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Fast and Reliable Alert Delivery in Mission-Critical Wi-Fi HaLow Sensor Networks

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ABSTRACT Rapidly evolving, the Internet of Things imposes new challenges for the developers of wireless networks. Various critical infrastructure monitoring scenarios require fast and reliable alert delivery. In such systems, multiple sensors are entrusted to react to the same emergency event. Thus, it is enough to receive an alert message from any of these sensors. However, such a message shall be reliably delivered as soon as possible. The recently published Wi-Fi HaLow standard defines the Restricted Access Window (RAW) mechanism that coordinates transmissions of numerous devices. Thus, it can improve reliability and reduce delays. The paper is the first to study the usage of RAW in a scenario of emergency alerts, where the alert shall be received from at least one sensor. The paper presents an easy-to-calculate mathematical model of alert delivery with RAW. The model allows dynamic online reconfiguration of RAW parameters to select such parameters that minimize consumed channel timeshare while providing satisfactory reliability and delivery delay for an alert. Intensive performance evaluation shows that the RAW is fruitful for mission-critical data delivery in the considered scenario.

INDEX TERMS IEEE 802.11ah, restricted access window, sensor network, alert.

I. INTRODUCTION

The Internet of Things (IoT) has evolved from funny geek demos to the vital paradigm that has a strong impact on almost all areas of economy and human social life. IoT involves more and more devices, the majority being wireless [1]. To satisfy heterogeneous requirements of various wireless IoT systems, the community both develops new technologies, such as LoRaWAN or NB-IoT, and adapts the existing ones, like Wi-Fi. Published in 2017, the IEEE 802.11ah [2] amendment, also known as Wi-Fi HaLow, aims at bringing a long Wi-Fi success story to the IoT. For that, it defines many new mechanisms, including those that coordinate channel access: e.g., Restricted Access Window (RAW), Fast association, and Target Wake Time (TWT), etc. [3].

In the near future, the IoT will connect everything: from an electric kettle in smart homes to a car in a smart city or robot control at an Industry 4.0 factory. If the technology for the smart home cannot deliver data reliably, sometimes a human needs to switch on the kettle manually. However, for vehicle interaction or factory automation, the consequences are more dramatic. On first sight, Wi-Fi cannot provide the required reliability, because Wi-Fi operates in the unlicensed spectrum where any device can transmit at any time instance. However, at factories and nuclear plants, the owner can restrict the transmission of unauthorized devices in some areas, which de facto makes the channel private. Being validated by many users all over the world, the Wi-Fi technology is very mature. Apart from that, it is incredibly cheap. So, there are many examples of dedicated Wi-Fi deployments for mission-critical data delivery at factories, nuclear plants, and similar industrial buildings (e.g., see [4]).

With new channel access mechanisms, namely, RAW and TWT, Wi-Fi HaLow can improve this experience by providing low-cost low-power data transmission infrastructure for massive heterogeneous IoT applications. While the performance of Wi-Fi HaLow in general IoT applications has been studied in [5]–[12], in this paper, we consider a specific scenario of alert delivery in mission-critical deployments.

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In this scenario, a set of sensors perform emergency monitoring and alert functions [13], [14] in large buildings, at factories and nuclear plants. Based on some measurements, the sensors detect an emergency event, such as a chemical leak, a sharp increase in radiation level, fire, or flood. When an emergency event is detected, the affected sensor transmits its measurements within the alert frame. The emergency event can almost simultaneously activate alert transmission from multiple sensors. However, for learning about the emergency event, it is enough to receive a single message from any device, but the delivery delay shall be as short as possible. One option is to deploy an exclusive sensor network for emergency monitoring with a dedicated channel to deliver emergency alerts fast and reliably. But as the emergency events rarely happen, most of the time, the channel is underutilized. Another option is a heterogeneous network [11] with emergency sensors and other devices. In that case, to provide fast and reliable alert delivery, the emergency sensors should be protected from channel contention with the other devices. The protection can be done using the RAW mechanism of Wi-Fi HaLow.

With RAW, an access point (AP) assigns time intervals called RAW slots to groups of stations (STAs). Only allocated STAs are allowed to transmit within corresponding RAW slots. Although the Wi-Fi HaLow standard describes the RAW mechanism, it does not provide any recommendations on how to choose the mechanism parameters, e.g., the RAW slot duration. A proper mathematical model of the RAW mechanism allows choosing RAW settings according to the scenario requirements, such as restrictions on transmission delay and reliability. The academic community already designed many RAW mechanism models, but none of them can be used for the scenario under consideration. We fill this gap. The contribution of our paper is three-fold:

- we first who consider the emergency alerts delivery scenario, where it is enough to receive an alert from any sensor,
- we develop an easy-to-calculate mathematical model for the considered scenario,
- we propose a method, based on the developed model, that allows selecting RAW parameters to minimize consumed channel timeshare.

The rest of the paper is organized as follows. Section II presents and explains details of channel access within the RAW. Section III reviews related works. We state the problem and develop the model in Section IV. In Section V, we describe the numerical results obtained with the model. Section VI concludes our work. For the description of any abbreviation, please refer to Table 1.

II. CHANNEL ACCESS

The main goal of the RAW mechanism is to reduce the number of STAs trying to access the wireless channel simultaneously. Using this mechanism, the AP determines a time interval called RAW and selects a set of the STAs that are allowed to transmit in this RAW. To minimize contention even further, the AP splits the STAs into groups and divides the RAW into slots, each slot being assigned to a single group. In this way, transmission attempts of the selected set of STAs are spread over all slots of the RAW.

TABLE 1. Table of abbreviations.

Abbreviation	Explanation
IoT	Internet of Things
RAW	Restricted Access Window
TWT	Target Wake Time
AP	Access Point
STA	Station
PRAW	Periodic Restricted Access Window
EDCA	Enchanced Distributed Channel Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
GS-DCF	Group-Synchronized Distributed Channel Function
QoS	Quality of Service

The AP notifies the associated STAs about currently established RAWs by sending RAW parameters in beacon frames. In particular, the beacons contain information about the division of STAs into groups, the time instant of the RAW beginning, and channel access parameters inside RAW. To decrease the advertisement overhead, the AP may set up a periodic RAW (PRAW) operation. When PRAW is enabled, RAWs are repeated within a predefined period T_{per}. Assigning PRAW efficiently grants the corresponding set of STAs a share of the available channel time.

Inside RAW slots, the STAs use the default Wi-Fi channel access method called Enhanced Distributed Channel Access (EDCA), which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with a binary exponential backoff. It means that before the transmission attempt, each STA initiates a backoff counter with a random value, uniformly distributed on the interval called Contention Window. The STA decrements the backoff counter after other STA transmissions or if the channel is idle during the backoff slot time T_{e} defined in the Wi-Fi HaLow standard [2]. Finally, the STA makes a transmission attempt when the backoff counter reaches zero. If more than one STA transmit simultaneously, their transmissions collide, and the STAs double the Contention Window for the retransmission backoff countdown. The detailed description of the EDCA algorithm can be found in the Wi-Fi standard [15]. However, we should highlight the peculiarities of the EDCA usage with the RAW mechanism.

