Uplink OFDMA-Based Random Access Mechanism With Bursty Arrivals for IEEE 802.11ax Systems

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***Abstract*—IEEE 802.11ax defines a new channel access scheme of OFDMA-based random access (UORA) for varying number of associated stations (STAs) to send their requests or data to the access point (AP) in a contention manner. This letter presents an analytical model to investigate the performance of UORA in transient condition under bursty arrivals with arbitrary distribution. The key performance metrics of access success probability; average access delay; cumulative distribution function (CDF) for the number of transmissions; and utilization of random access resource units (RA-RUs) were derived. Simulation results verified the accuracy of the proposed analytical model.**

***Index Terms*—IEEE 802.11ax, uplink OFDMA-based random access (UORA), multi-channel slotted ALOHA.**

I. Introduction

THE EXPLOSION in the number of wireless devices and high data rate applications introduces new demand for Wi-Fi systems in high-density environments. In these environments, a massive number of stations (STAs) may simultaneously transmit/receive data from an access point (AP), thus resulting in decreased per-user throughput and system stability. The new IEEE 802.11ax standard, also known as WiFi-6, is designed to improve the spectrum efficiency and per-user throughput of the WiFi system in dense environments [1]. One of the most important features of 802.11ax is the adoption of orthogonal frequency division multiple access (OFDMA) technology to support concurrent uplink multi-user transmission. In OFDMA, the frequency spectrum is divided into sub-carriers and a pre-defined number of sub-carriers can be grouped as a resource unit (RU). By assigning RUs to the STAs, the AP can have complete control of concurrent downlink/uplink transmissions to/from multiple STAs. According to 802.11ax standard [1], the AP can support up to 9, 18, 37, and 74 RUs in the 20, 40, 80, and 160 MHz WiFi channels in 5 GHz band, respectively.

A new channel access scheme, known as triggered uplink access (TUA), is defined to support uplink multi-user transmissions. In TUA, an AP gets the shared wireless channel by transmitting a *Trigger Frame* (TF) after sensing a channel as idle for PCF interframe space (PIFS). The AP uses the TF to solicit a number of STAs and allocate resources for their uplink multi-user transmissions. The TF carries association identities (AIDs) of specific STAs and their corresponding RUs, which are reserved based the buffer status report (BSR) informed by these STAs prior to TUA. The AIDs are indicated in the *AID12* subfield of the *User Info* field in the TF. Upon reception of the TF, the specific STAs should wait for a short interframe space (SIFS) before sending their short packets to the AP through the assigned RUs. The AP then waits for SIFS and transmits a *Multi-STA BlockAck* frame to the STAs as acknowledgment (ACK) of a successful packet reception [1].

Under the framework of TUA, 802.11ax optionally supports an uplink OFDMA-based random access (UORA) scheme, which allows associated STAs or unassociated STAs to transmit their short packets in a contention-based manner [2]. The AP enables the UORA by assigning one or more RUs as random access RUs (RA-RUs) and setting the corresponding *AID12* subfields of the RA-RUs to be 0 (for associated STAs) or 2045 (for unassociated STAs). With UORA, multiple associated STAs can simultaneously transmit their short packets or buffer status reports (BSRs) through the random access resource units (RA-RUs) reserved by the AP in frequency domain. An associated STA, which has a frame pending for transmission using UORA, will set its OFDMA contention window (OCW) to a minimum value of OCW, OCW_{min}, and randomly chooses an OFDMA backoff (OBO) counter in the range of 0 and OCW. Upon reception of a TF, the STA decreases its OBO counter by the number of RA-RUs announced in the TF. Once its OBO counter reaches zero, the STA randomly selects one of the RA-RUs to transmit its frame. The transmission is successful if the STA receives an ACK from the multi-STA BlockAck. Collision occurs if two or more STAs select the same RA-RU. Collided STAs then updates its OCW to (2*OCW + 1) (i.e., OCW $\leq OCW_{max}$, where OCW_{max} is the maximum value of OCW), and repeat the transmission procedure of UORA until a maximum re-transmission attempt limit, L_{max}, is reached. The values of OCW_{min}, OCW_{max}, and L_{max} are specified in the *OCW Range* field of *UORA Parameter Set* [1].

