Research Article

Enhancing IEEE 802.11ah Networks: A Spatial Multi-Channel MAC Protocol

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Abstract. *IEEE 802.11ah is designed to enhance IoT networks by supporting numerous stations, extending coverage range, reducing power consumption, and operating within the sub-1 GHz band. The Restricted Access Window is introduced to mitigate collisions and improve network throughput when multiple stations contend for the channel simultaneously. While the PHY layer in IEEE 802.11ah supports multiple channels with different bandwidths, the MAC layer only supports a single channel for communication between the Access Point (AP) and stations. However, network performance can be improved by enabling stations at different locations to exchange data packets on different channels concurrently. This paper proposes a Spatial Multi-channel MAC (SM-MAC) protocol for IEEE 802.11ah, which divides the AP's coverage area into sectors, each assigned a dedicated channel. Each sector is served by two Forwarders responsible for relaying data packets between stations and the AP. The performance of the SM-MAC protocol is evaluated against the IEEE 802.11ah MAC protocol in terms of packet delivery ratio, throughput, and energy efficiency.*

Keywords

IoT networks, IEEE 802.11ah, Multi-channel MAC protocol, Restricted Access Window, WiFi Halow.

1. Introduction

The Internet of Things (IoT) is a vast network of everyday objects, including devices, vehicles, and appliances, that can communicate and share information with each other. These devices range from simple home devices to complex industrial machinery, enabling communication with other internet-connected devices to create an interconnected network capable of autonomous data exchange and task execution. IoT applications are diverse and include smart homes, smart cities, industrial IoT, environmental monitoring, agriculture, and healthcare. IoT brings a whole new level of connectivity to the information and communication technology world, offering ubiquitous connectivity anytime, anywhere, for anything. The development of wireless communication technology that satisfies the needs of diverse Internet of Things applications, including long-range transmission, large-scale connectivity, low power consumption, bounded delay, and stable throughput, is essential. Wireless Personal Area Networks, such as ZigBee and Bluetooth Low Energy, offer medium data rates at a short range. Low-Power Wide Area Network technologies, such as LoRa, SigFox, NB-IoT, eMTC, Wi-SUN, and IEEE 802.11ah, support low or medium data rates and are focused on long-range communications. IEEE 802.11ah, also called Wi-Fi HaLow, is a recently introduced Wi-Fi standard that provides the highest data rate and a medium transmission range between WPAN and most LPWAN technologies (Fig. 1).

IEEE 802.11ah [2] offers network connectivity for up to 8,192 stations with data rates ranging from 150

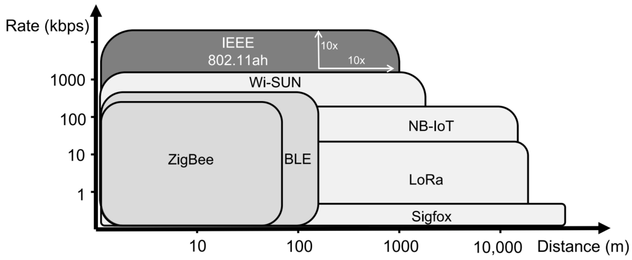

Fig. 1: WPAN and LPWAN technologies [1].

kbps to 78 Mbps within a 1 km transmission range. It supports different channel bandwidths on unlicensed sub-GHz frequency bands, including 863–868 MHz, 755–787 MHz, and 902–928 MHz in Europe, China, and North America, respectively (Fig. 2). In order to improve high scalability and energy efficiency, IEEE 802.11ah incorporates novel features, such as a short MAC header, fast association and authentication, a Restricted Access Window (RAW), a Traffic Indication Map (TIM), a Target Wakeup Time (TWT), and Hierarchical Organization.

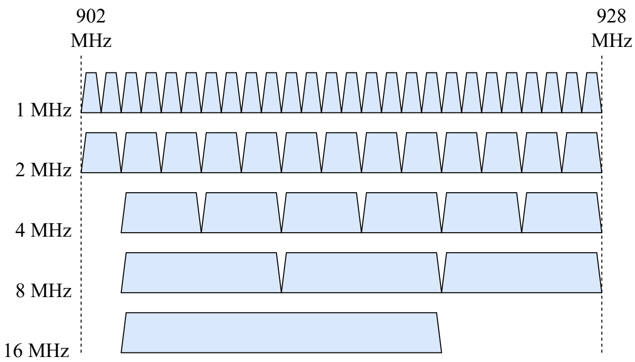

Fig. 2: US channelization.

To accommodate a large number of stations, IEEE 802.11ah utilizes a hierarchical Association Identification (AID) structure organized into pages, blocks, subblocks, and device position indexes. Stations within a page are allocated to different Delivery Traffic Indication Map (DTIM) periods, DTIM periods to TIM periods, and TIM periods to RAW slots in a hierarchical manner. Within a TIM period, there may be one or more RAWs, and the RAW mechanism is introduced to reduce collisions and interference among stations.

The use of scalable communication technologies to connect a large number of devices for IoT applications is essential. However, current implementations require the use of a combination of different techniques, leading to increased network complexity. In addition to enhancing scalability, utilizing frequencies below 1 GHz and supporting various modulation and coding schemes (MCS) allows for easy configuration of IoT applications. Data rates ranging from 150 Kbps to 78 Mbps are suitable for low-power IoT devices. Furthermore, IoT devices only need to wake up for short periods to transmit data and enter sleep mode for the remaining time to conserve energy.

The remainder of this paper is organized as follows. Section 2 describes the literature review on MAC protocols in IEEE 802.11ah networks. Section 3 presents the key features of the IEEE 802.11ah MAC protocol. The details of the proposed SM-MAC protocol are presented in Section 4. The performance analysis and evaluation are presented in Sections 5 and 6, respectively. Finally, Section 7 concludes our work.

2. Related works

RAW is designed to mitigate the collisions among stations in IEEE 802.11ah by using a station grouping mechanism. Raeesi *et al.* [3] proposed a model to analyze saturation throughput, packet delay, and energy efficiency for known collision probability and packet error rate. Tian *et al.* [4] evaluated the impact of the number of stations and traffic conditions on the optimal values of the number of RAW groups. An adaptive RAW group is necessary to maximize performance under dynamic conditions. By taking into account the reset of backoff state at the beginning of the RAW slot, Khorov *et al.* [5] developed a mathematical model for saturated state based on Bianchi's model [6], a discrete-time Markov chain model, to estimate throughput and energy consumption of the RAW with the cross-slot boundary. Chang *et al.* [7] proposed a traffic-aware grouping algorithm to improve channel utilization.