The STA uses two EDCA state machines, which may have different parameters: the first one is for general use, the second is for channel access inside the RAW specifically. At the beginning of the allocated RAW slot, the STA freezes the first EDCA state machine and switches to the second one. As contention conditions inside and outside RAW are different, the EDCA algorithm inside the RAW starts with the minimal contention window. After RAW ends, the STA resets its second EDCA state machine and returns to the first one.

The STA behavior at the RAW slot end depends on the cross-slot boundary option of the RAW mechanism. If the cross-slot boundary option is disabled, then a STA is allowed to start a transmission attempt only within the allocated RAW slot, and only if the corresponding frame exchange sequence ends before the RAW slot end. In the opposite case, the STA is allowed to either transmit at the RAW slot boundary or count down the backoff counter and make one transmission attempt in the following RAW slot. In the paper, we consider the RAW mechanism with the cross-slot boundary option disabled.

III. RELATED WORKS

RAW has already attracted significant attention from academia even before the release of the IEEE 802.11ah standard [2]. Many of them consider the saturated traffic [5]–[10].

The authors of [5] build a mathematical model that allows estimating throughput and energy efficiency if the collision probability is known. The paper [5] confirms that the RAW mechanism allows improving the network performance in case of high contention for the channel. The authors of [6] compare default and cross-slot boundary modes of the RAW mechanism showing that there is the tradeoff between throughput and energy consumption. The tradeoff follows from the opportunity to either enable or disable the cross-slot boundary mode.

Papers [7], [8] consider the RAW mechanism as a Group-Synchronized DCF (GS-DCF) channel access method. They examine different STA grouping schemes, enabled and disabled cross-slot boundary mode, and various options for the backoff counter behavior at the holding period. The *holding period* in the context of [8], [9] is the time interval at the RAW slot end when the STA cannot make a transmission without crossing the RAW slot boundary and should hold the transmission until the next available RAW slot. More options for the backoff counter behavior at the holding period are proposed in the paper [9], which also presents simulation results for the GS-DCF mechanism with 1000 STAs. Finally, the authors of the paper [10] use the model similar to the model described in [7], [8]. They indicate that when groups are of different sizes, then appropriate adjusting of RAW slot duration according to the groups size increases the RAW mechanism performance.

Unfortunately, saturated traffic assumption does not fit our scenario of emergency alerts delivery. The papers [11], [13], [16]–[21] consider the non-saturated traffic as well. The paper [13] examines the scenario where sensors switch between regular and emergency reporting, and the channel access mechanism automatically adjusts the behavior according to the reporting state estimation. We should note, however, that the authors of [13] consider ALOHA-based channel access [22] instead of EDCA. The paper [16] also does not consider EDCA. Instead, the authors of [16] consider the RAW mechanism with a proprietary retransmission scheme. Specifically, they present a retransmission algorithm that allows avoiding the channel time waste by reusing empty RAW slots. They also propose an algorithm to improve energy efficiency by adjusting the RAW slot duration.

Unlike [13], [16], the authors of [11], [17]–[21] analyze the EDCA operation inside RAW. The paper [17] presents the model that allows finding the proper RAW slot duration for the reliable delivery of machine-to-machine traffic. The paper [18] consider the same scenario of machine-to-machine traffic delivery, but pays primary attention to the energy consumption problem. In particular, the authors of [18] present a model that allows predicting battery lifetime. The authors of [19] conclude that in case of a high load, to avoid long transmission delay, the RAW mechanism should be complemented with so-called common contention period, where all devices are allowed to transmit. The model presented in [19] is further developed in [11]: the authors of [11] examine different EDCA access categories within one RAW slot. The authors of [20] confirm that the RAW mechanism has much better performance than the legacy EDCA. The paper [21] presents a traffic-aware approach for increasing the overall network energy efficiency by controlling the device grouping.

Sadly, none of the models described above consider the **first** successful transmission, made by **any** of the STAs. As this is important for our scenario of emergency alerts delivery, none of those models can be used. Our goal is to develop an analytical model that can be used for the optimization of RAW parameters in the emergency alerting scenario. As we show in Section IV-B, the model from the paper [17] can be adapted for the scenario under consideration. The adapted model takes into account the Contention Window doubling and retries. However, the computational complexity of the adapted model is too high. As we discuss in Section V-A, it takes too long to compute the model on typical hardware available at the AP. Therefore, the model can be hardly applied for the online dynamic reconfiguration of the RAW mechanism. If the number of active STAs is not large in our scenario, then with very high probability, the successful alert delivery happens on the first transmission attempt of some emergency sensor. Thus we can model EDCA assuming that STAs do not try to retransmit, e.g. like in the IEEE 802.11p VANET. This assumption allows a noticeable reduction of the analytical model computational complexity, thus allowing the AP to compute the model on-the-fly. Computing on-the-fly allows the AP to dynamically select the optimal RAW mechanism parameters, i.e., those parameters that minimize the consumed channel timeshare while satisfying given constraints on the alert delivery reliability and delay. We present a model with *no-retries* assumption in Section IV-A. We compare the proposed model and adapted model from [17] in Section V-A.

IV. TWO ANALYTICAL MODELS

We consider a group of M STAs that monitor the emergency event and transmit alerts in the uplink channel within PRAW, where the duration of each RAW is T_{R}, each RAW consists of N_{slot} RAW slots with duration $T_{\mathrm{slot}} = \frac{T_{\mathrm{R}}}{N_{\mathrm{slot}}}$, and RAWs follow with period T_{per} (see Fig. 1). We assume that the alert delivery processes corresponding to several emergency events do not overlap. Each STA detects the occurred emergency event with probability p independently from the others and tries to send a frame containing the information about the event within the upcoming RAW. If the emergency event occurs during the

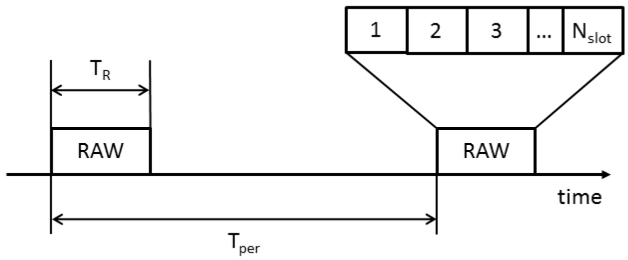

FIGURE 1. Illustration of PRAW.

RAW slot, the STA waits for the next RAW. If the packet is not delivered in the closest RAW, it is retransmitted in the next RAW. The AP waits for the first frame with the information about the emergency event, no matter which STA sends it.

As our primary goal is to study the performance of the channel access mechanism, we assume that there is no channel noise, no capture effect, and no hidden terminals. Note that the literature describes many approaches that can be used with the RAW mechanism to mitigate the hidden terminals problem, for example, [23], [24].

We further use the concept of **virtual slot** that is an interval of time between consecutive decrements of backoff counter [25]. The duration of the virtual slot depends on whether STAs make a transmission attempt or not. If nobody transmits in a virtual slot, then it is an empty slot with duration T_e. If only one STA makes a transmission attempt in a virtual slot, this attempt is always successful as we consider the ideal channel, the corresponding virtual slot is successful, and its duration is T_s. If more than one STA make transmission attempts simultaneously, their transmissions collide, and the corresponding virtual slot is a collision slot with duration T_c. We assume that all data frames are of equal length, so T_s and T_c do not depend on the transmitter.

