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Enabling the Internet of Things With Wi-Fi Halow–Performance Evaluation of the Restricted Access Window

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ABSTRACT IEEE 802.11ah, a new amendment to the Wi-Fi standard, adapts Wi-Fi networks to the emerging Internet of Things (IoT). A key component of .11ah is the Restricted Access Window (RAW), a new channel access mechanism, which reduces contention when even thousands of IoT devices operate in the same area by assigning them different channel times. This paper shows that existing studies incorrectly understand the RAW behavior, oversimplify its modeling and thereby overestimate the real system throughput in several times, especially for short durations of the reserved RAW slots. The core contribution of this paper is a new mathematical model based on a completely different approach, which yields more accurate results and thereby enables better IoT system dimensioning. The developed model is suitable for many scenarios typical for IoT. It allows finding RAW parameters that optimize system performance in terms of throughput, power consumption, and packet loss ratio. The proposed solution is can be used for various traffic patterns: when each device transmits a single packet, a batch of packets of random size, or it has full-buffer traffic.

INDEX TERMS Internet of Things, IEEE 802.11ah, Wi-Fi HaLow, restricted access window, throughput, energy consumption, performance evaluation.

I. INTRODUCTION

Wi-Fi was initially designed to provide broadband wireless Internet access for a small number of devices. Because of the usage of sub 1GHz (S1G) transmission bands and narrower channels, the novel amendment to the Wi-Fi standard — IEEE 802.11ah (also known as Wi-Fi HaLow) [1] — increases the coverage of an access point (AP) up to 1 km^2 and, naturally, can handle up to 8000 stations (STAs). To date, 802.11ah is the only Wi-Fi version that supports low-energy communications of a high number of the Internet of Things (IoT) devices placed in a large area. Although 802.11ax [2] or 802.11be, both being under development, are called as applicable for IoT sometimes, they mostly focus on providing high-rate spectrum efficient communications of usual devices at traditional distances of less than 100 m. By exploiting Orthogonal Frequency Division Multiple Access (OFDMA), they do allow narrow-band transmission, but even in this case, the frame preamble occupies at least a 20 MHz channel. At the same time, 802.11ah allows transmission in 2 MHz or even 1 MHz channel. Apart from that, a high number of STAs with sporadic IoT traffic results in high collision probabilities. Although 802.11ax implements OFDMA, which allows several STAs to transmit simultaneously, ALOHA-like OFDMA random access of 11ax is inefficient for a high number of contending STAs.

At the same time, Wi-Fi HaLow introduces a new channel access mechanism called Restricted Access Window (RAW). RAW limits the number of STAs that simultaneously contend for the channel. Specifically, with RAW, the AP divides

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all STAs into several groups, defines a set of time intervals called RAW slots, and allocates each group to a RAW slot. Apart from reducing the collision probability, such an approach reduces energy consumption — an important performance indicator for IEEE 802.11ah — since the STAs can sleep almost always except for the allocated time intervals [3].

The amendment was published in 2017 and already attracted significant attention from the academia [4]–[19]. These papers examine performance of RAW mechanism in different scenarios analytically [4]–[14], via simulation [15]–[18], or focusing only on PHY aspects [19]. Unfortunately, many papers that estimate the RAW performance do not take into account the peculiarities of the backoff countdown process with RAW (see details in Section II-A). In particular, they assume that a STA suspends its backoff counter between RAW slots. Such an assumption allows them to easily model transmission as a steady-state process, similarly to the well-known Bianchi model. In reality, at the RAW slot beginning, the backoff function is renewed for all the STAs assigned to this slot. Thus, during the RAW slot, the contention changes significantly. In Section IV, we show the numerical results confirming that the erroneous assumption made in various studies may manifold increase the throughput in comparison to the real behavior.

In this paper, we develop a mathematical model, which corrects this error. In contrast to the mentioned studies, we consider a non-trivial transient process instead of a steady-stated one. We validate the developed model by simulation. Also, we apply the model to analyze the transmission process in the scenario, when several STAs use the RAW mechanism to transmit data. In this scenario, the model allows finding such RAW parameters (the number of RAW slots and their duration) that maximize the throughput and guarantee packet delivery in time within a given delay budget. We also evaluate other performance indices such as packet loss ratio and energy consumption, which are very important for Wi-Fi networks [20], [21], especially for IoT scenarios.

The rest of the paper is organized as follows. In Section II, we describe RAW and point out the typical mistake made in the previous papers that study its efficiency. In Section III, we develop a mathematical model of RAW, and in Section IV we present and explain rich numerical results obtained with the model and simulation. Section V concludes the paper.

II. PROBLEM STATEMENT

A. RESTRICTED ACCESS WINDOW (RAW)

To reduce the contention, an 802.11ah AP can define time intervals called RAW of duration τ_{RAW} (see Fig. 1) and assign each interval to a list of STAs. Only these STAs can access the channel.

To reduce contention even more, each RAW can be divided into up to $K < 64$ equal RAW slots of duration $\tau_{slot} = \frac{\tau_{RAW}}{K}$ corresponding to different STAs. In the fairest case, the STAs are equally distributed between the slots, i.e., the number of STAs assigned to any two slots of the same RAW cannot differ by more than one. The frame format limits the duration of each slot to $\tau_{slot}^{\max} = 246.14$ ms if $K < 8$, and to 31.1 ms, otherwise.

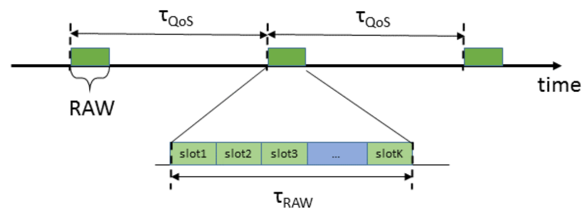

FIGURE 1. **RAW allocation.**

Specifically, the slot number of a particular STA is calculated as follows:

$$i_{slot} = (x + N_{offset}) \mod K,$$

where x is the STA position in the list of admitted STAs, and N_{offset} is a pseudo-random value which improves fairness.

To access the channel inside a RAW slot, the STAs use the legacy Enhanced Distributed Channel Access (EDCA) which implements the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). It means that before starting transmission, the STA senses the medium and does not transmit until the medium is idle. Besides that, to reduce the probability of a collision right after the medium becomes idle, EDCA uses truncated binary exponential backoff as follows.

When the STA RAW slot begins, it sets up a new backoff function and initializes the backoff counter with a random integer uniformly drawn from the interval $[0, CW_{\min} - 1]$ (hereinafter $CW_{\min} \equiv CW_0$). Then the STA senses the channel and decrements the backoff counter every time the channel is idle for backoff slot τ_e. If the channel becomes busy, the STA suspends the counter and resumes it only after the medium is idle for some time. This time equals $AIFS$ if the STA succeeded to decode a frame transmitted during the busy interval, or $SIFS + T_{ACK} + AIFS$, otherwise, where T_{ACK} is the duration of an acknowledgment frame (ACK), Short Interframe Space ($SIFS$) and Arbitrary Interframe Space ($AIFS$) are the intervals defined in the Wi-Fi standard.

When the backoff counter reaches 0, the STA transmits a data frame. $SIFS$ after a correct frame reception, the receiver sends back an ACK. If the ACK is received after $SIFS + T_{ACK}$ from data frame transmission, the STA finishes the packet transmission process. Otherwise, it repeats the attempt, unless the retry limit RL is reached. To transmit a new data frame for the first time, the STA initializes the counter again with a new random integer drawn from interval $[0, CW_{\min} - 1]$. For transmission attempt i, the STA draws a new backoff value from the uniform distribution over the interval $[0, CW_{i-1} - 1]$, where CW_{i-1} is doubled every transmission attempt until it reaches $CW_{\max}$:

$$CW_i = \begin{cases} CW_{\min}, & i = 0, \\ \min\{CW_{\max}, 2CW_{i-1}\}, & i > 0. \end{cases}$$

A key question is whether the STA can transmit a frame exceeding its RAW slot boundary. By default, such behavior is forbidden; however, the AP may allow crossing slot boundary. While sometimes crossing slot boundary may be useful, the performance for power saving STAs may degrade. That is why in the paper, we assume that crossing slot boundary is forbidden. Indeed, in that case, a STA, which wakes up just before the beginning of its slot, may use only physical channel sensing to determine that the channel is free. In contrast, when crossing slot boundary is allowed, a transmission sequence can be started in the previous slot and finished in the current one. At the beginning of such a sequence, the channel may be reserved with, say, legacy Request-to-Send/Clear-to-Send (RTS/CTS) procedure.