Šljivo *et al.* [8] investigated how RAW and TIM segmentation influence scalability, throughput, latency, and energy efficiency in the presence of bidirectional TCP/IP traffic. Kai *et al.* [9] designed the traffic distribution-based sensor grouping scheme to balance the energy efficiency of different groups in large-scale access networks. Nawaz *et al.* [10] proposed a method in which the RAW frame is divided into two subframes, and the timing of RAW slots for each sub-frame is selected based on group size, resulting in improved throughput for RAW in clustering scenarios. Ahmed and Hussain [11] introduced a method for the AP to predict transmission times by dividing RAW into two phases: a competing phase and a reservation phase, enabling the scheduling of data packets before their arrival. This advanced scheduling reduces channel competition and unnecessary wake-ups, making it suitable for large networks with a focus on low latency and energy efficiency. Sangeetha *et al.* [12] presented an analytical model to evaluate the saturation throughput of IEEE 802.11ah with different data rates and proposed a clustering algorithm based on data rates to improve fairness and overall system throughput.

Model-Based RAW Optimization Algorithm (MoROA) [13] used the trained surrogate RAW model to determine the optimal RAW configuration in different network and traffic conditions. Mondal *et al.* [14] evaluated network performance, particularly throughput, by varying the number of stations and RAW groups. Their findings indicated that the optimal number of RAW groups depends on the total number of stations within the network. Unlike the fixed RAW size in IEEE 802.11ah, Fahad *et al.* [15] proposed a method enabling the AP to dynamically adjust the RAW size based on network packet transmission and the number of transmitting stations. Taramit *et al.* [16] proposed an analytical model based on a two-level renewal process to assess channel access contention in IEEE 802.11ah networks operating under Rayleigh fading conditions with capture effects. The paper also introduced a Load-Aware Channel Allocation (LACA) algorithm designed to optimize RAW slot durations for complete packet delivery while maximizing channel utilization. Mondal *et al.* [17] proposed a Machine Learning (ML)-based station grouping model that accurately predicts RAW configuration parameters, aiming to enhance RAW performance in a real-world IoT network. Additionally, it introduces a channel access technique that employs an ML model to assign nodes to reserve slots and adjust their slot durations when nodes cannot access the channel due to collision detection. Nabuuma *et al.* [18] eliminated collisions in the zoned network by setting station back-off values according to their AID position within the group.

Jamali *et al.* [19] introduced an association control method aimed at reducing blocking probability in IEEE 802.11ah mIoT networks through two schemes: limiting the number of devices associated with an AP without utilizing information about IoT device traffic, and determining the number of devices an AP can admit based on the maximum traffic generated by those devices. Mahesh and Harigovindan [20] proposed a service differentiation model for Group-Synchronized Distributed Coordination Function (GS-DCF), grouping stations and assigning priorities based on their data transmission needs. In the Registration-Based Collision Avoidance Mechanism [21], the AP schedules station data transmission based on pre-registered back-off values to prevent collisions.

Existing works [22, 23, 24] have proposed sectorized grouping. In [22], stations are divided into sectors, then further grouped according to the number of stations and their location. By utilizing a spatially orthogonal access method, the stations in different groups within different sectors can access the channel during their assigned RAW slots. This approach reduces the packet collision probability, leading to a significant improvement in the network throughput and a decrease in system delay. In the directional ah MAC protocol (Dah) [23, 24], the AP partitions its coverage into different sectors, employing antennas capable of operating in both omnidirectional and directional modes. A RAW is divided into four SubRAWs, with each SubRAW aligned to a specific dual sector. During a given RAW slot, stations within a particular dual sector contend for channel access to communicate with the AP without collisions. Both proposals also reduce the number of stations contending for the channel compared to the IEEE 802.11ah protocol, resulting in a significant improvement in packet delivery ratio and system throughput. Additionally, the Dah protocol also implements an adaptive transmission power scheme for uplink transmission to improve the network energy efficiency in [24]. However, these proposals are implemented with a single channel at the MAC layer, and they cannot fully utilize the multiple-channel resources. The SF-MAC protocol [25] enables stations to communicate with the AP through Forwarders operating on different channels. By organizing stations into sectors and utilizing multiple channels for data transmissions, the SF-MAC improves packet delivery ratio and overall network throughput.

This paper introduces a Spatial Multi-channel Medium Access Control (SM-MAC) protocol designed for IEEE 802.11ah networks. The protocol employs a spatial organization strategy, clustering stations into distinct sectors based on their geographical locations. Intermediate stations, known as Forwarders, relay communication between the AP and stations within each sector. During each RAW, Forwarders and stations in a given sector operate on separate channels, while the AP alternates between the channels of each sector to receive and transmit data packets. Compared to IEEE 802.11ah, the SM-MAC protocol significantly improves network performance by taking advantage of multiple channel resources.

3. IEEE 802.11ah MAC protocol

3.1. Association and Authentication

IEEE 802.11ah supports two approaches for Association and Authentication: the Centralized Authentication Control (CAC) and the Distributed Authentication Control (DAC) approaches. In the CAC approach, the stations choose a random number in the range [0, 1023]. The AP sets an Authentication Control Threshold (ACT) and broadcasts it in every beacon interval. Each station with a random number less than or equal to the threshold ACT is allowed to send an Authentication Request to the AP within the same beacon interval. Otherwise, it is not allowed to access the channel until the next beacon interval. In the DAC approach, each beacon interval is divided into Authentication Control Slots (ACSs) of equal duration T_{ac}. Stations randomly select a beacon interval m and an ACS l to send their Authentication Request. If the Authentication Request attempt fails, the station increases the number of authentication retries and reselects m and l. Within the ACS, the station attempts to access the channel using the Enhanced Distributed Channel Access (EDCA) mechanism.

3.2. Restricted Access Window

IEEE 802.11ah introduces the Restricted Access Window mechanism to mitigate collisions and improve throughput in high-density IoT networks, where a large number of stations require access to the channel simultaneously. It combines TDMA and CSMA/CA, dividing the stations into groups, and allowing only those stations belonging to specific groups to access the channel using Distributed Coordination Function (DCF) and Enhanced Distributed Channel Access (EDCA) at certain times. Fig. 3 illustrates the RAW grouping mechanism. The channel access time is divided into several small intervals, some of which are assigned to RAWs, while others are considered shared channel airtime and can be accessed by all stations. Each beacon interval can include multiple RAWs, and each RAW is further divided into RAW slots. Stations assigned to a RAW are evenly split across the RAW slots using a round-robin approach. If a station belongs to a RAW group, it is allowed to contend for medium access only at the beginning of its assigned RAW slot and will not attempt to access the channel during any other RAW slot within that RAW. The number of slots N_{RAW}, Slot Format, and the Slot Duration Count C are also specified in the RPS element. At the beginning of the beacon interval, the AP broadcasts a beacon frame with a RAW Parameter Set (RPS) that specifies the RAW-related information, such as group start time, duration, and the stations assigned to RAW(s).