Our goal is to develop an analytical model that can be used to calculate the probability of at least one successful transmission within the time limit $T_{\lim}$. That is, the AP receives information about the emergency event with the delay D no more than the time limit $T_{\lim}$. The model can be used to determine the optimal parameters of RAW and EDCA mechanisms, such as the duration of the RAW, the number of RAW slots, the period of PRAW, and the initial size of the contention window, that allow the emergency alert delivery within time limit $T_{\lim}$ with probability no less than q_{QoS}, which is a reliability restriction, with the minimal channel timeshare. We present two models, namely, the model without retries and the model with retries.

In Section IV-A, we develop a model for the transmissions without EDCA retries taken into account. It means that each data frame in a RAW slot may be transmitted only once, even if the RAW slot duration is enough for additional transmission attempts. If the frame is not delivered at the first transmission attempt, additional attempts may be triggered by the application in the next RAW slot. As we can see from the numerical results, such an assumption does not lead to a significant error with respect to the model for the transmissions with EDCA retries, which is provided in Section IV-B. Both models are developed in two steps. In the first step, we consider only one RAW slot and a known number of active STAs. Then we generalize both models for the whole RAW and a random number of active STAs.

A. MODEL WITHOUT RETRIES

Let us define vectors $\vec{n} = \left[n_1 \dots n_{N_{\text{slot}}}\right]$ and $\vec{M} = \left[M_1 \dots M_{N_{\text{slot}}}\right]$, where component n_l corresponds to the number of active STAs in the RAW slot $l \in [1 \dots N_{\text{slot}}]$ and component M_l corresponds to the number of all STAs in the RAW slot l. As the cross-slot boundary is disabled, transmissions in different RAW slots are independent, so we further consider a single RAW slot l with n_l active STAs.

In the absence of retries, the behavior of the system in a RAW slot l is determined by the initial values of backoff counters of all active STAs. Each STA independently of the others generates the initial value b of the backoff counter, uniformly distributed on the interval $[0, CW_0 - 1]$. The STA makes the first transmission attempt after b virtual slots. We consider the space of equiprobable events, where each event is a set of initial values of the backoff counter of all active STAs. The total number of such events is:

$$N_{\text{total}}(n_l) = (CW_0)^{n_l}. \tag{1}$$

The number of events $N(v, k, c, n_l)$ such that the first successful transmission occurs exactly in virtual slot #k (numbering from zero, i.e., after k empty and/or collision virtual slots) with c STAs involved into v collisions before the first successful transmission is:

$$N(v,k,c,n_l) = n_l \binom{n_l-1}{c} (CW_0-k-1)^{n_l-1-c} \binom{k}{v} V(v,c). \tag{2}$$

Here n_l is the number of ways to choose a STA that transmits in the first successful slot, $\binom{n_l-1}{c}$ is the number of ways to choose c collided STAs from the remaining $n_l - 1$ STAs, $(CW_0 - k - 1)^{n_l-1-c}$ is the number of ways to place the rest $n_l - 1 - c$ STAs after the first successful transmission, $\binom{k}{v}$ is the number of ways to choose v collision slots from k virtual slots before the successful transmission, $V(v, c)$ is the number of ways to allocate c collided STAs in v collision slots. $V(v, c)$ is derived in [26]:

$$V(v,c) = \begin{cases} 0, & \text{if } c < 2v, \\ 1, & \text{if } v = 1, c > 2, \\ v^c - \sum_{y=1}^{v-1} \binom{v}{y} V(y,c) - \\ \quad \sum_{u=1}^{v-1} \binom{v}{u} \frac{c!}{(c-u)!} \times \\ \quad \sum_{y=1}^{v-u} \binom{v-u}{y} V(y,c-u), & \text{otherwise.} \end{cases} \tag{3}$$

The number of events $L(v, k, n_l)$ such that the first successful transmission occurs in the virtual slot number k with v collision slots before slot k is:

$$L(v, k, n_l) = \sum_{c=2v}^{n_l-1} N(v, k, c, n_l). \tag{4}$$

As before the first successful transmission, there are v collision slots and $k - v$ empty slots, then time T_f passed from the beginning of the RAW slot to the end of the first successful transmission is:

$$T_f(k, v) = (k - v)T_e + vT_c + T_s. \tag{5}$$

Taking into account a limited duration of the RAW slot, we find the number $N_{\text{succ}}(n_l)$ of events such that a successful transmission occurs within a RAW slot as follows:

$$N_{\text{succ}}(n_l) = \sum_{\substack{v \le k < CW_0 \\ T_f(k,v) \le T_{\text{slot}}}} L(v, k, n_l). \tag{6}$$

So, the probability of a successful transmission inside the RAW slot l equals:

$$P_{\text{succ}}(n_l) = \frac{N_{\text{succ}}(n_l)}{N_{\text{total}}(n_l)}. \tag{7}$$

The average number of RAWs without successful transmission in a RAW slot l that precede the RAW with successful transmission in a RAW slot l is:

$$N_R(n_l) = \frac{1 - P_{\text{succ}}(n_l)}{P_{\text{succ}}(n_l)}. \tag{8}$$

The average time $\langle T_f \rangle$ passed from the beginning of the RAW slot l to the end of the first successful transmission inside the RAW slot l with a successful transmission can be calculated as follows:

$$\langle T_f \rangle(n_l) = \frac{1}{N_{\text{succ}}(n_l)} \sum_{\substack{v \le k < CW_0 \\ T_f(k,v) \le T_{\text{slot}}}} T_f(k, v) L(v, k, n_l). \tag{9}$$

Since the emergency events happen independently from the sequence of RAWs, we can assume that the time passed since the emergency event till the beginning of any RAW slot is distributed uniformly within the interval $[0; T_{\text{per}})$. Then the average delay $\langle D \rangle$ until the first successful transmission within RAW slot l is:

$$\langle D \rangle(n_l) = \left(\frac{1}{2} + N_R(n_l)\right) T_{\text{per}} + \langle T_f \rangle(n_l). \tag{10}$$

The probability $\mathbb{P}^{\text{slot}}(D \le T_{\text{lim}}; n_l, l)$ that the first successful transmission within RAW slot l happens before the time limit T_{lim} can be found as:

$$\mathbb{P}^{\text{slot}}(D \le T_{\text{lim}}; n_l, l) = \sum_{i=0}^{\left\lfloor \frac{T_{\text{lim}}}{T_{\text{per}}} \right\rfloor} (1 - P_{\text{succ}}(n_l))^i \times \sum_{\substack{v \le k < CW_0 \\ T_f(k,v) \le T_{\text{slot}}}} \frac{L(v, k, n_l)}{N_{\text{total}}(n_l)} \mathbb{P}(D \le T_{\text{lim}} | k, v, l, i), \tag{11}$$

where

$$\mathbb{P}(D \le T_{\text{lim}} | k, v, l, i) = \begin{cases} 1, & \text{if } T_{\text{lim}} - iT_{\text{per}} - (l-1)T_{\text{slot}} - T_f(k, v) \ge T_{\text{per}}, \\ 0, & \text{if } T_{\text{lim}} - iT_{\text{per}} - (l-1)T_{\text{slot}} - T_f(k, v) \le 0, \\ \dfrac{T_{\text{lim}} - iT_{\text{per}} - (l-1)T_{\text{slot}} - T_f(k, v)}{T_{\text{per}}}, & \text{otherwise,} \end{cases} \tag{12}$$

is the conditional probability that the first successful transmission occurs before the time limit T_{lim} under the condition that this transmission is made in a RAW slot l after i RAWs with unsuccessful RAW slot l, and there are v collision slots and $k - v$ empty slots before the successful transmission in the successful RAW slot l.