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The steady-state performance of UORA has been investigated in [2], [3]. In [2], the authors used the discrete-time Markov chain to model the behavior of a STA in each OBO state. In [3], the authors presented a discrete-time Markov-chain-based model to derive the collision probability, RU efficiency, and average (saturation) throughput of UORA. In both works, the results were obtained based on the assumptions that the system was under saturated traffic conditions and the collision probability was a constant in all OBO stages. In [4], the author considered non-saturated traffic conditions and co-existence of 802.11ax and legacy STAs. The author assumed that arrivals of TF and new packets followed a Poisson process with a constant rate and used two Markov chains to model the behavior of 'AP and legacy STAs' and 802.11ax STAs, respectively. Noticing the excessive collisions resulted from high STA density in UORA, the authors in [5] proposed an adaptive grouping scheme to maximize the utilization efficiency of RA-RUs by dividing STAs into smaller contention groups. In [6], the authors proposed a probability complementary transmission scheme to mitigate the delay resulting from re-transmissions. In this scheme, the STA conducts a complementary transmission trial with a probability after each unsuccessful transmission. The delay and throughput of the proposed scheme were derived. In these works, the authors considered a fixed number of STAs and assumed that the collision probability and transmission probability of STAs are constants. However, the steady-state condition may rarely be satisfied for IoT traffic due to its nature of unexpected bursty arrivals [5]. Moreover, STAs which successfully transmit their BSRs in UORA, will stop its data transmissions and thus, the number of contending STAs is less likely to be always fixed.

While existing works in [2], [3], [4] focused on the performance of UORA in steady-state, this letter aims to investigate its performance in transient condition (i.e., a short period of time during which the steady-state cannot be reached) and with bursty arrivals. The performance of the random access channels (RACHs) of Long Term Evolution (LTE) networks in transient condition has been investigated in [7], [8]. In [7], the authors presented a multi-channel slotted ALOHA system to model a finite number of STAs simultaneously accessing the LTE RACHs. An approximation formula was proposed to estimate the average number of success and failed STAs in each trial. In [8], the authors derived the first exact expression for the probability distribution of the number of successful STAs over multiple channels and used the expression to verify the effectiveness of the approximation formula. A simple and computationally convenient drift approximation was then proposed to analyze LTE RACHs in transient conditions and with non stationary bursty arrivals. However, the operations of UORA and LTE RACH are quite different and thus, the model in [8] cannot be directly applied here. In UORA, all STAs perform pre-backoff before randomly choosing an RA-RU for their first transmission and know the success or failure of their transmissions via the multi-STA BlockAck; collided STAs follow an exponential backoff policy to update their OCW and update their OBO counter based on the available RA-RUs. Hence, the proposed model takes these issues into consideration. The main contribution of this letter is to present a mathematical model that can analyze the performance of UORA for a large number of STAs contending a fixed number of RA-RUs in a short period of time. The remainder of this letter is organized as follows: Section II describes the system model and the analytical model of UORA, Section III presents the numerical results, and Section IV summarizes conclusion.

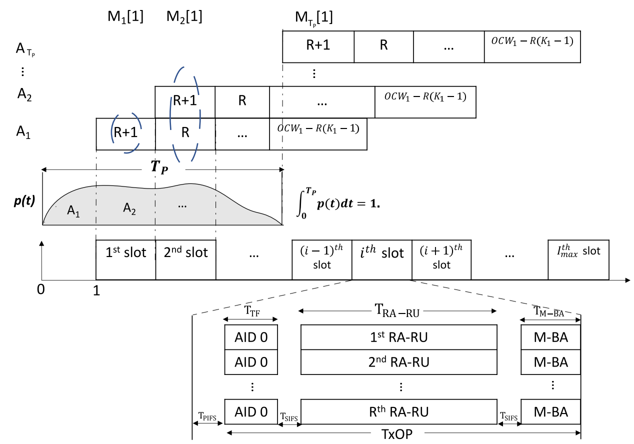

Fig. 1. Timing diagram of the system model considered in this letter.

II. System Model

Figure 1 shows a timing diagram of the system model considered in this letter. It is assumed that time is divided into slots. The length of a slot is equal to one PIFS plus one transmission opportunity (TXOP) reserved for a single packet transmission for UORA. The TXOP includes the time required to transmit/receive a TF, an RA-RU, a *Multi-STA BlockAck* frame (M-BA), and two SIFSs. Although the duration of RA-RUs in each slot may be varying, we consider fixed-length RA-RUs in this letter as in [2], [3], [4] and thus, fixed-length slots, without losing generality.