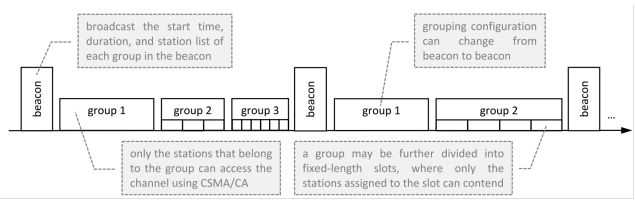

Fig. 3: RAW mechanism [1].

A station determines the index of its assigned RAW slot, i_{slot} as follows [8]

$$i_{slot} = (x + N_{offset}) \bmod N_{RAW} \quad (1)$$

where N_{offset} is the offset value used to improve the fairness among the stations, and x is the position index of the station's AID in the TIM bitmap; otherwise, x is the station's AID. Fig. 4 shows the RAW slot assignment for paged and non-paged stations.

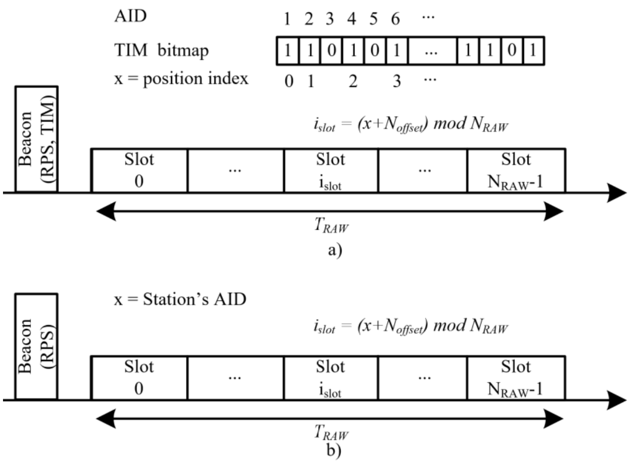

Fig. 4: RAW slot assignment [8].

4. The proposed SM-MAC protocol

Fig. 5 shows an IEEE 802.11ah network with N stations and a single AP for the SM-MAC protocol. The AP is equipped with two transceivers, each supporting omnidirectional and directional modes. Additionally, the AP supports a higher data rate on the channel f_a, while stations operate at a reduced data rate on different channels depending on their location. The AP divides its coverage into $S = 8$ sectors, and stations in sector $s, (s = 0, ..., 7)$ operate on the corresponding channel f_s. A dual sector is defined as two opposite sectors; *e.g.*, sectors 0 and 4 are considered to be a dual sector (0, 4). Since stations in each sector are within transmission range of each other, the hidden terminal problem is eliminated. For every sector s, the AP assigns a Uplink Forwarder (FWD_s^u) and a Downlink Forwarder (FWD_s^d). A Forwarder either receives the downlink data packets from the AP and passes them to stations on the corresponding channel f_s or collects the uplink data packets from their stations and transmits them to the AP on channel f_s.

During the Authentication/Association process, a new station attempts to connect with the AP on channel f_a. Based on the signal received from the station, the AP determines the station's location. The AP assigns a 16-bit Association ID (AID) to the station, where the sector index is represented by the three most significant bits (bits 0-2). Since the AID is 16 bits long, the SM-MAC supports up to 65,528 stations, with each

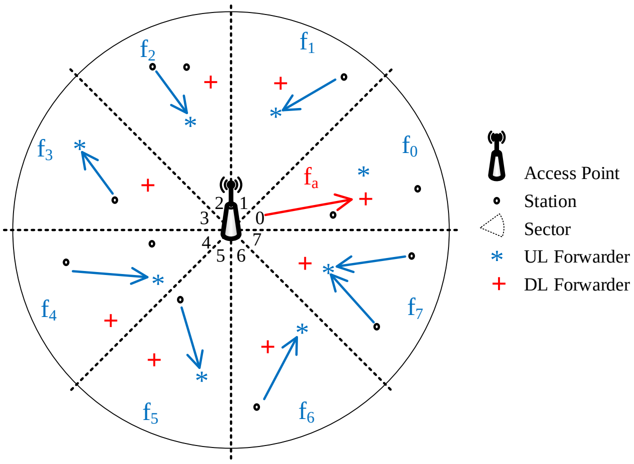

Fig. 5: Topology of the SM-MAC protocol.

sector having a maximum number of stations. Similar to [23, 24], the AID hierarchy includes sector, page, block, subblock, and station, as shown in Fig. 6. The first three bits of the AID indicate the station's sector, enabling it to communicate with forwarders FWD_s^u and FWD_s^d on the channel f_s.

Bit[th]	0–3	3–5	5–10	10–13	13–15
	Sector	Page	Block	Sub-block	Station
Station	001	00	00001	001	101

Fig. 6: AID structure in the SM-MAC protocol.

In the SM-MAC protocol, a RAW is divided into 2 SubRAWs: DL SubRAW and UL Sub RAW, as shown in Fig. 7. On the channel f_a, each SubRAW is further divided into 8 FD slots for the collision-free transmissions between AP and forwarders. On each channel f_s, SubRAW is divided into N_R RAW slots for the contention-based transmissions between the forwarder and its stations. Each RAW slot has a duration of $DSlot$.

In DL SubRAW, DL Forwarders FWD_s^d receive downlink packets from the AP on the channel f_a on behalf of their stations, while the stations transmit their uplink packets to the corresponding UL Forwarders FWD_s^u on the different channel f_s. In UL SubRAW, UL Forwarders FWD_s^u transmit the received uplink packets to the AP on the channel f_a, while the stations receive their downlink packets from the corresponding DL Forwarder FWD_s^d on the different channel f_s.

Fig. 8 illustrates the uplink (UL) communication process for stations in sector s. During the DL SubRAW, stations in sector s, denoted $STA_{\{s\}}$, contend for channel access to transmit the uplink packets to their UL Forwarder FWD_s^u within the assigned RAW slots on the channel f_s. Subsequently, in the UL SubRAW, the UL Forwarder FWD_s^u forwards the received uplink packets to the AP in the corresponding FD slot on the channel f_a at a high data rate in a collision-free manner.

Fig. 9 illustrates the downlink (DL) communications from the AP to the stations in sector s. In the FD slot of the DL SubRAW, the DL Forwarder FWD_s^d receives the downlink packets for its stations on the channel f_a. In the UL SubRAW, the stations contend to receive downlink packets from the DL Forwarder FWD_s^d on the channel f_s in the corresponding RAW slots.