RTS/CTS is a traditional for Wi-Fi procedure that allows two STAs (the transmitter and the receiver) to reserve the channel for impeding data transmission by exchanging short RTS and CTS frames. In the Duration field of these frames, the transmitter and the receiver indicate the time needed for transmission. Having received these frames, the neighbors of the transmitter or receiver defer channel access for the indicated time.

Thus, having woken up just before the start of the current RAW slot, the STA may sense the channel physically as free, while actually, it is virtually busy. To avoid collisions in such a situation, the STA shall wait until it receives any frame, which provides information about virtual channel state. If no frames are transmitted, the STA waits for a rather long Probe Delay interval and consumes much energy.

Another important peculiarity of RAW — explicitly defined in [1, Section 10.22.5.5], but omitted in many papers — is that, inside and outside RAW, the STA uses different backoff functions since contention inside and outside RAW differs. While the outside backoff function is just suspended for the duration of RAW and then resumed, the inside backoff function works as follows. At the beginning of each RAW, STA generates a new backoff function, setting $CW = CW_{\min}$ and drawing backoff from interval $[0, CW_{\min} - 1]$. Thus the backoff counter at the end of the previous RAW is not passed to a new RAW. The standard [1] defines such behavior to provide fairness. The STAs with high CW from the previous RAW may suffer because of the lower priority, than of the new STAs. In case of several contending STAs, the backoff function renewal at the RAW slot beginning changes contention during the RAW slot. If during the RAW slot new packets do not appear, the contention is higher at the slot beginning than at the end.

B. RELATED WORK

Choosing RAW parameters is connected to two issues.

The first one is related to hidden STAs. The presence of hidden STAs simultaneously contending for the channel increases collision probability and degrades both energy and channel efficiency [22]. Fortunately, in .11ah networks, this issue can be solved in several ways. For example, the authors of [23] propose an algorithm, which divides STAs into a small number of groups, having no hidden STAs in any group. In our paper, we assume that this or similar approaches [24]–[26] are used and do not consider hidden STAs at all.

The second issue is improving channel efficiency in a RAW slot. A too high number of STAs transmitting in a RAW slot results in a high number of collisions, while a too low number of STAs may result in long idle times. To find a tradeoff between collisions and idle channel, we need to evaluate network performance accurately. To the best of our knowledge, most of the papers that model the RAW omit the peculiarity described at the end of Section II-A.

Specifically, they use Bianchi's approach to evaluate the performance of Wi-Fi legacy channel access methods. In his pioneering work [27], Bianchi has introduced the concept of the virtual slot, i.e., the time interval between two consequent changes of the backoff counter. He has developed his mathematical model under the assumption that every STA always has a packet to transmit and the transmission process is steady, i.e., the probability that the STA transmits in a particular virtual slot does not change with time. Note that at the RAW slot beginning, each STA has the smallest contention window $CW = CW_{\min}$, then if collisions occur, CW increases. In other words, made for legacy Wi-Fi, Bianchi's assumption is not applicable for RAW unless the RAW slot is long enough and the number of STAs is low. However, the RAW slot duration is limited by 31.1 or 246.14 ms, as described in Section II-A. Nevertheless, many papers focused on RAW widely utilize his approach, though Bianchi has designed it for another scenario. Below are just several examples found in the literature.

The authors of [4] and [5] use Bianchi's approach while developing a mathematical model to study the efficiency of the Group-Synchronized Distributed Coordination Function (GS-DCF) mechanism, which is similar to RAW. The authors study if it is worth to allow crossing slot boundary. They assume that the backoff function used inside RAW saves its state between consequent RAWs. Also for the cross-slot boundary, they consider the case with the infinite number of RAW slots in one RAW. Since many papers use the GS-DCF approach to model RAW, in our paper, we compare the results of our model with the model of GS-DCF.

The model of GS-DCF is also used in [6], where the authors simulate the operation of a network with one AP and 1000 STAs randomly distributed in a circle with a 1 km radius. They validate results obtained with the mathematical model from [5] via simulation. Also, authors of [7] use the GS-DCF model for the analysis of their service differentiation scheme. A similar approach is used in [8] to evaluate the throughput, power efficiency, and delay in IEEE 802.11ah networks.

Finally, [9] uses the same approach to evaluate the performance of RAW for uplink and downlink traffic. Authors of [9] consider the case when inside RAW slots allocated STAs use PS-Poll mechanism. So, when inside a RAW slot, there are two or more STAs, the authors of [9] use the Bianchi model to evaluate the throughput. The authors of [10] use the Bianchi model directly to evaluate the performance of the proposed RAW grouping scheme. The authors of [11] apply the Bianchi model to evaluate the energy consumption for different grouping schemes. The authors of [12] modify Markov chain from Bianchi's paper to consider both saturated and non-saturated traffic in RAW. Unfortunately, they also do not take into account the backoff function renewal at the RAW slot beginning.

Generally speaking, as these papers omit the duration of RAW slot and backoff function renewal, they provide correct results, but only for the case of the infinite RAW slot, which never happens in reality. Finite length of the RAW slot has been taken into account in [13], [14]. The authors of [13], [14] build a mathematical model for the analysis of EDCA operation within a RAW slot and consider several EDCA Access Categories. The considered network operation is questionable since the authors assume that every RAW starts with a beacon, and a PS-Poll starts any uplink transmission, which is not valid. Although the authors point out the correct backoff operation in a RAW slot, they assume that the transmission probability does not depend on time. In [28], Fig. 1, we show that the transmission probability does significantly change with time. So contention also changes during the RAW slot. In that paper [28], we also build a model which takes into account the finite length of the RAW slot, and the backoff function renewal. The model allows estimating the minimal RAW slot duration needed to transmit a single frame in the scenario when several STAs are assigned to a RAW slot, and each STA has only one packet in the queue.

In this paper, we extend the model from [28] to a more general scenario with various traffic patterns and RAW configurations and analyze other performance indices such as energy consumption and packet loss ratio.

C. SCENARIO

Consider a set of M sensor STAs connected to an AP. The STAs react to some external events, like changes of temperature or pressure. When an event occurs, some STAs need to transmit information about this event to the AP. The information expires in τ_{QoS}.

To receive the traffic, the AP periodically allocates a RAW of duration τ_{RAW}, see Fig. 1. The period of RAW equals τ_{QoS} for the following reason. First, because of the packet lifetime constraint, it cannot exceed τ_{QoS}. However, given a limited amount of channel resources (proportion of a channel time), setting the RAW period smaller than τ_{QoS} is inefficient, since it makes RAW duration also shorter. Indeed, every RAW slot the contention window starts with the smallest value. So if many STAs need to send data in a RAW slot, their first transmission attempts collide. Because of the short RAW slot, the STAs have no time to increase their contention window enough to resolve collisions in the same slot, but in the next slot, the problem occurs again. Thus, making RAW slots shorter and more frequent (with the same amount of reserved channel time) increases packet loss ratio. So, we can consider the case when the AP sets the period of RAW to τ_{QoS}, i.e., the network should deliver the information about the event within one RAW.

