset to OCW_{min} when the transmission is successful for any back-off stage from 0 to m. Recall that the OCW control operation is similar to the BEB, which is adopted by the DCF to control CW in non-UORA transmissions.

Meanwhile, the UORA mechanism permits an AP to configure the OCW range (OCW_{min}, OCW_{max}) and advertises periodically using several uni-cast or broadcasting management (e.g., in association response or fast initial link setup discovery beacons) frames, respectively. In this regard, two 3-bit fields in the OCW range were contained in these various management frames to share the value of $EOCW_{min}$ and $EOCW_{max}$. After receiving these frames, each RA-STA updates the OCW values such as $OCW_{min} = 2^{EOCW_{min}} - 1$ and $OCW_{max} = 2^{EOCW_{max}} - 1$ to proceed with the UORA mechanism. If the RA-STA did not receive OCW-related management frames from the AP, it would consider the default OCW range (i.e., $OCW_{min} = 7$ and $OCW_{max} = 31$) to choose a random integer value of OBO counter.

Figure 1 parts (b) and (c) illustrate the operation of UORA for a transmission opportunity (TXOP). An AP configures a TF-R where a channel of 20 MHz is divided into 9 RUs consisting of 8 RUs with the AID 0 for associated RA-STAs and one RU with an AID of 2045 for un-associating RA-STAs, respectively. Further, before accessing an RU, each RA-STA initializes the OBO counter with an integer value from a uniform distribution in the defined range 0 up to OCW. After the successful reception of the TF-R, each RA-STAs from 1 to 8 updates the OBO is equal to (OBO - RUs) counter, and station 9 updates its OBO counter by 1. The updated OBO counter for stations 1 to 4 and 7 to 8 is less than or equal to 0; hence, these stations are eligible to access any RUs between 1 to 8 to transmit a Physical Protocol Data Unit (PPDU) frame. However, RA-STA 6 can't access the RU as its updated OBO (11 - 8 = 3) counter is greater than 0 and it resumes its OBO (3 - RUs with AID 0) upon reception of the next TF-R. Similarly, the un-associated station 9 updates its OBO (1 - 1 = 0) counter and accesses RU 9 to be a part of this network.

However, in this example, we considered the number of RA-STAs to be equal to the number of RUs where only four RUs were successfully accessed, two RUs collided, and RUs remained idle. It becomes more challenging and important to improve the channel efficiency: (i) when the number of RA-STAs is large (i.e., we assume ten times larger than RUs, (ii) the need for dynamic dense environments, and (iii) distributed and random operation of the UORA access mechanism. Noted that the DCF or EDCF medium access control (MAC) protocols proceed in the time domain (TD) to proceed with the transmissions. Simultaneously, the UORA allows each RA-STA to access a particular RU in the TD and frequency domain (FD) concurrently with each UORA TXOP.

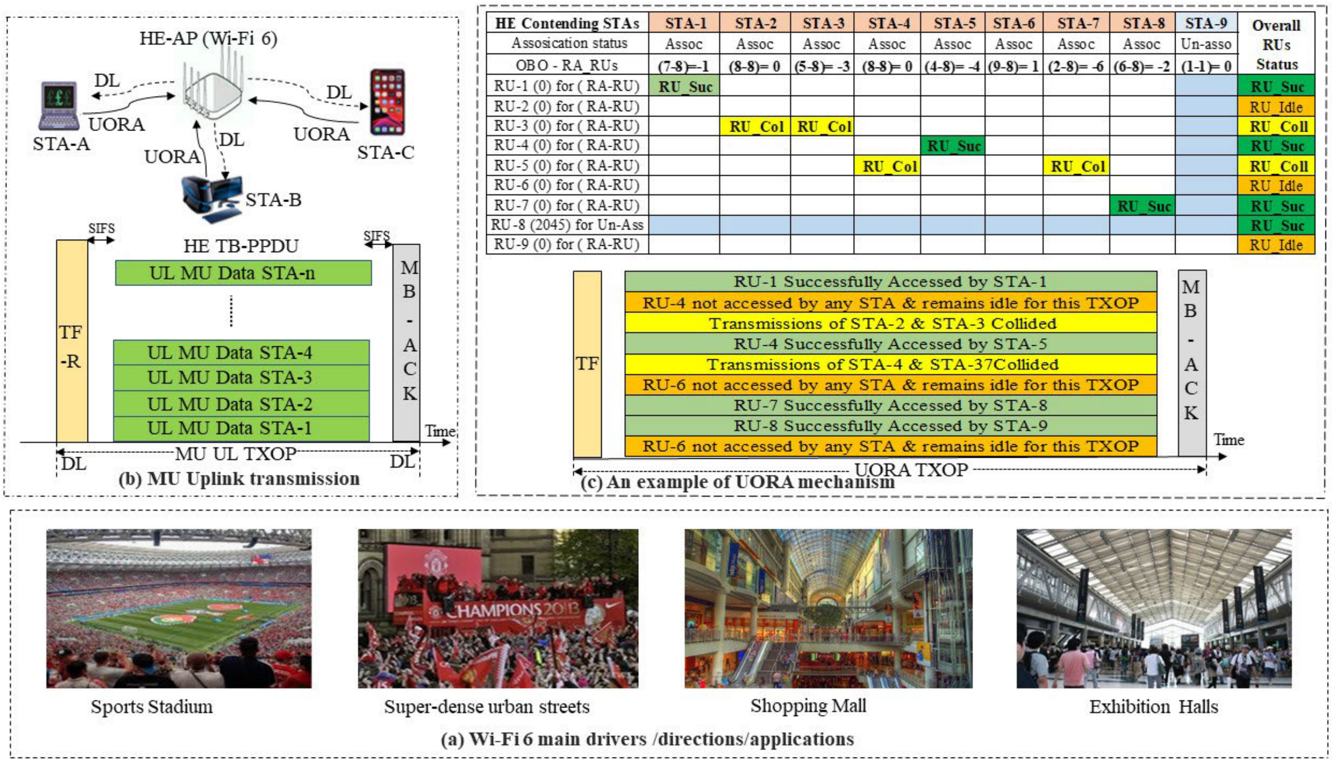

FIGURE 1. Illustrative examples of Wi-Fi 6 (a) applications, (b) multiuser uplink/downlink transmissions, and (c) working principle of UORA for one transmission opportunity.

III. RELATED WORKS

This section reviews the research on up-link channel resource allocation in dense WLANs. Several studies have (i) investigated the applications of future Wi-Fi networks [2], [3]; (ii) evaluated the performance of UORA transmissions [14], [15]; (iii) identified limitations or major challenges [22], [23]; and (iv) made efforts to find an optimal design [18], [24] to improve the performance of UORA transmission. This section discusses studies that have presented either centralized or distributed UORA schemes for channel resource allocation. Furthermore, Table 1 shows a performance comparison of existing related works and the proposed CODOBO_CTRL scheme.

A. CENTRALIZED UORA-BASED RESOURCE ALLOCATION SCHEMES

In [13], the authors proposed an analytical model to calculate the optimal value of OFMDA CW ($W* = OCW_{min}$ & OCW_{max}) for a centralized UORA scheme, assuming that the number of RA-STAs and RUs are fixed and the AP is aware of both values. This model is known as the Optimal OFDMA CW (OPT_OCW) scheme and is assumed to be an ideal UORA network. Prior to analyzing the performance of the OPT_OCW UORA transmissions, it is important to analyze Eqs. (1), (2) and (3), respectively. In this regard, Eq. (1) represents the value of the channel access probability (τ) that an RA-STA accesses a specific RU once its OBO is less than or equal to zero. Hence, according to [13] (τ) can be written as:

$$\tau = \frac{W+1}{(1-p_c)(W+1+X)} \tag{1}$$

where

$$X = \left(W - \frac{M_{ru}}{2}\right)\left[\frac{W}{M_{ru}}\right] - \left(\frac{M_{ru}}{2}\right)\left[\frac{W}{M_{ru}}\right]^2 \tag{2}$$

and

$$p_c = 1 - (1 - \frac{\tau}{M_{ru}})^{[(RA-STA)-1]} \tag{3}$$

In Eq. (2), W and M_{ru} or the RUs represent the optimal value (W*) of OCW and number of RUs, respectively. Eqs. (1) and 2 are used to obtain the value of the channel collision probability (p_c), which shows that there is a collision probability when a frame is transmitted by two or more stations in the same for uplink transmissions. Eq. (3) computes the value of p_c for each RA-STA, which indicates the probability that at least one of the remaining RA-STAs can transmit a frame by utilizing RU. The analytical model proposed in [13] can produce a peak efficiency of 37%. One limitation of [13] is that it is considered an ideal scenario that is impractical for real-world network applications.

