Configuration of the Group Membership on EDCA-enabled IEEE 802.11ah Networks

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***Abstract*—The Internet of Things (IoT) is making its way into most aspects of our daily lives, pushing for the requirements of more robust communication services. For this reason, the IEEE 802.11ah standard, also known as Wi-Fi HaLow, has been developed, seeking to deal with dense multiservice wireless networks. This paper addresses the performance of the Enhanced Distributed Channel Access (EDCA) and Restricted Access Window (RAW) mechanisms in terms of four metrics: the throughput, the number of transmitted packets, the number of collisions and the packet transmission latency. The objective of this work is to evaluate the performance of EDCA-enabled IEEE 802.11ah Networks and more importantly to define the best multi-priority grouping strategy.**

***Index Terms*—IEEE 802.11ah, Internet of Things, Performance evaluation, RAW mechanism, EDCA.**

I. Introduction

The increasing demand for the Internet of Things (IoT) has led to a growing number of devices, necessitating more robust networks and additional Access Points (APs). The IEEE 802.11ah standard, also known as Wi-Fi HaLow, introduces a significant advancement in wireless networks [1]. Adopted in 2016, this standard is specifically designed to address the challenges of applications requiring low power consumption and long-range connectivity. Operating in the sub-1GHz bands, IEEE 802.11ah facilitates increased signal penetration and offers extended coverage, proving particularly advantageous in challenging environments. This standard is tailored to support a large number of devices, thereby enhancing network management in scenarios where device density is high.

The primary objectives of this research work on IEEE 802.11ah networks encompass an approach aiming to gain comprehensive insights into this wireless standard. We focus on refining this innovative standard to amplify the number of successful transmissions while mitigating the risk of higher collision rates. The motivation behind our efforts lies in strategically planning scenarios to discern the best protocol configuration strategies that yield superior performance. Specifically, we evaluate the performance of the Restricted Access Window (RAW) and the Enhanced Distributed Channel Access (EDCA) mechanisms defined by the IEEE 802.11ah and IEEE 802.11e standards, respectively. This approach reflects our objective to advance the capabilities of IEEE 802.11ah to meet the evolving needs of an increasingly multiservice IoT landscape.

This work consists of five sections. Following this introduction, Section II reviews the IEEE 802.11ah standard MAC mechanisms. Section III covers an overview of related works. Section IV presents a performance evaluation of the EDCA-enabled RAW mechanism and introduces our multiservice grouping recommendations. Finally, Section V draws our conclusion and presents our future research directions.

II. The IEEE 802.11ah Standard

The IEEE 802.11ah standard is primarily designed for IoT networks mainly characterised by comprising a large number of low-power nodes. The standard uses frequencies below 1 GHz. The IEEE 802.11ah comes with several amendments on both physical and MAC layers that vary from the legacy 802.11 standards [2]. The IEEE 802.11ah PHY layer inherits most of its features from IEEE 802.11ac, adapted to frequencies below 1 GHz, increasing the range up to 1 km, and needing less power usage. To provide reliable connectivity in dense scenarios, IEEE 802.11ah introduced the RAW mechanism, which divides stations into groups and allocates a RAW period to each group. To reduce the contention overhead even more, each RAW can be divided into shorter periods, named RAW slots. The N STAs that are assigned to a RAW are also distributed across K RAW slots using a round-robin assignment policy with an offset value N_{offset}, as illustrated in Fig. 1. During a RAW slot, only the assigned STAs are allowed to compete for channel access.

During each RAW slot, the assigned STAs use Distributed Coordination Function (DCF) or EDCA protocols to access the channel. To make it viable for the RAW mechanism, each STA has two backoff function states to manage the access inside and outside the RAW slot to which they are assigned. The first backoff function is implemented outside RAW periods, where each STA retains and pauses the state of the backoff function to be restarted after the RAW period. The second backoff function is utilized within RAW slots, where each STA initiates a backoff timer at the beginning of its RAW slot, and discards it at the end of it.