We assume that during τ_{QoS} the registered event happens with probability q. We also assume that $\tau_{RAW} \ll \tau_{QoS}$, so we neglect the probability of event occurrence during RAW. To deliver incoming data, a STA needs to transmit a burst of frames. The frames have the same size, and we denote the transmission time of each frame as T_{DATA}. The number of frames B in a burst is random and has geometrical distribution with parameter p: $\mathbb{P}(B = b) = (1 - p)p^{b-1}, \quad b \geq 1$. If $p = 0$, then the STA may have only one frame in the queue at the RAW slot beginning; and if $p = 1$, then the STA transmits full-buffer (i.e., saturated) traffic until the end of the RAW slot. All frames have the same delay budget τ_{QoS} after which the frames are discarded. Once the STA delivers all its frames or drop them, it can switch off the radio to save power.

Since in the scenario described above, only a subset of STAs has uplink data, and the AP does not know exactly which STAs have traffic, it divides M STAs into $K \in [1; M]$ subgroups and assigns RAW slots to each subgroup. Note that if $q = 1$ and $p = 0$, the best way is to periodically allocate an individual RAW slot to each STA, and to set $CW_{\min} = 0$. However, if $q < 1$, such an approach leads to the waste of channel time.

We assume that there are no hidden STAs. Otherwise, we can divide STAs into several groups having no hidden STAs in each group, e.g., using approaches described in [23]–[26].

For the considered scenario, we need to develop a mathematical model, which can be used to find the total network throughput, energy consumption per delivered frame and packet loss ratio for a given RAW duration and the number of slots. To develop the model, firstly, we need to analyze the transmission process inside the RAW slot. Secondly, as the cross-slot boundary is not used, we can consider independent transmission processes in different RAW slots, which are inside one RAW. The model can be used to find such RAW parameters which maximize throughput or provide the required delivery reliability.

III. MATHEMATICAL MODEL

A. MODELING TRANSMISSION PROCESS INSIDE ONE RAW SLOT

Consider a STA, which transmits frames inside a RAW slot of duration τ_{slot}. Similar to Bianchi [27], we split the time into virtual slots, but this is the only common idea. In contrast to [27], we consider a transient process instead of the steady-state one.

During the transmission process, a STA may stop contending for the channel for two reasons: first, its queue may become empty; second, the RAW slot may end. In any case, even if all STAs empty their queues, the RAW slot continues, and the rest of RAW slot is filled with empty slots.

Let the RAW slot contain e empty slots of duration τ_e, s successful slots of duration τ_s, and c collision slots of duration τ_c. It means that

$$e\tau_e + s\tau_s + c\tau_c \in (\tau_{slot} - \tau_s; \tau_{slot}], \quad (1)$$

since τ_s before the end of the RAW slot, the STAs stop contending for the channel, because they cannot succeed to transmit a frame without crossing RAW slot boundary, which is forbidden. So, to take into account the RAW slot boundary, we need to track the number and type of virtual slots in the system.

However, as we consider the scenario without incoming packets during the RAW slot, the number of active STAs n is decreasing during the transmission process, which shall be taken into account.

So, for the stated above reasons, we need to consider a Markov chain with a time unit of one virtual slot and state (e, s, c, n). Note that in the saturated case ($p = 1$), $n = N$, and it is possible to use a Markov chain with state (e, s, c).

Before calculating transition probabilities for the aforementioned processes, let us introduce some auxiliary quantities.

Let $T_{r|t}$ be the probability that in virtual slot t the STA transmits and its retry counter equals r. This transmission can be successful or not. $C_{r|t}$ is the probability that the STA transmits and its transmission collides with another transmission, and $S_{r|t}$ is the probability that the STA successfully transmits in virtual slot t, while its retry counter equals r. So:

$$T_{r|t} = \begin{cases} \dfrac{1}{CW_{\min}}, & r = t = 0, \\ \dfrac{1}{CW_{\min}} + \dfrac{p}{CW_{\min}} \displaystyle\sum_{k=0}^{t-1} \left(C_{RL-1|k} + \sum_{m=0}^{RL-1} S_{m|k} \right), & r = 0, \quad 1 \le t < CW_{\min}, \\ \dfrac{p}{CW_{\min}} \displaystyle\sum_{k=t-CW_{\min}}^{t-1} \left(C_{RL-1|k} + \sum_{m=0}^{RL-1} S_{m|k} \right), & r = 0, \quad CW_{\min} \le t, \\ \dfrac{1}{CW_r} \displaystyle\sum_{k=\max(k-CW_r, r-1)}^{t-1} C_{r-1|k}, & 0 < r < RL, \quad t > 0, \\ 0, & \text{otherwise}. \end{cases} \quad (2)$$

Let us explain (2). First, obviously $T_{0|0} = \frac{1}{CW_{\min}}$, since the STA chooses uniformly one of $CW_{\min}$ virtual slots for its first transmission attempt.

For the next $(CW_{\min} - 1)$ virtual slots, $T_{0|t}$ consists of two components, see the second line of (2). The first one, i.e., $\frac{1}{CW_{\min}}$, has the same nature as $T_{0|0}$. The second one, i.e., $\frac{p}{CW_{\min}} \sum_{k=0}^{t-1} \left(C_{RL-1|k} + \sum_{m=0}^{RL-1} S_{m|k} \right)$, is the probability of transmission of the non-first packet in the batch. It corresponds to the case when at virtual slot k, the STA has already done a transmission attempt, after which the next frame in the queue has started its service. The latter means that the frame was dropped — because of being delivered (with probability $\sum_{m=0}^{RL-1} S_{m|k}$) or reaching retry limit $C_{RL-1|k}$ — and the STA has one more packet in the queue which happens with probability p.

By virtual slot $CW_{\min}$, the STA makes at least one transmission attempt of the first packet in the queue. Thus, for $t \ge CW_{\min}$, the first component disappears and $T_{0|t}$ has only the second one.

For $0 < r < RL$, the STA transmits in slot t only if it was involved into collision not earlier than CW_r slots before and chose slot t out of CW_r slots. It gives us the fourth line of (2).

Finally, the transmission with all other values of r and t is impossible. For example, a STA cannot make the second transmission attempt at virtual slot $t = 0$. So, $T_{r|t} = 0$, which ends the explanation of (2).

Let N STAs have frames to transmit at the RAW slot beginning. Since all STAs are under the same conditions, and count down backoff synchronously, $T_{r|t}$, $C_{r|t}$ and $S_{r|t}$ are the same for all of them. Assuming that the STAs decide to transmit a packet in a particular virtual slot independently, and their retry counters are independent, we obtain that:

$$S_{r|t} = T_{r|t} \left(1 - \sum_{m=0}^{RL-1} T_{m|t} \right)^{N-1},$$

$$C_{r|t} = T_{r|t} - S_{r|t} = T_{r|t} \left[1 - \left(1 - \sum_{m=0}^{RL-1} T_{m|t} \right)^{N-1} \right].$$

Next, let $Q_{r|t}$ be the probability that in virtual slot t the STA still has a packet in a queue and its retry counter equals r.

Similarly to (2), one can easily derive that

$$Q_{r|t} = \begin{cases} \displaystyle\sum_{k=0}^{t-1} C_{r-1|k} - \sum_{k=0}^{t-1} T_{r|k}, & 0 < r < RL, \\ 1 + p \left(\displaystyle\sum_{k=0}^{t-1} \sum_{m=0}^{RL-1} S_{m|k} + \sum_{k=0}^{t-1} C_{RL-1|k} \right) \\ \quad - \displaystyle\sum_{k=0}^{t-1} T_{r|k}, & r = 0. \end{cases} \quad (3)$$

To derive (3), first let us consider a case with $0 < r < RL$. The STA comes to a state with a particular r if its transmission attempt #$(r - 1)$ collides. The STA stays in a state with a particular r until the STA makes the next transmission attempt. Summing up, we obtain the first line of (3).

As for the second line, the STA is initially in the state with $r = 0$. It transits from this state if it makes a transmission attempt, and it transits to this state if it ends service of the previous packet, and there is at least one more packet in the queue.

Note that for any t and r, $Q_{r|t} \ge T_{r|t}$ because a STA can transmit only if it has a packet in the queue.

