



## Review

## A survey of energy efficient MAC protocols for IEEE 802.11 WLAN

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## ABSTRACT

In recent years, IEEE 802.11 wireless local area networks (WLANs) have been widely deployed, and more and more mobile devices have built-in WLAN interfaces. However, WLAN employs the carrier sense multiple access with collision avoidance (CSMA/CA) medium access control (MAC) protocol, which consumes a significant portion of the energy resources of a mobile device. Hence, minimizing the energy consumption of the WLAN interface in mobile devices has recently attracted considerable interest in both academia and industry. This article provides a survey and an experimental study of the energy consumption issues and energy-efficient technologies of the MAC protocol in IEEE 802.11 WLAN.

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## 1. Introduction

IEEE 802.11 wireless local area networks (WLANs) have been widely deployed in public and private areas in recent years. Meanwhile, more and more portable and mobile devices, such as mobile phones and personal digital assistants (PDAs), are equipped with WLAN interfaces, allowing users to access broadband mobile Internet applications and services via WLANs [1]. Unfortunately, WLAN employs a contention-based medium access control (MAC) protocol, called carrier sense multiple access with collision avoidance (CSMA/CA), which is an energy-consuming protocol. Table 1 shows the power consumption of two mobile devices and their WLAN interfaces, indicating that a WLAN interface consumes a significant portion of the energy resources of a mobile device, not only during the active state, but also the idle state [2,3]. Therefore, minimizing the energy consumption of a WLAN interface is an important design issue for mobile devices [4].

The energy consumption (in Joules) of a WLAN interface is determined by the power (in Watts) consumed by a WLAN interface in the transmitting, receiving, or doze states, and how long (in hours) the WLAN interface operates in these states. Solutions either reduce the power consumption of a WLAN interface or minimize the time that the WLAN interface operates in power-consuming states such as receiving and transmitting. Previous studies propose hardware approaches to reduce the power consumption of a WLAN interface, such as separating the voltage

and clock domains of a WLAN system-on-chip (SoC) for better power management, using low-power baseband algorithms, and using low-power circuits. On the other hand, MAC-layer solutions minimize the period that a WLAN interface stays awake. This article summarizes the energy consumption issues of IEEE 802.11 WLAN [5] in the infrastructure mode and MAC-layer technologies for improving energy efficiency.

The rest of this article is organized as follows. Section 2 presents the energy consumption of a WLAN interface employing the distributed coordination function (DCF), point coordination function (PCF), power saving mode (PSM), enhanced distributed channel access (EDCA), hybrid coordination function (HCF) controlled channel access (HCCA) mechanisms, and power saving enhancements in the latest IEEE 802.11 standards and Wi-Fi certifications. Section 3 discusses low-power MAC-layer technologies, and Section 4 further investigates cross-layer designs to reduce the energy consumption of the WLAN MAC for delivering TCP, web, and voice packets. Section 5 presents a measurement platform and an experimental study of the energy consumption of WLAN. Finally, Section 6 offers conclusions.

## 2. Energy consumption in WLAN MAC

The IEEE 802.11 standard specifies that a station (STA) can operate either in active mode or power-saving mode (PSM) [5]. In the active mode, an STA must stay awake to listen to the WLAN channel, and receive and transmit packets. Depending on its configuration, an access point (AP) may announce a contention free period (CFP) through beacon frames. During a CFP, all STAs must access the WLAN channel using a contention free mechanism called the point coordination function (PCF). After the CFP, the AP and STAs

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**Table 1**  
The power consumption of mobile devices and their WLAN interfaces.

Smart phone (Intel PXA 255@200Mhz)		
Power consumption	Idle state (power saving state)	Active state (packet receiving state)
External Wi-Fi (MediaTek MT5911)	10 mW	424 mW
Total system	58 mW	1612 mW
Percentage of the power consumed by Wi-Fi (%)	17.24	26.30
PDA (Intel PXA 270@520Mhz)		
Build-in Wi-Fi	52 mW	766 mW
Total system	172 mW	2211 mW
Percentage of the power consumed by Wi-Fi (%)	30.23	34.60

enter a contention period (CP), employing the distributed coordination function (DCF) for the channel access. On the other hand, IEEE 802.11 defines the PSM as an STA that is not transmitting or receiving packets, and can therefore sleep. During the sleep period, called the doze state, the STA does not listen to the WLAN channel, and can turn off most of the hardware components of a WLAN interface. This significantly reduces energy consumption. This section describes the energy consumption of an STA applying the DCF, PCF, PSM, EDCA, and HCCA access protocols.

