Space-Frequency Diversity based MAC protocol for IEEE 802.11ah networks

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***Abstract*—IEEE 802.11ah is a sub-GHz communication technology to offer longer range and low power connectivity for the Internet of Things (IoT) applications. A Restricted Access Window (RAW) is specified to decrease the collision probability. Stations are divided into groups and stations from each group attempt to access the channel by employing the Distributed Coordination Function during their assigned RAW slots. However, the network throughput is limited by a single channel MAC protocol. In this paper, Space-Frequency Diversity-based MAC protocol for the IEEE 802.11ah network (SF-MAC protocol) is proposed to allow stations of different sectors to transmit packets on different channels with the help of Forwarders. The proposed SF-MAC protocol improves the packet delivery ratio and aggregate throughput of the network.**

***Index Terms*—MAC protocol, Space-Frequency Diversity, WiFi Halow, IEEE 802.11ah, RAW, IoT.**

I. Introduction

IEEE 802.11ah [1], marketed as WiFi Halow, provides network connectivity up to 8192 stations from 150 kbps to 78 Mbps over a transmission range up to 1 km. IEEE 802.11ah operates in unlicensed sub-GHz frequency bands, i.e. 863–868 MHz in Europe, 755–787 MHz in China, and 902–928 MHz in North America (Fig. 1). It features fast association and authentication, restricted access window (RAW), traffic indication map (TIM), and target wakeup time (TWT) to provide access service to a large number of stations, energy efficiency, and extended network coverage.

To support a huge number of stations, IEEE 802.11ah utilizes the hierarchical Association Identification (AID) structure which is organized into pages, blocks, subblocks, and device position index. The stations from a page are allocated into different Delivery Traffic Indication Map (DTIM) periods, DTIM into TIM periods, and TIM into RAW slots in a hierarchical manner. There may be one or more RAWs in a TIM period. A RAW mechanism is introduced to reduce collision and interference among stations. A RAW period is divided into N_R RAW slots (Fig. 2), and a group of stations (RAW group)

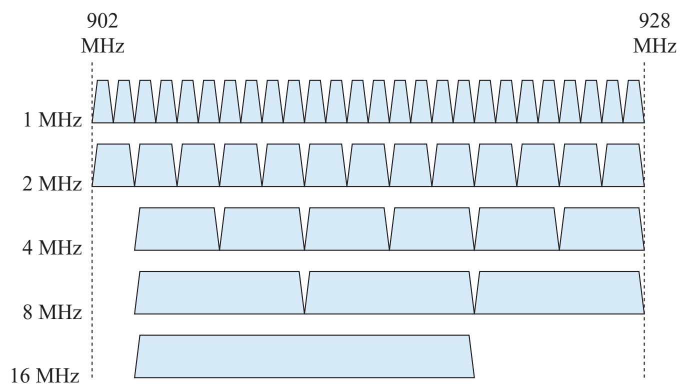

Fig. 1: US channelization.

is allowed to contend the channel for transmission in each RAW slot. Access Point (AP) broadcasts periodically the RAW Parameter Set (RPS) element which includes RAW start time, slot duration, number of RAW slots, RAW group, etc. Each station determines its RAW slot implicitly based on its AID or TIM bitmap as follows

$$i = (x + N_{offset}) mod N_R \tag{1}$$

where i represents the RAW slot index, N_{offset} is a parameter for improving the fairness among stations, and x is the station's AID or position index of the station in the TIM bitmap. During the RAW slot, stations use Enhanced Distributed Channel Access to access the channel.

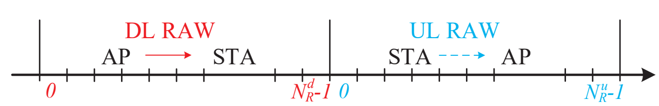

Fig. 2: RAW operation in IEEE 802.11ah.

