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RESEARCH ARTICLE

Load-Aware Channel Allocation for IEEE 802.11ah-Based Networks

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ABSTRACT Most wireless communication technologies for Internet of Things (IoT) applications face the bottleneck of dense and large-scale use cases. One solution to this problem is a periodic channel reservation strategy, in which only a small group of stations can compete for channel access during a given period. The IEEE 802.11ah standard, a.k.a. Wi-Fi HaLow, deploys this idea in its channel access protocol, named Restricted Access Window (RAW). A single RAW consists of one or more RAW slots during which only designated stations can contend for channel access. This paper considers an IEEE 802.11ah-based network with randomly distributed stations around the Access Point (AP), operating under a Rayleigh-fading channel with capture enabled. We develop an analytical model to evaluate the contention of a group of stations and propose a Load-Aware Channel Allocation (LACA) algorithm for the RAW slot period. The LACA algorithm ensures the delivery of all packets that designated stations carry, allowing for the allocation of load-aware RAW slots, which is effective in enhancing the Age of Information (AoI). We evaluate the Packet Delivery Ratio (PDR) and channel usage within a pre-allocated RAW slot to prove the effectiveness of our proposal. We further study the impact of the spatial distribution of the stations around the AP and the capture effect under a Rayleigh channel on the performance of the proposed LACA algorithm. Extensive simulations are used to validate our analytical results. Our proposal provides a load-aware and adaptive channel allocation scheme based on the dynamic conditions of the network. Our model can be implemented in a global configuration scheme for the RAW mechanism in heterogeneous networks or for alternative communication technologies that address dense scenarios with the integration of periodic channel reservations.

INDEX TERMS IEEE 802.11ah, Internet of Things, performance evaluation, Rayleigh channel, renewal process, Wi-Fi HaLow.

I. INTRODUCTION

Wi-Fi technology is one of the most widely deployed and used Internet access technologies in the world. However, the exponential growth of wireless devices has tended to overtake this technology in its traditional form, as it is designed for small networks over short ranges. Therefore, the IEEE Task Group ah (TGah) developed an enhanced Wi-Fi technology, named IEEE 802.11ah standard [1], and marketed it as Wi-Fi HaLow. The IEEE 802.11ah standard comes with several amendments, providing connectivity to thousands of devices within a range of up to 1 km [2]. One of its main features is a new channel access mechanism based on periodic channel reservations, called Restricted Access Window

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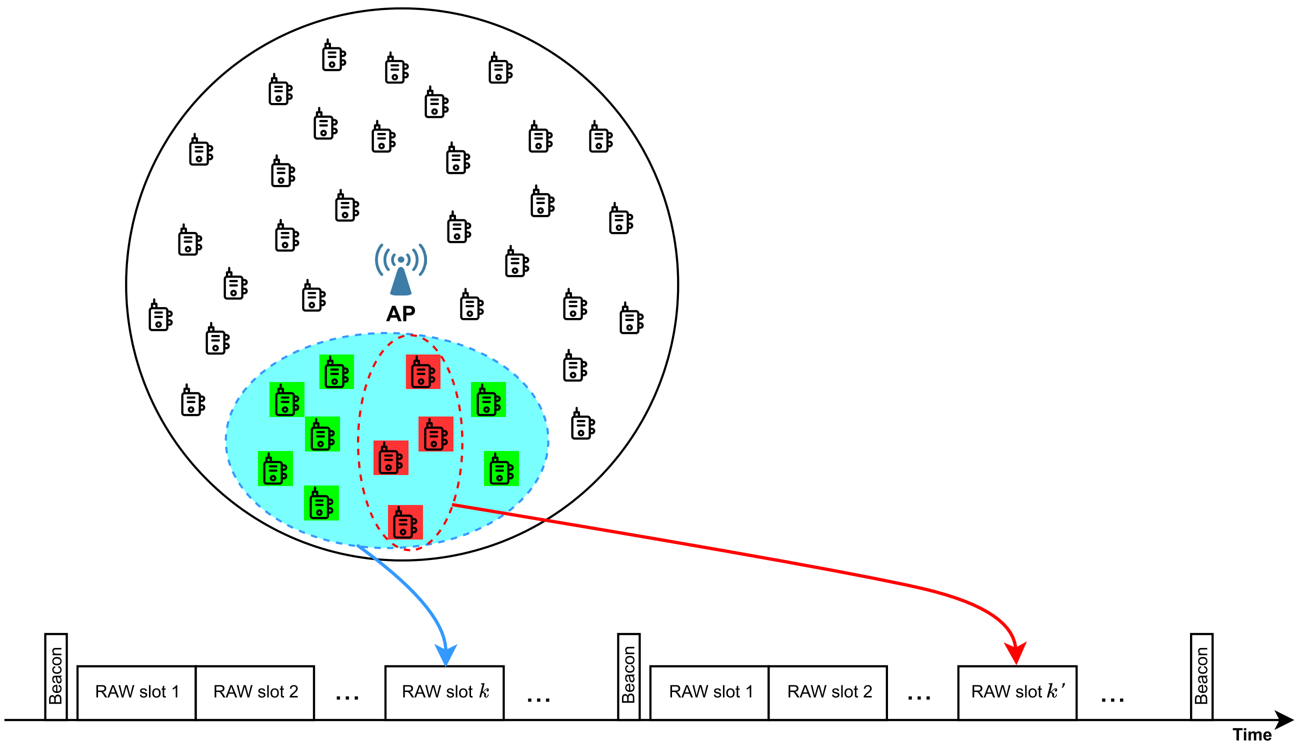

FIGURE 1. RAW-based channel access in the IEEE 802.11ah standard.

(RAW). Only a small group of devices can contend for channel access during a given period, called a RAW slot, using the Enhanced Distributed Channel Access (EDCA) protocol.

The IEEE 802.11ah standard presents an excellent solution for large-scale Internet of Things (IoT) applications, consisting of dense networks with energy-constrained devices [3]. Its new RAW-based MAC support allows this standard to meet the requirements of IoT applications, such as energy efficiency, coverage range, and scalability. Fig. 1 presents an illustration of RAW-based channel access in the IEEE 802.11ah standard. The channel time is divided into fixed-length Beacon Intervals (BI). Each BI contains one or more RAW periods, which are further divided into one or more RAW slots. The stations are distributed around the AP, and only one group of stations is allowed to contend for channel access during their allocated RAW slot. If a station does not transmit its traffic load during the allocated RAW slot, it will have to wait until the next allocated RAW slot to try again within a new contention, hence increasing the age of the generated packet. This is the case depicted in the figure where the stations located within the highlighted area are assigned to the RAW slot k. This RAW slot period resulted in a successful data delivery for the green stations, whereas the red stations were unable to transmit their data. The latter would have to wait for access to the RAW slot k' in the next BI. Since the AP broadcasts the RAW configuration through the beacon frame, additional stations could be assigned to the same RAW slot k'. However, the standard does not provide schemes or strategies for configuring the RAW mechanism or dividing stations into groups and the channel timeline into RAW slots.

In order to derive efficient RAW configuration schemes, current works focus on distributing stations among pre-allocated RAW slots [2]. This approach enhances network performance by eliminating the hidden nodes and decreasing collisions in each RAW slot. Such approaches enhance channel usage during the RAW slot period, but do not guarantee the successful delivery of all packets carried by the designated stations. For time-sensitive applications, the delivery of updates as they are generated is more crucial to optimizing system resources [4], [5]. Therefore, instead of packet delay, the latency metric gaining priority in such applications is the Age of Information (AoI), which measures the freshness of information at the receiver [6]. This is the time since the last received update was generated. Such a metric is crucial in many systems, such as Unmanned Aerial Vehicle (UAV) networks, where exchanging the latest position, speed and control information is vital and can contribute to significant performance enhancements [7].

