An Efficient Backoff Procedure for IEEE 802.11ax Uplink OFDMA-Based Random Access

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ABSTRACT IEEE 802.11ax stations can use multi-user (MU) uplink OFDMA-based random access (UORA) to improve per-station throughput in dense deployments in comparison to legacy IEEE 802.11 single-user access. Unfortunately, UORA suffers from a high collision probability and low efficiency under high contention. In this paper, we address this problem by modifying the UORA backoff selection method. The proposed solution allows an access point to adjust the OFDMA random access backoff (OBO) countdown rate to decrease the probability of uplink transmission failures. The implemented changes considerably improve UORA performance. We show through extensive simulations, that the proposed efficient OFDMA random access backoff (E-OBO) ensures throughput, efficiency, and collision probability close to optimal and outperforms state-of-the-art solutions.

INDEX TERMS IEEE 802.11ax, uplink OFDMA random access, UORA, efficiency.

I. INTRODUCTION

The IEEE 802.11ax amendment introduces uplink (UL) multi-user (MU) orthogonal frequency-division multiple access (OFDMA) to improve the efficiency of Wi-Fi networks. OFDMA can operate in two modes: scheduled access (SA) and random access (RA). This letter was designed to provide uplink OFDMA-based random channel access (UORA). Unfortunately, UORA is known to be inefficient under saturation. Therefore, in this paper we focus on RA and we refer the readers to [1] for a detailed analysis of the scheduled version of OFDMA in IEEE 802.11ax.

In OFDMA-based channel access, radio channel resources are divided into several sub-carrier groups, called resource units (RUs). This allows multiple stations to perform transmissions at the same time, which improves efficiency in comparison to single user channel access. In case of uplink 802.11ax RA, stations contend for RUs using a novel UL OFDMA random access (UORA) method. In short, the operation of UORA is based on the OFDMA contention window (OCW) and OFDMA random access backoff (OBO). Each station selects a random OBO counter from the range (0, OCW) and then decreases it by the number of eligible RUs assigned by the access point (AP) for the uplink transmissions. Stations transmit when OBO = 0. The OCW range can

be configured by the AP in the UORA parameter set element, sent to stations in beacon frames.

It is expected that UORA will be applicable in dense scenarios, e.g., in Internet or Things (IoT) deployments or industrial wireless sensor networks. However, it was shown in the literature that UORA is inefficient in saturation (cf. in Section II). Therefore, in this paper we address UORA efficiency. We distinguish ourselves from the state of the art (SoA) by proposing only simple modifications to the OBO selection procedure at the AP side, as opposed to, e.g., developing new medium access control (MAC) protocols or implementing deterministic access to RUs. We show that the performance of the proposed efficient OBO (E-OBO) is close to the optimum one (UORA-OPT), i.e., when the optimal setting of the OFDMA contention window (OCW) is found by an exhaustive search, and to the recently proposed OBO control procedure (OBO-CTRL) [2].

The article is composed as follows. In Section II, we present a detailed overview of the state-of-the-art research papers. In Section III, we present details of the UORA procedure. In Section IV, we describe the proposed E-OBO mechanism. In Section V, we present simulation results which confirm the advantages of the proposed solution under different metrics: overall throughput, network efficiency, collision probability, average channel access delay, and channel access fairness. Additionally, in Section VI, we compare the operation the new mechanism with the legacy UORA in

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case of heterogeneous traffic sources (i.e., saturated and non-saturated stations). Finally, in Section VII we conclude our work.

II. STATE OF THE ART

A number of research papers concentrate on improving UORA operation in various ways. They can be divided into several groups (Table 1). Most papers address the problem of UORA efficiency [2]–[10]. The second most popular topic is the coexistence of random access and scheduled access [11]–[15]. Other works propose novel MAC protocols [16], [17], extend UORA to provide deterministic channel access [18]–[20], introduce efficient channel schedulers [21], or modifying UORA version to support Vehicle-to-Anything (V2X) communication [25]. These are mainly theoretical studies verified by simulations.

A. UORA EFFICIENCY

A popular way to improve UORA efficiency is by grouping stations into non-interfering clusters [3]–[6], [10], [17]. Other works propose to modify the backoff mechanism [7], [8] (i.e., they propose to add additional backoff or even resign from performing backoff) or OBO control mechanism [2]. Each of these mechanisms leads to decreased contention, which not only lowers the collision probability but also improves UORA performance.

B. COEXISTENCE OF RA AND SA

Coexistence of random access and scheduled access is addressed in [11]–[15]. Yang *et al.* [11], [13], [14] propose to transfer resources between SA and RA to maximize the total satisfaction of stations using a simulation-assisted method. Bhattarai *et al.* [12] analyze the impact of distribution of RA and SA RUs on MAC performance and define an algorithm for their optimal assignment. Xie *et al.* [15] propose an optimal frame duration boundary selection between RA and SA. They also improve UORA efficiency by mandating stations to contend for a RU using a busy tone arbitration mechanism to reduce collisions.