Existing works ([2]–[4]) have proposed sectorized grouping. Stations in [2] are divided into sectors, then further divided into different groups according to the number of stations and their location information. The stations of distinct groups in different sectors access the channel in the allocated RAW slots. The AP divides its coverage area into different sectors in the directional ah MAC protocol (Dah) [3], [4]. A RAW is divided into 4 SubRAWs corresponding to 4 dual-sectors. In each RAW slot, a group of stations of a dual-sector contends to access the channel. The Dah protocol also implements the adaptive transmission power scheme for uplink transmission to improve the network energy efficiency [4]. A RAW frame in [5] is partitioned into two sub-frames and the duration of RAW slots of each sub-frame is determined by the number of stations in the corresponding RAW slots. In the hybrid, MAC protocol [6], the AP predicts the service intervals of the transmitting stations and schedules the periodic traffic efficiently to reduce contention and unnecessary wake-ups, so that it is suitable for large-scale, energy efficient, and latency-aware networks.

In the Registration-Based Collision Avoidance Mechanism [7], the AP schedules the data transmission of stations based on the backoff counter of each station to avoid collision. By setting the backoff counter of stations based on the position of their AIDs in the group, the approach in [8] eliminates the collisions in a sectorized network. Sangeetha *et al.* [9] presented an analytical model to evaluate the saturation throughput of IEEE 802.11ah with heterogeneous data rates under a RAW-based channel access scheme, and further designed an algorithm to group stations based on their data rate to improve fairness and aggregate network throughput. Khorov *et al.* [10] developed the mathematical model of data transmission in RAW mechanism with the enabled cross-slot boundary to estimate throughput and energy consumption.

In this paper, we propose a Space-Frequency Diversity-based MAC protocol for IEEE 802.11ah networks. Stations are grouped into sectors based on their locations. Forwarders are intermediate stations between the AP and stations in each sector. In each RAW, Forwarders and stations in each sector operate on different channels while the AP switches between the sector's channels to receive and transmit data packets. By exploiting the multiple channel resources, the SF-MAC protocol enhances the network performance compared to IEEE 802.11ah.

The rest of this paper is organized as follows. Section II describes the operation of the SF-MAC protocol. Section III presents the performance analysis. The performance evaluation is presented in Section IV. Finally, Section V concludes our work.

II. The proposed SF-MAC protocol

A. Network model

We consider an IEEE 802.11ah network with a single AP and N stations. The AP has two transceivers that support omnidirectional and directional modes. Moreover, the AP supports a higher data rate on different channels, while stations operate on an assigned channel based on their location. Fig.

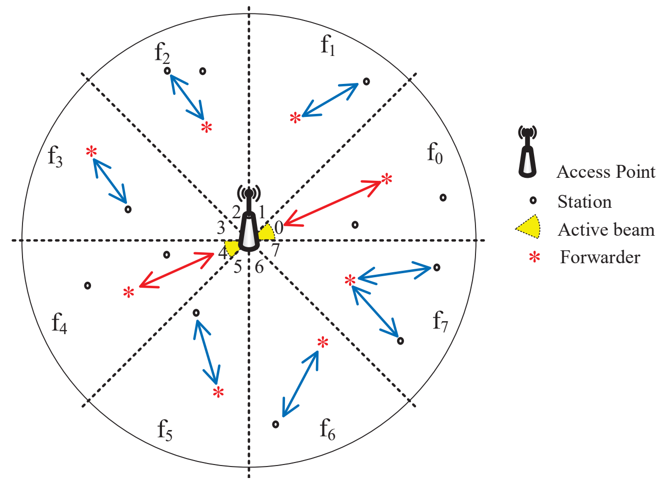

Fig. 3: Topology of the SF-MAC protocol.

3 describes the network topology of the SF-MAC protocol. The AP divides its coverage into 8 sectors, and stations in sector $i, (i = 0, ..., 7)$ operate on the corresponding channel f_i. Stations have to switch the default channel f_0 to receive a DTIM beacon from AP. Two opposite sectors are called a dual sector, *e.g.*, dual sector (0, 4) is sectors 0 and 4. Since stations in each sector are in the transmission range of each other, the hidden terminal problem is eliminated. The AP assigns a Forwarder (FD) for each sector. Forwarder receives the downlink data packets from the AP and forwards them to stations on the corresponding channel f_i or collects uplink data packets from their stations and transmits them to the AP on channel f_i.