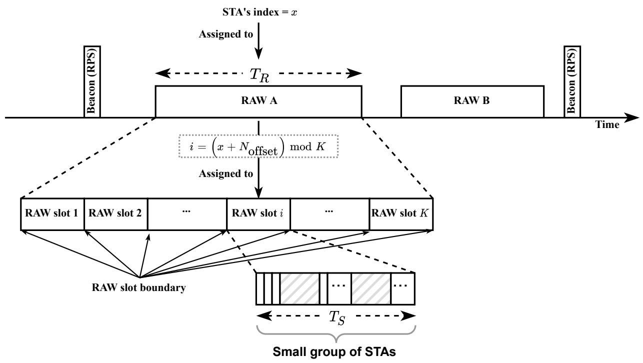


Fig. 1: Representation of RAW mechanism

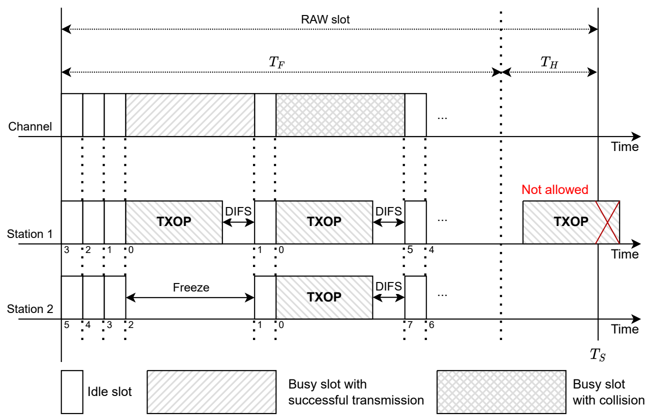


Fig. 2: Structure of a RAW slot

The structure of a RAW slot is depicted in Fig. 2. The RAW slot period T_S is divided into a free access period T_F and a holding period T_H. During T_F the STAs contend for channel access. During T_H the STAs are not allowed to start transmitting, so that the transmissions do not cross the RAW slot boundary T_S.

A. EDCA protocol

In the case where IEEE 802.11ah supports various types of services, the channel access within a given RAW slot operates under the EDCA protocol [3]. The EDCA mechanism defines four different access categories (ACs), according to the types of services that the STAs support [4]:

1) **Background traffic (BK)**: All traffic not requiring strict throughput or latency is set into this category.
2) **Best Effort traffic (BE)**: This group defines a network service in which the network does not provide any guarantee that data is delivered.
3) **Video traffic (VI)**: This category provides the support for time-constrained video services, such as video streaming or video conferencing applications.
4) **Voice traffic (VO)**: This category includes Voice over Internet Protocol (VoIP) calls and allows concurrent calls with low latency and high voice quality.

These categories will be assigned different priorities depending on the EDCA protocol, the IEEE 802.11ah incorporates two different sets of values according to the types of STAs, namely sensor or non-sensor STAs. Each AC is characterized by the following EDCA parameters:

- $CW_{\min}$ and $CW_{\max}$ (minimum and maximum Contention Window (CW) sizes, respectively), which define the maximum deferral time that the Binary Exponential Backoff (BEB) can generate a backoff counter in the range [0, CW] before transmitting the packets.
- Arbitrary InterFrame Spacing (AIFS) is the period the medium is sensed to be idle before the backoff is initiated [5]. EDCA uses AIFS for deferring the time before channel access occurs, giving different values of AIFS-number (AIFSN) to each AC. The difference from DCF used in legacy IEEE 802.11 is that instead of working with DCF Interframe Space (DIFS), we change it to the AIFS, which is calculated as follows:

$$AIFS_{AC} = AIFSN_{AC} \cdot \sigma + SIFS \tag{1}$$

The EDCA parameters have been set by assigning the smaller values to the AIFSN parameter. However, some studies have revealed that the values do not ensure a better service to the high-priority ACs [6]. Fig. 3 shows the timing diagram of the EDCA mechanism.

Due to the different characteristics of the applications to be supported by IEEE 802.11ah networks, the EDCA parameter values have been redefined. In fact, the standard includes two different sets of EDCA parameters: one for sensor STAs and a second one for non-sensor STAs. In this work, we consider only sensor STAs with the default EDCA parameters depicted in Table I.