5. Analytical Model

Consider an IEEE 802.11ah network comprising a single AP and N stations randomly distributed within the AP's one-hop coverage area. The stations always have uplink data to transmit to the AP, while the AP also always has downlink data for the stations. The downlink and uplink SubRAWs contain N_R^d and N_R^u RAW slots, respectively.

Our analytical model assumes that n stations simultaneously contend for channel access to communicate with their forwarders in a RAW slot. Following the approach in [7, 9, 11], we employ a Markov chain model under saturated conditions as described in [6]. Let $b(t)$ and $s(t)$ denote the stochastic processes representing the back-off counter and back-off stage, respectively, at slot time t. The discrete-time Markov chain models the two-dimensional process $\{s(t), b(t)\}$, as shown in Fig. 10. The maximum back-off stage is denoted by m, and the contention window (CW) for the i^{th} back-off stage is calculated as $W_i = 2^i \cdot W_0$, where i ranges from 0 to m.

The station attempts to transmit a packet when the back-off counter reaches zero. The probability, τ, that a station transmits a packet in a time slot is [6]

$$\tau = \frac{2(1-2p)}{(1-2p)(1+W_0) + pW_0(1-(2p)^m)} \tag{2}$$

The collision occurs when more than one station transmits in a time slot. The conditional collision probability p is assumed constant and independent [6]

$$p = 1 - (1-\tau)^{n-1} \tag{3}$$

The channel can be in one of three states: idle, successful, or collision. Let p_{ilde}, p_{suc} and p_{col} denote the probability that the channel is idle, the channel has a successful transmission, and the channel has collisions, respectively

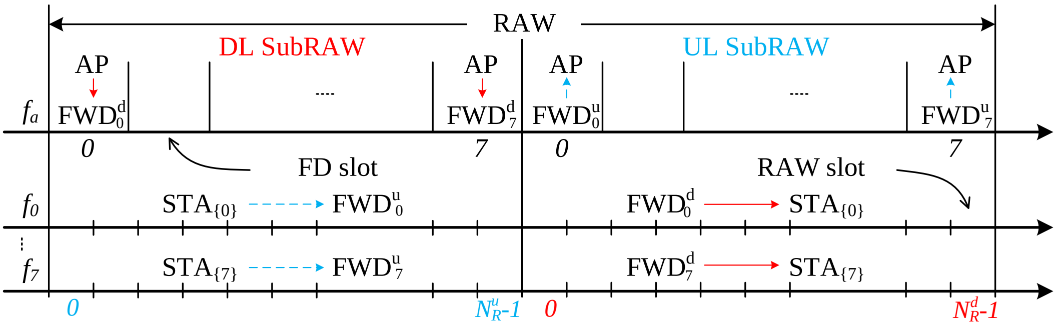

Fig. 7: The operation in the Restricted Access Window of the SM-MAC protocol .

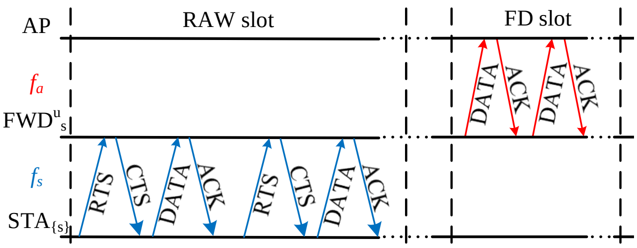

Fig. 8: Uplink communication in the SM-MAC protocol.

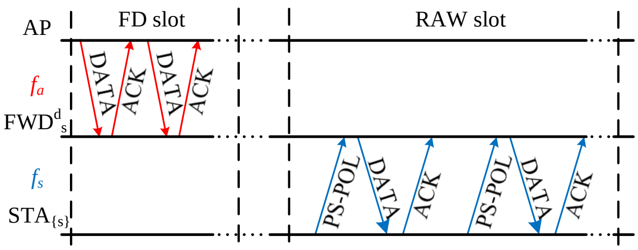

Fig. 9: Downlink communication in the SM-MAC protocol.

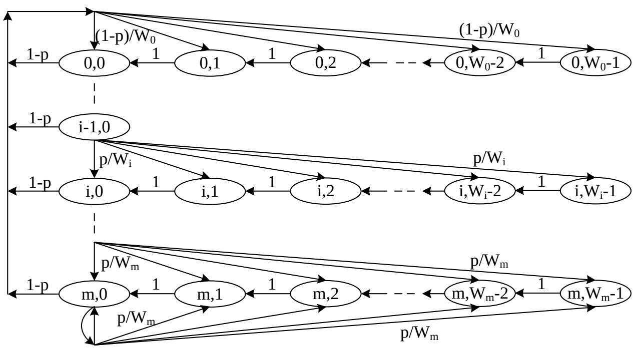

Fig. 10: Markov chain of the saturated network.

$$\begin{cases} p_{idle} = (1-\tau)^n \\ p_{suc} = n\tau(1-\tau)^{n-1} \\ p_{col} = 1-(1-\tau)^n - n\tau(1-\tau)^{n-1} \end{cases} \quad (4)$$

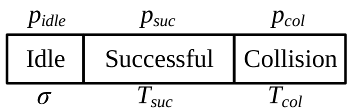

Fig. 11: Virtual transmission cycle.

Let δ and σ represent the propagation delay and an empty slot time duration, respectively. Fig. 11 illustrates a virtual transmission cycle with three possible states: idle, successful transmission, and collision transmission. The average time of a virtual transmission cycle and each successful packet transmission are denoted as $E[TC]$ and $E[TX_{suc}]$, respectively, and are given by

$$\begin{aligned} E[TC] &= p_{idle}\sigma + p_{suc}T_{suc} + p_{col}T_{col} \\ E[TX_{suc}] &= \tfrac{p_{idle}}{p_{suc}}\sigma + \tfrac{p_{col}}{p_{suc}}T_{col} + T_{suc} \end{aligned} \quad (5)$$

where T_{suc} and T_{col} are the durations for a successful transmission and a collision transmission, respectively.