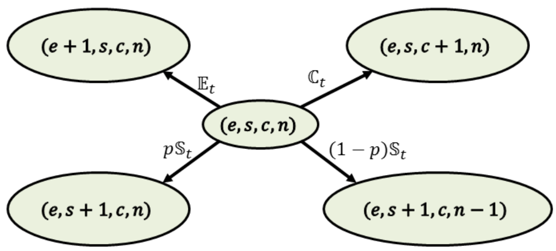

FIGURE 2. **Markov chain (e, s, c, n) and transition probabilities.**

Let us introduce $\mathbb{T}_t$, the probability for an arbitrary chosen STA to transmit in virtual slot t:

$$\mathbb{T}_t = \frac{\sum_{m=0}^{RL-1} T_{m|t}}{\sum_{m=0}^{RL-1} Q_{m|t}}.$$

Depending on STAs' transmissions, a virtual slot can

- be empty with probability $\mathbb{E}_t = (1 - \mathbb{T}_t)^n$,
- contain successful frame delivery with probability $\mathbb{S}_t = N \cdot \mathbb{T}_t(1 - \mathbb{T}_t)^{n-1}$,
- contain a collision of frames with probability $\mathbb{C}_t = 1 - \mathbb{E}_t - \mathbb{S}_t$,

where n is the total number of active STAs (with at least one packet in a queue).

The only question is how to find the probabilities $\mathbb{P}(e, s, c, n)$ that after $t = e + s + c$ virtual slots, the number of virtual slots of each type and number of active STAs is described by a particular quadruplet (e, s, c, n).

To answer this question, we observe how this quadruplet changes with time. At the RAW slot beginning ($t = 0$), the state is $(0, 0, 0, N)$ with probability 1. Each virtual slot, e, s, or c is incremented. Specifically, let the chain be in state (e, s, c, n) at the beginning of virtual slot $t = e + s + c$ (see Fig. 2). With probability $\mathbb{E}_t$ the chain transits to state $(e+1, s, c, n)$. With probability $\mathbb{C}_t$, it transits to $(e, s, c+1, n)$. With probability $p\mathbb{S}_t$, it transits to $(e, s + 1, c, n)$, and with probability $(1 - p)\mathbb{S}_t$ it transits to $(e, s + 1, c, n - 1)$ because after a successful transmission a STA has no packets in queue with probability $1 - p$.

The chain evolution stops in some absorbing states which satisfy condition (1). Note that the chain allows the nonzero probability of impossible states, such as $(CW_{\min}, 0, 0, N)_{CW_{\min}}$. We also do not take into account frame dropping after RL unsuccessful transmission attempts. However, as we show in Section IV, the error caused by this inaccuracy is small.

Note that if the STA is alone, its transmissions are always successful and we consider a more accurate Markov chain with states (e, s) and the following transition rule. With probability $\frac{p}{CW_{\min}}$ the chain transits from state (e, s) to one of the states $(e + i, s + 1)$, $i = 0, \ldots, CW_{\min} - 1$. The absorbing states satisfy (1).

Finally, using the calculated probabilities of Markov chain states, we obtain throughput inside one RAW slot as the average throughput over all absorbing states:

$$V(N, \tau_{slot}, p) = \frac{D}{\tau_{slot}} \sum_{n=1}^{N} \sum_{e\tau_e + s\tau_s + c\tau_c \in (\tau_{slot} - \tau_s, \tau_{slot})} s \cdot \mathbb{P}(e, s, c, n), \quad (4)$$

where D is the packet length.

To obtain the mean power consumption of a STA during the RAW slot, let us firstly calculate the average energy that one STA from n active ones consumes in virtual slot t:

$$\mathbb{W}_t = W_{TX}\mathbb{T}_t + W_{idle}\mathbb{E}_t + W_{busy}(1 - \mathbb{T}_t - \mathbb{E}_t),$$

where W_{TX} is the amount of energy consumed by the transmitting STA, W_{idle} is the amount of energy consumed by a STA, which listens for an empty virtual slot, W_{busy} is the amount of energy consumed by a STA, which listens for a busy virtual slot. Given voltage U and current I in different TX/RX/idle states, these values can be found according to the following equations:

$$\begin{aligned} W_{idle} &= U I_{idle} \tau_e, \\ W_{busy} &= U\left[I_{RX}(T_{DATA} + T_{ACK}) + I_{idle}(SIFS + AIFS)\right], \\ W_{TX} &= U\left[(I_{TX} T_{DATA} + I_{idle}(SIFS + AIFS) + I_{RX} T_{ACK}\right]. \end{aligned}$$

Similarly to the throughput, the average power consumed by a STA during the RAW slot, can be calculated as follows:

$$W = \sum_{n=1}^{N} \sum_{e\tau_e + s\tau_s + c\tau_c \le \tau_{slot}} \mathbb{P}(e, s, c, n)\mathbb{W}_{c+e+s}\frac{n}{N}.$$

Here we assume that having delivered all its frames, the STA switches off its radio and goes to the doze state.

Note that in spite of a high dimension of the Markov chain, the computational complexity of the described part of the model is $O\left(N \cdot \lfloor \frac{\tau_{slot}}{\tau_e} \rfloor^3\right)$.

B. CONSIDERING SEVERAL RAW SLOTS

Eq. (4) defines the throughput for a given number N of transmitting STAs. When the AP divides M STAs into K subgroups as described in Section II, the number of transmitting STAs in each group can be found as follows.

Let us determine number G of STAs in each subgroup. $g_1 = M \bmod K$ subgroups contain $G_1 = \lfloor M/K \rfloor + 1$ STAs while other $g_2 = K - (M \bmod K)$ subgroups contain just $G_2 = \lfloor M/K \rfloor$ STAs. Here $\lfloor x \rfloor$ means the highest integer less than or equal to x. Since each STA has packets in its queue with probability q, the number N of STAs accessing the channel in a RAW slot is the random value with binomial distribution:

$$\mathcal{P}(N, G, p) = \binom{G}{N} q^N (1 - q)^{G-N}.$$

Thus, the average throughput in RAW is given by the following equation:

$$\langle V\rangle = \frac{\sum_{i=1}^{2}\left(g_i \sum_{N=1}^{G_i} \mathcal{P}(N; G_i, q) V(N, \frac{\tau_{RAW}}{K}, p)\right)}{K}.$$

The average power consumption of an arbitrarily selected STA can be calculated similarly:

$$\langle W\rangle = \frac{\sum_{i=1}^{2}\left(g_i \sum_{N=1}^{G_i} \mathcal{P}(N; G_i, q) W(N, \frac{\tau_{RAW}}{K}, p)\frac{N}{G_i}\right)}{K}.$$

The energy consumption per delivered frame is given by the following equation:

$$\Omega = D\frac{\sum_{i=1}^{2}\left(g_i \sum_{N=1}^{G_i} \mathcal{P}(N; G_i, q) W(N, \frac{\tau_{RAW}}{K}, p)\frac{N}{G_i}\right)}{\sum_{i=1}^{2}\left(g_i \sum_{N=1}^{G_i} \mathcal{P}(N; G_i, q) V(N, \frac{\tau_{RAW}}{K}, p)\right)}.$$

The packet loss ratio PLR for $p < 1$ can be calculates as follows:

$$PLR = 1 - \frac{\langle V\rangle \tau_{RAW}(1-p)}{MDq}.$$

Given p and q, RAW duration τ_{RAW}, and the total number of STAs M, we can use the model to select such K, which maximizes the throughput inside RAW:

$$K_{\text{opt}} = \arg\max_K \langle V\rangle(K),$$

We can also use the model to select such RAW slot parameters that allow us to deliver data with the required reliability and to meet the requirement on power consumption. We give several examples in Section IV.

