Scalable internet of things network design using multi-hop IEEE 802.11ah

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Abstract
The emerging IEEE 802.11ah is a promising communication standard for large-scale networks particularly the Internet of Things (IoT). The single-channel-based centralized channel access mechanism employed in 802.11ah does not scale well in such networks and leads to poor data reception quality. In this paper, we propose an Enhanced and Scalable Medium Access Control (ES-MAC) protocol, which employs multi-band sectorization and dynamic load balancing. These features facilitate multi-hop communication more efficiently and enhance network capacity. Traffic congestion issues prevailing around the access point node due to the large volume of uplink traffic is mitigated by allowing simultaneous transmission using multiple orthogonal channels and sectors. Simulation and analytical results establish the essence of the novel protocol by showing significant improvements in terms of throughput and average packet delay over the existing schemes. The proposed network architecture improves throughput and delay performance up to 150% and 100% respectively compared to the relevant schemes.

Keywords IEEE 802.11ah · Sub-1 GHz · Restricted access window (RAW) · Internet of things (IoT) · M2M communication · Relay AP

1 Introduction
IEEE 802.11ah-based large-scale IoT provides poor network performance due to long communication range and higher delay in multi-hop transmission. As it uses a single channel, only one node in the network is allowed to transmit at a particular time. In a network with a large number of relay nodes and multi-hop links, uplink traffic forwarded by the end stations (STAs) create congestion around the Access Point (AP). Such networks cannot support smooth and efficient communication which remains a key challenge for many IoT applications.

This paper proposes ES-MAC, an enhanced and scalable MAC layer protocol for the IEEE 802.11ah network. Our scheme maximizes the overall network performance by an adaptive sectorization and channel allocation mechanism. For supporting distribution channel access in terms of restricted access window (RAW) scheduling among different relay nodes, the proposed architecture enables the nodes to contend and get associated with the Relay APs (RAPs) in a distributed manner. Additionally, a dynamic bandwidth adjustment is incorporated at the relay nodes to improves channel efficiency and Quality (QoS) requirements of IoT applications [1].

1.1 Motivation
The deployment of IoT is growing very fast, ranging its applications and services from the environment to healthcare [2]. The emerging IEEE 802.11ah technology has proven as a promising communication standard for IoT [3, 4]. To meet the technical requirements such as scalability, heterogeneity, and low power consumption, IEEE 802.11ah has come up with some novel ideas. It allows up to 8,191 devices to be associated with an AP by using a new hierarchical Association IDentification (AID) scheme. With the use of sub-1 GHz channel bands, it can cover up to 1 km in a single hop, which can further be extended by using relay nodes between the AP and STAs [5, 6]. IEEE 802.11ah adopts strategies like Target Wake Time (TWT), Traffic Indication Map (TIM) and Segmentation, and RAW for efficient...
communication in large-scale networks. It enables seamless communication among heterogeneous applications such as smart cities, industrial IoT, and smart healthcare. Figure 1 shows a network architecture for the smart city including a few possible IoT applications. Interconnection among various components like AP, RAP, and STAs, and the Internet backbone have been clearly depicted. The extended coverage range supported by RAP facilitates connectivity among multiple service regions such as car parking, street light control, and video surveillance in a multi-hop scenario.

Large-scale network architecture contains a huge number of relay nodes and multi-hop links. Uplink traffic forwarded by the end STAs create congestion towards the AP node. Due to lack of parallel transmission facilities at AP and RAP nodes, such heavy traffic region becomes a bottleneck in large scale networks. Further, IoT networks need to support heterogeneous traffic requirements. For example, a surveillance application requires a higher data rate than a smart lighting system. Severe hidden node problem in communication may also arise if the STAs are not grouped according to their geographic locations, especially in urban infrastructures. In such a dense network scenario, the overall network may lead to beggarly performance without spatial reuse of the channel. Many IoT applications require some sort of QoS guarantees in terms of parameters like delay and throughput. Further, an efficient RAP solution which considers the channel access and traffic requirements of STAs is also an open area of research.

