IEEE 802.11ax: Next Generation Wireless Local Area Networks

Der-Jiunn Deng [1], Kwang-Cheng Chen [2], Rung-Shiang Cheng [3]

[1] Department of Computer Science and Information Engineering, National Changhua University of Education, Taiwan
[2] Graduate Institute of Communication Engineering, National Taiwan University, Taiwan
[3] Department of Computer and Communication, Kun Shan University, Taiwan

djdeng@cc.ncue.edu.tw, ckc@ntu.edu.tw, rscheng@mail.ksu.edu.tw

Abstract—**Recently, IEEE 802 started a task group to investigate and deliver next generation WLAN technologies for the scenarios of dense networks with a large number of stations and access point. The proposal is specified as the IEEE 802.11ax amendment. Due to the significant network capacity increase achieved by 802.11ax, the term high-efficiency WLAN (HEW) is also used in reference to this new amendment. This paper summarizes the IEEE 802.11ax standardization activities in progress and presents an overview of the most important features proposed in the 802.11ax amendment. Expected features and challenges for 802.11ax in the design of physical layer (PHY) and media access control sub-layer (MAC), toward a new era of wireless LANs, are also discussed.**

Keywords-802.11ax, WLANs, GRAP, OFDMA, MU-MIMO, medium access control, multiple access

I. INTRODUCTION

In past two decades, the IEEE 802.11 wireless local area networks (WLANs) have experienced tremendous growth with the proliferation of IEEE 802.11 devices as a major Internet access for mobile computing. The IEEE standard for WLANs was initiated in 1988 as IEEE 802.4L, a part of the IEEE 802.4 token bus wired LAN standard, and then change its name to IEEE 802.11 to form a WLAN standard in 1990. This standard describes the physical layer (PHY) and medium access control sub-layer (MAC) specification for wireless connectivity for fixed, portable and moving stations within a local area. After delay for many years, IEEE 802.11 working group approved the draft and later evolving into many amendments, particularly for higher speed physical layer transmission, namely IEEE 802.11a, 11b, 11g, 11n, 11ac, for enhancement of higher level service support like 11e (quality of service) and 11i (security), for wireless access in vehicular environments, 11p, and for mesh networking , 11s. The list of most popular past and present 802.11 amendments is shown in Table 1.

A. Beyond 802.11ac

The tremendous growth of mobile data traffic and the advent of bandwidth-hungry wireless applications highlight the impending need for large bandwidth and high data rate in next generation mobile networks. To this end, 802.11ac, the latest approved 802.11 amendment, has been under development and has the goal of reaching maximum aggregate network throughput of at least 1 gigabit per second and a single link throughput of at least 500 megabits per second on unlicensed bands at 5 GHz band. This is accomplished by extending the air interface concepts embraced by 802.11n: wider channel bandwidth (20/40/80/160/80+80 MHz), more multiple-input multiple-output (MIMO) spatial streams (up to eight antennas), and high-density modulation (up to 256-QAM). In particular downlink multi-user MIMO technology (up to four clients) adopted improves the spectrum efficiency by allowing simultaneous transmissions of multiple data frames to different users. 802.11ac is backward compatible with 802.11a and 802.11n, and the first generation 802.11ac chips are already available in the market. In contrast to all previous 802.11 amendments, 802.11ac is aimed at improving total network throughput as well as individual link performance, with possible integration with cellular systems. The evolution of WiFi technology is illustrated in Fig. 1.

In the past, the standardization efforts have been very much focused on increasing the link throughput, rather than efficient use of spectrum and user experience such as latency. Nowadays, WLAN devices are currently being deployed in diverse environments. These environments are characterized by the existence of many access points (AP) and mobile stations in geographically limited areas. Increased interference from neighboring devices and severe collisions from channel contention in dense environments give rise to network performance degradation. In addition, WLAN devices are increasingly required to support a variety of applications such as voice, video, cloud access, and traffic offloading. While cellular companies are planning to kick off LTE-A service and offering up to 1 gigabit per second data rate in the next few years, WLAN also need to be upgraded to support increasing demands of network performance by emerging applications, including improved power consumption for battery-operated devices, as shown in Fig. 2.