2.1. Distributed coordination function (DCF)

In the CSMA system, carrier access is based on contention. For the DCF access, an STA that has a packet to send needs to perform a virtual and physical carrier sense before transmitting the packet. The virtual carrier sense is based on the network allocation vector (NAV) in the MAC header indicating the time period that the MAC frame will occupy the WLAN channel. When an STA see the NAV in a frame, it cannot send any packets. The physical carrier sense, on the other hand, senses the WLAN channel physically to see if there is any activity in the WLAN channel. If the NAV expires and there is no packet transmission, the STA can send a packet. When the STA has a packet to send but notices a packet transmission in the WLAN

channel through either the virtual or physical carrier sense, contention occurs and the STA must wait for a back-off period, called a back-off counter, before transmitting its packet. The back-off counter is randomly selected between the minimal contention window size (CW<sub>min</sub>) and the maximal contention window size (CW<sub>max</sub>). After the NAV expires, the STA waits for a short period of time, called DCF inter-frame space (DIFS), and then counts down the back-off counter. The STA must listen to the WLAN channel throughout the back-off period. If the STA detects any packet transmission during the contention period, it stops counting down the counter. Once the back-off counter reaches zero, the STA can transmit its packet. If the packet transmission fails due to channel error or a collision, retransmission is necessary. In this case, the STA generates another back-off counter and attempts to transmit the packet again. Unlike the first transmission attempt, the maximal contention window size doubles due to the packet collision. Since the WLAN applies the CSMA mechanism, an STA in active mode must stay awake to listen to the WLAN channel. Even during the back-off, inter frame space (IFS), and NAV periods, the STA must consume the receiving state power, say  $P_{rx}$ , to monitor incoming packets. When transmitting MAC frames, the STA is in the transmitting state and consumes  $P_{tx}$  power. The power consumption of a WLAN interface in the transmitting state is higher than that in the receiving state. This is because whenever an STA transmits a packet, it must amplify the signal so that the packet can be received by the AP, which may be far away from the STA.

The CSMA protocol is insufficient for handling all medium access problems in a wireless channel. A typical problem is called the hidden node problem. For example, STA B is situated between STA A and STA C, but STA A and STA C cannot hear each other. Although STA A and STA C can send MAC frames to STA B simultaneously without collisions from their own perspectives, the MAC frames collide on STA B. Therefore, the WLAN must further add collision avoidance (CA) mechanisms to resolve this problem. In this case, STA A and STA C must send a short message, called request-to-send (RTS), to STA B before transmitting data packets. After STA B sends a clear-to-send (CTS) message to STA A or STA C, the data packet from STA A or STA C can be delivered to STA B. This mechanism avoids the collision of data frames. Fig. 1 illustrates

