MAC protocols for IEEE 802.11ah-based Internet of Things: A Survey

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***Abstract*—The IEEE 802.11ah, also known as WiFi HaLow, is a scalable solution for medium-range communication in Internet of Things (IoT). While provisioning support for the IoT and Machine-to-Machine (M2M) communication, IEEE 802.11ah leverages various innovative Medium Access Control (MAC) layer concepts such as Restricted Access Window (RAW), hierarchical Association IDentification (AID), Traffic Indication Map (TIM) Segmentation etc. This paper presents a survey on various MAC protocols for IEEE 802.11ah. While discussing the essential features of IEEE 802.11ah, this survey points out various issues and limitations of such MAC protocols. Although there are some surveys available for MAC protocols of IEEE 802.11ah, they do not include a large number of schemes that have been recently proposed to solve different standardization and implementation-based issues. This paper individually surveys issues and challenges in the different problem domains of IEEE 802.11ah MAC protocol and analyzes the recently proposed solutions. Moreover, this paper identifies various factors for further improvement of these protocols. Compared to other relevant surveys, this paper emphasizes the issues and challenges to enable researchers to easily identify the problem domain.**

Keywords*—IEEE 802.11ah, Internet of Things (IoT), Machine-to-Machine (M2M) Communication, Medium Access Control (MAC) Protocol, Restricted Access Window (RAW)

I. INTRODUCTION

THE vision for Smart World brings fast growth in research, development, and deployment of Internet of Things (IoT). *Things* in IoT are not only connected computers and mobile phones, but also sensors/actuators and day-to-day objects such as books, medicines, vehicles, TVs, and refrigerators ([1] and [2]). The future of IoT lies in the success of Machine-to-machine (M2M) communication, where billions to trillions of objects, sensors/actuators in the surrounding environments are connected and operated through a set of electronic devices supported by communication networks, and one or more cloud-based servers [3]. The emerging IEEE 802.11ah is considered as a promising and scalable solution for communication among such a large-scale nodes ([4], [5], and [6]). With the use of sub-1GHz channel bands and various Modulation and Coding Schemes (MCSs), 802.11ah can achieve up to 1km of coverage in a hop with more than 100 Kbps data rate. It allows up to 8,191 devices to be associated with an Access Point (AP) using a new hierarchical Association IDentification (AID) scheme.

The existing networks, such as smart city, smart grid, smart agriculture, and Industrial IoT, operate in both sensor and backhaul scenarios. Standards such as IEEE 802.15.4, Radio-Frequency IDentification (RFID), or Bluetooth Low Energy (BLE) work over relatively shorter coverage (1-100 meters), supporting low-data rates (bytes to megabytes) and low-energy consumption. Backhaul network standards like Wireless Fidelity (WiFi), Worldwide Interoperability for Microwave Access (WiMAX), General Packet Radio Services (GPRS), and Long-Term Evolution (LTE) work over relatively longer distances (100 meters to a few kilometers) with the infrastructure of base STA demanding proper line of sights [7]. These solutions can provide high throughput (kilobytes to gigabytes) but consume more energy. Some recent testbeds like JEJU Testbed [8], Telefonica Ubiquitous Sensor Networks (USN) Platform [9], SmartGridLab [10], EAR-IT [11], Birmingham Urban Climate Laboratory (BUCL) [12], SmartSantander [13], and OpenTestBed [14] follow this approach for communication. These procedures open spaces in coverage range, energy consumption, and data-rate while connecting the sensor devices smoothly in different conditions. Further, their capabilities are limited by —*number of devices, throughput*, and *coverage range*, and hence scalability is less. IEEE 802.11ah standard fills this space up to a good extent by exploiting the edge of both WiFi and low-power sensor network communication technologies ([15] and [16]). Fig. 1 shows a typical multi-hop network architecture for IoT using 802.11ah for smart city and smart home applications. With the use of the sub-1GHz channel band, 802.11ah can achieve coverage of up to 1km in a single hop. This range can further be extended by using a new relay node concept between the AP and STAs which will reduce power consumption by allowing shorter transmissions ([17] and [15]). IEEE 802.11ah can overcome several IoT communication issues by handling complexity and coexistence and making the network easier to manage. For example, in a remote environment or agriculture monitoring and alarming system for preventing crops' damage by wildlife, a single IEEE 802.11ah network can efficiently do the job. Otherwise, we need multiple communication technologies for supporting the required data-rate and coverage range making it more complex to manage.

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TABLE I: Abbreviations and Acronyms

IoT	Internet of Things
MAC	Medium Access Control
RAW	Restricted Access Window
PHY	Physical
(D-)AID	(Dynamic) Association IDentifier
SID	Short IDentifier
M2M	Machine-to-Machine
AP	Access Point
DL/UL	Downlink/uplink
(D)TIM	(Delivery) Traffic Indication Map
NDP	Null Data Packet
NDP CMAC	NDP Carrying MAC
BDT	Bi-Directional TXOP
TWT	Target Wakeup Time
TXOP	Transmission Opportunity
MCS	Modulation and Coding Scheme
TBTT	Target Beacon Transmission Time
TGah	IEEE 802.11ah Task Group
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ITU	International Telecommunications Union
IBSG	Internet Business Solutions Group
ICT	Information and Communication Technology
ISM	Industrial, Scientific and Medical
RFID	Radio-Frequency IDentification
BLE	Bluetooth Low Energy
LTE	Long Term Evolution
WiMAX	Worldwide Interoperability for Microwave Access
WiFi	Wireless Fidelity
T/FDM	Time/Frequency Division Multiplexing
TDMA	Time-division Multiple Access
GPRS	General Packet Radio Service
RTS/CTS	Request to Send/ Clear to Send
ACK	Acknowledgment
CSMA (/CA)	Carrier Sense Multiple Access (/Collision Avoidance)
OFDM	Orthogonal Frequency-Division Multiplexing
AIFS/SIFS	Arbitration/Short Inter Frame Space
DCF	Distributed Coordination Function
DIFS	DCF Interframe Space
EDCA	Enhanced Distributed Channel Access
CSB	Cross-Slot Boundary
CAC/DAC	Centralized/Distributed Authentication Control
APSD	Automatic Power Save Delivery
PSMP	Power Save Multi-Poll
PS-OLi	Power Save with OffsetListenInterval
RID	Response Indication Deferral
NAV	Network Allocation Vector
PV0 (/1)	Protocol Version 0(/1)
QoS	Quality of Service
FCS	Frame Check Sequence
(O)BSS	(Overlapping) Basic Service Set
CRC	Cyclic Redundancy Check
MPDU	MAC Protocol Data Unit
(C)TW	(Control) Traffic Window
CPF	Cell Polling Frame
PS-Poll	Power Save Polling
AFH	Adaptive Frequency Hopping
CCA	Clear Channel Assessment
RSS	Received Signal Strength
SDN	Software-Defined Networking
LLN	low-power and Lossy Networks
UAV	Unmanned Aerial Vehicle
TSCH	Time Synchronized Channel Hopping

A. *MAC protocols for IoT communication*

For supporting flawless performance in the M2M network, having a massive number of IoT devices, MAC protocol plays the most important role ([18] and [19]). Compared to traditional ones, the MAC protocol for IoT demands features like—*low-power, low cost, adaptive, cognitive, and large-scale operation* [20]. The most critical MAC layer challenge in M2M communication is to provide channel access among a massive number of devices supporting their various service requirements. At the same time, communication needs to be efficient in terms of *power consumption, data rate, latency, and cost*. In these scenarios, channel access has the potential to solve many of them, as foreseen by many industries and standardization bodies [21]. As a result, the MAC protocol design for M2M communication has emerged as an important area of considerable work for researchers and practitioners.

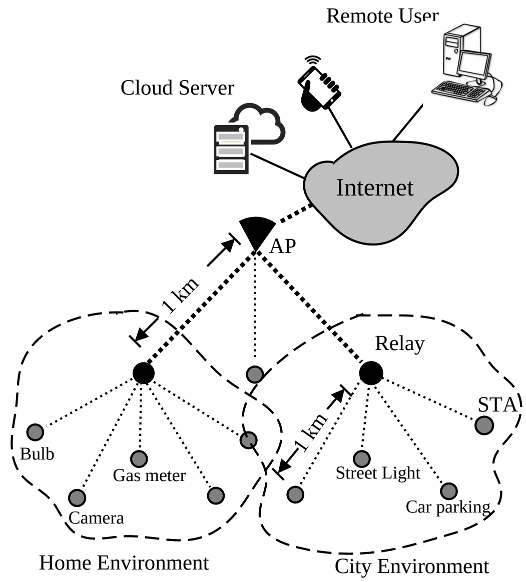

Fig. 1: An example of IEEE 802.11ah-based multi-hop IoT network architecture combining smart city and smart home applications

Various standardization bodies such as the Institute of Electrical and Electronics Engineers (IEEE), International Telecommunications Union (ITU), Internet Engineering Task Force (IETF), etc., are working hard to make low-cost communication feasible. Among them, IEEE 802.11 and IEEE 802.15.4 specifications have continuously evolved to include new technologies and functionalities, and several amendments [22]. These technologies have been used widely in current IoT testbeds available worldwide, penetrating a wide variety of markets, including consumer, mobile, and automotive [23]. There are two critical reasons for such remarkable acceptance:

(i) the use of ISM band for communication channel and low-cost hardware
(ii) the adaptation of MAC protocol called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which enables communication of multiple stations (STAs)

Due to the short and infrequent M2M communication, Low-Power Wide-area Network (LPWAN) technologies such as LoRa [24], SigFox [25], NB-IoT [26] are suitable for IoT communication. These technologies use a lightweight (low overhead) MAC protocol for channel access [27]. For this reason, SigFox and LoRa restore the use of random access based ALOHA scheme, where a node transmits without any carrier sensing mechanism. TDMA-based MAC approaches are used by NB-IoT technology with a higher cost for channel band. NB-IoT is also considered to be scalable due to the availability of licensed channels in GSM and LTE frequency bands.

RFID and BLE are some of the key IoT enabling technologies, which are expected to be used in a wide-scale manner [28]. Issues related to collision, unfairness, and relatively low throughput do exist in the RFID-based MAC protocols ([29] and [30]). Similarly, BLE faces challenges of large-scale and large coverage network support for IoT. IEEE 802.15.4 provides a low-rate and low-power Wireless Personal Area Network (WPAN) that has been commercially used for a diverse range of embedded wireless sensing and control applications. It is noticed that most of the testbeds ([9], [8], [13], etc.) use 802.15.4-based technology for implementing a large-scale network. However, 802.15.4 performs very poorly, showing a steep reduction in throughput and an increase in energy consumption in the dense deployment of IoT devices ([31], and [15]). A low-power MAC protocol for IEEE 802.15.4e [32] is proposed, which maintains a low duty cycle with Time Synchronized Channel Hopping (TSCH). Therefore, it is suitable for efficient IoT communication [33]. MAC protocols in WLAN technologies such as 802.11a/b/g/n/ac are designed to send a large frame with huge power consumption, hence not efficient and suitable for IoT communication.