The study of AoI is typically carried out using queueing theory, where the objective is to evaluate the average age and the peak age of information [6]. The authors in [5] considered a multiserver queuing system, where updates are generated following a renewal process. The system contains a controller that routes arriving packets to servers and decides the service distribution time and the service order of packets in each server. The authors carried out the age-delay and age-delay variance tradeoff and showed that the average age achieves its minimum when the packet delay tends to infinity. In [7], the authors considered a UAV-assisted wireless powered IoT system and established an optimization problem to minimize the average AoI of the data collected from sensor nodes on the ground by jointly optimizing the UAV's trajectory, energy transfer and data collection time for each sensor node. They showed that the AoI increases when the altitude of the UAV rises and that the average AoI increases linearly with the size of data frames.

Configuring the RAW mechanism based only on distributing stations among pre-allocated RAW slots does not guarantee timely communication of data [8], and may not be reliable for time-sensitive remote sensing and control applications. If the RAW slot is not long enough to allow for full delivery of all stations' data, some stations will have to compete for channel access in subsequent RAW slots, which increases the AoI of data at the AP. However, if the RAW slot duration is longer than the time required to transmit the stations' traffic load, the extra time will result in channel waste. Therefore, to reduce the AoI at the AP upon successful delivery and prevent channel waste, we propose to allocate adaptive load-aware RAW slots, ensuring the successful delivery of all packets carried by designated stations.

Rather than configuring the RAW mechanism in terms of grouping stations and dividing the RAW duration into RAW slots, as we established in a previous work [9], this paper addresses a load-aware channel allocation for the lengths of RAW slots. We assume that stations access the channel only through the RAW mechanism. That is, the channel time consists of successive RAW slots periods, and the performance of the entire network is hence proportional to the performance of these periods. Therefore, we consider here a single RAW slot allocated to a group of stations. We evaluate the contention performance of the designated stations under a Rayleigh channel with capture, considering the stations' traffic load and their spatial distribution. Then, we develop a LACA scheme for the RAW slot duration based on a two-level renewal process model. A load-aware RAW slot allows all the packets of the assigned stations to be delivered successfully without extra waste of channel time. Such an approach is highly beneficial for time-sensitive applications that require data to be received as soon as they are generated. As illustrated in Fig. 1, a load-aware allocation of the RAW slot k shall serve all assigned stations and avoid having red stations that need to wait for a subsequent allocated RAW slot in order to compete again for channel access.

In this work, we target time-sensitive applications where the RAW slot duration should meet the requirements of its designated stations. That is, to be long enough to deliver packets up to the desired ratio and not too long to avoid wasting channel time. Such an adaptive RAW slot allocation requires predicting the duration needed to serve the traffic load of the designated stations. Since a station may not have data available to transmit or might be in a sleep state, each group may have a different traffic load that requires an adaptive RAW slot duration, ensuring the successful delivery of all the packets. To the best of our knowledge, allocating RAW slots in terms of the dynamic conditions of the network has not yet been addressed in the literature [3]. Therefore, in this paper, we develop an analytical framework based on a two-level renewal process to model the contention within one group of stations. We assume that each station has a sufficient buffer for only one packet. That is the case of sensor stations where the previous data is disregarded when new data is generated. Considering the spatial distribution of stations operating under a Rayleigh-fading channel with capture effect enabled in the AP, we derive a LACA for a given group of stations, representing an efficient length of the RAW slot that ensures successful delivery of all packets without extra waste of channel time.

The contributions of this work are as follows:

- We develop an analytical model for channel access contention of a group of stations operating under a Rayleigh-fading channel. We then develop a two-level renewal process based model for the channel timeline.
- Based on the analytical framework, we propose a Load-Aware Channel Allocation (LACA) algorithm for the duration of RAW slots, considering the spatial distribution of stations and the capture effect in the AP.
- We validate our analytical framework via extensive simulations and prove the effectiveness of the proposed algorithm through the metrics of packet delivery ratio and channel usage. We show that our proposal provides an adequate solution for channel allocation under Rayleigh fading conditions and capture effect, making it practical to ensure data delivery from the first contention attempt, which minimizes the AoI at the AP.

The remainder of this paper is organized as follows. Section II reviews various related works. Section III explains the scenario considered and the problem addressed. Section IV then presents the proposed analytical model and the LACA algorithm. Section V validates our analytical findings via simulations and analyzes the impact of different parameters. Finally, Section VI concludes our paper.

II. RELATED WORKS

The configuration of the RAW mechanism depends on several parameters, such as the stations assigned and their locations, the payload size, the channel model, and the capture threshold. Therefore, an accurate mathematical model with closed-form results is the best solution for this task. It permits the RAW performance to be predicted given the input values of all related parameters, hence deriving the best configuration optimizing the entire network performance. Several researchers have proposed analytical models to study and evaluate the IEEE 802.11ah standard [2], [10]. Due to the time-limited contention introduced in the RAW mechanism, analytical models based on steady-state results such as Bianchi's [11] are not applicable for this standard. Although several modified and enhanced models have been proposed [12], they are still all based on stationary results.

The limited duration of a RAW slot prevents the contention from reaching the stationary state [13]. Therefore, new innovative approaches have been required to model and evaluate the IEEE 802.11ah standard.

In [14], the authors proposed a Markov chain model, where the Markov process counts the number of active stations and slots that occurred in the idle, collision, and success states. This model is based on the derivation of the probabilities of the absorbing states, which are the states where the total duration of the occurring events reaches the length of the RAW slot. The same model is deployed in [15] to assess the energy consumption within a RAW, under the assumption that every station has only one packet to transmit in each BI. This model is based on the absorbing states of the Markov chain, which are defined by the constraint of the total duration of events reaching the RAW slot limit. Thus, it is complex and challenging to define closed-form results to evaluate the network. Zheng et al., [16] proposed a mean value analysis approach to model the contention within a RAW slot and evaluate the saturated throughput for cases where the RAW slot boundary-crossing is either enabled or disabled. This approach is not applicable in the case of unsaturated traffic conditions, as the channel access probabilities change when a station leaves the contention. Other mathematical models for EDCA within RAW with no retransmissions are presented in [17], where a station has only one attempt to transmit its packet, and in [18], where a RAW slot can host, at most, only one transmission attempt.

In contrast to these works, we developed models based on a new approach in our previous studies [9], [13], [19]. We deployed the renewal theory, in which a counting process tracks transmissions up to the end of the RAW slot [13]. This approach allows one to predict the number of events occurring within the RAW slot period in terms of time, and hence evaluate the gain of the time-limited contention. In [9], we proposed an analytical framework based on renewal theory to evaluate the RAW throughput and then optimize the RAW configuration to maximize the throughput in the cases of both an ideal channel and a channel with transmission errors. We further developed an accurate model for an IEEE 802.11ah-based network, operating under a Rayleigh-fading channel with capture effect enabled at the AP [19]. These models allowed us to evaluate network performance and study the impact of different parameters in both RAW configuration and network conditions. Subsequently, in [20], we developed a resource-efficient scheme to reconfigure the RAW mechanism under saturated traffic and Rayleigh channel conditions. The new configuration eliminates the extra time wasted during the RAW period, which significantly improved the RAW throughput and energy efficiency and optimized the channel allocation resources.