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TABLE I. IEEE 802.11 amendments

802.11 Amendments	**Responsibility**
802.11a Approved in 1999	Specification enabling up to 54 Mb/s to be achieved in the 5 GHz unlicensed radio band by utilizing orthogonal frequency division multiplexing (OFDM).
802.11b Approved in 1999	Specification enabling up to 11 Mb/s to be achieved in the 2.4 GHz unlicensed radio band by utilizing high rate direct sequence spread spectrum (HR/DSSS).
802.11d Approved in 2001	Covers additional regulatory domains, which facilitates the development of WLAN devices that comply with the wireless communications regulations of their respective countries.
802.11c Approved in 2001	Provides required information to ensure proper bridge operations, which is required when developing access points.
802.11f Approved in 2003	Covers Inter Access Point Protocol (IAPP), ensuring the user can roam in the different access points.
802.11g Approved in 2003	Specification enabling high data rate up to 54 Mb/s to be achieved in the 2.4 GHz unlicensed radio band.
802.11h Approved in 2003	Covers dynamic frequency selection (DFS) and transmit power control (TPC). The protocol solves the interferential problem of satellites and radar that using the identical 5 GHz frequency band.
802.11i Approved in 2004	Enhance WLAN security to replace the previous security specification Wired Equivalent Privacy (WEP).
802.11j Approved in 2004	Specially designed for Japanese market. It allows Wireless LAN operation in the 4.9 to 5 GHz band.
802.11e Approved in 2005	Defining a set of Quality of Service (QoS) enhancements for wireless LAN applications through modifications to the MAC layer.
802.11r Approved in 2008	Provide the fast and secure handoffs from one base station to another managed in a seamless manner.
802.11n Approved in 2009	Supporting for MIMO technology and security improvements utilized in the 2.4 GHz or 5 GHz frequency bands and the transmission speed is greater than 100 Mb/s.
802.11p Approved in 2010	For wireless access technology applied on wireless access in vehicular environments (WAVE), defined the architecture of communications system and a series of standardized services.
802.11s Approved in 2011	Defining the wireless mesh network. The wireless devices can interconnect to create a wireless mesh network.

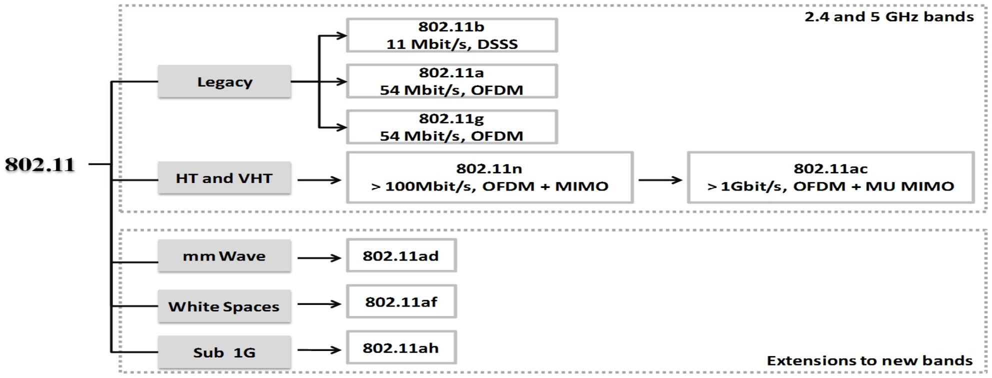

Figure 1. WiFi technology evolution.

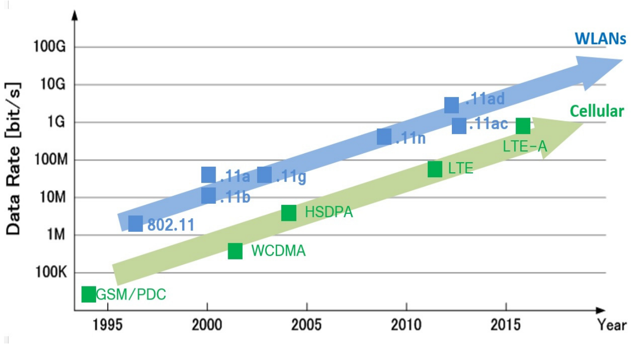

Figure 2. Evolution of wireless communication protocols [1].