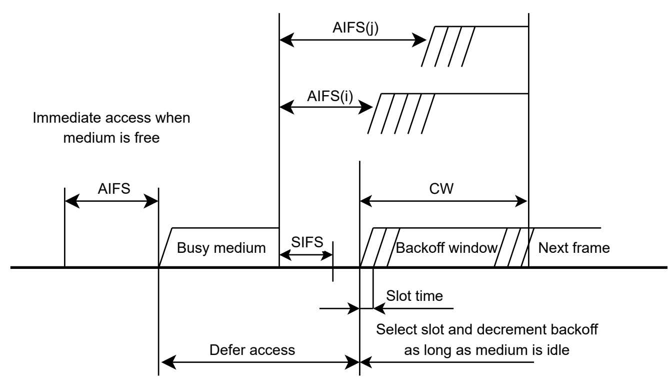


Fig. 3: EDCA timing diagram

TABLE I: Default EDCA parameter values for sensor STAs

AC	$CW_{\min}$	$CW_{\max}$	AIFSN
BK	$aCW_{\min}$	$aCW_{\max}$	7
BE	($aCW_{\min}$+1)/4 - 1	$aCW_{\min}$	2
VI	($aCW_{\min}$+1)/2 - 1	$aCW_{\min}$	5
VO	($aCW_{\min}$+1)/2 - 1	$aCW_{\min}$	4

III. Related works

Over the past years, many research groups have conducted numerous studies on the performance and configuration of the IEEE 802.11ah RAW mechanism. However, fewer have investigated the performance of the EDCA mechanism as defined by the IEEE 802.11ah standard. Most of these studies report modelling and simulation results. Fortunately, some recent works report some preliminary experimental evaluations of IEEE 802.11ah platforms [7].

In [4], the authors provided a survey of the IEEE 802.11ah MAC protocols reported in the literature. Among the major issues covered by the review, some works have focused on: 1) the ideal size and number of RAW slots for optimizing throughput; and 2) the scheduling of multiple-priority traffic. However, different to the work herein, previous works have not explored the impact of the EDCA parameters on the network performance with the goal of deriving better grouping strategies. In this work, we derive a grouping strategy derived from a study of EDCA and RAW parameters. Furthermore, our proposal provides the guidelines on how to configure the RAW slot groups taking into account the characteristics and requirements of popular low-bitrate voice codecs.

In [8], the authors studied the performance of IEEE 802.11ah in supporting real-time data delivery for applications such as remote sensing and control, highlighting the critical nature of receiving sensor updates as they are generated. To address latency concerns, they proposed an adaptive approach that adjusts the duration of each RAW slot to accommodate the delivery of data from all assigned STAs. This adaptive slot duration aims to eliminate the need for STAs to contend for access in subsequent RAW slots, thereby ensuring smoother and more efficient data transmission. However, they only consider the DCF mechanisms as the primary MAC protocol.

In [9], the authors delved into the dynamics of an IEEE 802.11ah-based network architecture, specifically examining how the AP manages channel time by segmenting it into RAW slots and controlling access for designated STAs within each slot. The study focused on scenarios with unsaturated traffic, where individual STAs possess a single packet for transmission during the RAW slot period, a practical scenario typically found in sensors requiring periodic updates. Additionally, the research incorporated a consideration of a Rayleigh fading channel with capture enabled.

In [10], Oktaviana et al. investigated the performance of IEEE 802.11ah with EDCA, focusing on the AIFS parameter. They considered non-sensor STAs, which have EDCA parameters different from those of the sensor STAs. They found that the value of the AIFSN affected network performance, but the evaluation metrics, the number of STAs and the traffic load on the network also influenced it.

In another close-related work, Coronado et al. [6] studied the adequacy of the IEEE 802.11 EDCA parameters. Their findings revealed that in the presence of hidden nodes, the parameters are unable to mitigate the number of collisions encountered by the VO and VI services.