IV. NUMERICAL RESULTS

A. VALIDATION

Consider a scenario described in Section II-C with M STAs. Let the STAs transmit 100-byte frames at Modulation and Coding Scheme (MCS) 8, the highest possible MCS in 2 MHz channel, with short guard intervals and nominal PHY rate of $\approx$ 8.7 Mbps. We assume that no RTS/CTS mechanism is used, so $\tau_s = \tau_c$. Inside RAW slot, the STAs use the default channel access parameters represented in Table 1. The values for power consumption are taken from [29].

First of all, let us prove the accuracy of the model. For that, we consider a single RAW slot. Figs. 3–5 show the throughput, energy consumption per delivered frame, and PLR depending on the RAW slot duration, obtained with the mathematical model and simulation for the case when all the STAs belong to the same group. The curve "ideal" corresponds to the transmission of frames in a round-robin manner one by one without collisions and backoff. In the saturated case ($p = q = 1$), the longer is the RAW slot, the higher is throughput, since the STAs have enough time

TABLE 1. Model parameters.

τ_e	$52\mu s$	τ_s	$1064\mu s$
W_{idle}	$2.9\mu J$	τ_c	$1064\mu s$
W_{TX}	$160\mu J$	W_{busy}	$91\mu J$
$\tau_{slot}^{\max}$	$246ms$	RL	7
$CW_{\min}$	16	$CW_{\max}$	1024
T_{DATA}	$348\mu s$	T_{ACK}	$240\mu s$
$SIFS$	$160\mu s$	$AIFS$	$SIFS + 3T_e$
U	$1.1V$	I_{TX}	$280mA$
I_{listen}^{busy}	$100mA$	I_{listen}^{idle}	$50mA$

to increase their contention windows. When $\tau_{slot} \to \infty$, the throughput becomes close to the one, obtained with the Bianchi model.

For the cases with non-saturated traffic ($p < 1$), the throughput tends to 0 when $\tau_{slot} \to \infty$. Such degradation of throughput happens because the STAs have no more traffic to send during long τ_{slot}. In other words, they stop their transmissions when their queues become empty. The difference in throughput between the cases shown in Figs. 3–5 — namely, $p = q = 0.5$ and $p = 0, q = 1$, having the same average traffic rate of one packet per RAW slot per STA, but different batch size distribution — can be noticed when the RAW slot duration is small. In case of $p = 0, q = 1$, the throughput is lower because of a higher contention. When the RAW slot duration exceeds 150 ms, PLR becomes close to zero, and almost all the packets are delivered. Thus, the throughput equals the total size of the packets divided by the RAW slot duration. Figs. 3 shows this estimation as curve "approx".

When the RAW slot duration tends to ∞, the energy consumption per delivered frame decreases. For a short RAW slot, high energy consumption is caused by high contention, which prevents the STA from the transmission. In other words, in this case, the STA consumes some energy to sense the channel and receive other frames, if any, but the RAW slot duration is not enough for the STA to succeed in frame transmission because of high contention. Thus, during the RAW slot, the STA consumes much energy but hardly delivers a frame. The power consumption per delivered frame is thus high. With a higher RAW slot duration, the time is enough to increase the contention window significantly, and power consumption per delivered frame decreases.

The longer is the RAW slot, the more time the STAs have, and the more frames they can deliver. So the PLR reduces. Notice that such a RAW slot duration that maximizes the throughput does not provide zero PLR. It happens because for throughput maximization, we need both to fill the RAW slot with transmission attempts and to have contention window high enough. At the same time low PLR is only achieved when contention is low, e.g., because of a long RAW slot.

Let us compare the results obtained with our model and the ones from the literature. Since many papers [4]–[12] use very similar approaches assuming that the backoff is not renewed at the RAW slot beginning, we choose the model of GS-DCF

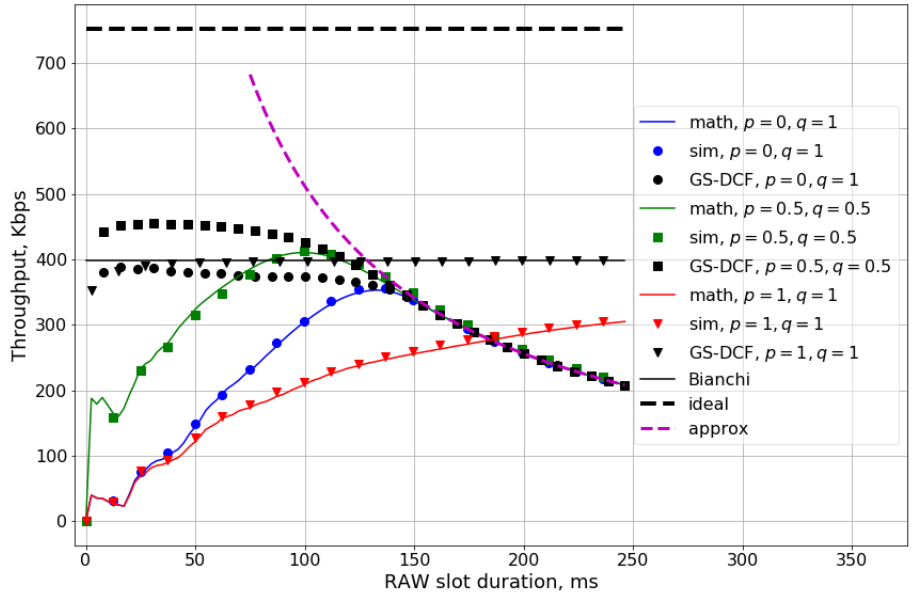

FIGURE 3. **Throughput in a RAW slot for $N = 64$ STAs obtained with our mathematical model (math), simulation (sim), and other approaches from the literature.**

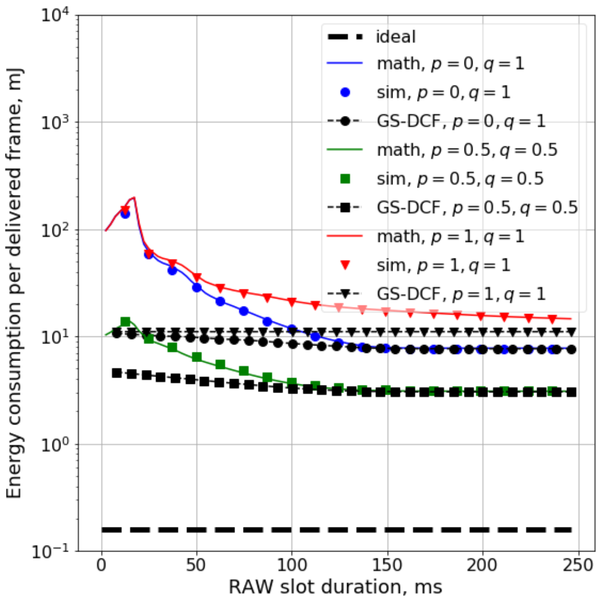

FIGURE 4. **Energy consumption per a delivered frame in a RAW slot for $N = 64$ STAs obtained with our mathematical model (math), simulation (sim) and other approaches from the literature.**

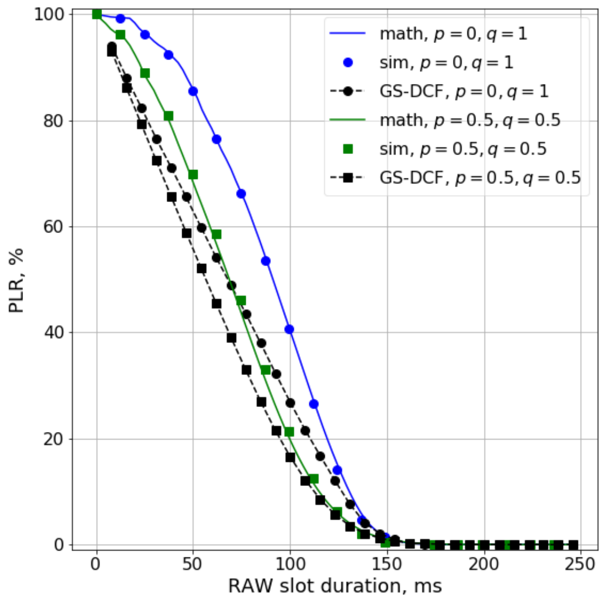

FIGURE 5. **PLR in a RAW slot for $N = 64$ STAs obtained with mathematical model (math), simulation (sim) and other approaches from the literature.**

for the saturated case [4], [5], [7] as the first paper among them. Fig. 3 shows that for small RAW slot durations, GS-DCF overestimates the performance of RAW in comparison to both our model and simulation of the saturated case ($p = q = 1$). Since the assumption that the transmission process is steady, made in the GS-DCF model, becomes valid if $\tau_{slot} \to \infty$, the throughput obtained with GS-DCF tends to the simulation results when the RAW slot duration increases. However, according to the standard [1], the duration of the RAW slot cannot exceed $\tau_{slot}^{\max}$. Even at the maximal RAW slot duration, GS-DCF overestimates the network throughput by about 30 %.