The state-of-the-art works such as [7–12] improve scalability up to a certain extent. However, due to the traffic congestion and high channel access delay, the existing solutions are not adequate for enabling scalable communication in IoT. Dynamic bandwidth allocation schemes such as [13,14] are not sufficient for heterogeneous traffic demands of the groups and STAs. The growing traffic demands of IoT requires spatial reuse of channels and network capacity enhancement.

1.2 Contribution

In summary, the following are the key contributions of this work:

- We introduce multi-band sectorization scheme for IEEE 802.11ah to combat the congestion issue and improve holistic network performance. The proposed solution uses Frequency-division multiplexing (FDM) at the AP node for supporting multiple sector antennas and allows concurrent transmissions using multiple channels.
- A MAC scheme is designed, which periodically checks the current load at the AP or RAPs nodes, and accordingly adjust bandwidth by switching to suitable Modulation and Coding Schemes (MCSs) dynamically. The congestion state of a RAP node is determined by measuring the current collision ratio.
- An efficient Transmission Opportunity (TXOP)-based scheduling scheme for AP and RAP communication is presented. The proposed MAC protocol switches its TXOP operation based on traffic patterns such as Uplink or Downlink.

2 Background and related works

To support the requirements of heterogeneous traffic in IoT, IEEE 802.11ah has proposed different MCSs to be used in various scenarios. For data transmission, 1, 2, 4, 7, and 16 MHz channel bands are defined [15]. Considering a wider channel bandwidth (16 MHz), MCS9 can provide up to 78 Mbps of data rate.

2.1 Channelization

The channelization scheme of IEEE 802.11ah inherits the PHY layer of 802.11ac. The available license-exempt channels in the sub-1 GHz spectrum depends on the country’s regulation. For example, current availability of sub-1 GHz bands in different countries – 902-928 MHz (US), 755-787 & 614-787 MHz (China), 917-923.5 MHz (South Korea), 863-868.6 MHz (Europe), 865-867 MHz (India), 915.9-929.7 MHz (Japan), 866-869 MHz, 920-925 & 866-869 MHz (Singapore) [16]. The channel bandwidth in IEEE 802.11ah includes 1, 2, 4, 8, and 16 MHz, whereas 1 and 2 MHz are widely available in many countries and more suitable for low
rate traffic. In United States, there are 26 numbers of 1 MHz and 13 numbers of 2 MHz channels.

2.2 Relay node support

A relay node which is positioned between the AP and end nodes, extends connectivity to the STAs located outside AP’s coverage. IEEE 802.11ah implements RAP consisting of an AP and a STA module in it [5]. A Relay function is responsible for connecting AP entity with STA entity. A MAC protocol proposed by Kumar et al. [7] uses a static channel allocation mechanism for the distributed relay nodes. Enhancing this, a dynamic channel allocation and organization approach is proposed in [9] to improve the performance of relay-based large networks. Further to enhance relay to relay communication, Rao et al. [8] introduces dual-hop relay to extend the connectivity till the STAs. A cooperative relay with a cross-layer design for minimizing the power consumption of an IEEE 802.11ah network is proposed by Argyriou et al. [17]. However, the detailed deployments in different geographic locations are not considered while placing a relay node. None of these schemes consider elastic and inelastic heterogeneous traffic coexisting in the same IEEE 802.11ah network while utilizing the bandwidth efficiently. Shafiq et al. [10] proposes a Cognitive Radio (CR) based MAC protocol which regroups STAs based on the probabilistic analysis of collisions. Further to enhance grouping, Nabuuma et al. [11] proposes a backoff scheme with AID for reducing collisions in sectorized network. A Received Signal Strength (RSS)-based solution to the hidden node problem is proposed in [20]. 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. A channel access mechanism for relay-based network is proposed in [18] to improve multi-hop channel utilization. However, their solution fails to support proper bandwidth allocation and capacity in the network. The efficiency of the RAW mechanism under non-ideal channel condition is measured in [19]. Ali et al. [21] proposes an analytical model for differentiated QoS mechanisms of RAW, which is suitable in a heterogeneous IoT environment. Seth et al. [22] proposes an edge-assisted AP scheduling scheme for 802.11 based WiFi to reduce energy consumption in a QoS-aware IoT network. A data-rate aware grouping scheme is presented in [12] which provides fair resource allocation in a network. Moreover, dynamic bandwidth allocation at RAPs has been a well-established problem. Hussain et al. [13] identified the congestion problem in a relay-based multi-hop WiFi-based long-distance networks. A dynamic bandwidth allocation scheme was proposed to mitigate that problem. Cooperative relay-based approaches have been used for reliable and efficient transmission [14]. Considering the heterogeneous traffic demands of STAs, scalability support in RAPs and AP node is extremely important in large scale networks.