B. 802.11ax Project Target and Timeline

The IEEE Standards Association (IEEE-SA) Standards Board approved 802.11ax in March, 2014. The scope of 802.11ax amendment is to define standardized modifications to both the 802.11 PHY and the IEEE 802.11 MAC that enable at least one mode of operation capable of supporting at least four times improvement in the average throughput per station (measured at the MAC data service access point) in a dense deployment scenario, while maintaining or improving the power efficiency per station. It shall enable backward compatibility and coexistence with legacy IEEE 802.11 devices operating in the same band.

Unlike previous amendments where the focus was on improving aggregate throughput, this amendment focuses on improving metrics that reflect user experience. Improvements will be made to support environments such as wireless corporate office, outdoor hotspot, dense residential apartments, and stadiums [2]. Fig. 3 illustrates the possible timeline and progress toward the 802.11ax standard. The study group was initiated in 2013. Submission of draft to the IEEE-SA for initial sponsor ballot is expected in July, 2017. It is anticipated that actual deployment of the standard will take place at the earliest in late 2019 [3].

II. DIFFICULTIES FOR LEGACY 802.11 IN DENSE DEPLOYMENT

As the current IEEE 802.11 WLANs adopting inter-frame space (IFS), backoff window size, and beacon, to effectively control the operation of MAC, vulnerability under dense deployment arises as a common troublesome for users since the backoff parameters of its collision avoidance mechanism are far from the optimal setting in some network configuration conditions. To begin with, carrier sensing multiple access with collision avoidance (CSMA/CA) might incur a high collision probability and the channel utilization could be degraded in dense scenario. This is because it selects a small initial value of backoff window by a naive assumption of a low level of congestion in the system. Second, CSMA/CA might lead to the “fairness problem” because its de-facto contention resolution algorithm, binary exponential backoff (BEB) algorithm, always favors the last successfully transmitted station. For example, considering the network topology shown in Fig. 4, two connections established from station D to station C and from station B to station A respectively. Compare with Station B, Station D will get less chance to access the channel since Station B will “grab” the channel by using a smaller contention window size.

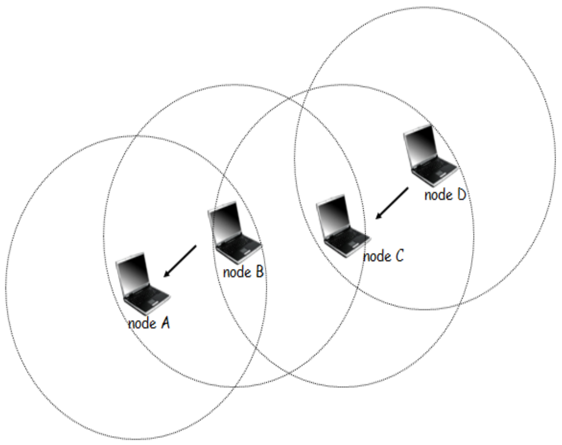

Figure 4. Fairness problem in wireless environments

RTS/CTS mechanism is proposed to solve hidden terminal problem and enhance transferring performance for IEEE 802.11 WLANs. Hidden terminal problem occurs when there is a station in a service set, while trying to detect whether the media is busy, is not aware of the ongoing transmission of another station. However, research demonstrates while RTS/CTS mechanism can only partly overcome hidden node problem, and performance of the network throughput decreases as well. This is because overhead brought by RTS and CTS packages might relatively occupy bandwidth and consequently lower the network throughput. Besides, the RTS/CTS frames might not be able to solve another problem called the exposed terminal problem in which a wireless station that is nearby, but is associated with another access point overhears the exchange and then is signaled to backoff and cease transmitting for the time specified in the RTS. Please note that, according to our study, in general the performance of RTS/CTS mechanism is better than the basic access mode only in very few scenarios, for example, multi-rate environment.