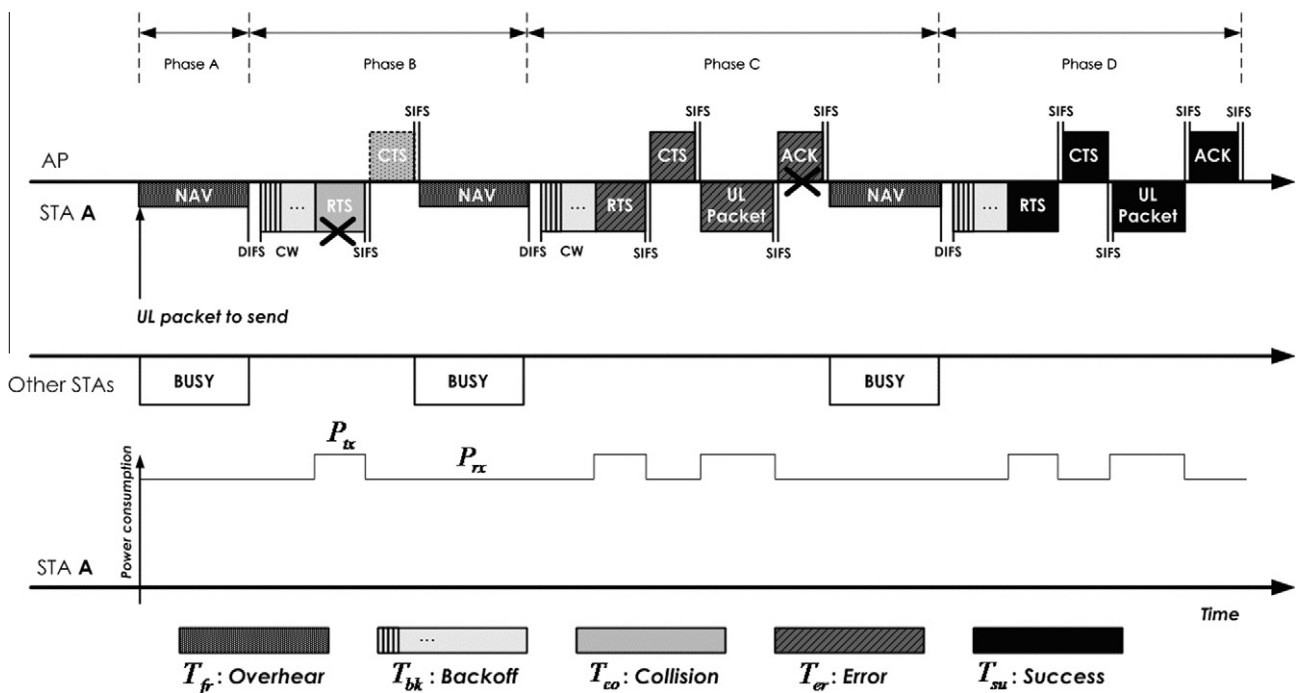


Fig. 1. DCF access and its power consumption.

the operations of the CSMA/CA mechanism based on the distributed coordination function of the WLAN. For more detailed information on the CSMA/CA protocol, readers may refer [6].

Fig. 1 provides an example of a DCF access and its power consumption. This figure contains three parts. The top part of the figure shows the MAC frame exchanges between the AP and an STA which we observed, say STA A. The middle part of the figure depicts the MAC activities for other STAs. The bottom part of the figure shows the power consumption of STA A. Yin et al. [7] categorized packet transmission into five periods during a DCF access. As shown in Fig. 1, the periods for overhearing the transmissions between other STAs and the AP are  $T_{fr}$ . The waiting back-off period is  $T_{bk}$ , while  $T_{co}$ ,  $T_{er}$ , and  $T_{su}$  denote the periods for transmitting a packet which is lost due to a collision, for transmitting a packet which is lost due to an error, and for transmitting a packet which is successfully delivered, respectively.

Another two configurable parameters for WLAN accesses are the fragmentation threshold and RTS/CTS threshold. The MAC fragmentation mechanism divides a MAC frame into several smaller sub-frames and transmits them one by one. If a sub-frame is lost, retransmission is applied at the sub-frame level, but not the entire MAC frame. This mechanism introduces more MAC overheads, such as inter-frame spaces (IFSs) and acknowledgments, but its sub-frame loss penalty is not as high as a MAC frame loss. This fragmentation approach is useful when the channel quality is not good and frames are frequently lost. The STA can set a fragmentation threshold. If the size of a MAC frame is larger than the threshold, the fragmentation mechanism is applied. Otherwise, the MAC frame is not fragmented. The RTS/CTS threshold is another configuration parameter for WLAN MAC transmission. As mentioned above, the RTS/CTS mechanism tries to resolve the hidden node problem. If the size of a MAC frame is larger than the RTS/CTS threshold, the RTS/CTS mechanism is applied to transmit the MAC frame. That is, an RTS/CTS handshake which also introduces some overheads is required before transmitting a MAC frame.

In the example shown in Fig. 1, the RTS/CTS mechanism is activated. During Phase A, STA A has an uplink packet to send but the channel is occupied by another STA. Therefore, STA A must stay awake and wait to send its packet. After the STA releases the WLAN channel, STA A starts to count down its back-off counter. During Phase B, STA A transmits an RTS frame and waits for the CTS frame after the contention window. Unfortunately, the RTS is lost due to a channel collision. In this case, STA A does not receive the CTS frame and must resend the RTS frame. During Phase C, STA A successfully transmits the RTS and receives the CTS frame. STA A then sends the uplink packet but does not receive the acknowledgment frame. Since the acknowledgment frame is lost due to channel error, STA A must send the packet again. During Phase D, the RTS/CTS, uplink packet, and acknowledgment are successfully sent or received. During the entire DCF access, STA A consumes  $P_{tx}$  power while it sends the packet. Otherwise, the STA must consume  $P_{rx}$  power for listening to, or receiving the packets.

