Channel Access Mechanism for IEEE 802.11ah-Based Relay Networks

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***Abstract*—In this paper, we propose a channel access scheme for relay-based IEEE 802.11ah network and analyze the feasibility and efficiency of it for multi-hop and large-scale Internet of Things (IoT). A new Restricted Access Window (RAW) scheme is designed to consider the currently active number of stations in a group for channel access. The proposed protocol facilitates multi-hop communication efficiently by utilizing the available channels. Accordingly, the relay node can maintain the best possible frame size for multi-hop communication. Simulation and analysis results show that the proposed protocol improves throughput performance up to 30.7% and the average frame delay up to 41.6% over the traditional scheme.**

***Index Terms*—MAC; IEEE 802.11ah; Restricted Access Window (RAW); Internet of Things (IoT); Smart City.**

I. Introduction

Internet of Things (IoT) deployment is growing very fast. The prominent communication technology for IoT constitutes a combination of sensor and backhaul networks ([1] and [2]). Short-range (1-100 meters), low data-rate (bytes to megabytes), and low power consumption technologies such as ZigBee, Radio-Frequency IDentification (RFID), and Bluetooth Low Energy (BLE) are used in sensor networks. On the contrary, long-range (100 meters to few kilometers) and high data-rates (kilobytes to gigabytes), and power-consuming solutions such as WiFi, GPRS, LTE, and WiMAX are typically adopted for backhaul communication [3]. However, for holistic operations in the network, there exists a requirement of seamless communication from the sensor/actuator to the Internet. Also, the existing solutions are not suitable for supporting communication among a massive number of sensor/actuator devices. As such, a clear gap in terms of coverage range, data-rate, and power consumption is created in properly connecting such devices to the Internet.

The latest IEEE 802.11ah standard, which is also known as Wi-Fi HaLow [4], has emerged as a new candidate to solve the above problems. It proposes some innovative concepts for supporting a large number of low-power devices (more than 8000) in IoT applications such as smart city, and smart grid [5]. With the support of the sub-1 GHz frequency band, it is possible to cover up to 1 km in a hop. A grouping-aware access mechanism, called Restricted Access Window (RAW), is proposed to enable communication among the devices. New Traffic Indication Map (TIM) and Target Wake Time (TWT) schemes help in energy saving. It also proposes a Relay AP (RAP) solution, which can increase the coverage range beyond 1-hop distance and can support more number of devices in the network ([6] and [4]).

For efficient IoT communication, the IEEE 802.11ah-based solutions need to go through some unique challenges. A possibility of poor quality data reception due to long communication range using single channel. As IEEE 802.11ah uses only a single channel, only one node in the network can transmit at a time. As a result, there exist the problems of inefficiency of the network and hidden node problem due to interference. In such a dense network scenario, without spatial reuse of channel, the overall network may lead to performing beggarly. Due to the availability of limited number of non-overlapping channels available for IEEE 802.11ah, an efficient channel utilization scheme can be applied to improve throughput, reduce interference, and save energy consumption. Also, the network scenarios might be dynamic, where, nodes enter/leave and go to sleep/idle status at any time. In such a case, the number of active nodes in a group may not always be the same. Lack of proper RAP node support with channel access and dynamic channel allocation may create higher delay and larger RAW frame duration. Hence, achieving Quality of Service (QoS) for latency-sensitive IoT applications remains a challenge. Moreover, IoT requires support for heterogeneous traffic requirements. For example, a surveillance application requires a higher data-rate than a smart lighting system. Unfortunately, IEEE 802.11ah fails to provide these requirements.

We propose a Medium Access Control (MAC) and channel allocation mechanism named *RMAC.11ah* for the IEEE 802.11ah to maximize the overall network efficiency. It holds a suitable RAP to RAP/AP and vise-versa communication mechanism to enhance the multi-hop performance of a network. Further, RAP solutions can dynamically adjust bandwidth requirements in different parts of the network. In summary, the following are the key *contributions* of this paper:

- ✦ A dynamic and non-interfering channel and MCS allocation scheme is proposed to increase the efficiency of the network
- ✦ A hybrid channel access mechanism is proposed to optimally utilize time frame over a multi-hop network

The remainder of the paper is organized into four sections. A study of some important features of IEEE 802.11ah and related works is presented in Section III. Detail of the proposed MAC protocol is discussed in Section IV. The simulation and analytical results of the proposed scheme are presented in

Section V. Section VI concludes this paper.