Eventually, there emerges a need to enhance the MAC protocol for supporting the communication of a large number of low-power devices. To meet the requirements of IoT and M2M communication such as scalability, heterogeneity, and low-power consumption, IEEE 802.11ah Task Group (TGah) [34] extends the features of current 802.11-based MAC schemes with some new innovative ideas ([4], [35], [15], and [36]). The hybrid MAC protocols use the advantages of both contention and reservation-based protocols. It has been a solution to the issues with high collisions and low scalability in IoT ([37] and [38]). IEEE 802.11ah encompasses a hybrid approach of MAC solutions, where contention and reservation schemes are used for allocating a slot for successful transmission, and all of these happen within a RAW frame. The new channel access mechanism divides the STAs into groups to reduce the collision domain due to contention. From multiple groups, the AP allows only one of them for channel access in a particular RAW frame. A comparison of different IoT characteristics supported by the MAC layer is shown in Table II. Existing IoT technologies are compared considering the features – grouping of stations, relay support for multi-hop communication, scalability during channel access, polling approach for energy saving, lesser contention, support of ISM band, distributed channel access, heterogeneity support, handle coexistence among other technologies, better throughput, low latency support, and lightweight Null Data Packet (NDP) support. With the use of sub-1GHz channel and longer coverage and multiple MCSs, IEEE 802.11ah can solve coexistence and traffic load heterogeneity up to a certain extent. However, a complete solution to heterogeneity, coexistence, and high latency are still challenging. The new MAC design is expected to consider traffic heterogeneity in terms of load, intervals, and frame size. For supporting scalability with large-scale nodes, distributed MAC decisions (e.g., at relays or APs) are essential. The following section discusses the MAC features provided by IEEE 802.11ah in details.

B. IEEE 802.11ah MAC: Vision and motivations

To support energy efficiency and scalability in 802.11ah, TGah has worked on the PHY and MAC layers. With the use of sub-1GHz and different Modulation and Coding Schemes (MCSs), 802.11ah can achieve up to 1km of coverage range in 1-hop. It allows up to 8,191 devices to be associated with an AP using a hierarchical Association IDentification (AID) scheme. The use of newly proposed Null Data Packet (NDP) MAC frames, short MAC header, and management frames reduces Tx/Rx time significantly. It supports low energy consumption by adopting strategies like Target Wake-up Times (TWT), Traffic Indication Map (TIM), and Segmentation. To reduce collisions due to contention, 802.11ah uses Bidirectional Transmission opportunity (BDT) and Restricted Access Window (RAW), and slotted channel access with synchronization frame. STAs are divided into *non-TIM* for periodic and low-traffic, *TIM* for high-traffic, and *unscheduled* for very low-traffic, so that channel access and power-saving scheme can be applied accordingly. Relay and sectorization operation allows the network to extend and organize more accurately.

Overall, IEEE 802.11ah is a true IoT-enabling solution for seamless communication among a massive number of devices. The channel bandwidths– 1 MHz and 2 MHz and coding schemes – MCS0 and MCS10 are widely used in IoT and M2M communication for short burst data-rates and long-range communication ([39] and [40]). This new standard is of interest to both industry and research communities. The specifications of 802.11ah are mostly discussed concerning a list of published literature. Apart from this, dozens of research papers discuss the idea of MAC and PHY layer concepts in detail. However, for making smart and scalable IoT, many exciting and salient issues are still not considered. In summary, the primary MAC issues and challenges– dense network operation, the power efficiency of sensor devices, the presence of many hidden nodes, distributed and synchronized access, dynamic association and grouping, and massive overhead due to multi-hop forwarding, are to be resolved. These challenges and their existing solutions are discussed in Section IV.

C. Contributions

This survey paper provides different features and uses cases of 802.11ah network based on the recent research articles. We highlight the problems and prospects of 802.11ah and their enhancements and identify the factors for improvement. The contribution of this paper, as compared to recent literature, are:

- This paper starts by giving details about the characteristics of IoT communication, different supported standards, and requirements of MAC protocol.
- The recent updates in terms of products, use-cases, and features of 802.11ah based on the latest research papers are presented in this work.

TABLE II: Different IoT characteristics and MAC layer support for some of the key enabling technologies

Standard	Grouping	Relay	Long range	Scalability	Polling	Less contention	ISM band	Distributed access	Heterogeneity	Coexistence	High throughput	Low latency	NDP frame
802.15.4e	✗	✓	✓	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗
NB-IoT	✓	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗
LoRa	✓	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗
SigFox	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗
RFID	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗
BLE	✗	✓	✗	✗	✓	✗	✓	✗	✓	✗	✗	✓	✗
802.11ah	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✗	✓

- Compared to other related literature in this field, this paper mainly concentrates on MAC layer features of 802.11ah and their issues. While discussing those problems, existing solutions with their advantages and disadvantages are also highlighted.
- The open research issues, challenges, and future works in this field are provided.

D. Paper organization

The rest of the paper is organized into five sections. Section II discusses the related survey works. Use-cases and features of 802.11ah suitable for IoT are presented in Section III. Section IV presents a survey of the features of 802.11ah along with their issues addressed by many researchers, and future directions are pointed out. Section VI concludes this paper.

II. Related Surveys

In this section, we mention the existing surveys relevant to 802.11ah and its enhancements.

A large number of research articles discuss the novelties and features of the 802.11ah standard. A few of them mention about different issues and challenges while analyzing those features over IoT scenarios. Park *et al.* [39] highlights the key features of 802.11ah and discusses its support for IoT. After a detailed analysis of this standard's features, some of the fascinating issues are presented in Khorov *et al.* [4]. The RAW performance in the IoT environment is analyzed in [41]. Ahmed *et al.* [15] presents a short comparison of 802.11ah and 802.15.4 in light of their support in IoT communication. Aust *et al.* [35] presents the PHY and MAC layer features of 802.11ah and points out the future directions for outdoor communication support. Oliveira *et al.* [40] studies the MAC layer protocols for IoT. This paper first assisted different short-range and long-range standards, including 802.11ah for IoT communication then their MAC layer supports are surveyed. Other related works such as [42], [43], [44], [45], [46], and [5] primarily discuss the features and innovations of this standard.

Synthesis: To support low-power and large-scale communication in IoT, IEEE 802.11ah has come up with various new and innovative MAC concepts. The existing state-of-the-art works mostly discuss these concepts in the MAC and PHY layers. A large number of schemes are proposed to solve different standardization and implementation-based issues of IEEE 802.11ah. This paper considers these enhancements and solutions and discusses their suitability in IoT. Moreover, based on a survey based on these schemes, we discuss different challenges and future works. To the best of our knowledge, this survey comes as the first for reviewing these works. We discuss the enhancements or solutions and identify the factors for future improvements.

III. IoT enabling features in IEEE 802.11ah

The recently addressed innovative feature have made IEEE 802.11ah a suitable communication standard for smart and scalable networks like IoT ([47], [42], and [43]). TGah has developed OFDM-based PHY, which operates in the license-free sub-1GHz band. An enhancement to the MAC protocol is carried out to support a transmission range up to 1km in a single hop with a minimum data rate of 150 Kbps. In this section, we have discussed the use-cases and features of 802.11ah in brief.

A. IoT Use-case of IEEE 802.11ah

It is required to use scalable communication technology to connect a large number of devices for different IoT applications. The current deployment mostly uses heterogeneous technologies together, creating more complexities. In addition to the scalable MAC layer design, utilization of the sub-1GHz band and various MCSs support over 802.11ah allows configuring different IoT applications easily. The varying data rates ranging from 150 Kbps to 78 Mbps has been found to be suitable for low-powered and resource-constraint IoT ([48], and [39]). With short and burst transmissions, IoT devices' sensors need to be in wake-up mode only for a short time, thereby conserving battery and energy. A list of IoT applications and their traffic requirements are discussed in Table III. IEEE 802.11ah-based backhaul/backbone network for various IoT applications such as industrial and agriculture provide a low cost and flexible infrastructure with improved coexistence management. The WiFi and IEEE 802.15.4-based solutions are challenging to deploy due to the coexistence issues on the 2.4GHz band [49]. Also, wireless backhaul requires long-distance connectivity with higher bandwidth, which is lacking in state-of-the-art solutions. The remote environment/agriculture monitoring and alarming system to prevent crops' damages by the wildlife and forest fire detection require longer-range connectivity to check the status in the region. This also demands higher throughput to enable the transfer of image data. IEEE 802.11ah is a suitable communication technology that efficiently connects such large areas, consequently reducing economic damage and assisting in fire prevention. Smart Grid brought great benefits to the electric energy

TABLE III: IoT use-cases of 802.11ah

Use-case	Traffic flow	Data rate	Traffic types	Example works (Ref.)
Smart grid	Bi-Directional	100Kbps	Continuous/Periodic /Burst	[10], [50], [37]
Environment /Agriculture Monitoring	Mostly Up-link	100Kbps	Periodic, Event-driven	[51], [49]
Industrial process automation	Bi-Directional	$<$1Mbps	Periodic, Burst	[52], [53]
Indoor healthcare system	Mostly Up-link	100Kbps	Periodic, Event-driven	[54]
Healthcare /Fitness	Bi-Directional	100Kbps	Periodic, Event-driven	[55], [56]
Backhaul/ Backbone	Bi-Directional	$>$200Kbps	Continuous/Periodic /Burst	[57], [15]

segment by monitoring smart meters and protection devices, making electrical distribution more reliable [10]. Different power transmission and distribution units ultimately transfer power from generation units to smart meters, vehicles, and micro-grid. The existing network architecture with multiple network technologies for communication creates issues related to complexity, coexistence, and difficulty to manage. IEEE 802.11ah with relay nodes can cover a longer distance and connect many power consumption units situated far apart. In addition to sensing and actuation operations, 802.11ah can reveal vulnerabilities and run telemetry in various smart grid operations.

An AP or relay with sub-1GHz can cover thousands of sensors/actuators connected to the Internet. The devices like a camera for a surveillance system or WiFi node of the Internet require some bandwidth to transmit. On the other hand, devices like lights or alarms send a concise packet with a very low data rate. As 802.11ah has different MCSs with the various data-rate for different applications, it is proven to be suitable for a complex network such as Smart Home, Smart campus, etc. ([4] and [39]). Again, when a large number of STAs try to communicate simultaneously, collision increases. Long transmission range leads to higher IFS duration, and smaller packet increase overhead caused by a large header size. Hence, IEEE 802.11ah uses different novel schemes to cope with these kinds of issues and solves many. Fig. 2 highlights the key IoT enabling features. The terms – lightweight and efficiency indicate the short size and channel usage efficiency, respectively. For supporting various IoT applications, different MAC layer enhancements are discussed in the below section.

B. A summary of the MAC layer features for IoT

To provide heterogeneous traffic requirements of IoT applications, TGah has developed different MCSs to be applied in various scenarios. Considering the wide channel band of 16 MHz, MCS9 can provide up to 78 Mbps of data rates. Along with the PHY layer improvements, TGah has incorporated innovative MAC layer solutions for better scalability. The suitability of IEEE 802.11ah in IoT are discussed in literature such as [39], [4], [15], [47], and [58]. We discuss some of the key IoT-enabling features in the remainder of his section.

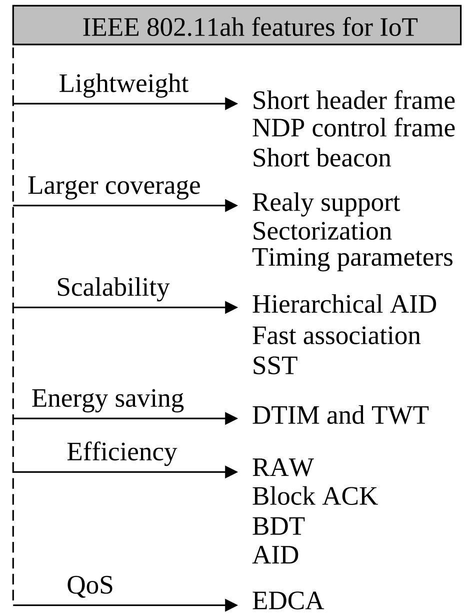

Fig. 2: IoT-enabling features of IEEE 802.11ah

1) Short frame header: TGah proposes a shorter header size in Protocol Version-1 (PV1) [16]. The key differences between traditional PV0 and PV1 header are shown in Table IV. The PV1 MAC header's basic components include addresses, Frame Control (FC), and optional Sequence Control information, a variable frame body saying the type of the frame, and an FCS containing 32bit CRC [4].

