Target Wake Time for IEEE 802.11ax based Next Generation WLANs: A Brief Overview

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Abstract

In order to improve the throughput and energy efficiency in dense scenarios, IEEE 802.11ax based next generation Wireless Local Area Networks (WLANs) introduce Orthogonal Frequency Division Multiple Access (OFDMA) based uplink multi-user simultaneous transmission and broadcast Target Wake Time (TWT) mechanism. They provide new resolutions of high efficiency WLANs. To cope with dense deployement, we investigates the following problems: 1) Adaptive resource unit scheduling schemes for hign density WLANs, which improve the channel utilization; 2) Efficient resource allocation algorithms under tranditional power management mechanism, which target to realize low energy consumption and maximization the runtime of the system, and improve the throughput and energy efficiency with dynamic sleep/wake-up scheduling policy; 3) A channel access scheme with TWT scheduling, which is proposed to ensure efficient data transmission for WLANs of high density. This paper gives a brief overview on power save mechanism including TWT for IEEE 802.11 WLANs, and provides reference for channel access control, resource allocation, and power management for efficient application of the new WLAN standard in China.

Keywords

Next Gerneration WLANs; IEEE 802.11ax; Power Save Mode; Target Wake Time (TWT).

1. Introduction

Since the first version of IEEE 802.11 standard in 1997, it has been more than 20 years. Due to its advantages of user mobility, flexible deployment, strong scalability and low maintenance cost, IEEE 802.11 based wireless local area networks (WLANs) have been widely deployed in thousands of households, which affects all aspects of people's lives. According to Cisco white paper [1], it is estimated that 63% of mobile data traffic will be diverted to WLAN by 2021, and the number of public hot spots will increase to 541.6 million. With the explosive growth of mobile data traffic, WLAN deployment will become more intensive than ever before.

However, the performance of conventional WLANs deteriorates sharply in the dense deployment environment. The Institute of Electrical and Electronics Engineers (IEEE) 802.11 Committee established the 11ax Task Group (TGax) in Mar. 2014 to develop the sixth generation of 802.11 standard, namely IEEE 802.11ax, which is postponed to release in Feb. 2021. The new standard of 802.11ax plans to introduce 1024-QAM, Orthogonal Frequency Division Multiple Access (OFDMA), Multiple Input and Multiple Output (MIMO), Spatial Reuse (SR), and so on [2,3], so as to increase the average throughput per user.

To ensure the mobility and portability of WLAN terminals, most terminals use batteries for power supply. The power carried by batteries is often limited. With the continuous enhancement of the terminal function, how to use power efficiently to support the more durable operation of the equipment under the limited power allocation is of great significance. The power save mechanisam has become a research area of great concern for wireless access. Mobile terminal devices, such as smart phones, PADs, and PCs, are integrated with wireless network interface card (WNIC) for wireless transmission. However, the WINCs consume nearly 10% to 50% power of these terminals

[4], which is one of the main power consumption components [5]. About 10% power in portable computers is used for the operation of WNICs, while the handheld type devices account for about 50% of the total power [6]. In wireless data transmission, the interface power consumption is more significant [7].

Hence, a new mode, named sleep mode or doze mode, is proposed to solove the porblem of high power consumption since the first version of IEEE 802.11 standard. In doze mode, terminals are permitted to turn off the wireless transceivers so as to reduce the power consumption of WNICs. The task of the power save mode in IEEE 802.11 standard is to ensure that the wireless transmission to meet the QoS and QoE of the end use, and meanwhile, it can keep the terminals in sleep mode as far as possible, and thus to prolong lifetime of the WLAN.

The next generation WLAN standard, i.e. IEEE 802.11ax, introduces the target wake time (TWT) which is proposed for IEEE 802.11h based networks with large-scale terminals. The TWT of all assocsiated stations (STAs) is handed over to access point (AP), and is considered to be one of the key technologies to achieve collision free and deterministic media access for future WLANs [8]. In order to make full use of sub-channels,the OFDMA based uplink multi-user simultaneous transmission technology and the broadcast TWT is innovatively proposed in the new IEEE 802.11ax standard. AP and STAs negotiate the target beacon transimssion time (TBTT) to determine when to wake up. Then, the dozing STAs wake up at the corresponding TBTT to receive the TWT service period (SP) information specified in the beacon frame broadcasted by the AP. Finally, the STAs completes their data transmission within these periods. After the investigation of related literatures, there are still three main deficiencies in sleep/wake-up scheduling of existing work on TWT.