C. NOVEL MAC

Two papers propose novel MAC protocols [16], [17]. Zhang *et al.* [16] implement an OFDMA-based joint reservation and coordination MAC (OJRC-MAC). The new MAC adopts a channel reservation scheme to reduce collisions and increase throughput. It also introduces a cooperative relay scheme, in which helper stations support UORA stations, to enhance the transmission reliability. Peng *et al.* [17] propose an asymmetric full duplex MAC with spatial grouping and a two-level buffer state report (BSR) information collection mechanism. This allows an AP to schedule two non-interfering groups for MU full duplex transmission.

D. DETERMINISTIC CHANNEL ACCESS

Collision-free channel access can be obtained with the target wake-up time (TWT) mechanism, which allows the AP to

optimally assign resource units [18]–[20] and minimize the contention among stations. As a result, not only throughput is improved but also high energy efficiency is obtained.

E. EFFICIENT CHANNEL SCHEDULER

Efficient allocation of data flows in high density scenarios is addressed in [21]. The authors implement a flexible radio channel scheduler at the AP that allocates RUs based on QoS priority and the amount of buffered data of the associated stations. The information is collected with the BSR mechanism.

F. REAL-TIME APPLICATIONS

The main requirement of real-time applications is low latency. Therefore, Avdotin *et al.* propose to protect 802.11ax/be real-time transmissions with deterministic channel access when collisions are detected [22]–[24]. They also implement implicit signaling of the stations' channel resource requirements to avoid unnecessary delays and propose that, in the case of high noise channels, each station transmits several copies of the same frame in different RUs to improve reliability.

G. V2X COMMUNICATIONS

V2X UORA-based channel access for dense IEEE 802.11p connected car networks is addressed in [25]. It is proposed that dedicated RUs should be used for high priority sensor stations gathering traffic information and transmitting periodical reports to V2X infrastructure. This is obtained with an assignment of dedicated association identifiers (AIDs). RUs with dedicated AIDs can be accessed only by selected STAs. All other V2X UORA STAs need to contend for other RUs, which may extend their delays and increase their frame loss rate.

H. LITERATURE REVIEW

The primary goal of this paper is the improvement of the efficiency of UORA transmissions. Based on the literature review and to the best of our knowledge, [2] is the only paper in this area, which modifies the operation of the OBO control mechanism. We follow a similar approach and propose modifications which further improve UORA efficiency, as described in Section IV.

III. STANDARD UORA OPERATION

The UORA procedure starts with a Trigger frame (TF) transmitted by the AP, which ensures the synchronization of participating stations. The AP sets the AID field to 0 (in the transmitted TF) to indicate RA RUs allocated for associated stations, and AID = 2045 to indicate RA RUs allocated for unassociated stations. Each TF can contain one or more RUs for random access. Stations can contend to access eligible RA RUs *only if they have pending data frames destined to the AP*.

The AP can indicate the OFDMA contention window (OCW) range (i.e., OCW_{min} and OCW_{max} values) in the UORA Parameter Set element being a part of management frames (such as beacon or association frames). Stations that

TABLE 1. Literature review. Evaluation types: theoretical (T) and simulation (S).

Goal	Key	UORA enhancement	Result	Evaluation Type	Amendment	Year
High efficiency	[3]	Adaptive grouping scheme	Improved throughput	T+S	802.11ax	2018
	[4]					2019
	[5]	Spatial clustering	Improved area throughput			2019
	[6]	Extra backoff stage, opportunistic sub-channel hopping	Improved bandwidth utilization and reduced collisions			2019
	[7]	Stations transmit without backoff with a complementary probability after unsuccessful transmissions	Improved throughput, reduced packet delay			2019
	[8]	Hybrid OFDMA RA with carrier sensing, secondary backoff mechanism	Improved throughput			2020
	[9]	Retransmission-aware channel access	Reduced delay	S		2020
	[2]	New OBO control scheme	Improved throughput	S		2021
	[10]	Grouping-based channel access	Improved fairness and QoS	T+S		2021
Coexistence of RA and SA	[11]	Transfer of resources between SA and RA	Improved QoS	T+S	802.11ax	2019
	[12]	Optimal RU allocation scheme	Balance between RA and SA	S		2019
	[13]	Hybrid access with scheduled transmissions	Improved capacity for MU access	T+S		2019
	[14]	Transfer of resources between SA and RA	Improved QoE for OBSSs			2020
	[15]	Multi-dimensional busy-tone arbitration	Improved access efficiency and throughput	T+S		2020
Novel MAC	[16]	Joint reservation and cooperation	Improved throughput and transmission reliability	T+S	802.11ax	2019
	[17]	Spatial grouping and two-level BSR information collection mechanism	Improved throughput			2020
Deterministic channel access	[18]	TWT	High throughput and energy efficiency	S	802.11ax	2019
	[19]					2019
	[20]			T+S		2020
Efficient channel scheduler	[21]	Resource allocation control, QoS adaptation	Improved efficiency in RU allocation	S	802.11ax	2020
Real-time applications	[22]	Resource allocation mechanism	Low latency		802.11ax	2019
	[23]	Cyclic and group resource reservation	Low latency for massive real-time traffic	S	802.11be	2019
	[24]	Resource assignment	Low latency for real-time applications			2020
V2X communication	[25]	Dedicated RUs for selected stations	Efficient channel access	T+S	802.11p/ax	2018

did not receive an UORA Parameter Set element use the default OCW settings, i.e., $OCW_{min} = 7$ and $OCW_{max} = 31$.