The authors in [25], proposed an analytical model for a centralized UORA scheme to improve throughput and efficiency considering that an AP can estimate the number of contending stations. In [29], BSR-based RA and scheduled

TABLE 1. Performance comparison of existing related works and the proposed scheme.

Ref-Year	Scala bility	Control overhead	Static Network	Highly Dynamic Network	Throughut	Delay	Fairness
[13] - (2017)	Medium	Low	Yes	Supports	High	low	High
[25] - (2017)	Medium	High	Yes	Not tested	Improved 39%	low	High
[17] - (2019)	Medium	Low	Yes	Not tested	Improved 25 %	low	Low
[19] - (2019)	Medium	Low	Yes	Not tested	Improved 25 %	low	High
[16] - (2020)	Medium	medium	Yes	Not tested	Improved 20 %	very low	High
[26] - (2020)	Medium	Low	Yes	Not tested	Improved 15 %	low	Medium
[15] - (2020)	High	medium	Yes	Not tested	Improved 100 %	medium	High
[18] - (2021)	High	Low	Yes	medium Supports	Improved 150 %	low	High
[21] - (2021)	High	Low	Yes	medium Supports	Improved 10 %	low	High
[24] - (2022)	High	High	Yes	medium Supports	Improved 25 %	medium	High
[27] - (2022)	High	High	Yes	medium Supports	Improved 24 %	medium	High
[28] - (2023)	Medium	High	Yes	Not tested	Improved 25 %	low	High
Proposed Scheme	Very High	Zero	Yes	Highly supports	Improved 207 %	Very low	High

access (SA) modes for data transmissions were combined for UL transmissions in IEEE 802.11ax. In [16], a slot-based Hybrid UORA (H-UORA) scheme was proposed to minimize the impact of collisions. The work proposed in [19] is called the probability complementary transmission scheme (PCTS) to address the increased delay because of the doubled OCW range. The PCTS adopts complementary transmission in addition to a back-off process.

In addition, the study presented in [30] offers an analytical framework for evaluating the performance of the Wi-Fi 6 MAC protocol. The analysis considers non-saturated traffic patterns and the coexistence of Wi-Fi 6 with legacy users. In [17], the authors proposed a Collision Reduction and Utilization Improvement (CURI) scheme to mitigate transmission collisions and enhance channel efficiency. This scheme utilizes an extra back-off (EBO) mechanism and opportunistic RU hopping (ORH) approach. Furthermore, in [26], the authors introduce an MU-MIMO-enabled Uplink On-demand Request-Based Access (MU-MIMO UORA) channel access mechanism based on virtual time slots (VTS). This approach aims to reduce transmission collisions and improve the overall system performance. To address the transmission delay caused by collisions, the authors in [20] proposed re-transmission number aware channel access (RNACA) scheme. RNACA probabilistically controls the Open Contention Window (OCW) values for Random Access Stations (RA-STAs) based on factors such as the re-transmission count and number of available RUs. In [24], the authors introduce a centralized heuristic Efficient OFDMA Random Access Backoff (E-OBO) scheme. This scheme enhances the throughput and efficiency of Wi-Fi 6 networks by observing the network density using an AP. Additionally, in [27], the same work was extended using a machine-learning-based reinforcement learning (RL) approach to compare its performance against the heuristic E-OBO scheme.

In [12], the authors proposed a target wake-up time (TWT) mechanism to enhance power-saving capabilities. They classified the optimal number of contending stations into different groups and employed TWT to collectively control their wake and sleep times. This approach effectively reduces transmission collisions and improves the efficient utilization of random access RUs. The aforementioned work was further extended in [14], where the authors focused on analyzing the relationship between RUs and group size. They considered BSR messages based on the UORA scheme and developed an adaptive and variable group size algorithm. This algorithm ensures optimal and efficient delivery of BSR messages, leading to improved transmission success. In [15], the authors proposed a multi-dimensional busy-tone arbitration (MBTA) approach to minimize collision probabilities in RU transmissions within the UORA scheme. The MBTA mechanism effectively reduces the probability of collisions, thereby improving the channel efficiency. Additionally, the authors extended their work in [15] to design a Dynamic Access Mode Selection (DAMS) approach. This approach allows High-Efficiency Access Points (HE-APs) and contending stations to dynamically select the optimal access mode (e.g., Random Access (RA) or Scheduled Access (SA)) based on current network conditions. This adaptive access mode selection further enhances the overall system performance in dense scenarios.

In [28] the authors proposed a hybrid resource allocation scheme based on the average access delay for RA and SA users. The proposed adaptive uplink resource allocation scheme uses a two-step approach. In the first step, it estimates the average access delay of each user then it allocates RUs to users based on their estimated access delay. The simulation results showed that it can significantly improve the performance of the fixed UORA network in terms of throughput, access delay, and fairness. However, this scheme is not suitable for highly dynamic dense network users.

B. DISTRIBUTED UORA AND NON-UORA BASED RESOURCE ALLOCATION SCHEMES

In distributed channel access schemes, contending stations make transmission decisions based on their own view of the network and they adjust their back-off intervals without depending on the access point or centralized view. The aforementioned concept has been well-researched for single-channel resource allocation, but it has recently been used in multi-channel environments for UORA. In [18], the authors proposed a distributed OFDMA BO control scheme (OBO_CTRL) to improve UORA performance in WiFi 6. After every successful or unsuccessful transmission, a node in OBO_CTRL adjusts the value of OBO aggressively or conservatively. The adjustment factor is defined as (α), which is a self-tunable parameter for determining the OBO that is derived empirically from a simulation study. After every successful or unsuccessful transmission, a node in OBO_CTRL adjusts the value of OBO using α aggressively or conservatively. The value of α can vary in the range of [0.01 to ∞] to achieve the best channel fairness index for various network configurations. In [18] for a station to accurately adjust its OBO value, it has to be aware of the network status (i.e., the total number of contending stations), which can be unpredictable in dynamic and dense environments. In the remainder of this subsection, distributed single-channel resource allocation schemes (non-UORAs) are briefly discussed focusing on their applicability or performance within dense networks.

IV. COLLISION BASED DISTRIBUTED OFDMA BACK-OFF CONTROL (CODOBO_CTRL) SCHEME

The (CODOBO_CTRL) scheme uses realistic network parameters to dynamically adjust the random access OFDMA Back-Off (OBO) mechanism for each random access station (RA-STA) using a cautious increase and decrease strategy. In the CODOBO_CTRL scheme, each RA-ST independently makes a decision based on the ACKs (Acknowledgments) received from previous transmissions to control the OBO counter in the subsequent UORA Transmission Opportunity (TXOP). The CODOBO_CTRL scheme dynamically controls the channel access probabilities of the standard UORA in a distributed manner to achieve optimal UORA performance in terms of channel efficiency, average network throughput, and per-station throughput, particularly in highly dynamic networks.

The design considerations for the CODOBO_CTRL scheme are as follows: (i) the scheme should be comparable in performance to the OPT_OCW scheme, as robust as possible, and must not be affected by changes in the number of RA-STAs; (ii) the CODOBO_CTRL scheme must be compatible with the IEEE 802.11ax UORA standard, which follows the BEB in the OCW control mechanism; and (iii) the CODOBO_CTRL scheme must attempt to maintain the default standard values of OCW(OCW_{min}, OCW_{max}) while modifying the OBO calculation procedure.