Synthesis Table 1 summarizes the related works. The current research works attempt to improve network scalability mostly with the support of multi-hop, multi-channel, and sectorization. However, the possibility of high collisions at the time of slot assignment with the dense network still persists. The centralized single-channel access mechanism in IEEE 802.11ah affects the network performance with many devices trying to access the channel during a time slot simultaneously. Moreover, a hierarchical and multi-hop network faces challenges such as high latency and jitter. Further works are required to deal with low scalability, heterogeneity, and dynamicity issues in large-scale IoT.

3 The proposed protocol

The design of the proposed protocol is greatly influenced by the multiple available 1 and 2 MHz bandwidth channels in sub-1 GHz and flexible MCSs proposed in IEEE 802.11ah. The available channels are distributed among the nodes spread over various sectors in a larger coverage area. It allows simultaneous channel access in different RAW groups implemented by the sectors. A TXOP-based mechanism is also used by the RAP and AP nodes for faster data sharing (Table 2).

3.1 The network topology

The RAP nodes are be connected with the AP using multi-hop distances. Figure 1 shows a typical IoT network architecture using IEEE 802.11ah where three IoT networks are connected to the Internet.

The architecture can be thought of as a combination of sensor and backhaul networks. The overall network can be represented as a set \( N(A, R, E) = \{ B(A, R), T(R, E) \} \), where \( B \) and \( T \) are the backhaul and sensor networks respectively. Here, \( A \) is the AP node, \( R \) is the set of RAP nodes \(( R = R_1, R_2, \ldots, R_n )\), and \( E \) is the set of end nodes (sensor/actuator) \(( E = E_1, E_2, \ldots, E_m )\). \( A \) takes the responsibility of initialization, synchronization, slot assignment, and channel allocation of the whole network. The \( R_s \) are the owners of channels and hold the responsibility of forwarding data from \( E_s \) to \( A \) and vice versa.

3.1.1 Relay organization

The RAP nodes are as powerful as the AP node. An RAP node carries out operations like association, RAP organization, and synchronization. An organization and planning scheme is important to use as less number of RAPs as possible. We can calculate the coverage range of AP or RAP nodes by...
using the signal strength of the radio. The IEEE 802.11ah standard uses the macro model of propagation [23] for Tx/Rx. Considering an antenna height of 15 meters above a rooftop, the propagation loss (in dB) in this model can be calculated as:

\[ L(d) = 8 + 37.6 \log_{10}(d) + 21 \log_{10}\left(\frac{f}{900 \text{MHz}}\right) \]

where \( d \) is the wireless distance between the sender and the receiver node, and \( f \) is the carrier frequency. The value of \( d \) can be calculated as, \( d = 10^{(TXP - TRSSI) / 20} \) [24], where \( TRSSI \) is the Received Signal Strength Indicator (RSSI). It depends on the loss, sensitivity, fading effect, and carrier frequency band. \( TXP \) is the transmission power of an IEEE 802.11ah node. For better coverage range, a node at the edge of \( d \) coverage maintains its mode of operation as RELAY mode. Enhancing [9], another RAP node is selected using angular separation (refer Fig. 2),

\[ \Delta \theta = \frac{360^\circ \times 2C}{2\pi d} \]

where \( C \) is the RAP node coverage. As the coverage of RAP and AP are the same, the value of \( d \) and \( C \) are also same, hence \( \Delta \theta = \frac{360^\circ}{\pi} \). So, the required number of RAPs in 1-hop distance can be calculated as, \( N_{1^{hop}} = \left\lceil \frac{360^\circ}{\Delta \theta} \right\rceil \). Similarly, angular separation for \( h \)-hop RAP node is given by \( \Delta \theta / h \). We can calculate the number of RAP nodes in \( h^{th} \) hop as:

\[ N_{n}^{h} = \left\lceil \frac{h \times 360^\circ}{\Delta \theta} \right\rceil \]

This procedure gives the lowest number of RAPs to be deployed around the AP node. Once the nodes are organized, the AP or RAP nodes can start association with the STAs.