After successful reception of a TF, a RA station maintains two parameters: OCW and OBO. OCW is set to the OCW_{min} value. Then the station initializes its OBO counter with an integer value randomly selected from a uniform distribution in the range 0 to OCW. If the OBO counter is lower than the number of eligible RA RUs (i.e., the RUs assigned by the AP for RA transmissions), a station randomly selects one of the RUs for data transmission. Otherwise, it decrements the OBO counter by the number of eligible RUs and waits for the next TF. In case of an unsuccessful transmission, the station follows the following retransmission procedure. First, the station updates its OCW counter to $2 \times OCW + 1$ every time when $OCW \leq OCW_{max}$. Once $OCW = OCW_{max}$, the OCW value remains unchanged. Then, the station randomly selects a new OBO value in the range of 0 and OCW (cf. Algorithm 1).

An exemplary illustration of the UORA procedure in time is shown in Figure 1. First the AP sends a Trigger frame, then all stations select their OBO counters. If OBO = 0, stations transmit their data frames in randomly selected RUs. Associated stations (stations 1, 2, and 4) use RUs with AID = 0, the unassociated station (station 3) uses RUs with

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Algorithm 1 Standard UORA

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

AID = 2045 for their transmissions. The reception of the high efficiency (HE) triggered based (TB) PHY layer protocol data unit (PPDU) is acknowledged by the AP with a multi-station block ACK frame.

The calculation of the OBO counter, after TF reception, is shown in Figure 1b. Each station compares its OBO counter
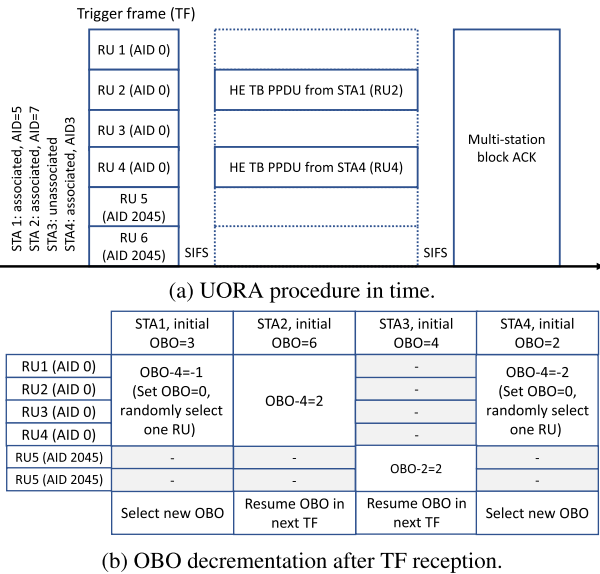
(a) UORA procedure in time.

	STA1, initial OBO=3	STA2, initial OBO=6	STA3, initial OBO=4	STA4, initial OBO=2
RU1 (AID 0)	OBO-4=-1 (Set OBO=0, randomly select one RU)	OBO-4=2	-	OBO-4=-2 (Set OBO=0, randomly select one RU)
RU2 (AID 0)			-	
RU3 (AID 0)			-	
RU4 (AID 0)			-	
RU5 (AID 2045)	-	-	OBO-2=2	-
RU5 (AID 2045)	-	-		-
	Select new OBO	Resume OBO in next TF	Resume OBO in next TF	Select new OBO

(b) OBO decrementation after TF reception.

FIGURE 1. Exemplary illustration of the UORA procedure. Based on [26].

value to the number of eligible RA RUs. In the presented example, the associated stations decrement their OBO counters by 4 and the unassociated stations decrement their OBO counters by 2. If, for a particular station, the OBO counter is not greater than the number of eligible RUs, then the station sets its OBO counter to zero. Each time $OBO = 0$, the station selects a RU for transmission and a new OBO value from the range 0 and $OCW_{\min}$. In the presented example, stations 1 and 4 transmit data, while stations 2 and 3 wait for the next contention round.

IV. EFFICIENT OFDMA RANDOM ACCESS BACKOFF PROCEDURE

We propose to change the operation of the standard UORA behaviour (summarized as Algorithm 1) to improve its efficiency. In particular, we propose the following efficient OBO backoff (E-OBO) control algorithm (summarized as Algorithm 2).