Eq. (4), represents the basic mathematical equation of the CODOBO_CTRL scheme, where $OBO - M_{ru}$ describes the standard UORA operation and β represents the resource optimization index, which represents a correlation between the channel bandwidth (i.e., number of RUs) and assumes the number of RA-STAs in a dense environment.

$$OBO = [(OBO - M_{ru}) + \beta] \tag{4}$$

Specifically, three distinct values of β are considered: First, β_{ini} is set to 0 for the first UORA TXOP. Second, β_{min} is determined by dividing the channel bandwidth (i.e., the number of RUs) by the maximum number of RA-STAs (i.e., we assumed that the number of RA-STAs is ten times greater than the number of RUs, reflecting a dense environment for resource allocations). Finally, β_{max} is computed as the maximum value of the RUs, with specific values assigned to different channel bandwidths. For instance, in our case, we consider RUs to be 8 and 16 for channel bandwidths of 20 MHz and 40 MHz, respectively. This ensures an efficient resource allocation corresponding to the available channel bandwidths.

$$OBO_{\beta i+1} = [(OBO - M_{ru}) + (\beta_i + CF)] \tag{5}$$

Eq. (5) illustrates the OBO operation at the $(i+1)^{th}$ transmission after an unsuccessful transmission by RA-STA. In this scenario, the intended RA-STA increases the value of β in proportion to the Collision Factor (CF) value. CF represents the maximum collision probability of the OPT_OCW UORA scheme which is 0.63 [13] when the number of RA-STAs exceeds the available RUs. Hence, the primary objective of the CODOBO_CTRL scheme is to optimize the allocation of RUs for a significantly larger number of RA-STAs, ensuring efficient utilization of resources. Furthermore, in the case of consecutive unsuccessful transmissions by the RA-STAs, Eq. (6) shows the operation of the proposed scheme. In this case, the value of CF (i.e., 0.63) is added to the β_i index in an additive increase manner after each unsuccessful transmission. The CF value is carried over from i_{th} or previous transmission to β_{max} for the intended RA-STA.

$$\beta_{i+1} = \min(\beta_i + CF, \beta max) \tag{6}$$

It is important to note that the maximum value of β, denoted by β_{max}, can be equal to the channel bandwidth, which corresponds to the number of RUs. For example, in the case of a 20 MHz channel, the maximum value of β is 8, whereas for a 40 MHz channel, it is 16. This implies that the resource optimization index is based on the available channel bandwidth, allowing for efficient allocation of resources and improved network performance.

$$OBO_{\beta i+1} = [(OBO - M_{ru}) + (\beta_i - CF)] \tag{7}$$

Algorithm 1 Operation of CODOBO_CTRL Scheme in Comparison With UORA_STD [11], and OPT_OCW [18]

Each RA-STA sets $OCW(OCW_{min}, OCW_{max})$
Initialize OBO int$(1 \leq OBO \leq OCW)$
Procedure 1: Receive_TF-R()
  Switch scheme type do
  Case 1 or **Case 2**: **UORA_STD** or **OPT_OCW**
  $OBO = OBO{-}M_{ru}$
   Case 3: CODOBO_CTRL
  $OBO = [(OBO - M_{ru}) + (\beta)]$
    end
if OBO≤ 0 **than**
   access a RA-RU
     else
  resume OBO in next TF-R
      end
  Procedure 2: ACK_Frame_Timeout()
     Switch scheme type do
     Case 1: UORA_STD
     $OCW = 2 \times (OCW + 1) - 1$
     $OCW = min(OCW, OCW_{max})$
     Case 2: OPT_OCW
     $OCW = Get\_Opt\_OCW(M_{ru}, N_{stas})$
     Case 3: CODOBO_CTRL
      $OCW = 2 \times (OCW + 1) - 1$
     $OCW = min(OCW, OCW_{max})$
      $\beta = \beta + CF$
     $\beta_{i+1} = \max(\beta_i + CF, \beta_{min})$
      end
   Select a new OBO$(1 \leq OBO \leq OCW)$
     end
   Procedure 3: ACK_Frame_Received()
     Switch scheme type do
      Case 1: UORA_STD
     $OCW = OCWmin$
      Case 2: OPT_OCW
      $OCW = Get\_Opt\_OCW(M_{ru}, N_{stas})$
     Case 3: CODOBO_CTRL
     $OCW = OCWmin$
      $\beta = \beta - CF$
     $\beta_{i+1} = \min(\beta_i - CF, \beta_{max})$
      end
   Select a new OBO$(1 \leq OBO \leq OCW)$
     end

Eq. (7) describes the OBO operation for the intended RA-STA in the case of a successful transmission at the i^{th} transmission. The OBO counter for the next $(i+1)^{th}$ UORA transmission is determined as follows: The intended RA-STA individually updates its OBO counter (e.g., actively decreases) at the $(i+1)^{th}$ UORA transmission based on the previous $(i)^{th}$ transmission results and the CF value.

$$\beta_{i+1} = \max(\beta_{imax} - CF, \beta_{min}) \tag{8}$$

The CF value is subtracted from β for each consecutive successful transmission until β is reached β_{min}, as shown in Eq. (8). The value of β_i along with the CF (i.e., 0.63) value is updated for each $i + 1^{th}$ transmission using Eq. (7). Additionally, β_{min} was calculated by dividing the channel bandwidth (i.e., the number of RUs) by the maximum number of RA-STAs. It is assumed that the number of RA-STAs is ten times higher than the number of RUs, indicating a dense environment that requires efficient resource allocation.

Algorithm 1 explains the procedures for UORA_STD [11], OPT_OCW [13], and the proposed UORA scheme. Procedure 1 is invoked by each RA-STA with a successfully received TF-R() from an AP, to read the configured value of RUs or M_{ru}. The BO operation is identical to that of Case 1 for STD_UORA or case 2 for OPT_OCW (that is, each RA-STA decreases the OBO counter as $OBO = (OBO - M_{ru})$. Procedure 1 concludes that in the case of 1, 2, and 3 each RA-STA updates the OBO counter according to the configuration rules, and an RA-STA can access the RU if its OBO counter value is equal to or less than 0. Similarly, the RA-STAs must wait for the next TF-R if OBO-Mru gives values greater than zero, as mentioned in Algorithm 1. Furthermore, the values of β and CF are considered to be zero at the first TXOP and do not affect the back-off operation at the first TXOP. In CODOBO_CTRL, OBO is controlled using β and CF values depending on whether the last transmission collided or succeeded. In the case of a collision transmission,

Procedure 2 is executed when an ACK_Frame() is not received from an AP to the intended RA-STAs within *ACK_Timeout* (i.e., the transmission collided). In this procedure, the UORA scheme controls OCW values to avoid transmission collisions for the next TOXP. In the case of 1 and 2 the OCW value is increased (i.e., doubled) at each collision $OCW = 2 \times (OCW + 1) - 1$ until it reaches up to $OCW = min(OCW, OCW_{max})$ as per the OCW configurations. For Case 2, an AP calculates the optimal value of OCW according to the number of RA-STAs and RUs for the next TXOP using the OPT_OCW UORA scheme. However, using the CODOBO_CTRL scheme intended unsuccessful RA-STAs to operate individually in a conservative manner for the next TXOP, which increases the CF value using Eqs. (5) and (6), respectively. Furthermore, in the case of successful transmission,

Procedure 3 is performed when ACK_Frame_Received() from an AP to the intended station within *ack_timeout* (i.e., the transmission succeeds). In this procedure for Case 1, the RA-STAs update their OCW to COW_{min}, for case 2 OCW value is set to its optimal OCW value according to the number of RA-STAs and RUs. However, using the CODOBO_CTRL scheme the intended successful RA-STAs individually decreased the value of CF (i.e., 0.63) along β in Eqs. (7) and (8) to increase the transmission opportunity in the next $(i+1)^{th}$ TXOP.

TABLE 2. Simulation parameters.

Parameters	Value
PHY/MAC Specifics	IEEE 802.11ax
OFDMA Channel Access mode	UORA
OFDM Channel BW	20 and 40 MHz
Number of sub-carriers/RU	24
OFDM Symbol duration	12.8 us
Guard Interval(GI)	1.6 us
Number of RUs (Mru) with AID = 0	8, 16
Number of RUs with AID = 2045	1, 2
OCW_{min}	7, 15, 31
OCW_{max}	31, 255, 1023
RA-STAs	1 to 120
Length of MPDU	2000 bytes
Modulation index	64-QAM
Coding rate (CR)	2/3
Data rate per RU	6.67 Mbps
Length of PHY header	40 us
Length of Trigger frame	100 us
Length of BACK-ACK frame	68 us
Length of association request frame	38 bytes
SIFS Interval	16 us
Slot time	9 us
Simulation time	60 sec

V. SIMULATION ANALYSIS

The proposed CODOBO_CTRL scheme is implemented and evaluated using MATLAB, considering key components such as RUs, RA-STAs, and p_c in the context of the IEEE 802.11ax network. During the simulation analysis, certain assumptions were made: (i) the network consisted of a single AP without external interference, (ii) the physical channel was free from impairments, (iii) collisions occurred only when multiple RA-STAs accessed the same RU, (iv) the AP configured the complete bandwidth for RUs with specific AID values (e.g., 0 or 2045), (v) there were are no hidden terminals, and (vi) all network stations competed for the channel in the UORA mode. The simulation parameters used in this analysis are listed in Table 2. The performance evaluation metrics of the proposed CODOBO_CTRL scheme are compared with those of the STD_UORA [11], OPT_OCW [13], E_OBO_CTR [24], and OBO_CTRL [18] schemes for Wi-Fi 6 networks.