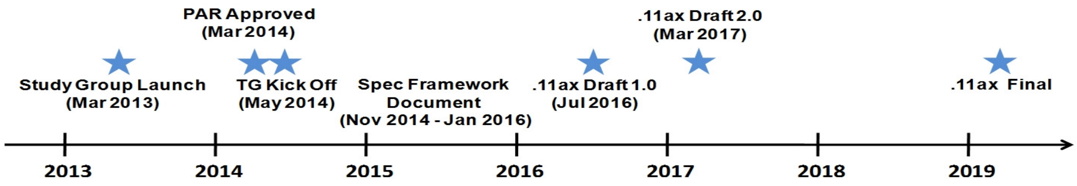

Figure 3. Predicted 802.11ax timeline.

Finally, non-collision frame loss is another key factor diminishing the performance since it does not take into account the occurrence of non-collision losses. Unfortunately, wireless transmission links are noisy and highly unreliable. Path loss, channel noise, fading, and interference may cause significant bit errors. If the sender is unable to distinguish the causes of frame loss, it is difficult to make the correct decision.

In [4], a theoretical upper bound of IEEE 802.11 distributed coordination function DCF on achievable throughput was computed, and in this paper authors also reported that DCF operated very far from the theoretical limit and its performance can be improved by reducing the time spent for negotiating channel access, for example, contention alleviation and collision resolution. In other words, by appropriately tuning the contention window size and backoff algorithm, the DCF scheme can achieve better performance and operate close to the theoretical limit.

Most existing contention window control mechanisms can be classified into two categories, namely semi-dynamic and quasi-dynamic approaches, according to the theory used for contention window controlling. In general, quasi-dynamic approaches tend to achieve better performance than semi-dynamic approaches because they can operate according to the observed actual channel conditions. However, in addition to the difficulties in acquiring sufficient knowledge of the system, these type of approximations tend to be very computationally complex, and subject to significant errors, especially in congested situations. Furthermore, almost all the quasi-dynamic backoff algorithms require the knowledge of the number of contending stations (active stations) which is difficult to predict in the absence of a central controller.

Although in early studies [5] the author analytically derived the optimal contention window size that maximize the WLAN system throughput under saturated condition. However, to perform this tuning, each mobile station must have an exact knowledge of the network status. Besides, this is based on saturation analysis and in the real world the traffic is heterogeneous traffic. Hence, it is difficult to be implemented in WLANs, as a technology opportunity.

III. POSSIBLE TECHNOLOGIES AND CHALLENGES FOR 802.11AX

A. OFDMA PHY and CCA

A good approach to alleviate the intensive contentions and to fully use the channel resource is to divide the whole frequency spectrum into multiple narrow-band sub-channels, and mobile stations adapt different set of sub-channels based on their channel selection strategies and transmit their packets simultaneously. Physically, channel means a frequency band in orthogonal frequency division multiple access (OFDMA) systems since new generation WLAN will base on OFDMA technology. Hence, it is suggested that IEEE 802.11ax MAC should be able to work well with OFDMA technology and fully use the un-contiguous bandwidth.

OFDMA is also known as multiuser OFDM to allow multiple users to share the radio blocks centered at one single carrier frequency [6]. In a given frequency band, there usually exist multiple carrier frequencies and thus multiple sub-carrier-time planes of radio blocks. Via proper radio resource allocation and optimization at scheduler, bandwidth efficient physical layer transmission is enabled, which is adopted in IEEE 802.16e mobile WiMAX and 3GPP Long-Term Evolution (LTE) and LTE-Advanced (LTE-A) cellular systems. The introduction of OFDMA into IEEE 802.11 WLANs enjoys advantages of mature high-efficient PHY and smooth hybrid integration with cellular systems as heterogeneous wireless communication networks. On the other hand, OFDMA PHY creates a new and fundamental challenge in 802.11ax MAC design. The major interaction between MAC and PHY lies in adaptive modulation and coding (AMC) and clear channel assessment (CCA). Legacy IEEE 802.11 PHY actually transmits data through all data sub-carriers of the single carrier frequency at one time, and thus CSMA/CA protocol and its variants can perfectly work. The CCA can also be reliably executed. However, CCA and thus CSMA/CA face new challenges for OFDMA. As an illustration, we can clearly observe that one user occupies a specific carrier frequency does not necessarily imply non-permissible for other users to access the radio blocks at this carrier frequency.