In E-OBO, the AP influences the rate of counting down the OBO counter at the stations (using the α parameter to either increase or decrease the channel access probability) depending on the observed probability of unsuccessful RUs (p_{RU}^u) and empty RUs (p_{RU}^e) within the measuring interval. Therefore, both probabilities are recalculated every ζ contention rounds in the following way:

$$p_{RU}^u = \frac{\sum_{i=1}^{\zeta} n_{RU}^u(i)}{\sum_{i=1}^{\zeta} n_{RU}^s(i) + n_{RU}^u(i) + n_{RU}^e(i)} \quad (1)$$

and

$$p_{RU}^e = \frac{\sum_{i=1}^{\zeta} n_{RU}^e(i)}{\sum_{i=1}^{\zeta} n_{RU}^s(i) + n_{RU}^u(i) + n_{RU}^e(i)}, \quad (2)$$

where $n_{RU}^s, n_{RU}^u, n_{RU}^e$ are the number of successful, unsuccessful, and empty RUs, respectively.

An RU is considered successful if the AP can reply with an acknowledgement upon the reception of an UL data frame transmitted within this RU. An RU is considered empty if there was no transmission in this RU in the ongoing transmission opportunity. The RU is considered unsuccessful if it was detected as busy, but no valid data frame was received (e.g., a collision of several UL frames occurred and none of them can be successfully decoded).[1]

The α parameter should assume values in the range [0.1, 2] and $\alpha = 1$ by default. If $p_{RU}^u \geq 0.33$ and $p_{RU}^e < 0.33$ (i.e., when symptoms of congestion are noticed – there are many unsuccessful RUs observed and there are not many empty RUs), the AP updates the α value by decreasing its previous value by 0.1. If $p_{RU}^u \leq 0.5$ and $p_{RU}^e \geq 0.5$ (i.e., when symptoms of non-saturation are noticed – not many unsuccessful RUs are observed and many RUs are empty), the AP updates the α value by increasing its previous value by 0.2. Otherwise, the α value remains unchanged. The AP informs stations about the current α setting using TFs preceding each random UL OFDMA transmissions. After receiving a TF with a global α setting, stations decrement their OBO counters in the following way:

$$OBO \longleftarrow OBO - \alpha \times n_{RU}. \quad (3)$$

The rest of the standard UORA operation is left unchanged: (i) stations for which $OBO = 0$ select random RUs for transmission, other stations resume their OBO countdown in the next TF, (ii) the OBO counter is randomly selected from the range $(0, OCW)$, and (iii) the OCW value is updated similarly as in legacy UORA (Algorithm 1).

Importantly, the proposed solution is partially based on the OBO-CTRL procedure described in [2]. However, Kim *et al.* propose that stations calculate their OBO counters in a distributed fashion and they decrement/increment their local α parameter value after each unsuccessful/successful transmission to control their own channel access probability. We propose to modify the channel access probability only if certain network conditions are noticed by the AP (saturation or non-saturation). Therefore, all calculations are performed by the AP, which has the best knowledge of the network status. In the next section we show that this simple modification of the standard UORA and OBO-CTRL procedures could considerably improve IEEE 802.11ax performance.

V. RESULTS
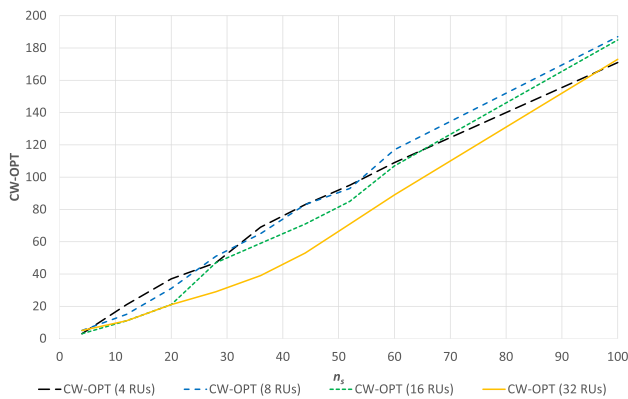We compared the proposed UORA-E-OBO procedure with:
- standard UORA [26],

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[1]RUs can also be unsuccessful due to random noise. In this case, we assume that the reaction to poor channel conditions are left for other mechanisms, e.g., rate control algorithms. If used together, UORA-E-OBO will decrease the contention for a short while and allow the rate adaptation mechanism to resolve the problem of noise by adjusting transmission rates to current network conditions and, therefore, decrease the probability of unsuccessful RUs. If the noise is temporary, the rate control mechanism will return to a higher modulation.

Algorithm 2 E-OBO Procedure

$\alpha = 1$

Measuring interval: ζ contention rounds

if $p_{\text{RU}}^u \geq 0.33$ and $p_{\text{RU}}^e < 0.33$ **then**

   AP decreases the α value: $\alpha = \max(0.1, \alpha - 0.1)$

else if $p_{\text{RU}}^u \leq 0.5$ and $p_{\text{RU}}^e \geq 0.5$ **then**

   AP increases the α value: $\alpha = \min(2, \alpha + 0.2)$

else

   $\alpha = \alpha$;

end if

AP sends α in the TF to inform stations of the level of contention in the network.