II. IMPORTANT FEATURES OF IEEE 802.11AH

Channelization in IEEE 802.11ah inherits the physical layer of IEEE 802.11ac. It can use channel bandwidth 1, 2, 4, 8 and 16 MHz for different Modulation and Coding Scheme (MCSs) for various data-rate supports. The most suitable channels for IoT, i.e., 1 and 2 MHz under sub-1GHz are available in almost all the countries under the license-exempt band. For example, 902-929 MHz band is available in US regulation; there are 26 channels of 1MHz bandwidth. To support a large number of STAs, i.e., 8191 under single AP, IEEE 802.11ah proposes a RAW mechanism, which is further simplified by a hierarchical AID. The RAW scheme divides STAs (identified by AIDs) into groups and divides the time frame into slots to reduce contention [4]. The RAW consist of a set of slots of duration (T_x), which is calculated as:

$$T_x = 500\mu s + C \times 120\mu s \tag{1}$$

where, C is the slot size count sub-field with having a maximum value of $2^{11} - 1$. Fig. 1 shows a RAW frame structure. Getting a slot is dependent on a mapping function. In the RAW, a STA is only allowed its access over the channel in a slot (I_s), which is calculated as:

$$I_s = (A + F_{offset}) \bmod N_{RAW} \tag{2}$$

where A is the AID (also knows as the position index) of the STA, F_{offset} value in the mapping function is used to decide fairness, N_{RAW} is the number of slots in a RAW.

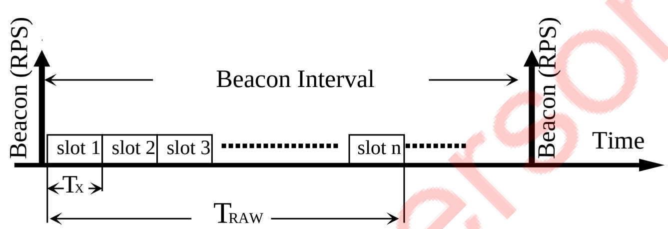


Fig. 1: RAW frame structure in IEEE 802.11ah

The IEEE 802.11ah standard provides RAP support which works as a relay between AP and station (STA). It also provides connectivity for a STA located outside the coverage of AP. IEEE 802.11ah proposes relay solutions having an AP and a STA module attached [4]. A *Relay function* module connects the AP entity with STA entity. However, efficient channel access and association for RAP node are not discussed in the existing solutions.

III. RELATED WORKS

Optimizing the RAW size in IEEE 802.11ah according to the requirements of the different applications is a challenge. Enhancements such as [7], [8], and [9] adjust the RAW characteristics based on the current network conditions. Considering metrics such as loads, number of STAs, and energy, these schemes solve some optimization problems. However, in a dynamic and heterogeneous network environment, there may exist a STA that transmits at any rate or leave and join at any time and can be associated with a RAP or AP. So, without proper channel access, and dynamic bandwidth allocation, network capacity will be reduced. Kumar *et al.* [10] proposes a multi-channel allocation scheme for the distributed RAP nodes with TDMA-based dedicated time sharing. Rao *et al.* [11] introduces a dual-hop RAP node to extend the connectivity till STAs. An analysis of control-loop latency for delay and jitter sensitive traffic is carried by Seferagic *et al.* [12]. None of these schemes considers the multi-hop communication in IEEE 802.11ah network while efficiently utilizing the bandwidth.

Shafiq *et al.* [13] propose a Cognitive Radio (CR) based MAC protocol, which regroups the STAs based on the probabilistic analysis of collisions. Nabuuma *et al.* [14] proposes a backoff scheme with AID for reducing collisions in sectorized network. A Received Signal Strength (RSS) based hidden node problem solution is proposed in [15]. The protocol senses the neighbors by measuring the RSS and ensures that nodes in the same group are known, which is not always true in dynamic network conditions. Enhancing this, Laipeng *et al.* [16] additionally use several reference nodes according to their location to reduce collision probability. However, collision chains remain in the network due to the presence of a large number of sleeping nodes. Also, the existing schemes assumed that the network is saturated to uplink traffic only. Yu *et al.* [17] proposes a grouping mechanism based on a list of exposed terminal nodes. The factors like wide coverage range, CSMA/CA mechanism, large power-saving STAs, and uplink traffic, the IEEE 802.11ah-based network is severely affected by the hidden terminal node.