During the Authentication/Association process, a new station attempts to connect with the AP on the channel f_0. The AP determines the station's location based on the received signal from the station. The AP assigns 16-bit AID to the station in which the three most significant bits (bits 0-2) represent the sector index. The AID structure is given in Fig. 4.

Bitth 0	3	5	10	13 15
Sector	Page	Block	Sub-block	Station

Fig. 4: AID structure in SF-MAC protocol.

B. Restricted Access Window

In the SF-MAC protocol, a RAW consists of DL RAW and UL RAW as shown in Fig. 5. Each DL RAW/UL RAW is slotted into N_R^d/N_R^u RAW slots and is divided into 4 SubRAWs corresponding to 4 dual-sectors. During DL RAW/UL RAW, the AP uses two transceivers in directional mode to exchange data packets with two Forwarders of two opposite sectors. In the SubRAW$_j$, the AP communicates with Forwarder FD_i of sector i, where $j = i \ mod \ 4$ while the other Forwarders FD_k of sector k, where $k \neq i$ communicate with their stations to exchange DL/UL data packets. For example, in

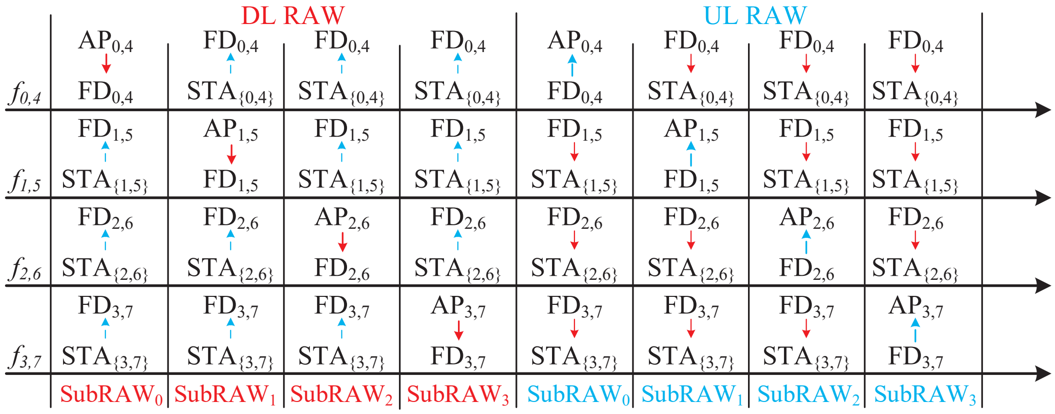

Fig. 5: Restricted Access Window of the SF-MAC protocol.

the SubRAW$_0$ of the DL RAW, the AP transfers DL data packets by its two transceivers to Forwarders of sectors 0 and 4 on the channel f_0 and f_4 while Forwarders of sectors other than sectors 0 and 4 receive UL data packets from their stations. A similar procedure applies to the UL RAW. The transmission between the AP and Forwarder is collision-free but the transmission between Forwarder and stations is contention-based. Stations use the back-off procedure to access the channel to transmit/receive data packets to/from Forwarders.

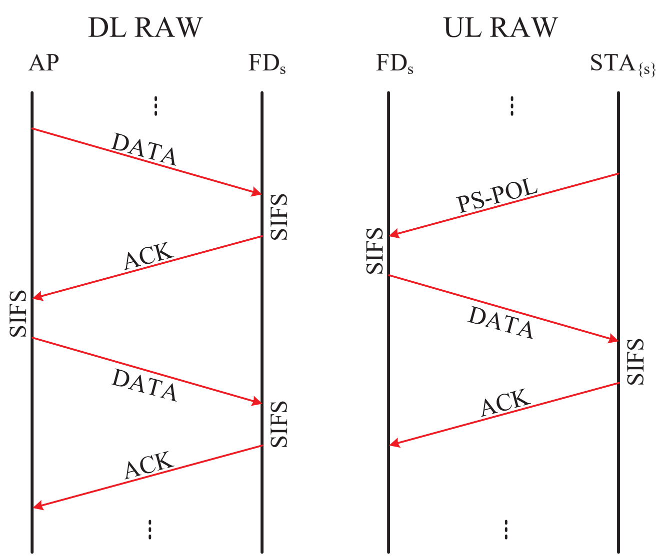

Fig. 6: Downlink communication in the SF-MAC protocol.