B. DL/UL MU-MIMO

Needless to say, 802.11ax shall likely continue the use of Multi-input Multi-output (MIMO) technology and it shall reference technology based on 802.11ac technology. However, some key changes might be able to boost theoretical data rate to multi-gigabit depending on modulation and coding, channel bandwidth, and MIMO configuration. For example, some usage scenarios in 802.11ax are outdoor, but current 802.11ac numerology, 64 Fast Fourier Transform (FFT) and 0.8us guard interval (GI), cannot support outdoor channel environment since our packet error rate simulation results show severe performance degradation in UMi non-line-of-sight (NLOS) channel. Hence, according to our research results, large delay spread with the outdoor channel environment results in requirement of longer GI, and extending the (Inverse) Discrete Fourier Transform (IDFT/DFT) period is necessary because it can reduce the overhead caused by longer GI.

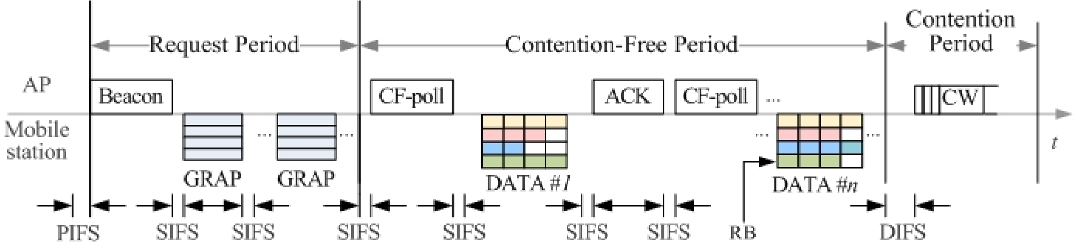

Figure 5. The proposed access scheme for 802.11ax

Although the MIMO technology and associated interference alignment/management technology have been widely studied for cellular systems in Long Term Evolution (LTE) and LTE-A, some further evolution of MIMO and inference technology is still needed further investigations due to lacking of circuit-switching feature and closed loop channel estimation in WLANs. For example, excessive overhead could result from the signaling required by Peer-to-Peer communications for resource allocation and interference management in WLANs, and without careful management, such overhead can decrease spectral efficiency and offset the gain from using Peer-to-Peer communications.

C. *GRAP based MAC*

CSMA has a stable throughput of zero and highly infeasible to multimedia traffic like voice and video that dominates today's Internet traffic. However, random access is a critical function for application scenarios of WLANs, and appears non-replaceable in WLAN MAC design. A compromised design approach might be as the group randomly addressed polling (GRAP) [7], allowing backward compatible to CSMA and transform to centralized polling/reservation in multiple access mechanism. We depict the super-frame structure of GRAP based MAC in Fig. 5. In order to gain control of the medium, the AP performs the function of the coordinator by broadcasting a beacon frame at the beginning of a super-frame after sensing the medium to be idle for a PIFS period, and the AP informs all the stations of the super-frame structure through the beacon message.

The request period is used for mobile stations within the group to compete transmission intent, and the AP will listen to all random numbers at each sub-carriers. After that, the AP coordination of packet transmission by polling and allocates sub-carrier bandwidth to mobile stations. The AP will maintain a list of registered mobile stations and poll them according to the MAC address listed in the polling list. As shown in figure 4, in the GRAP based MAC the AP reserves the radio resource for mobile stations. Using the QoS requirements information specified in GRAP message, the AP coordinates resource allocation for up-link transmission, and notifies it by transmitting CF-poll frame. Each mobile station transmits its packet to the AP on the allocated radio blocks (RBs). Finally, the AP broadcasts an ACK frame and releases the channel resource. Here, a radio block is a minimum allocation unit of the channel resource. It is defined in a two-dimensional plane represented by a frequency domain and a time domain.