A. PERFORMANCE EVALUATION OF UORA SCHEMES IN A STATIC NETWORK

In this regard, we first calculate the optimal value of OCW ($i.e., W* = OCW_{min}$ and OCW_{max}) by solving Eqs. (1), (2), and (3) considering the analytical model used in [13]. Figure 2 shows the value of W* for the number of RA-STAs (1 ≤ RA-STAs ≥ 100) when the RUs are 4, 8 and 16, respectively. The value of $W*$ increased almost linearly increased as long as RA-STAs ≥ RUs, which is similar to the conventional DCF. It is also important to note that we used W* values when simulating a centralized OPT_OCW scheme for all network scenarios.

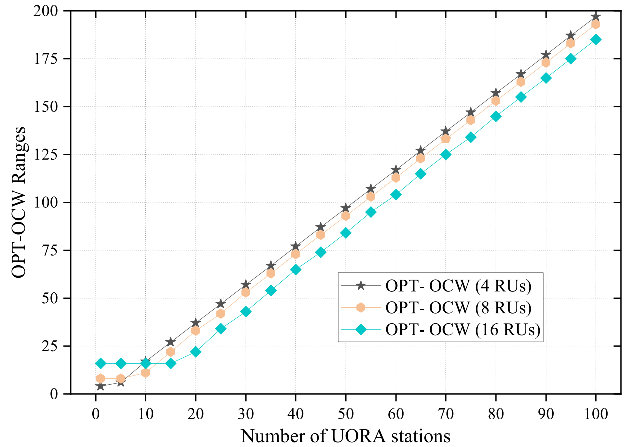

FIGURE 2. Optimal OCW (W*) range vs number of UORA station.

Next, we also analyzed and computed the channel efficiency (η) of the UORA using Eq. (9) which is a function of τ, p_c, W*, RA-STAs, and RA-RUs. Hence, η can be expressed as:

$$\eta = \frac{RA - STAs \times \tau(1 - p_c)}{RUs} \tag{9}$$

According to Eq. (9), η is the ratio of the expected RA-STAs that successfully transmits a frame (e.g., physical-layer protocol data unit (PPDU)) to the number of RUs, which represents the fraction of RUs (i.e., successful RUs) that are neither idle nor collided into during one UORA TOXP. We observe that in the case of OPT_OCW the value of η reaches a maximum (i.e., RUs ≅ 8), even {though it remains almost constant as long as RA-STAs ≥ RUs. In addition, it should be noted which is the maximum achievable efficiency of UORA is not greater than 37% even when employing the OPT_OCW scheme. This mainly arises from the random access nature of the UORA scheme and is similar to the slotted ALOHA protocol because of the absence of a carrier sensing mechanism for each RU.

Figure 3 shows a comparative analysis of channel efficiency η for the eight RUs. In the case of standard UORA schemes, the maximum η can be achieved for specific RA-STAs and is comparable to that of the OPT_OCW scheme. In Figure the 3, for STD_UORA(7, 31) scheme, the value of η is smaller than 0.25 when RA-STA > 30. The channel efficiency diminishes as the collision probability increases with a higher number of stations, mainly because of the low range of the OCW. Meanwhile, it was greater than 0.35 for the same number of RA-STAs in the case of STD_UORA(15, 255) & STD_UORA(31, 1023) schemes, respectively.

The performance of a centralized UORA with a default OCW range (i.e., STD_UORA(7, 31)) may degrade significantly as the number of RA-STAs exceeds a certain limit, as shown in Figures 3. However, this performance can be improved by large OCW ranges (e.g., STD_UORA(31, 1023)), although this configuration shows

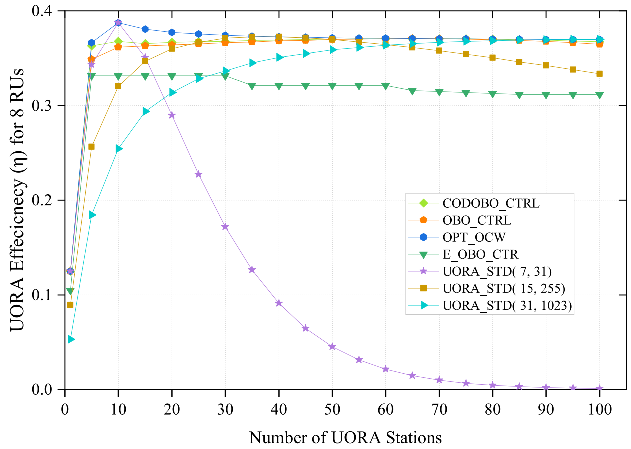

FIGURE 3. Comparison of channel efficiency (η) for UORA_STD, OPT_OCW, E_OBO_CTR, OBO_CTRL and CODOBO_CTRL schemes for 8 RUs.

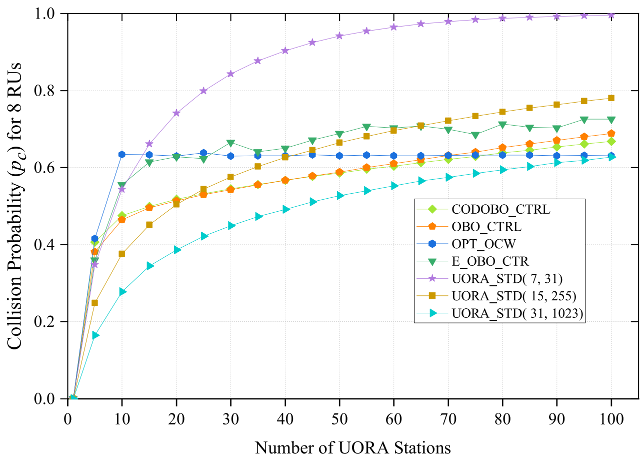

FIGURE 4. Comparison of Channel Collision probability (p_c) for UORA_STD, OPT_OCW, E_OBO_CTR, OBO_CTRL and CODOBO_CTRL schemes.

alower performance for small RA-STAs. Furthermore, the efficiency of E_OBO_CTR remains between 31 % and 33 % for the same number of RA-STAs. However, the CODOBO_CTRL scheme shows almost similar channel efficiency compared to the OPT_OCW UORA scheme for 1 - 100 RA-STAs. In addition, as the number of RA-STAs increased, the channel access probability remained almost equal, and CODOBO_CTRL behaved similarly to the OPT_OCW UORA scheme.

Figure 4 illustrates the impact of the number of RA-STAs (i.e., 1 to 100) on the channel collision probability (p_c) for the UORA_STD, OPT_OCW, E_OBO_CTR, OBO_CTRL, and CODOBO_CTRL schemes for eight RUs. In the case of the STD_UORA schemes, the value of p_c increases linearly as the number of RA-STAs exceeds the available RUs. Furthermore, in the case of the OPT_OCW scheme, Figure 4 shows an interesting and remarkable result regarding p_c value that remains almost constant (i.e., 0.63) or does not vary even when the number of RA-STAs is greater than that of

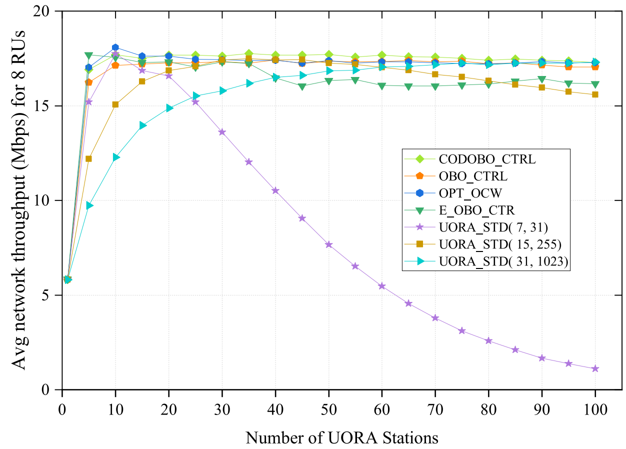

FIGURE 5. Comparison of average Network throughput for UORA_STD, OPT_OCW, E_OBO_CTR, OBO_CTRL and CODOBO_CTRL Schemes for 8 RUS.

