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# Design of MAC Layer Resource Allocation Schemes for IEEE 802.11ax: Future Directions

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**ABSTRACT**

Wireless local area networks (WLANs) are widely deployed for internet-centric data applications. It is predicted that by 2018, about two-thirds of the world's internet traffic will be video, and more than half of the traffic will be offloaded to Wi-Fi networks. Consequently, WLANs need major improvements in both throughput and efficiency. New technologies continue to be introduced for WLAN applications for this purpose. The IEEE 802.11ac standard is the currently implemented amendment by the IEEE 802.11 standard working group that promises data rates at gigabits per second. The main features of the IEEE 802.11ac standard are adopting increased bandwidth and higher order modulation than the previous standard, and multiple-input multiple-output (MIMO) and multi-user MIMO transmission modes. These features are designed to improve the user experience. In addition to technologies that enhance the efficiency of the WLAN, the IEEE 802.11ax standard is also investigating and evaluating advanced wireless technologies to utilize the existing spectrum more efficiently. These modern communications technologies are steadily advancing physical layer data rates in WLANs, although data throughput efficiency of the WLAN may degrade rapidly as the physical layer data rate increases. The fundamental reason for the degradation is that the current medium access control (MAC) protocol allocates the entire channel to one user as a single source due to equally distributed time domain contention resolution. The challenges and difficulties have already been identified for designing efficient MAC layer resource allocation (MAC-RA) schemes for the upcoming IEEE 802.11ax high-efficiency WLAN. However, there is no profound investigation outcome for this kind of efficient resource allocation. Therefore, in this paper, we conduct an extensive survey of the expected features and challenges for IEEE 802.11ax in the design of fair and efficient MAC-RA. The associated previous research work is summarized as to future directions. Moreover, the need for each directed scheme is highlighted.

**KEYWORDS**
Contention resolution; Distributed coordinated function; Future WLAN, IEEE 802.11ax; MAC layer resource allocation and scheduling; WLAN

## 1. INTRODUCTION

Wireless local area networks (WLANs) are experiencing extensive growth in internet-centric data applications. Advanced technology markets are utilizing WLANs, and deployments are rapidly flourishing in public and private areas, like shopping malls, cafes, hotels and restaurants, bus/train stations, airports, etc. It is predicted that by 2018, about two-thirds of the world's internet traffic will be video, and more than half of the traffic will be offloaded to Wi-Fi networks. In addition, there is the rapid increase of WLAN-enabled electronic devices, because consumers demand that their entertainment devices be internet-enabled. In order to cover new device categories and new applications, exciting new technologies are emerging for WLANs in order to address the need for increased network capacity and coverage, efficient energy consumption, and ease of use. Consequently, WLANs need major improvements in both throughput and efficiency.

New technologies for WLAN applications are continuously introduced. The IEEE standard for WLANs was initiated in 1988 as IEEE 802.4L [1], and in 1990, the designation changed to IEEE 802.11 to form a WLAN standard. This standard describes the physical (PHY) layer [2] and medium access control (MAC) sub-layer specifications for portable, stationary, and mobile devices within a local area for wireless connectivity. The IEEE 802.11ac [3] standard is the currently implemented amendment from the 802.11 standard working group (WG) promising data rates at gigabits per second. These modern communications standards and technologies are steadily advancing PHY layer data rates in WLANs. This capacity growth is achieved primarily through increased channel bandwidths and advanced PHY layer techniques, like multiple-input multiple-output (MIMO) and multi-user MIMO (MU-MIMO). These modern communications technologies are advancing PHY layer data rates in WLANs, although data throughput efficiency in

WLANs may degrade rapidly as the PHY layer data rate increases. The fundamental reason for this degradation is that the current random access-based MAC protocol allocates the entire channel to one user as a single source due to equally distributed time domain contention resolution. Even if senders have a small amount (or less critical) data to send, they still need to contend for the entire channel and get an equally distributed time opportunity for transmission. As a result, the higher the PHY layer data rate, the lower the throughput efficiency achieved.

The strategies like channel bonding, frame aggregation and block acknowledgment, reverse direction forwarding, etc. enhance the high throughput capabilities in 802.11 MAC protocol [3,4]. IEEE 802.11 standard-based WLANs often struggle to service diverse workloads and data types. Since the applications are categorized into different priorities by the access layer protocol, the method how to provide enhanced and efficient resource allocation has become an interesting and challenging topic. Recently, WLAN technologies and research work have introduced enhanced channel access mechanisms to increase network throughput. Although the researchers have spent plenty of time on 802.11 MAC protocol throughput enhancements using above mentioned techniques, efficient medium allocation in the MAC layer is still one of the important target areas for future WLAN researchers. Therefore, our study mainly focuses on the design of efficient MAC layer resources allocation (MAC-RA).

The MAC layer resources can mainly be allocated in three dimensions: channel frequency dimension, access time dimension, and space dimension. These are known as frequency division multiple accesses (FDMA), time division multiple access (TDMA), and space division multiple access (SDMA) mechanisms. Second, there are two main categories for accessing the channels. The first is fixed assignment where channel access is predefined for the stations (STAs). The second is random access, where each STA freely determines when to compete for medium resources, e.g., the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Random access-based CSMA/CA has dominated MAC layer schemes for WLANs due to its backward compatibility and coexistence with other networks.

While future physical-link technologies promise to deliver sufficient bandwidth to serve user demands, existing CSMA-based channel access schemes under IEEE 802.11 are inefficient for large numbers of nodes with extensively changing demands. However, the efficiency of the current medium access protocols will soon encounter challenges when networks are deployed even more densely, like a network having to support thousands of users, or access points (APs) deployed in very close proximity to each other. Such that a stadium, a train or an apartment building where the density of WLAN users is very high. To address inefficiencies in WLANs, especially in dense indoor and outdoor network environments, and to improve robustness against interference, a new IEEE 802.11 task group (TG) called IEEE 802.11ax [5] was formed by the IEEE 802.11 standard WG in 2014. The TG is in the early stages of specifications development, with a projected completion date somewhere around the 2019 timeframe. The key technical target for the TG is to increase parallelization of traffic in the spatial and frequency domains, and to achieve at least four times higher average MAC protocol throughput per STA than in current IEEE 802.11ac networks [5]. In terms of performance, the focus of the IEEE 802.11ax WG has shifted from aggregated network throughput to per-STA throughput. Implementation of MAC-RA in upcoming WLANs like the IEEE 802.11ax high-efficiency WLAN (HEW), which is another name for the IEEE 802.11ax standard, is feasible. However, there are several issues that pose difficulties for HEW to become four times more efficient than current WLANs. Most of the challenges come with the efforts to implement MAC-RA in distributed types of wireless network, specifically when there is no centralized station controlling the dedicated resource allocation and disseminating the reservation control information. In this paper, we summarize the IEEE 802.11ax standardization activities currently in progress, and present an overview of the expected features and challenges for IEEE 802.11ax in the design of fair and efficient MAC-RA. One of the issues with proposing MAC-RA schemes is how to efficiently allocate available resources to STAs. A proper MAC-RA scheme is required to serve that purpose.

The rest of this paper is structured as follows. Section 2 focuses on the overview of legacy IEEE 802.11 MAC-RA and some of the key elements involved in designing MAC-RA. In Section 3, challenges for designing MAC-RA schemes in IEEE 802.11 are described. The IEEE 802.11ax TG is examined in Section 4 for its expected features and challenges, along with proposed MAC-RA schemes. Section 5 summarizes the design considerations for MAC-RA in legacy 802.11 WLAN focused by associated researchers. In Section 6, we enumerate the possible future directions for designing efficient MAC-RA in the upcoming IEEE 802.11ax (a.k.a. HEW). Finally, in Section 7, we conclude with final remarks. Table 1 lists terms and notations used in this paper.

**Table 1:** Terms and abbreviations

| Access category (AC) | Enhanced DCF (EDCF) | Point coordination function (PCF) |
|---|---|---|
| Access point (AP) | Enhanced distributed channel access (EDCA) | Physical (PHY) layer |
| Acknowledgment (ACK) | Extended inter-frame space (EIFS) | Quality of service (QoS) |
| Aggregated MAC service data units (A-MSDUs) | Extended service set (ESS) | Reception (RX) |
| Arbitrary inter-frame space (AIFS) | Frequency division multiple access (FDMA) | Registered random number (RRN) |
| Association identifier (AID) | Group-synchronized DCF (GS-DCF) | Resource unit (RU) |
| Basic service set (BSS) | HCF controlled channel access (HCCA) | Restricted access window (RAW) |
| Binary exponential backoff (BEB) | Head of line (HOL) | Request-to-send (RTS) |
| Carrier sense (CS) | High-efficiency WLAN (HEW) | Single user (SU) |
| Carrier sense multiple access with collision avoidance (CSMA/CA) | Hybrid coordinator (HC) | Station (STA) |
| Clear channel access (CCA) | Hybrid coordination function (HCF) | Working group (WG) |
| Clear-to-send (CTS) | IEEE Standards Associations (IEEE-SA) | Task group (TG) |
| Code division multiple access (CDMA) | Industrial, scientific and medical (ISM) | Time division multiple access (TDMA) |
| Contention-free burst (CFB) | MAC layer resource allocation (MAC-RA) | Traffic specification (TSPEC) |
| Contention-free period (CFP) | MAC protocol data units (MPDUs) | Transmission (TX) |
| Contention resolution period (CRP) | MAC service data units (MSDUs) | Transmit opportunity (TXOP) |
| Contention window (CW) | Medium access control (MAC) | Transmit power control (TPC) |
| CFP maximum duration (CFPMaxDuration) | Multiple-input multiple-output (MIMO) | Triggered frame (TF) |
| DCF inter-frame space (DIFS) | Multi-user MIMO (MU-MIMO) | Triggered frame for random access (TF-R) |
| Discrete sequence spread spectrum (DSSS) | Network allocation vector (NAV) | Uplink MU-MIMO (UL-MU-MIMO) |
| Distributed coordinated function (DFC) | Orthogonal BSS (OBSS) | Wired equivalent privacy (WEP) |
| Dynamic frequency selection (DFS) | Orthogonal frequency division multiple access (OFDMA) | Wireless access for vehicular environment (WAVE) |
| Dynamic sensitivity control (DSC) | Orthogonal frequency division multiplexing (OFDM) | Wireless local area network (WLAN) |
| Energy detection (ED) | Point coordinator (PC) | Wireless sensor network (WSN) |

## 2. OVERVIEW OF LEGACY IEEE 802.11 MAC PROTOCOL RESOURCE ALLOCATION METHODS

Since the inception of the WLAN in 1990, with its technical specifications rooted in the current IEEE 802.11 standard, most of the progress made has been for higher data throughput. It took many years for IEEE 802.11 WGs to approve the first draft and to later evolve it into its many standards and amendments, particularly for higher speed PHY layer transmission [6].