This letter considers M STAs competing for access in UORA from an AP which reserves R RA-RU per slot. Each STA transmits a single packet carrying a small data or a BSR. The bursty traffic model for massive MTC applications defined by 3GPP TR 37.868 [9] was adopted and illustrated in the upper part of Fig. 1. In this model, M STAs follows a general arrival process $p(t)$ from the 0th to the T_pth slots, where

$$\int_0^{T_p} p(t)dt = 1. \tag{1}$$

In UORA, the STAs which wants to transmit a packet at the beginning of a slot have to select their initial OBO counters. Let OCW_{min}, OCW_{max}, and L_{max} be the initial OCW, maximum OCW, and the maximum number of transmission attempts for each STA, respectively. Note that L_{max} counts the first transmission and maximum number of re-transmissions [1] (i.e., 1+*RetryLimit*). Let OCW_n ($1 \leq n \leq L_{max}$) be the OCW at the nth transmission, which is given by [1]

$$OCW_n = \begin{cases} OCW_{min}, & n = 1, \\ min(2 * OCW_{n-1} + 1, OCW_{max}), & \\ \qquad n = 2, \ldots, L_{max}. & \end{cases} \tag{2}$$

The duration of UORA can be an arbitrary value determined by the AP. In this letter, the duration is chosen to ensure all STAs can re-transmit their packets up to L_{max} transmissions. Let I_{max} be the length of this duration in term of slots. I_{max} can be specified based the worst case scenario, in which a STA arrives at the beginning of the T_pth slot; fails at each transmission attempt; and selects the maximum value of OCW in each backoff for successive L_{max} times. Hence, I_{max} is given by

$$I_{max} = T_p - 1 + \sum_{n=1}^{L_{max}} K_n, \tag{3}$$

where $K_n = \left\lceil \frac{OCW_n}{R} \right\rceil$ is the length of backoff interval for OCW_n in term of slots.

A. Performance Metrics

Let $M_i[n]$ be the average number of STAs that transmit their packets for the *n*th time in the *i*th slot ($1 \leq n \leq L_{max}$, $1 \leq i \leq I_{max}$). Among the $M_i[n]$ STAs, an average of $M_{i,S}[n]$ STAs yield successful transmissions while an average of $M_{i,F}[n]$ STAs are failed. In other words, $M_i[n] = M_{i,S}[n] + M_{i,F}[n]$ [7]. The $M_{i,F}[n]$ STAs may re-transmit if they meet certain condition explained later. To evaluate the system performance, four metrics recommended by 3GPP [9] are adopted herein, namely access success probability, P_S; average access delay (unit: slot), $\bar{D}$; cumulative distribution function (CDF) for the number of transmissions, *F*(*N*), where $N \leq L_{max}$; and utilization of RA-RUs, *U*. These four performance metrics can be derived based on $M_{i,S}[n]$.

P_S is the probability that a STA successfully transmits a packet. It is the ratio between the number of successful STAs and the total number of STAs. In our model, number of successful STAs can be obtained by counting all successful STAs from every slots (from slot 1 to slot I_{max}), regardless of number of transmissions that they have conducted (including $1, 2, \ldots,$ or L_{max}). That is,

$$P_S = \frac{\sum_{i=1}^{I_{max}} \sum_{n=1}^{L_{max}} M_{i,S}[n]}{M}. \tag{4}$$

$\bar{D}$ (unit: slot) is obtained as the sum of access delay from all successful STAs normalized by the number of successful STAs. Hence, we have

$$\bar{D} = \frac{\sum_{i=1}^{I_{max}} \sum_{n=1}^{L_{max}} (M_{i,S}[n] \sum_{j=1}^{n} \bar{d}_j)}{\sum_{i=1}^{I_{max}} \sum_{n=1}^{L_{max}} M_{i,S}[n]}. \tag{5}$$

where $\bar{d}_j$ is the average delay for a STA in its *j*th packet transmission. $\bar{d}_j$ will be derived in Eq. (16).

The utilization of RA-RUs, *U*, is the ratio between successful RA-RUs and the total number of reserved RA-RUs for the whole I_{max} slots in an UORA opportunity. Note that the total number of successful RA-RUs is the same as the total number of successful STAs. Hence, we have

$$U = \frac{\sum_{i=1}^{I_{max}} \sum_{n=1}^{L_{max}} M_{i,S}[n]}{I_{max} R}. \tag{6}$$

F(*N*) is the ratio between the number of successful STAs that transmit no more than *N* times to the total number of successful STAs, which shows the distribution of the number of transmissions for successful STAs. It can be obtained as

$$F(N) = \frac{\sum_{i=1}^{I_{max}} \sum_{n=1}^{N} M_{i,S}[n]}{\sum_{i=1}^{I_{max}} \sum_{n=1}^{L_{max}} M_{i,S}[n]}. \tag{7}$$

B. Analytical Model

In the following, we show the steps to estimate $M_{i,S}[n]$ for every combination of *i* and *n*, which will be used to derive the performance metrics.