RA-STAs. It is important to note that the collision factor (CF), a fixed value used in the CODOBO_CTRL scheme is adopted from the p_c of the Optimal UORA scheme for dense environments. Further, regarding CODOBO_CTRL scheme, the value of p_c increased from 0.46 to 0.65 when number of RA-STAs increased from 10 to 100. Compared with other UORA schemes, the p_c value for the CODOBO_CTRL mechanism is much closer to that of the OPT_OCW scheme, which is considered to be an ideal network in terms of a centralized UORA scheme.

Next, Eq. (10) shows basic data rate calculation per RU:

$$Data\ Rate/RU = \frac{(N_{sd} \times N_{bp} \times CR \times N_{ss})}{(T_{dft} + T_{gi})} \tag{10}$$

where, N_{sd}, N_{bp}, CR, N_{ss}, T_{dft} and T_{gi} are the number of sub-carriers, number of coded bits per subcarrier, coding rate depending on the modulation order, number of spatial streams, OFDM symbol duration and guard interval, respectively. For example, we configured $N_{sd} = 24$, $N_{bp} = 6$, $CR = 2/3$, $N_{ss} = 1$, $T_{dft} = 12.8\ us$, and $T_{gi} = 1.6\ us$ to use 6.666 Mbps data per RU.

Eq. (11) is used to calculate per station throughput:

$$N_{sta}^{th} = \frac{(8 \times L_{MPDU})}{(N_{slot} \times U_{slot}) \times 10{-}6} \tag{11}$$

where, L_{MPDU}, N_{slot}, U_{slot} denote shows the length of the MAC protocol data unit, the simulation time in slots, and the time of one-time slot, respectively. The average network throughput was calculated using $N_{sta}^{th} \times$ RA-STAs. Eq. 12 was used to calculate the average network throughput of the UORA stations.

$$Avg\ NW\ Thr = N_{sta}^{th} \times number\ of\ stations \tag{12}$$

Figures 5 and 6 show a comparison of the average network throughput for the UORA_STD, OPT_OCW, E_OBO_CTR, OBO_CTRL and CODOBO_CTRL Schemes for eight RUs

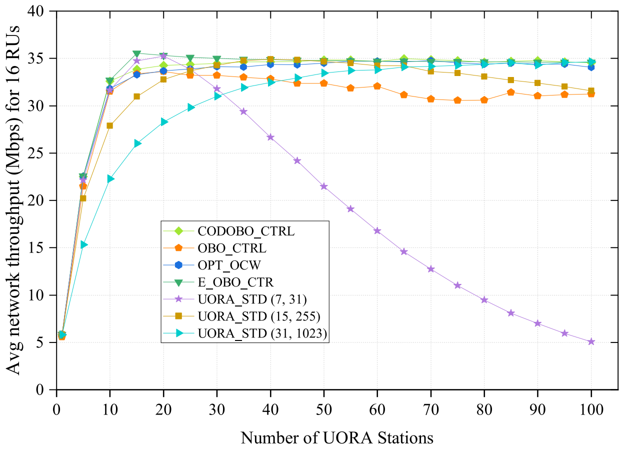

FIGURE 6. **Comparison of average Network throughput for UORA_STD, OPT_OCW, E_OBO_CTR, OBO_CTRL and CODOBO_CTRL Schemes for 16 RUs.**

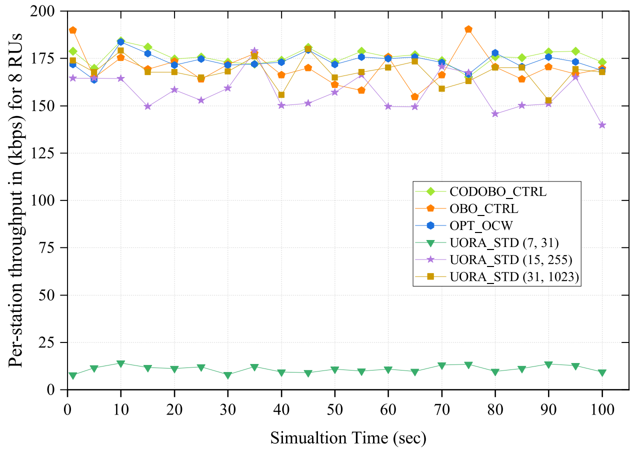

FIGURE 7. **Comparison of Per-station throughput for UORA_STD, OPT_OCW, OBO_CTRL and CODOBO_CTRL schemes for 8 RUs.**

(i.e., 20 MHz) and 16 RA-RUs (i.e., 40 MHz), respectively. In the case of 20 MHz channel, for STD_UORA(7, 31), the throughput gradually increased to 17.74 Mbps when the number of RA-STAs increased from 1 to 10, as shown in Figure 5. However, the throughput began to decrease from 17.64 Mbps and dropped to 1.09 Mbps as the number of RA-STAs increased from 15 to 100.

At the same time, when we consider a widened range of OCW, in the case of the STD_UORA(31, 1023) scheme that shows higher throughput (i.e., 16.20 to 17.30 Mpbs) when the number of RA-STAs is greater than 30 but lower throughput (i.e., 5.80 to 15.51 Mbps) when the number of RA-STAs is less than 25 as compared to the OCW value of the STD_UORA(7, 31) scheme. Furthermore, in the case of STD_UORA(15, 255) scheme, the throughput results are compared with those of STD_UORA(7, 31) and STD_UORA(31, 1023).

Furthermore, Figure 6 demonstrates a similar behavior, that is, higher throughput results, when considering the UORA_STD, OPT_OCW, E_OBO_CTR, OBO_CTRL, and CODOBO_CTRL schemes. The CODOBO_CTRL scheme can be extended to work with 16 RUs, which corresponds to a 40 MHz channel. In this case, the scheme achieves a performance almost equal to that of the OPT UORA scheme. This is because the resource optimization index (β) values are based on primitive network parameters (i.e., channel bandwidths), which allows it to operate efficiently even for 40 MHz channel bandwidth.

These discussions and findings confirm the limitations of the state-of-the-art STD_UORA scheme, where throughput maximization is achieved only for a specific number of RA-STAs and is highly sensitive to variations in the number of RA-STAs. Furthermore, in the case of the proposed CODOBO_CTRL scheme notably outperforms compared to STD_UORA, E_OBO_CTR, and OBO_CTRL schemes for the same number of RA-STAs as shown in Figure 5. Further, the average network throughput observed for E_OBO_CTR 16.09, CODOOBO_CTRL 16.97, OPT_OCW 16.88, OBO_CTRL 16.66, STD_UORA(7, 31) 8.25, STD_UORA(15, 255) 15.91, and STD_UORA(31, 1023) 15.51 Mbps for 8 RUs, respectively.

Figure 7 shows a comparison of the per-station throughput for the UORA schemes considering eight RUs. The vertical scale for per-station throughput is represented in kilobits per second (kbps) to clearly illustrate the variations observed with varying numbers of RA-STAs. We also measured the average per-station throughput for E_OBO_CTR 162.70, CODOBO_CTRL 177.60 kbps, OPT_OCW 172.99 Kbps, OBO_CTRL 171.55 Kbps, STD_UORA(7, 31) 11.10 kbps, STD_UORA(15, 255) 157.79 kbps, and STD_UORA(31, 1023) 173.43 kbps, respectively. This shows that the performance of CODOBO_CTRL remains dominant compared with other UORA schemes for 1 to 100 RA-STAs, as shown in Figure 7.

In the case of the STD_UORA(7, 31) scheme, the RA-STAs experience a higher channel access delay than other UORA schemes. In the case of the STD_UORA (15, 255) scheme, the RA-STAs face less channel access delay for 1 -65 stations and experience higher delay for 70 to 100 RA-STAs. Furthermore, the STD_UORA(31, 1023) scheme behaves in the opposite manner for the same number of random stations as shown in Figure 8. However, the CODOBO_CTRL scheme shows an almost similar access delay compared with the OPT_OCW UORA scheme.