### 2.1 Legacy IEEE 802.11 Standards/Amendments

The terms standard and amendment can be used interchangeably; however, more precisely standards are documents with mandatory requirements and amendments are the documents that add to, remove from in a portion of existing standards. These were designated as IEEE 802.11b, 11a/g, 11n, and 11ac. For enhancement of quality of service (QoS), there is 802.11e; for security, 802.11i; for wireless access in vehicular environments, 802.11p; and to describe mesh networking, 802.11s. In the following sub-sections, we focus on the background information of some of the important standards/amendments that are closely related to the topic of the paper. Figure 1 summarizes a fictional journey of IEEE 802.11 standards until current 11ac amendment. In Table 2, we highlight and summarize some of the important standards and amendments.

#### 2.1.1 IEEE 802.11b Amendment

The IEEE 802.11b amendment to the original standard (IEEE 802.11-97) was endorsed in 1990. It is the most

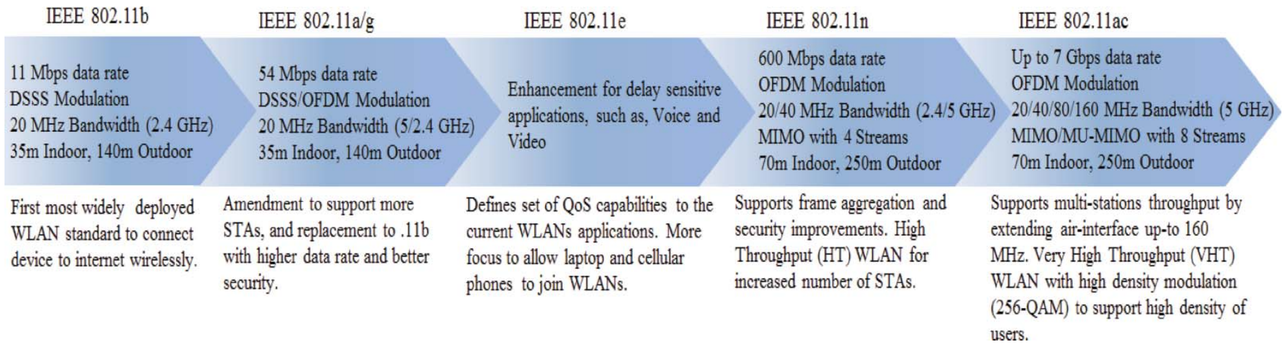

**Figure 1:** Fictional journey of 802.11 standards until 11ac amendment

**Table 2: Popular 802.11 amendments**

| Amendments | Purpose |
|---|---|
| 802.11 (1997) | Original release, data rate up to 2 Mbps in 2.4 GHz ISM band based on DSSS PHY |
| 802.11b (1999) | Extends the DSSS PHY layer, enabling up to 11 Mbps data rates in 2.4 GHz ISM band; high-speed PHY layer extension |
| 802.11a (1999) | Adds an OFDM-based PHY layer at 5 GHz, enabling 54 Mbps to be achieved in ISM band |
| 802.11g (2003) | Defines higher data rate PHY layer extension up to 54 Mbps at 2.4 GHz (backward compatible to 802.11b) |
| 802.11i (2004) | Includes improved security; replaces previous WEP security specification |
| 802.11e (2005) | Enhances the 802.11 MAC protocol to support QoS, including packet bursting |
| 802.11r (2008) | Faster and secure handoff from one base station to another; managed in a seamless manner |
| 802.11n (2009) | Improves standard by MIMO in both 2.4 and 5 GHz bands to maximize data rate from 54 to 600 Mbps; improves security |
| 802.11p (2010) | WAVE, it defines architecture and series of services |
| 802.11s (2011) | To create the mesh topologies of wireless networks, ESS |
| 802.11ac (2013) | Extends 802.11n in 5 GHz band to offer higher throughput, higher density modulation, and additional MIMO streams to give a theoretical throughput of 7 Gbps in bands $<$ 6 GHz |
| 802.11ah (2015-2016) | Extends range, making it useful for rural communications and offloading cell phone tower traffic; expected to be finalized and implemented in 2016 |
| 802.11ax (2019) | Expected to be approved in 2018-19, a HEW that will modify both 802.11 PHY layer and 802.11 MAC protocol, especially for densely deployed environments |

frequently used WLAN extension of the discrete sequence spread spectrum (DSSS) at 2.4 GHz to achieve data rates of 5.5 and 11 Mbps. The rate shift mechanism of 802.11b makes it possible for high data rate networks to slow the rate down to 1 or 2 Mbps. The techniques like channel bonding and burst transmission were also introduced by the researchers to increase the speed up to 22/33/44 Mbps. The IEEE 802.11b uses the same CSMA/CA resource allocation schemes defined in the original standard.

### 2.1.2 IEEE 802.11a/g Amendment

This amendment was also ratified in 1999, to use the same core protocol as in original standards. It operates in 5 GHz frequency band, and uses an orthogonal frequency division multiplexing (OFDM) with a maximum data rate of 54 Mbps. Similar to the 802.11b, the shifting of rate can help to reduce the data rate to 48/36/34/18/12/9 and 6 Mbps under lossy environments. The fundamental distributed coordination function (DCF) medium access scheme, which relies on the CSMA/CA, was carried on by the 802.11a amendment.

In June 2013, another modulation standard was introduced with letter “g”. This amendment used the 2.4 GHz band (like in b), and can also operate in 5 GHz band (like in a) with the maximum data rate of 54 Mbps. Therefore, it is fully backward compatible with both, 11b and 11a. The presence of 802.11b STAs in the WLAN significantly reduces the speed of an 802.11g STA due to the use of DSSS and OFDM. This backward compatibility in 802.11g can be considered as disadvantage. Furthermore, the drawback of 802.11g involves the complexities of implementation since the later amendments involves a less complex implementation.

### 2.1.3 IEEE 802.11e Amendment

In 2005, IEEE developed a new extension of 802.11 to support QoS provisioning in WLAN. The extension was to overcome the problem tempted by the MAC layer techniques like point coordination function (PCF) and DCF in the earlier extensions. With PCF, a centralized device allocates the resources to the STA in the network [3]. Since such centralized devices are not available in certain cases, a distributed scheduling scheme is expected to be implemented. Due to the best effort service nature of DCF, it is unable to provide efficient performance for voice and video applications in WLANs. A hybrid coordination function (HCF) is introduced, which combines the features of PCF and DCF for resource allocation in 802.11. IEEE 802.11e is one of the WLAN standards providing QoS for voice and video applications using HCF, along with enhanced DCF (EDCF). In addition to these, two more MAC enhancements were also introduced in 802.11e to improve the MAC layer throughput; the Block Acknowledgement which enabled sending of a single acknowledgment (ACK) for a block of frames; and Direct Link Protocol, which enabled direct link between two STAs in a single WLAN network.

### 2.1.4 IEEE 802.11n Amendment

In 2004, IEEE announced a new TG to develop a new amendment to the 802.11 standard. The purpose was to increase the real data throughput to at least 100 Mbps, which may require even high raw data rate at the PHY layer to come up with 4–5 times faster than the 802.11a or 802.11g, and 20 times faster than 802.11b. The IEEE 802.11 TG announced high throughput 802.11n in 2009, improving standard by MIMO in both 2.4 and 5 GHz bands to maximize the data rate from 54 to 600 Mbps. The IEEE 802.11n MAC enhancements are aimed at overcoming the inefficiencies of the legacy 802.11 MAC while preserving the backward compatibility. The enhancements such as adaptive coordination function, an extension to HCF and enhanced distributed channel access (EDCA), frame aggregation, and closed loop operation were made to make MAC layer highly efficient. The techniques like block ACK and reverse direction forwarding were introduced to enhance the efficiency of TXOP. The security was also improved as compared to the legacy amendments.

### 2.1.5 IEEE 802.11ac Amendment

The latest amendment to the journey of 802.11 is the 802.11ac, approved in 2013. It is designed to work exclusively in the 5 GHz band. This amendment was driven by the need for high speed due to rapid increase in the use of internet-centric devices. IEEE 802.11ac aims to provide an aggregated throughput of up to 1 Gbps, namely very high throughput (VHT) WLANs. This significant improvement is achieved by introducing novel PHY and MAC layer features, such as the use of 80 and 160 MHz channel bandwidths, a denser modulation scheme that is 256 quadrature amplitude modulation, an aggregated MAC protocol data unit (A-MPDU), and most importantly, the support for MU-MIMO to support simultaneous transmission of up to four STAs in the maximum of eight streams. Most of the enhancements were made to PHY layer in 802.11ac amendment and MAC layer is mostly modified to adapt to these PHY layer changes. The introduction of SDMA resource allocation for MU-MIMO has increased 802.11 MAC layer's efficiency to multiple folds. Many 802.11 devices are battery powered, thus power saving enhancements are worthwhile. IEEE 802.11ac introduced VHT TXOP power-save feature, in which an STA can switch off its radios after knowing that AP has assigned TXOP to another STA.

## 2.2 Domains of MAC-RA

As mentioned earlier, the MAC layer resources can be allocated in three dimensions; channel frequency-based (frequency domain), temporal-based (access time domain), and spatial-based (space domain) resource allocation.

### 2.2.1 Channel Frequency-based Resource Allocation

One of the emerging technologies to improve the MAC resource allocation efficiency is orthogonal frequency division multiple access (OFDMA). The OFDMA technology is used to divide whole channel into several sub-channels, and sub-channels are further divided into several sub-carriers. It enables multi-user channel access and multi-user data transmission since different STAs could use different sub-channels simultaneously. The associated researchers [7–24] have proved that the introduction of OFDMA into 802.11 MAC protocol makes remarkable improvements for efficiency. Even if all STAs are capable of transmitting on the entire available frequency, the current 802.11 MAC protocol allows the AP to transmit to, or receive from, only a single STA in a time slot. The latest amendment IEEE 802.11ac allows the AP to transmit to multiple STAs simultaneously in the downlink using the OFDMA. Although the OFDMA is an efficient candidate for the future WLANs [22], it still has problems due to the channel contention and backoff that have to be performed for each transmission thus causing excessive overhead. When an AP has packets to transmit to more than one STA, it has to compete for the medium at least total number of receiving STAs before it can send out packets. Another challenge is to maintain QoS, especially in densely deployed scenarios, where relatively large number of STAs in a single basic service set (BSS) exists having packets with high QoS requirements. The throughput of WLANs can be improved by taking advantage of multi-user (MU) diversity in channel frequency-based domain. The challenge is to select the specific STAs that will take part in the uplink MU transmission. Therefore, the design of an efficient mechanism to create groups of STAs with low channel correlation and similar channel quality is still an open issue for the next-generation WLANs.