Stations decrement their OBO counters by $\alpha \times n_{\text{RU}}$ and select random RUs for transmission if $OBO = 0$.

TABLE 2. Simulation parameters.

Parameter	Value
Simulation time (T)	25 s
Number of stations (n_s)	variable
$OCW_{\min}$	7
$OCW_{\max}$	31
ζ	10
Channel width	20-160 MHz
Number of RUs (n_{RU})	4, 8, 16, 32
RU type	52-tone RU
Data rate per RU (r)	6.67 Mb/s
Slot time	9 μs
SIFS time	16 μs
PHY header duration	40 μs
TF duration	100 μs
MU-BACK duration	68 μs
MPDU length (L)	{1,10} kb
Modulation and coding scheme (MCS)	3
Guard Interval (GI)	1.6 μs
OFDM symbol duration	12.8 μs

FIGURE 2. Optimal OCW settings.

- optimum UORA (UORA-OPT), in which we used exhaustive search to find the optimum $OCW = OCW_{\min} = OCW_{\max}$ settings (Figure 2),
- UORA with the OBO control mechanism proposed in [2] (UORA-OBO-CTRL).

UORA, UORA-OPT and UORA-E-OBO were implemented in Python, using the NumPy library. A link to the Matlab implementation of OBO-CTRL is provided in [2].

Simulation parameters are given in Table 2. We compared different UORA variants for multiple channel widths, a different number of RUs, and a varying number of associated stations using the following metrics:

- **cumulative network throughput**, calculated as:

$$\sum_{i=1}^{n_s} t_i = \sum_{i=1}^{n_s} \frac{s_i \times L}{T}, \qquad (4)$$

where t_i is the throughput of station i, s_i is the total number of data frames of length L successfully transmitted by station i, and T is the total simulation time;

- **network efficiency**, calculated as:

$$\frac{\sum_{i=1}^{n_s} t_i}{n_{\text{RU}} \times r}, \qquad (5)$$

where r is the data transmission rate and n_{RU} is the number of eligible RUs;

- **average collision probability**, calculated as:

$$\sum_{i=1}^{n_s} \frac{c_i}{n_s \times (c_i + s_i)}, \qquad (6)$$

where c_i is the number of collided frames for station i experienced within time T;

- **average channel access delay**, calculated as:

$$\frac{1}{n_s} \sum_{i=1}^{n_s} \frac{d_i}{s_i}, \qquad (7)$$

where d_i is the total channel access delay experienced by station i within time T.

A. THROUGHPUT, EFFICIENCY, AND COLLISION PROBABILITY

As shown in Figure 3, under high contention, throughput and efficiency stabilize for UORA-E-OBO, UORA-OPT, and UORA-OBO-CTRL. For legacy UORA, throughput and efficiency drop considerably with the increasing number of stations, which is a result of the growing probability of collisions, as shown in Figure 3b.

When the number of stations (n_s) is greater than the number of available RUs (n_{RU}) the efficiency of UORA-E-OBO, UORA-OBO-CTRL, UORA-OPT is between 0.3 and 0.36 (Figure 3c), while the efficiency of standard UORA drops far below 0.3.

The increase in the number of available RUs results in a proportionally higher throughput (Figure 3a). For UORA-E-OBO from ∼10 Mb/s up to ∼66 Mb/s was achieved for 4 and 32 RUs, respectively, which is close to the optimal behaviour (UORA-OPT). UORA-OBO-CTRL performs slightly worse for a large number of RUs (16, 32) and under medium contention.

In most configurations, the collision probability is the smallest for UORA-OBO-CTRL and the largest for
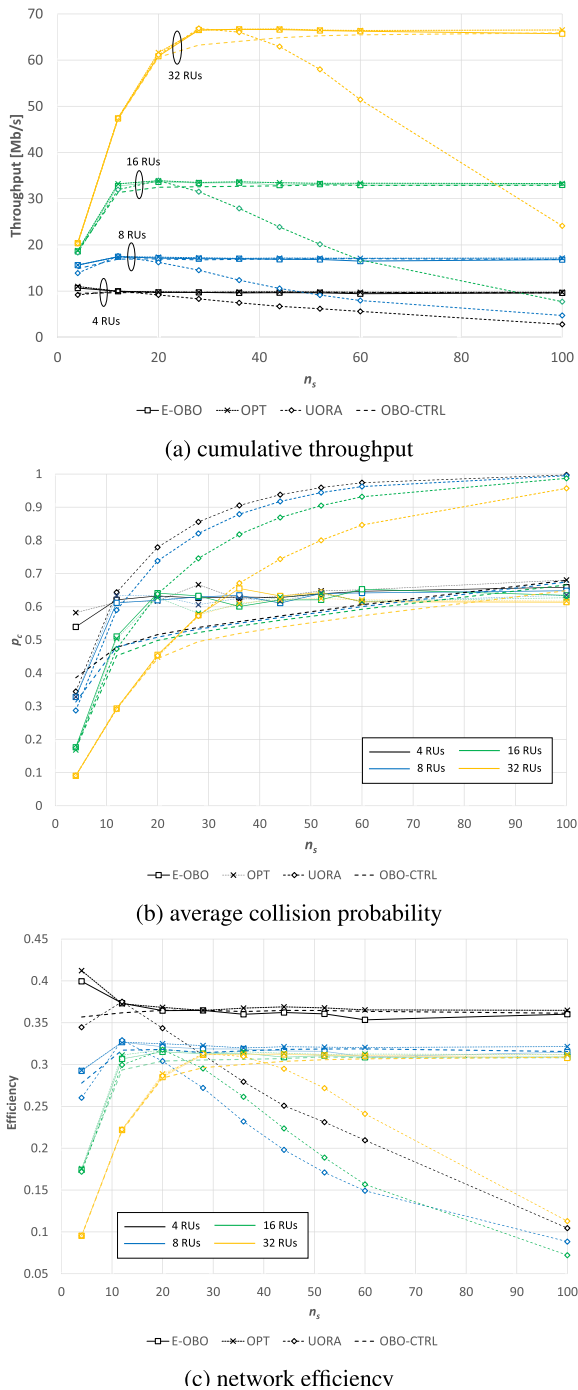
(a) cumulative throughput