In contrast to throughput improvements, it is important to observe the effects of the proposed scheme on channel fairness. Hence, Eq. (13) is used to calculate Jain,s fairness index [31], where th_i is means the throughput achieved by the number of RA-STAs.

$$\mathit{fairness\ index} = \frac{(\sum_{i=1}^{RA-STAs} th_i)^2}{RA - STAs \sum_{i=1}^{RA-STAs} th_i^{2}{}'} \qquad (13)$$

TABLE 3. Static Scenario: UORA RUs analysis and channel fairness calculations.

UORA Scheme	TF_tot	RA_RUs	trasnmitted RUs	RUs_idl (%)	RU_suc (%)	RU_coll (%)	fairness index
STD_UORA(7, 31)	21858	8	174864	0.11	0.02	0.86	0.97
STD_UORA(15, 255)	21858	8	174864	0.30	0.30	0.40	0.99
STD_UORA(31, 1023)	21861	8	174888	0.44	0.33	0.23	0.99
OPT_OCW	21866	8	174928	0.43	0.33	0.24	0.99
OBO_CTRL	21858	8	174864	0.38	0.32	0.29	0.99
CODOBO_CTRL	21859	8	174872	0.40	0.33	0.27	0.99

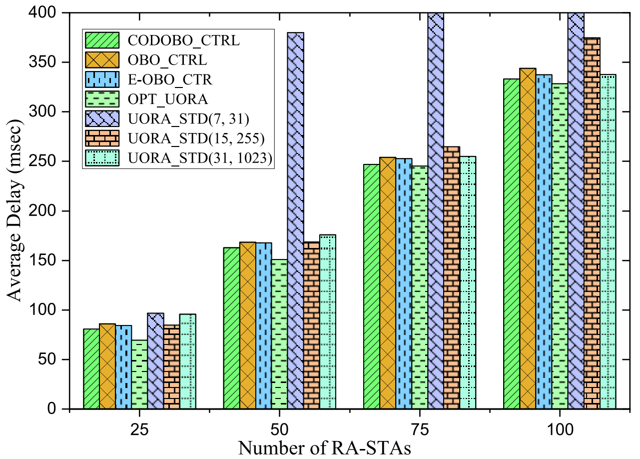

FIGURE 8. Comparison of channel access delay for UORA_STD, OPT_OCW, OBO_CTRL and CODOBO_CTRL schemes for 8 RUs.

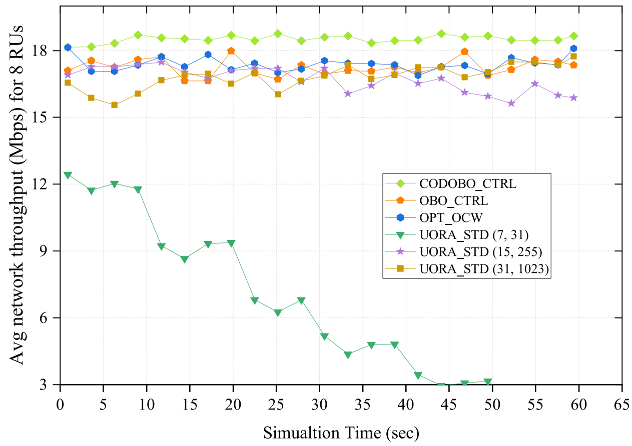

FIGURE 9. Comparison of network throughput for CODOBO_CTRL, OPT_OCW, OBO_CTRL, and UORA_STD schemes for 8 RUs considering SCN-1.

All RA-STAs have equal rights to access the network resources and achieve the same throughput, and the fairness index has the maximum value (e.g., in the ideal case = 1). However, it shows a minimum value when only one 1/RA-STA monopolizes the entire network resources. In the CODOBO_CTRL scheme, the fairness index was similar to that of the OPT_OCW scheme which is close to 1 (i.e., the ideal value) for the entire range of RA-STAs as described in the last column of Table 3.

The average access delay (Del), is the number of stages that an RA-STA needs to pass through to successfully contend for the RUs. Because the average channel access delay follows a geometric distribution with parameter the probability of successful RA-STAs ($p_{s,stas}$) follows in Eq.14

$$Avg[Del] = \frac{1}{\tau(1-\frac{\tau}{RUs})^{n-1}} \tag{14}$$

where, τ, RUs, and the number of random access stations (n or RA-STAs) are already explained in earlier equations.

Figure 8 compares the average channel access delay (i.e., in ms) of UORA_STD, OPT_OCW, OBO_CTRL, E_OBO_CTR and CODOBO_CTRL schemes for eight RUs. Figure 8 clearly shows that the CODOBO_CTRL scheme has a significantly lower channel access delay than the UORA_STD scheme. The stations using the CODOBO_CTRL scheme experience less channel access delay than those using the OBO_CTRL, and E_OBO_CTR scheme. In addition, the CODOBO_CTRL schemes have almost the same channel access delay as the OPT_UORA scheme.

In addition, we assessed the performance of UORA schemes based on various parameters such as Jain's fairness index, transmitted TFs, configured RUs, percentage of collided RUs ($^{C}_{RU}$), successful RUs ($^{S}_{RU}$), and Idle RUs ($^{I}_{RU}$) for the same configured parameters. Our observations indicate that the performance of OFDMA channel resources is directly influenced by the UORA channel access mode (centralized or distributed), range of OCW, and number of RA-STAs. For example, in the case of STD_UORA(7, 31), the value of RUs_coll was very high (i.e., 0.86% collided) and RUs_succ observed very low (i.e., 0.02% were successfully accessed). However, in STD_UORA(15, 255) these values are between (i.e., 0.40% collided and 0.30% successfully accessed) those of the STD_UORA(7, 31) and STD_UORA(31, 1023) schemes. Furthermore, in the case of CODOBO_CTRL compared to the OBO_CTRL and OPT_OCW schemes, collided RUs were observed (i.e., 0.27%, 0.29%, and 0.24%), whereas the $^{S}_{RUs}$ measured (i.e., 0.33%, 0.32%, and 0.33%) of the total configured RUs are shown in Table 3.

B. PERFORMANCE EVALUATION OF UORA SCHEMES UNDER DYNAMIC NETWORK SCENARIOS

In this subsection, we assess the performance of the UORA schemes by considering various dynamic scenarios (e.g.,

TABLE 4. Network configuration for dynamic scenarios using UORA Schemes.

Dynamic Scenarios	N_stas_A	N_STAs_J	J_Time(s)	N_STAs_L	L_Time(s)
SCN-1	25	10	10	0	0
SCN-2	100	0	0	10	10
SCN-3	50	15	15	10	20
SCN-4	100	8	1.25	8	1.25
SCN-5	20	8	1.25	8	1.25

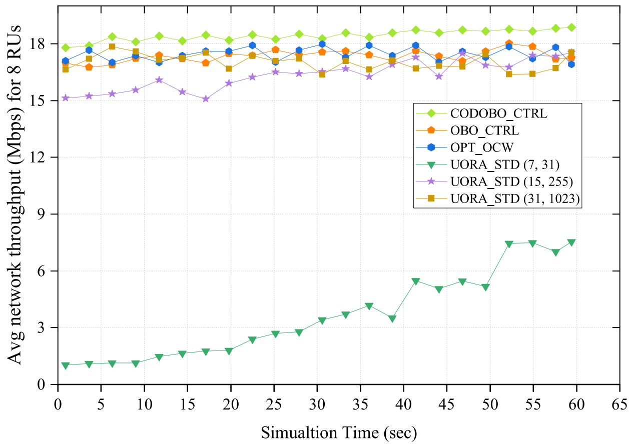

FIGURE 10. Comparison of network throughput for CODOBO_CTRL, OPT_OCW, OBO_CTRL, and UORA_STD schemes for 8 RUs considering SCN-2.

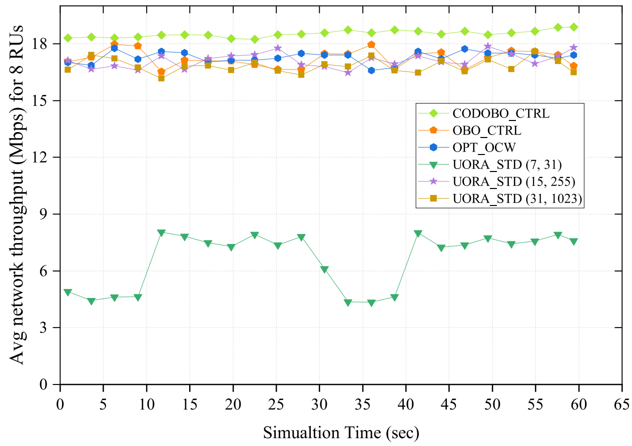

FIGURE 11. Comparison of network throughput for CODOBO_CTRL, OPT_OCW, OBO_CTRL, and UORA_STD schemes for 8 RUs considering SCN-3.