In this work, we develop the principles of the configuration of groups of STAs in an IEEE 802.11ah network that supports more than one AC. In particular, we are interested in configuring an IoT network supporting voice and data services. Our choice is justified by the interest in supporting time-constrained services over IEEE 802.11ah networks. We have discarded the use of video services since recent experimental studies have found the deployment of video in a multiservice scenario to be unfeasible [11]. However, the deployment of low-bitrate voice applications should be made possible. In particular, low-bitrate codecs, such as the OPUS codec, support bitrates as low as 6 kbps [12].

IV. Configuration Grouping Scheme

In this section, we start by evaluating and identifying the benefits and shortcomings of two main grouping configuration strategies in an IEEE 802.11ah network that provides service to STAs belonging to different ACs. First, we study groups consisting of STAs belonging to a single AC, and then groups of STAs of two different ACs. As previously mentioned, we do not consider the VI AC due to recent findings reported in [11]. Therefore, we shall derive the guidelines to configure groups consisting of STAs belonging to different ACs.

Throughout our work, we use a MATLAB simulator implementing the EDCA and RAW mechanisms as defined by the IEEE 802.11ah standard. We assume that at the beginning of the RAW slot, all assigned STAs are ready to transmit. Furthermore, each STA will be allowed to transmit one packet per RAW slot. This traffic scenario will be particularly useful to set the basis for a mechanism guaranteeing the periodic delivery within the time-constraint of VO AC services. Similarly to [10], we consider the values 15 and 1023 for $aCW_{\min}$ and $aCW_{\max}$, respectively. Table II and Table III summarize the values of EDCA and network parameters.

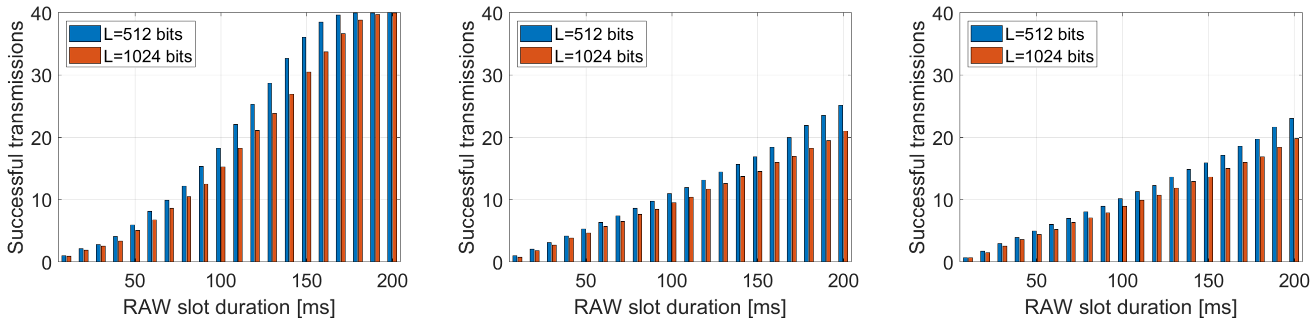
We refer to a packet with a payload of L-bits as an L-bits packet and we set L by considering the use of popular low-bitrate codecs, such as OPUS. OPUS offers bitrates between 6 kbps and 510 kbps. For instance, we may consider a codec operating at a bitrate of 32 kbps and voice blocks of 20 ms. This setting corresponds to voice block of 80 Bytes which

TABLE II: EDCA parameters for sensor STAs.