We use the superscript $^{d/u}$ for DL and UL communications without loss of generality, respectively. For DL and UL communications, T_{suc} and T_{col} are determined as follows

$$\begin{aligned} T^d_{suc} &= T_{ps\_pol} + T^d_{data} + T_{ack} + 2T_{sifs} + 3\delta + T_{difs} \\ T^u_{suc} &= T_{rts} + T_{cts} + T^u_{data} + T_{ack} + 3T_{sifs} + 4\delta + T_{difs} \\ T^d_{col} &= T_{ps\_pol} + \delta + T_{difs} \\ T^u_{col} &= T_{rts} + \delta + T_{difs} \end{aligned} \quad (6)$$

The number of data packets transmitted successfully in a RAW slot is given by

$$N_{suc} = \frac{DSlot}{E[TX_{suc}]} \quad (7)$$

The total number of packets that are transmitted in a RAW slot is

$$N_{tx} = \frac{N_{suc}}{(1-\tau)^{n-1}} \quad (8)$$

Let P_i be the power consumption of a station in an idle state. The average energy consumption in each transmission cycle consists of the energy consumption in an idle state, the energy consumption of successful transmission, and the energy consumption when a collision happens. In case of a successful transmission, a transmitter consumes energy of E_{tx} and a receiver consumes energy of E_{tx} while the other stations consume energy of $P_i T_{suc}$. In case of a collision transmission among i stations, these stations consume energy of E_{col}, while the other stations consume energy of $P_i T_{col}$. The average energy consumption in each transmission cycle is

$$E[E_{TC}] = p_{idle} n P_i \sigma + p_{suc}(E_{tx} + E_{rx} + (n-2)P_i T_{suc}) + \sum_{i=2}^{n} \binom{n}{i} \tau^i (1-\tau)^{n-i} (iE_{col} + (n-i)P_i T_{col}) \quad (9)$$

Next, we compare the performance of the IEEE 802.11ah and the proposed SM-MAC protocol in terms of packet delivery ratio and throughput. Considering a network with N stations, the average number of contending stations in each RAW slot for the IEEE 802.11ah and the SM-MAC protocol is as given in Tab. 1.

Tab. 1: Number of stations in each RAW slot

	IEEE 802.11ah	SM-MAC
DL RAW/SubRAW	$n^d_{ah} = \frac{N}{N^d_R}$	$n^d_{sm} = \frac{N/8}{N^d_R}$
UL RAW/SubRAW	$n^u_{ah} = \frac{N}{N^u_R}$	$n^u_{sm} = \frac{N/8}{N^u_R}$

The probabilities that a station in the IEEE 802.11ah protocol transmits a packet in a time slot for downlink or uplink are denoted by τ^d_{ah} and τ^u_{ah}, respectively. Similarly, the probabilities for the SM-MAC protocol are represented by τ^d_{sm} and τ^u_{sm}, respectively.

5.1. Performance Analysis of IEEE 802.11ah

The packet delivery ratio (PDR) for the downlink (DL) and uplink (UL) RAW is

$$PDR^{d/u}_{ah} = (1-\tau^{d/u}_{ah})^{n^{d/u}_{ah}-1} \quad (10)$$

Let $DSlot$ denote the duration of each RAW slot. The total number of successfully transmitted packets downlink and uplink communication

$$N^{d/u}_{ah\_suc} = N^{d/u}_R \frac{DSlot}{E[TX^{d/u}_{ah\_suc}]} \quad (11)$$

where $E[TX^{d/u}_{ah\_suc}]$ is the average time of each successful packet transmission for DL/UL communication.

Let $E[P]$ represent the average packet payload length. Throughput is calculated as

$$S^{d/u}_{ah} = \frac{N^{d/u}_{ah\_suc} E[P]}{T_{RAW}} \quad (12)$$

Let $E\left[energy^{d/u}_{ah}\right]$ be the total energy consumption for downlink/uplink communications in a RAW. The energy efficiency η is defined as the ratio between successfully transmitted data and energy consumption.

$$\eta^{d/u}_{ah} = \frac{N^{d/u}_{ah\_suc} E[P]}{E\left[energy^{d/u}_{ah}\right]} \quad (13)$$

5.2. Performance Analysis of the SM-MAC protocol

The number of successfully transmitted packets for downlink/uplink communications

$$N^{d/u}_{SubRAW\_suc} = N^{d/u}_R \frac{DSlot}{E\left[TX^{d/u}_{sm\_suc}\right]} \quad (14)$$

The total number of data packets transmitted in downlink/uplink communications

$$N^{d/u}_{SubRAW\_tx} = \frac{N^{d/u}_{sm\_suc}}{(1-\tau^{d/u}_{sm})^{n^{d/u}_{sm}-1}} \quad (15)$$

Let TX_{suc} be the transmission duration for each data packet in the FD slot on channel f_a, and it can be calculated as

$$TX^{d/u}_{suc} = T^{d/u}_{data} + T_{ack} + 2T_{sifs} + 2\delta \quad (16)$$

The total data packets transmitted in each FD slot

$$M^{d/u}_{FD\_suc} = \frac{FDslot}{TX^{d/u}_{suc}} \quad (17)$$

The packet delivery ratio for downlink/uplink communications

$$PDR^{d/u}_{sm} = \frac{\min(N^{d/u}_{SubRAW\_suc}, M^{d/u}_{suc})}{\min(N^{d/u}_{SubRAW}, M^{d/u}_{FD\_suc})} \quad (18)$$

The total data packets transmitted successfully in downlink/uplink communications

$$N_{sm\_suc}^{d/u} = 8 \cdot \min(N_{SubRAW\_suc}^{d/u}, M_{FD\_suc}^{d/u}) \quad (19)$$

The downlink/uplink throughput

$$S_{sm}^{d/u} = \frac{N_{sm\_suc}^{d/u} E[P]}{T_{RAW}} \quad (20)$$

Let $E\left[energy_{sm}^{d/u}\right]$ be the total energy consumption of DL/UL communication in each RAW. The energy efficiency of the SM-MAC protocol is given by

$$\eta_{sm}^{d/u} = \frac{N_{sm\_suc}^{d/u} E[P]}{E\left[energy_{sm}^{d/u}\right]} \quad (21)$$

6. Performance Evaluation

An event-driven simulation program implemented in MATLAB is employed to validate our model. Based on the performance analysis in Section 5, the performance of UL and DL communication is comparable. Consequently, this section presents the performance evaluation for UL communication in saturated conditions in terms of packet delivery ratio (PDR), throughput, and energy efficiency. The simulation parameters used for this evaluation are summarized in Tab. 2.

6.1. Performance comparison versus the number of stations

This section compares the performance of the SM-MAC protocol to the IEEE 802.11ah protocol under varying numbers of stations. The number of RAW slots N_R^u is set to 20 slots. The number of stations is changed from 20 stations to 8,000 stations. The stations are allocated to RAW slots based on Eq. 1. Analytical results are denoted "-ana", while simulation results are denoted "-sim" in the figures. With the simplifications and assumptions inherent in our Markov chain model [6] proposed by Bianchi, there may be some discrepancies between analytical and simulation results.