Now let us consider the whole RAW and a random number of active STAs. The probability $\mathbb{P}(\vec{n})$ that the numbers of reacted sensors are $\vec{n} = [n_1 \ldots n_{N_{\text{slot}}}]$ is:

$$\mathbb{P}(\vec{n}) = \prod_{l=1}^{N_{\text{slot}}} \binom{M_l}{n_l} p^{n_l} (1-p)^{M_l - n_l} = p^{|\vec{n}|} (1-p)^{M - |\vec{n}|} \prod_{l=1}^{N_{\text{slot}}} \binom{M_l}{n_l}, \tag{13}$$

where $|\vec{n}| = \sum_{l=1}^{N_{\text{slot}}} n_l$. Then the probability that the first successful transmission attempt happens before the time limit T_{lim} is:

$$\mathbb{P}(D \le T_{\text{lim}}) = \sum_{\vec{n}} \mathbb{P}(\vec{n}) \left(1 - \prod_{l=1}^{N_{\text{slot}}} \left(1 - \mathbb{P}^{\text{slot}}(D \le T_{\text{lim}}; n_l, l)\right)\right), \tag{14}$$

where we sum up over all $\vec{n}$ which satisfy condition $0 \le n_l \le M_l \quad \forall 1 \le l \le N_{\text{slot}}$.

B. MODEL WITH RETRIES

For the default access method with retries, the analytical model is proposed in [17]. For consistency, we repeat the previous findings and extend them. The paper [17] considers a scenario where each STA has only one frame to transmit in a RAW slot. Each STA can make at most RL (Retry Limit) transmission attempts. The scenario is modeled using two stochastic processes: process A and process B. The model allows us to find the distribution of time needed for an arbitrarily chosen STA to successfully deliver the frame, and for all STAs to successfully deliver their frames.

Process A describes the behavior of an arbitrarily selected STA and is a Markov chain with states $(e, s, c, r)_t$, where t is the number of virtual slots that have passed since the beginning of RAW slot, e, s and c are the numbers of empty, collision and successful virtual slots, r is the value of retry counter. Process B describes the behavior of STAs in the aggregate and is a Markov chain with states $(e, s, c)_t$, where t, e, s, and c have the same meaning as in process A.

The authors of paper [17] derive the formula for probability $\mathbb{P}(TX | r, t)$ of transmission of an arbitrarily selected STA in

TABLE 2. Transition probabilities for Process A.

from	to	probability
$(e, s, c, r)_t$	$(e, s, c, r)_{t+1}$	Π_e
$(e, s, c, r)_t$	absorbing state	Π_s^+
$(e, s, c, r)_t$	$(e, s+1, c, r)_{t+1}$	Π_s^-
$(e, s, c, r)_t$, $r+1 \neq RL$	$(e, s, c+1, r+1)_{t+1}$	Π_c^+
$(e, s, c, r)_t$, $r+1 = RL$	absorbing state	Π_c^+
$(e, s, c, r)_t$	$(e, s, c+1, r)_{t+1}$	Π_c^-

TABLE 3. Transition probabilities for Process B.

from	to	probability
$(e, s, c)_t$	$(e+1, s, c)_{t+1}$	$\hat{\Pi}_e$
$(e, s, c)_t$	$(e, s+1, c)_{t+1}$	$\hat{\Pi}_s$
$(e, s, c)_t$	$(e, s, c+1)_{t+1}$	$\hat{\Pi}_c$

virtual slot t under the condition that the STA has not finished transmission process yet and its retry counter equals r. They also derive a formula for probability $\mathbb{P}(TX|t, e, s, c)$ of transmission of any STA in virtual slot t under the condition that there is a STA that has not finished transmission process yet, and overall there were e empty, s successful and c collision virtual slots in a RAW slot. Next, they derive transition probabilities for both processes.

For process A, the transition probabilities are present in Table 2, where:

- $\Pi_e = (1 - \mathbb{P}(TX|r, t))(1 - \mathbb{P}(TX|t, e, s, c))^{n_l - s - 1}$ is the probability that no station transmits in a virtual slot t,
- $\Pi_s^+ = \mathbb{P}(TX|r, t)\,(1 - \mathbb{P}(TX|t, e, s, c))^{n_l - s - 1}$ is the probability that an arbitrarily selected STA transmits successfully in virtual slot t,
- $\Pi_s^- = (1 - \mathbb{P}(TX|r, t))(n_l - s - 1)\mathbb{P}(TX|t, e, s, c)\times$ $\times\,(1 - \mathbb{P}(TX|t, e, s, c))^{n_l - s - 2}$ is the probability that virtual slot t contains successful transmission that is made not by the selected STA,
- $\Pi_c^+ = \mathbb{P}(TX|r, t) - \Pi_s^+$ is the probability that virtual slot t contains collision that involves the selected STA,
- $\Pi_c^- = (1 - \mathbb{P}(TX|r, t)) - \Pi_e - \Pi_s^-$ is the probability that virtual slot t contains collision that does not involve the selected STA.

Process A goes into the absorbing state whenever the selected STA successfully delivers the frame or drop the frame because of reaching the retry limit.

For process B, the transition probabilities are present in Table 3, where:

- $\hat{\Pi}_e = (1 - \mathbb{P}(TX|t, e, s, c))^{n_l - s}$ is the probability that no station transmits in virtual slot t,
- $\hat{\Pi}_s = (n_l - s)\mathbb{P}(TX|t, e, s, c)(1 - \mathbb{P}(TX|t, e, s, c))^{n_l - s - 1}$ is the probability that virtual slot t contains successful transmission,
- $\hat{\Pi}_c = 1 - \hat{\Pi}_e - \hat{\Pi}_s$ is the probability that virtual slot t contains collision.

The process B goes into the absorbing state when the time until the RAW slot end is not enough to make a transmission attempt. Let us introduce the time T_B passed from the beginning of the RAW slot to the moment that corresponds to the Markov chain state (e, s, c):

$$T_B(e, s, c) = eT_\mathrm{e} + sT_\mathrm{s} + cT_\mathrm{c}. \tag{15}$$

So, the set of process B absorbing states is just $\{(e, s, c) : T_\mathrm{slot} - T_\mathrm{s} < T_B(e, s, c) \leq T_\mathrm{slot}\}$.