(b) average collision probability

(c) network efficiency

FIGURE 3. Comparison of UORA, UORA-E-OBO, UORA-OBO-CTRL, UORA-OPT for $L = 10$ kb for different number of RUs ($n_{RU} \in \{4, 8, 16, 32\}$).

legacy UORA. This is a result of the differences in the OBO operation implemented by each procedure:

- UORA-OBO-CTRL decreases the probability of collisions in the next contention round after each unsuccessful transmission by lowering the channel access probability for stations which experienced collisions using the local α parameter,
- UORA-E-OBO decreases the probability of collisions in the next contention round only if a certain congestion

level is observed ($p_{RU}^u \geq 0.33$ and $p_{RU}^e < 0.33$), by lowering the probability of channel access using the global α parameter,
- in legacy UORA OBO decrementation does not depend on collision probability.

In our simulations, we found that UORA-E-OBO outperforms standard UORA and provides comparable results to UORA-OPT for all tested configurations. Additionally, in selected cases it may outperform UORA-OBO-CTRL.

B. DATA FRAME LENGTH
In Figure 4a, we show how throughput and efficiency of UORA-E-OBO change depending on the MAC protocol data unit (MPDU) length for an exemplary setting of eligible RUs ($n_{RU} = 8$). For short MPDUs ($L = 1$ kb) both throughput and efficiency drop considerably in comparison to large MPDU size ($L = 10$ kb). The probability of collisions is similar for each setting ($p_c \approx 0.63$), as shown in Figure 4b. Additionally, the average channel access delay increases proportionally to the data frame length. Therefore, for urgent transmissions, large data frames should either be avoided or dedicated RUs should be set aside for delay-intolerant data as proposed, e.g., in [25]. Finally, similar dependencies can be observed for other UORA types because this is a result of data vs. overhead length.

C. CHANNEL ACCESS DELAY
In Figure 5, we present a comparison of the average channel access delay for UORA-E-OBO and UORA-OBO-CTRL. The results are comparable for both mechanisms.

D. FAIRNESS
To verify the applicability of the proposed UORA-E-OBO procedure, we additionally calculated Jain's fairness index as:

$$f_x = \frac{(\sum_{i=1}^{n_s} x_i)^2}{n_s \times \sum_{i=1}^{n_s} x_i^2}, \qquad (8)$$

where x_i is either throughput (t) or collision probability (p_c) of the i-th station.

For all tested configurations, stations experience similar collision probability fairness ($f_{p_c} \approx 1$) and obtain comparable throughput fairness (Figure 6). However for UORA-E-OBO throughput fairness is better guaranteed (for each configuration $f_t > 0.99$) than for UORA-CTRL ($f_t < 0.99$ for several configurations). Therefore, we conclude that the proposed E-OBO procedure ensures satisfactory fairness in RU access and, overall, it outperforms UORA-OBO-CTRL.