### 2.2.2 Temporal-based Resource Allocation

In wireless communication, continuous transmission is not required because STAs do not use the allocated bandwidth all the time. In such cases, temporal-based access technique is favorable to 802.11 WLANs. The initial IEEE 802.11 standard defines a contention-based distributed medium access algorithm known as DCF. The DCF uses CSMA/CA to contend for channel access. DCF can either operate under the basic access scheme (Figure 2(a)) or the optional request-to-send/clear-to-send (RTS/CTS) (Figure 2(b)) scheme. Binary exponential backoff (BEB) and a deferral mechanism are used to differentiate the transmission start time of each station. BEB is used by STAs to contend with other STAs to access a medium and to transmit data. It is defined as the discrete backoff time slots for which the STA has to defer before accessing the medium. Other STAs overhear the transmission from neighboring STAs by carrier sensing (CS) and set up their network allocation vector (NAV) to avoid collisions.

### 2.2.3 Spatial-based Resource Allocation

Multiple STAs can transmit different information in different physical areas, known as the spatial separation. The spatial-based resource allocation utilizes the physical space separation of the users in order to optimize the use of spectrum. In the space domain, the transmit power of each STA is controlled by SDMA [25]. SDMA serves different STAs by using spot beam antenna

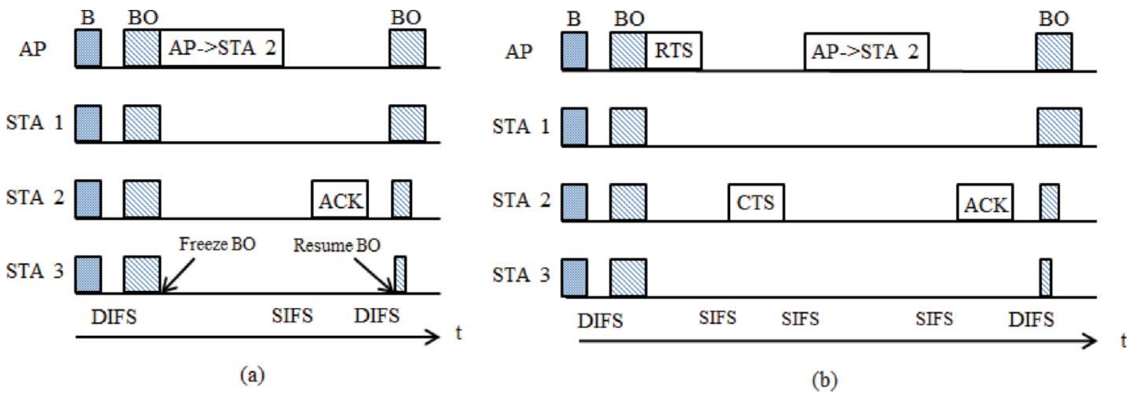

**Figure 2:** IEEE 802.11 DCF transmission procedure: (a) basic access mechanism and (b) RTS/CTS mechanism

technology [26]. These areas may be served by the same frequency or different frequencies. There is comprehensive work done by the researchers [25–31] to show the importance of spatial-based resource allocation. However, it is required that the WLAN coverage cells are sufficiently separated due to the co-channel interference. It limits the number of coverage cells, hence limits the frequency re-use factor. More advanced method combined with other resource allocation schemes (frequency domain and time domain) can further increases the capacity of the network.

We observe that among the above resource allocation domains, temporal-based resource allocation is the dominant and most important resource allocation in 802.11 WLAN. The reason is the randomness and distributed nature of the STAs in the WLAN. Although the channel frequency-based and spatial-based resource allocation allow multi-user uplink and downlink transmissions in WLANs, which is one of the promising techniques of the future WLANs, these schemes are still bound to be followed by time domain to transmit at the same time. Therefore in our survey, we study and summarize the future directions for upcoming IEEE 802.11ax WLAN with respect to temporal-based MAC-RA.

### 2.3 MAC Layer Coordination Functions

Figure 3 describes the MAC layer medium access coordination functions used for temporal-based resource allocation in WLANs. These functions are mainly divided into two categories: contention-based (random channel access) and contention-free (fixed assignment channel access). Both categories differ in the topological structure of the network, as well as in coordination function. These categories are further divided into DCF, EDCA, PCF, and HCF.

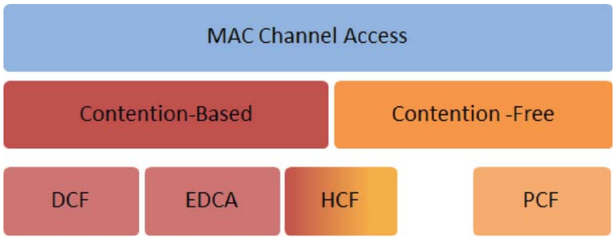

**Figure 3:** MAC layer channel access coordination functions

Similarly in case of high traffic load and density, collisions will increase dramatically for the contending nodes. The main difference between DCF and EDCA is that DCF possesses only one queue for all types of data, whereas EDCA divides the coming packets into four types of logical queue, known as access categories (ACs). These ACs are defined according to the prioritized applications. The higher priority data is assigned a shorter backoff and deferral duration to obtain more chances to access the medium than other types of session. If any collision happens among more than one AC, the higher priority AC secures the opportunity to access the channel, while the others restart their backoff processes [32]. This differentiated access service for different types of application still suffers from degraded performance under densely deployed traffic situations where many contending STAs are present. That is because EDCA still follows contention-based medium access, and collisions are still possible. Moreover, high priority applications hardly provide low priority traffic any opportunity to access the resources. EDCA has this kind of unfairness. The effectiveness of EDCA suffers from more issues in the presence of hidden terminals and interference [33].

PCF is different from the distributed medium access of DCF, where all STAs communicate with each other via a centralized STA called a point coordinator (PC), which usually resides in the AP. The PC controls the access period of the medium by splitting the resource airtime into super-frames of contention-free periods (CFPs). The controlled access period still follows the polling-based contention process. In the CFP, each STA initially sets its NAV to the maximum duration (CFPMaxDuration) at the beginning of each CFP. This NAV duration is reset if the STA receives a CF-End or a CF-End plus ACK frame from the AP, indicating the end of the CFP. Although the PCF is a contention-free medium access in the CFP, there are still several issues with providing efficiency like QoS for applications, because it does not support AC differentiation for priority applications. There is no prediction for the occupancy of the resource by the polled STA. Therefore, the fairness issue persists in the network for each STA, because the transmission time is not bounded. With densely deployed networks, this problem can cause more severe unfairness [34].

The issues faced by the PCF, especially for QoS, have been considered in the proposed HCF controlled channel access (HCCA) [32]. A hybrid coordinator (HC) maintains the traffic specification (TSPEC) for the network. Every STA is required to negotiate this TSPEC before contending for the medium under HCCA. This TSPEC contains information such as mean data rate, maximum service interval, MAC service data unit (MSDU) size, PHY layer minimum data rate, etc. The transmission opportunity (TXOP) is assigned to the STA after this negotiation. The duration of the TXOP is decided by a scheduling process. The HC is responsible for controlling the medium access for data transmission in its dedicated TXOP. HCCA has improved the definition of TXOP, which standardizes the maximum transmission duration of a STA during the CFP. It increases the fairness among the non-AP STAs in the BSS. Additionally, the HC uses an embedded message in a QoS data frame to detect the queue size of the STAs. It is helpful in the design of dynamic resource allocation in WLANs.

Although it seems easy to achieve MAC-RA-centralized schemes like HCCA, some problems are still present; for instance, they cannot address the issue of polling overhead introduced by the STAs before data transmission, which has a significant effect on network performance. In addition, the schemes also rely on the AP/HC, which inhabits transmission among STAs. The whole network can go down if the AP/HC is disabled. Another issue is controlling the collisions caused by inter-cell interference among STAs under multiple BSSs [33]. Moreover, scalability is also an issue for centralized resource allocation schemes in densely deployed networks with distributed and dynamic traffic patterns. Therefore, most of the research work has concentrated on the design of resource allocation schemes in DCF- and EDCA-based networks.

## 3. OVERVIEW OF IEEE 802.11AX MAC PROTOCOL RESOURCE ALLOCATION METHODS

The IEEE Standards Association (IEEE-SA) approved standardization activity of the IEEE 802.11ax TG, concerned with densely deployed WLANs, in May 2014 [5]. Calling it HEW, the scope of the IEEE 802.11ax amendment is to define modifications for both the 802.11 PHY and 802.11 MAC layers that enable at least four-fold improvement in the average throughput per station in densely deployed networks. It is also assumed that it shall provide backward compatibility with existing IEEE 802.11 devices operating in the same band. Unlike previous amendments, this one focuses on improving metrics that reflect the user experience. The desired enhancements will be made to support dense environments, such as wireless corporate offices, outdoor hotspots, residential apartments, and stadiums [5]. Submission of the first draft to IEEE-SA is expected in July 2017, and the actual deployment of the standard is anticipated for late 2019 [35]. Figure 4 illustrates the possible timeline and progress towards the IEEE 802.11ax standard. The main emphasis in IEEE 802.11ax is to improve real-world performance as experienced by end users by enhancing the per-STA throughput. Possible approaches deal with three major problems in dense WLAN environments: congestion, interference, and frame conflicts. Figure 5 shows few of the technologies discussed in the IEEE 802.11ax TG [36].

Full-duplex (FD) is one of the key focused technologies under discussion [37]. FD transmission in WLANs can take place as either a paired or an unpaired operation. In paired operation, two STAs transmit to, and receive from, one another, whereas in unpaired operation, one STA transmits to the other STA, and other STA at the same time transmits to a third. New design of a MAC protocol for paired and unpaired operations is required.