Since none of the GS-DCF-like models found in the literature are designed for the case when each of the STAs has a random batch of packets during RAW slot, we run simulation of the GS-DCF operation in the considered scenario for $p < 1$, see Fig. 3. From the obtained results, it is also clear that this approach is not valid for small and moderate RAW slot durations. For example, for durations less than 100ms,

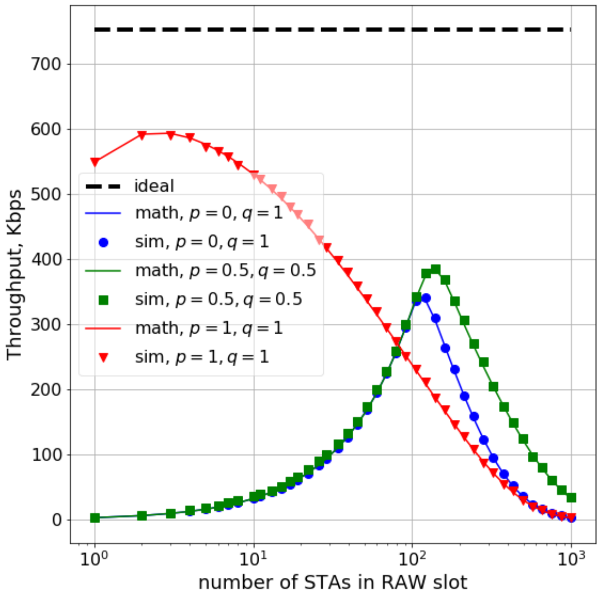

FIGURE 6. **Throughput for a RAW slot of duration $\tau_{slot} = \tau_{slot}^{max}$. The results are obtained with mathematical model (math) and simulation (sim).**

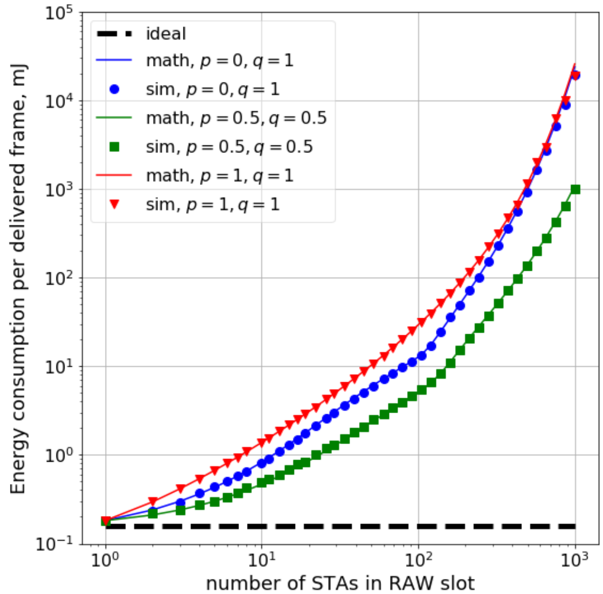

FIGURE 7. **Energy consumption per delivered frame for a RAW slot of duration $\tau_{slot} = \tau_{slot}^{max}$. The results are obtained with mathematical model (math) and simulation (sim).**

the GS-DCF approach gives several times higher throughput than the accurate simulation of the standardized behavior and our model. Apart from that, the simulation of GS-DCF manifold underestimates energy consumption. Moreover, with GS-DCF, the energy consumption per delivered frame almost does not depend on the duration of the RAW slot, while the accurate simulation of the standardized operation and our model shows significant dependencies, see Fig. 4. Apart from that, GS-DCF underestimates PLR for small RAW slots, see Fig. 5.

Figs. 6–8 present results for a scenario when the RAW slot duration is fixed and equal to the maximum value τ_{slot}^{max} while the number G of STAs inside RAW slot varies. For the saturated case, we see that the maximal throughput is achieved if $G = 2 \dots 4$, which means that if we have a high number of STAs, we should divide them into a relatively high number of groups. For the considered unsaturated cases, the throughput maximum is achieved when $G = 125 \dots 135$. Energy consumption per delivered frame increases, since a higher number of STAs results in higher contention and longer carrier sensing. Note that since RAW slot duration is limited, the higher is the number of STAs, the higher is the probability that the RAW slot is not enough to deliver all the packets. Thus, the packet loss ratio increases.

Note here that again the traditional Bianchi approach for saturated Wi-Fi networks [27] and the GS-DCF approach overestimates throughput even at the maximal RAW slot duration, almost doubling the throughput for >300 STAs. As shown in Fig. 3, this error only increases when the RAW slot duration decreases.

The analysis of the obtained results leads us to the following conclusion.

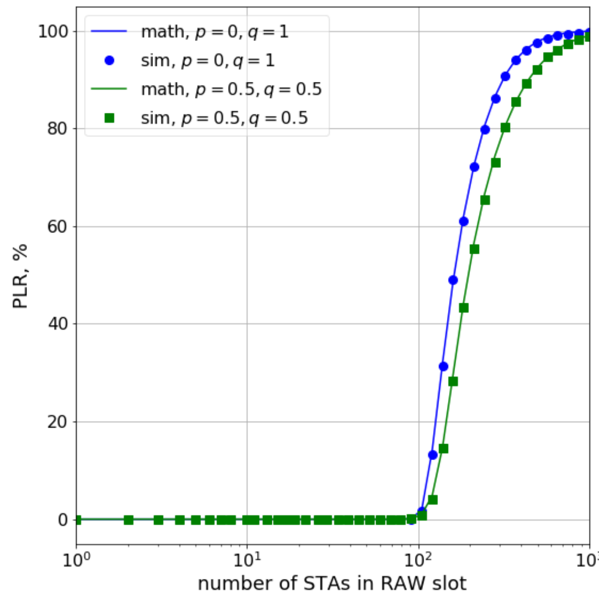

FIGURE 8. **PLR for a RAW slot of duration $\tau_{slot} = \tau_{slot}^{max}$. The results are obtained with mathematical model (math) and simulation (sim).**

First, energy consumption grows with the number of devices. As for the dependence of energy consumption on the RAW slot duration, it is better to allocate rather long slots, since after some threshold, the energy consumption per delivered frame decreases and tends to some value which corresponds to the case when all STAs succeed to transmit their packets in time.

Second, as for the throughput, the model allows finding the optimal RAW slot duration and the optimal number of

STAs in the RAW slot in case of unsaturated traffic. Note, that the dependences of the throughput on the number of STAs in a group are completely different for the saturated and unsaturated cases, as shown in Fig. 6.

- For saturated traffic, it is worth to have two or three STAs in a group to maximize throughput. When the STA is alone, some portion of the channel time is wasted due to the backoff procedure, which results in the throughput just a bit less than the maximal one. A higher number of STAs increases contention.
- For unsaturated traffic, a low number of STAs in a group means that the channel time may be wasted because none of the STAs have data for transmission. That is why throughput tends to zero when the number of STas in a group decreases. Throughput reaches a peak when the number of packets at the STAs is enough to fill in the whole slot. The further increase in the number of STAs in a group increases contention, and throughput goes down because of collisions. Note that at this point, the values of PLR sharply go up, see Fig. 8.