### 3.2 Node association

To solve the problem of a huge delay in association procedure, IEEE 802.11ah has proposed Centralized Authentication Control (CAC) as well as Distributed Authentication Control (DAC) [25]. We use CAC for associating STAs, which are distributed over different RAPs. The fast association mechanism is initiated by the AP or an RAP node which transmits an authentication control threshold (\( \theta \)) value along with the beacon. A STA selects a random value (\( \vartheta \)) within the window range of \([0, 1022]\) and then associates itself with \( A \) or \( R \) only if \( \vartheta < \theta \). Figure 3 shows an example scenario of the distributed association mechanism. Total number of association groups is \( \Gamma + 1 \) (\( \Gamma \) number of distributed active
A multi-band sectorization scheme

IEEE 802.11ah proposes a sectorization scheme to partition the coverage of a BSS into different non-overlapping sectors. The AP uses beacon to inform the transmission slots for different sectors. The beacon carries sector option elements with the group ID. Each STA is allocated a group ID to enable transmission in different sectors around the AP using Time Division Multiplexing (TDM). With the support of the proposed RAP solution and multiple available channels, we have incorporated two features — (i) multi-band sectorized transmission using Frequency Division Multiplexing (FDM), and (ii) configurable RAPs with multiple channels and MCSs, to the group sectorization scheme.

The current sectorization scheme proposed for IEEE 802.11ah dominantly use TDM-based approaches. These schemes solve hidden node problem up to a certain extent without any improvement in overall network capacity. The proposed solution allows the AP node to use multiple channels and hence STAs from different sectors can transmit simultaneously using different channels. The number of radios employed in an AP depends on the number of available channels. For \( N \) number of channels, the same number of radios and sector antennas are required. Due to the limited number of available channels, we restrict the value of \( N \) to 4. In this case, the angular beam of a sector antenna is 360/\( N \) degree. Hence, we consider four sectors to cover all around the AP (can be seen in Fig. 4). Algorithm 1 discusses the proposed sectorization scheme. Lines #1-4 allocates the sector antennas to the radios that are mounted in an AP. Lines #7-15 discusses the channel allocation and transmission procedure. STAs or RAPs check the received signal strength (\( P_r \)) from the AP through one or more sectorized beacons and join a better sector. Considering the fast fading effect, the power received at the receiver (\( P_r \)) is given by [11]:

\[
P_r = P_t + G_t + G_r - \left( L(d) + X_\sigma \right)
\]

where \( P_t \) is the received power, \( G_t \) and \( G_r \) are the transmitter and receiver gains respectively, and \( X_\sigma \) is the shadowing, which is a zero-mean log random variable with a standard deviation, \( \sigma \). The STAs or RAPs collect other information like group ID, RPS, and channel information from the beacon.

### Algorithm 1 Multi-band sectorization scheme for AP

**Initialize**: \( \{STA, RELAY, AP\} \leftarrow \) modes of STAs
\( C \leftarrow \) a set of available channels
\( S \leftarrow \) a set of sectors to be used around the AP
\( S_A \leftarrow \) a set of sector antennas
\( m \leftarrow \) number of available channels
\( k \leftarrow \) total number of sectors