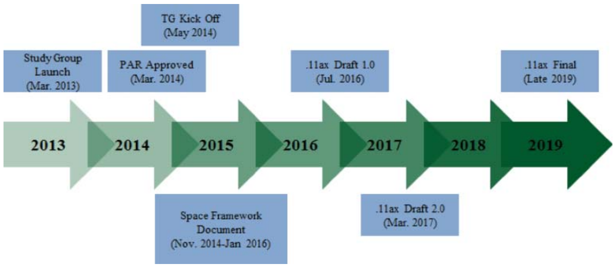

Figure 4: Possible IEEE 802.11ax timeline and progress

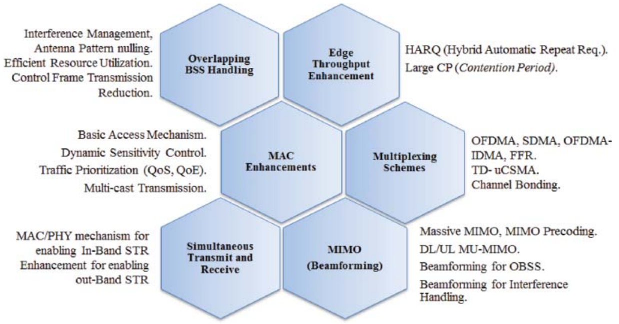

**Figure 5:** Technologies discussed in the IEEE 802.11ax study group

The deployment of downlink and uplink OFDMA is also challenging for MAC protocol design under IEEE 802.11ax. Similar MAC layer design challenges arise for uplink MU-MIMO (UL-MU-MIMO) to efficiently schedule STAs to maximize spectrum utilization [3]. Multi-user function in the PHY layer creates new and fundamental challenges for the design of MAC-RA under the IEEE 802.11ax standard. The reason CSMA/CA works efficiently is that the current IEEE 802.11 standard adopts the PHY layer for the single user (SU), where each STA uses all of the sub-carriers for one OFDM symbol at one time [20]. Simple and straightforward clear channel assessment (CCA) based on predefined CS-threshold (CST) seems to be an obstacle for the upcoming new-generation WLANs owing to complex channel fading and different interference levels. Therefore, the MAC layer design needs different solutions for the IEEE 802.11ax standard. A new resource allocation scheme has to be developed for the MU PHY layer, which should also be backward-compatible with the legacy IEEE 802.11 standard MAC protocol [38].

## 3.1 Collision-Free MAC-RA

A random access method is a critical function for WLANs, and appears non-replicable in future WLANs, like the HEW MAC protocol design. In the past, standardization efforts have focused on increasing the link throughput, rather than on efficient use of the spectrum and the quality of the user experience (e.g., latency). Nowadays, WLANs are deployed in more diverse and dense environments, increasing both interference from neighboring devices and severe collisions due to channel contention. Therefore, a high data rate WLAN like HEW requires an enhanced MAC layer, where multiple STAs can contend for and use a channel simultaneously or in allocated periods according to their traffic demands, thereby increasing overall efficiency. Generally, the most feasible solution to collision issue seems to be a centralized resource allocation [20] of the resource units (RUs), because a centralized device can manage the resources efficiently, while centralized option were never adopted in WLANs [39]. IEEE 802.11ax may consider both possibilities; a centralized solution, or enhancing the current CSMA/CA protocol [40].

### 3.1.1 Centralized Solution

In the currently proposed MAC-RA for IEEE 802.11ax, an AP performs the function of the coordinator by broadcasting a trigger frame for random access (TF-R) at the beginning of the random access period [20]. Every active STA randomly chooses an RU and sends a bandwidth request (BR) to the AP. Transmission by multiple users is supposed to be simultaneous and orthogonal. After successfully receiving the BRs, the AP sends ACK frames, allowing delivery of the information to the corresponding STAs. In these ACK frames, the AP allocates the available amount of bandwidth to the STAs as per their requirements, and sends resource allocation periods in a TF. Finally, the registered STAs simultaneously transmit their data on the allocated RUs after receiving a TF [20]. The 802.11ax standard-based STAs (hereafter called "802.11ax-STAs") can co-exist with the legacy 802.11-based STAs (hereafter called "legacy STAs" for simplicity). The AP allocates a portion of the time period to the legacy STAs. During the allocated time period, legacy STAs can transmit their packets after ensuring that the medium is idle for the DCF inter-frame space (DIFS) period. The AP also broadcasts control frames to announce the duration to 802.11ax-STAs, so that the legacy STAs can update their NAV and avoid transmission in that specified period. In this way, 802.11ax-STAs can co-exist with legacy STAs in the same BSS. The TF designates at least one RU to randomly access the medium. In the TGax meetings, multiple selection processes based on backoff values for random RU selection for STAs in UL-MU transmissions were proposed [41]. These proposed methods are valuable for AC management of QoS-based protocols like EDCA. TGax expects improved efficiency in random RU usage [41]. Figure 6

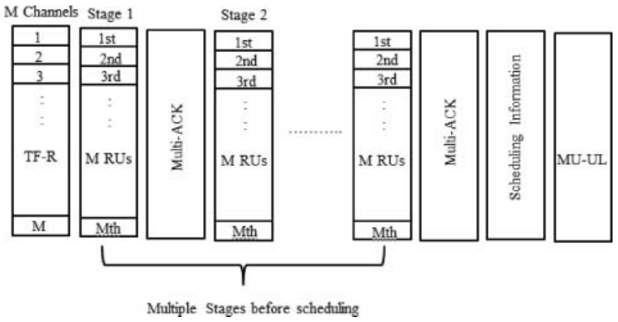

**Figure 6:** Random access mechanism under IEEE 802.11ax

illustrates the proposed random access mechanism of IEEE 802.11ax [20]. From the figure, in the TF-R frame, an AP broadcasts the number of stages and the RUs for the random access process. Following this information, the AP sends the scheduling information to the STAs that replied via the TFs. And then, the STAs can transmit in their scheduled time periods.

### *3.1.2 Enhanced CSMA/CA (CSMA/ECA)*

In TGax group for HEW standard, a focus on enhancing current CSMA/CA appears more feasible. An enhanced CSMA/CA (CSMA/ECA) [42] seems good candidate due to its backward compatibility [39]. The CSMA/ECA is easy to implement and efficiently outperforms current CSMA/CA. A deterministic backoff is used after successful transmission, and backoff stage is not reset after service. The backoff stage is reset only when the STA decides to leave the contention. Moreover, the number of successfully transmitted packets is chosen as the function of the backoff stage to fairly deal with sharing of resources [42]. The criterion to select deterministic backoff value is that the contention window (CW) value of the backoff stage in which STA has successfully transmitted is divided into half. This value is used as a backoff counter value for the next transmission. In deterministic differing technique, the network can reach a collision free operation. Due to larger CW size at higher stage, STAs may have higher backoff values than others, and STAs have to wait longer between TXOPs. To allow a fair share of the medium, at each TXOP in collision free operation, each STA transmits a number of packets proportional to the length of its deterministic backoff [42]. Further detailed working of the CSMA/ECA can be found in [42,43]. Maintaining QoS service differentiation is very important to the upcoming WLAN standards. Therefore, a QoS-based MAC-RA which offers collision-free environment and is also compatible with the legacy QoS STAs is expected to be proposed in 802.11ax. The QoS and traffic differentiation in CSMA/ECA is discussed in [44]. One of the important reasons that CSMA/ECA can serve as a good collision-free MAC-RA is that it achieves a deterministic backoff schedule. In addition, because the AP can learn about the transmission time of each STA in the WLAN, the use of FD can be possible. The FD can attain a huge WLAN performance. Figure 7 shows the basic operation of CSMA/ECA with FD capabilities. In the figure, it can be observed that the use of deterministic backoff allows prediction of time when AP will transmit after successful transmission.

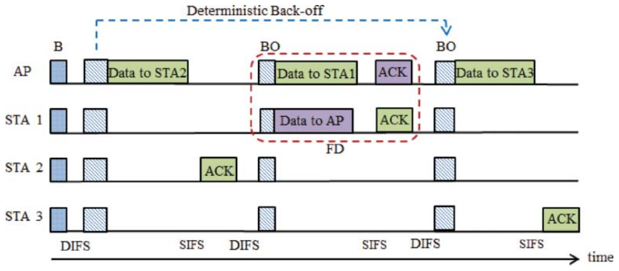

Figure 7: Basic operation of CSMA/ECA with FD capability

### *3.2 Adaptive Clear Channel Assessment*

Until now, all WLAN systems have followed the medium access rules defined in the IEEE 802.11-2012 standard, in which each STA contends for the medium based on the CCA threshold of the channel. TGax has discussed using different CCA levels for access within the BSS (referred to as inter-BSS) and for access among the BSSs (referred to as intra-BSS) traffic, in order to facilitate spatial reuse. Adaptive CCA threshold has been studied in the literature [42–49], and the intention is to allow a STA to access the medium when it detects inter-BSS transmission. A STA accesses the channel in two stages under IEEE 802.11ax. In stage 1, the STA follows the medium access process according to the aforementioned BEB. If the medium is detected as “busy” at any time during a BEB slot, the backoff procedure is suspended. A new STA continues to listen to any ongoing frame over the channel, and determines whether the frame is an inter-BSS or intra-BSS frame. That can be determined from the MAC address in the MAC layer header. If the frame is an intra-BSS frame, the STA continues to follow the traditional medium access process. And in stage 2, if the detected frame is an inter-BSS frame, the STA increases the CCA threshold; if the CCA detection indicates the channel is idle, it resumes the BEB countdown process after the DIFS. The proposed medium access method for the IEEE 802.11ax standard is effective and simple because it benefits the STAs close to the edge of a BSS and facilitates spatial reuse of the channel. This setting of different CCA threshold values enables a STA to resume the countdown sooner once it determines the detected frame is an inter-BSS frame. Both transmission frames may overlap in time and achieve spatial reuse. Since 802.11ax-STAs do not follow the observed TXOP of overlapping BSS (OBSS), the idea of using different CCA thresholds may be helpful for OBSS STA transmission, but it may be unfair to legacy STAs of the same BSS, as they are operating on a fixed CCA level [50]. One possible approach for the enhancement can be that if STAs overhear an inter-BSS RTS frame, not CTS, they are allowed to reuse resources of the OBSS’s TXOP [51].

## 4. KEY ELEMENTS AND CHALLENGES FOR DESIGNING MAC-RA SCHEMES

### *4.1 Key Elements to Design MAC-RA*

In this sub-section, we present few of the key elements for designing 802.11 MAC-RA. We introduce and discuss importance of these elements for designing MAC-RA of upcoming future WLANs, like 802.11ax (HEW).

### *4.1.1 Admission Control*

*4.1.1.1 Introduction.* The main role of admission control is to validate the process of medium access before resource allocation to see whether the current resources are sufficient for the requirements of the demanding STA. Admission control estimates the available resources based on metrics like transmission budget and channel busyness ratio. The purpose is to keep the total allocated traffic under the available resources.

*4.1.1.2 Importance.* The main purpose of admission control is to protect the performance of the resources by efficiently deciding on the available resources. Besides, admission control collects the available resources information, and it can be helpful for MAC-RA to decide whether there are sufficient resources available for newly arriving packets. It makes admission control one of the key elements for MAC-RA. Recently, researchers have spent plenty of their time for enhancing the techniques to utilize this element efficiently [52–56]. A proportional admission control scheme [57] to use the beacon frame for managing resources in OBSSs is already introduced by the IEEE 802.11aa amendment. The proportional admission control scheme has limitation of restricting the throughput of the OBSS to maintain the QoS.