Here we end describing the model from [17] and begin adapting this model to the alert delivery scenario. The main difference of adapted model is another absorbing states. The following set of absorbing states corresponds to the event that RAW slot ended before any successful transmission happened:

$$\Omega_{end} = \{(e, s, c) : s = 0,\, T_\mathrm{slot} - T_\mathrm{s} < T_B(e, s, c) \leq T_\mathrm{slot}\}. \tag{16}$$

The following set of absorbing states corresponds to the event that one successful transmission happened before the end of the RAW slot:

$$\Omega_{del} = \{(e, s, c) : s = 1,\, T_B(e, s, c) \leq T_\mathrm{slot}\}. \tag{17}$$

Then the new set of absorbing states for the process B is just $\Omega_{abs} = \Omega_{del} \cup \Omega_{end}$. The probability of at least one successful frame delivery is:

$$P_\mathrm{succ}(n_l) = \sum_{\Omega_{del}} \mathbb{P}(e, s, c), \tag{18}$$

where $\mathbb{P}(e, s, c)$ is the probability that process B ends up in the absorbing state (e, s, c).

The average time passed from the beginning of the RAW slot to the first successful transmission inside the RAW slot with a successful transmission can be calculated as follows:

$$\langle T_f \rangle (n_l) = \frac{\sum\limits_{\Omega_{del}} \mathbb{P}(e, s, c) T_B(e, s, c)}{\sum\limits_{\Omega_{del}} \mathbb{P}(e, s, c)}. \tag{19}$$

We can use (10) to find the average delay $\langle D \rangle$. The probability $\mathbb{P}^\mathrm{slot}(D \leq T_\mathrm{lim}; n_l, l)$ can be found as follows:

$$\mathbb{P}^\mathrm{slot}(D \leq T_\mathrm{lim}; n_l, l) = \sum_{i=0}^{\left\lfloor \frac{T_\mathrm{lim}}{T_\mathrm{per}} \right\rfloor} (1 - P_\mathrm{succ}(n_l))^i \times \sum_{\Omega_{del}} \mathbb{P}(e, s, c)\mathbb{P}(D \leq T_\mathrm{lim}|e, s, c, l, i), \tag{20}$$

where

$$\mathbb{P}(D \leq T_\mathrm{lim}|e, s, c, l, i) = \begin{cases} 1, & \text{if } T_\mathrm{lim} - iT_\mathrm{per} - (l-1)T_\mathrm{slot} - T_B(e, s, c) \geq T_\mathrm{per}, \\ 0, & \text{if } T_\mathrm{lim} - iT_\mathrm{per} - (l-1)T_\mathrm{slot} - T_B(e, s, c) \leq 0, \\ \dfrac{T_\mathrm{lim} - iT_\mathrm{per} - (l-1)T_\mathrm{slot} - T_B(e, s, c)}{T_\mathrm{per}}, & \text{otherwise.} \end{cases} \tag{21}$$

The probability $\mathbb{P}(D \leq T_\mathrm{lim})$ can be found using (14).

TABLE 4. Scenario parameters.

Parameter	Description	Values
T_{R}	RAW duration	$\mathbb{R}^{+}$
T_{per}	RAW period	$\mathbb{R}^{+}$
$\frac{T_{\mathrm{R}}}{T_{\mathrm{per}}}$	Consumed channel timeshare	$\mathbb{R}^{+}$
CW_0	Initial Contention Window size	$\mathbb{N}$
T_{lim}	Frame delay budget	$\{10, 20\}ms$
q_{QoS}	QoS requirement on the frame delivery reliability	$\{0.75, 0.9, 0.95, 0.99\}$
RL	EDCA retry limit	7
T_{s}	Duration of a successful virtual slot	$1064\mu s$
T_{c}	Duration of a collision virtual slot	$1064\mu s$
T_{e}	Duration of an empty virtual slot	$52\mu s$
p	Probability that the emergency event triggers transmission from an arbitrary chosen sensor	$\{\frac{1}{8}, \frac{1}{2}, 1\}$
M	Total number of emergency sensors	$\{5, 64, 40, 100\}$
N_{slot}	Number of RAW slots	$\{1, 2, 3, 4\}$

V. NUMERICAL RESULTS

In this section, we describe numerical results obtained with the models with and without retries. Section V-A compares the accuracy of the models with and without retries. In Section V-B, we study how to use RAW to minimize channel time allocated for a particular group of sensors provided that the requirement on the alert delivery delay is satisfied. Channel time consumption is an important metric: the lower is channel time consumption, the more devices apart from the considered emergency sensors can work in the heterogeneous Wi-Fi HaLow network. Apart from that, Wi-Fi HaLow supports high rate data transmission, and the lower is channel time consumption for the emergency sensor slice, the more resources can be used for transmitting broadband traffic, such as files or video. Thus, Section n V-B presents the results related to the minimization of consumed channel timeshare $\frac{T_{\mathrm{R}}}{T_{\mathrm{per}}}$, i.e., the percentage of consumed channel time, over system parameters, such as initial contention window CW_0, RAW duration T_{R}, number of RAW slots N_{slot}, and PRAW period T_{per} with restrictions on emergency alert delivery delay T_{lim} and reliability q_{QoS}. As in [6], we consider STAs that transmit 100 byte frames with the Modulation and Coding Scheme (MCS) 8 in a 2 MHz channel, with short guard intervals and nominal PHY rate of $\approx$ 8.7 Mbps. For the approach adopted from [17] we use EDCA retry limit $RL = 7$. We assume that the RTS/CTS mechanism is not used, so the durations of successful and collision slots are $T_{\mathrm{s}} = T_{\mathrm{c}} = 1064\mu s$, respectively. The duration of backoff slot $T_{\mathrm{e}} = 52\mu s$ is taken from the standard [2]. For the description of any scenario parameter, please refer to Table 4.

A. COMPARISON

Figs. 2 and 3 present comparison results between models with and without retries. Please note that the model with retries has

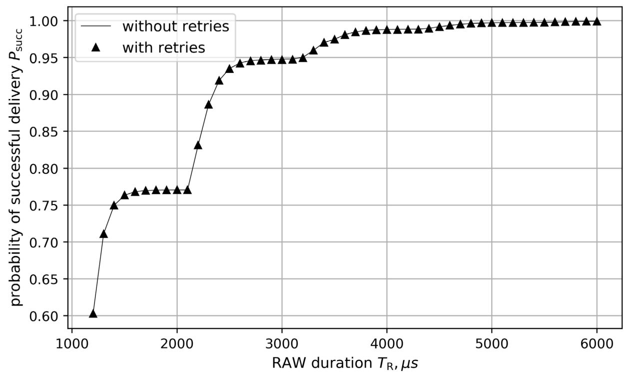

FIGURE 2. Probability of successful delivery in a RAW slot depending on T_{R}; $M = 64$ STAs, $p = 1$, $T_{\mathrm{per}} = 10\ T_{\mathrm{R}}$, $CW_0 = 128$.

been validated using NS-3 [27] in [17]. We consider $M = 64$ emergency sensors allocated to one group. All sensors react to the emergency event, i.e., $p = 1$. The channel access mechanism uses $CW_0 = 128$ as a Contention Window initial size. Fig. 2 shows how the probability of successful delivery P_{succ} depends on the RAW slot duration. The longer is the RAW slot, the higher is the probability. The steps on the graph correspond to the RAW slot duration values, where the RAW slot becomes long enough to contain one more transmission attempt.