III. PROBLEM STATEMENT

We consider an IEEE 802.11ah-based network where stations are distributed around the Access Point (AP). The stations periodically obtain access to the channel following the configuration of the RAW mechanism. Such a configuration is based on two primary operations: (1) dividing stations into groups, and (2) allocating a certain amount of channel time to each group, named RAW slots. According to the standard, the stations are distributed among RAW slots following a round-robin rule, and the number of groups within each RAW interval cannot exceed 64 [1]. To the best of our knowledge, existing research works focus on evaluating and studying the assignment of stations into pre-defined RAW slots. Such approaches improve the gain of the RAW mechanism but do not guarantee that all stations will have a chance to transmit their packets during their allocated RAW slot. Therefore, in this paper, we propose to define the duration of the RAW slot after determining the conditions of its designated stations, including their traffic load and locations. Note that this procedure can be applied repeatedly to every group of stations and an adequate channel time can be allocated to every RAW slot.

The channel time reserved for a given RAW slot greatly depends on the number and state of the designated stations. As proven in our previous works [9], [13], [19], a slight change in the length of a RAW slot can either enhance or degrade the overall performance of the RAW slot. This is due to the holding period, which might be long enough to host an additional transmission or otherwise be wasted. Henceforth, the RAW slot throughput results in a fluctuating behavior, when its duration varies. The fluctuation is more significant for a short RAW slot, where the holding period represents a large part of the RAW slot interval. In contrast, it becomes less significant when the length of the RAW slot is longer.

Therefore, defining the channel duration allocated to each RAW slot is critical, especially in the case of unsaturated traffic conditions. Thus, the duration of the RAW slot shall be efficiently allocated according to the traffic load of the designated stations. Note that the overall RAW duration is simply the total length of its composed RAW slots. Hence, in the rest of this paper, we focus on evaluating only one RAW slot allocated to a group of stations. We consider a Rayleigh fading channel that models a dense urban environment where transmissions are subject to multipath fading and non-line-of-sight (NLOS) propagation in the wireless medium [21]. We assume that the buffer of a station can store only one packet. That is, a newly generated packet replaces the old one. This is practical in the case of remote sensing applications, where old packets are not informative [5] and only packets with fresh updates are considered by the AP for a better AoI performance [8].

We henceforth consider a group of N_S stations to be assigned to a RAW slot, where each station has a single packet to transmit. We aim to prevent having red stations in Fig. 1 and to have all stations served in the first allocated RAW slot. Therefore, we shall accurately derive the RAW slot duration that is long enough to allow the successful delivery of all packets from the N_S stations without wasting extra channel time. We refer to this result as LACA time for the RAW slot period, denoted by T_S^*.

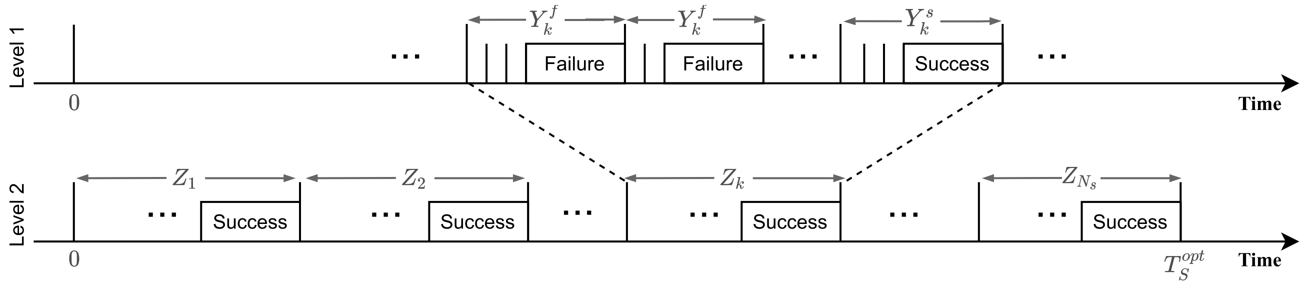

FIGURE 2. Illustration of the proposed two-level renewal process.

IV. PROPOSED MODEL

During the contention of N_S stations, the channel timeline is occupied by both idle and busy slots. Each busy slot occurs after a sequence of idle slots, where the stations count down their backoff counters. A good mathematical approach to model this behavior is the renewal theory [22], where stochastic processes update at random instants, during which the state of the system becomes probabilistically equivalent to the starting state. This approach effectively derives closed-form solutions for time-dependent events by implementing the counting process associated with the renewal process [19]. To derive the LACA time for a group of stations, we seek the average time required to transmit all packets successfully. Therefore, we model the channel timeline using a two-level renewal process, as illustrated in Fig. 2. The main model parameters are listed in Table 1.

The first-level process represents the time between consecutive transmission attempts, whether they result in a successful or failed packet delivery, whereas the second-level process depicts the interarrival times of successful transmissions. The second-level renewal cycle is defined by the period between two successive successful transmissions. We denote the level-2 renewal process by $\{Z_k\}_{k\geq 1}$, where Z_1 is the arrival instant of the first successful transmission and $Z_k, k \geq 2$ is the period between the $(k-1)$-th and the k-th successful transmissions.

For each process Z_k, we associate a first-level process $\{Y_k\}_{k\geq 1}$, representing the inter-arrival times of busy slots within the RAW slot channel time. The process $\{Y_k\}_{k\geq 1}$ has a binary outcome, where $Y_k = Y_k^f$ if the busy slot is a failure and $Y_k = Y_k^s$ if the busy slot contains a successful delivery of a packet. Note that a successful transmission can occur when a single station is transmitting or when the AP captures a packet involved in a collision.

Since each station has only one packet to transmit, the number of contending stations decrements by one after each successful packet transmission. That is, $N_S - k + 1$ stations compete for channel access during the period Z_k.

Hereafter, we define the LACA time for the RAW slot T_S^* as the time required to deliver all packets from the N_S stations. Therefore, T_S^* coincides with the end instant of the period Z_{N_S}. Denoting by $\overline{Z_k}$, the average length of the renewal cycle Z_k, we define the LACA time for the RAW slot as follows:

$$T_S^* = \sum_{k=1}^{N_S} \overline{Z_k}\,. \tag{1}$$

A. CHANNEL ACCESS

After each successful transmission, the corresponding station goes to sleep mode and leaves the contention. Thus, the level of contention decreases, resulting in different channel access probabilities within each cycle Z_k. Hence, to determine the average lengths of the renewal cycles of the process $\{Z_k\}_{k\geq 1}$, we need to evaluate the channel access within each cycle.

The renewal cycle Z_k contains $N_S - k + 1$ stations, competing for channel access using the EDCA protocol [1]. Each station obtains a transmission opportunity (TXOP) to initiate the transmission of its packets when its backoff time counter reaches zero [19]. We assume that a TXOP allows transmitting only one single packet, and its duration is given by [1]:

$$T_{\mathrm{TXOP}} = T_{\mathrm{DATA}} + \mathrm{SIFS} + T_{\mathrm{ACK}}\,, \tag{2}$$

where T_{ACK} is the transmission time of an acknowledgment frame (ACK). The Short Inter-frame Space (SIFS) is the time interval between the transmission of a data frame and its corresponding ACK, defined in the standard [1]. Denoting by L the payload size, the transmission time of a data frame is defined as follows [1]:

$$T_{\mathrm{DATA}} = T_{\mathrm{PLCP}} + \frac{L + \mathrm{MacHeader}}{\mathrm{DataRate}}\,. \tag{3}$$

where T_{PLCP} is the duration of the physical layer convergence protocol (PLCP) header.