AC	$CW_{\min}$	$CW_{\max}$	**AIFSN**
BK	15	1023	7
BE	3	15	2
VI	7	15	5
VO	7	15	4

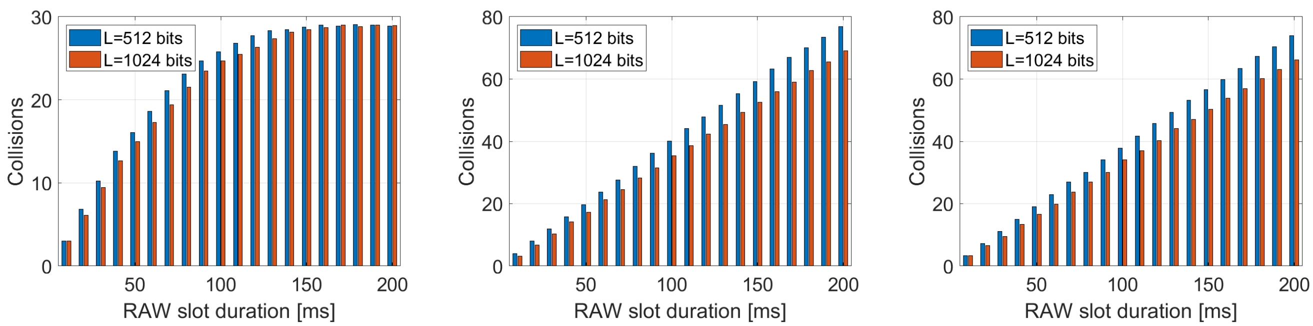
TABLE III: Network parameters

Parameters	Value
Data rate	1.95 Mbps
Payload size (L)	512 and 1024 bits
MacHeader	272 bits
σ	52 μs
SIFS	160 μs
T_{PLCP}	80 μs
T_{ACK}	1000 μs



(a) 40 BK stations (b) 40 BE stations (c) 40 VO stations

Fig. 4: Number of successful transmission for single AC case.



(a) 40 BK stations (b) 40 BE stations (c) 40 VO stations

Fig. 5: Number of collisions for single AC case.

is encapsulated into a MAC layer. Accordingly, our study provides the basis to evaluate the feasibility of deploying codec-based voice services, such as OPUS.

A. Single AC groups

Fig. 4 and Fig. 5 show the number of successful transmissions and collisions for three of the four ACs, namely BK, BE and VO. Each bar is the result of averaging the number of successful transmissions and collisions obtained in 1000 simulations for a given RAW slot length. Fig. 4a reveals that all 40 BK STAs are able to transmit when the RAW slot length is set to 170 ms/190 ms or longer in the case of 512-bits/1024-bits packets. However, in the case of the BE and VO ACs, not all 40 STAs are able to transmit even when the RAW slot length is set to its maximum value. Since our study assumes an error-free channel, our results reveal that the EDCA parameter setting for the BE and VO ACs are unable to effectively mitigate the channel access conflicts. Fig. 5 shows that the collisions for the BE and VO ACs are substantially higher than the ones reported for the BK AC traffic. Increasing the RAW slot length up to 200 ms results in a slightly increase in the number of successful transmissions at the expense of significant increase on the number of collisions. In fact, the results report a ratio of 4 collisions per successful transmission. Such a ratio will have a very negative impact not only on the packet loss ratio, but also on the energy wasted by the sensor STAs [13].

B. BK/VO AC groups

This section explores the performance of groups consisting of two ACs. Since our experiments have revealed similar results for both payload lengths and due to space limitation, we only include results for 512-bits packets. Furthermore, we will focus on groups consisting of two different ACs, in particular groups composed of BK and VO STAs. The main reason behind this choice is twofold: 1) the BK exhibited better results in terms of successful transmissions and lower collision rates than the BE and VO ACs, and 2) our interest in evaluating the latency experienced by the VO STAs.

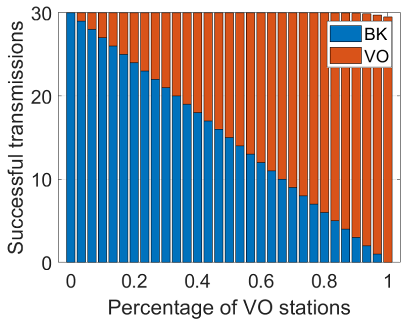
We explore the performance of RAW mechanism by varying the number of STAs and percentage of VO STAs. It should be noted that this study can be straightforwardly applied to groups consisting of STAs of two other or even more ACs.