1. if (mode=AP) then
2. for \( i = 1 \) to \( k \) do
3. Create sector \( S_i \) \( \triangleright \) based on their geographic location
4. \( S_A \rightarrow S_i \) \( \triangleright \) assignment of sector antennas
5. Transmit beacon \( \rightarrow \) (RAW Parameter Set (RAW), group ID, allowed channel, allowed MCSs)
6. Associate STA and Relay
7. if (\( k \leq m \)) then \( \triangleright \) more number of channels than the sectors to cover areas all around the AP
8. Allocate channel \( C_i \rightarrow S_i \)
9. Transmit data using allocated slot
10. else
11. if (\( m == Even \)) then \( \triangleright \) even number of sectors to cover areas all around the AP
12. Allocate \( C_i \rightarrow S_i, C_{i+1} \rightarrow S_{i+1} \)
13. Transmit data using allocated slot
14. else if (\( m == Odd \) and \( m > 1 \)) then \( \triangleright \) odd number of sectors to cover areas all around the AP
15. Allocate \( C_i \rightarrow S_i, C_{i+1} \rightarrow S_{i+1}, C_{i+2} \rightarrow S_{i+2} \)
16. Transmit data using allocated slot

Fig. 3 Example scenario of node association, where STAs associate with an RAP or AP and RAP with the AP.
where $T_{col}$, $T_{idl}$, and $T_{bus}$ are the collision, idle, and busy times respectively. The value of $L_t$ lies between 0 and 1; lower bound 0 says that there is no collision and upper bound 1 means there are collisions in the complete $t$ duration. Considering application’s traffic requirements, number of STAs, and network conditions, a factor $B_γ$ is chosen. $B_γ$ is the current available bandwidth of an RAP, calculated for a duration $γ$. The RAP chooses an MCS with higher data-rate when $L_t > B_γ$ and lower MCS for $L_t < B_γ$.

### 3.4 Channel access mechanism

In the proposed enhancement, we use the maximum three different levels of RAWs. The AP and RAP nodes broadcast their RPS element with the beacon frame for the children Rs and Es which are connected with AP directly. To communicate with STA and RAP or AP, RAW frame and TXOP frame are used respectively. For better efficiency, our solution dynamically use BlockACK and BD-TXOP for directional and bidirectional communication, respectively. If channels are sufficiently available, RAP further can use a different channel. But, to communicate with AP, relay needs to switch to its parent AP or RAP’s channel (refer Algorithm 2) (Fig. 5).

After selecting the RAW and TXOP, a node can initiate channel access. If a STA needs to transmit, it sends a PS-Poll frame using DCF as shown in Fig. 6. Once successful, a MAC Protocol Data Unit (MPDU) can be transmitted. If AP needs to send a frame, it informs through the TIM beacon and then waits for a PS-Poll frame from the STA. AP to RAP or RAP to RAP access mechanism is done using BD-TXOP for better efficiency. As shown in Fig. 6, in BD-TXOP an MPDU is sent without waiting for ACK. more data field of the header is used to inform the destination about pending data. The more data field is set to 1 or 0 to notify about more data or no more data pending respectively. The data Tx/Rx procedure of the proposed scheme is discussed in Algorithm 3.
4 Performance evaluation

To validate the proposed scheme, initially, we carry out a theoretical analysis of throughput enhancement of the proposed scheme. After that, an extensive simulation analysis of the proposed, the traditional IEEE 802.11ah, and one of the most relevant state-of-the-art schemes are carried out and their results are systematically compared.

4.1 Theoretical analysis

Bianchi et al. [27] defines saturation throughput $(Th)$ as the average amount of payload bits transmitted successfully in a slot over the average duration of a slot time. The proposed protocol allows STAs to use non-interfering channels for simultaneous transmission. Therefore, contention happens with STAs belonging the same group and using the same channel. The state $(s(t), b(t))$ indicates that at time $t$, a node or the AP is at backoff stage $s(t)$ with backoff counter $b(t)$. We assume the maximum backoff stages, $m$, and retry limit,
where the value of a node’s backoff counter becomes zero, it transmits. So, the transition probabilities can be given by [27]:

\[
\begin{align*}
P[i, j|i, j + 1] &= 1, & j &\in [0, W_i - 2], & i &\in [0, m] \\
P[i, j|i, j - 1, 0] &= \frac{\beta}{W_i}, & j &\in [0, W_i - 1], & i &\in [0, m] \\
P[0, j|i, 0] &= \frac{1 - \beta}{W_i}, & j &\in [0, W_i - 1], & i &\in [0, m - 1] \\
P[0, j|m, 0] &= \frac{1}{W_0}, & j &\in [0, W_0 - 1], & i &\in [0, m - 1]
\end{align*}
\]