For convenience of analysis, we assume that the traffic of all N_S stations belongs to the same Access Category (AC) with fixed-size payloads. Furthermore, we assume that each station initiates the transmission of its packet in a randomly chosen slot within the renewal cycle Z_k with the same probability τ_k. Let p_k be the probability that a transmitted packet fails to be delivered successfully after encountering a collision and not being captured. Denoting by W_0 the starting value of the Contention Window (CW) and m the retry limit,

TABLE 1. List of the main model parameters.

Parameter	Description
$\mathcal{C}_\ell^n$	the set of all n-combinations of the distances of stations interfering with the station STA$_\ell$
$\lvert\mathcal{C}_\ell^n\rvert$	the cardinality of the set $\mathcal{C}_\ell^n$
CU(T_S)	the CU for a RAW slot of duration T_S
DIFS	the duration of a DIFS interval
L	the payload size
m	the retry limit
N_S	the number of stations in the RAW slot
p_k	the packet failed-delivery probability during the renewal cycle Z_k
$p_{k,cap}^p$	the packet capture probability during the renewal cycle Z_k
$p_{k,col}^p$	the packet collision probability during the renewal cycle Z_k
$P_{k,cap}$	the probability that a randomly chosen slot within Z_k contains a captured packet
$P_{k,i}$	the probability that a randomly chosen slot within Z_k is idle
$P_{k,s}$	the probability that a randomly chosen slot within Z_k contains a successful transmission
T_{PLCP}	the duration of the PLCP header
PDR(T_S)	the PDR for a RAW slot of duration T_S
$p_{cap}(z,n+1)$	the ACCP for $n+1$ interfering packets
r_i	the distance of the station i from the AP
$R_{k,n}$	the probability that a transmitted packet encounters n interfering packets
SIFS	the duration of an SIFS interval
T_{ACK}	the transmission time of an ACK frame
T_{DATA}	the transmission time of a data frame
T_S	the duration of a pre-allocated RAW slot
T_S^*	the LACA time
T_{TXOP}	the duration of one TXOP
W_0	the minimum value of the CW
X_k	the number of idle slots before a busy slot
Y_k	the level-2 renewal process (see Fig. 2)
z	the capture threshold
Z_k	the level-1 renewal process (see Fig. 2)
β	the length of a busy slot
γ	the signal-to-interference ratio
σ	the length of an idle slot
τ_k	the probability that a station initiates a transmission within Z_k
ω_ℓ	the instantaneous power of a packet received from a tagged station STA$_\ell$
ω_{int}	the instantaneous joint power of interfering packets

we have the probability τ_k expressed as follows [19]:

$$\tau_k = \left[2(2p_k-1)\left(1+(m+1)p_k^{m+2}-(m+2)p_k^{m+1}\right)\right] \Big/ \left[W_0(1-p_k)\left(\left(2^{m+2}-1\right)p_k^{m+1}-\left(2^{m+2}-2\right)p_k^{m+2}-1\right) + 2(2p_k-1)\left(1+(m+1)p_k^{m+2}-(m+2)p_k^{m+1}\right)\right]. \tag{4}$$

The packet collision probability $p_{k,col}^p$ is the probability that at least one of the remaining N_S-k stations transmits in the same slot. Since each station transmits with probability τ_k, we have [9]:

$$p_{k,col}^p = 1-(1-\tau_k)^{N_S-k}. \tag{5}$$

A transmitted packet fails to be delivered when it encounters a collision and is not captured. Hence, the probability p_k of failed delivery of a transmitted packet is given by [19]:

$$p_k = p_{k,col}^p \cdot (1-p_{k,cap}^p), \tag{6}$$

where $p_{k,cap}^p$ is the probability of capturing a transmitted packet after encountering a collision. A prior definition of $p_{k,cap}^p$ is expressed as follows [19]:

$$p_{k,cap}^p = \frac{\sum_{n=1}^{N_S-k} R_{k,n}\cdot p_{cap}(z,n+1)}{p_{k,col}^p}, \tag{7}$$

where $R_{k,n}$ is the probability that the transmitted packet encounters n interfering packets and is given by [19]:

$$R_{k,n} = \binom{N_S-k}{n}\tau^n(1-\tau)^{N_S-k-n}. \tag{8}$$

$p_{cap}(z,n+1)$ is the Average Conditional Capture Probability (ACCP) for $n+1$ interfering packets. It represents the probability of the AP capturing one of the $n+1$ interfering packets. This probability depends on the received powers of the colliding packets. Denote by ω_ℓ the instantaneous power of a packet received from a tagged station STA$_\ell$, located at a distance r_ℓ from the AP. Under the conditions of a Rayleigh fading channel, ω_ℓ is a random variable exponentially distributed as follows [23]:

$$f_{\omega_\ell}(x) = \frac{1}{\omega_{0\ell}}e^{-\frac{x}{\omega_{0\ell}}}, \quad x\geq 0 \tag{9}$$

where $\omega_{0\ell}$ is the local mean power of the transmitted packet at the receiver, and is defined as:

$$\omega_{0\ell} = A\cdot r_\ell^{-\alpha}\cdot\omega_T, \tag{10}$$

where ω_T is the transmitted signal power, A is a dimensionless constant in the path-loss law, and α is the path-loss exponent. For convenience of analysis, we assume that ω_T is constant for all stations.

When a collision of $n+1$ stations occurs, the AP captures one of the interfering packets if its received power exceeds the joint received power of the other packets by a given threshold. Hereafter, the ACCP is defined by the probability that the Signal-to-Interference Ratio (SIR) $\gamma = \frac{\omega_\ell}{\omega_{\text{int}}}$ exceeds a given threshold z, where $\omega_{\text{int}} = \sum_{i=1}^{n}\omega_k$ is the instantaneous joint power of interfering packets, and z represents the capture performance of the AP, and is called the capture threshold. Hence, we have

$$p_{cap}(z,n+1) = \Pr\{\gamma > z|n+1\}. \tag{11}$$

The instantaneous power of a received packet at the AP depends on the location of the source stations. Hence, the evaluation SIR γ requires the distances of colliding stations from the AP. Let $r_1, r_2, \ldots, r_n$ be the distances from the AP of the n interfering stations with STA$_\ell$, respectively. The conditional capture probability for the packet of STA$_\ell$ can be expressed as follows:

$$p_{cap}(z, r_\ell, r_1, \ldots, r_n) = \Pr\{\gamma > z | r_\ell, r_1, \ldots, r_n\} = \Pr\left\{\omega_\ell > z \cdot \sum_{i=1}^{n} \omega_k | r_\ell, r_1, \ldots, r_n\right\} \tag{12}$$

Therefore, by implementing the instantaneous power distribution of the received packets defined in (9), we obtain [19]:

$$p_{cap}(z, r_\ell, r_1, \ldots, r_n) = \prod_{i=1}^{n} \frac{1}{1 + z \cdot \left(\frac{r_i}{r_\ell}\right)^{-\alpha}}. \tag{13}$$