SCN-1 to SCN-5). Each scenario was simulated using various configuration parameters the in Table 4. For instance, the variable N_{sta}^{a} represents the initial number of RA-STAs already associated with an Access Point (AP), whereas N_{sta}^{J} and N_{sta}^{L} indicate the number of RA-STAs joining and leaving a Base Service Set (BSS) within each time interval T_{sec}, respectively. It is important to note that N_{sta}^{Jo} denotes an un-associated station that joins a BSS and contends for RUs with AID-2045. Once a station becomes associated with a BSS, it follows the UORA standard procedure to compete with the existing associated stations for transmitting a data frame. Throughout the simulation, we measure the throughput every 100,000 slots, as specified in Table 4.

1) DYNAMIC SCENARIO 1

In this subsection, we present the performance evaluation of dynamic SCN-1 in terms of the average network for UORA schemes. Figure 9 illustrates the throughput comparison for SCN-1, where ten RA-STAs join every 10 sec (that is, $N_{sta}^{J} = 10$ and $T_{sec}^{J} = 10$). In this scenario, the initial number of associated RA-STAs (N_{sta}^{a}) was 25, and up to 60 new stations joined the network throughout the simulation time. The network throughput of STD_UORA(7, 31) reached its maximum when the number of RA-STAs was approximately 20 and started to decrease when the number of RA-STAs exceeded 25. In contrast, the throughput of other UORA schemes (STD_UORA(15, 255) and STD_UORA(31, 1023)) gradually increases until the number of RA-STAs reached 32. In dynamic SCN-1, CODOBO_CTRL achieved the highest average network throughput of 18.513 Mbps, followed by OPT_OCW at 17.240 Mbps, OBO_CTRL at 17.390 Mbps, and UORA_STD at 13.269 Mbps.

2) DYNAMIC SCENARIO 2

In Figure 10, we present the throughput performance in SCN-2, where the initial number of associated stations (N_{sta}^{a}) is set to 100, and 10 stations depart every 10 sec (i.e., $N_{sta}^{L} = 10$, and $T_{sec}^{L} = 10$) throughout the simulation. As the number of RA-STAs gradually decreased from 100 to 60, the contention for UORA channel access decreased over time, resulting in improved throughput, as depicted in Figure 10. For the STD_UORA(7, 31) scheme, the throughput exhibits a linear increase from 1.03 Mbps to 7.53 Mbps throughout the entire simulation. In the case of the STD_UORA(15, 255) and STD_UORA(31, 1023) schemes, the throughput slightly increases from 15.12 Mbps to 17.53 Mbps and from 16.633 Mbps to 17.53 Mbps, respectively. On the other hand, the CODOBO_CTRL scheme demonstrated a gradual increase in throughput over time compared to the OPT_OCW and OBO_CTRL UORA schemes, as illustrated in Figure 10. In dynamic SCN-2, CODOBO_CTRL achieved the highest average network throughput of 18.439 Mbps, with respect to OPT_OCW at 17.343 Mbps, OBO_CTRL at 17.456 Mbps, and UORA_STD at 12.349 Mbps.

3) DYNAMIC SCENARIO 3

Next, in Figure 11, we analyze the throughput variations of the UORA schemes in SCN-3, where the initial number

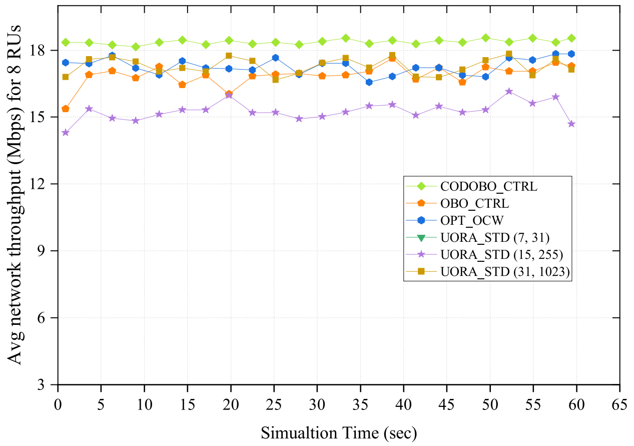

FIGURE 12. Comparison of throughput for UORA_STD, OPT_OCW, OBO_CTRL and CODOBO_CTRL schemes for 8 RUs considering SCN-4.

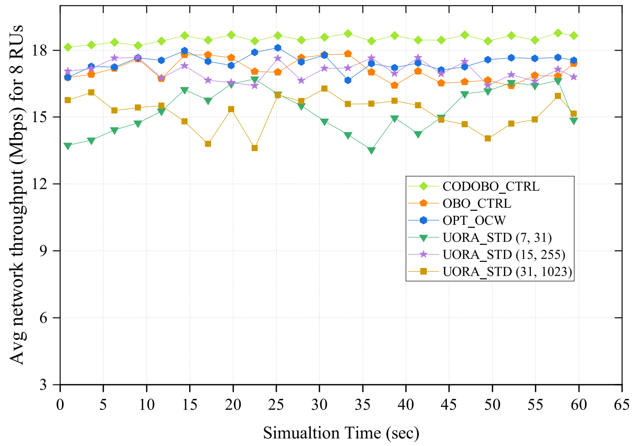

FIGURE 13. Comparison of throughput for UORA_STD, OPT_OCW, OBO_CTRL and CODOBO_CTRL schemes for 8 RUs considering SCN-5.

of associated stations (N_{sta}^{a}) is 50. Additionally, 15 stations joined every 20 sec, while 15 stations left every 10 sec during the simulation time. For the STD_UORA(7, 31) scheme, the throughput showed higher fluctuations corresponding to the variations in the number of RA-STAs throughout the simulation time. Similarly, throughput variations were observed for all other UORA standard schemes. However, the CODOBO_CTRL scheme supports a higher throughput with smaller variations owing to the dynamic adjustment of the OBO operation, even in the presence of fast user changes within a dense and dynamic network. In dynamic SCN-3, CODOBO_CTRL achieved the highest average network throughput of 18.525 Mbps, with respect to OPT_OCW at 17.287 Mbps, OBO_CTRL at 17.173 Mbps, and UORA_STD at 13.532 Mbps.

4) DYNAMIC SCENARIO 04

Further, in SCN-4, we set the configuration parameters to have a larger value for N_{sta}^{a} compared to SCN-1, SCN-3, and SCN-5 as shown in Table 4.

In this scenario, we configured $N_{sta}^{a} = 100$, eight stations join and leave every 1.25 sec during the simulation time. In the case of SCN-4, the CODOBO_CTRL, STD_UORA(31, 1023), OBO_CTRL and OPT_OCW schemes achieved similar throughput performances, as shown in Figure 12. However, the average network throughput of STD_UORA(7, 31) was significantly degraded in a highly dense dynamic network.

5) DYNAMIC SCENARIO 5

Figure 13 reveals that, in the case of SCN-5, the throughput of all UORA schemes fluctuated more than in all other dynamic scenarios. In this dynamic scenario, we configured $N_{sta}^{a} = 20$, and eight stations joined and left every 1.25 sec during the simulation time. The STD_UORA(7, 31) and STD_UORA(31, 1023) schemes show low throughput performance compared to the STD_UORA(15, 255) and other UORA schemes. Achieved throughput for STD_UORA(7, 31) or STD_UORA(31, 1023) starts from 13.73 Mbps or 15.76 Mbps and ends with 14.85 Mbps or 15.15 Mbps, respectively. Figure 12 also shows one more interesting result that the average network throughput of STD_UORA(15, 255) was higher than that of the STD_UORA(7, 31) and STD_UORA(31, 1023) schemes, which was not the case for dynamic scenarios 1, 2, 5 or the static scenario (Figure 5). Furthermore, the COBODO_CTRL scheme achieved a higher throughput level than the OBO_CTRL and OPT_OCW schemes as shown in Figure 13. In dynamic SCN-3, CODOBO_CTRL achieved the highest average network throughput of 18.510 Mbps, with respect to OPT_OCW at 17.465 Mbps, OBO_CTRL at 17.113 Mbps, and UORA_STD at 15.871 Mbps.