In this study, we define by N_{BK} and N_{VO} the number of BK and VO STAs, respectively. We express the total number of STAs assigned to the RAW slot as follows:

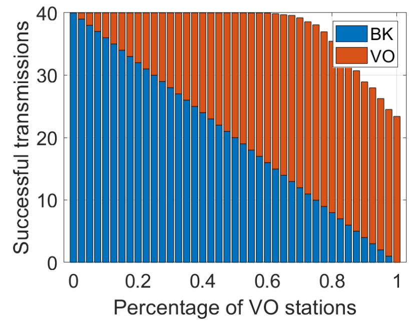
$$N = N_{BK} + N_{VO} \tag{2}$$

where N_{BK} and N_{VO} are given by

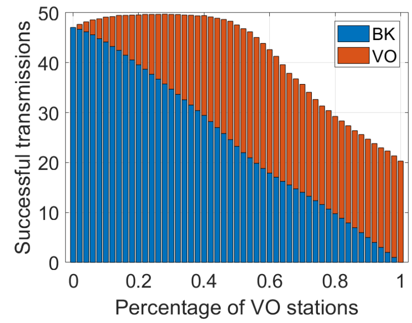
$$N_{BK} = \alpha \cdot N \tag{3}$$



(a) 30 BK/VO stations

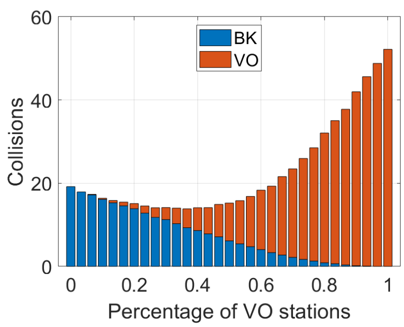


(b) 40 BK/VO stations

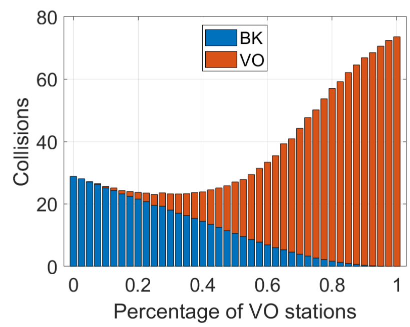


(c) 50 BK/VO stations

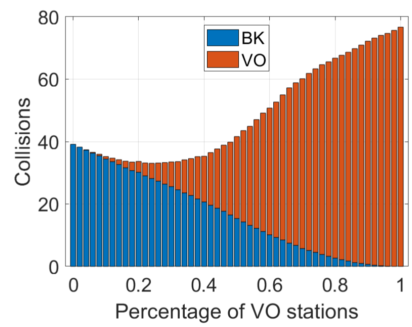
Fig. 6: Number of successful transmissions for BK/VO groups - 512 bits.



(a) 30 BK/VO stations



(b) 40 BK/VO stations



(c) 50 BK/VO stations

Fig. 7: Number of collisions for BK/VO groups - 512 bits.

$$N_{VO} = (1 - \alpha) \cdot N \tag{4}$$

with α being the percentage of BK STAs.

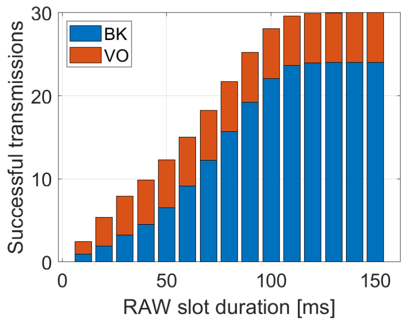
Fig. 6 and Fig. 7 show the number of successful transmissions and collisions for the three different group sizes under study and a RAW slot of 200 ms. As shown in Fig. 6b, if we reduce the size of the RAW group to 30, all 30 STAs are able to transmit independently of the percentage of BK or VO STAs making part of the group. Fig. 7a confirms once more that when the group of STAs is made up of only BK STAs, the number of collisions is significantly less than in the case of a group composed of only VO STAs. Furthermore, we should also notice that the minimum number of collisions is reported for a BK/VO group consisting of 40% of VO STAs, i.e., 12 VO STAs and 18 BK STAs. We should further explore this scenario in the following section to evaluate the VO AC transmission delay.