To derive the ACCP for a colliding packet of STA$_\ell$ when encountering n interfering packets, we need to average over all possible combinations of potential interfering stations. Let $\mathcal{C}_\ell^n$ denote the set of all n-combinations of the distances of the $N_S - k$ stations that are contending with the tagged stations STA$_\ell$. Thus, the ACCP for a packet of STA$_\ell$ when encountering n interfering packets is defined as follows:

$$p_{cap}(z, r_\ell, n) = \frac{1}{|\mathcal{C}_\ell^n|} \cdot \sum_{\{r_1,\ldots,r_n\} \in \mathcal{C}_\ell^n} p_{cap}(z, r_\ell, r_1, \ldots, r_n). \tag{14}$$

To obtain the ACCP for $n + 1$ interfering packets within the period Z_k, we take the average of the ACCPs for all the stations in contention. Denoting by $r_1, r_2, \ldots, r_{N_S-k+1}$ the distances from the AP for the $N_S - k + 1$ contending stations, we have the following:

$$p_{cap}(z, n + 1) = \frac{1}{N_S - k + 1} \cdot \sum_{\ell=1}^{N_S-k+1} p_{cap}(z, r_\ell, n). \tag{15}$$

Consequently, substituting (8) and (15) in (7), we derive the expression of the probability $p_{k,cap}^p$. We have:

$$p_{k,cap}^p = \frac{1}{p_{k,col}^p} \sum_{n=1}^{N_S-k} \left[\binom{N_S - k}{n} \tau_k^n (1 - \tau_k)^{N_S-k-n} \cdot \frac{1}{N_S - k + 1} \cdot \sum_{\ell=1}^{N_S-k+1} \frac{1}{|\mathcal{C}_\ell^n|} \cdot \sum_{\{r_1,\ldots,r_n\} \in \mathcal{C}_\ell^n} \prod_{i=1}^{n} \frac{1}{1 + z \cdot \left(\frac{r_i}{r_\ell}\right)^{-\alpha}} \right] \tag{16}$$

Therefore, the values of probabilities τ_k, p_k, and $p_{k,cap}^p$ can be obtained by solving numerically (e.g., using Newton's method [24]) the non-linear system defined by (4), (6) and (16).

B. LOAD-AWARE CHANNEL ALLOCATION

The probability $P_{k,i}$ for a randomly chosen slot within the period Z_k to be idle is given by the following:

$$P_{k,i} = (1 - \tau_k)^{N_S-k+1}. \tag{17}$$

The probability $P_{k,s}$ of successfully transmitting a single packet without interference in a randomly chosen slot within Z_k is defined as the conditional probability that one single station transmits given that the slot is not idle. We have

$$P_{k,s} = \frac{(N_S - k + 1) \cdot \tau_k \cdot (1 - \tau_k)^{N_S-k}}{1 - P_{k,i}}. \tag{18}$$

Let $P_{k,cap}$ be the probability that a randomly chosen slot within Z_k contains a successful packet delivery by capture. That is, when a collision occurs and a packet from one of the colliding stations is captured successfully, we have

$$P_{k,cap} = (N_S - k + 1) \cdot \tau_k \cdot p_{k,cap}^p. \tag{19}$$

The renewal cycle Z_k is constructed by the cycles of the process $\{Y_k\}_{k\geq1}$, with each having an average length of $\overline{Y_k} = \sigma \cdot \overline{X_k} + \beta$, where X_k is the number of idle slots before at least one of the stations starts transmitting. σ is the length of an idle slot. $\beta = T_{\mathrm{TXOP}} + \mathrm{DIFS}$ is the duration of a busy slot, where DIFS is the duration of a Distributed Coordination Function (DCF) Interframe Spacing (DIFS) time [1].

The random variable X_k follows a geometric distribution on $\mathbb{N}$ with parameter $(1 - P_{k,i})$, and thus we have

$$\Pr\{X_k = j\} = (1 - P_{k,i})P_{k,i}^j, \quad j \geq 0. \tag{20}$$

Hence, the average number of idle slots before the occurrence of a busy slot is given by:

$$\overline{X_k} = \frac{P_{k,i}}{1 - P_{k,i}}, \tag{21}$$

and the average length of a renewal cycle of the process $\{Y_k\}_{k\geq1}$ is given by:

$$\overline{Y_k} = \sigma \cdot \frac{P_{k,i}}{1 - P_{k,i}} + \beta. \tag{22}$$

Let W_k be a random variable representing the number of renewal cycles of the process $\{Y_k\}_{k\geq1}$ within the period Z_k. Therefore, we have

$$Z_k = \sum_{n=1}^{W_k} Y_n. \tag{23}$$

We have $\{Y_k\}_{k\geq1}$ is a sequence of Independent and Identically Distributed (IID) random variables with the same mean $\overline{Y_k}$ Additionally, the cycle Z_k ends after a period of $\{Y_k\}_{k\geq1}$ of type Y_k^s and a packet can be successfully delivered through a single transmission or capture from a collision. Therefore, W_k is geometrically distributed on $\mathbb{N}^*$ with probability $P_{k,s} + P_{k,cap}$, and we have

$$\overline{W_k} = \frac{1}{P_{k,s} + P_{k,cap}}. \tag{24}$$

Algorithm 1 Load-Aware Channel Allocation

Input: N_S: Number of stations.
$r_1, \ldots, r_{N_S}$: Distances of stations from the AP.
z: Capture threshold.
L: Payload size.
Output: T_S^*: LACA time for the RAW slot.
1: **for** $k = N_S$ to 1 **do**
2: Derive τ_k, p_k and $p_{k,cap}^p$ using the non-linear system defined by (4), (6) and (16).
3: $P_{k,i} \leftarrow (1-\tau_k)^{N_S-k+1}$
4: $P_{k,s} \leftarrow \frac{(N_S-k+1)\cdot\tau_k\cdot(1-\tau_k)^{N_S-k}}{1-P_{k,i}}$
5: $P_{k,cap} \leftarrow (N_S-k+1)\cdot\tau_k\cdot p_{k,cap}^p$
6: **end for**
7: $T_S^* \leftarrow \sum_{k=1}^{N_S} \frac{1}{P_{k,s}+P_{k,cap}} \cdot \left(\sigma \cdot \frac{P_{k,i}}{1-P_{k,i}} + \beta\right)$
8: **return** T_S^*

Hereafter, $\overline{W_k} < \infty$ and according to Wald's equality [22], we have the average length of the cycle Z_k expressed as follows:

$$\begin{aligned}\overline{Z_k} &= \mathrm{E}\left[\sum_{n=1}^{W_k} Y_n\right] \\ &= \overline{W_k}\cdot\overline{Y_k} \\ &= \frac{1}{P_{k,s}+P_{k,cap}}\cdot\left(\sigma\cdot\frac{P_{k,i}}{1-P_{k,i}}+\beta\right) \end{aligned} \tag{25}$$

Finally, by substituting (25) in (1), we obtain the LACA time for the RAW slot, allowing for the successful delivery of all the packets of the N_S station expressed as follows:

$$T_S^* = \sum_{k=1}^{N_S} \frac{1}{P_{k,s}+P_{k,cap}}\cdot\left(\sigma\cdot\frac{P_{k,i}}{1-P_{k,i}}+\beta\right). \tag{26}$$

We summarize the proposed procedure for obtaining the LACA time T_S^* in Algorithm 1. The input parameters are the number of stations, their locations, the payload size, and the capture threshold. Since a station leaves the contention after delivering its packet, the channel access is evaluated in every renewal cycle of the process $\{Z_k\}_{k\geq 1}$ for $k = 1, \ldots, N_S$. Therefore, by evaluating the average length of renewal cycles of the process $\{Y_k\}_{k\geq 1}$ within each cycle Z_k, we obtain the average length of the cycle Z_k. Finally, the LACA time for the RAW slot in the considered scenario is derived as the aggregated length of renewal cycles of the process $\{Z_k\}_{k\geq 1}$.