TABLE IV: Comparison of 802.11ah MAC header with legacy 802.11 MAC header

Field	PV0 Header	PV1 Header
Size (Min.)	34 Bytes	14 Bytes
Optional Address(es)	A4	A3, A4
No. of Types	1	2 (Downlink, Uplink)
Overhead (100 Bytes payload)	30%	10%
Sequence Control	Not optional	Optional
DS field of FC	Present	Absent
Duration/ID	Present	Absent

2) NDP CMAC frames: Null Data Packet Carrying MAC (NDP CMAC) reduces the overhead of control frames (e.g., PS-Poll, ACK, etc.) transmitted by STAs [16]. The typical 802.11 frame has a PHY header followed by a payload. However, NDP removes payload and includes a preamble of bits ("0" or "1") and the PHY. Therefore, it does not carry any data to reduce control overhead. For example, a STA sends NULL frame "0" to say about its wake-up status. Otherwise, it sets NULL frame "1" to indicate AP about sleep mode. With this, if 802.11ah transmit a 100 Bytes frame at the lowest rate (i.e., 1 MHz with NSS =1 and MCS10), it takes $\sim$8ms. With reference to this, a legacy ACK requires 1.5ms, which is 20% of the data frame, whereas an NDP ACK requires $\sim$0.5ms, i.e., 6% of the data frame.

3) Short Beacons: Two types of beacons – (i) short beacons, which are sent frequently at the lowest rate, and (ii) full beacons, which are transmitted infrequently, are used in 802.11ah. Due to the broadcast nature, not used, and sender address type, the destination address, sequence control, and BSSID are removed, respectively.

4) Relay node support: The relay concept in IEEE 802.11ah extends a WiFi hotspot network containing an AP and several non-AP STAs with relay nodes. Relay nodes forward frame between the STAs associated with the relay and the parent AP. Thus, the relay feature can further reduce power consumption by making shorter range transmission [15]. It increases coverage with multi-hop support and allows different MCSs to be applied over a particular relay BSS. A relay consists of a relay AP, a relay function, and a relay STA.

5) Hierarchical station organization: The legacy 802.11 can only associate 2007 STAs per AP due to the limitation in *AID* field size. On the other hand, 802.11ah uses a hierarchical structure using which a 13bits AID is assigned to each of the associated STAs. The new AID/TIM structure is organized into *pages, blocks, sub-blocks*, and finally to *STAs* (can be seen in Fig. 3). A set of STAs having AIDs within a specific range is kept in the same TIM block. With the help of 13bits AID, a single AP can support up to 2^{13}-1=8191 number of stations to be associated.

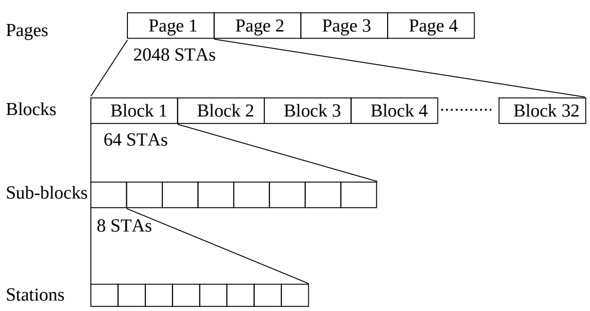

Fig. 3: Hierarchical AID/TIM organization [16]

6) Power saving mechanism: IEEE 802.11ah divides time into pages, pages into DTIM periods, DTIM into TIM periods, and TIM into slots in a hierarchical manner [59]. The duration of DTIM and TIM for STA starts on the received of a beacon. AP sends a DTIM beacon informing about the pending data to the TIM groups. Then, the TIM beacon carries in the information of which STA has pending data at AP. Fig. 4 shows an example of TIM and DTIM structure. In the DTIM mapping, among 8 TIMs, a STA from TIM5 only has pending data at AP. Similarly, TIM mapping needs to create for STAs like 770, 773, etc. A STA keeps itself in the power-saving state following conditions – (i) DTIM beacon notifies the STA of TIM group that there is no pending data at AP, and (ii) STAs know about pending data in AP but not explicitly aware of the TIM beacon. In many cases, 802.11ah can use TWT scheme, allowing AP to set a specific time or list of time duration to different STAs for channel access [60]. A STA can then keep itself in sleep mode until the allocated time, which reduces energy consumption.

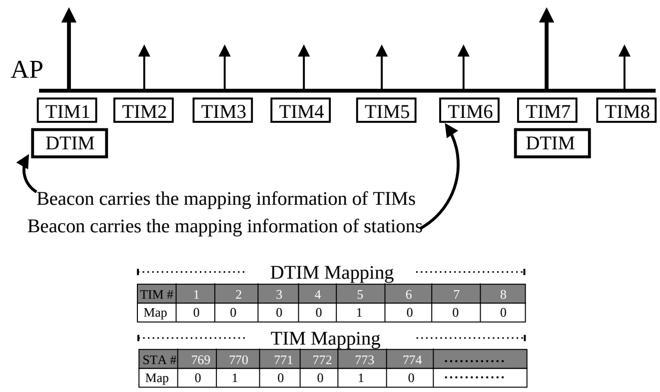

Fig. 4: Example of TIM and DTIM mapping

7) Sectorization: The PHY layer of IEEE 802.11ah is inherited from 802.11ac. It can also support sectorized beamforming, increasing the system capacity by the simultaneous transmission for multiple STAs. The AP of 802.11ah can organize a network by using sector antennas to reduce interference at the same time. This is useful when multiple BSSs overlap and create a hidden node problem.

STAs of a particular sector are allowed to access the medium through a sectorized beacon. The STAs in a BSS are divided into three sectors, and three sectorized beacons are transmitted at different sequential intervals. Also, omni-beacon is used for all the STAs available under the BSS. IEEE 802.11ah proposes two types of sectorization schemes, viz., Group-based and TXOP-based.

- *Group sectorization* - The STAs which are in the spatial vicinity of each other are grouped into sectors, and the AP transmits a sectorized beam-formed beacon to them. All STAs in the same sector can hear each other's signals and can transmit in a particular time interval to avoid the hidden node problem.
- *TXOP-based sectorization* - This scheme is used to minimize interference caused by Overlapping BSS (OBSS) while allowing the associated STAs for simultaneous transmission. In TXOP-based sectorization, during the frame exchange between the AP employing sectorized beam-forming and a non-AP STA, spatial reuse by OBSS APs or non-AP sharing the same wireless medium is allowed.

8) Fast association and authentication: To solve the problem of a huge delay in association procedure, 802.11ah has proposed Centralized Authentication Control (CAC) [61] as well as Distributed Authentication Control (DAC) [62]. A value called authentication control threshold is set by an AP that is transmitted through the beacon frame in CAC. A STA can associate only if the value of it is smaller than the threshold. The DAC scheme divides beacon into different slots of equal duration. It uses two random variables uniformly distributed in beacon and transmission interval, respectively. An authentication request containing the two random variables is sent to the AP using truncated binary exponential backoff. The proposed solution reduces overall association delay by reducing the number of STAs for sending simultaneous requests.

9) Efficient small frame transmission: IoT networks require small data frequently to be sent by creating a high overhead. An AID of 18 Byte header is used instead of the MAC address of 28 Bytes header. It defines many NDP frames to transmit ACKs, block ACKs, PS-Polls, RTS, or CTS. A new scheme called Speed Frame Exchange [43] is proposed for acknowledging frame reception with data instead of an ACK.

10) Channel access mechanism: The RAW mechanism divides the STAs into different RAW groups that spread channel access over a long period. The RAW is further divided into slots; a STA can only run its Tx/Rx mechanism in the mapped slot [16], [4]. The STAs belonging to a RAW group are allowed for contention within the assigned slot duration. Getting a slot is dependent on a mapping function, as mentioned below:

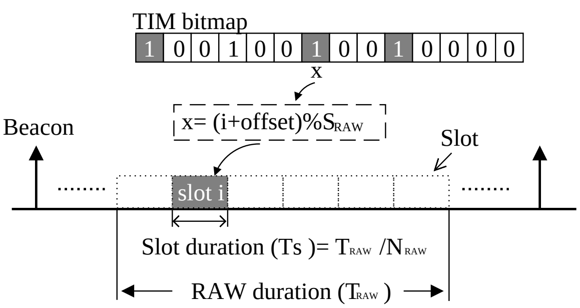

Fig. 5: Mapping of RAW slots and STAs

$$\mathsf{x} = (\mathsf{i} + \mathsf{offset})\%\mathsf{S}_{\mathsf{RAW}} \quad (1)$$

where x is the slot number in a RAW frame of size $\mathsf{S}_{\mathsf{RAW}}$, the offset value is for improving fairness among the STAs in a RAW, and i is the position index or AID of the STA. If the STA has already paged, uses AID, otherwise the position index is used. As shown in Fig. 5, if a STA finds the TIM bitmap field set to "1", a slot x is calculated using Eq. (1). The slot duration (T_{s}) is calculated from slot duration count (S_{c}) specified in RPS as:

$$\mathsf{T}_{\mathsf{s}} = 500\mu\mathsf{s} + \mathsf{S}_{\mathsf{c}} \times 120\mu\mathsf{s} \quad (2)$$

where, S_{c} is dependent on the value of k ($\mathsf{S}_{\mathsf{c}} = 2^{\mathsf{k}} - 1$), which is the number of bits in sub-field–*slot format*. If the slot format field is set to 0, $k = 11$ otherwise for 1, $k = 8$. Once a slot is identified using Eq. (1), a STA can start its contention for data transmission. A RAW frame can be further divided for uplink and downlink transmission. It can also maintain a Periodic RAW (PRAW) frame for non-TIM STAs, and a frame for unscheduled STAs. STAs want to initiate a transmission, need to send a PS-Poll frame after successful backoff. If AP acknowledges the PS-Poll, STA can send the data frame. AP

TABLE V: Timing parameters of 802.11ah compared to other standards

Standard	SIFS (μs)	DIFS (μs)	Backoff slot time (μs)
802.11a	16	34	9
802.11b	10	50	20
802.11n	16	34	9
802.11ac	16	34	9
802.11ah	160	264	52

informs about the buffered data through TIM-mapping for the downlink traffic, and then the STA needs to send a PS-Poll frame like before. If succeeded, AP can send data in the allocated slot. At the beginning of RAW, AP broadcasts a synchronization (SYNC) frame. The STAs can detect the availability of the channel and can initiate its transmission. Hence, the STAs do not need to wait for an allocated time frame called *ProbeDelay* timeout [63]. Additionally, other key features of 802.11ah are mentioned below.

- *EDCA*: 802.11ah adopts Enhanced Distributed Channel Access (EDCA) for service category-based access [64]. It provides traffic-aware channel access employing different inter-frame spaces for each category [65]. A flexible time duration named Arbitration Inter-Frame Space (AIFS) is used before the backoff period. Accordingly, the contention period is not the same for different types of traffic classes.
- *PRAW*: In IoT, a massive number of STAs may be deployed for monitoring purposes [59]. The STAs mostly transmit traffic periodically. To reduce overhead for such traffic, 802.11ah proposes a PRAW as a part of the existing RAW frame. If the periodicity is known, STAs can be scheduled in the PRAW phase without requiring multiple contentions. This reduces overall access time, which further increases the efficiency of the network. The PRAW allocation may be indicated by the RAW Parameter Set (RPS). The allocated indication is further broadcasted by AP such that all other PRAW STAs can know about the scheduled details.
- *Cross-slot boundary*: If a STA is transmitting or counting down in backoff over EDCA, there is an option for AP to allow the transmission over the cross-slot boundary (CBS) case [66]. The CBS indication is sent using RPS with 1bit field. If the CSB field is "0", a STA can cross the slot boundary. Otherwise (i.e., CSB field "1"), there is not enough space in the RAW called a non-cross boundary case.