The first is the low media access efficiency during the TWT SPs. The STAs in doze mode still use the channel resources in the TWT SP with the competition mechanism based on fast backoff. However, CSMA / CA is a media access protocol of high power consumption and low efficiency due to the backoff mechanism. In WLANs, the AP can collect the upload requirements of the STAs by designing a polling medthod, and then the AP schedules the resources uniformly. In this way, the AP needs to take into account the global information. The overall polling might cause a longer delay and low energy efficiency. Hence, the deterministic access mechanism becomes an optional scheme for WLANs with TWT scheduling. This is because the STAs use the sub-channels with a plan. We need to design a reasonable and efficient media access control process for the shared SPs according to the network density, the number of sub-channels, and the transmission requirements.

The second is that it is difficult to schedule the TWTs in dense deployment environments. Given TWT SP and medium access control protocol, how to schedule the wake-up time of STAs has an important impact on network performance. An improper scheduling will result in the waste of resources because of the excessive competition during TWT SPs. The IEEE 802.11ax standard introduces OFDMA technology to cope with dense environment. Sleep scheduling has to consider the characteristics of multi-channels which is of high complexity. In order to make better use of multi-channels, we need to give a reasonable sleep scheduling strategy for different channel access and different STA density. In addition, sleep scheduling is closely related to the number of STAs. In the dense deployment environment with limited resources, it is difficult to schedule quickly, efficiently, and reasonably. However, in the next generation WLAN, it is not clarified how to schedule the wake-up time under the broadcast TWT. Since the IEEE 802.11ax standard is under study and has not been finalized. At present, there are few references about sleep scheduling based on the improvement of related technologies. Therefore, we have to optimize the design of the TWT scheduling, comprehensively considering various technical improvements to maximize the throughput of the whole network.

Finally, it is difficult to coordinate the wake-up time in mutiple overlapping WLANs. With the increase of internet access demand, AP deployment also becomes intensive, and there often exist multiple overlapping WLANs. The data transmission in the overlapping area directly affects the data transmission procedure in adjacent WLANs, and might decreases the overall throughput of the network. How to alleviate the competition and interference between overlapping WLANs, and improve the overall network throughput has become a hot research topic. The related literature points out that the grouping mechanism will effectively improve the network performance in the strong competitive environment. One feasible solution is to let the STAs in different coverages turn off the WNICs in time-sharing to reduce the competition. The other is to let the wake-up STAs in the same coverage area use orthogonal subchannels to eliminate interference and realize the rational utilization of the media. Therefore, we have to combine the TWT scheduling and subchannel resource management to study the cooperative scheduling problem under the coexistence of multiple APs, and finally achieve the efficient coexistence of multiple WLANs.

The increasing demand for internet access, large-scale terminals and the intensive deployment of APs are one of the important reasons for the redevelopment of IEEE 802.11 standard. The above changes, new problems, and new environments put forward challenging requirements for the application and deployment of IEEE 802.11ax based WLANs. Combining with different network situations, we focus on how to improve the corresponding energy efficiency while ensuring the quality of service (QoS) and user experience (QoE) of terminals. The most import aspects of research include: 1) Research on wake-up time scheduling strategy under the dense deployment environment; 2) Research on the cooperative TWT scheduling in overlapping WLANs.

In this paper, we briefly overview the research state and future development tendency of the power save mode in the WLANs, and give some suggestions on the future work about efficien TWT scheduling explicitly considers the dynamic characteristics of mobile terminals and the new media access procedure in the coming verstion of IEEE 802.11 standard.