### *4.1.2 Clear Channel Assessment and Network Allocation Vector*

*4.1.2.1 Introduction.* CCA is a mechanism for determining whether the medium is idle or not, and is defined in the IEEE 802.11 standards as part of the PHY layer. It is composed of two related functions: CS and energy detection (ED). CS refers to the ability of the STA to detect and decode incoming signal preamble. ED refers to the ability of a STA to detect different energy levels present on the channel, based on conditions like noise floor, surrounding energy, and interference. The CCA is reliable because ED is a straightforward measure of received signal strength of a valid 802.11 symbol. CCA for any STA is accomplished by detecting energy on the radio interface. ED and CS are synchronized, and both are significantly different from each other in terms of performance and efficiency. NAV is virtual CS, which is used by the STAs to reserve the medium for mandatory packets that follow the current packet. CCA and NAV are totally different, because CCA indicates that the medium is busy for the current packet, and NAV reserves the medium as busy for prospective packets that need to be transmitted immediately following the current packet. NAV information is carried in the duration field of 802.11 MAC protocol headers, indicating the medium is busy for a specified period of time. It is usually contained in control messages, but not always.

*4.1.2.2 Importance.* If it is above a certain threshold, the medium is considered as busy. CS is one of the most essential ingredients of WLANs. Due to their multiple access nature, WLANs require vastly different protocol design and architecture than other networks. Moreover, the medium access is randomly distributed across the STAs in the network, which makes CS a core component of efficiency in medium access resource allocation. CCA belongs to PHY layer CS, and the primary impact of its complexity is on MAC layer performance, like throughput and energy efficiency. This cross-layer characteristic has not been sufficiently explored in the research, with the exception of a few works [46, 58–60]. Therefore, it is necessary to consider CCA and NAV as important elements while designing MAC-RA.

### *4.1.3 Scheduling Schemes*

*4.1.3.1 Introduction.* Scheduling the access period for STAs is one of the main responsibilities in allocation of the resources, by which a STA can transmit its packet successfully. Since neighboring STAs' transmissions in WLANs interfere with each other, the availability of the medium varies according to the distribution of the flows in the network. EDCA, a QoS-based medium access scheme, can optimize resource allocation for certain categories of packets to give them priority. In EDCA, there is unfairness and higher delay for the lower priority traffic. QoS-based applications perform effectively only if sufficient bandwidth can be ensured via resource allocation. Therefore, good resource management needs to identify the sufficient allocation of resources to the STAs in order to meet their desired requirements, as well as QoS requirements. Actual resource scheduling depends on channel contention in the MAC layer. MAC layer scheduling schemes determine the efficiency of channel utilization in WLANs.

Synchronization among the STAs is crucial to the resource allocation mechanism [61]. When the medium is fully synchronized for transmission, it is called

TDMA. Each STA has its own pre-scheduled transmission time, and resources appear periodically after a certain amount of time. This scheme is efficient at giving sufficient bandwidth to QoS-based traffic, but achieving tight synchronization is very sophisticated. There is a chance of resource waste if the network topology and the demand for resources dynamically change. IEEE 802.11-based networks use PCF and HCCA, semi-synchronized schemes to access the channels in centralized networks. Here, the AP is responsible for synchronization, and disseminates the polling frame to inform other STAs within its transmission range. Even if the transmission is scheduled by the centralized controller, inter-cell interference is possible when two or more controllers are located within each other's transmission range. There is no centralized controller for synchronization of the STAs in IEEE 802.11 distributed wireless networks. Therefore, a contention-based medium access mechanism is used within the contention range.

*4.1.3.2 Importance.* The STAs can temporarily be synchronized by exchanging control or data messages. But collisions happen frequently due to interfering STAs. Thus, a good MAC layer resource scheduling scheme with a high level of synchronization is needed for state information of resource allocation. The important concern for MAC-RA is how to schedule medium access for QoS-based applications. For example, a guaranteed maximum delay is demanded by audio/video applications. Fairness among the different levels of QoS (i.e. audio/video, background, and best-effort) is maintained in IEEE 802.11e [32]. Consequently, the effectiveness of MAC-RA depends on the level of synchronization of state information of the STAs for the scheduling. Thus, it is the key element to solve the problems of channel contention and collisions due to the interference and hidden terminals.

### 4.1.4 Exponential Backoff (Contention Window)

*4.1.4.1 Introduction.* To maintain a collision-free environment within the WLAN, DCF channel access is the integral and mandatory part of the 802.11 standard, which provides distributed contention-based resource allocation on the wireless medium to the STAs. As mentioned earlier, DCF channel access has two modes: basic and RTS/CTS. The introduction of RTS/CTS mode was to avoid the hidden terminal problem in WLANs. In both cases, each STA checks the medium status by CS before transmission. If the medium is sensed as idle for the DIFS period, a BEB procedure is invoked. While the medium is sensed as idle, the BEB decrements by one time slot for each backoff slot. The packet is transmitted when the timer reaches zero. In addition, if the medium is sensed as busy, the STA keeps sensing the channel until it senses the channel for the DIFS period. The key element for medium access is to select an optimal BEB value. We have shown the access modes used by DCF for resource allocation in Figure 2. The value of the backoff counter is uniformly chosen in the range [0, CW-1], where CW is the contention window size. On the first transmission attempt, CW is set to the minimum contention window, and is doubled whenever an unsuccessful transmission is detected. It stops incrementing when it reaches the maximum value. The CW is maintained at its maximum value for subsequent transmission attempts. This retry process also has a limit. When the number of retransmissions exceeds the limit, the frame is discarded and the CW is reset to the minimum value. This CW value returns to the minimum value after every successful frame transmission. If the medium becomes busy during BEB counting, the counter is frozen until the detected transmission is finished, and it resumes after sensing the medium for another idle DIFS. A STA transmits its frame once its BEB times out successfully.

*4.1.4.2 Importance.* The CW decides the frequency and the order of medium resource access, and is a key consideration for fair MAC-RA in 802.11. There has been a wide range of research into BEB optimization to control the CW and improve performance of medium resource allocation [62–68]. Figure 8 shows the standard BEB procedure under 802.11.

## 4.2 Challenges for Designing MAC-RA

Several issues pose challenges for MAC-RA design in 802.11 wireless networks. In this section, some of the key challenges are discussed along with the associated research work and limitations in order to understand their impact on future design of MAC-RA for HEW. More detailed associated research work for the design of efficient MAC-RA schemes in legacy 802.11 standards is discussed in Section 5.

### 4.2.1 Node Mobility

*4.2.1.1 Introduction.* Due to the mobile nature of wireless devices, WLANs have dynamic and unstable topologies. Information like the location of the device, signal strength, and state of the device at a certain point can become inaccurate if they move out of the range of other devices. This dynamic type of information will create extra burdens for resource allocation schemes and will affect performance of the network. Handover has also

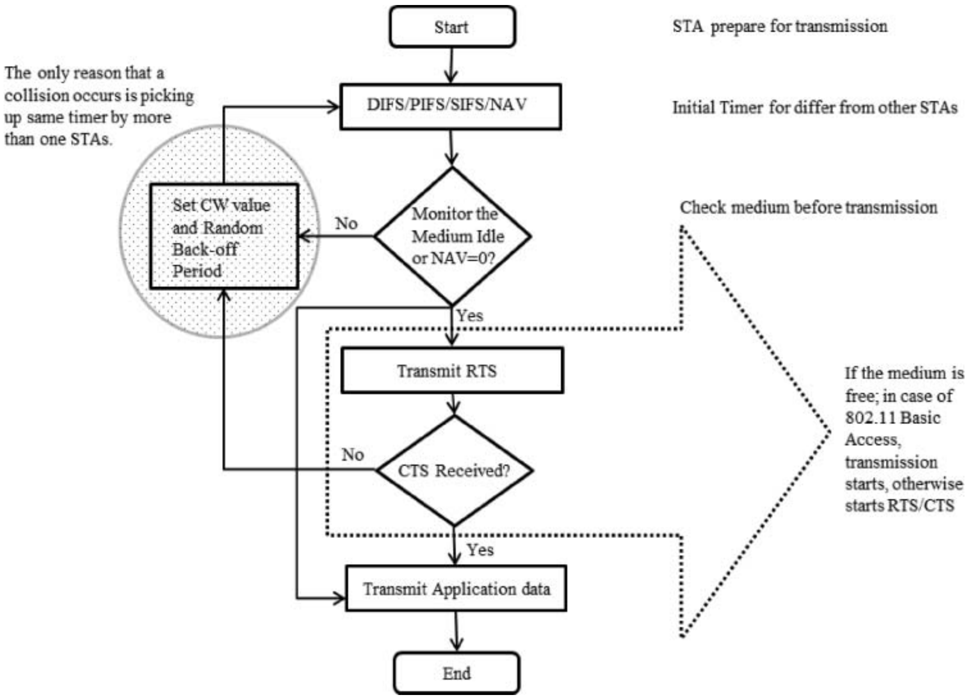

**Figure 8:** The standard BEB procedures under 802.11

been mentioned one of the main challenge for the upcoming dense networks.

*4.2.1.2 Associated Research.* The researchers [69–72] have spent plenty of time to tackle the node mobility challenge appropriately, and the techniques that aim to find the optimal point of handover time are also have been explored. Multi-rate mobile node architecture is proposed in [69] for efficient handover using software defined networks (SDN). A similar work was carried by [70] to improve the transmission speed and reduce the hand-off latency by using two interfaces at the STA, by making it dual link with AP. [71] worked on mobility prediction approaches and found some deficiencies on previously proposed works. They proposed a novel mobility prediction approach which utilizes mobility rules from multiple similar users' discovery, and used combination of clustering and sequential pattern mining. A virtualized control plane, placed in the Cloud can also help to envision by enabling distributed mobility management [72].

*4.2.1.3 Limitations.* The methods which handle the mobility require significant time and cost when applied to the WLANs. The distributed nature of the WLANs and their link stability pose critical challenges in the design of MAC-RA for them.

### *4.2.2 Limited Resources*

*4.2.2.1 Introduction.* Wireless networks have limited resources, such as bandwidth and device battery life, which are insufficient for 802.11-based WLANs. These limitations in resources create challenges for medium access mechanisms. For instance, limited bandwidth availability leads to a low physical data transmission rate. For QoS transmission, applications with high priority need to get longer transmission durations to maintain their QoS service requirements. This leads to unfair resource allocation for other applications. Similarly, if the limited battery life of a mobile STA is exhausted, the mobile device would either be disabled or enter into sleep mode. In a distributed medium access mechanism like DCF, if a device enters into sleep mode or a disabled state after sending CTS, it can cause the sender STA to send frames repeatedly until ACK is received, and the device needs to go through the BEB procedure for each transmission. This will directly degrade overall performance of the network. The errors induced by the channel condition and collision caused by transmission failures within the WLAN waste bandwidth and energy resources.