11) Timing parameters: The long distance coverage of 802.11ah creates high propagation delay. Therefore, the timing parameters need to be set accordingly. The 802.11ah uses relatively longer time intervals for SIFS, DCF, DIFS, and idle slot time as compared to 802.11a/b/n/ac standards due to the longer coverage. Table V gives a comparison of modified parameters in 802.11ah.

12) Types of stations: IEEE 802.11ah divides the STAs in a network into different categories for better channel access and to maximize energy efficiency. Considering the traffic generation behaviors, STAs are divided into TIM, non-TIM, and Unscheduled.

- *TIM STAs*- This type of STAs have a high amount of traffic and hence, request a slot frequently to take a chance for Tx/Rx. The STAs always listen to the TIM beacons transmitted by an AP and send/receive data with an allocated RAW frame.
- *Non-TIM STAs*- The STAs which follows a periodic nature of transmission are kept in non-TIM STAs category. To simplify this operation, this type of STAs directly negotiates with AP to acquire a periodic slot.
- *Unscheduled STAs* - There are many STAs in an IoT network having very low traffic to send. In such a case, STAs can send a Poll frame requesting a slot without following any beacon.

13) Response Indication Deferral (RID) protocol: Response Indication Deferral (RID) is a new virtual carrier sense mechanism replacing Network Allocation Vector (NAV) of 802.11. NAV cannot be used in 802.11ah as the *Duration* field is absent. So, RID is set after the complete reception of the PHY header. The new RID uses 2bits field in the PHY header for indicating four distinct types of operations, those are– *Normal response* (SIFS time + ACK time), *NDP response* (SIFS time + NDP frame time), *No response* (Broadcast frame), and *Long response* (SIFS time + Longest TXOP time used for speedy exchange).

14) Dynamic AID assignment: The dynamic AID allocation scheme allows an AP to change the group structure to keep the performance stable if there are changes in the network.

15) Subchannel Selective Transmission (SST) protocol: Other than the primary channel, 802.11ah defined sub-channel to be used by STAs, where they rapidly switch to different channels and enable communication. This procedure helps to solve the fading problem in large-scale IoT networks. The AP may add an SST element in the beacon to carry a subset of channels on which SST operation can be carried out. The STAs within the beacon interval can use the best channel for communication.

16) Block ACK operation: To improve efficiency, a STA that receives a series of frames can use a single ACK frame to acknowledge them. In 802.11n, the sender only responds to the lost frame. Additionally, 802.11ah includes preferred MCS and bandwidth information in the ACK. Further, a fragment block ACK to acknowledge the portion of a complete MPDU is introduced. It may use immediate ACK by sending NDP-based ACK or standard ACK mechanism in response.

17) Bi-Directional Transmit (BDT) protocol: Earlier in 802.11n, Reverse Direction (RD) protocol has been used to improve TXOP-based transmission by eliminating the need for both the communicating devices to initialize. Additionally, Bi-Directional Transmit (BDT) protocol in 802.11ah allows us to acknowledge frames without sending only extra ACK implicitly. The reception of a current data frame is to imply that the previous data frame was successfully received. In the case of BDT, MPDUs are shared without sending any ACKs in between. A *more data* field is used to inform the recipient for further use of TXOP. If *more data* bit is “1”, then there are data yet to be sent, otherwise “0” is used to indicate that all data has been successfully sent.

IV. IEEE 802.11AH-BASED MAC PROTOCOLS FOR SUPPORTING IOT

Till now, we have discussed the suitability of 802.11ah towards IoT. Researchers have investigated many issues and tried to resolve them to enhance network performance to an acceptable level. However, many are remaining unaddressed. The state-of-the-art solutions solve IoT communication issues from the perspective of scalability, heterogeneity, energy efficiency, adaptivity, multi-hop support, and QoS (Refer Sec. I-A). Concerning these, we compare the existing solutions by highlighting the future challenges. The current works mostly solve the issues related to RAW size, grouping, relays, distributed channel scheduling, and AID. We discuss the state-of-the-art schemes in the following subsections.

A. RAW mechanism for large-scale heterogeneous network

The RAW-based channel access in 802.11ah provides feasibility to a high-density network for communication. Although grouping based access mechanisms were available in literature before it was proposed ([67], [68], [69], [70], [64], and [71]), but incur high control overhead in group management. Further, devices are considered static with fixed proximity conditions, and thus groups do not change once configured. To simplify the grouping and access mechanism, 802.11ah has developed a combined method where nodes are not only grouped but also RAW-based access, and TIM-based power-saving features are applied. The Tx/Rx nature of different RAW depends on the network. For example, in dynamic and heterogeneous network scenarios, the use of RAW slots may get overflow or remain unused.

Determining the optimal RAW size based on the current number of STAs and traffic load is challenging. The number of RAWs in a group also impacts the performance of the channel access scheme. If there are a few RAW groups, contention will be less, and throughput will be increased. However, there will be high latency due to the larger contention period. Similarly, if there are many RAW groups in the same beacon period, contention will be high, and throughput will be less for a massive number of devices. Again, a lesser delay is expected as there is low contention. Performance of RAW is measured and analyzed in existing literature such as [58], [36], [4], [91] and more. When the number of nodes is very high, the RAW with a larger size performs better while sending packets for a particular duration of time. Future works are required to accurately predict RAW size under heterogeneous and dynamic IoT network conditions. Unlike the homogeneous scenario, heterogeneous networks are defined by traffic intervals and parameters like sleep time and QoS requirements. This leads to an enormous design space.

Different enhancements are proposed to solve RAW-related issues. Bel *et al.* [72] divides RAW time into equal time slots and allows STA to select a slot for further contention randomly. So, there are collisions, if more than one devices select the same slot. The performance results show 100% packet delivery for 600 stations. Park *et al.* [73] allocates the RAWs according to the number of devices, which can be estimated by a developed mathematical model. The author divides the

TABLE VI: RAW and grouping Schemes

Protocol/ Scheme (Ref.)	Year	Scope	Description	Limitation	Multi-hop support	Adaptive Support	Heterogeneity support	Scalability support
[72]	2014	RAW	RAW is divided into slots, STAs randomly select a slot for transmission	Traditional DFC scheme degrades performance for a network with a large number of STAs	✗	✗	✗	✗
[73]	2014	RAW size	Estimates the size of RAW based on probability of successful transmission	A full buffer approach, i.e., the network is always considered to be fully connected,	✗	✗	✗	✓
[74]	2015	RAW	Considers STAs backoff stage for adjusting RAW duration	The enhancement shows suitability only to homogeneous traffic	✗	✗	✗	✓
[50]	2015	RAW and Energy	Optimizes RAW size based on energy consumption	It does not consider the traffic heterogeneity and network dynamicity	✗	✗	✗	✗
[75]	2017	RAW and Energy	RAW size optimization based on energy consumption and data-rate	It does not consider the heterogeneous traffic scenarios	✗	✓	✗	✗
[76]	2016	RAW	RAW size adjustment based on periodic reporting of alarms	It is not easy to accurately set the threshold for alarm event detection. Also, it requires the number of RAW to be changed dynamically	✗	✓	✗	✓
[77]	2014	Group and Hidden node	Proposes a guideline to set the number of groups in the network based on hidden nodes	It only considers the number of active nodes whereas traffic load and energy are also some important issues in IoT	✗	✓	✗	✓
[78]	2017	RAW and Group	Predict the RAW size based on the number of PS-Poll messages in a hybrid access manner	The proposed protocol does not consider dynamic traffic patterns and intensities	✗	✓	✗	✓
[79]	2017	RAW	Identify the traffic scenarios and proposes different RAWs	No solution provided to RAW or group adjustment over changing network conditions	✗	✗	✓	✗
[80]	2017	RAW and Group	Adjust the RAW parameter set based on the real-time uplink traffic nature	The adjustment is done by only considering available information at AP, RAW grouping is not efficient for long time performance	✗	✓	✓	✓
[81]	2017	RAW and Group	In addition to [80], it uses *more data* field in header to estimate traffic load	RAW grouping is not efficient for long time performance and it considers only homogeneous STAs	✗	✓	✓	✓
[82]	2018	RAW and Group	The RAW slot size is set based on group size to improve throughput	Does not consider the traffic and collisions in the network	✗	✗	✓	✓
[83]	2018	RAW and Group	Considers heterogeneous MCSs in the network to improve RAW performance	However, it does not consider heterogeneous STAs (i.e., different MCSs) within a RAW group	✗	✗	✓	✓
[84]	2016	RAW	Estimate the size of RAW based on backoff window size at saturation scenarios	It always considers the saturation state of a network	✓	✓	✓	✓
[85]	2018	Group	It holds regression and greedy approach while proposing a traffic aware grouping scheme	Does not consider the requirements of applications	✗	✓	✓	✓
[66]	2018	RAW	A mathematical performance model is developed to allow cross slot boundary transmission	The proposed solution may increase energy consumption	✗	✗	✓	✓
[86]	2016	Beacon Interval	A mathematical model is developed to calculate suitable beacon Interval over heterogeneous scenarios	It does not consider the types of STAs in terms of low and heavy load, and energy	✗	✗	✓	✓
[87]	2018	RAW and QoS	Earlier RAW slots are kept reserved to ensure QoS for critical traffic	It does not consider the RAW, group, and fairness issues created due to the priority scheduling	✗	✗	✓	✓
[88]	2018	RAW and QoS	Traffic are categorized into different types and earlier slots are assigned to the higher priority traffic	It does not consider the RAW, group, and fairness issues created due to the proposed scheme	✗	✓	✓	✓
[89]	2019	RAW	Allocates RAW slots to applications based on their requirements	Optimization of RAW size considering dynamic network conditions is still an issue	✗	✓	✓	✓
[90]	2019	RAW	A surrogate model is developed to predict the RAW size over heterogeneous network scenarios	Energy consumption and multi-hop support are not considered while predicting the RAW size	✗	✓	✓	✓
[53]	2019	RAW and QoS	Control loop latency and jitter are calculated for sensor-cum-actuator network	Does not consider the dynamicity in the network	✗	✗	✓	✓
[59]	2020	RAW	Traffic Interval prediction model is developed to find periodicity of traffic	Prediction accuracy is a concern	✗	✓	✗	✓

RAW into uplink (RAW-UL) and downlink (RAW-DL). The size of RAW is estimated based on the probability of uplink transmission. A theoretical model is developed to calculate the possible number of devices that try to transmit in the next RAW. This scheme achieves a higher access probability than the legacy IEEE 802.11ah-based RAW. But, their enhancement does not solve problems like energy consumption and network dynamics. Also, it assumes that all the devices generate a uniform traffic load.

With the use of backoff size's increasing and decreasing nature, the RAW size is considered to improve throughput in saturation condition in [92]. An analytical approach [93] is considered to get the optimal backoff window in [92]. Considering the characteristics of uplink traffic, an optimal RAW is calculated from the optimal backoff window. Tian *et al.* [80] proposes a real-time grouping which optimizes RAW parameters by analyzing the current traffic conditions. However, it only considers homogeneous and saturated network conditions. With the use *more data* field of the header, a better traffic-aware RAW estimation technique is proposed in [81]. Further, the author in [83] enhances it to support heterogeneous MCSs in STAs. Considering heterogeneous traffic loads, [92] and [80], improves throughput approximately 36%, and 43%, compared to the traditional DCF/EDCA mechanism. Similarly, a significant delay improvement was also noticed from the performance results.