Let us first consider the first transmission attempt of the STAs, i.e., $n = 1$. Let A_i be the number of new arrivals at the beginning of the *i*th slot. We can have

$$A_i = \begin{cases} M \int_{i-1}^{i} p(t)\,dt, & \text{for } i = 1, \ldots, T_p; \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

Before actually conduct the first transmission, the newly arrived STAs have to perform a backoff by randomly choosing a value in the inclusive range of 0 to OCW_1 as their OBO counter. The STA decreases its OBO counter by *R* in each elapsing slot, and transmit the packet when the counter reaches 0. By this manner, the first transmission of A_i STAs are spread from the *i*th to the $(i + K_1 - 1)$th slots.

For $OCW_1 \leq R$, all A_i STAs will transmit at the *i*th slot immediately. Hence, the average number of STAs that transmit their packets for the first time in the *i*th slot, $M_i[1]$, is equal to A_i.

$$M_i[1] = A_i, \text{ for } OCW_1 \leq R. \tag{9}$$

For $OCW_1 > R$, $M_i[1]$ equals the sum of a portion of A_{i-K_1+1} to A_i as illustrated in the upper part of Fig. 1. The range of $M_i[1]$ starts from 1 and ends at $(T_p + K_1 - 1)$. Thus, $M_i[1]$ is given in (12) as shown at the bottom of the next page.

For $n \geq 2$, $M_i[n]$ is originated from STAs whose (n − 1)th transmission in the *k*th slot has failed (i.e., $M_{k,F}[n-1]$, with $(i - 1) \geq k \geq 1$) and have their *n*th transmissions in the *i*th slot after backoff. To conduct the *n*th transmission attempt, STA needs to conduct backoff with window of OCW_n. The number of slots that the previously-failed STAs may use for their *n*th transmission attempt, which is spread by backoff window OCW_n, is K_n. Hence, for $n \geq 2$ we have

$$M_i[n] = \sum_{k=\max(i-K_n,1)}^{i-1} \alpha_{k,i,n} M_{k,F}[n-1], \tag{10}$$

where $\alpha_{k,i,n}$ is the portion of STAs whose (n − 1)th transmission attempt in the *k*th slot has failed and conduct the *n*th transmission attempt in the *i*th slot ($k < i$). For STAs that fail in the (i − 1)th slot ($k = i - 1$), they can conduct the *n*th transmission in the *i* slot if their *n*th OBO counters (was randomly chosen from $[0, OCW_n]$) fall between 0 to *R*. Similarly, for $k = (i - 2)$, the feasible values of the OBO counter are between (R + 1) and 2*R*. The range of *k* starts from $(i - K_n)$ to $i - 1$. For $OCW_n \leq R$, the backoff counters of all STAs reach zero within one slot. Hence, $\alpha_{k,i,n}$ is given by

$$\alpha_{k,i,n} = \begin{cases} 1, & k = i - 1, \\ 0, & \text{Otherwise.} \end{cases} \tag{11}$$

In contrast, the backoff counters of STAs may spend K_n slots to count down to zero if $OCW_n > R$. Hence, $\alpha_{k,i,n}$ is given by

$$\alpha_{k,i,n} = \begin{cases} \frac{OCW_n - R*(K_n-1)}{OCW_n+1}, & k = i - K_n, \\ \frac{R}{OCW_n+1}, & k = i - K_n + 1, \\ & \ldots, i-2, \\ \frac{R+1}{OCW_n+1}, & k = i-1, \\ 0, & \text{Otherwise} \end{cases} \tag{13}$$

According to [7], when X STAs ($X \in \mathbb{R}$) contending for Y RUs ($Y \in \mathbb{N}$), the average number of failed STAs can be approximated by $X(1 - e^{-X/Y})$. The approximation is tight when Y is large [8]. The total number of contending STAs at the ith slot is equal to $\sum_{n=1}^{L_{max}} M_i[n]$. The average number of STAs that failed in their nth transmission at the ith slot is proportional to the average number of STAs which conduct their n transmissions in the ith slot. Hence, $M_{i,F}[n]$ can be estimated by

$$M_{i,F}[n] = M_i[n](1 - e^{-\sum_{n=1}^{L_{max}} M_i[n]/R}). \tag{14}$$

The average number of STAs that transmit their packets for the nth time and yield success in the ith slot, $M_{i,S}[n]$, can then be obtained by

$$M_{i,S}[n] = M_i[n] - M_{i,F}[n] = M_i[n]e^{-\sum_{n=1}^{L_{max}} M_i[n]/R}. \tag{15}$$