Most of the current research focuses on RAW estimation scheme attempting scalability, however, the possibility of high collisions at the time of channel allocation in the dense network still exists. For a large-scale network with RAPs and STAs, without dynamic channel adjustments and proper access mechanism, the network may perform inefficiently. The single-channel and centralized access scheme in IEEE 802.11ah affects the overall performance of such networks considering a huge number of devices trying to access a time slot at the same time. Further, in a hierarchy based multi-hop network, chances of delay and poor quality data reception are high.

IV. THE PROPOSED PROTOCOL

The proposed IEEE 802.11ah-based MAC protocol is designed for efficient multi-hop communication. The design is greatly influenced by the multiple available channels of 1 and 2 MHz bandwidth in sub-1 GHz frequency band. It optimizes the total time frame for efficient communication. The proposed protocol allows simultaneous channel access in different RAW groups implemented by the RAPs.

A. Hybrid Channel Access Mechanism

We propose a new time frame containing RAW and TXOP as shown in Fig. 2 for STA and RAP/AP communication, respectively. Also, the existing channel access mechanism in RAW is configured to work in a hybrid manner, i.e., a combination of *contention* and *reservation*. Initially, RAW is divided into the contention period (T_{CP}) and reservation period (T_{RP}) over the time frame, T_{FRAME}. This mechanism allow to appropriately predict the number of active STAs in a group. To increase the efficiency of the large-scale networks, it provides the Resource Allocation (RA) frame. We use the RA frame after the contention period to inform the STA to schedule their Tx in the reserved period. In this manner, the proposed protocol dynamically sets the best RAW size based on the active number of STAs. The traditional DCF mechanism is used for contention, where successful Tx in a frame depends on the competence over the backoff window (W). Let $t_{m,i}$ be the time moment between the $(m-1)^{th}$ and m^{th} contentions which was successful in a frame. Let $X_{m,i}$ denote the number of collisions that occur during the time frame of RAP, γ. Then, $t_{m,i}$ for γ can be calculated as [18]:

$$t_{m,i,\gamma} = \sum_{j=1}^{X_{m,i}} [I_{m,j} + C_{m,j}] + I_{X_{m,i}+1} + P_{m,j} \qquad (3)$$

where, $I_{m,j}, C_{m,j}$ and $P_{m,j}$ are the duration of the j^{th} idle, collision, and polling time, respectively. If $E[t_{i,\gamma}]$ is the average contention time in time frame i for γ, then

$$E[t_{i,\gamma}] = E[Idl_i](E[X_i]+1) + E[X_i].E[C_i] + E[P_i] \qquad (4)$$

where, $E[I_i], E[C_i], E[P_i]$, and $E[X_i]$ are the average durations of idle slot, collision, poll message, and number of collisions, respectively. The value of $E[I_i], E[C_i], E[P_i]$, and $E[X_i]$ can be easily calculated using the probability of success and collision. Following the Bianchi's Markov Chain Model [19], the probability values of success and collision are calculated as:

$$P_{suc} = \frac{n\tau(1-\tau)^{n-1}}{P_{tx}} \qquad (5)$$

$$P_{col} = (1-P_{suc})P_{tx} \qquad (6)$$

where, $P_{tx} = 1-(1-\tau)^n$ satisfies that there is at least one Tx in a slot time, for given n STAs contending on the channel. If the total number of devices that successfully contend at frame i is N_i, then the contention period T^i_{CP} is calculated as:

$$T_{CP,i,\gamma} = \sum_{n=1}^{N_i} t_{m,i,\gamma} \qquad (7)$$

where, T^i_{CP} is a random variable (as it is the sum of the same type). Therefore, we can calculate the expected T_{CP} for RAP, γ as:

$$E[T_{CP,i,\gamma}] = E[C_i].E[t_{i,\gamma}] \qquad (8)$$

However, with increasing the values of C_i, the $E[T^i_{CP}]$ increases, using which T_{RP} is reduced. To balance this tradeoff and to maximize the channel uses, we will formulate an optimization problem in future. In the reservation phase, for sending an MPDU following an ACK, a slot size is calculated as:

$$E[T_{s,i}] = T_{MPDU} + T_{ACK} + 2T_P \qquad (9)$$

where, T_P is the propagation latency. Hence, the expected duration of T_{RP} is,

$$E[T_{RP,i}] = E[C_i].E[T_{s,i}] \qquad (10)$$

1) TXOP-Based Data Exchange: Although the efficiency of a network increases with the use of parallel Tx (using multiple channels), AP and RAP communication also needs to be efficient. We incorporate a Transmission Opportunity (TXOP)-based communication between the AP and RAP for improving performances. In case of multi-hop communication, the TXOP duration needs to be calculated for the detailed overview of the time frame. With the use of TXOP in the proposed protocol, the total time required, T_{suc}, that successfully transmits a data frame for RAP k, is updated as:

$$T^k_{txop} = T_{PS-POLL} + \delta T_{DATA} + T_{ACK} + (\delta+1)(T_{SIFS} + T_{DIFS} + T_P + T_{FH}) \qquad (11)$$

where, δ is the number of data frames that we can be sent in a TXOP. Hence, the total time maintained by AP or RAP is,

$$T^k_{total} = T^j_{RAW} + T^k_{txop} \qquad (12)$$

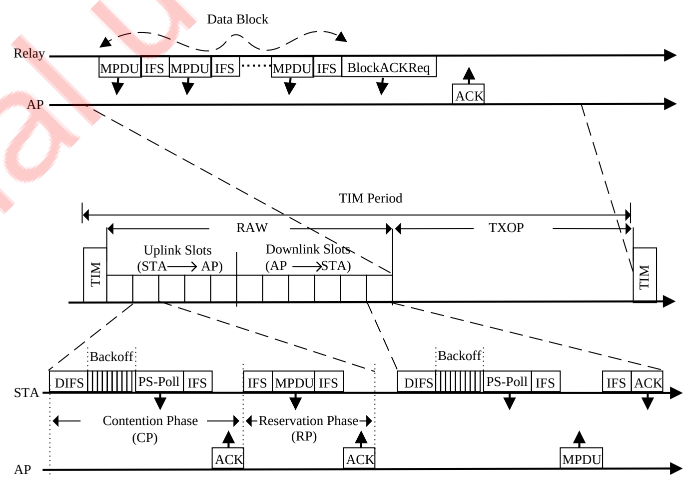


Fig. 2: The proposed communication paradigm for RAP and AP in IEEE 802.11ah

Algorithm 1 presents the hybrid and multi-hop slot scheduling mechanism. Although, the proposed MAC protocol optimally utilizes the channel by considering the current requirement of nodes, it is limited to a single AP or RAP. With the addition of multiple hops, the total time frame increases. In such a case, achieving QoS for delay-sensitive traffic is still remains as an issue.

B. Dynamic Channel and Bandwidth Allocation Scheme

To increase the efficiency of communication between STAs, we propose a non-interfering channel allocation scheme for parallel Tx of in the network. The proposed protocol monitors the entire network and uses some centralized decisions based

Algorithm 1: Channel access for multi-hop and large-scale network

Inputs: STAs, RAPs, and AP
Output: Access to the requested STAs
if *STA* **then**
  RAW=CP+RP
  Allow contention in CP // uses PS-Poll frames for contention
  if *Contention Successful* **then**
    Adjust RP duration based on CP // as mentioned in Eq. (10)
    Allow transmission in RP
else if *AP or RAP* **then**
  Adjust TXOP duration based on T_{RAW}
  $FRAME = T_{RAW} + T_{TXOP}$
  Allow BlockAck in TXOP

Algorithm 2: Multi-channel allocation scheme

1 **Inputs:** Channels c={1,2,...,m}; RAPs r={1,2,...n}; h← hops
  Output: Non-interfering channel allocation
2 **for** $i \in c, r, h$ **do**
3   *i is adjacent to i+1 and i-1*
4 **for** *i=1 to m* **do**
5   **for** *j=1 to n* **do**
6   **for** *h=1 to 3* **do**
7   *Allocate i→ j*
8   *Such that:*
9       $i \notin [j-1, j+1]$
10       $i \notin [h-1, h+1]$
11   *i=m-i*
12   *m=m-1*
13   **if** m **then**
14   *Calculate L(j,h)* // Eq. (13)
15   **if** $L(\gamma,h) \geq L^t(\gamma,h)$ **then**
16   *Allocate* $MCS_k \rightarrow j$
17           $| \, k > i$*; i is the current MCS*
18   **else**
19   *Allocate* $MCS_k \rightarrow j$
20           $| \, k < i$*; i is the current MCS*
21

on the typical requirements of IoT applications. The primary decisions are as follows:

(a) to allocate non-interfering channels to the RAPs for allowing parallel Tx.
(b) to dynamically replace the current MCS that has been used by an RAP node, with a new MCS channel.