Lei *et al.* [78] proposes a RAW grouping approach based on the transmission request received by the AP node. A RAW begins with a short period called Control Traffic Window (CTW), which is included in the devices to reserve their channel access time followed by a Transmission Window (TW). The protocol reserves transmission slots by obeying the same sequence of CTW. The sequence of the successful channel is reserved and maintained in TW for data transmission. Although 100% and 56% of throughput and delay improvement can be noticed as compared to the legacy RAW with MCS3, respectively, it would be interesting to see the same with a large number of stations. Also, for event-driven traffic, pre-scheduling for a channel is not a suitable solution. A similar approach considers the report activities from alarm-based application in [76]. The RAW is a periodically recurring pool of time slots, the size of which can be dynamically tuned based on the reporting activity in the cell. The authors find the number of collisions while fitting the traffic in the time slots. However, overall delay and throughput improvements are not measured. A traffic interval prediction model is developed in [59] to reduce unnecessary wake-ups and contentions. Almost, 25% throughput improvement and 55.5% latency reductions are measured, as compared to 802.11ah. However, in a heterogeneous traffic scenario where a STA may transmit any time, at any rate, the protocol fails to fulfill the traffic requirements. Energy efficiency, traffic load, and node dynamicity are not considered in the RAW group optimization.

Considering the current backoff stage in the STAs, Hamzi *et al.* [74] estimates the RAW size at AP. To provide guaranteed QoS for delay-sensitive STAs, Charaniya *et al.* [79] categorized RAW operation into slot reservation-based access for Delay Sensitive Machine type Devices (DSMDs) and conventional 802.11ah-based access for non-Delay Sensitive Machine type Devices (non-DSMDs). Ahmed *et al.* [88] schedules the RAW slots of a group according to the priority of STAs. STAs are classified into higher priority traffic as critical and relatively low priority as periodic. However, it does not mention the effect on a load of group, RAW, and fairness. If the detailed deployments conceding different geographic locations and efficiency are not measured. In IoT, different automation applications like factory and industry monitoring require low-latency control-loop communication for actuation. Seferagic *et al.* [53] evaluated the time-critical control-loop scheduling for limited jitter and high reliability in IEEE 802.11ah. Ali *et al.* [65] analyzes the performance of 802.11ah network with different EDCA access categories within a RAW frame. However, the solution does not optimally utilize the load among different RAW groups. While provisioning priority scheduling over the RAW frame, [88], [53], and [65], show significant improvement on critical action, control-loop, and higher class (e.g., delay-sensitive) traffic, respectively. Although they reduce latency up to a certain extent, these lack support of flexibility and traffic requirements in different computation and communication parameters. A summary of different RAW-based schemes is presented in Table VI. Most of the works are carried out on RAW and grouping mechanisms considering single-hop scenarios. Further works are required to solve the RAW and grouping problem for IoT-based heterogeneous, dynamic, and multi-hop networks.

B. Power saving mechanism for a large-scale IEEE 802.11ah-based network

IEEE 802.11ah enhances the power-saving mechanism using a TIM and page segmentation powered by the RAW mechanism. It efficiently limits the level of contention and able to keep more STAs in a low-power state. The beacon-based power-saving scheme in 802.11ah allows a node to remain in the sleep state for most of the time. More freedom is provided to a STA to negotiate with AP about its next wake-up time in the TWT mechanism, and accordingly, it can stay in the sleeping mode to save energy. However, for a network like IoT, first, a massive number of STAs may unnecessarily wake-up due to its paging in the TIM group. Second, it lacks a proper time synchronization mechanism for scheduling traffic having longer intervals and non-TIM stations, especially in multi-hop IoT scenarios. Third, due to issues such as the hidden terminal problem and synchronization issue, there are re-transmissions, increasing drastically with the increasing number of STAs. Finally, IoT traffic flows are unpredictable; hence, slot scheduling for large-scale IoT nodes is challenging.

In order to solve the power saving issues in different types of STAs, 802.11e standard includes Automatic Power Save Delivery (APSD) [94] to keep wake-up mode itself only on the service time. But, APSD provides no mechanism to control the wake-up time of a STA. Enhancing APSD, Power Save with Offset Listen Interval (PS-OLi) [95] is proposed. In PS-OLi, the AP node sets a calculated offset to STAs for controlling their initial wake-up time. This allows the STAs to avoid wake-up time alignment, and as a result, the network collision probability is reduced. However, this mechanism considers the only collision reduction scheme to improve energy efficiency for such a network. Moreover, this paper shows suitability for periodic traffic, but in many cases, traffic is unscheduled in nature. Ogawa *et al.* [64] enhance the power saving in 802.11ah when the network is congested. The STAs are classified into contending and non-contending groups to reduce contention. Based on a number of idle states a STA goes to sleep mode.

Zhao *et al.* [96] proposes a method to save energy for uplink transmitting nodes. It allows a STA to sleep mode for a random amount of time when the channel is busy. Performance analysis of [64] shows a reduction of 90% energy consumption with a 5% increase in the delay, compared with conventional PS-Poll-based techniques. Later, it is found that the higher number of RAWs in each TIM group gives higher delay as experienced in [96]. Wang *et al.* [50] proposes an adaptive RAW mechanism based on total energy consumption. The size of the RAW determines the energy consumption for transmitting overhead. If the window size is small, overhead is high, as scheduling information needs to be transmitted in short intervals. This approach uses a simulated annealing mechanism for optimal RAW size and improves energy consumption in an 802.11ah-based network. The minimum energy efficiency improvement of this new RAW is approximately 7.3% compared to the existing RAW.

Che *et al.* [97] proposes a new mechanism using Cell Polling Frame (CPF), which schedules the STAs within one community or one cell. This mechanism improves the PSMP power-saving scheme by reducing the overall overhead in the network while reducing power consumption. The STA information field size decreased with the use of existing hierarchical AID mechanisms. However, power saving for unscheduled and non-TIM STAs is still challenging. A hybrid MAC protocol proposed by Beltramelli *et al.* [98] considers both RAW and TWT-based power saving in the contention phase. Detail scenarios of the strategies are informed using short control frames, and slots are only assigned to the STAs having data to send or receive. Here, the proposed scheme reduces average energy consumption for a successful transmission up to 55%, compared to the traditional RAW. Bel *et al.* [99] develops an analytic model to predict energy consumption and lifetime for an 802.11ah STA. The computation considers beacon, the density of STAs, transmission period, TIM, and segmentation STAs. Simulating the network with battery power of 1500mAh, 2200 mAh, and 7500mAh, results show energy saving by 20%, 22%, and 8%, respectively.

While resolving the unnecessary wakeup problem in TIM and DTIM grouping, Kim *et al.* [100] proposes a temporary membership and traffic scheduling scheme. Wang *et al.* [75] optimizes the size of RAW based on energy consumption. Considering the overall energy consumption and data-rate, optimal RAW size is estimated analytically. Santi *et al.* [101] presents an analytical model to calculate the average energy consumption during a RAW slot and TWT duty cycle. For the first time, the authors show that TWT outperforms RAW by over 100% beyond five transmission minutes. Tian *et al.* [6] develops a surrogate model considering energy and throughput to optimize RAW. Here, simulation results show 96% lesser energy consumption in dense heterogeneous networks. However, the solution does not consider the reasonable requirements of traffic during their schedule. Ngo *et al.* [102] proposes a directional MAC protocol, which uses an adaptive transmission power control scheme for improving energy efficiency. Ahmed *et al.* [59] saves energy for an IoT network with periodic traffic. A STA is scheduled over the RAW frame based on the predicted packet interval, consequently reducing unnecessary wakeups. Ngo *et al.* [102] improves energy-saving up to 30% which is further improved by 48.4% in [59]. Some of the MAC protocols proposed to solve energy issues are compared in Table VII. While improving energy efficiency, a few works are carried on TIM-based STAs. However, these do not consider heterogeneity, scalability, longer sleep duration, and multi-hop support while supporting IoT communication.

C. Presence of a large number of hidden and exposed terminal nodes

The collision due to hidden nodes is a major problem for the wireless network. Researchers have been trying to solve this problem from the time the standards were evolved. However, these mechanisms (e.g., [107], [108], [109], and [110]) mainly focus on more number of control packet exchange to ensure hidden node free network. But, for low-powered and resource-constraint IoT network, it cannot handle high overhead (e.g., RTS and CTS) as it degrades performance in a drastic manner [111]. The group-based access on 802.11ah reduces collisions to a great extent, but it suffers from a severe hidden node problem. The reasons behind this can be listed as:

- A large number of STAs (8000 STAs) are deployed in many use-cases of 802.11ah. The STAs are heterogeneous in nature and do not follow the same type of rules and regulations.
- Due to the long-distance communication links within a BSS, scheduling and control information loss is common.
- Uses CSMA/CA-based contention, i.e., to acquire the channel, at first it needs to send PS-Poll or RTS message. So, if the positive response from AP having NAV value is not known to other STAs, collisions are imminent.
- As most of the nodes stay in power saving mode, missing the AP's beacon is high.
- In IoT, uplink traffic is generated for most cases; a STA needs to initiate the channel access and transmission. Hence, PS-Poll messages among STAs within a BSS may collide.

Zang *et al.* [116] analyzes the hidden node probabilities in 802.11ah network. The size of RAW, number of RAWs, and geographical distribution of nodes affect the hidden node problems. With the increasing RAW groups, hidden node probability decreases. The solution to the hidden node problem mainly works in two phases viz., hidden node detection, and hidden node removal. Extensive researches have been done on 802.11 using the CCA mechanism, but it needs cooperative help from neighboring AP. It can observe that the proposed solution achieves up to a margin of 10% better performance in gaining throughput considering the distance is lesser between stations and AP comparing RTS/CTS and Basic network node scenarios. A hidden node detection mechanism proposed in [121] uses CCA, but due to the inaccurate CCA information, problems still exist. Active and passive approaches used by [122] utilizes RTS, CTS, and probe to detect hidden pairs. The author improves the number of hidden nodes by 50% in case of increasing the mobile nodes. With the help of neighbor AP, [123] detects hidden nodes, however multiple

TABLE VII: Energy saving schemes

Protocol/ Scheme (Ref.)	Year	Scope	Description	Limitation	Types of STA	Multi-hop support	Heterogeneity support	Scalability support
[103]	2006	Energy	AP maintains the detail scheduling for all STAs in the network and keep in sleep mode if not transmitting	A significant overhead due to STA's information for a large size network	TIM	✗	✗	✗
[104]	2010	Energy	STA decides when to keep itself in sleep mode	Fails to save power when different types traffic are considered and less deployment information is available	TIM	✗	✗	✗
[95]	2013	Offset listening	Adding offset in STA's sleep time, wake-up time of STAs are nonaligned to reduces collisions	The proposed solution is not incorporated with the existing RAW for communication	TIM	✗	✗	✓
[96]	2015	Energy Optimization	New energy saving scheme for uplink traffic.	Does not address the problems like unnecessary wake-up, uplink delay, and complexity	TIM	✗	✗	✗
[97]	2017	Compressed bitmap	The STA info field size in PSMP is decreased with the use of existing hierarchical AID mechanism	Does not solve the real energy issues like unnecessary wake-up and support for RAW schemes	TIM	✗	✓	✓
[98]	2017	RAW and TWT	Considers both RAW and TWT based power saving in their scheme at the same time to reduce uplink traffic congestion	Due to hidden nodes, high collision probability still exist	TIM and non-TIM	✗	✗	✓
[100]	2017	DTIM and TIM	Saves unnecessary power consumption by increasing sleeping duration of STAs	The proposed solution creates more communication delay	TIM	✗	✗	✓
[105]	2017	TIM and RAW	Proposes a mathematical method to accurately calculate throughput and energy consumption in a heterogeneous network	Issues like delay, unnecessary wake-up, and complexity considering same network scenarios still exist	TIM	✗	✓	✓
[106]	2018	TWT	Discusses the TWT-based low-consumption mode with low traffic requirements	Does not solve coexistence issues arises at the time of negotiation	Unscheduled	✗	✗	✓
[6]	2019	RAW optimization	A surrogate model is developed considering energy and throughput to optimize RAW	The solution does not consider the traffic classes in IoT to save energy according to their requirements	TIM	✗	✓	✓
[102]	2020	Directional MAC	Adaptive transmission power scheme is proposed for energy efficiency	Energy saving in a multi-hop topology with large-scale nodes is still challenging.	TIM	✗	✓	✓