Fig. 6b and Fig. 7b show the number of successful transmissions and collisions for a group of 40 BK/VO STAs. Fig. 6b shows that all 40 STAs are able to transmit during a 200 ms-long RAW as far as the number of VO STAs does not make more than 60% of the total number of STAs, i.e., a group composed of 24 VO STAs and 16 BK STAs. This is a high relevant result since it sets the basis to develop a group configuration scheme. However, we should notice that the minimum number of collisions is reported for a similar group composition found when the group size if fixed to 30, see Fig. 7a and Fig. 7b. That is to say when the number of VO STAs is set to 40% of the total number of STAs.

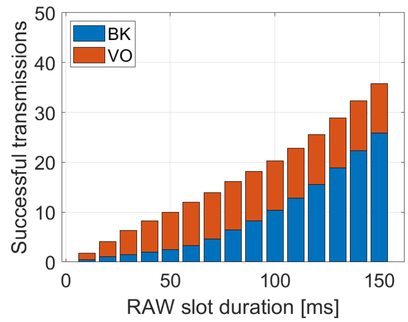
Fig. 6c and Fig. 7c depict the number of successful transmissions and collisions for a larger group of STAs consisting of 50 BK/VO STAs. We notice that different to the two previous cases, when the group is exclusively composed of BK STAs, not all 50 STAs are able to transmit. Furthermore, as the percentage of VO STAs increases, the total number of successful transmissions rises up to the maximum of 50. It is worth noticing that when the percentage of VO STAs is set to 40%, i.e., 20 VO and 30 BK STAs, all STAs are able to transmit. These results represent a substantial gain on the network throughput. Similar to the case of a group of 40 STAs, as the percentage of VO STAs is increased, the total number of transmissions decreases substantially and the number of collisions increases, see Fig 7c.

C. QoS-aware BK/VO AC groups

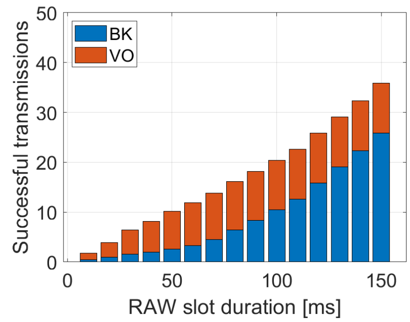
In this section, we should now set the guidelines on how to configure QoS-aware groups of BK and VO STAs capable of meeting the latency requirements of low-bitrate voice services. Given that the maximum acceptable end-to-end delivery delay of 150 ms for voice communication [12], we set the percentage of VO STAs to 20% and the RAW slot



(a) 24 BK - 6 VO stations



(b) 32 BK - 8 VO stations



(c) 40 BK - 10 VO stations

Fig. 8: Number of successful transmissions for groups consisting of 80% BK and 20% VO - 512 bits.

duration to 150 ms. This percentage is lower than the optimal value of 40% reported in Fig. 8. In the case of a group of 30 STAs, all the STAs of the BK/VO group are able to deliver their packets.

Fig. 8 shows the results for the different group sizes. In all cases, all VO STAs are able to transmit their packets in less than 150 ms. However as the group size is increased not all BK STAs are able to transmit their packets. According to the IEEE 802.11ah, the ungranted BK packet transmission requests will be required to restart the access procedure. It is therefore left up to the developers to make use of shorter or longer RAW slots accordingly.

Since time-sensitive applications require very low values of Age of Information (AoI) to guarantee the freshness of updates [14], our findings provide valuable insights for deploying IEEE 802.11ah in such scenarios. The results of this work can serve as a basis for designing effective protocols that assign STAs with different AC traffic to RAW slots of adequate lengths. Such an approach ensures the successful delivery of all packets from the same group of STAs in the first allocated RAW slot. Consequently, each STA delivers a fresh packet (update) in the first attempted RAW slot, significantly enhancing the AoI in the network.

V. Conclusion and Future Work

In this work, our main findings revealed that the values of the EDCA parameters set by the IEEE 802.11ah standard have a negative impact on the MAC protocol performance. We then studied different AC grouping schemes. Our findings provided the means to define the best grouping scheme by combining STAs belonging to two different ACs. Furthermore, for the case of time-constrained voice services, we developed a grouping strategy based on the requirements of OPUS low-bitrate codec. Our immediate research plans will focus on extending the grouping schemes to all the four EDCA ACs.

Acknowledgment

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