Algorithm 2 shows the propose channel allocation mechanism. AP allocates an available channel to a RAP such that any of its neighbor RAP does not use the same channel (line # 7-13). Further, we try to allocate the farthest channel (concerning the non-interfering channel as in line # 2) to the immediate neighbor RAPs. We propose a method to detect losses in RAPs using the existing BlockAck algorithm [20]. For uplink traffic, immediately after the buffered frames have sent, RAP sends a BlockAckReq containing the sequence numbers. The AP can calculate the number of missing sequence numbers for MPDUs from the BlockAckReq frame. Similarly, for uplink traffic, AP can easily get the number of missing frames from the BlockAck frame. Accordingly, AP can have the packet loss ratio for RAP γ in hop h, which is calculated as:

$$L^r(\gamma, h) = \frac{\nu_b - \nu_r}{\nu_b} \tag{13}$$

where, ν_b and ν_r are the buffer size and number of successfully transmitted frames, respectively at RAP. A threshold loss value $L^t(\gamma, h)$ is considered based on the current acceptability of applications. A new MCS with higher rate is selected if $L^r(\gamma, h) > L^t(\gamma, h)$ and vice-versa.

V. Performance Evaluation

A. Theoretical Analysis

Bianchi *et al.* [19] calculates the saturation throughput, Th, as the amount of average data payload transmitted successfully is a slot over the average slot size s_t. The saturation throughput for DCF-based channel access can be calculated as:

$$Th = \frac{P_{tx} P_{suc} E[Payload]}{(1 - P_{tx}) s_t + P_{tx} P_{suc} T_{suc} + P_{col} T_{col}} \tag{14}$$

where, T_{suc} and T_{col} are the busy time for successful transmission and collision respectively. For IEEE 802.11ah, these can be calculated as below:

$$T_{suc} = T_{FH} + T_{PS-POLL} + T_{DATA} + T_{ACK} + + T_{SIFS} + T_{DIFS} + 3T_P \tag{15}$$

$$T_{col} = T_{FH} + T_{DATA} + T_{DIFS} + T_P + T_{Timeout} \tag{16}$$

where, $T_{DATA}, T_{SIFS}, T_P, T_{ACK}, T_{timeout}$ and T_{DIFS} are the data, SIFS, propagation, ACK, ACK-timeout, and DIFS duration, respectively. The values of different parameters are mentioned in Table II. The duration of data and control frame used in IEEE 802.11ah can be calculated using the Eqs. (17) and (18), respectively [21]:

$$T_{DATA} = \lceil \frac{8 \times (L_d + m_h)}{\frac{R}{D_r} \times L^{D_s}} \rceil \times T_{sym} + T_{PHY} \tag{17}$$

$$ACK = \lceil \frac{8 \times L_c}{L^{D_s}} \rceil \times T_{sym} + T_{PHY} \tag{18}$$

where, $m_h, R, D_r, L^{D_s}, T_{sym}$, L_d, L_c, and T_{PHY} are the MAC header size, basic data rate, number of bits in one OFDM, symbol duration of OFDM, size of payload, size of control frame, and PHY header size respectively. For 256 Bytes (MCS0, 2MHz), T_{DATA}=4.56 ms and T_{ACK}=0.34 ms for 1 Byte size. The proposed protocol can deploy λ number of channels in the network. However, actual number of channels that effectively works for simultaneous transmission may not be same. If $E[\lambda]$ be the expected number of channels, then the saturation throughput can be updated as:

$$E[Th_{\lambda}] = E[\lambda] \times Th \tag{19}$$

The proposed TXOP operation reduces contention and extra overhead due to control frames. The value of existing T_{suc} can be updated as:

$$\begin{aligned} E[T_{suc}^{txop}] &= T_{PS-POLL} + T_{DIFS} + \delta T_{DATA} + T_{ACK} + \\ &\quad (\delta+1)(T_{SIFS} + T_{P} + T_{FH}) \end{aligned} \tag{20}$$

where, δ is the number of data frames (depends on the buffer size) that we can send in a TXOP duration. Then, the expected saturation throughput will be:

$$E[Th_{txop}] = \frac{P_{tx}P_{suc}(\delta \times E[Payload])}{(1-P_{tx})s_t + P_{tx}P_{suc}E[T_{suc}^{txop}] + P_{col}T_{col}} \tag{21}$$

In addition to the above delays, a preamble time, i.e., from contention to the reservation slot is also considered in the proposed protocol. The average frame delay is calculated by Chatzimisios *et al.* in [22]. A comparison of the theoretical throughput results is shown in Table. I. The proposed protocol finds the active number of STAs for scheduling with a hybrid access scheme in each frame. Additionally, the use of multiple channels and TXOP operation in RAP increases the performance of the network. As compared to the traditional RAW scheme, the proposed protocol shows 31.2% of improvement in single-channel and 3000 nodes scenarios.

TABLE I: Comparison of theoretical throughput results

Protocol, Channel (s)	Throughput (Kbps) [No. of STAs in network, RAP group, and RAW group]		
	[1000,100,10]	[2000,200,20]	[3000,300,30]
802.11ah-RAW, 1	197.6	150.3	110.2
RMAC.11ah, 1	230.8	187.5	143
RMAC.11ah, 2	331.3	290.7	256.1
RMAC.11ah, 3	396.5	334.6	275.5

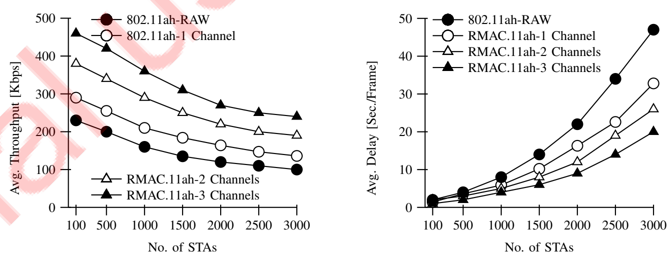
B. Simulation Analysis

We evaluate extensive analyze on the proposed protocol using NS-3 [23]. The detail parameters used in the simulation are presented in Table II. Results are compared with the traditional RAW-based access mechanism of IEEE 802.11ah. As existing hybrid mechanisms are based on traditional DCF based channel access without grouping, we compare the scheme with existing IEEE 802.11ah. We also present the results considering single group of STAs.

Fig. 3a and 3b show the performance of the proposed scheme as compared to the traditional scheme. Along with exiting grouping, multi-channel operations and efficient channel access scheme increase the throughput performance up to a great extent. As shown in Fig. 3a, throughput in the proposed scheme improved almost 30.7% and 90% considering single and multiple channels, respectively. Generally, multiple channels operations supported in the scheme can multiply the exiting capacity, but due to the channel switching delay and AP/RAP's capacity, the achieved throughput is lesser.

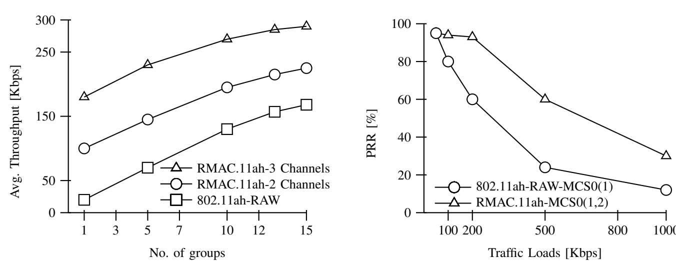
TABLE II: List of parameters and their values used in the simulation and theoretical analysis