Fig. 3 shows how the average delay $\langle D \rangle$ depends on the RAW slot duration and the PRAW period, when channel timeshare is fixed at the value $\frac{T_{\mathrm{R}}}{T_{\mathrm{per}}} = 0.1$. The delay mostly increases when the RAW slot duration is high as for a long RAW slot, P_{succ} is very close to 1, so only one RAW is needed, but PRAW period increases. For small values of the RAW slot duration, we notice two local minimums. These minimums correspond to the steps in Fig. 2. When the RAW slot duration slightly grows, such that there appears an opportunity to make an additional transmission attempt, the probability of delivering a frame within the RAW slot significantly increases, but at the same time the PRAW period does not change too much, so the average number of RAWs required to deliver the frame decreases, and the delivery delay decreases, too. When the RAW slot duration increases such that no additional transmission attempts can be made, the probability to successfully deliver the frame grows slowly, and the average number of RAWs required to deliver the frame remains nearly the same, so because the PRAW period grows, the delivery delay grows, too.

The presented results show that the probability of successful delivery (on Fig. 2) and average delay before the first successful delivery (on Fig. 3) are almost the same for both models. This empirical result means that the first successful alert delivery happens on the first transmission attempt of some emergency sensor with a rather high probability, the exact value of which definitely depends on the number of contending STAs and the initial contention window size. We must also notice the obvious advantage of the model

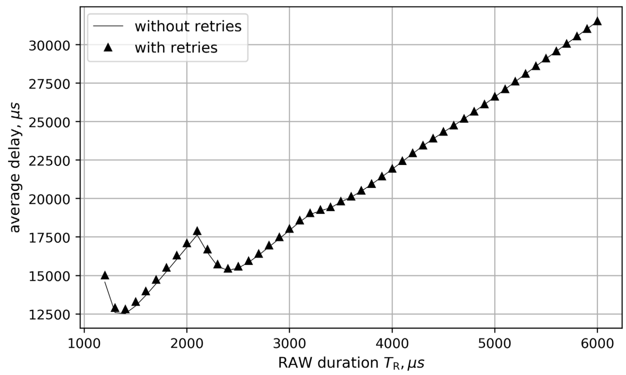

FIGURE 3. Average delay before the first successful transmission depending on T_R; $M = 64$ STAs, $p = 1$, $T_{per} = 10\ T_R$, $CW_0 = 128$.

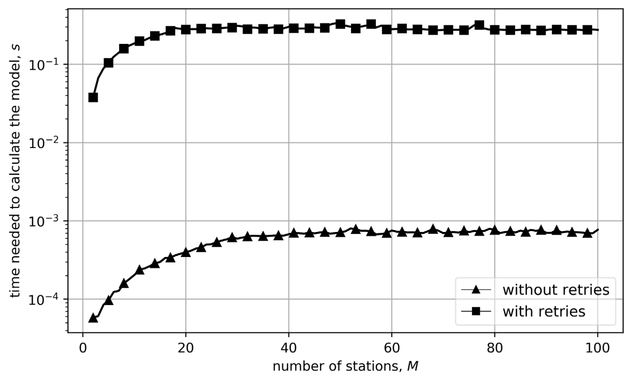

FIGURE 4. Time needed to calculate model depending on number of emergency sensors.

without retries: while the model with retries requires the calculation of all probabilities to end up in the absorbing state of the Markov chain, the model without retries does not require such heavy computations. Moreover, with the model without retries, it is possible to use precached array $L(v, k, n)$ to increase the speed of calculations. Fig. 4 presents the comparison of computation times of both models. It shows how computation time depends on the number of emergency sensors. Time measurements were done using a single core of a non-over-clocked Intel Core i7-7700HQ processor. As we can see in Fig. 4, the model without retries requires more than 100 times less time for computations compared to the model with retries.

So, the model without retries allows us to calculate the same results with the same accuracy as the model with retries, but as it requires much less time, the model without retries can be used for on-the-fly optimization of the RAW mechanism parameters.

B. OPTIMIZATION

Let us discuss results related to the minimization of consumed channel timeshare with a given number of emergency sensors M. To minimize the consumed channel timeshare we solve the following optimization problem:

$$\min_{T_{per}, T_R, N_{slot}, CW_0} \frac{T_R}{T_{per}}, \quad \text{s.t.} \quad \mathbb{P}(D \le T_{lim}) \ge q_{QoS}, \tag{22}$$

where $\mathbb{P}(D \le T_{lim})$ can be found using (14). However, for further analysis we fix part of optimization variables $\{T_{per}, T_R, N_{slot}, CW_0\}$, performing optimization over the rest. As emergency alerts need to be delivered fastly and reliably, we considered the following constraints on delivery delay: the alert shall be delivered to the AP with delay less than $T_{lim} = 10ms$ with probability P_{lim} no less than reliability bound $q_{QoS} = 0.75, 0.9, 0.95, 0.99$. At first, we consider case $p = 1$, i.e., any emergency event triggers all sensors, and $N_{slot} = 1$, i.e., no RAW splitting.

Figs. 5 and 6 show the dependency of the consumed channel timeshare, minimized over RAW duration T_R and PRAW period T_{per}, on the Contention Window for different constraints q_{QoS} on delivery reliability and different fixed number of active STAs $M = 5$ and $M = 40$. The lower is q_{QoS}, the lower is the channel timeshare consumption.

For a small number of STAs $M = 5$, the optimal CW_0 is small, around $10 \ldots 25$ for different q_{QoS}, see Fig 5. For CW_0 lower than optimal, the consumed channel timeshare is large because due to small CW_0, channel contention is high, and the probability to transmit successfully within RAW slot is small, so we need more frequent RAWs. If CW_0 is too large, then STAs try to make transmission attempts too rarely, so again we need more frequent RAWs.

For a larger number of STAs, such as $M = 40$, see Fig. 6, the optimal CW_0 is also larger, around 100 for $q_{QoS} = 0.75$ and around 200 for $q_{QoS} = 0.99$. That increase happens because a larger number of STAs create higher contention for the channel, so they require larger CW_0 to reduce the contention.

For any $CW_0 \in [100; 250]$ and fixed q_{QoS}, the consumed channel timeshare is almost the same, in contrast to Fig. 5 where we see a sharp increase for CW_0 bigger than optimal. To explain this, let us notice that for a large CW_0, the probability of transmission can be roughly estimated as $1 - \left(1 - \frac{1}{CW_0}\right)^M \approx \frac{M}{CW_0}$. But in Figs. 5 and 6 for the same CW_0 this probability is of different orders: for $M = 40$, it is 8 times bigger than for $M = 5$. So, on both Figs we observe similar behavior, but on different scales. As the contention window $CW_0 = 250$ is too high for $M = 5$ STAs, the probability of transmission attempt is very low, so STAs almost do not transmit, the consumed channel timeshare is large and it is wasted. For $M = 40$, the transmission probability is larger, that is why the consumed channel timeshare is not increasing sharply; similar behavior can be seen on Fig. 5 for lower $CW_0 \in [25; 50]$.