2. Research State and Future Development Tendency of TWT

In order to obtain a faster, more stable, and more energy efficient WLANs, IEEE 802.11ax standard is expected to improve the end-user experience and achieve the goal of intensive deployment. Many existing literatures use stochastic process, Markov decision process, and other theories or methods to study the power management scheme for the next generation WLANs. A high-efficient sleep scheduling strategy plays an important role to improve the operation life of terminals, and is very practical to solve the power shortage.

In recent years, relevant papers have been published at high-level international academic conferences, such as MobiCOM, MobiSYS, INFOCOM, SenSYS, etc., showing an increasing trend. In this part, we will introduce an extensive and in-depth study and analysis on power save mode, and report the research status and future development from the following aspects.

2.1 Medium access control for WLANs of high density

Collision is the main reason for the throughput decline in traditional WLAN. Carrier sense multiple access with collision avoidance (CSMA/CA) used in traditional WLAN adopts carrier sensing (CS), four times handshake (RTS/CTS), binary exponential back-off (BEB), and etc.. The BEB mechanism alleviates the channel contention to a certain extent by randomly distributing each STA to participate in competition for resources in different time periods. However, the collision probability of these mechanisms increases rapidly in high-density environment due to over protection. As a result, throughput drops sharply or even deteriorates to zero, and energy efficiency decreases.

To slove above problems, Y. Kim et al. [9] proposed a new MAC protocol for dense environment, called renewable access protocol (RAP). Different from the traditional backoff mechanism, RAP selects the backoff count value from the fixed distribution, and updates the backoff count value at the end of each transmission. Besides, Y. Kim et al. derived the optimal access probability under RAP, and realized the optimal network throughput performance with different number of groups [10]. L. Barretta et al. [11] analyzed throughput and delay of slotted ALOHA protocol combined with exponential backoff through Markov model, and pointed out the optimal setting of index value. Y. Le et al. [12] achieved fair sharing of channel occupancy time between STAs by adjusting the size of contention window, and maximized throughput under the constraint of time fairness. M. Karaca et al.

[13] revised the backoff freezing process, and proposed to determine whether to execute the decline of backoff count value under the condition of conforming to the decline of backoff count value by a certain probability. It was proved that the scheme achieves higher throughput in dense environment.

In addition, L. Sanabria Russo et al. [14] proposed Carrier Sense Multiple Access with Enhanced Collision Avoidance (CSMA/ECA). By applying hysteresis phenomenon, introducing fair compensation mechanism, and adding reset module, a contention free channel access scheme suitable for dense environment was proposed, which achieves higher throughput under the condition of ensuring certain fairness. J. Lee [15] proposed a new hybrid MAC (HMAC) strategy for the next generation WLANs by combining centralized access control and distributed random access. The performance evaluation results show that the HMAC scheme significantly improves the channel utilization [16]. M. Karaca et al. [17] proposed a centralized scheduling scheme. With the help of the maximum weight strategy, it not only improves the throughput, but also reduces the delay in the interference situation. M. Zulfiker et al. [18] proposed a MAC protocol under centralized control of the AP to solve the problem of low utilization of uplink transmission resources, which can carry out multi-user transmission in the uplink. The protocol improves the throughput by 150% and reduces the backoff time of all traffic categories by 50%. The above research ideas coincide with the formulation of new proposed IEEE 802.11ax standard.

2.2 Power management schemes in IEEE 802.11 based WLANs

Due to the scarcity of power, green communication has always attracted much attention. As the terminals of the network, they are often powered by batteries to ensure mobility and portability. However, the power storage of these batteries is very limited. The strategy of how to use the power efficiently and effectively will prolong the operation life of the STAs in the WLAN has become a research hotspot.

To solve the problem of high power consumption in the WNICs, IEEE 802.11 proposes sleep mode, which allows idle terminals to turn off transceivers and enter into sleep state. Hence, the power consumption of WNICs decreases. The task of power management mechanism is to ensure that the STAs meets the quality of service (QoS) and QoE during the wireless communication procedure. At the same time, the idle STA can be put into sleep state by turning off the transceiver, so as to prolong the sleep duration and achieve power saving.