Fig. 12 illustrates the probability of successful packet transmission of the SM-MAC protocol compared to the IEEE 802.11ah MAC protocol under varying numbers of stations. As the number of stations increases, the number of stations in each RAW slot also increases, leading to an increased probability of collision when competing for channel access. From there,

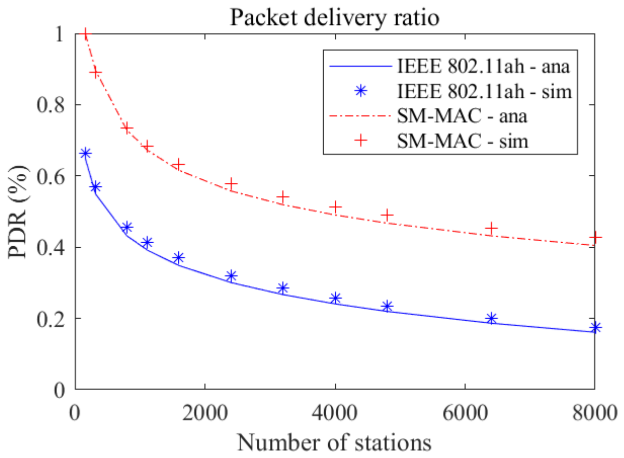

Fig. 12: Packet delivery ratio versus the number of stations.

the probability of successful packet transmission decreases with an increasing number of stations. However, the number of stations in the SM-MAC protocol contending for the channel in a RAW slot is less than the number of stations in the IEEE 802.11ah protocol since the stations are divided into sectors and use different channels for concurrent data transmissions in the SM-MAC protocol. Therefore, stations in the SM-MAC protocol have a higher packet delivery ratio than the IEEE 802.11ah protocol when there is the same total number of stations in the network.

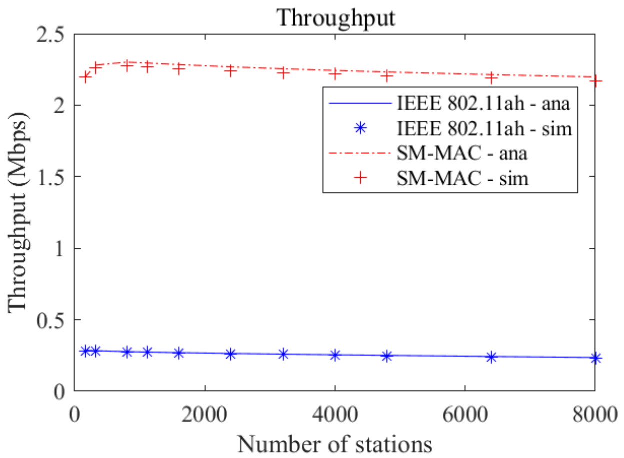

Fig. 13: Throughput versus the number of stations.

Fig. 13 shows a comparison of the throughput of the SM-MAC protocol and the MAC protocol in IEEE 802.11ah according to the number of stations. The throughput of both protocols decreases as the number of stations increases. In the SM-MAC protocol, all stations in the network are divided by sectors and then grouped into each RAW slot. This segmentation reduces contention when stations compete to exchange data with Forwarders, resulting in a higher probability of success. Additionally, up to eight channels are used concurrently for data transmissions, further boosting

Tab. 2: MAC parameters

Parameters	Value	Parameters	Value
Data rate on f_s	0.65 Mbps	Data rate on f_a	26 Mbps
T_{PLCP}	20 μs	MAC Header	224 bits
$[CW_{min}, CW_{max}]$	[16, 1024]	PS-POLL	20 bytes
RTS	20 bytes	ACK	14 bytes
CTS	14 bytes	Payload	128 bytes
Slot time σ	52 μs	SIFS	160 μs
Propagation time δ	1 μs	DIFS	264 μs

the overall system throughput of the SM-MAC protocol compared to the IEEE 802.11ah protocol.

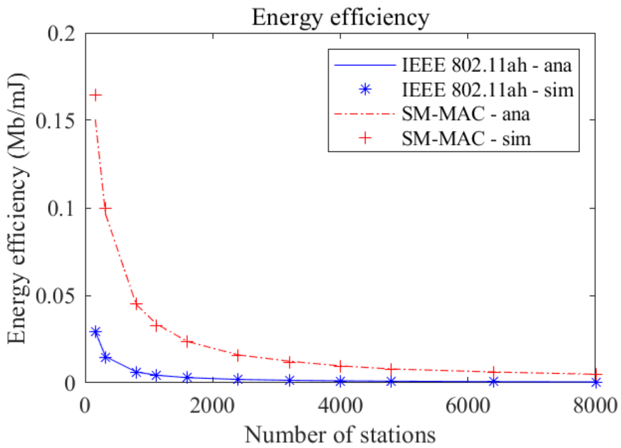

Fig. 14: Energy efficiency versus the number of stations.

Fig. 14 illustrates the energy efficiency of the SM-MAC and IEEE 802.11ah protocols according to the number of stations. Energy efficiency is defined as the ratio between total throughput and total energy consumption of the system. The energy efficiency of both protocols decreases as the number of stations increases. As the number of stations increases, the probability of collision increases, leading to increased energy consumption for successful data transmission. Throughput decreases and energy consumption increases as the number of stations increases, leading to reduced energy efficiency. However, the SM-MAC protocol offers a notable advantage over the IEEE 802.11ah protocol. It supports simultaneous data transmission on eight channels, thereby reducing collision probabilities, increasing successful data packet transmissions, and ultimately consuming less energy. Consequently, the energy efficiency of the SM-MAC protocol surpasses that of the IEEE 802.11ah protocol.

6.2. Performance comparison versus the number of RAW slots

This section presents a comparison of the performance of the SM-MAC protocol and IEEE 802.11ah protocol when changing the number of RAW slots while fixing the number of stations at 800 stations. The number of RAW slots is changed from 5 slots to 50 slots. Analytical results are denoted "-ana", while simulation results are denoted "-sim" in the figure.

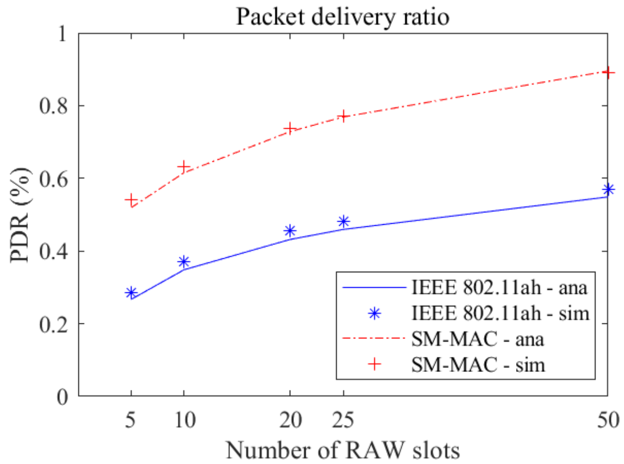

Fig. 15: Packet delivery ratio versus the number of RAW slots.