C. Downlink and Uplink communications

Forwarder communicates with the AP in one SubRAW and with its stations in three SubRAW of the same DL RAW or UL RAW. Fig. 6 illustrates the collision-free transmissions between the AP and Forwarder and the contention-based transmissions between Forwarder and its stations in downlink communication. Stations receive downlink data packets via Forwarder as follows

1) In DL RAW, the AP transfers the downlink data packets to Forwarder using the collision-free transmissions in an appropriate SubRAW on the corresponding channel.
2) In UL RAW, stations contend the channel to receive downlink data packets from their Forwarder in 3 appropriate SubRAWs on the corresponding channel.

In Fig. 5, during the SubRAW$_0$ of the DL RAW, the AP uses one transceiver to transmit the downlink data packets to Forwarder FD_0 on the channel f_0. Then, in the following SubRAW$_1$, SubRAW$_2$ and SubRAW$_3$ of the UL RAW, stations in sector 0 back-off to contend the channel to get their downlink data packets from Forwarder FD_0 on the channel f_0.

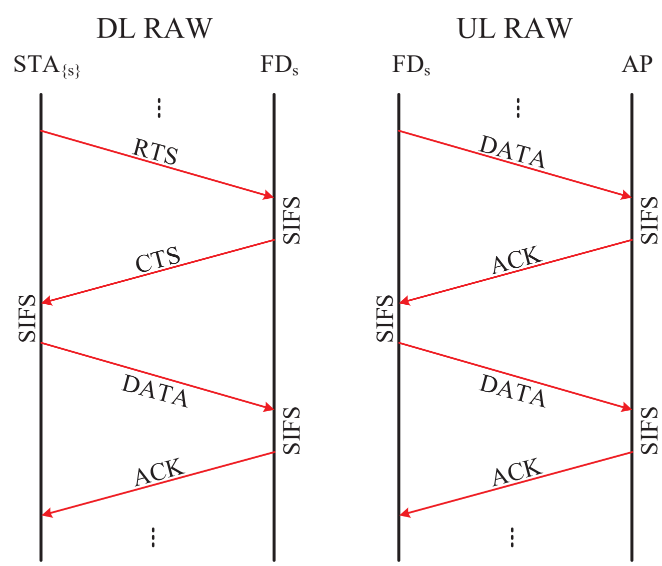

Fig. 7: Uplink communication in the SF-MAC protocol.

Similarly, for uplink communication (Fig. 7), stations transmit the uplink data packets to the AP via Forwarder as follows

1) In DL RAW, stations contend the channel to transmit the uplink data packets to their Forwarder in 3 appropriate SubRAWs on the corresponding channel.

2) In UL RAW, Forwarder relays uplink data packets to the AP using collision-free transmissions in an appropriate SubRAW on the corresponding channel.

In Fig. 5, Forwarder FD_0 receives the uplink data packets from its stations during the SubRAW_1, SubRAW_2 and SubRAW_3 of the DL RAW on the channel f_0. Then, in the SubRAW_0 of the UL RAW, Forwarder FD_0 forwards the received uplink data packets to the AP on the channel f_0.

III. Analytical Model

In our analytical model, we assume n stations contending the channel to communicate with their Forwarder in a RAW slot. We adopt the Markov chain model under saturated condition in [11]. Let $b(t)$ and $s(t)$ denote the stochastic process representing the back-off counter and back-off stage at slot time t, respectively. The discrete-time Markov chain models the bi-dimensional process $\{s(t), b(t)\}$, as given in Fig. 8. Let m be the maximum back-off stage. The contention window (CW) of i^{th} back-off stage is $W_i = 2^i \cdot W_0$, where $i \in [0, m]$.