TABLE VIII: Proposed solutions to the hidden node problem

Protocol	Year	Scope	Description	Limitation	Multi-hop support	Adaptive support	Heterogeneity support	Scalability support
[112]	2016	Hidden node	Uses start time of two STAs to detect a hidden node pair	Difficult to get the start time if traffic are event-driven in nature	✗	✗	✗	✗
[113]	2016	Dynamic Grouping	Detects a hidden nodes and regroups them based on geographical location	Not adjustable with dynamic network	✗	✓	✗	✓
[114]	2016	Hidden node	Detects hidden nodes using collision chain	Collision chains still remain in the network due to a large number of sleeping nodes	✗	✓	✗	✓
[115]	2017	Hidden node	Avoids hidden nodes using RSSI	Nodes within a group may not be available in their coverage range	✗	✓	✗	✓
[116]	2017	Grouping Scheme	Hidden node pairs are detected based on signal strength	Hidden issues with the mobile STAs will still be a problem	✗	✓	✗	✓
[117]	2017	Exposed node	Detects exposed terminal nodes for neighbor transmission	Nodes within a group may not be in their coverage range	✗	✓	✗	✓
[118]	2018	Grouping	Proposes a grouping algorithm using association process to prevent hidden node collision	The solution does not cope with the dynamic and heterogeneous network condition	✗	✓	✗	✓
[119]	2019	AP for OBSS	Proposes an Interference-aware Dynamic Frequency Allocation (IDFA) scheme to reduce hidden node problem	Mobility, complexity, heterogeneity, etc., are the issues need to be solved yet	✗	✓	✗	✓
[120]	2019	Hidden pair	Linear programming model is developed to minimize the number of hidden pairs	Heterogeneity, mobility, etc., are still remains as a challenge	✗	✗	✗	✓

AP in 802.11ah based network is not beneficial. A review paper, [124] discusses different issues related to hidden node problems and their solutions thereof. The authors mainly discuss the traditional mechanism to solve hidden node problems where STAs are assumed to be connected with equal coverage range, and they never go to sleep mode. Hence, in IoT scenarios, the same solutions may not work.

Since most of the nodes in the 802.11ah-based network are powered by battery, they periodically wake-up for AP's beacon at the same time. Immediately, they try to transmit a PS-Poll frame, which results in a huge collision. For such randomly deployed network scenarios, the probability that any two nodes become hidden from each other increases up to 41% [125]. Dong *et al.* [113] proposes a method to calculate the range of STA's energy detection from the large-scale fading model. From this, AP can detect the hidden nodes from a transmitting node and regroup them based on geographical locations. However, knowing the AP coverage, detecting nodes, etc., are difficult in a dense and heterogeneous network. Authors in [112] proposes a solution, where the hidden pair is detected based on the start time of two PS-Poll messages. If the difference between the start times of two STAs within a group is small, the chances of these two nodes being hidden from each other are high. The pair nodes are regrouped into two different RAW groups. However, it is not possible to get the start time if the traffic is event-driven. The proposed scheme reduces the number of hidden node pairs by 98.3% and the PS-Poll transmission end time by 68.5% in comparison to the standard algorithm. Taking collision as a reference point for hidden node problem, Damayanti *et al.* [114] uses AP to monitor the duration of an energy-saving time interval in a channel and considers any abnormally long duration as an occurrence of a collision chain to detect hidden pairs. The authors find throughput performance improvement up to 146% than the traditional approaches. A Received Signal Strength (RSS)-based solution of the hidden node problem is proposed in [115]. The protocol senses the neighbors by measuring the RSS and ensures that nodes in the same group are known, bit it is not always accurate in dynamic conditions. Enhancing this, Laipeng *et al.* [116] additionally uses several reference nodes according to their location to reduce the collision probability. However, collision chains remain in the network due to a large number of sleeping nodes. In this paper, throughput is claimed to be increased up to 15% in comparison to random grouping and a similer throughput has achieved in compare to K-means grouping. A node in sleeping mode may wake-up at any time and start transmitting irrespective of any ongoing transmission. Also, they assumed that the network is already saturated with only uplink traffic. Yu *et al.* [117] proposes a grouping mechanism based on a list of exposed terminal nodes. At the time of association, STAs sense the neighbor transmission to select a suitable group to join. The major challenge here is the huge scheduling overhead, which may become a serious bottleneck. The authors claimed achieving 20% improvement in network throughput by the proposed scheme. Response Indication Deferral (RID) is a new virtual carrier sense mechanism replacing NAV. A *Long-response* in RID is used for the speed exchange of frames. A STA updates the value within a TXOP. However, the long response is not received by the hidden STAs while updating RID values. The STAs from the uncovered area get the first frame but do not get the second as they are hidden from the receiver.

A summary of different MAC protocols solving the hidden node problem is compared in Table VIII. These works on hidden node problems are designed overlooking the issues of more extensive coverage range, energy-efficiency, and scalability.

D. Distributing the channel access mechanism over the network to improve scalability

The TXOP mechanism in 802.11ah [132] improves the performance in a relay-based distributed network. TXOP-based sectorization allows to connect STAs from different relay-enabled BSSs. Block ACK is suitable for better channel efficiency in such a multi-hop network. This scheme allows for sending multiple frames in a burst with a gap of SIFS time acknowledged by a single ACK. In explicit block ACK, an extra Block Request (BREQ) is sent to the sender.

IEEE 802.11ah uses only a single channel at a time, and hence only one node in the network can transmit at any given time. A primary channel of a BSS set up by an AP is static. But, due to STA's location, current channel conditions, etc., the primary channel's quality may significantly degrade compared to other channels, which may further interfere with each other. As a result, the chances of hidden node problems also increase. Without spatial reuse of the channel, the overall network may lead to beggarly performance. Further, many IoT applications require some sort of QoS guarantees.

Utilizing the available channels in 802.11ah is important for improving the network performances. The SST mechanism [16] enables STA to choose a sub-channel from a set of channels and communicate with other STAs. However, in a single-hop network, communication mainly occurs between STAs and the AP. The authors in [126] propose a static multi-channel allocation method for different 802.11ah based relay nodes in a network. Ahmed *et al.* [128] proposes a distributed and dynamic channel access mechanism for 802.11ah. The relay nodes which extend connectivity from a 1-hop network use different channels to allow parallel transmission within the relay group. In this, a dynamic network organization and channel allocation mechanism is also proposed. Compared to the work of Kumar *et al.* [126], Ahmed *et al.* [128] extensively analyses the coverage range (e.g., it achieves up to 1500m in two hops) and throughput with multi-channel support (e.g., almost double throughout achieved with three channels). However, heterogeneity in the relay network is not considered. Rao *et al.* [130] introduces a dual-hop relay node to extend the connectivity to the STAs. However, the detailed deployments conceding different geographic locations are not considered. The proposed solution achieves two hops and covers up to 2000m distance with 10mW transmission power. Further to improve heterogeneity, authors in [84] extends [128] to allow different MCSs to work within a network. In a hierarchical network, relay nodes in two levels are responsible for allowing communication among distributed STAs using different RAWs. To communicate with a Relay or AP, it uses dedicated TDMA slots. The implementation achieves a coverage range of 1500m in three hops in a saturated network environment. However, normal load conditions have not been expected. A cooperative relay with a cross-layer design for minimizing an 802.11ah network's power consumption is proposed by Argyriou *et al. [129]. Performance results show that the proper deployment of relays among sensors can reduce power consumption significantly regardless of whether it incurs additional power cost*. Considering the longer coverage and multi-hop support

TABLE IX: Relay and sectorization schemes

Protocol	Year	Scope	Description	Limitation	Multi-hop support	Adaptive Support	Heterogeneity support	Scalability support
[126]	2015	Relay	Allow to use different channel at relay	Does not solve problems like node dynamic and traffic heterogeneity	✓	✗	✗	✓
[127]	2015	Mesh	Discusses the feasibility of 6LoWPAN and mesh support in 802.11ah	Still is in draft stage	✓	-	-	-
[128]	2016	Relay	Dynamic multi-channel allocation at Relay	Does not solve problems like node dynamic and traffic heterogeneity	✓	✗	✗	✓
[92]	2016	Relay	Provides heterogeneity by supporting different MCSs	Does not considers data aggregation and prediction	✓	✗	✓	✓
[129]	2015	Relay	Saves energy by opportunistically considering relay node	Optimal bandwidth allocation for heterogeneous traffic is required to consider	✓	✓	✗	✓
[130]	2018	Relay	Uses dual hop relay node to extend connectivity	Does not consider the location of the relay node	✓	✗	✗	✓
[131]	2018	Group & Sector	Uses sectorization from AP node to improve network performance	Does not talk about the simultaneous Tx using multiple channel in different sector	✗	✗	✗	✓

of 802.11ah, Ali *et al.* [133] proposes an Unmanned Aerial Vehicle (UAV) network architecture for security surveillance. For a multi-hop 802.11ah network for UAV, they observe that the backoff time of non-QoS traffic is not impacted severely with the increase of packet arrival rate. However, none of these schemes consider heterogeneous traffic in terms of non-elastic and elastic traffic.

6LoWPAN is an IPv6-based low-power WPAN that runs over the devices that supports IEEE 802.15.4. It allows interoperability between the IPv6 domain using an adaptation mechanism adopted by it. So, it can not provide interoperability and other light-weight upper layer activities such as mesh routing, end-to-end security, and application processing. The current works on 802.11ah define only a star type topology at link-layer connectivity. Here, any communication is made through the AP node. The popular mesh topology is not supported in this standard. Also, communication between the AP nodes is not supported directly. IPv4 and IPv6 are compatible with 802.11ah via the LLC [127]. In that situation, 6LoWPAN [134] or 802.11s [23] based approaches may also be suitable. However, 802.11ah presents a trade-off between energy saving and the data rate of the link. To be compatible with it, the upper layer protocol also needs to be modified. Consequently, 6LoWPAN techniques are beneficial to reduce the overhead of transmissions, save energy, and get better throughput. Providing support for 6LoWPAN in 802.11ah considering different MCSs based data-rate is a promising challenge. A summary of different MAC protocols proposed on the relay and sectorization is mentioned in Table IX. Relay and sectorization schemes improve scalability but fail to provide energy efficiency and can not work in a heterogeneous environment.

E. Dynamic association and AID allocation

In IEEE 802.11ah-based network, if all the STAs try to associate and authenticate simultaneously, collisions are obvious, and most of the requests will not be received. Even having received a request, the AP cannot access the channel to respond. For 100 STAs, the time required for all of them to finish the authentication procedure can exceed 5 min. [4]. Bankov *et al.* [61] proposes an analytic approach to find the threshold value in the CAC mechanism. Similarly, the value of the lower and upper limit in truncated binary exponential backoff is predicted based on the analytic approach [62]. However, estimating the number of connecting STAs and selecting a proper threshold value is still an important issue. Another open issue is to avoid collisions of authentication requests or reply, e.g., Authentication Reply (AuthRep), Authentication Request (AuthReq), etc., and traffic of already associated STAs.

IEEE 802.11ah employs the structure as mentioned above to group STAs based on similar characteristics. The original AID allocation does not consider network parameters such as service types, traffic interval, sleeping duration, etc. So, it is not possible that the assigned AIDs are placed in a sequence. It is also unfair for some applications to have data to send, but could not get a chance for channel access. The Dynamic AID (D-AID) assignment is proposed to solve this problem, where STA may change its AID over time [16]. Chen *et al.* [97] propose a dynamic AID allocation scheme considering the service duration of periodic smart grid traffic. Assigning successive AIDs to STAs of similar services, the network overhead is reduced significantly. However, dynamic AID allocation can be applied to a network that requires some priority in case of sensitive traffic types and battery-operated devices. Maintaining a minimum performance balance in their context is challenging.