The average delay for a STA in its jth packet transmission, $\bar{d}_j$, in Eq. (5) can be approximated by

$$\bar{d}_j = \begin{cases} 1, & K_j = 1, \\ \frac{(R+1)+\sum_{k=2}^{K_j-1} R*k+(OCW_j-R(K_j-1))*K_j}{OWC_j+1}, & K_j > 1 \end{cases} \tag{16}$$

where $K_j = \left\lceil \frac{OCW_j}{R} \right\rceil$ is the maximum delay (unit: slots) of the jth transmission due to backoff.

With Eqs. (9) to (15), we can derive $M_{i,S}[n]$ for all i and n recursively using the drift approximation method presented in [8] and obtain P_S, $\bar{D}$, $F(N)$, and U from Eqs. (4) to (6), respectively.

III. Numerical Results

Computer simulation is conducted to verify the accuracy of the proposed analytical model in estimating the performance metrics under different combinations of M and R. In the following figures, lines and markers denote analytical and simulation results, respectively. In the simulations, each marker represents the average value obtained from 10^6 samples along with its 95% confidence interval. For each sample, we simulated an 802.11ax AP that reserved R RA-RUs in each slot for an UORA duration of I_{max} slots.

In the simulation, management traffic generated from associated STAs [10] was considered. Asynchronous arrivals $p(t) = U(0, T_p)$ where $T_p = 10$ slots, were investigated. The 802.11ax parameters used in the simulation

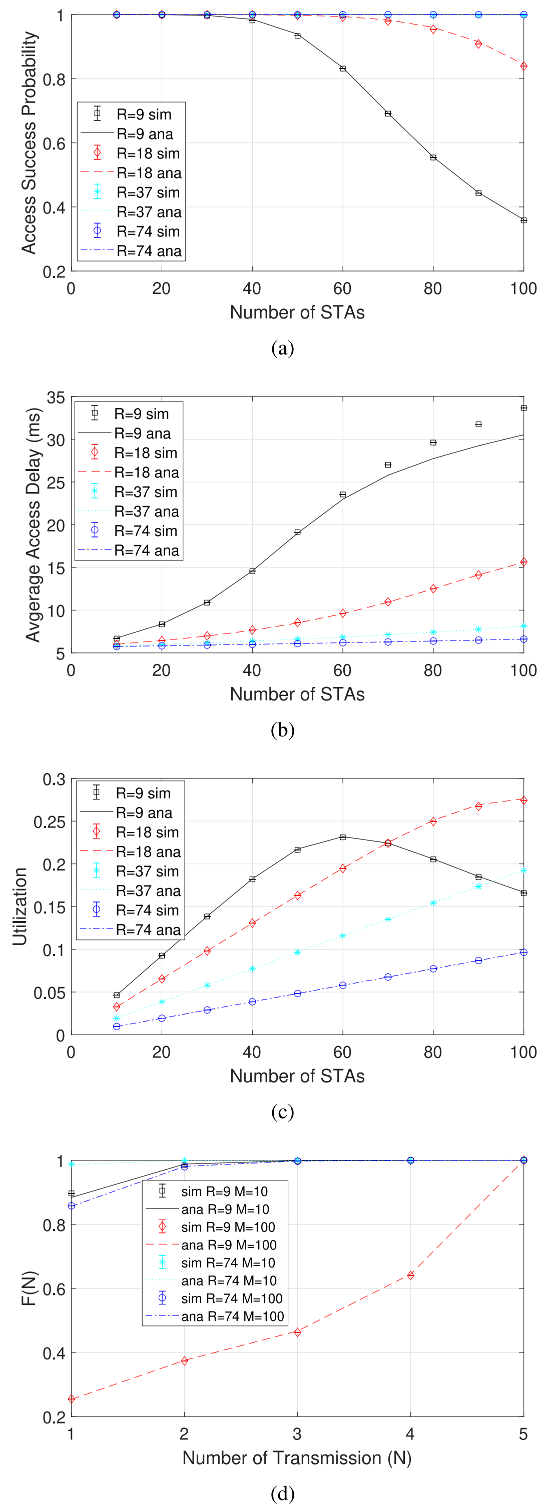

Fig. 2. Results for $p(t) = U(0, T_p)$ with $T_p = 10$ slots (a) The access success probability, P_s. (b) The average access delay, $\bar{D}$. (c) The CDF for the number of transmissions N, $F(N)$. (d) The utilization of RA-RUs, U.