Figs. 7 and 8 show the dependency of the consumed channel timeshare minimized over T_R and CW_0 on the PRAW period for different constraints q_{QoS} on delivery delay and different fixed number of active STAs. Figs. 9 and 10 show

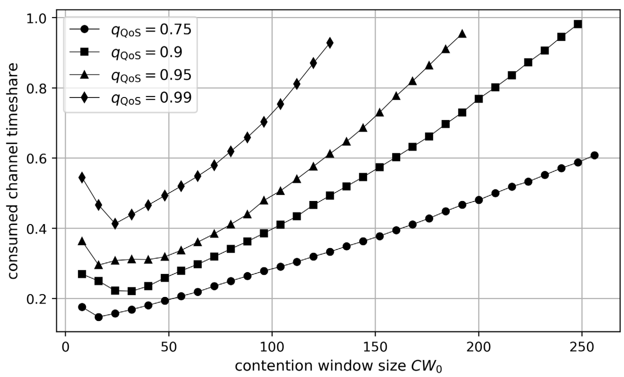

FIGURE 5. Minimal consumed channel timeshare depending on CW_0; $M = 5$ STAs, $p = 1$, delay budget $T_{\text{lim}} = 10$ ms.

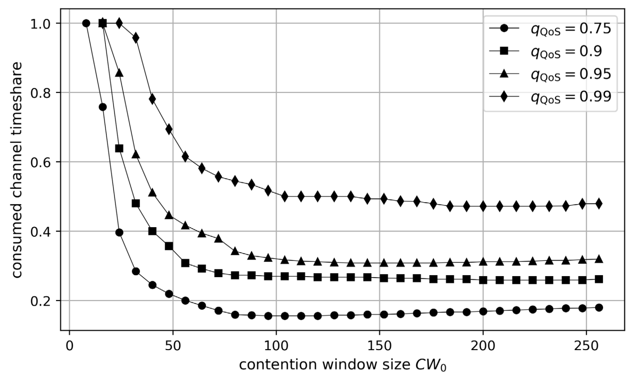

FIGURE 6. Minimal consumed channel timeshare depending on CW_0; $M = 40$ STAs, $p = 1$, delay budget $T_{\text{lim}} = 10$ ms.

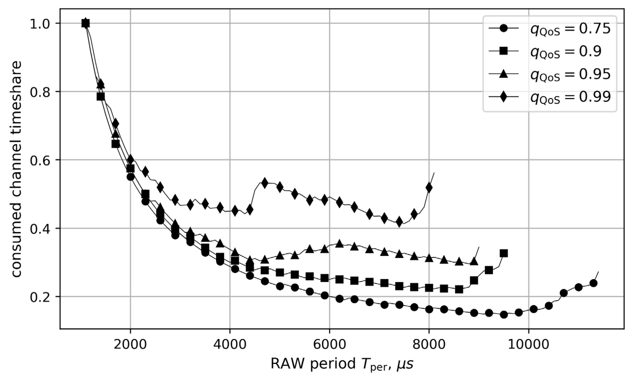

FIGURE 7. Minimal consumed channel timeshare depending on T_{per}; $M = 5$ STAs, $p = 1$, delay budget $T_{\text{lim}} = 10$ ms.

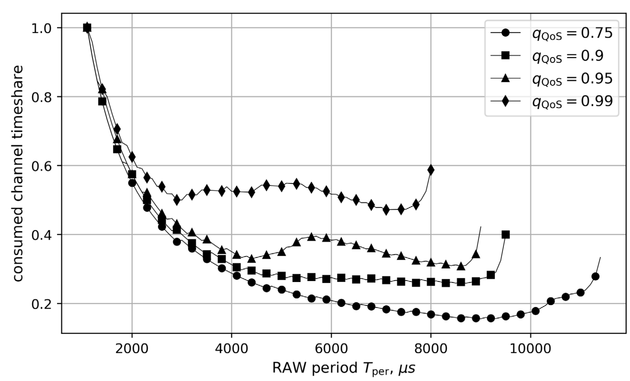

FIGURE 8. Minimal consumed channel timeshare depending on T_{per}; $M = 40$ STAs, $p = 1$, delay budget $T_{\text{lim}} = 10$ ms.

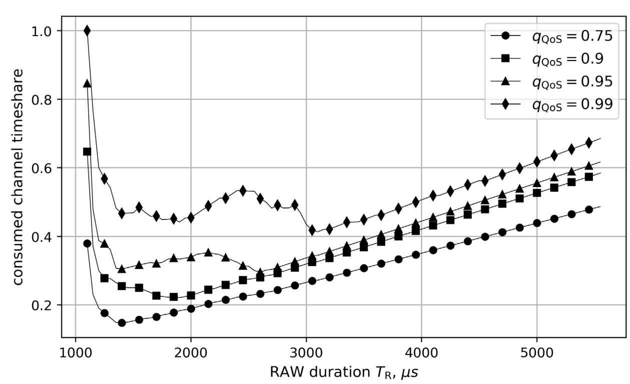

FIGURE 9. Minimal consumed channel timeshare depending on T_R; $M = 5$ STAs, $p = 1$, delay budget $T_{\text{lim}} = 10$ ms.

the dependency of the consumed channel timeshare minimized over T_{per} and CW_0 on the RAW duration for different constraints on delivery delay and a different fixed number of active STAs. For high-reliability restrictions q_{QoS}, there appears two or more local minimums with close values of the consumed channel timeshare. So, in some cases, we can balance the RAW duration and the RAW period. For example, we can choose more frequent but less long RAWs, thus exchanging higher probability to succeed within one RAW for a larger frequency of attempts to try again in the next RAW. The rationale behind this choice may be, for example, the desire to lower the channel time fragmentation or adjusting the frequency of RAW for alert sensors according to the frequency of other RAWs.

We may not know in advance how many STAs an emergency event will trigger, so we consider the case when the number of transmitting STAs is random. Figs. 11, 12, and 13 present the results for binomial distribution of the number of active STAs. We consider a network with $M = 40$ sensors that can detect and react to the emergency event. Each sensor reacts on the emergency event with probability $p = \frac{1}{8}$, so the average number of active STAs is $Mp = 5$.

Comparing with results from Figs. 5, 7 and 9 related to the same number of active STAs $M = 5$, we see that the dependencies are similar, but with the following differences. The consumed channel timeshare is higher in case of the random number of STAs because for the random number of STAs, it is harder to satisfy the delay and reliability constraints as the same set of RAW and EDCA parameters is used for a different number of active STAs. However, we still see 2 local minimums on the graphs for T_R and T_{per}, i.e., the tradeoff between RAWs frequency and RAW duration still exists.

Finally, let us study whether we need to split the RAW into slots. Consider the case with several RAW slots. Fig. 14

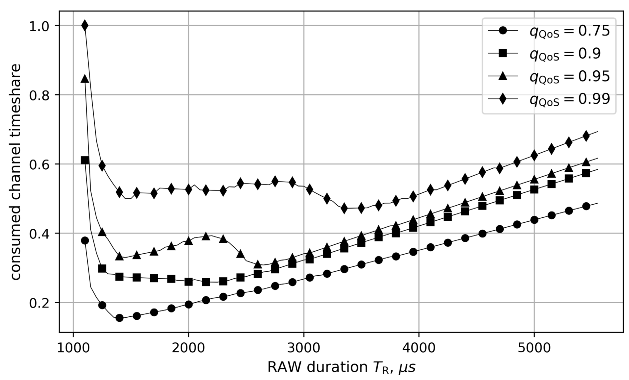

FIGURE 10. Minimal consumed channel timeshare depending on T_R; $M = 40$ STAs, $p = 1$, delay budget $T_{lim} = 10$ ms.