*4.2.2.2 Associated Research.* The researchers [73–75] have proposed efficient schemes for improving the usage of limited resources of WLANs. In [73], authors investigate the throughput management by TXOP scheduling schemes. The dynamic selection of TXOP, which is originally proposed in IEEE 802.11e standard, is investigated through a game theoretic optimization framework. Current channel capacity and transmission requirements of the STAs are considered to improve the resource utilization. Most of the resource allocation schemes do not consider partially overlapped channels [74], and it is assumed that the WLAN has one single channel or orthogonal channels. In [75], authors have proposed scheme which mitigates channel induced errors and collisions. They used two ideas to improve the energy efficiency of battery powered wireless mobile STAs; backoff free fragment retransmission and collision-free transmission schedules [75].

*4.2.2.3 Limitations.* As a result of scarcity of available bandwidth resources, the critical issue is to determine the optimal density for APs. Thus, channel selection and allocation have to be considered in the planning and designing phases to maximize the network resource utilization. Partially overlapped channels consideration is important to accommodate the extended coverage and to support higher network capacity in densely deployed WLANs, especially to facilitate interference mitigation.

### 4.2.3 Unreliable Wireless Channels

*4.2.3.1 Introduction.* One of the requirements of MAC-RA is correct reception of control messages like RTS/CTS and ACK. Error-prone wireless channels are unreliable owing to thermal noise and channel fading effects. PHY layer CS can be affected due to errors in CCA reception, and the control messages may not be decoded properly. In such cases, resource allocation will lead to additional interference and will impact scheduled transmissions. A transmission attempt can fail without a collision due to such unreliability.

*4.2.3.2 Associated Research.* Many of the operations of 802.11 WLAN and other proposed schemes for 802.11 which behave adaptively to transmission failure assume ideal situation in which all transmission failures occur due to collisions. However, transmission failures can also occur by channel errors. The thermal noise and fading effects can be analyzed and detected based on radio frequency (RF) energy duration in WLAN [76]. The adaptive network coding mechanism takes an adaptive approach to improve the robustness and the reliability of the networks in unreliable wireless channels [77]. The intermediate STAs can overhear the channels to measure the quality.

*4.2.3.3 Limitations.* The challenge is to analyze the noise by using active receiving antenna of the STA, and to detect the RF energy duration. Understanding noise sources and the methods of degradation of these noises allow optimal MAC-RA design trade-offs for a given cost.

### 4.2.4 Node Interference

*4.2.4.1 Introduction.* In 802.11 single channel-based networks, the interference caused by other STAs is one of the key challenges. Such issues significantly affect the available channel capacity for each STA. Before medium reservation for transmission, a STA must know traffic patterns within its contending region, because they may interfere with its transmission, and collision can occur. On the other hand, if the medium is already accessed by another STA and the reserved bandwidth duration has already been announced by that STA, the other STAs should set their NAV and avoid transmission during the reservation period. A CS threshold is utilized to properly receive frames, despite detecting interference signals at a lower power level than the threshold. CS depends upon transmit power as well as signal propagation properties.

Some STA's transmissions are not detected during CS by other STAs, but those transmissions interfere with transmission of other STAs. These STAs are hidden from each other and can cause collisions due to unawareness of the medium access conditions. One of the solutions to the hidden terminal problem is the RTS/CTS mechanism, which effectively avoids collisions from hidden terminals. Similarly, two sender STAs having different receiver STAs that interfere with each other are known as exposed terminals. Figure 9 shows collision faced due to hidden (Figure 9(a)) and exposed (Figure 9(b)) terminals. The exposed and hidden terminals are challenging elements when designing MAC-RA schemes.

*4.2.4.2 Associated Research.* Even though the STAs use techniques like CS and RTS/CTS to handle the node interference at the MAC layer, they still suffer from the issues of spatial reuse and collisions of RTS packets [78].

*4.2.4.3 Limitations.* The CS range is extended by decreasing the CS threshold, which reduces the collision probability as well. On the other hand, the sacrifices are in the form of spatial reuse efficiency, while efficiency of spatial reuse determines the number of possible simultaneous transmit and receive in the network. It also impacts network capacity. On the other hand, the increase in CS threshold can increase the efficiency of spatial reuse by shrinking coverage. However, the

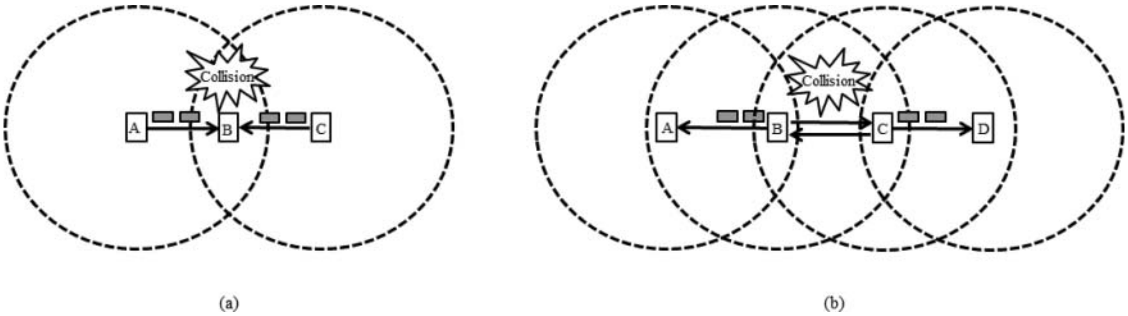

**Figure 9:** (a) Collision due to hidden terminal and (b) collision due to exposed terminal

probability of collision will increase. This will lead to a waste of network bandwidth as well as delay. Consequently, the balance between spatial reuse and the probability of collision needs to be handled in MAC-RA design.

### 4.2.5 Service Differentiation

*4.2.5.1 Introduction.* One of the key challenges in WLAN is to maintain the QoS according to the application requirement. The different applications use different services for the consumers. This service differentiation is the use of multiple services with diverse requirements, such as real-time audio and video transmission. Overprovision of network resources for such diverse requirements is not always possible in wireless networks. Therefore, service differentiation is an integral part of most QoS applications. For service differentiation, ACs define how a flow should access the resources. QoS of the network is enhanced by differentiating the priority of each STA, offering them different level-of-access parameters. EDCA and HCCA schemes introduced by IEEE 802.11e are used for QoS provisioning at the MAC layer to support QoS-based applications [32]. EDCA uses different CWs to differentiate high-priority from low-priority services. Instead of using DIFS for all types of traffic, they use variable length inter-frame spacing (IFS), called arbitrary inter-frame spacing (AIFS). Therefore, traffic having a smaller AIFS has a higher priority [32].

*4.2.5.2 Associated Research.* The current approaches to handle the service differentiation in the STAs are quite satisfactory[79,80]. Some researchers spent their time on optimal BEB window sizes [45,66]. The delay sensitive backoff range and distributed flow admission control can also be adopted to provide QoS in WLANs [81]. Techniques such as delay deviation ration and channel busyness ration [82], Renewal-Reward approach [83], the frequency of acquiring TXOP on the medium [84], MAC protocol buffer size [85], contention-free burst (CFB) in 802.11e [86], are proposed by the researchers to enable the service differentiation within the WLANs.

*4.2.5.3 Limitations.* The challenge is to design an efficient MAC layer access mechanism for the scenarios where STAs and APs are densely deployed whereas keeping QoS applications in mind. Although IEEE 802.11e and 802.11ac standards have sufficiently provided solutions to service-differentiated applications, challenges to the WLAN efficiency still exist due to overprovisioning issues. The bandwidth greedy application can occupy the wireless channel for longer periods and hence the low priority STAs will suffer from throughput degradation. Therefore, adaptive and fair service differentiation schemes are required for the design of MAC-RA.

## 5. MAC-RA DESIGN CONSIDERATIONS IN LEGACY WLAN

To deal with efficient resource allocation in IEEE 802.11 standard-based densely deployed networks, different approaches have been proposed to lessen the impact of channel contention by improving communications efficiency. However, limiting medium contentions is still challenging for researchers. Access to the medium is critical, and it is supposed to be managed optimally under MAC-RA schemes in order to achieve network efficiency. In this section, we discuss some of the important MAC-RA design considerations used by the associated researchers to improve efficiency of MAC layer medium access in legacy WLANs. The main motivation to discuss design considerations used by the researchers is to understand the research directions in legacy 802.11 and to predict and propose future directions for the upcoming WLAN, HEW. Some key design considerations are summarized and a comprehensive comparison is given in Tables 3 and 4. Table 4 compares the work of researchers using analytical modeling. Note that in the tables, TP, MAC-CA, KE, and NS stand for topology,

**Table 3: Comparative study of design considerations for MAC-RA**

| Associated work (scheme) | TP | MAC-CA | KE | NS | Concept used |
|---|---|---|---|---|---|
| Distributed contention control [89] | D | DCF | CW | L | DDC automatically adapts to network congestion by channel contention level |
| Dynamically tuned BEB [91] | D | DCF | BEB | S | Tuning of BEB based on estimation of network status |
| Extended DFWMAC [92] | D | DCF | BEB | S | "Fairness index" as a metric to quantify fairness; extension to DFWMAC |
| Dynamic CW Resetting [67] | D | DCF | CW | FL | Dynamic CW selection; BEB oscillates around the optimal value |
| Asymptotically Optimal Backoff (AOB) [90] | D | DCF | BEB | FL | Optimal backoff selection on the basis of slot utilization and average size of transmitted frames |
| Self-adaptive CW [68] | D/C | DCF/PCF | CW | FL | Self-adaptive CW scheme based on MIMD |
| Idle sense [85] | D | DCF | CW | L | Mean number of idle slots between transmission attempts to dynamically control CW |
| WISC [62] | D | DCF | CW | FL | Locally available state information |
| Bounded delay [81] | D | DCF (EDCA) | CW | M | Delay-sensitive backoff range adaptation and distributed-flow admission control |
| CW optimization [101] | D | DCF | CW | M | Turn-around-time measurement of channel status |
| Dynamic adaption of CW [94] | D | DCF | CW | M | Channel congestion status-based CW |
| ABTMAC [88] | D | DCF | CW/BEB | M | Varying transmission attempt rate |
| ACWB [96] | D | DCF | CW | M | Run-time CW adjustment |
| k-CR [98] | D | DCF | MA | L | k-round contention resolution scheme |
| Energy-efficient CW [97] | D | DCF | CW | FL | Network load conditions |
| CSMA/ECA [99] | D | DCF | MA | M/L | Deterministic BEB after successful transmission; reset BEB stage when STA leaves contention |
| Multi-priority DCF [80] | D/C | DCF/PCF | MA | S | Shorter IFS and shorter BEB |
| Survey [4] | D/C | DCF/PCF/HCF | MA /CS | S/M/FL/L | TXOPs sharing and use of TDMA and CSMA/CA in beacon intervals |
| Failure of CSMA [102] | D/C | DCF/PCF/HCF | CS | S/M/FL/L | Increase in ratio of propagation delay to packet transmission degrades CSMA performance |
| CSMA/CDA [103] | C | PCF/HCF | MA | L | RRN |
| Dynamic CS-threshold [45] | D/C | PCF/HCF | CS | L | DSC to vary CS-T levels at each STA |
| DRP-TPC [104] | C | DCF | MA | FL | TPC to exploit capture effect |
| Survey [105] | C | DCF | MA | L | Varying TX power and CS-T to split contention domain into multiple domains |
| Technical overview TGah [107] | C | DCF (GS-DCF) | MA | L | Grouping of STAs and using RAW |
| Backing out of BEB [106] | D | DCF | MA | L | Partial ordering o STAs into groups |
| GS-DCF in TGah [108] | D | DCF (GS-DCF) | MA | L | Guidelines for choosing number of groups |
| Improved channel access [109] | C | PCF | MA | S/M/FL/L | Cellular network assistance over WLAN |

Note: TP = topology, MAC-CA = MAC protocol channel access, KE = focused key element, NS = network size, C = centralized, D = distributed, MA = medium access, CS = carrier sensing, AC = admission control, S = small network size, M = medium network size, FL = fairly large network size, and L = large network size

MAC protocol channel access, focused key element, and network size, respectively. In the TP column, C and D stand for centralized and distributed, respectively; in the KE column, MA, CS, and AC stand for medium access, carrier sensing, and admission control, respectively. The S, M, FL, and L in the NS column stand for small, medium, fairly large, and large (network sizes), respectively.