Based on the above transition probabilities, the steady state probability, \(b_{i,j}\) can be calculated as:

\[
b_{i,j} = \lim_{t\to\infty} P[s(t) = 1, b(t) = j], & i &\in [0, m], & j &\in [0, W_i - 1]
\]

Then, the transmission probability of a STA can be calculated as [27]:

\[
\tau = \sum_{i=1}^{m} b_{i,0} = \sum_{i=0}^{m} \beta^{i} b_{0,0} = \frac{1 - \beta^{m+1}}{1 - \beta} b_{0,0}
\]

The final equation to calculate the saturation throughput, \(T_h\) is given as follows [27]:

\[
T_h = \frac{P_{tx} P_{suc} E[Payload]}{(1 - P_{tx}) T_{slot} + P_{tx} P_{suc} T_{suc} + P_{col} T_{col}}
\]

where probability \(P_{tx} = 1 - (1 - \tau)^n\) indicates that there are \(n\) number of STAs in the network and each of them get at least one transmission opportunity in a slot. \(P_{suc} = \frac{\alpha}{\alpha + 1} \frac{m}{m + 1} \frac{T_{sym}}{T_{PHY}}\) is the probability of transmission occurring on a slot is successful, \(s_{sym}\) is the average duration of a slot, and \(P_{col} = (1 - P_{suc}) P_{tx}\) is the collision probability. \(T_{suc}\) and \(T_{col}\) are the busy times for successful transmission and collision respectively. For IEEE 802.11ah, \(T_{suc}\) and \(T_{col}\) can be calculated as below:

\[
T_{suc} = T_{FH} + T_{PS-POLL} + T_{DATA} + T_{ACK} + T_{SIFS} + T_{DIFS} + T_{P} + T_{Timeout}
\]

\[
T_{col} = T_{FH} + T_{DATA} + T_{DIFS} + T_{P} + T_{Timeout}
\]

where \(T_{DATA}, T_{SIFS}, T_{P}, T_{ACK}, T_{timeout}\) and \(T_{DIFS}\) are the Data, Short Inter-frame Spacing (SIFS), Propagation, ACK, ACK-Timeout, and Distributed Coordination Function (DCF) with Interframe Space, called DIFS duration respectively. The values of different parameters are mentioned in Table 3. The duration of data and control frame used in IEEE 802.11ah can be calculated by the Eqs. 3 and 4 respectively [28]:

\[
T_{DATA} = \left[ \frac{8 \times (L + m_b)}{R \times \beta} \right] \times T_{sym} + T_{PHY}
\]

\[
T_{ACK} = \left[ 8 \times L_{ctrl} \right] \times T_{sym} + T_{PHY}
\]

where \(L, m_b, R, \alpha, \beta, T_{sym}, L_{ctrl}, \) and \(T_{PHY}\) are MAC payload size, header size, basic data rate, number of bits in one Orthogonal Frequency-Division Multiplexing (OFDM), symbol duration of OFDM, size of control frame, and PHY header size respectively. Theoretically, the saturation throughput of the proposed protocol can be calculated by multiplying throughput with number of channels (\(\lambda\)):

\[
T_{hprop} = \lambda \times T_h
\]

With the use of TXOP in the proposed protocol, the value of \(T_{suc}\) can be updated as:

\[
T_{suc}^{TXOP} = T_{PS-POLL} + \delta T_{DATA} + T_{ACK} + (\delta + 1)(T_{SIFS} + T_{DIFS} + T_{P} + T_{FH})
\]

As a part of the proposed scheme, we can further implement multiple channels in AP. Then, the saturation throughput will be updated as:

\[
T_{h\lambda} = \lambda \times T_{h\lambda TXOP}
\]

### 4.2 Simulation analysis

The performance of the proposed enhanced and scalable MAC protocol (ES-MAC) is evaluated through extensive simulations using NS-3 [29]. Table 3 presents different parameters used in the simulation. Results are compared with Traditional access mechanism of IEEE 802.11ah and a sectorization scheme FE-MAC [30]. In FE-MAC, the AP node broadcasts beacons to the specific locations by utilizing the sectorized beams created with multiple antennas in it. We compare the throughput and delay performance of FE-MAC as shown in Fig. 7a, b, and d. We analyze the proposed sectorization scheme in terms of throughput, delay and Packet Received Ratio (%). Later, the overall network performance is measured considering different PRR enhancements.