Since the sleep state of the WNICs consumes the minimal power, it is called power save mode (PSM). During the sleeping state, the transceivers of the STAs is off, and the STAs cannot receive data normally. Data sent to sleeping STAs will be temporarily stored in the buffer of the other STAs. The data transfered to the sleepling STAs in an infrastructure basic service set (IBSS) is temporarily buffered in the AP. When the STA wakes up, the WNIC is turned on, and the packet receiving process starts. In contrast, the WNICs in active state consumes relatively high power. The principle of the conventional power management scheme in IEEE 802.11 based WLANs is to optimize the scheduling of the switch between these two states for WNICs.

The STAs in PSM usually stays in sleep state, but sometimes it enters active state to receive or send data frames. The STA wakes up every multiple of beacon interval (i.e. Listen Interval) to receive beacon frame from AP. According to IEEE 802.11 standard, beacon interval is the management parameter of AP, which is 100 ms in default. When the traffic indicator map (TIM) in the beacon frame received by the STA indicates that there are data packets dilivered to itself in the buffer, the STA remains active to receive the frames temporarily stored in the AP buffer.

Obviously, the PSM mode can save power by timely closing the WNIC and entering into sleep state, so as to ensure the operation of the STA operate a longer time. The longer the sleep duration, the lower frequency of periodic wake-up, the shorter duration staying in active mode, and the less power consumed [19]. The STA achieves minimal power consumption by minimizing the duration being activ. However, ,the probability of active mode is getting much more higher when in the dense environment. The intense channel competition leads to collision, which makes the STA have to stay in an active state for a longer time. In order to solve the problem of collision, researchers have studied the traditional IEEE 802.11 power management scheme from different aspects, and proposed many feasible improved schemes, such as adaptive LI, dynamically adjusting LI under different constraints, modifying TIM information, and etc..

In [20], a smart adaptive power management scheme is proposed. The priority of each application is marked by machine learning method, which allows high priority applications to switch to "active" mode to optimize network performance, while low priority applications will be in sleep state to obtain higher energy efficiency. A. Saeed and M. kolberg [21] proposed a network traffic classification method combined with machine learning. They use the classification results to optimize LI settings so that LI can dynamically adjust according to network traffic. C. Gan and Y. Lin [22] proposed a scheme to adjust the wake-up time of different STAs by the first target beacon transmission time so as to ensure the minimum number of wake-up STAs in each beacon slot, and achieve higher throughput by reducing competition and collision.

R. P. Liu et al. [23] proposed a offset LI scheme (OLI) for M2M networks, which reduces power consumption by evenly distributing the number of wake-up STAs in each beacon slot. In order to enable all STAs in AD hoc network to wake up at the same time to receive common broadcast information, Y. Kuo and C. Chen [24] used the Chinese Remainder Theorem to adjust LI to ensure efficient transmission of broadcast information even under the condition of clock offset. In the scheme, when the clock drift occurs, all STAs can be waken up at the same time to receive multicast messages.

In addition, the researchers have proposed many power saving schemes under different constraints [5]. X. Chen, S.Jin, and D. qiao[25] proposed an adaptive LI scheme using intelligent buffer strategy. The scheme calculates the transmission time of the next target beacon by evaluating the channel conditions. When the channel conditions are with better quality, the STAs is waken up and the data is received at a higher rate, so as to effectively utilize the power. The scheme is very suitable for the delay insensitive scenarios. A power management scheme based on timer is proposed in the literature [26-29]. Under the condition of limited storage space, the number of STAs that can enter the doze state can be optimized by adding idle timer and doze timer in the STAs to ensure better throughput and delay. When STAs in doze mode, packets sent to PSM STAs are staged by AP. The longer the STA sleeps, the more data that the AP buffer stores sent to the STA. Under the condition of limited AP buffer size, PSM mechanism has the possibility of AP buffer overflow and packet loss. Therefore, Zhu et al. also study power saving strategies from the view of buffer size limitation, and studies to accommodate as many power saving STAs as possible under the buffer constraints.

The above schemes mainly focus on the TBTTs and LIs, while P. Si et al. [30] discussed the different settings of TIM to save power. TIM indicates the data status of AP buffer. They proposed that AP should determine the number of STAs to be active in the next TBTT according to the tramsimission demands, and then determine how to set the TIM in the beacon frame. In short, the scheme proposed by P. Si et al. is to improve throughput and reduce power consumption by adjusting the TIM indicator.