Hence, the better performance of CODOBO_CTRL in highly dynamic networks is due to the use of realistic network parameters, which effectively control the OBO operation, adapt to user associations, and improve network throughput. It outperformed other UORA schemes, making it a better choice for highly dynamic scenarios. Overall, the adaptability and performance of the CODOBO_CTR make it a reliable choice in highly dynamic environments.

6) PER-STATION THROUGHPUT COMPARISON UNDER DYNAMIC NETWORKS

In addition to analyzing the overall network throughput, we also assessed the per-station (PS) throughput of the proposed scheme, measured in kilobits per second (Kbps). The PS values for the five dynamic scenarios are presented in Table 5. Across all dynamic scenarios, our proposed CODOBO_CTRL performed consistently better than STD_UORA, OBO_CTRL, and OPT_OCW in terms of per-station throughput.

7) THE EFFECT OF VARYING RA-RUs ON VARYING NUMBER OF RA-STAs

It is important to note that for all of the above analyses, we configured the constant number of RUs configured

TABLE 5. The comparison of average per-station throughput in (Kbps) of UORA schemes under various dynamic environments.

Dyn SCN	CODOBO_CTRL	OBO_CTRL	OPT_OCW	STD_UORA(7, 31)	STD_UORA(15, 255)	STD_UORA(31, 1023)
SCN-1	213.29	203.64	203.47	72.58	198.53	201.80
SCN-2	181.09	172.49	173.18	37.15	164.59	171.27
SCN-3	276.86	266.17	266.70	102.88	264.09	259.07
SCN-4	168.87	156.35	159.56	8.44	142.41	160.91
SCN-5	641.18	613.99	626.20	549.12	607.38	545.16

TABLE 6. The impact of varying RUs on a changing number of RA-STAs in terms of throughput (Mbps).

UORA Schemes	RA-STAs	Fixed RUs								Avg RUs Thr	Avg NW Thr	% of increased wrt UORA_STD [11]
		1	2	3	4	5	6	7	8			
UORA_STD (7, 31)	20	2.21	3.80	5.73	7.73	9.82	12.11	14.26	16.54	9.02	3.67	–
	50	0.62	1.32	2.11	3.02	4.00	5.05	6.35	7.67	3.77		
	75	0.17	0.41	1.02	1.02	1.41	1.86	2.47	3.13	1.44		
	100	0.04	0.11	0.19	0.29	0.43	0.59	0.83	1.08	0.44		
OPT_OCW	20	3.35	4.98	6.87	8.89	11.03	13.19	15.46	17.54	10.16	10.05	174%
	50	3.41	4.96	6.75	8.76	10.88	12.98	15.18	17.26	10.02		
	75	3.38	5.00	6.78	8.69	10.92	12.98	15.12	17.31	10.02		
	100	3.38	4.94	6.78	8.74	10.89	12.98	15.07	17.27	10.01		
OBO_CTRL	20	3.98	5.39	7.07	9.07	11.02	13.06	15.13	17.23	10.24	10.00	172%
	50	3.55	5.10	6.90	8.81	10.90	12.98	15.17	17.31	10.09		
	75	3.27	4.87	6.70	8.73	10.73	12.93	15.09	17.21	9.94		
	100	2.98	4.60	6.53	8.54	10.52	12.70	14.91	17.06	9.73		
COBODO_CTRL	20	5.23	5.60	7.40	9.68	12.97	15.54	17.60	18.24	11.53	11.24	207%
	50	4.29	5.81	7.85	10.14	12.22	15.29	17.41	17.97	11.37		
	75	3.85	5.24	7.86	9.96	12.03	14.15	17.15	17.90	11.02		
	100	3.24	5.77	7.62	9.64	12.80	14.69	17.09	17.57	11.05		

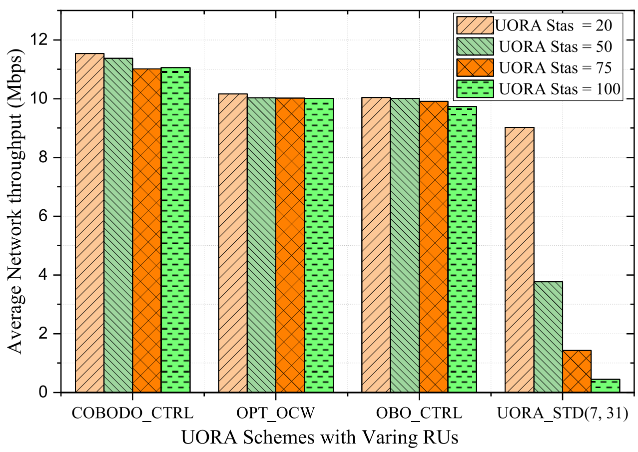

FIGURE 14. Comparison of average throughput for UORA_STD, OPT_OCW, OBO_CTRL and CODOBO_CTRL schemes when number of RUs (i.e., 8) and RA-STAs are varying.

with AID 0 as eight. In this subsection, we extend the detailed performance analysis of the UORA schemes by varying the number of RUs and RA-STAs. Figure 14 and Table 6 show the average throughput comparison of the STD_UORA(7, 31), OBO_CTRL, OPT_OCW, and CODOBO_CTRL schemes using a variable and uniformly distributed random value for RUs from one to eight for each UORA TXOP. Recall that CODOBO_CTRL is completely identical to STD_UORA(7, 31) if the β and CF values of CODOBO_CTRL are not considered and are fixed at 0. For the centralized UORASTD_UORA(7, 31) scheme, when the number of RA-STAs increased from 20 to 100, the throughput decreased rapidly from 10.3 to 0.445 Mbps. Even so, CODOBO_CTRL remained almost constant and the throughput was higher, regardless of the number of RA-STAs varies as shown in Table 6. The average network throughput of CODOBO_CTRL, OPT_OCW, OBO_CTRL, and STD_UORA(7, 31) was observed to be 11.24 Mbps, 10.05 Mbps, 10.00 Mbps, and 3.66 Mbps, respectively.

It is also worth mentioning that the change in RUs did not significantly affect the throughput per RU for the proposed UORA scheme. Further, the average throughput of CODOBO_CTRL was 17.92 when M_{ru} was fixed at eight for all variable numbers of stations, and the average network throughput per RU was 2.19 Mbps. Using the average (1 to 8 = 4.5) of variable M_{ru} in this simulation, the average throughput per RU was 2.23 Mbps even in the OPT_OCW scheme, which is almost similar to the case when we consider M_{ru} count to be fixed. Consequently, the CODOBO_CTRL UORA scheme shows outstanding performance in highly dynamic environments by adjusting the OBO operation using channel bandwidths and collision factors parameters.

VI. CONCLUSION

In this paper, we proposed CODOBO_CTRL, a collision-based distributed OBO control scheme that uses channel bandwidths (i.e., 20 MHz and 40 MHz) and collision probabilities to improve UORA efficiency in Wi-Fi 6 networks.

In the proposed scheme, each random access station actively determines and updates a value channel resource optimization index to individually control the OBO counter in a distributed manner, depending on whether the previous transmission succeeded or collided. The motivation for CODOBO_CTRL is to improve the performance of the UORA in highly dynamic networks by using the primitive network parameters of IEEE 802.11ax. The CODOBO_CTRL scheme accesses the channel effectively and in a distributed manner accesses the channel, resulting in a reduction in idle RUs for a small number of stations and minimizing the number of collided RUs for a large number of stations. Furthermore, the proposed scheme does not require a signaling mechanism among network entities prior to data transmission and is also considered to be free from transmission signaling overhead. We provide a comprehensive and concise comparative analysis of the proposed CODOBO_CTRL scheme with centralized and non-centralized UORA schemes. The average network throughput of the proposed CODOBO_CTRL scheme is improved by up to 207%, 12%, and 11%, in highly dynamic scenarios in Wi-Fi 6, compared to the STD_UORA [11], OBO_UORA [18], and OPT_UORA [13] schemes, respectively.

As a potential future work, the CODOBO_CTRL scheme can be extended for channel resource allocations to incorporate Quality of Service (QoS) traffic differentiation, specifically for real-time or latency-sensitive applications in dense environments.

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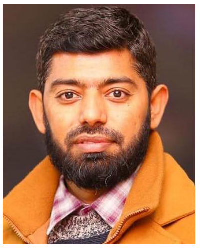

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