#### 4.2.1 Association time

The RAPs create different Basic Service Sets (BSSs) in the network. Randomly scattered nodes get associated with the AP or RAP in a distributed manner. It is obvious that the association time of the proposed scheme is equal to the time
required to associate all the STAs from the largest BSS. As shown in Fig. 8a, the total association time for 2000 devices in the proposed protocol is about 37 Seconds, whereas, in traditional IEEE 802.11ah, it is 42 Seconds. The RAP nodes are further supported with multiple MCSs, where it can choose an MCS with a higher or lower data-rate according to the current requirements of a BSS.

### 4.2.2 Throughput in proposed vs. existing schemes

To see the throughput performance over normal load conditions, we compare the proposed scheme considering lesser number of STAs in the network. Traffic is generated with an interval of 0.5 Sec. As shown in Fig. 7a, once the saturation point is reached, the performance of the proposed protocol starts deteriorating. The saturation point for the proposed scheme is higher than the existing schemes.

Figure 7b shows the throughput characteristics of the proposed scheme as compared to the traditional scheme with an increasing number of STAs. The throughput performance of the proposed scheme is significantly improved with 2, 3, and 4 sectors with the same number of channels. Although the use of multiple channels multiplies the available network data-rate capacity, due to the limited memory and processing capabilities of AP and RAP, the achieved throughput in the simulation seems to be lesser. In the case of FE-MAC scheme with 2 sectors, the throughput performance is improved as compared to the traditional scheme. However, due to the lack of FDM support at AP and multi-channel operation, it gives lesser throughput than the proposed scheme. Due to the lack

| Parameter | Value |
|-----------|-------|
| Basic data rate | 650, 300 Kbps |
| Payload size | 256 Bytes |
| Radio propagation model | Outdoor (macro [31]) |
| OFDM symbol time ($T_{sym}$) | 40 $\mu$s |
| MAC header | 14 bytes |
| PHY header | 6 x $T_{sym}$ |
| Slot time | 52 $\mu$s |
| SIFS | 16 $\mu$s |
| DIFS | SIFS + 2 x Slot time |
| Modulation and Coding | MCS0, MCS1 |
| [W₀, Wₘ] | [15, 1023] |
| Backoff time | (W₀/2) x Slot time |
| Initial backoff window | 64 |
| Types of traffic | UDP |
| Traffic interval | 700 ms |
| Simulation area | 2000 m x 2000 m Flat-grid |
| Bandwidth | 1, 2 MHz |
| TXOP | BlockACK (Uplink), Bi-Directional |
| No. of STAs/RAPs (Max.) | 3000/100 |
| RAW size | 15 |
| Group size | 8 |
| Beacon interval | 100 ms |

![Fig. 7](image-url) Performance of the proposed sectorization mechanism—

- a Throughput at normal load,
- b throughput at saturation load,
- c throughput over group sizes, and
- d delay performance
of multi-channel support in FE-MAC, the improvement with 2 sectors is sufficient to describe its efficiency. We compare the performance of the proposed and the traditional scheme considering 2 sectors over a varying number of RAW groups in a larger coverage area. The node grouping mechanism in IEEE 802.11ah reduces the collision domain. For a large number of STAs, throughput performance improves with higher group size. However, without a proper RAP organization over a larger coverage area, the hidden terminal problem remains a major concern. So, along with the RAW grouping for the STAs, our protocol uses a location-aware sectorized beacon from AP. Figure 7c shows the throughput achieved at AP node with an increasing number of groups. The proposed scheme achieved superior performance as compared to the traditional one.

4.2.3 Delay in proposed vs. existing schemes

As shown in Fig. 7d, the proposed scheme significantly improves the delay characteristics considering 2 to 4 sectors for the same number of channels. As discussed, the multiple channel operations supported in the scheme allows efficient transmission among different STAs in the network. The delay is reduced by the proposed protocol as shown in Fig. 7d. The proposed protocol allows simultaneous transmission in different sectors by using different channels. The RAPs added in a particular sector also transmit simultaneously as per the allocated channel. Further, when the number of STAs is divided based on the channels, the size of contention is also reduced, hence access delay is less.