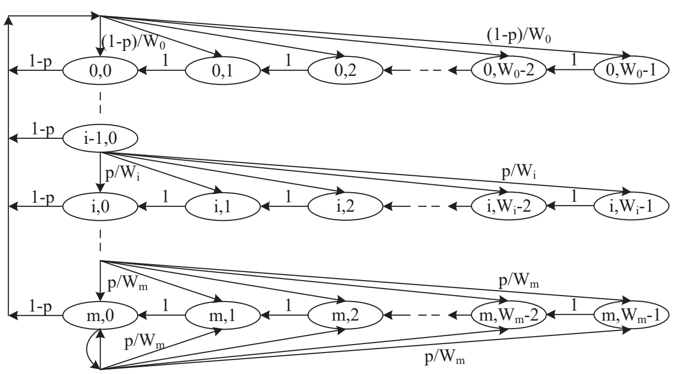

Fig. 8: Markov chain of the saturated network.

Once the back-off counter is zero, the station transmits a packet. The probability τ that the station transmits a packet in a time slot is

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

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

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

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

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

Let δ and σ be the propagation delay and the duration of an empty slot time, respectively. Fig. 9 illustrates a virtual transmission cycle. The average time of the virtual transmission cycle $E[TC]$ and each successful packet transmission $E[TX_{suc}]$ are given by

$$\begin{aligned} E[TC] &= p_{idle}\sigma + p_{suc}T_{suc} + p_{col}T_{col} \\ E[TX_{suc}] &= \frac{p_{idle}}{p_{suc}}\sigma + \frac{p_{col}}{p_{suc}}T_{col} + T_{suc} \end{aligned} \tag{5}$$

where T_{suc} and T_{col} are the duration 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

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

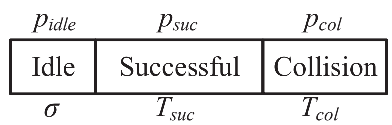

Fig. 9: Virtual transmission cycle.

Next, we compare the performance of the IEEE 802.11ah and the proposed SF-MAC protocol in terms of packet delivery ratio and throughput. Given a network with N stations, an average number of contending stations in each RAW slot of the IEEE 802.11ah and the SF-MAC protocol is as follows

TABLE I: Number of stations in each RAW slot

	IEEE 802.11ah	SF-MAC
Downlink RAW/SubRAW	$n^d_{ah} = \frac{N}{N^d_R}$	$n^d_{sf} = \frac{N/6}{N^d_R}$
Uplink RAW/SubRAW	$n^u_{ah} = \frac{N}{N^u_R}$	$n^u_{sf} = \frac{N/6}{N^u_R}$

The probabilities that the station transmits a packet in a time slot for downlink/uplink of the IEEE 802.11ah and the SF-MAC protocols are τ^d_{ah} and τ^u_{ah}, τ^d_{FS} and τ^u_{SF} respectively.

A. Performance of the IEEE 802.11ah

The packet delivery ratio (PDR) in the DL/UL RAW is

$$PDR^{d/u}_{ah} = (1-\tau^{d/u}_{ah})^{n^{d/u}_{ah}-1} \tag{7}$$

Let $DSlot$ be the duration of each RAW slot. The total number of successful packets transmitted in DL/UL communication

$$N^{d/u}_{ah\_suc} = N^{d/u}_R \frac{DSlot}{E[TX^{d/u}_{ah\_suc}]} \tag{8}$$

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

Let $E[P]$ be the average packet payload size. The throughput can be evaluated

$$S^{d/u}_{ah} = \frac{N^{d/u}_{ah\_suc}E[P]}{T_{RAW}} \tag{9}$$

B. Performance of the SF-MAC protocol

1) Downlink communications: Let $TX^d_{AF\_suc}$ be the time for transmitting a downlink packet of the collision-free transmission from the AP to the Forwarder in a DL RAW. The average number of successful packets that the AP transmits to a Forwarder in one sector

$$M^d_{AF\_suc} = \frac{N^d_R}{4}\frac{DSlot}{TX^d_{AF\_suc}} \tag{10}$$

Then, the Forwarder tries to forward $M^d_{AF\_suc}$ received downlink packets to its station in three SubRAWs of the UL RAW. In the contention-based transmissions between Forwarder and stations, the maximum number of packets that can be transmitted within three SubRAWs is

$$N^d_{FS\_max} = \frac{3}{4}N^d_R\frac{DSlot}{E\left[TX^d_{FS\_suc}\right](1-\tau^d_{FS})^{n^d_{sf}-1}} \tag{11}$$