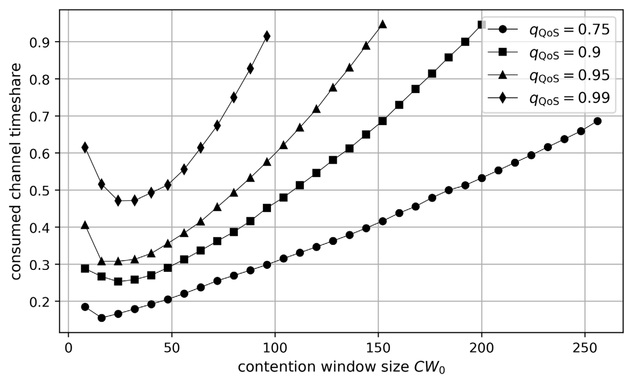

FIGURE 11. Minimal consumed channel timeshare depending on CW_0; $M = 40$ STAs, $p = \frac{1}{8}$, delay budget $T_{lim} = 10$ ms.

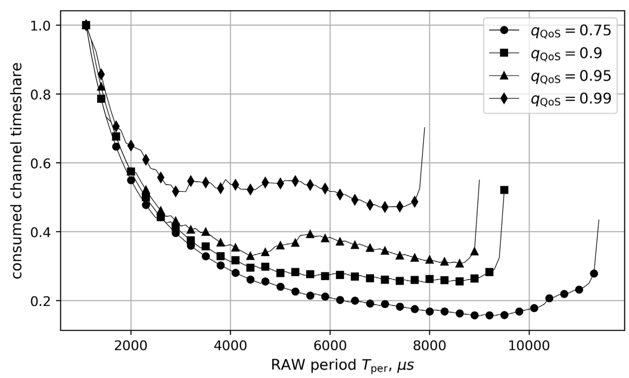

FIGURE 12. Minimal consumed channel timeshare depending on T_{per}; $M = 40$ STAs, $p = \frac{1}{8}$, delay budget $T_{lim} = 10$ ms.

shows results for $M = 100$ STAs, probability that the emergency event triggers the transmission $p = \frac{1}{2}$, time limit on the alert delivery $T_{lim} = 20ms$ and reliability bounds $q_{QoS} = 0.75, 0.9, 0.95, 0.99$. We consider equal RAW slots and groups of equal size. For N_{slot} groups there are $M \bmod N_{slot}$ groups of size $\lfloor M/N_{slot} \rfloor + 1$ and $N_{slot} - M \bmod N_{slot}$ groups of size $\lfloor M/N_{slot} \rfloor$.

On the one hand, splitting RAW reduces the duration of RAW slots (for fixed T_R) and thus decreases the successful alert delivery probability, efficiently shifting the working point in Fig. 2 from the distribution tail. On the other hand,

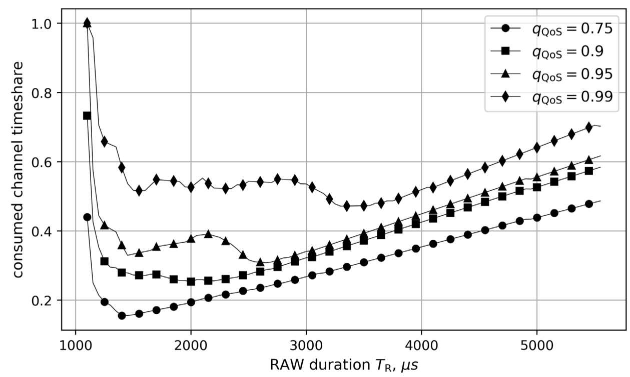

FIGURE 13. Minimal consumed channel timeshare depending on T_R; $M = 40$ STAs, $p = \frac{1}{8}$, delay budget $T_{lim} = 10$ ms.

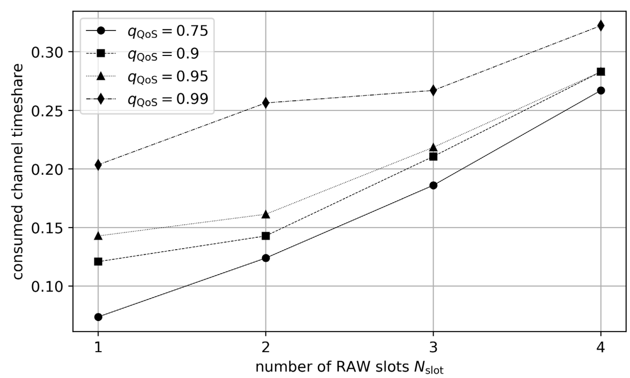

FIGURE 14. Minimal consumed channel timeshare depending on RAW slots number N_{slot}; $M = 100$ STAs, $p = \frac{1}{2}$, delay budget $T_{lim} = 20$ ms.

splitting RAW reduces the number of contending STAs within a RAW slot and the number of RAW slots where the alert can be delivered, which leads to increasing of successful alert delivery probability, efficiently shifting the distribution tail on Fig. 2 to the lower T_R. Fig. 14 shows that the first effect is more impactful: the larger is the number of RAW slots N_{slot}, the higher is the required channel timeshare.

VI. CONCLUSION

Emergency monitoring is one of the key industrial Internet of Things scenarios. To the best of our knowledge, this paper is the first to study using the IEEE 802.11ah RAW mechanism for fast and reliable emergency alert delivery, when we need to deliver data from at least one sensor. In the paper, we have proposed to model EDCA within RAW without retries. We compare models with and without retries and show that both the models have almost the same accuracy. However, the model without retries is much easier-to-calculate and provides better opportunities for dynamic optimization of RAW parameters (concerning minimization of the consumed channel timeshare). If the network serves several sensor systems with different requirements, RAW allows solving the resource allocation problem separately for each traffic.

We applied the designed model without retries for the optimization of channel access parameters. Obtained results show that in some cases, there is a tradeoff between the frequency of RAWs and RAW duration, which can be used with the rationale. Also, the results show that a large contention window results in low performance if the number of triggered sensors is relatively small. When the number of triggered sensors is random, more channel resource is required for the same requirements for delay and reliability of the alert delivery. Uniting all sensors into a single group appears to be more efficient than splitting them into several groups.

In future works, we are going to take into account the issues of a non-ideal channel, i.e., the hidden nodes problem and channel noise. In our paper, the impact of hidden nodes is not taken into account and obtained results show that single RAW group is more efficient than several groups, however, if hidden nodes are present in the network, they may significantly reduce the network performance [24], and RAW with several groups may be more efficient than RAW with one group. Also, we plan to consider different grouping strategies for a mixed set of STAs, where some sensors should deliver emergency alerts while satisfying QoS requirements, and other sensors transmit usual Machine-to-Machine traffic.

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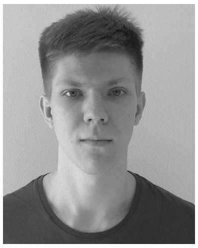

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