VI. CONSIDERATIONS FOR NON-SATURATED STATIONS
We also compared the behaviour or UORA-E-OBO and legacy UORA when the network consist of heterogeneous traffic sources. For each configuration ($n_s = \{8, 16, 32, 64, 96, 128\}$) we set 25% of all stations to be saturated and 75% of stations to be non-saturated. Additionally, we set 16 eligible RUs.
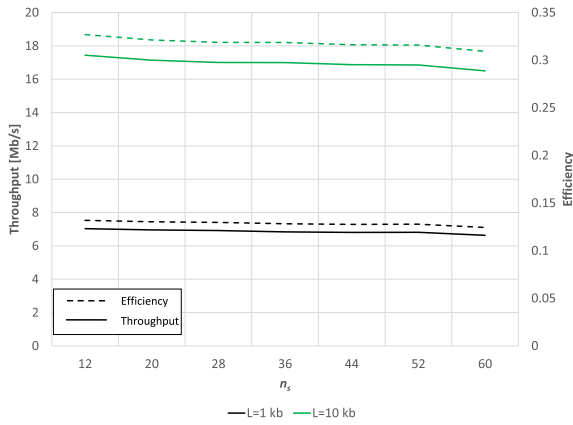
(a) throughput and efficiency
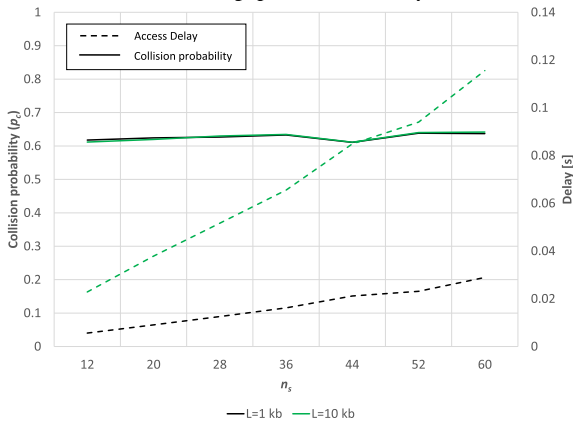
(b) collision probability and average channel access delay

FIGURE 4. UORA-E-OBO performance for different MPDU lengths (*L*) for eight eligible RUs ($n_{RU} = 8$).
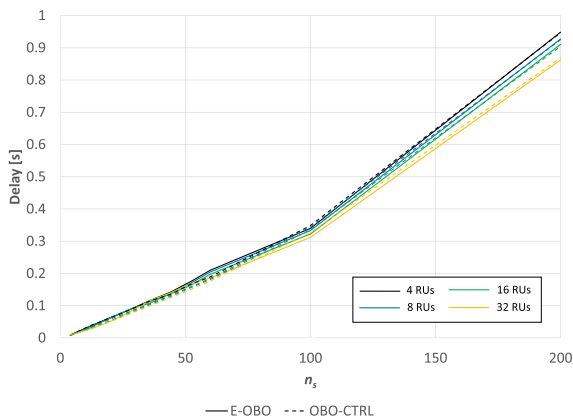

FIGURE 5. Comparison of the average channel access delay for UORA-E-OBO and UORA-OBO-CTRL for different number of RUs.

We modeled non-saturated sources in our simulator in the following way. If a station did not have any frame ready for transmission or it successfully transmitted a frame in the previous contention round, a new frame was generated with the probability of 0.001. If in the previous round the station had a frame ready to transmit but it did not succeed (either as a result of a collision or due to the lack of a transmission
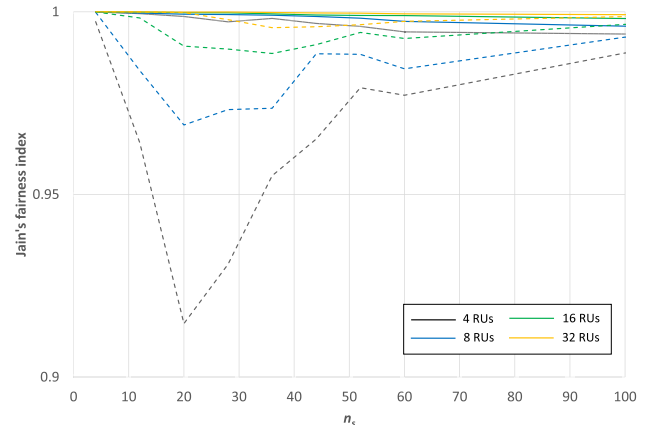
(a) throughput fairness
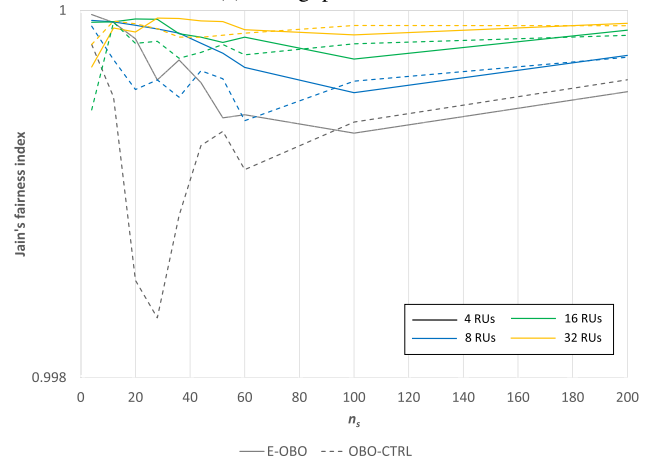
(b) collision probability fairness

FIGURE 6. UORA-E-OBO performance comparison with UORA-OBO-CTRL for different number of RUs.

opportunity grant) it retries to transmit the frame in the next contention round.

The throughput of legacy UORA and UORA-E-OBO is similar under non-saturation, as shown in Figure 7 for $n_s \le 64$. However, when the network load increases, UORA throughput starts dropping. This can be observed for $n_s > 64$ (i.e., when there are 16 saturated and 48 non-saturated stations). The performance of UORA-E-OBO, in contrary to legacy UORA, stabilizes with the increasing network load.