**Table 4: Comparative study of design considerations for MAC-RA using analytical modeling**

| Associated work (scheme) | TP | MAC-CA | KE | NS | Concept used |
|---|---|---|---|---|---|
| Analytical model [64] | D | DCF | CW | FL | Throughput analysis with assumption of finite number of STAs |
| Analytical model [111] | D | DCF | CW | M | Analytically derived average size of CW to maximize throughput |
| Analytical model [110] | D | DCF | MA | FL | IFS-based priority mechanism to support QoS in 802.11 |
| Analytical model [85] | D | DCF (EDCA) | MA | M | MAC protocol buffer size under loaded and saturated regimes |
| Analytical model [66] | D | DCF (EDCA) | CW/BEB | M | Minimum CW size, BEB increasing factor, and retransmission limit |
| Queuing model [112] | D | DCF | AC | M | 3D Markovian model for buffer size under a particular QoS constraint |
| Analytical model [84] | D | DCF (EDCA) | MA | M | The frequency of acquiring TXOP on the medium, and the duration of this acquired TXOP |
| Renewal-reward approach [83] | D/C | DCF (EDCA) | MA | M | Impact of an arbitrary buffer size with buffer overflow probability and MAC access delay distribution |
| Analytical model [86] | D | DCF (EDCA) | CW/BEB | L | Linearly increasing initial BEB window size for each AC |
| Analytical model [113] | D | DCF (EDCA) | MA | M | Saturation depends on factors like number of STAs and their relative loads |
| Analytical model [114] | D | DCF (EDCA) | MA | M | CFB in 802.11e |
| Analytical model [63] | D/C | DCF (GS-DCF) | MA | L | Decentralized grouping scheme |
| Analytical model [82] | D | DCF (EDCA) | CW | S | Delay deviation ratio and channel busyness ratio for delay-aware distributed dynamic adaptation of CW |

Note: TP = topology, MAC-CA = MAC protocol channel access, KE = focused key element, NS = network size, C = centralized, D = distributed, MA = medium access, CS = carrier sensing, AC = admission control, S = small network size, M = medium network size, FL = fairly large network size, and L = large network size

### 5.1 Optimal BEB and CW Selection Considerations

In DCF, the CW is the main factor in reducing collision probability, and it is doubled after each collision until reaching the maximum value. Bianchi used an enlarged CW approach to reduce channel contention [64], proposing that the optimal value of the minimum CW depends on the number of active STAs in the network. For optimal selection of the CW value, a dynamic CW resetting scheme was proposed [67] to let the BEB oscillate around the optimal value. Similar work was done by Ref. [68], who presented a novel self-adaptive CW adjustment algorithm based on multiplicative increase, multiplicative decrease. The purpose of the proposed work is to improve efficiency for not only when a few STAs contend for resources but also for when many STAs compete. Medium utilization is reduced by either time lost due to collisions or from the following retransmissions and idle backoff slots before successful transmissions; therefore, the optimal operating point falls between the time spent in collisions and retransmissions versus idle time slots. A new CW adjustment scheme, window idle slots-based control (WISC) using a control theoretic approach, was proposed [62]. The basic idea behind WISC is to adjust the CW based on locally available state information with the help of a well-designed controller to automatically determine the optimal value. The key element of 802.11 MAC-RA is its simple DCF protocol-based resource allocation operation, which was proven to be robust and adaptive to varying conditions and able to fulfill most of the needs sufficiently well. However, the procedure may need to change in the future because of limited capacity [87]. The higher protocol capacity in comparison with legacy DCF-based MAC layer medium access was achieved by tuning the backoff window size and using an optimal packet length [88]. For tuning backoff window size, a fixed transmission attempt rate is used by the STAs. An adaptive backoff tuning MAC (ABTMAC) protocol was proposed [88] to dynamically adjust the CW size, considering network status. The use of a feedback mechanism to adaptively set the CW to achieve high performance in WLANs is not new in the literature.

Due to the inefficiency of current default values of MAC parameters with respect to current dense WLANs, associated researchers have proposed many schemes to allow the STAs to be adaptive under present network conditions. The work done by Ref. [89] introduced automatic adaption of the CW according to network congestion by using additional control on frame transmission. Ref. [89] investigated further [90] and proposed a runtime estimation of slot utilization by probabilistically controlling the transmission of a STA to enhance spatial reuse. Ref. [91] tuned the CW via runtime estimation of the current network busyness and load status. Ref. [81] defined adjustment of the CW to provide QoS opportunity and fairness among all the STAs transmitting with the same priority. Other authors [92, 93] proposed adjustment of the CW with the use of idle sense, an optimal access method for achieving fairness and higher throughput in rate-diverse WLANs. Hong et al. proposed a channel condition-based dynamic CW adaptation for saturated and unsaturated network conditions to achieve optimal throughput [94]. A dynamic, deterministic CW control scheme is proposed by Ref. [95], in which the backoff range is divided into several small backoff subranges. Similar work to dynamically adjust the CW size in a distributed manner at run time to maximize throughput and fairness according to statistics of the idle backoff slots was proposed [96]. Those authors proposed a practicable distributed backoff algorithm called adaptive CW backoff (ACWB) for 802.11 WLANs. The dynamic adjustment of CW size according to network load, which represents the level of congestion in a network, can maximize energy efficiency of wireless STAs [97]. The CW adaptation algorithm proposed by Ref. [97] adaptively changes CW size according to the load to achieve the required energy savings and QoS objectives. Another suggestion by Ref. [98] handles the contention process in multiple rounds. The process of selecting an adaptive CW size is based on the number of observed idle backoff slots. In order to achieve high efficiency and robustness during the resource allocation process under the MAC protocol in IEEE 802.11 networks, a k-round contention resolution (k-CR) scheme was proposed [98]. Each of the transmission periods contains a contention resolution period (CRP) to contend for the channel. The contention process among the STAs is performed in multiple rounds within the CRP until successful transmission by a STA. The contention rounds are further divided into mini slots. Numerical results of the k-CR scheme show that it is more efficient than traditional DCF [98]. Due to the hostile nature of the BEB schemes, an infinite second moment of access delay may be incurred if the network size exceeds a certain threshold in future deployments [99].

The backoff design for 802.11 DCF networks was characterized by Ref. [99] in view of fundamental tradeoff and design issues. However, under some uncertain conditions, collision-free operation can be reached in a distributed and adaptive manner, even if the number of STAs in the network increases. Three changes to the basic CSMA/CA DCF were proposed to handle such situations [100]. First, a deterministic backoff is used after a successful transmission. Second, the backoff stage is not reset after a packet is serviced, and is only reset when the STA leaves contention because it has no packet to transmit. And third, the number of packets transmitted in every TXOP is chosen as the function of the backoff stage for a fair share. The proposed algorithm is called CSMA with enhanced collision avoidance (CSMA/ECA). The work done by Ref. [101] additionally considers the "imperfect channel condition" (usually referred as bit error rate) for the design of a dynamically adjusted CW size. However, the proposed methods do not consider factors like channel access delay and transmission delay in WLANs. Another recently proposed scheme, delay-aware distributed dynamic adaptation of CW channel access [82], covered the shortcomings of channel access delay and imperfect channel condition.

### 5.2 Transmission Opportunity (TXOP) and Cross-Layer Consideration

A survey to investigate an efficient scheduling mechanism in MAC layer schemes adopted by the IEEE 802.11ac from the legacy 802.11 was presented [4]. The authors highlighted the use of new TXOP-sharing techniques and use of a mix of TDMA and CSMA/CA in beacon intervals for HCF-based WLANs. Associated researchers have also investigated the effects on performance of increasing data rates and small packet sizes under CSMA/CA. Ref. [102] investigated how an increase in the ratio of propagation delay to packet transmission time dramatically degrades the throughput obtained using CSMA/CA. The continuous impulse for higher raw data rates under 802.11 and changes in traffic patterns toward a greater proportion of prioritized traffic is bringing CS to its limits in WLANs [102]. A modified CSMA/CA mechanism, named as CSMA with collision detection and avoidance (CSMA/CDA), to lessen performance degradation problems in densely deployed WLANs was proposed [103]. Under CSMA/CDA, mobile STAs attach a registered random number (RRN) in the frame. The associated AP adds this RRN into an RRN scheduling list and sends an ACK upon receipt, taking note of the transmitter and other STAs near the AP. On receiving the RRN, legacy CSMA/CA STAs can also update the prescheduling medium information and adjust the backoff timer to reduce collisions. The authors proposed this scheme as suitable for next-generation WLANs like IEEE 802.11ax. This scheme exploits the medium access information gathered by the associated STAs so the AP can continually coordinate resource allocation across the network. On the other hand, obtaining a single optimal CST for all STAs in IEEE 802.11ax dense networks may not be a feasible solution, because mobile STAs are not always available at the desired location. Similarly, interference levels are also variable due to the random positions and penetration losses. Increasing or decreasing the CS threshold may result in more concurrent transmissions. A dynamic sensitivity control (DSC) algorithm to adjust the CS threshold based on the average received signal strength was proposed [45]. In order to optimize system performance, we need an optimal CS range that should be employed by each STA accordingly, to balance spatial reuse and the impact of collisions. The general 802.11 DCF employs contention-based resource allocation, and collisions happen only when more than one STA starts transmission simultaneously. However, from the PHY layer perspective, if the received signal strength of one STA is much higher than the others, then the AP or receiver will be able to decode the frame. This characteristic of the PHY layer is called the capture effect. It can be utilized to improve contention efficiency [104]. Su et al. [96] proposed a novel design for this transmit power control (TPC), named differentiated received power TPC (DRP-TPC). In the proposed scheme, each STA configures transmit power such that the received power at the receiver will meet the pre-specified requirements. The use of PHY layer elements like DSC and TPC can also be helpful in designing an efficient future MAC-RA.