The number of packets that the Forwarder transmits to its station depends on the received downlink data packets $M^d_{AF\_suc}$ and the capacity of the Forwarder - Stations link

$$N^d_{FS\_tx} = \min(M^d_{AF\_suc}, N^d_{FS\_\max}) \tag{12}$$

The number of downlink data packets that stations receive successfully

$$N^d_{FS\_suc} = N^d_{FS\_tx}(1-\tau^d_{FS})^{n^d_{sf}-1} \tag{13}$$

The downlink PDR of the SF-MAC protocol

$$PDR^d_{sf} = \frac{N^d_{FS\_suc}}{M^d_{AF\_suc}} \tag{14}$$

With 8 sectors, the downlink throughput of SF-MAC can be evaluated

$$S^d_{sf} = \frac{8N^d_{FS\_suc}E[P]}{T_{RAW}} \tag{15}$$

2) Uplink communications: During the DL RAW, stations contend the channel to transmit the total of $N^u_{SF\_tx}$ uplink data packets, and Forwarder receives $N^u_{SF\_suc}$ number of uplink data packets successfully

$$N^u_{SF\_suc} = \frac{3}{4}N^u_R\frac{DSlot}{E\left[TX^u_{SF\_suc}\right]} \tag{16}$$

$$N^u_{SF\_tx} = \frac{N^u_{SF\_suc}}{(1-\tau^u_{SF})^{n^u_{sf}-1}} \tag{17}$$

where $E[TX^u_{SF\_suc}]$ is the time for transmitting an uplink packet in a DL RAW.

The maximum number of packets that a Forwarder can forward to the AP is the capacity of the Forwarder - AP link

$$M^u_{FA\_max} = \frac{N^u_R}{4}\frac{DSlot}{TX^u_{FA\_suc}} \tag{18}$$

where $TX^u_{FA\_suc}$ is the time for transmitting an uplink packet of the collision-free transmission from the Forwarder to the AP in a UL RAW

The number of packets that Forwarder transmits successfully to the AP depends on the received uplink data packets $M^d_{AF\_suc}$ and the capacity of the Forwarder - AP link

$$N^u_{FA\_suc} = \min(M^u_{FA\_max}, N^u_{SF\_suc}) \tag{19}$$

The uplink PDR of the SF-MAC protocol

$$PDR^u_{sf} = \frac{N^u_{FA\_suc}}{N^u_{SF\_tx}} \tag{20}$$

The uplink throughput of the SF-MAC can be evaluated

$$S^u_{sf} = \frac{8N^u_{FA\_suc}E[P]}{T_{RAW}} \tag{21}$$

IV. Performance Evaluation

We use the event-driven simulation program in MATLAB to validate our analytical model with the MAC parameters presented in Table. II. This section presents the performance evaluation for DL/UL communications in saturated conditions in terms of throughput and packet delivery ratio (PDR).

TABLE II: MAC parameters

Parameters	Value	Parameters	Value
Data rate STA-FD	0.65 Mbps	Data rate FD-AP	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

Fig. 10 shows the performance comparison of downlink communications between the IEEE 802.11ah and the SF-MAC protocol according to the number of stations. As the number of stations increases, the downlink throughput of the SF-MAC protocol decreases, but the throughput of the IEEE 802.11ah decreases slowly (Fig. 10a). In our simulation settings, the number of packets that the AP transmits to Forwarder is less than the maximum number of packets that Forwarder can transmit to stations. The Forwarder-Stations link has a lower PDR as the number of stations increases. That is why the throughput of the SF-MAC protocol decreases significantly as the number of stations increases. However, the SF-MAC protocol exploits multiple channel resources so that it has higher downlink throughput than the IEEE 802.11ah. The downlink PDR of both the IEEE 802.11ah and the SF-MAC protocol decreases as the number of stations increases (Fig. 10b). The downlink PDR of the SF-MAC protocol is higher than that of the IEEE 802.11ah. In the IEEE 802.11ah, the larger the number of stations, the higher the collision probability. In the SF-MAC protocol, stations are grouped by sectors (corresponding to different channels)and, the number of stations in each RAW slot is significantly smaller than in the IEEE 802.11ah.