F. Huge network overhead due to a large number of devices sending small frames

MAC header of traditional 802.11 containing three addresses of 30 Bytes size and FCS gives another 4 Bytes. Thus, for 100 Bytes of payload, MAC header overhead exceeds 30%. With the incorporation of a shortened header and NDP frames, 802.11ah enhanced a low data rate network's performance. However, periodic DTIM and TIM transmitted, large-sized AID, and uncontrolled PS-Poll frames create a huge overhead in such a network. For example – the maximum size of the TIM is 255 Bytes. Each of the TIM address supports up to 2000 STAs. Two more bitmaps need to be added to provide support of 6000 STAs. So, the total bitmap size will be 576 Bytes. This overhead is significant for a large beacon cycle. As a result, new directions are required to solve the problem. Zheng *et al.*

TABLE X: Association, AID, overhead, and backoff based schemes

Protocol	Year	Scope	Description	Limitation	Multi-hop support	Adaptive Support	Heterogeneity support	Scalability support
[61]	2015	Association	Analytical method to set threshold value dynamically	Does not solve issues of collisions due to a large association requests	✗	✗	✗	✓
[62]	2016	Association	Analytical method to set parameters of DAC	Does not solve issues of collisions due to a large association requests	✗	✗	✗	✓
[114]	2016	AID	Finds the insensible devices and regrouped them by dynamic AID allocation	Collisions remain due to a longer sleep duration	✗	✗	✗	✓
[97]	2017	AID	Dynamic AID allocation to devices having similar traffic nature	Does not consider energy efficiency as the similarity index	✗	✓	✗	✓
[91]	2014	Overhead	Find that RTS/CTS is not suitable for dense IoT	Reliability still an issue for critical IoT application	✗	✗	✗	✓
[135]	2014	Overhead	Encodes TIM value to reduce its size	Overhead due to Association, PS-Poll, ACK etc., still challenging	✗	✗	✗	✓
[128]	2016	Overhead	TDMA between AP and relay allows lesser control overhead	Overhead due to Association, PS-Poll, ACK etc., is a challenge	✗	✗	✓	✓
[136]	2018	Coexistence	Q-learning approach is used to avoid coexistence with sub-1GHz of 802.15.4 radio transmission	The sectorization beam-forming and frame aggregation of 802.11ah is not suitably use in this scheme	✗	✗	✗	✓
[137]	2018	Backoff	The backoff window is set based on the number of STAs and collisions	Does not consider the traffic loads and classes	✗	✗	✗	✓
[138]	2018	Backoff	Introduces alternative solutions to the unnecessary idle slots issues in BEB scheme	Does not consider the traffic requirements	✗	✗	✗	✓
[36]	2018	BD Traffic	An immediate reply scheme is proposed for downlink traffic, which reduces the extra RTT delay	Knowing the status of STAs (sleep or awake) is still challenging	✗	✗	✓	✓
[139]	2019	AID and Backoff	With the use of AID, a deterministic backoff scheme is developed to reduce collision	Does not suitably work with existing RAW scheme	✗	✗	✓	✓

[135] proposed a TIM bitmap encoding mechanism to reduce network overhead. By encoding across multiple blocks, bitmap length reduction percentage noticed up to 25%. Multi-hoping causes a higher delay, traffic load variation, and introduces significant overhead for topology management. So, 802.11ah has limited the number of hops up to 2-hops only. Ahmed et al. [128] proposes a 3-hops 802.11ah network. To reduce overhead, it uses TDMA-based scheduling in the relay and AP communication. However, problems like massive PS-Poll messages, frequent DTIM, TIM, etc., still exist.

G. Scheduling of a huge amount of traffic with multiple priority levels waiting at AP or relay node

Although EDCA is the default priority-based access mechanism adopted by 802.11ah considering some basic traffic characteristics, the same may not work in the case of IoT application. Here, traffic priority should be mostly based on battery lifetime, sleeping duration, traffic interval, etc.

Also, while provisioning priority, only the AIFS parameter is not sufficient, but other parameters like the backoff window and TXOP duration are also needed to explore. Frames from different applications with their individual priority waiting for transmission at the AP, such as downlink RAW scheduling of traffic, become an issue. In the currently available uplink RAW scheduling scheme, slots are selected randomly by the STAs who wants to transmit a packet. While provisioning priority, mostly dedicated channel allocation schemes are used. However, the fairness of lower priority traffic also needs to be seen simultaneously. By monitoring the packet arrival characteristics of a particular type of STAs from different priority groups, the RAW frame can be efficiently scheduled to fulfill their requirements.

A few MAC protocols, improving further scalability are discussed in Table X. These works discuss the dynamic AID allocation schemes, associations, coexistence, and bi-directional traffic. However, further improvements are required to handle dynamic IoT conditions.

V. Future Scopes and Research Challenges

Having discussed the various state-of-the-art research works on 802.11ah MAC protocol in detail, we present some more key problems and challenges below pertaining to the IoT solutions with an 802.11ah-based network that has not received sufficient attention from the researchers.

A. Congestion due to the event-driven or query-driven traffic still exists as the RAW mechanism may restrict the ongoing transmission

This is considered as a bottleneck of the existing RAW mechanism. The STAs are divided into groups and are scheduled into different non-interfering time frames. In such a case, for any event, if the STA is not in the current RAW, it is not allowed to transmit. Adaptive and load-aware solutions in RAW may be suitable to adhere to the optimal performance over such traffic scenarios. For instance, a mechanism may be implemented in which STAs are made to wait for a random number of RAW periods before they can start a transmission. This approach would effectively distribute the traffic over a longer period in overcrowded conditions. Otherwise, access delays have increased unnecessarily.

B. Selection of proper RAW size in dynamic scenarios is essential, which would yield better utilization of channel

The STAs spread over different groups, may or may not have data to transmit or maybe in sleep or awake state; mobile nodes may enter or leave their respective group dynamically and may have different traffic loads for transmission. Full buffer-based solutions are not suitable for large-scale IoT communication with heterogeneous traffic requirements. Time slots in a RAW are equally divided with no consideration of the device's traffic load and energy consumption; hence the time resources could be inefficiently used. Further, these assumptions do not correspond to the nature of sending data by devices where the STAs send data triggered by certain external events. Similarly, these schemes help to estimate the uplink and downlink RAW. The optimal RAW group size is also needed to be calculated for maintaining a minimum performance in terms of throughput, delay, energy consumption, etc.

C. Issues of congestion in periodic RAW and time synchronization in TWT based power saving schemes for large network

The existing works in power saving mainly focus on TIM-based mechanisms. However, significantly less effort is given to non-TIM periodic STAs. Identifying the scenarios in which the use of such STAs is beneficial and further investigating how they negotiate over with periodic RAW with a large number of STAs is a challenge. Maintaining time interval records accurately for massive non-TIM STAs and allocation or negotiation for a channel is still an open issue.

For the TWT mechanism followed by STAs, other than the time synchronization issue, if a STA stays in doze state for a long time, timer error is very high [4]. Also, the channel may be busy with other STAs for transmission or other cases. In such a case, the transmission of the TWT STA may lead to collisions and hence wastage of energy and bandwidth.

D. Power saving issues on a large-scale and multi-hop IEEE 802.11ah-based network

An STA needs to wake up in a TIM if any other STA in the same TIM group is paged. But, this causes wastes of extra energy consumption. In terms of the entire network, such individual energy cost creates huge degradation as overall. Similarly, relay nodes should be scheduled in such a way that re-transmission can be reduced as much as possible. Power saving of relay nodes is also another challenge for such a network.

E. Guaranteeing a large-scale battery-operated STAs allocated to a RAW group which are inside each other's coverage range

The factors like wide coverage range, CSMA/CA mechanism, large power-saving STAs, and uplink traffic, the 802.11ah-based network is severely affected by the hidden terminal problem. From the above discussion, we can conclude that RTS/CTS-based schemes are not suitable for IoT use-cases. The regrouping in an existing solution is suitable. However, the hidden nodes detection schemes are needed to be improved. The existing solutions ([113] and [112]) for hidden node problem considers some parameters such as locations, start time of transmission, etc. However, in a dynamic network and heterogeneous traffic scenarios, identifying such parameters is difficult. New mechanisms need to be incorporated in 802.1ah in order to guarantee that the STAs assigned to the same RAW group are inside each other's coverage range. From the above discussion, we found that *Long response* is not received by the hidden STAs while updating RID values. The STAs, hidden from the receiver STA, get the first frame but do not get the second. This decreases the number of available channels and increases packet service time and power consumption. Hidden node issues due to *Long response* in RID is still an open issue.

F. Generation of dynamic Tx/Rx time schedule for a relay node to support scalability over multi-hop networks

Provisioning support for the relay in 802.11ah improves energy efficiency, coverage range, and facilitates multi-hop transmission. However, relay issues such as the efficient balance of power-saving operations and proper time scheduling at the relay node to collect frames from STAs and forward to the AP node still exist. The above issues need to be resolved to achieve improved performance in a relay-based multi-hop network. Choosing a perfect relay or AP, switching from one relay to another in a condition when the currently associated relay goes down or moves, etc., are also not discussed in the existing literature. Data aggregation, data prediction, and dynamic bandwidth allocation at the relay node may need to be incorporated for better efficiency.

G. Issues with the pre-configured or static AID allocation for heterogeneous and dynamic IoT

The existing works on AID have mainly considered the static nature of a network. The IoT network is characterized by heterogeneity and dynamicity, i.e., characteristics of STAs are not the same, and a STA may join or leave over time. It is crucial to design new schemes to dynamically distribute STAs among different TIM groups considering their characteristics like the priority, battery level, traffic profile, location, etc., which is entirely an open area of research. Identifying the current issues in the network and dynamically regrouping can improve the performance of a network, but AP needs a smart and adaptive scheme to do that.

H. Dynamic grouping and AID allocation mechanism for different types of IEEE 802.11ah STAs with diverse requirements within the same network

The grouping approach increases the scalability of a network in many directions. However, a proper grouping scheme can significantly impact or stable the performance of the network. The AP or relay AP must monitor uplink and downlink traffic characteristics and the remaining battery life of the STAs and accordingly place them into different groups. Further, an efficient grouping will be enabled by a dynamic and fast AID allocation scheme. Further works need to be carried out to efficiently group the STAs and estimate different parameters used in centralized and distributed association mechanisms with lesser latency.

I. Adaptation of dynamic MCSs within the same network for better support of bandwidth

The IEEE 802.11ah has proposed many MCS schemes that provide different data rates and can be used in many places on a single network. However, provisioning support of required MCSs in single STA and dynamically changing its operation mode is difficult. Again, to facilitate multiple MCSs, support for relay node is essential. Deployment of a requirement-based relay in a large IoT network is a challenging task.

J. Ensuring QoS for delay and reliability sensitive IoT application over a long-range and multi-hop IEEE 802.11ah-based network

Many applications are time-controlled or delay-sensitive in nature, i.e., a packet needs to be delivered within a fixed time period – some demands dedicated bandwidth for its smooth flow. Again, enabling communication among such a huge number of devices, some STAs may not get a chance to transmit for a longer period. Performance analysis of real-time VoIP services is carried out in [140], and unsuitable results are noticed. Reliability is another important issue for such applications as a single packet may carry the required critical value. Identifying mission-critical applications and then provisioning QoS with fairness for other STAs is a challenge.