### 5.3 Splitting and Grouping of Contention Space Consideration

A WLAN network can be split into multiple collision domains such that the APs can transmit frames within their domain independently to exploit concurrent transmission [105]. This can be achieved by varying TX power and CS threshold. Intra-domain transmission was also suggested by exposing at least two APs to each other [105]. The legacy DCF is randomized backoff-based, where a WLAN creates total ordering among the STAs contending for the resources. Ref. [106] revisited this randomized backoff problem, where a WLAN creates total ordering among the STAs contending for resources. They proposed a backing out of linear backoff to envision breaking away from this total ordering. The STAs are forced to pick a random number from a smaller range to create groups with a partial ordering. The group with smallest range proceeds to the next round for contention. Medium utilization improves because the time spent for partial ordering small groups is less than the time needed to totally order all the STAs. A similar situation is supported by the IEEE 802.11ah standard. The IEEE 802.11ah MAC protocol supports associated STAs where an AP can have up to 8000 STAs. Grouping the STAs to increase the number of supportable STAs is proposed in this standard. Restricted access window (RAW) is the time duration (composed of several slots) allocated to a group of STAs for medium contention [107].

Although the idea of grouping was already proposed in IEEE 802.11ah [107], the critical factor is to choose the optimal number of groups for this group-synchronized DCF (GS-DCF) where about 8000 STAs are handled by a single AP. Both group sizes, whether too large or too small, degrade network performance, because too few groups induces a large number of retransmissions, and too many groups causes unnecessary overhead [108]. Moreover, for large numbers of users, if they pick a small initial backoff window, some users capture the resources by obtaining a better transmission probability. For medium access optimization, a network-assisted access parameter distribution prototype was proposed [109].

### 5.4 Analytical Model Consideration

In the literature, the work done by associated researchers for performance evaluation of 802.11 is also valuable. Most of the performance evaluation work was carried out either via simulation or analytical modeling with simplified assumptions. These performance evaluation analytical models not only help to evaluate the efficiency of medium access algorithms, but also contribute to enhancement of MAC-RA schemes in 802.11 WLANs. Bianchi was the first researcher to propose a discrete time Markov chain (MC) model to obtain the saturated throughput of DCF [64]. Several papers were published to extend that model to consider different practical issues [66–68]. Bianchi and Tinnirello extended Bianchi's analytical work to throughput and delay of IFS-based priority mechanisms to model QoS under IEEE 802.11 DCF [110]. Similar backoff-based priority scheme for newly arrived standard 802.11e with differentiated minimum CW size and backoff window, increasing factors and the retransmission limit was modeled by Ref. [66]. A model that accounts for all of the differentiated services and that considers varying collision probabilities in different contention zones to provide accurate AIFS was proposed [83]. The authors showed that the MAC protocol buffer size significantly affects EDCA performance between under-loaded and saturation regimes, especially when EDCA TXOPs are enabled. Ref. [111] developed an analytical model for the $p$-persistent IEEE 802.11 protocol, and derived the optimal value of $p$. The optimal value of $p$ is used to adjust the size of the current CW to maximize the protocol capacity. Another work to determine adequate buffer sizes under a particular QoS constraint was presented [112]. The authors embedded the queuing process of the STA into the contention process to develop a three-dimensional MC model. It draws the steady state probabilities of the MC in a more efficient manner. There are two sets of differentiation parameters; the first set controls the frequency of acquiring a TXOP on the medium, and the second set controls the duration of this acquired TXOP [84]. Ref. [84] analyzed and highlighted these sets of parameters, which are used in EDCA to achieve airtime differentiation. It was observed that network efficiency under the current EDCA standard may significantly degrade as the network size grows. Hence, it remains largely unknown as to how to tune BEB parameters under certain differentiations [86]. A new analytical model was proposed to address this issue [86]. The optimal initial backoff window sizes and AIFS to maximize network throughput were derived. The proposed analysis revealed that maximum network throughput is determined by the holding time for head of line (HOL) packets in successful transmission and collision states. The initial BEB window size should linearly increase with the network size.

The above-mentioned analysis and modeling done by researchers were based on assumptions like saturated conditions, whereas in reality, a STA may face saturated, non-saturated and heterogeneous traffic conditions. An analytical model of 802.11 MAC protocol under non-saturated and heterogeneous conditions was proposed [113], and the authors captured many interesting features, like the fact that peak throughput occurs prior to the saturation point. The saturated throughput of the STA depends on factors like the number of STAs and their relative loads. Another promising burst transmission scheme, named CFB, was defined in the 802.11e MAC protocol to achieve differentiated QoS and improve scarce wireless bandwidth utilization. Ref. [114] proposed a simple analytical model of 802.11e EDCA with CFB consideration. A proposed renewal-reward model [83] was also used to adjust the current CW value on the basis of a renewal-reward scheme. The use of GS-DCF was analyzed in the analytical modeling by Ref. [63] to track the performance of GS-DCF in saturated 802.11ah networks. They analyzed throughput efficiency using both centralized and decentralized grouping schemes. They suggested the possibility of implementing a decentralized grouping scheme with small throughput loss.

## 6. FUTURE DIRECTIONS

The main aim of the reviewed MAC-RA proposals from the associated researchers is to direct the researchers for the improvement of MAC efficiency in essence. More specifically, MAC-RA tries to allocate resources to the STAs as efficiently as possible for MAC throughput enhancement. With this goal in mind, we discuss possible future research directions for designing efficient MAC-RA schemes for the upcoming IEEE 802.11ax (HEW). We discuss some important performance-efficiency aspects that have not been specified in currently implemented WLANs like IEEE 802.11n and IEEE 802.11ac. We also envision MAC-RA's role in facilitating integration of future heterogeneous networks.

### 6.1 Optimized Intelligent Collision Resolution

Until now, the random BEB scheme has been a key function employed by 802.11 to avoid collisions. Unfortunately, in WLANs, collision cannot be completely eliminated and it remains one of the most significant factors degrading network performance. As we mentioned in the earlier section on associated research, few researchers have proposed collision-free solutions, where STAs adopt a deterministic BEB and CW size (instead of a random one) after a successful transmission. On the other hand, some work also suggested adaptively or dynamically setting BEB values according to network conditions. These innovative ideas can be considered when designing an optimized intelligent collision resolution.

### 6.2 An Analytical Model

Analytical performance modeling plays a vital role in understanding and analyzing network performance parameters. The present proposed performance analysis models for wireless communications rely on many assumptions that might be crucial to network performance in reality. The future emerging WLANs are expected to have denser and more congested deployments with a large number of users. Such networks require more realistic analysis modeling. Moreover, HEW focuses on per-STA performance efficiency. Therefore, performance modeling focusing on queuing behavior of a single STA also needs to be integrated into current throughput and delay analysis-based models of the overall network. There is a need for more accurate and realistic analytical models.

### 6.3 Grouping or Splitting Dense Networks into Multiple Collision Domains

Although it is debatable that the way of grouping or splitting STAs into multiple collision domains depends on the specific application, a smart grouping scheme can be designed to identify STAs that can be co-scheduled efficiently in densely deployed WLANs. Similarly, the conditions under which re-grouping in the network would be triggered need to be designed.

### 6.4 Adaptive TPC and DSC

The associated research work discussed has shown the significant impact on WLAN performance from the use of TPC and DSC for resource allocation. A clear dilemma regarding the scope of the use of differing TPC and DSC is that a large scale (e.g. all STAs in the network) will shrink network coverage more frequently. Therefore, adaptive algorithms are needed to dynamically adjust the scope of TPC and DSC for transmission and reception.

### 6.5 MAC-RA for Full-Duplex Transmission

The current form of transmission in WLANs is half-duplex, where transmissions are differentiated using time slots or frequency bands. FD transmission can double channel capacity by allowing simultaneous transmits and receives on the same frequency. FD transmission is one of the discussion topics in the IEEE 802.11ax TG. The coming of FD transmissions prompts us to rethink and redesign 802.11 MAC schemes, mainly CSMA/CA-based mechanisms, which rely on the assumptions that wireless devices cannot transmit and receive simultaneously, and cannot detect collisions while transmitting. The research into FD transmission has just started in recent years, and MAC-RA schemes need to be revised as well.

### 6.6 Integration of Heterogeneous Networks

It seems that, in the future, there will be a smart densely deployed WLAN that integrates heterogeneous networks, which means individual networks will have to team up with other types of networks to provide services. The outdoor deployments of future WLANs face some significant challenges to the current MAC due to limited mobility support. In future, cellular operators may off-load their paid user traffic to public WLANs, such as carrier-class Wi-Fi [115], femto-cells [116] in dense public areas, and LTE-U [117]. To make IEEE 802.11ax part of such integration, seamless transfer and the QoS promised by the cellular network need to be ensured in the MAC-RA.

## 7. CONCLUSION

As an important way to provide efficient resource utilization, schemes based on MAC-RA have been concentrated on for many years. In this paper, we first summarized the IEEE 802.11 standardization activities in progress and presented an overview of resource allocation under the 802.11 MAC protocol. Subsequent sections defined the key elements and challenges to designing an efficient MAC-RA scheme for WLANs. Secondly, we outlined the expected features and challenges for IEEE 802.11ax in the design of MAC-RA. In the later sections, design considerations when devising efficient medium allocation were discussed through associated research work. In view of the design considerations for researchers, interesting future directions for the design of MAC-RA in the upcoming WLAN IEEE 802.11ax (HEW) were highlighted. Towards the entire HEW design, there remain many interesting research topics that require further investigation. The *optimized intelligent collision resolution* scheme for STAs in dense environments needs to be developed in the future. Another study needs to consider *an analytical model* that accurately evaluates fair resource allocation in HEW. The use of *grouping* STAs for contention under IEEE 802.11ah needs to be further investigated for dynamic communications scenarios. Similarly, *splitting the dense networks into multiple collision domains* to reduce collisions in the WLAN network can be a good topic for consideration. The use of *dynamic and adaptive TPC and DSC* values is also interesting for future MAC-RA design. Under FD inclusion in the upcoming HEW, MAC-RA needs to be redesigned and rethought. And finally, the integration of HEW into heterogeneous networks to form next-generation technologies like LTE-U will also open up research areas for MAC-RA design. All these future directions can be a good complement to the existing solutions designed for the upcoming IEEE 802.11ax (HEW).

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