Parameter	Value
Radio propagation model	Outdoor (Macro [24])
OFDM symbol time (T_{sym})	40 μs
PHY header	6 x T_{sym}
Modulation and Coding Schemes	MCS0, MCS1
Data rate (D_r)	650, 300 Kbps
Types of traffic	UDP
Payload size	256 Bytes
MAC header size	18 Bytes
Slot time	52 μs
SIFS duration	16 μs
DIFS duration	SIFS + 2 x Slot time
$[W_{min}, W_{max}]$	[15 1023]
Initial backoff window	64
Backoff time	$(W_{min}/2) \times Slot\ time$
Traffic interval	0.01-5 Sec.
Simulation area	2000m $\times$ 2000m Flat-grid
Bandwidth	1, 2 MHz
TXOP	BlockAck
No. of nodes (Max.)	3000
RAW size	10
RAW group size	10
No. of RAPs	10 (Random)
No. of channels	1-3
Buffer size	50
Beacon interval	100 ms
Loss rate ($L^t(\gamma, h)$) (Max.)	5%



(a) (b)

Fig. 3: (a) Average throughput, (b) Average per frame delay, as calculated at AP



(a) (b)

Fig. 4: (a) Throughput performance with increasing number of groups, (b) PRR (%) considering MCS0 (1 MHz) in IEEE 802.11ah and MCS0 (1,2 MHz) in RMAC.11ah

The parallel Tx is suitably supported by TXOP operations at AP/RAPs, which allows sending all the buffered frames with lesser overhead. As the proposed protocol allows simultaneous transmission under RAPs using different channels and the hybrid MAC scheme can reduce access time, the overall delay is reduced as shown in Fig. 3b. The proposed protocol gives delay improvements up to 41.6%.

The grouping mechanism in IEEE 802.11ah reduces collisions due to contentions. For a large number of STAs, throughput performance will be better when group size is higher. However, the use of single-channel over a larger coverage area, the hidden terminal problem is a major concern. So, along with the RAW grouping for the STAs, our protocol uses different channels in the RAP nodes. Fig. 4a shows the throughput, achieved at AP node with an increasing number of groups. The proposed scheme achieved superiors' performance as compared to the traditional one.

RAP nodes are further supported with multiple MCSs, where, it can choose an MCS with a higher or lower data-rate according to the current requirements. We measure the Packet Received Ratio (PRR) for the traditional scheme with 300Kbps (MCS0, 1MHz), and proposed scheme with 300Kbps (MCS0, 1MHz) and 650Kbps (MCS0, 2MHz). We provide uplink varying traffic loads from 100Kbps to 1000Kbps from different RAPs towards AP. The saturation capacity for the traditional scheme is almost 150Kbps, whereas the proposed scheme can carry up to 325Kbps. Due to the support of multiple MCSs, at saturation capacity, the RAP in the proposed scheme switches its MCS to another having a higher data-rate. Therefore, as shown in Fig. 4b, the proposed scheme performs almost 25% better than the traditional. Although the threshold packet loss ratio is kept as 5%, due to the unavailability of bandwidth, losses are higher.

VI. Conclusion

This paper presented a multi-channel and hybrid MAC protocol for multi-hop IEEE 802.11ah networks. It showed significant performance improvement over the IEEE 802.11ah-MAC protocol. The proposed protocol achieves a higher success rate and lesser delay than the traditional scheme. It can dynamically adjust bandwidth using MCS with a higher data-rate. From the performance results, it is clear that the proposed scheme is a solution for large-scale IoT applications. In the future, we plan to optimize the trade-off between contention and reservation period, and TIM and RAW size for better QoS in IoT scenarios.

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References

[1] G. M. Lee, J. Park, N. Kong, and N. Crespi, "The Internet of Things: Concept and problem statement: 01," *Internet Engineering Task Force, Institut TELECOM, Draft*, 2011.

[2] H. Tschofenig, J. Arkko, D. Thaler, and D. McPherson, "Architectural Considerations in Smart Object Networking," *Internet Engineering Task Force, RFC-7452*, 2015.

[3] I.-G. Lee and M. Kim, "Interference-aware Self-optimizing Wi-Fi for high Efficiency Internet of Things in dense Networks," *Computer Communications*, 2016.

[4] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment 2: Sub 1 GHz License Exempt Operation," *IEEE P802.11ah/D10.0, Sep 2016*, pp. 1–660, Jan 2016.

[5] E. Khorov, A. Lyakhov, A. Krotov, and A. Guschin, "A Survey on IEEE 802.11ah: An Enabling Networking Technology for Smart cities," *Computer Communications*, vol. 58, pp. 53–69, 2015.