Third, note that the RAW parameters, though optimal in terms of throughput, are not optimal in terms of PLR. Moreover, all Figs. 3-8 show that with the found "optimal" RAW parameter values, PLR is very high, exceeding 10%. In contrast, low PLR is obtained if we select long RAW slots with a low number of contending STAs. However, in this case, we obtain low throughput and low efficiency of channel usage.

Summing up, it is hardly possible to simultaneously optimize RAW with respect to all the considered performance indices. However, we can use the developed model to find a tradeoff between the considered performance indices by varying the number of groups K in which we split the STAs. It makes sense to optimize only one performance index, for example, the most important, e.g., throughput, considering limitations on the other ones and channel resource consumption. We do it in the next sections.

B. INFLUENCE OF THE NUMBER OF GROUPS

Let us now consider the scenario described in Section II-C. The AP reserves for RAW only some portion of channel time, namely $\frac{\tau_{slot}^{max}}{\tau_{QoS}}$. Then the AP splits RAW into K slots and divides $M = 100$ STAs into K groups, each of which corresponds to a unique slot. With the developed model, we can find how throughput, energy consumption and PLR depend on K, see Figs. 9-11.

The obtained results on the energy consumption (see Fig. 10) clearly show that for any scenario parameters, energy consumption sharply decreases when the number of groups increases because of reduced contention and, thus, the shorter time the STA needs to wait before it delivers its packet. So, the main goal of the RAW mechanism is achieved, i.e., the channel contention and energy consumption are reduced. Such a result is rather apparent as the higher is the

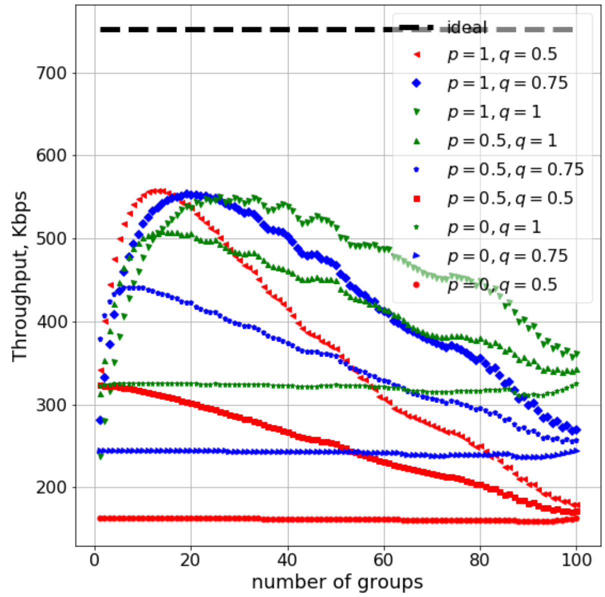

FIGURE 9. Throughput for various numbers of groups K.

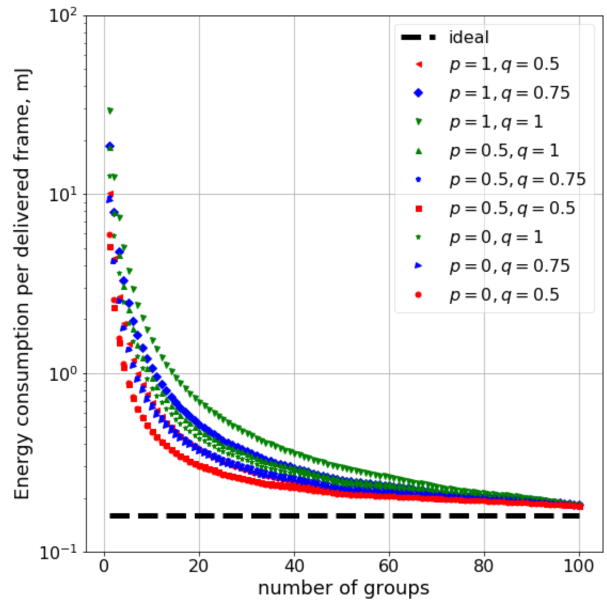

FIGURE 10. Energy consumption per delivered frame for various numbers of groups K.

number of groups, the less is the number of STAs inside one group and the less is contention for the channel.

The graph for throughput is much more interesting (see Fig. 9). In the saturated case ($p = 1.0$), when K changes, the throughput fluctuates because of the following reason. Increasing K means decreasing RAW slot duration. If after a transmission the rest of the RAW slot is less than τ_s, the STAs do not transmit, and this channel time is wasted.

For $p = 0$ (i.e., if STAs may have only one packet with probability q), the throughput does not depend on K. The load is quite low, and the reserved channel time is enough whatever K is since even for $K = 100$ RAW slot duration exceeds the time needed for a STA to send the only frame.

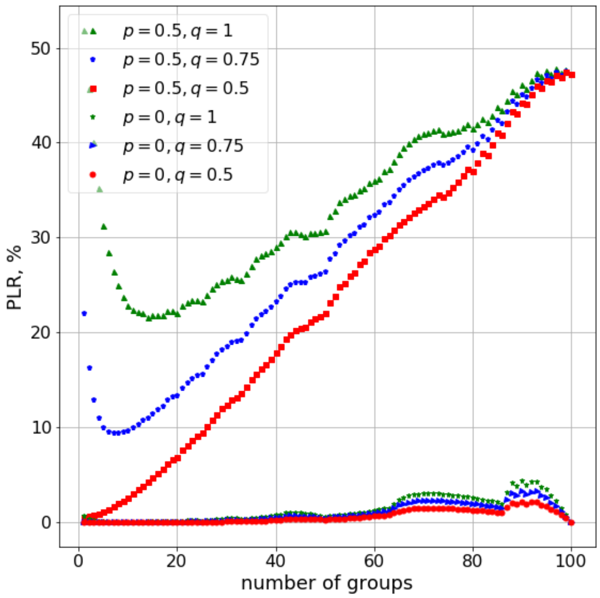

FIGURE 11. PLR for various numbers of groups K.

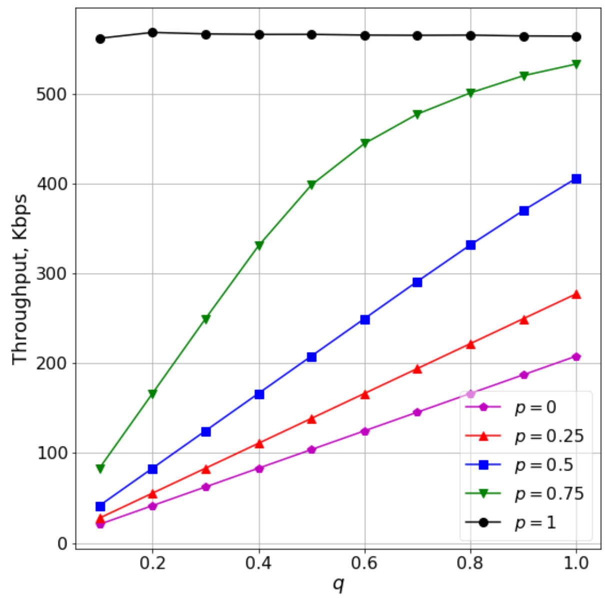

FIGURE 12. The maximal throughput for $M = 64$ STAs.

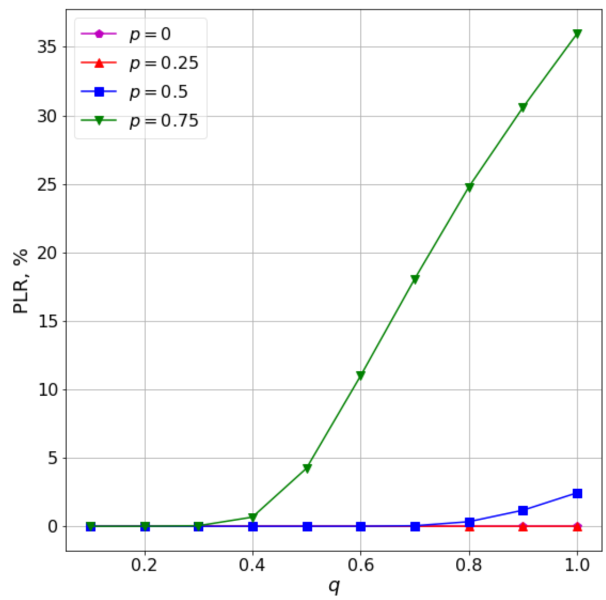

FIGURE 13. PLR corresponding to the maximal throughput for $M = 64$ STAs.