Since the main objective of the RAW mechanism is to limit the number of stations accessing the channel simultaneously in order to decrease collisions, the number of stations N_S in the input of Algorithm 1 is supposed to be small, which lowers the computation complexity. Additionally, it is very likely to have several groups of stations with the same traffic characteristics, and the algorithm is then executed only once to derive the common LACA time T^* for all RAW slots allocated to these groups.

The LACA time for a given group of stations represents the channel time required to deliver all these stations' traffic load. We henceforth propose to investigate the impact of different duration on the network performance in terms of Packet Delivery Ratio (PDR) and channel usage. We consider a pre-defined RAW slot of duration T_S allocated to N_S stations. We define the PDR for this RAW slot by the portion of delivered packets among the total stations' traffic load. Since the process $\{Z_k\}_{k\geq 1}$ starts a new cycle after each successful transmission, the number of delivered packets is given by the number of occurred renewal cycles of $\{Z_k\}_{k\geq 1}$. Thus, we have:

$$\mathrm{PDR}(T_S) = \begin{cases} \dfrac{\sum_{k=1}^{n^*}\overline{Z_k}}{T_S} + \dfrac{T_S - \sum_{k=1}^{n^*}\overline{Z_k}}{\overline{Z_{n^*+1}}}, & \text{if } T_S < T_S^* \\ 1, & \text{otherwise} \end{cases} \tag{27}$$

where

$$n^* = \arg\max_n \left\{\sum_{k=1}^{n}\overline{Z_k} < T_S\right\}. \tag{28}$$

The channel usage during the RAW slot period is defined as the portion of the time used to deliver data successfully during T_S. Using the previous result of PDR, the number of delivered packets can be expressed by $PDR \cdot N_S$. Therefore, we define the channel usage within the considered RAW slot as follows:

$$\mathrm{CU}(T_S) = \frac{\mathrm{PDR}(T_S)\cdot N_S\cdot\beta}{T_S}. \tag{29}$$

V. NUMERICAL RESULTS AND DISCUSSION

This section validates our proposed model and analytical findings via extensive simulations obtained by a discrete-event simulator we developed with MATLAB. The simulator mimics the DCF mechanism, considering the location of stations, the channel fading, and the capture effect. The depicted simulation results represent the average outcome of 1000 simulations. We also evaluate and analyze the performance of a RAW slot in terms of different parameters and scenarios. The slight differences between the analytical and simulation results depicted below are due to the analytical assumption of the same transmission probability τ_k of stations in each renewal cycle of the process $\{Z_k\}_{k\geq 1}$. In the simulator, the first transmission attempt of each station is initiated after its backoff counter reaches zero during the first backoff stage, while τ_k considers the transmission attempts initiated from all backoff stages. Additionally, if a station successfully transmits its packet, it leaves the contention, and a new renewal cycle of the process $\{Z_k\}_{k\geq 1}$ starts. During this cycle, the remaining stations continue to contend for channel access with their current backoff counter states. This effect is not considered analytically, as τ_k represents the transmission attempt probability for $N_S - k + 1$ contending stations without any inheritance of backoff counter states from the previous

TABLE 2. Parameters.

Parameter	Value
Data rate	1.95 Mbps
MacHeader	272 bits
T_{ACK}	1000 µs
T_{PLCP}	80 µs
σ	52 µs
SIFS	160 µs
DIFS	264 µs
CW_{min}	8
CW_{max}	16
m	1
α	4

contention. We define the spatial distribution of N_S contending stations by an interval $[\rho_1, \rho_2]$, where the distances $r_1, r_2, \ldots, r_{N_S}$ of the stations from the AP are defined by N_S evenly spaced points in this interval. The latter is also referred to as the stations' area, with a range $\rho_2 - \rho_1$. We consider sensor stations transmitting voice or video data, with one retransmission attempt of a collided packet according to the standard [1]. The system setup parameters are presented in Table 2.

A. LOAD-AWARE CHANNEL ALLOCATION

This section validates and analyzes our proposal, Algorithm 1. Fig. 3 presents the LACA time for a RAW slot in terms of the number of assigned stations located in [1, 10]. We observe an excellent match with the simulations, which validates the closed-form analytical result of T_S^* in (26). More stations in a group result in a higher traffic load, which requires more time to ensure the delivery of all packets. Moreover, extra stations in the RAW slot escalate the contention, which results in more collisions, and hence expands the time T_S^* needed to successfully transmit all packets. The figure shows the results for two payload sizes, $L = 16$ bytes and $L = 160$ bytes. The case of stations with larger payloads requires more service time. However, the difference in T_S^* values between the two payloads is not of great significance due to the considerable ACK frame length $T_{\text{ACK}} = 1$ ms that is introduced in the IEEE 802.11ah standard.

To analyze the impact of both payload size and the capture effect, we present in Fig. 4 the results for T_S^* in terms of the capture threshold z for the two different payloads. We first observe that the simulations validate the analytical results. As mentioned previously, a more extended payload requires more channel access time to deliver the packets of all stations in the group successfully. Furthermore, a more significant value of the capture threshold z lowers the capture probability, as it becomes more unlikely for the received power of a given packet to exceed the joint received powers of the interfering packets by the threshold z. Therefore, the length of the first-level renewal cycle Y_k becomes longer, affecting the renewal cycles Z_k, and hence the value of T_S^* for the RAW slot increases. On the other hand, a lower value of the capture threshold z allows packets to be captured more frequently,

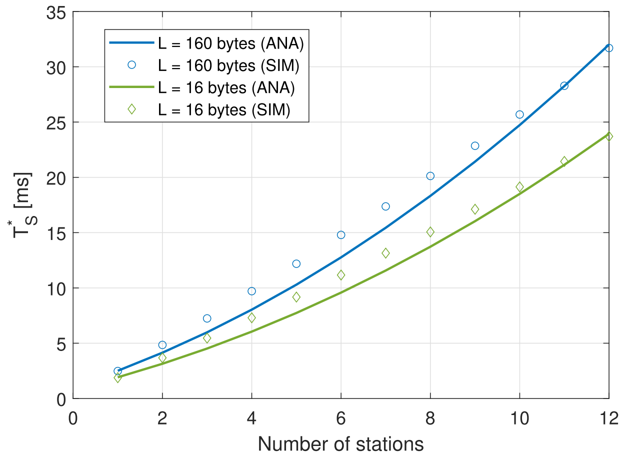

FIGURE 3. LACA time for stations located in the area of range [1, 10], with a capture threshold $z = 4$ dB.

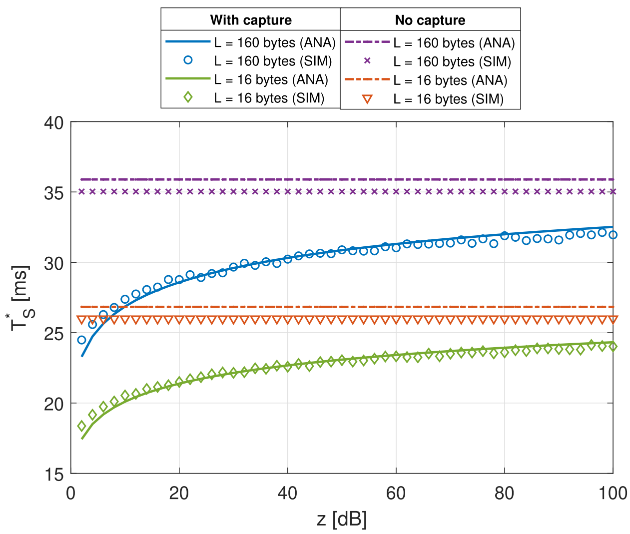

FIGURE 4. LACA time in terms of the capture threshold for stations located in the area of range [1, 10].

hence making good usage of channel time. This allows all the packets to be delivered faster in a shorter period. Meanwhile, a higher value of z has an inverse impact, resulting in a larger T_S^* and converging to the case of a no-capture channel.