[6] L. Tian, S. Latré, and J. Famaey, "Evaluation of the IEEE 802.11ah Restricted Access Window Mechanism for dense IoT networks," in *International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pp. 1–9, IEEE, 2016.

[7] C. W. Park, D. Hwang, and T.-J. Lee, "Enhancement of IEEE 802.11ah MAC for M2M Communications," *IEEE Communications Letters*, vol. 18, no. 7, pp. 1151–1154, 2014.

[8] X. Lei and S. H. Rhee, "Performance Improvement of Sub-1 GHz WLANs for Future IoT Environments," *Wireless Personal Communications*, vol. 93, no. 4, pp. 933–947, 2017.

[9] L. Tian, E. Khorov, S. Latré, and J. Famaey, "Real-time station grouping under dynamic traffic for ieee 802.11 ah," *Sensors*, vol. 17, no. 7, pp. 1–24, 2017.

[10] S. Kumar, H. Lim, and H. Kim, "Hierarchical MAC protocol with Multi-channel allocation for enhancing IEEE 802.11 ah Relay Networks," in *Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 1458–1463, IEEE, 2015.

[11] S. N. Rao, P. Akhil, V. B. Kumaravelu, and M. Arthi, "Dual—Hop Relaying for Quality of Service Improvement in IEEE 802.11 ah-Downlink," in *International Conference on Communication and Signal Processing (ICCSP)*, pp. 0249–0253, IEEE, 2018.

[12] A. Seferagić, I. Moerman, E. De Poorter, and J. Hoebeke, "Evaluating the suitability of IEEE 802.11 ah for low-latency time-critical control loops," *IEEE Internet of Things Journal*, 2019.

[13] M. Shafiq, M. Ahmad, A. Irshad, M. Gohar, M. Usman, M. Khalil Afzal, J.-G. Choi, and H. Yu, "Multiple Access Control for Cognitive Radio-Based IEEE 802.11 ah Networks," *Sensors*, vol. 18, no. 7, p. 2043, 2018.

[14] H. Nabuuma, E. Alsusa, and M. W. Baidas, "AID-based backoff for throughput enhancement in 802.11ah networks," *International Journal of Communication Systems*, vol. 32, no. 7, pp. 1–20, 2019.

[15] M. Ghasemiahmadi, Y. Li, and L. Cai, "RSS-based grouping strategy for avoiding hidden terminals with GS-DCF MAC protocol," in *Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, IEEE, 2017.

[16] L. Zhang, H. Li, Z. Guo, L. Ding, F. Yang, and L. Qian, "Signal strength assistant grouping for lower hidden node collision probability in 802.11 ah," in *International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1–6, IEEE, 2017.

[17] T.-H. Yu and S.-T. Liang, "Grouping Method Based on Exposed Terminal Detection in IEEE 802.11 ah," in *International Conference on E-Society, E-Education and E-Technology*, pp. 37–41, ACM, 2017.

[18] Y. Liu, C. Yuen, X. Cao, N. U. Hassan, and J. Chen, "Design of a scalable hybrid MAC protocol for heterogeneous M2M networks," *IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 99–111, 2014.

[19] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on selected areas in communications*, vol. 18, no. 3, pp. 535–547, 2000.

[20] I. Tinnirello and S. Choi, "Efficiency analysis of burst transmissions with blockACK in contention-based 802.11e WLANs," in *International Conference on Communications (ICC)*, vol. 5, pp. 3455–3460, IEEE, 2005.

[21] O. Raeesi, J. Pirskanen, A. Hazmi, T. Levanen, and M. Valkama, "Performance evaluation of IEEE 802.11 ah and its Restricted Access Window mechanism," in *International Conference on Communications Workshops (ICC)*, pp. 460–466, IEEE, 2014.

[22] P. Chatzimisios, V. Vitsas, and A. C. Boucouvalas, "Throughput and delay analysis of IEEE 802.11 protocol," in *International Workshop on System-on-Chip for Real-Time Applications*, pp. 168–174, IEEE, 2002.

[23] "What is ns-3." https://www.nsnam.org/overview/what-is-ns-3/. online.

[24] B. Bellekens, L. Tian, P. Boer, M. Weyn, and J. Famaey, "Outdoor IEEE 802.11 ah range characterization using validated propagation models," in *Global Communications Conference (GLOBECOM)*, pp. 1–6, IEEE, 2017.