4.2.4 Dynamic load balancing

We measure the Packet Received Ratio (PRR%) for the traditional scheme with 300Kbps (MCS0, 1MHz) and the proposed scheme with 300Kbps (MCS0, 1MHz) and 650Kbps (MCS0, 2MHz) loads. We have introduced varying uplink traffic loads (100-1000Kbps) from different BSS towards the AP. The saturation capacity for the traditional scheme is almost 150Kbps, whereas the proposed scheme can carry almost up to 325Kbps. Due to the support of multiple MCSs, at saturation capacity, the RAP in the proposed scheme switches its MCS to another MCSs having a higher data rate. Therefore, as shown in Fig. 8a, the proposed scheme performs almost 25% better than the traditional one.

4.2.5 TXOP-based efficient access for AP and RAP

Finally, we have measured the efficiency of the BD-TXOP scheme used in the proposed protocol compared to the BlockAck mechanism. As shown in Fig. 8c, a significant improvement can be seen in the BD-TXOP-based solution considering bi-directional traffic. As BD-TXOP does not send ACK for all received packets, the overall efficiency is improved.

4.3 Comparison of theoretical and simulation results

The saturation throughput of the proposed protocol is calculated using the Markov Chain model. By using the Eqns. 5, 3, and 4, throughput characteristic is evaluated with increasing number of STAs. Figure 8c shows the trend of analytically computed results. Results of analytical (A) and simulation (S) studies are shown in Fig. 8c and d use 1 and 2 channels respectively. The theoretical and simulation analyses display harmonized throughput performance in the same configuration. The proposed protocol exhibits 24% overall throughput improvement using single channel which is shown in Fig. 8d.

5 Multi-hop performance vs. beacon intervals

With the use of 2000 stations and 2 sectors in the considered network, we monitor average throughput and per-packet latency for varying beacon (DTIM) intervals as shown in Fig. 9a and b. Although FE-MAC uses sectorized beacon for dedicated TIM information, the use of dedicated channels in ES-MAC increases the throughput performance (Fig. 9b). As the station wakes up in every DTIM interval, the smaller value of it decides shorter waiting time, consequently increases the frequency of transmissions. Moreover, in case of a larger DTIM interval, the RAPs and the associated STAs may need to wait for a longer duration for their transmission. Therefore,
throughput performance decreasing with increasing DTIM intervals. Additionally, the proposed TXOP-based operation at RAP improves throughput performance as compared to the FE-MAC protocol. Figure 9b shows the average delay performance with increasing DTIM intervals. Due to the wait time increases with increasing DTIM values, the delay also increases. In the case of multi-hop scenarios, the communication from STA to the AP thought RAPs incurs more delay. Our protocol uses multi-band sectorization at AP and efficient channel access at RAPs, which reduces the delay significantly.

6 Conclusion

This work presented a distributed, multi-sector, multi-channel, and load-aware MAC protocol for IEEE 802.11ah-based large-scale networks. It shows significant performance improvement in throughput and delays over the traditional and state-of-the-art MAC schemes. The proposed distributed node association mechanism requires 11% lesser time than the traditional fast association scheme. Scalability issues at AP and RAP nodes are resolved by allowing simultaneous transmission using multiple channels and sectors. The dynamic load balancing and TXOP operation at the RAP node significantly increase the efficiency of large-scale IoT networks.

However, IoT applications mostly generate a huge volume of periodic, event-driven, and query-driven traffic for monitoring and other purposes. A channel access mechanism can be redesigned to achieve better efficiency in terms of throughput and power consumption. The proposed scheme may fail to provide efficient channel access among a large number of IoT nodes with both periodic and non-periodic traffic. In future, we plan to optimize the time frame duration for AP and RAP nodes based on the heterogeneous traffic requirements of STAs.

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Fig. 9 Performances of the proposed multi-hop network—a throughput, and b delay performance
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