B. RAW SLOT PERFORMANCE

We now investigate how to set up the RAW slot duration T_S according to the design objective and performance requirements of the end application. To this end, two performance metrics are of interest. First, we evaluate the PDR of a pre-allocated RAW slot, representing the portion of successfully delivered packets among the total packets of all stations assigned to the RAW slot. Let us consider a RAW slot with pre-defined duration $T_S = 10$ ms, and evaluate the PDR in terms of the number of its designated stations, as depicted in Fig. 5. By definition, if the RAW slot duration is less

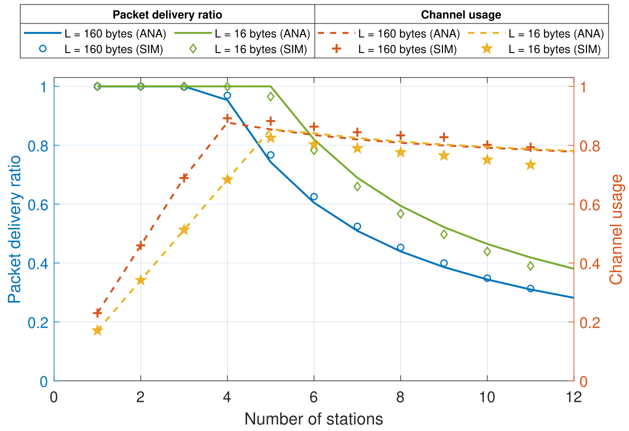

FIGURE 5. PDR and channel usage for stations in the area of range [1, 10], assigned to a 10 ms RAW slot, with capture threshold $z = 4$ dB.

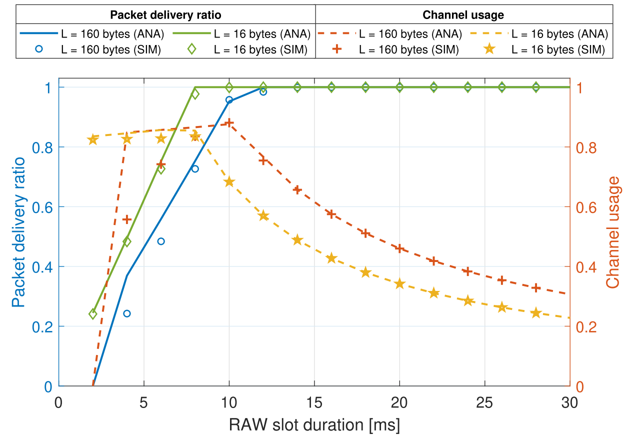

FIGURE 6. Performance of a pre-defined RAW slot in terms of its duration, with 4 assigned stations and capture threshold $z = 4$ dB.

than T_S^*, the time allocated to the stations will be insufficient to deliver all their traffic load (packets). Otherwise, when the length of the RAW slot is greater than T_S^*, all packets will be delivered before the RAW slot ends, and the remaining channel time will be wasted. Furthermore, the larger payload $L = 160$ bytes results in a lower PDR than the shorter payload of $L = 16$ bytes. However, the difference is not significant due to the higher overhead of the ACK frame and the inter-frame spaces defined in the standard [1].

Fig. 5 also depicts the channel usage representing the portion of the RAW slot duration that is used to transmit packets successfully. The channel usage starts with its lowest value when only one station is assigned to the RAW slot. This is because only a small portion of the RAW slot is used to transmit the station's packet and the remaining time in the RAW slot is wasted. The channel usage keeps increasing as long as the assigned stations yield a 100% PDR, for the same reason as in the case of one station. However, this trend changes when the PDR starts to degrade due to the inadequacy of the 10 ms RAW slot to host the entire traffic load of stations. Hereafter, the extra contention introduced by more stations increases the collision probability, which expands the time needed to achieve a successful transmission, i.e., the length of the renewal cycle Z_k is extended. Eventually, the RAW slot T_S becomes occupied by more idle slots, failed transmissions, and less successful packet deliveries, which diminishes the channel usage.

The results also show that the gain of a pre-defined RAW slot can be maximized when an adequate number of stations is assigned to it. The gain of the RAW slot can be presented by a trade-off between PDR and channel usage. In the case of the scenario considered in Fig. 5, we see that four stations for $L = 160$ bytes and five stations for $L = 60$ bytes are good choices for this RAW slot of 10 ms, as they provide higher combined values for PDR and channel usage. These results can also be seen in Fig. 3, where T_S^* is valued at about 10 ms for four and five stations with a payload size of 160 and $L = 60$ bytes, respectively. In such cases, the RAW slot is efficiently allocated, providing two main gains: (1) maximizing the channel usage and avoiding waste of channel time; (2) ensuring successful delivery of all stations' packets and guaranteeing that no station will have to wait for another allocated RAW slot in the future to attempt again to transmit the same packet, which eventually enhances the AoI of received data at the AP.

To analyze the impact of allocating a different duration from T_S^* to a group of stations, we present in Fig. 6 the performance of a RAW slot allocated to four stations in terms of its duration. As the RAW slot length increases, more channel time becomes available to transmit packets, which enhances the PDR. Nevertheless, a very short period may not be enough to host at least one transmission, resulting in a null performance, as the case here for the length of 2 ms with a 160-byte payload. The channel usage maintains an almost stable performance up to the duration corresponding to T_S^*, where it starts decreasing. As seen above in Fig. 3, T_S^* for four stations with a 160-byte payload is around 10 ms, which is the adaptive length observed in Fig. 6, maximizing the PDR and enhancing the channel usage up to more than 80%.

Furthermore, Fig. 7 presents the simulation results for the percentage of different events occupying the RAW slot period when allocated to four stations with a 160-byte payload. As the length of 2 ms is not enough to host at least one transmission, it results in a complete waste of channel time. A more extended RAW slot duration allows more packets to be transmitted. However, the waste of channel time still appears when the additional time is insufficient to host an extra transmission, and is hence wasted. Nevertheless, in this case, the efficient choice corresponding to 10 ms yields the best results with the highest percentage of successful packet delivery through single transmissions and the capture of packets from collisions. A higher value for the RAW slot provides a complete delivery of the stations' traffic load but

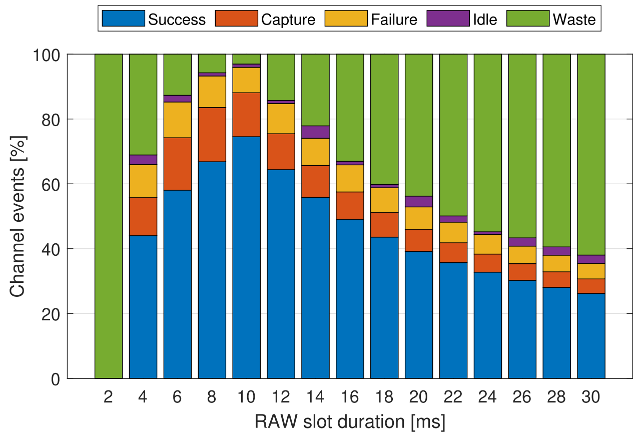

FIGURE 7. Channel events occupying a RAW slot allocated to 4 stations with a 160-byte payload and capture threshold $z = 4$ dB.