K. Designing configurable MAC sub-layer mechanism to provide support for lightweight upper layer activities

Mesh support with IP-based routing schemes in 802.11ah can solve many real-life issues. Designing an adaptive and smart sub-layer with 802.11ah's MAC layer to support the lightweight upper-layer protocol is still an open issue. Accordingly, a new lightweight and configurable upper-layer protocol for 802.11ah is needed to be carried out. For example, 6LoWPAN, currently used in 802.15.4, can be used in the upper layer of 802.11ah. This further allows interoperability between the IPv6 domain using an adaptation mechanism used by it. Due to the lack of 6LoWPAN support in 802.11ah, it can't provide interoperability and other lightweight upper layer activities such as mesh routing, end-to-end security, and application processing.

L. Ensuring harmonious coexistence with other standards operating in sub-1GHz channel band

The larger coverage range of IEEE 802.11ah may need to interfere with different communication technologies working in the same frequency band. For example, 802.11ah and 802.15.4-based networks are likely to coexist in different IoT deployments. It is evident that for longer coverage range, 802.15.4 will use the sub-1GHz band. Lie *et al.* [136] analyses the performance of 802.11ah within the vicinity of 802.15.4 network, and severe degradation in performance results can be noticed. This paper proposes a learning-based backoff scheme for 802.11ah to avoid interference with the ongoing 802.15.4 transmission. A scalable and energy-efficient cognitive MAC protocol solution will improve the performance of 802.11ah in such a network.

M. Designing an adaptive sectorization scheme for dynamic 802.11ah-based IoT

A suitable sectiorization mechanism is very important for large-scale networks like 802.11ah with entities like AP, relay, and STAs. A beam-forming technique is used to divide the network into different sectors and uses Time Division Multiplexing (TDM) scheme to spread the communication among the sectors. The 802.11ah operates over a set of unlicensed channel bands (all sub-1GHz) that depend on the country regulations [43]. Also, 1 and 2 MHz channel bands are mostly available and suitable for IoT communication [5]. Use of Frequency Division Multiplexing (FDM) considering the multiple available channels will increase efficiency and reduce interference. Kumar *et al.* [126] calculated the angular separation in the AP node to position different relay nodes with multiple channels. Sabin *et al.* [131] proposes a grouping and sectorization mechanism using multiple antennae with sectorized beam-forming. Nabuuma *et al.* [139] 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 [115]. 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 conditions. Standardizing the sectorized operations, dynamic channel allocation, and positioning relay nodes in a large-scale network are future areas that deserve researchers' attention.

N. An appropriate contention resolution scheme for large-scale heterogeneous STAs

The 802.11 standards are based on DCF and EDCA contention techniques. Gopinath *et al.* [138] extends the existing Binary Exponential Backoff (BEB) in 802.11ah. The BEB scheme keeps unnecessary idle slots in a non-saturated network. Replacing it, this paper introduces a Tribonacci sequence [141], Perrin sequence [142] and Jacobsthal sequence [143] while increasing the window size. A backoff window is measured using a number of STAs and collisions in the network to improve the RAW performance in [137]. Ali *et al.* [65] analyses differentiated QoS performance of IoT networks using Markov-Chain model [144]. Setting an appropriate backoff scheme (changing their stages) in a dynamic network like IoT is still a critical issue. Further, using the value of it, a proper RAW or group size can be predicted.

O. Mobility facilities and handoff among different relay-enabled BSSs

Taking the advantages of a longer communication range of 802.11ah, different mobile IoT devices can be connected. The performance of different mobility models is presented in paper [145]. Due to the extra tuning parameter available in Gauss-Markov mobility [146], it gives better results in dynamic conditions than other models like Random walk [147] and Random Waypoint mobility model [148]. Mobility issues are not discussed in 802.11ah. While mobile IoT application roams from one BSS to another, association and grouping of the new nodes are challenging. IEEE 802.11k [149] based solution can be used in 80.11ah network to facilitate a seamless transition of mobile nodes over different relays.

P. Intelligent and massive access mechanism for large-scale IoT

Machine learning-based massive access communication is a new trend for wireless communication in IoT [150]. Smart decisions in resource allocation, signal processing, channel estimation, and transceiver design can improve network performances, especially, with resource-constraint device characteristics. Moreover, in such a large-scale network, machine learning-based analytic on traffic also an important area of research for improved network performance [151]. Machine learning can decrease the design complexity of wireless communication networks while achieving better performance. The application of machine learning for massive access is expected to significantly decrease complexity. There is a lack of analytical frameworks for machine learning as applied in wireless networks, which currently limits its applicability in practice. Also, areas such as MAC layer-directed antenna alignment and sectorized beam-forming can help in achieving massive access with better performance.

Q. Securing IEEE 802.11ah-based large-scale and resource-constraint IoT

Provisioning security in the 802.11ah-based large-scale network is also a typical responsibility of the MAC layer [152]. Along with the innovations, a list of security issues may be evolved in the considered network. A large association delay becomes a bottleneck for a better authentication mechanism. The recent IEEE 802.11ai [153] proposes a solution for fast and secure link association. Zhang *et al.* [154] proposes a security scheme to enable key exchange mechanisms in a faster-way with the help of 802.11ai. The work is further enhanced in [155] for lightweight solutions. However, many issues remain unsolved. As 802.11ah can extend the distance more than 1km using sub-1GHz channel band and relay support. Therefore, it is expected that the STAs can be attacked from such a distance. Also, the relay node creates more things to worry about. For example, identifying the relay's owner and authorization of using the relay to pass traffic through. Tandon et al. [156] proposes a malicious relay detection scheme in the 802.11ah network using some special passive nodes called sentinel nodes. However, monitoring the relays and traffic passing through it is a challenge. As 802.11ah standard only specifies the PHY and MAC layers leaving out the network and transport layers, it leaves room to the various IoT vendors to implement their versions, thus possibly introducing risky security functionalities. Client authentication and segregation (i.e., an IoT device could be used as a stepping stone for attacking others) should also be supported. Moreover, designing a lightweight but secure solution for such a resource-constraint network is still an intricate problem.

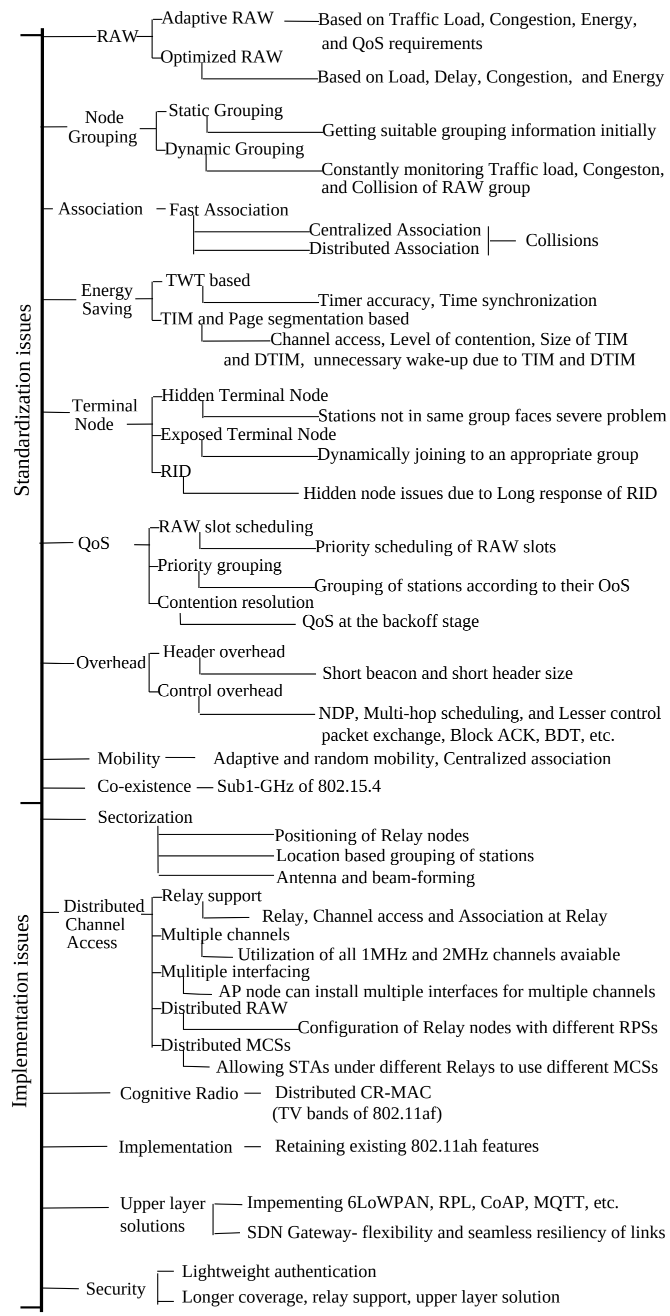

Fig. 6: Issues, challenges, and research directions of IEEE 802.11ah-MAC protocol

R. Supporting SDN for better flexibility and resilience in 802.11ah-based large-scale network

A large-scale 802.11ah-based communication architecture contains a huge number of multi-hop links. The long-distance links should be able to instantly self-repair with any failure. The emerging Software Defined Networking (SDN) technology provides excellent flexibilities that can be applied to such networks [157]. An SDN-powered gateway solution can help such a network for better flexibility and provide seamless resiliency if there are redundant wireless links. Further, considering a large-scale network for smart-city or smart-grid communication, SDN can control multiple AP for better handoff, association, and resource allocation. Moreover, programmable and configurable AP and relay device (using OpenFlow [158] or P4 [159] protocol) can provide more flexibility and virtualization to the large-scale network.

For supporting practical IoT applications, further enhancements are significant. Also, the analysis of most of the features is not yet discussed in the considered scenarios. Finally, the issues or challenges, along with the possible future works, are highlighted in Fig. 6. Overall, we can divide the existing issues and challenges into standardization and implementation. The existing RAW scheme is not fully suitable for large-scale heterogeneous IoT networks. For a network with massive numbers of IoT devices, issues due to simultaneous association requests, hidden nodes, mobility, coexistence, huge overhead, etc., still exist. Moreover, different implementation works, such as support for efficient security mechanisms, upper layer solutions, network management, etc., also need to be incorporated. The settlement of the above issues and challenges is very important for a scalable and efficient IoT network using the IEEE 802.11ah standard.

VI. Conclusion

By looking at the growing popularity and its speedy adaptation of IoT, it is expected that the novel IEEE 802.11ah technology will emerge as a game-changer in near future. IEEE 802.11ah overcomes the issues of complexities and coexistence in IoT networks over and above the basic requirements of IoT applications such as scalability, heterogeneity, energy-efficiency etc. The MAC support in 802.11ah carries the major responsibility to support these requirements. This paper surveyed the MAC features of 802.11ah and analyzed them relating to IoT application scenarios, emphasizing what is being discussed in the recent advancements of IEEE 802.11ah and what are the issues that require further research. While solving some of the issues, several enhancements have been made in the literature. This paper surveys these enhancements and presents advantages and disadvantages. The hidden terminal problem in 802.11ah-based use-cases will create a huge negative impact on the performances. Dynamic AID allocation and dynamic regrouping may solve the hidden node problems to some extent. Dealing with the rare but critical event-driven traffic in IoT is one of the major issues for 802.11ah. In such a case, adaptive and smart MAC protocols are more suitable. Ensuring a minimum level of performance for the different types of nodes present in the network characterized by low-power and heterogeneity is challenging. Features such as centralized management, dynamic reconfigurability, and programmability are very important in the case of a large-scale network like IoT and M2M. Finally, for the implementation of this standard in IoT, we mentioned some of the major issues, challenges, and possible future directions of research. As 802.11ah is a relatively new standard, many of the features are not yet been explored. This provides the opportunity of research for improving performance. It is expected that this survey can serve as a guideline for taking up possible future works in 802.11ah MAC protocols.

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