Most of the researches on PSM focuse on the solution of minimizing the wake-up time and maximizing the sleep duration, but there are also studies on the power consumption with different channel access mechanisms. J. Snow et al. [31] realized the channel access scheme of time division multiple access (TDMA) by scheduling channel access, and R. Palacios [32] realized enhanced distribution coordination function (DCF) through bidirectional transmission, and improved MAC layer protocol to achieve higher performance. In addition, the researchers also study the power save mechanisms combined with physical layer technology, such as adjusting transmission power or adaptive sampling rate. W. Wang et al. [33] reduced the sampling frequency of equipment to reduce power consumption without considering channel conditions. X. Zhang and K. G. Shi [34] proposed the E-MiLi scheme, which reduces the overall power consumption by reducing the power consumption when idle listening. L. Feng and J. Yang [35] proposed the optimal listenning interval under delay constraint for channel access strategy of point coordination function (PCF).

The above research has carried on the extensive discussion to the power save schemes in different application scenarios, and effectively promoted the development of WLAN power management scheme based on the traditional IEEE 802.11 standard.

2.3 Power management schemes and research progress in next generation WLANs

Although IEEE 802.11 standards defines power management schemes, it still faces great challenges in complex and changeable applications with diverse quality of service requirements. Therefore, different versions of IEEE 802.11 standards propose different power management strategies to adapt to different application scenarios as shown in Table I.

Tabel I Power Management Schemes in IEEE 802.11 standards

Year	Version	Bandwidth	Power Management Schemes
1997	IEEE 802.11	2.4 GHz	Power Save Mode (PSM)
2004	IEEE 802.11e	5 GHz	Automatic Power Save Delivery (APSD)
2009	IEEE 802.11n	2.4 GHz 5 GHz	Power Save Multi-poll (PSMP) Spatial Multiplexing Power Save (SMPS)
2011	IEEE 802.11v	2.4 GHz 5G Hz	Wireless Network Management Sleep Mode (WNM-Sleep Mode)
2017	IEEE 802.11ah	Sub 1 GHz	Target Wake Time (TWT)
2019	IEEE 802.11ax	2.4 GHz 5 GHz	Cascade Indication Opportunistic Power Save (OPS) Intra-PPDU Power Save Operation Mode Indication (OMI)

Take IEEE 802.11ah standard for example, it works in the license free frequency band of 1GHz, and provides longer transmission distance for large-scale sensor networks. In order to make the terminal nodes to save more powe, it is necessary to turn off the transceiver module as much as possible and then enter into sleep state. The nodes only wake up when the packets are sent or received. IEEE 802.11ah standards employ TWT, which allows AP to manage the wake-up time of STAs so that different STAs can wake up in different time periods. Hence, it will reduce competition, improve the efficiency of the system, and greatly reduce the power consumption of the STAs.

The situation of energy scarcity has not changed, and power saving is also one of the key issues in the next generation WLANs. The new standard, i.e. IEEE 802.11ax [36], intends to introduce the above TWT which is proposed in IEEE 802.11ah standard [37]. The TWT determines the sleep period through negotiation, which alleviates collision and interference in time dimension. At the same time, IEEE 802.11ax draft 3.0 porposes the new mechanism of broadcast TWT that combines with the new characteristics of uplink multi-user transmission (MU). In [8], it shows that the broadcast TWT has higher throughput and lower power consumption.

The negotiation process of establishing broadcast TWT protocol in IEEE 802.11ax based WLANs is divided into two phases. In the first phase, the STA negotiates with AP to determine the first TBTTs and listening intervals (LIs). In the second phase, the STA wakes up at the corresponding TBTT, receives the TWT service period (SP) information contained in the beacon frame, and wakes up at the corresponding TWT SP start time to diliver packets. The broadcast TWT takes TBTT scheduling as the lead, and receives the broadcast TWT service information by controlling the beacon frame of the STAs.