were TF $= 100$ μs, PIFS $= 25$ μs, SIFS $= 16$ μs, BlockAck $= 32$ μs [11], and RA-RU $= 5484$ μs (i.e., aPPDU-MaxTime in [1]). Together, these parameters gave a slot duration

$$M_i[1] = \begin{cases} \frac{(R+1)A_i + R\sum_{k=i-K_1+2}^{i-1} A_k + (OCW_1 - R*(K_1-1))A_{i-K_1+1}}{OCW_1+1}, & i = 1, \ldots, T_p + K_1 - 1 \\ 0, & \text{Otherwise} \end{cases} \tag{12}$$

of 5673 μs. In accordance with [1], we set $OCW_{min} = 7$, $OCW_{max} = 31$, and $L_{max} = 5$. We considered these parameters for $M = 10, \ldots, 100$ for $R = 9$, 18, 37, and 74 (i.e., the maximum number of RA-RUs that can be used in the 20, 40, 80, and 160 MHz bands, respectively). I_{max} can then be calculated from (3) and were set to be 15, 8, 5, and 5 for $R = 9$, 18, 37, and 74, respectively.

The accuracy of the proposed analytical model are demonstrated in Fig. 2. The results showed that the proposed analytical results can accurately predict the access success probability (P_s), the utilization of RA-RUs (U), and the CDF for the number of transmissions, $F(N)$. Noticeable errors for the average access delay ($\bar{D}$) were observed in Fig. 2(b) for $R = 9$ and $M \geq 70$ due to re-transmissions. It is because Eq. (16) under-estimates the access delay for $K_j > 1$ (i.e., $K_j = \left\lceil \frac{OCW_j}{R} \right\rceil$). It can be found in Fig. 2(a) and (b) that, for the same RA-RUs, the access success probability decreases and the access delay increases as we increase the number of STAs. One can easily increase the access success probability or decrease the access delay by increasing the number of RA-RUs at the cost of extra bandwidth. Fig. 2(c) shows the utilization of RA-RUs for different values of R. Inferring from Fig. 2(c), one may set $R = 9$ and 18 for $M \leq 60$ and $M \geq 70$, respectively, to maximize the utilization of RA-RUs. However, the setting may not be proper if we take the access success probability into consideration. To ensure a 100% access probability, instead, we should set $R = 9$, 18, and 37 for $M \leq 30$; $M = 40$ to 50; and $M \geq 60$, respectively. The CDF for the number of transmissions, $F(N)$, in Fig. 2(d) can be used as a reference to set the proper L_{max} for different offered load M. $F(N)$ always reaches 1 because the number of transmissions N cannot exceed the $L_{max} = 5$. For $R = 74$, it can be found from Fig. 2 that the STAs need up to four transmissions to achieve a 100% access success probability when $M = 100$. However, the STAs only need up to three transmissions when $M = 10$. For $R = 9$, the STAs need up to three transmissions to achieve a 100% access success probability when $M = 10$. However, the STAs can only achieve a 36% access success probability even when they can transmit up to five times when $M = 100$.

IV. CONCLUSION

This letter presents a mathematical model to analyze the performance of the UORA mechanism for a large number of STAs contending a fixed number of RA-RUs in a short period of time. We investigate the performance of UORA during I_{max} consecutive slots, where all STAs can re-transmit their packets up to L_{max} times. We derive a closed-form formula for the performance metrics of the access success probability, the average access delay, the utilization of RA-RUs, and the CDF for the number of transmissions. The accuracy of the formulae are verified via computer simulations. The proposed model may be used to find the proper number of RA-RUs to be reserved for an estimated instantaneous traffic load, set the proper L_{max}, and identify the optimal values of R to maximize the utilization of RA-RUs.

As pointed out in [12], some hybrid access schemes may be adopted along with UORA to minimize delays for massive real-time applications. It implies that the number of reserved RA-RUs will not be fixed as assumed in existing works and will be changed over time. Hence, one of the important future works is to extend the analytical model of UORA to accommodate a varying number of RA-RUs.

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