Now we explain the way that the proposed scheme compliant stations can coexist with the legacy 802.11 stations. The basic idea behind our method is we save some portion of time allocated to the legacy 802.11 stations in each super-frame. Hence, by time division, legacy 802.11 stations are able to send their packets in contention period, after ensuring that the medium is idle for DIFS duration. Besides, the AP may set the duration field in the beacon message to announce the duration of the time occupied by the request period and contention period for 802.11ax stations. Upon receiving the beacon message, the legacy 802.11 stations will update their NAV and avoid sending their packets in the specified time duration, thereby making the 802.11ax proposed stations to coexist with legacy 802.11 stations in one BSS.

D. *OBSS Management and QoS/QoE support*

To provide a mechanism for the reliable transmission of multicast streams in WLANs and to address the overlapping BSS (OBSS) management, a few years ago, a new task group 802.11aa was created to develop a set of enhancements for robust multimedia streaming. Another recognized problem is related to management frames. According to the current standard, management frames in WLANs are transmitted with the highest priority, and this could interfere with the transmission of multimedia traffic. Hence, another task group 802.11ae was also created to develop flexible prioritization mechanisms for such frames. In 802.11ax, more traffic types will be supported by the new traffic differentiation mechanism in order to reach better QoS/QoE expectations. Each traffic type is characterized by a mandatory set of QoS/QoE parameters, which is tailored to best describe the guarantees required by the applications that the service is designed for. Furthermore, 802.11ax shall focus more on latency for Internet applications, in addition to QoS. To sum up, 802.11ax shall consider both 802.11aa and 802.11ae and have above multiple fold of purpose.

E. *Traffic Offloading and Network Economy*

Due to the proliferation of smart handheld devices and traffic hungry applications in recent year, modern wireless communication systems are facing severe traffic overloads and tremendous need of high bandwidth support. Now mobile operators are compelled to find new ways to significantly boost network capacity, provide better coverage, reduce network congestion, and save transmission energy. To cope with mobile data explosion, upgrading to 4G/5G may be an immediate solution. However, the boom of smart phones and social media services has pushed cellular networks to their limits and it seems users' traffic demand is expected to exceed network capacity in the near future. To offload cellular networks from this extreme data stream demand by users, femtocells seem an alternative because the spectrum can be re-used more frequently over a smaller geographical region. Another alternative is to offload some of the traffic to the WLANs to alleviate the interference and ease congestion, where users use WiFi networks prior to cellular networks whenever they have delay tolerated data to transmit, since WiFi networks are readily available in most homes and are easy to install and manage. However, despite the potential of WiFi offloading in alleviating mobile data explosion, its success largely depends on the economic incentives provided to users and operators to deploy and use delayed offloading.

IV. CONCLUSIONS

Devising a well-performing PHY and MAC protocol for new generation WLANs can be a challenging task, but it is also an interesting area of research. In this paper the need for new generation WLAN protocol is articulated. We also summarize the IEEE 802.11ax standardization activities in progress and discuss the expected features and challenges in the design of PHY and MAC for IEEE 802.11ax amendment. Toward the entire design of new generation WLAN, there also remain many interesting research topics which require further investigation. An analytical model that accurately evaluates the normalized system saturation or un-saturation throughput has not yet been studied. Another research subject is to design a simple but efficient call admission control and packet transmission policy used by the AP to decide whether a network accepts a new connection or not and determine which station gets permission to transmit a packet, which is a very important implement issue, especially in the realm of providing QoS. A cross layer optimization between MAC layer and PHY layer should also be one of the research subjects in the future. Finally, an optimized intelligent collision resolution algorithm for mobile stations to transmit their request to AP in request period needs to be developed as well in the future.

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