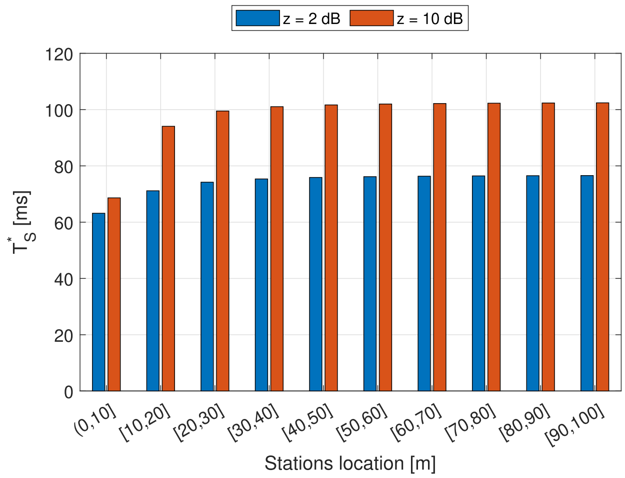

FIGURE 8. Impact of the distance of the location area from the AP for 15 stations.

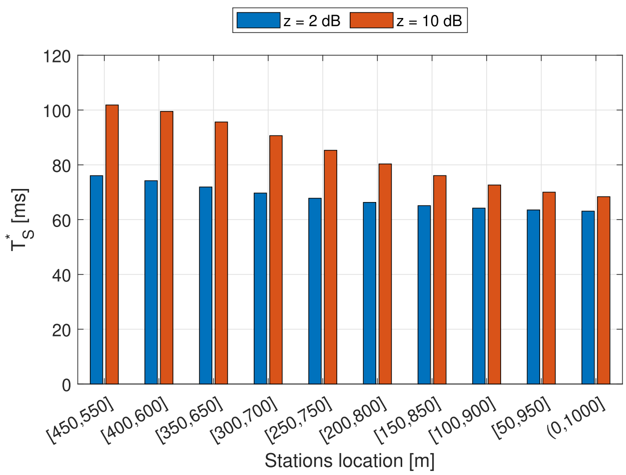

FIGURE 9. Impact of the location area range for 15 stations.

with a significant waste of channel time since each station leaves the contention after successfully delivering its packet. Henceforth, an adaptive allocation of the RAW slot as our proposal is essential to ensure a complete delivery of all packets, on the one hand, and to save resources by preventing the waste of channel time, on the other hand.

C. SPATIAL DISTRIBUTION OF STATIONS

To further investigate the impact of the capture effect, we present in Fig. 8 the LACA time for 15 stations distributed in an area of range 10 m. We evaluate T_S^* for this group of stations in terms of the distance of their area from the AP, under two different capture thresholds ($z = 2$ dB and $z = 10$ dB). The lower threshold value 2 dB increases the ACCP, providing more captured packets than the case of a 10 dB threshold; That is, eliminating the slots containing a failure transmission and eventually shortening T_S^* for the stations. We observe that the capture is more efficient when the stations are closer to the AP, where T_S^* yields minimal values. Even when the stations maintain the same interdistance within a range of 10 m, the value of T_S^* increases when the stations' area is located far from the AP, and almost stabilizes when the stations are at a distance of 40 m or more. This behavior is due to the Rayleigh-fading channel considered in this scenario, where the capture of packets depends on the received power at the AP, which is distributed exponentially in terms of the stations' distance from the AP, as expressed in [19]. Such distribution of received power yields higher power attenuation when the station is located at a greater distance. Additionally, the distance between stations becomes ineffective when they are located in an area far from the AP.

Hereafter, we analyze the impact of the stations' area range in Fig. 9. Starting from the distance of 500 m, we increase the area range for 15 stations by a step of 50 m in both directions, and we present the results of T_S^* for two capture thresholds of 2 dB and 10 dB. As long as the stations are distributed over a wider area, the packets sent by stations closer to the AP are more likely to be captured when encountering a collision. Hence, as seen in the figure, the entire group of stations requires a shorter T_S^* to deliver its traffic load. That is explained by the fact that a lower ratio of the distances of two colliding stations (i.e., r_i/r_ℓ in (13)) increases the conditional capture probability. Henceforth, the best case is when the stations are distributed in a range of 1000 m. Although all stations have the same chances of encountering a collision, the closest ones to the AP will mostly have their packets captured during a collision due to their higher received power. We additionally observe that the case of a 10 dB capture threshold is more affected by the stations' area range than the case of a 2 dB threshold. This is because the 2 dB threshold tolerates more packets being captured than the 10 dB threshold even if the stations are close to each other, as the SIR is more likely to exceed the lower threshold [19]. These results show that the best strategy to profit from the capture effect at the AP is to assemble stations located in a broader area. This will provide shorter RAW slot periods to serve the stations. However, the hidden node problem may appear if the stations are outside each other's sensing range, e.g., when two stations are located on opposite sides of the AP. This issue can be solved by performing sectorization before configuring the RAW and choosing stations from the same sector where all stations can hear one another.

VI. CONCLUSION

This paper considers an IEEE 802.11ah-based network where stations are distributed around the AP and operate under a Rayleigh-fading channel with capture enabled. We developed an analytical model to evaluate the channel access performance and propose an algorithm to derive a LACA time for a group of stations assigned to a RAW slot. Our framework is based on a two-level renewal process that models the events within the channel when allocated to a group of stations, where each station has one packet to transmit. The first-level renewal cycle resets after every transmission attempt within the channel, while the second-level renewal cycle ends after every successful transmission, which can occur either when only one single station transmits or when the AP captures a packet from a collision. To highlight the effectiveness of the proposed LACA algorithm, we evaluated the PDR and channel usage for a pre-allocated RAW slot in terms of designated stations, payload size, and capture threshold. We further investigated the impact of the spatial distribution of stations in terms of both the area range and the distance from the AP.

Our analytical findings have been validated via extensive simulations obtained by a discrete-event simulator we developed with MATLAB. While most scheduling schemes for dense networks are based on assigning stations into groups with pre-allocated channel time, this paper shows that allocating an adequate channel time to every group of stations is crucial. This operation is based on the state of contending stations (i.e., traffic load and locations) and can ensure successful delivery of all packets or a PDR and channel usage up to a certain extent. This approach of load-aware RAW slots is practical for remote sensing applications to minimize the AoI at the AP and enhance the freshness of received data. With appropriate RAW slot allocation, all designated stations can transmit their packets without further attempts in subsequent RAW slots. Compared to a random pre-allocation of the RAW slot period, the proposed algorithm yields complete delivery of all packets while improving the channel usage up to more than 80%.

The analytical framework developed in this paper provides an adaptive and load-aware channel allocation scheme based on the dynamic conditions of the network. This framework can be implemented in a global configuration scheme for the RAW mechanism in a heterogeneous network. Different types of stations with different payload sizes and rates of generating packets could be considered. The proposed LACA algorithm can be improved towards dynamic inputs, such as the arrival rate of packets and the mobility of stations. Additionally, our proposals are practical for alternative communication technologies addressing dense scenarios with the integration of periodic channel reservations.

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