When a STA needs to save power, it sends the TWT request frame with the LI parameter to the AP. After receiving the frame, the AP sends the TWT response frame containing information about whether it can enter into the sleep state or not, the first TBTT and LI to the TWT requesting STA. When the STA receives the response frame, it enters into sleep state until the first TBTT time comes, if there is no necessary condition to keep it active. According to the broadcast TWT information element, the STA chooses to participate in or modify its TWT settings, and wakes up to transmit data during the specified TWT SP. During the TWT SP, all the active STAs use UORA procedure for data transmission.

The research and development of IEEE 802.11ax standard pays attention to the global view of AP. The TWT uses the global view of AP to coordinate the sleep time of all terminal STA to improve the overall network efficiency. It is a key step for WLAN to achieve deterministic access in the future [8]. It is pointed out that the TWT combined with MU capability has higher throughput and lower power consumption. However, the IEEE 802.11ax 3.0 draft does not specify the scheduling schemes of TBTT and the scheduling of TWT SP. Instead, it is implemented by various wireless network interface hardware manufacturers.

At present, IEEE 802.11ax standard has not been published, and only a few studies are concerned with TWT. We lack of TBTT scheduling strategy suitable for broadcast TWT scheduling with MU capability. Although the multi-user data transmission scheme is proposed and analyzed in reference [38], the scheduling method of TBTT is not mentioned.

Combining with the new characteristics of multi-user transmission, Y. Hang et al. [39] proposed an power saving scheme for random access in IEEE 802.11ax WLANs. For ultra dense scenarios, J. Bai et al. [40] proposed an adaptive grouping algorithm for MU-OFDMA mechanism. D. Bankov et al. [41] studied the clock drift in the uplink transmission procedure with TWT in IEEE 802.11ax/ah WLANs, and shew that trigger based transmission process effectively reduce the power consumption. In addition, M. nurchis and B. bellata [8] analyzed the broadcast TWT in IEEE 802.11ax based WLANs, and proved that the TWT with MU capability increases the throughput by 10 times compared with the traditional power saving mechanism, and only a small amount of communication overhead is introduced.

The research on TWT scheduling in IEEE 802.11ax has just started, and the research on traditional PSM mechanism [4,42] is also under continuous development. G. Naik et al. [43] and T. Uwai et al. [44] analyzed the performance of UORA channel access procedure in IEEE 802.11ax. The model used in [43, 44] are developed from the Markov chain [45] proposed by Bianchi. Then, they derived the throughput formula from the model. From another point of view, it confirms that the number of active STA at the same time greatly affects the overall throughput and energy efficiency during TWT service periods which employs UORA. Therefore, the unbalanced number of active STAs may inevitably lead to excessive competition in part of the beacon frame slot and waste of resources in part of the other time slot, resulting in performance degradation.

As a result, we need to learn from the key ideas of traditional power management schemes, and combine them with the new features of IEEE 802.11ax, such as UORA procedure, broadcast TWT or other technologies. To save power, we have to focus on broadcast TWT by controlling the active periods of each STA, and propose suitable TWT scheduling strategy for dense deployement.

3. Conclusion

Above research involves the WLAN medium access control, power saving, and power management solutions. However, the existing discoveries do not consider the new features of the IEEE 802.11ax [46] based next generation WLANs, such as the MU-OFDMA and the broadcast TWT. Therefore, we further discuss the following four issues. 1) The original power management schemes do not consider the characteristics of multi-channels, nor can it reflect the advantages of the next generation WLANs, which leads to the waste of multi-channel resources; 2) The existing research has not put forward the adaptive sleep scheduling strategy under different network density combined with the new mechanism; 3) The integration of new technologies and the new mechanism of TWT will provide a new perspective for energy efficient channel access control of TWT service period in dense environment; 4) The next generation WLAN is designed for dense deployment, in which the multiple APs are overlapped. Multiple homogeneous or heterogeneous WLANs coexist, which brings new challenges to the research of TWT sleep time scheduling.

Facing the new environments and characteristics of high density, we combine the new technologies in the next generation WLAN standard to study the dynamic sleep/wake-up scheduling mechanism in multiple overlapped basic service set to achieve higher energy efficiency.

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