The delay of UORA and UORA-E-OBO reflects the above observations. With the increasing network load: minimum delay (i.e., lowest delay experienced by any station in the network), maximum delay (i.e., highest delay experienced by any station in the network), and the average delay increase (cf. Figure 8) for both mechanism. However, the delay growth is higher for legacy UORA than for UORA-E-OBO.

Finally, we compare the efficiency and probability of collisions p_c for both mechanisms. Under non-saturation, legacy UORA and UORA-E-OBO perform similarly. However, legacy UORA is outperformed by UORA-E-OBO for higher network loads, since UORA-E-OBO enables p_c stabilization thanks to its more intelligent OBO countdown procedure.
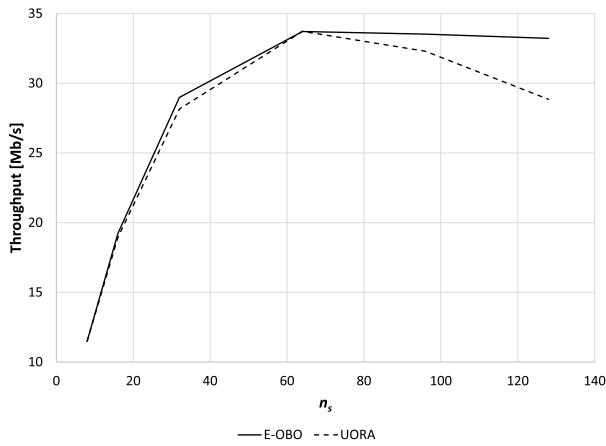
FIGURE 7. UORA-E-OBO throughput comparison with UORA for different number of RUs and heterogeneous stations (non-saturated and saturated).
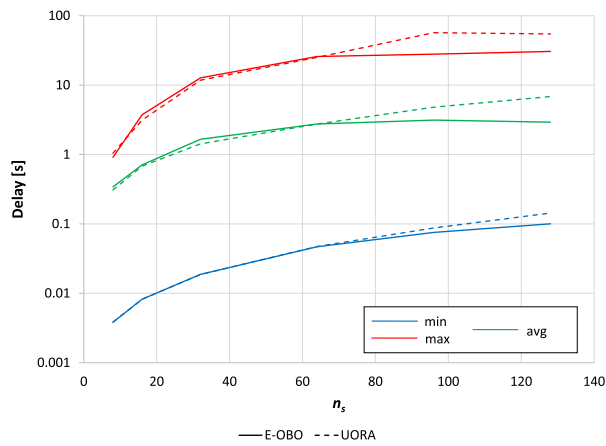

FIGURE 8. UORA-E-OBO delay comparison with UORA for different number of RUs and heterogeneous stations (non-saturated and saturated).
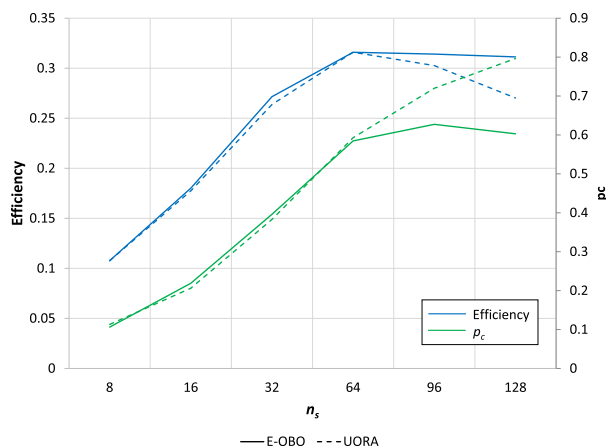

FIGURE 9. UORA-E-OBO efficiency and p_c comparison with UORA for different number of RUs and heterogeneous stations (non-saturated and saturated).

It can be concluded that UORA works well under non-saturation and no modifications are required. However,

when either the per-station load is high or the number of traffic sources is considerably higher than the number of eligible RUs, the performance of legacy UORA is unsatisfactory. As a remedy to these problems solutions like E-OBO can be helpful to improve the performance of future Wi-Fi networks.

VII. CONCLUSION

In this paper we addressed the problem of low UORA efficiency under dense deployments with high station contention. We proposed simple modifications of legacy UORA behaviour, which considerably improve its throughput, efficiency, collision probability, and channel access delay. In case of growing contention (which is measured by the AP as the probability of unsuccessful or empty RUs), the proposed E-OBO procedure mandates stations to decrease the probability of channel access. In case of non-saturation, E-OBO increases the speed of counting down the OBO counter.

Importantly, the proposed solution ensures good fairness in RU access and needs only a small additional overhead in comparison to the legacy UORA (the α parameter needs to be delivered as part of the TF) and it provides results close to optimal. As future work, we envision developing other effective versions of UORA, which adapt to different traffic requirements.

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