Fig. 15 shows the probability of successful packet transmission of the two protocols SM-MAC and IEEE 802.11ah as the number of RAW slots changes. Both protocols exhibit an increasing probability of successful transmission with a higher number of RAW slots. When the number of RAW slots increases, the number of stations in each slot will decrease, and the probability of collision between stations in the same RAW slot will decrease. Consequently, the packet delivery ratio increases as the number of RAW slots increases. The SM-MAC protocol further reduces collision probabilities by dividing the collision domain, enhancing successful transmission probability. This explains why the SM-MAC protocol consistently achieves a higher packet delivery ratio than the IEEE 802.11ah protocol when the number of RAW slots increases.

The throughput of both SM-MAC and IEEE 802.11ah protocols according to the number of RAW slots is depicted in Fig. 16. The throughput of both protocols is relatively stable and is not affected by changing the number of RAW slots. However, it is worth noting that the SM-MAC protocol enjoys an ad-

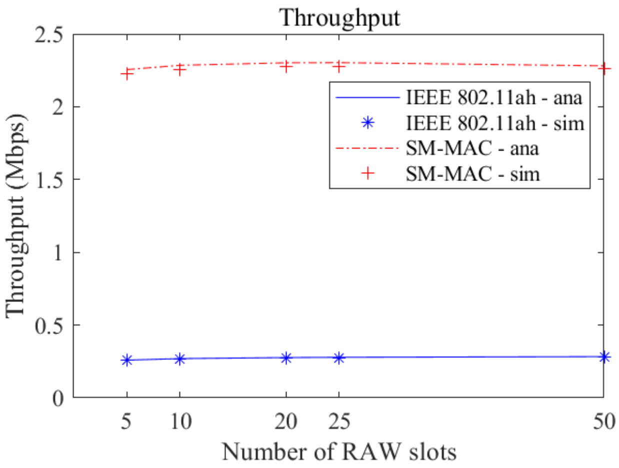

Fig. 16: Throughput versus the number of RAW slots.

vantage in that it supports simultaneous data transmission across eight channels. This feature contributes to a higher total throughput for the SM-MAC protocol compared to the IEEE 802.11ah protocol.

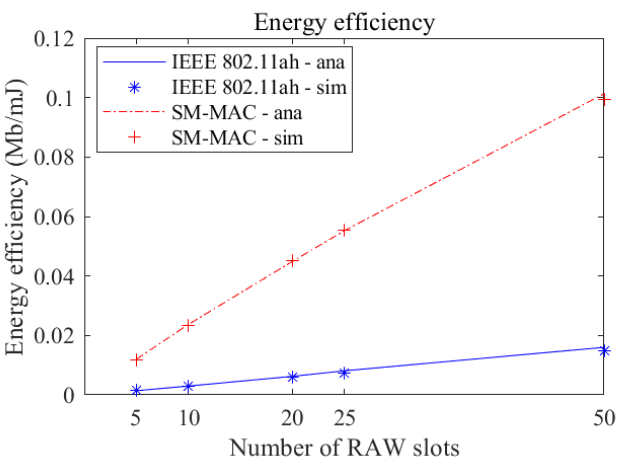

Fig. 17: Energy efficiency versus the number of RAW slots.

Fig. 17 presents a comparison of the energy efficiency of the two protocols when varying the number of RAW slots. It is evident that as the number of RAW slots increases, the energy efficiency of both protocols also increases. This improvement is attributed to the fact that as the number of RAW slots grows, the probability of successful packet transmission likewise increases, resulting in reduced energy consumption and reduced contention for channel access among stations. The SM-MAC protocol divides stations by sectors and groups them into RAW slots, so the probability of successful transmission is higher than in IEEE 802.11ah. Furthermore, the SM-MAC protocol minimizes waiting times for packet transmission and can simultaneously transmit more data packets than the IEEE 802.11ah protocol. Consequently, the energy efficiency of the SM-MAC protocol significantly outperforms that of IEEE 802.11ah.

7. Conclusion

This paper introduces a novel Spatial Multi-channel Medium Access Control (SM-MAC) protocol for IEEE 802.11ah networks. The SM-MAC protocol requires two transceivers, each capable of operating in omnidirectional and directional modes. The AP spatially groups stations into sectors, with each sector having uplink and downlink forwarders to facilitate data transmission/reception from the AP. Communication between stations and forwarders, as well as between forwarders and the AP, occurs on different channels. Analysis and performance evaluation demonstrate that the SM-MAC protocol significantly improves system capacity, reduces collision probability, and improves energy efficiency, albeit at the cost of increased transceiver implementation complexity.

References

[1] L. TIAN, S. SANTI, A. SEFERAGIĆ, J. LAN, and J. FAMAEY. Wi-Fi HaLow for the Internet of things: An up-to-date survey on IEEE 802.11ah research. *Journal of Network and Computer Applications*, 2021, vol. 182, p. 103036. ISSN 1084-8045. DOI: 10.1016/j.jnca.2021.103036.

[2] IEEE. *ISO/IEC/IEEE International Standard - Information technology–Telecommunications and information exchange between systems - Local and metropolitan area networks–Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation*, 2019.

[3] O. RAEESI, J. PIRSKANEN, A. HAZMI, T. LEVANEN, and M. VALKAMA. Performance evaluation of IEEE 802.11ah and its restricted access window mechanism. In: *2014 IEEE International Conference on Communications Workshops (ICC)*, 2014, pp. 460–466. ISBN 978-1-4799-4640-2. DOI: 10.1109/ICCW.2014.6881241.

[4] L. TIAN, J. FAMAEY, and S. LATRÉ. Evaluation of the IEEE 802.11ah restricted access window mechanism for dense IoT networks. In: *2016 IEEE 17th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2016, pp. 1–9. ISBN 978-1-5090-2185-7. DOI: 10.1109/WoWMoM.2016.7523502.

[5] E. KHOROV, A. LYAKHOV, and R. YUSUPOV. Two-slot based model of the IEEE 802.11ah restricted access window with enabled transmissions crossing slot boundaries. In: *2018 IEEE 19th*

International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM), 2018, pp. 1–9. ISBN 978-1-5386-4725-7. DOI: 10.1109/WoWMoM.2018.8449756.

[6] G. BIANCHI. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE Journal on Selected Areas in Communications*, 2000, vol. 18, no. 3, pp. 535–547. ISSN 0733-8716. DOI: 10.1109/49.840210.