Similarly, the uplink throughput of the SF-MAC protocol is higher than that of the IEEE 802.11ah (Fig. 11a) as the number of stations increases. In this scenario, the throughput of the

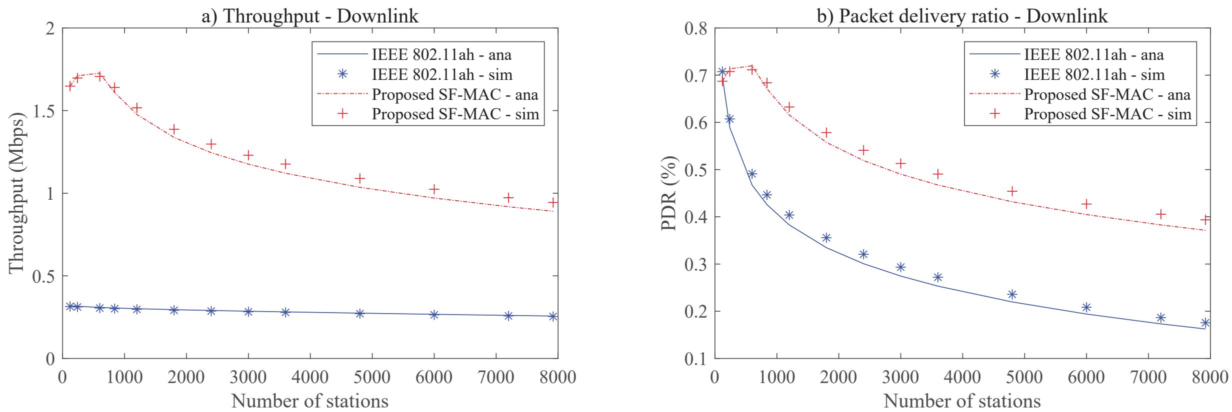

Fig. 10: Performance comparison of downlink communication.

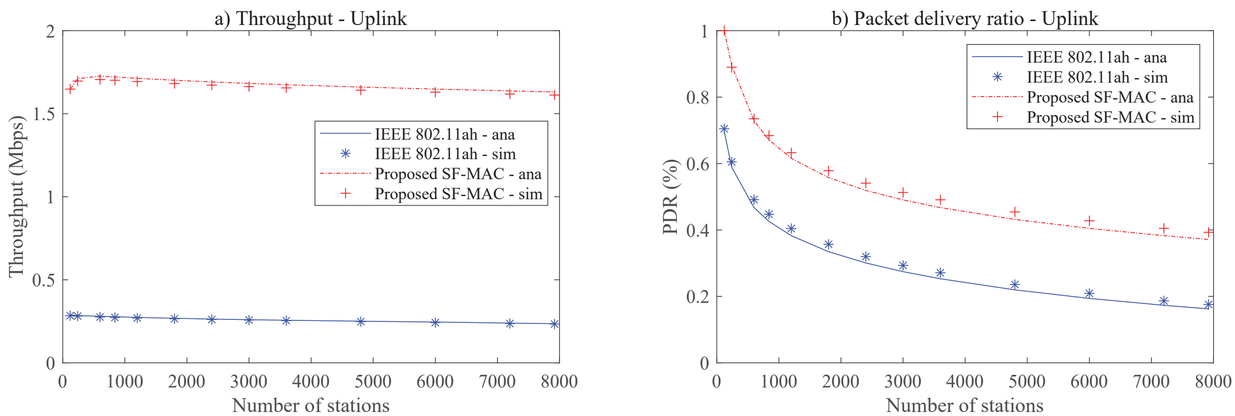

Fig. 11: Performance comparison of uplink communication.

SF-MAC protocol depends on the throughput of the Stations - Forwarder link. When the number of stations increases, the uplink PDR of both the IEEE 802.11ah and the SF-MAC protocol decreases (Fig. 11b) because the number of contending stations in each RAW slot increases.

V. Conclusion

In this paper, we propose the SF-MAC protocol which allows stations to exchange data packets with the AP through Forwarders on different channels. By grouping stations by sectors and employing multiple channels for data transmissions, the proposed SF-MAC protocol outperforms IEEE 802.11ah in terms of packet delivery ratio and throughput. However, the SF-MAC protocol requires two transceivers for the AP.

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