The case with $p = 0.5, q = 0.5$ is the most sophisticated among considered. If K is low, we have huge contention which results in a large number of collisions, channel time waste, and low throughput. In contrast, if we split STAs into 100 groups, we obtain too short RAW slots. Their duration is enough only for one packet transmission. Thus many packets are lost, and throughput is low. At the same time, some other slots can be fully idle, if corresponding STAs do not have packets at all. Thus with the model, we can find a tradeoff between these two effects, e.g., we can find such K, which maximizes throughput.

A similar conclusion can be done by analyzing PLR (see Fig. 11). If $p = 0$, PLR is also close to zero because of too low load. With nonzero p, we can see that there is some optimal value of K, which depends on how many STAs react to the events. If many STAs react to the event, selecting a low value of K results in high contention. When K is higher, the contention reduces. At the same time the higher is K, the lower is the number STAs in a group and the more probable is the situation when in some slots there is no more data to be transmitted, while others experience lack of channel time.

We also can see that in some cases (i.e., for $p = 0.5$, $q = 1$) the minimal value of PLR is too high. However, it can be reduced by increasing the percentage of the reserved channel time, i.e., by increasing the duration of RAW intervals.

C. THROUGHPUT OPTIMIZATION

The developed model can be used to select such RAW parameters that provide required low energy consumption, high throughput, or low packet loss ratio with the minimal amount of reserved channel time. In this section, we use the model to solve an inverse problem, namely to maximize the throughput for a given amount of reserved channel time, i.e., the duration of a RAW interval, and the number M of STAs.

Let RAW duration be τ_{slot}^{max}, and $M = 64$. We vary p and q. With the model, for each pair of p and q, we find such a number of groups K that maximizes throughput. We also calculate PLR for the found value of K. Figs. 12-13 show the obtained results. The PLR curve for $p = 1$ is skipped since $p = 1$ means saturation and PLR has no sense. Fig. 12 shows that at low event triggering probability q, the maximal throughput increases linearly with the load, which is proportional to q. The corresponding PLR is almost zero in that case, as shown by Fig. 13. However, after some point (e.g., $q = 0.4$ for $p = 0.75$), the channel load becomes too high, and PLR starts to increase. Correspondingly, the growth of the maximal throughput slows down. In case of a small

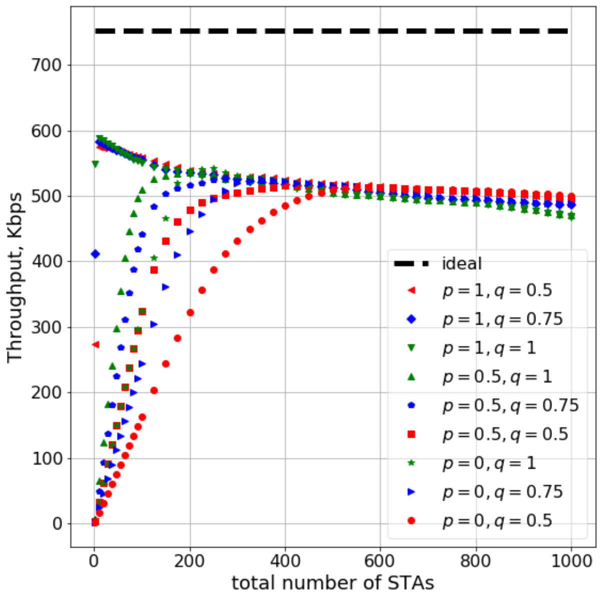

FIGURE 14. **Throughput for different numbers of STAs.**

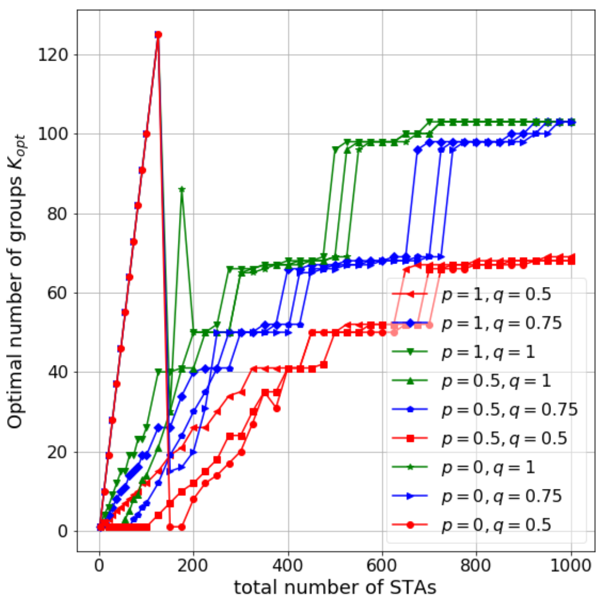

FIGURE 15. **The optimal number of groups for different numbers of STAs.**

average batch of packets ($p = 0.25$), even a high triggering probability q provides PLR close to zero.

Finally, we consider the throughput maximization problem for various numbers of STAs M. We set the duration of the RAW interval to $\tau_{slot}^{\max}$ and obtain such values of $K = K_{\text{opt}}$ which maximize throughput for various M, see Figs. 14-15.

On the first sight, in the saturated case, the optimal K_{opt} shall equal the number of STAs. However, because of a nonzero value of CW_{min}, it is better to allocate two or even three STAs per each RAW slot to minimize channel waste during the backoff phase. Moreover, for very high K, the duration of a RAW slot may become shorter than a data frame transmission which leads to zero throughputs. Thus, even for saturated traffic, K_{opt} has non-trivial dependence from M.

In the case of non-saturated traffic and low number of STAs, a low value of throughput is explained by the low load, rather than the channel time limits.

V. CONCLUSION

In this paper, we have developed a mathematical model, which — in contrast to prior adaptations of Bianchi's approach originally designed for traditional Wi-Fi networks — accurately estimates the performance indices of an IEEE 802.11ah network with Restricted Access Window while previous models, like GS-DCF, may severely overestimate the throughput, up to ten times underestimate the power consumption, and up to 20% underestimate PLR, as we demonstrate with numerical results. Moreover, the existing analytical models typically consider only saturated networks. Some other studies focus on non-saturated cases but assume that the contention does not change in time, which is not applicable for RAW. This paper describes the first RAW model that is applicable for both saturated and non-saturated networks and takes into account the RAW slot duration, the backoff function renewal at the RAW slot beginning, and hence changes of the transmission probability during the RAW slot. The model allows finding performance indices, such as throughput, packet loss ratio, and energy consumption. One can use the model to determine optimal RAW parameters, which provide the required QoS or maximize the throughput.

With the developed model, we show that being the essential MAC-layer feature of IEEE 802.11ah, RAW indeed allows the AP to reduce contention and, consequently, increase throughput and decrease power consumption and PLR. At the same time, RAW is just a flexible framework, and its efficiency significantly depends on its parameters. Moreover, it is hardly possible to find such RAW parameters which maximize throughput, and at the same time minimize PLR and power consumption. However, the developed model allows us to solve the optimization problem for one of these performance indices while the other ones (together with channel time) are considered as limitations.

For future work, we plan to consider scenarios with hidden STAs and allowed crossing slot boundary and estimate other performance indices, e.g., the transmission delay within RAW and fairness of channel time allocation. Also, we are going to compare RAW with OFDMA of 802.11ax/11be.

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