[7] T.-C. CHANG, C.-H. LIN, K. C.-J. LIN, and W.-T. CHEN. Traffic-aware sensor grouping for IEEE 802.11ah networks: Regression based analysis and design. *IEEE Transactions on Mobile Computing*, 2019, vol. 18, no. 3, pp. 674–687. ISSN 1558-0660. DOI: 10.1109/TMC.2018.2840692.

[8] A. ŠLJIVO, D. KERKHOVE, L. TIAN, J. FAMAEY, A. MUNTEANU, I. MOERMAN, J. HOEBEKE, and E. D. POORTER. Performance evaluation of IEEE 802.11ah networks with high-throughput bidirectional traffic. *Sensors (Switzerland)*, 2018, vol. 18, no. 2 . ISSN 1424-8220. DOI: 10.3390/s18020325.

[9] C. KAI, J. ZHANG, X. ZHANG, and W. HUANG. Energy-efficient sensor grouping for IEEE 802.11ah networks with max-min fairness guarantees. *IEEE Access*, 2019, vol. 7, pp. 102 284–102 294. ISSN 2169-3536. DOI: 10.1109/ACCESS.2019.2931709.

[10] N. NAWAZ, M. HAFEEZ, S. ZAIDI, D. MCLERNON, and M. GHOGHO. Throughput enhancement of restricted access window for uniform grouping scheme in IEEE 802.11ah. In: *IEEE International Conference on Communications (ICC)*, 2017, pp. 1–7. ISBN 978-1-4673-8999-0. DOI: 10.1109/ICC.2017.7996899.

[11] N. AHMED and M. I. HUSSAIN. Periodic traffic scheduling for IEEE 802.11ah networks. *IEEE Communications Letters*, 2020, vol. 24, no. 7, pp. 1510–1513. ISSN 1558-2558. DOI: 10.1109/LCOMM.2020.2981087.

[12] U. SANGEETHA and A. V. BABU. Fair and efficient resource allocation in IEEE 802.11ah WLAN with heterogeneous data rates. *Computer Communications*, 2020, vol. 151, pp. 154–164. ISSN 1873-703X. DOI: 10.1016/j.comcom.2019.12.043.

[13] L. TIAN, M. MEHARI, S. SANTI, S. LATRÉ, E. DE POORTER, and J. FAMAEY. IEEE 802.11ah restricted access window surrogate model for real-time station grouping. In: *2018 IEEE 19th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*, 2018, pp. 14–22. ISBN 978-1-5386-4725-7. DOI: 10.1109/WoWMoM.2018.8449738.

[14] M. A. MONDAL, S. KHONGJOH, and M. I. HUSSAIN. RAW optimization of IEEE 802.11ah networks. In: *2023 4th International Conference on Computing and Communication Systems (I3CS)*, 2023, pp. 1–5. ISBN 979-8-3503-2377-1. DOI: 10.1109/I3CS58314.2023.10127498.

[15] F. MALOOK, O. MUJAHID, Z. ULLAH, and T. FOUZDER. On enhancing the performance of IEEE 802.11 ah by employing a dynamic RAW approach in IoT networks. *Wireless Personal Communications*, 2023, vol. 129, no. 3, pp. 1983–1997. ISSN: 1572-834X. DOI: 10.1007/s11277-023-10221-w.

[16] H. TARAMIT, L. OROZCO-BARBOSA, A. HAQIQ, J. J. C. ESCOTO, and J. GOMEZ. Load-aware channel allocation for IEEE 802.11ah-based networks. *IEEE Access*, 2023, vol. 11, pp. 24 484–24 496. ISSN 2169-3536. DOI: 10.1109/ACCESS.2023.3251896.

[17] M. A. MONDAL and M. I. HUSSAIN. Station grouping mechanism using machine learning approach for IEEE 802.11ah. *Ad Hoc Networks*, 2023, vol. 149, p. 103238. ISSN 1570-8705. DOI: 10.1016/J.ADHOC.2023.103238.

[18] H. NABUUMA, E. ALSUSA, and M. W. BAIDAS. AID-based backoff for throughput enhancement in 802.11ah networks. *International Journal of Communication Systems*, 2019, vol. 32. ISSN 1099-1131. DOI: 10.1002/dac.3923.

[19] A. JAMALI, B. SHAHGHOLI GHAHFAROKHI, and M. ABEDINI. Improving performance of association control in IEEE 802.11ah-based massive IoT networks. *IEEE Internet of Things Journal*, 2022, vol. 9, no. 11, pp. 8572–8583. ISSN 2327-4662. DOI: 10.1109/JIOT.2021.3114192.

[20] M. MAHESH and V. P. HARIGOVINDAN. Restricted access window-based novel service differentiation scheme for group-synchronized DCF. *IEEE Communications Letters*, 2019, vol. 23, no. 5, pp. 900–903. ISSN 1558-2558. DOI: 10.1109/LCOMM.2019.2904689.

[21] C.-M. HUANG, R.-S. CHENG, and Y.-M. LI. The registration-based collision avoidance mechanism for IEEE 802.11 ah. In: *International Symposium on Pervasive Systems, Algorithms and Networks*. Springer, 2019, pp. 240–255. ISBN 978-3-030-30143-9. DOI: 10.1007/978-3-030-30143-9_19.

[22] S. BHANDARI, S. K. SHARMA, and X. WANG. Device grouping for fast and efficient channel access in IEEE 802.11ah based IoT networks. In: *IEEE International Conference on Communications Workshops (ICC Workshops)*,

2018, pp. 1–6. ISBN 978-1-5386-4328-0. DOI: 10.1109/ICCW.2018.8403521.

[23] Q. T. NGO, D. N. M. DANG, Q. LE-TRUNG, and D. K. LAM. A novel directional MAC in restricted access window for IEEE 802.11ah networks. In: *26th International Conference on Telecommunications (ICT)*, 2019, pp. 167–171. ISBN 978-1-7281-0273-3. DOI: 10.1109/ICT.2019.8798775.

[24] Q. NGO, D. N. M. DANG, and Q. LE-TRUNG. An extreme power saving directional MAC protocol in IEEE 802.11ah networks. *IET Networks*, 2020, vol. 9, no. 4, pp 180–188. ISSN 2047-4954. DOI: 10.1049/iet-net.2019.0176.

[25] D. N. M. DANG, V. T. TRAN, H. L. NGUYEN, N. T. PHAM, A. K. TRAN, and N.-H. DANG. Space-frequency diversity based MAC protocol for IEEE 802.11ah networks. In: *2022 International Conference on Advanced Technologies for Communications (ATC)*, 2022, pp. 159–164. ISBN 978-1-6654-5188-8. DOI: 10.1109/ATC55345.2022.9943042.