The power consumption of a WLAN interface for transmitting a packet using the DCF can be derived following the description above. For more detail mathematical models of the power consumption of the WLAN DCF access, readers can refer to [7–9].

## 2.2. Point coordination function (PCF)

In a PCF access, an AP initiates a CFP by broadcasting a beacon frame. The AP serves as a point coordinator (PC) to poll the STAs. Only an STA that is polled by the AP can send or receive a packet. If an STA which is polled by the AP has no packet to transmit, the STA acknowledges the AP by sending a *Null-Data + CF-ACK* frame. If the STA has a packet to send, it transmits the packet. During the entire CFP, the STA must stay awake to listen to the *CF-Poll* frames

from the AP (PC). The power consumption models for the DCF accesses presented in [7–9] can be used to model the energy consumption of a PCF access.

Fig. 2 illustrates a PCF access and its power consumption. During Phase A, STA A has an uplink packet to send, but it must wait for the AP polls. During Phase B, the AP polls STA A, but the uplink packet is lost due to a channel error. Finally, STA A is again polled by the AP and successfully sends its packet. Unlike a DCF access, the PCF access does not have a back-off period or collision period since all channel accesses are coordinated by the AP (PC).

PCF is an optional access method in the IEEE 802.11 specification and Wi-Fi Alliance does not mandate the implementation of the PCF on WLAN APs and STAs. Therefore, a very limited number of commercial APs and WLAN interface cards support this functionality.

## 2.3. Power saving mode (PSM)

According to the IEEE 802.11 specification, an AP broadcasts a beacon frame for every beacon interval. If an STA does not have any packets to send or receive, the STA notifies the AP with a preferred listening interval and switches to the PSM. The beacon interval length, say 100 ms, is a management parameter for an AP, and the listening interval must be a multiple of this beacon interval [10]. In the PSM, the STA stays in the doze state and only wakes up to listen to beacon frames at each listening interval. If the AP receives a packet for the STA but the STA is sleeping, the AP must buffer the packet. The AP then notifies the STA by embedding traffic-indicator-map (TIM) information in the beacon frames. When the STA wakes up and receives a TIM beacon frame, it sends *PS-Poll* frames to the AP to retrieve the buffered packet. Therefore, packet buffered on the AP should be stored for at least one listening interval. If the STA cannot retrieve the packet within one listening interval, the packet might be dropped by the AP.

Fig. 3 provides an example of an STA accessing the WLAN channel in the PSM. During the listen interval, STA A turns off most of its hardware components, remains in the doze state, and consumes much less power than the receiving or transmitting states. If the AP receives packets for STA A, it notifies STA A using a TIM beacon frame. During Phase A, STA A wakes up and listens to the beacon. The beacon indicates a packet buffered on the AP. The STA contends for the channel and sends *PS-Poll* frames to retrieve the buffered packet from the AP. In the example shown in Fig. 3, STA A does not gain access to the channel in Phase A, and must continue listening to the channel and waiting. In Phase B, STA A sends the *PS-Poll* frame, but the *PS-Poll* frame collides with other frames. In Phase C, STA A tries again, but the downlink packet is received with error. Finally, STA A successfully receives the downlink packet in Phase D and then goes to sleep. Unlike the DCF and PCF schemes, this approach allows the STA to go to sleep before the next listen interval. Note that an STA must send *PS-Poll* frames to retrieve the downlink packet for each downlink packet access. In this paper, we assume that the AP can immediately send the buffered packet to the STA. Another possible implementation is that the AP first acknowledges the *PS-Poll* frame, and sends the buffered packet to the STA later. Then, the contention is required to transmit the buffered packet.

Lei and Nilsson [11] presented analytical models of the mean packet delay and percentage of time an STA remains in the doze state for the PSM. Based on their models, an STA could determine a suitable listening interval that satisfies the response time requirement, and the power consumption of a PSM STA can be also derived. He et al. [56] further analyzed the power consumption of WLAN PSM with background traffics.

The WLAN PSM operations in the infrastructure mode and ad hoc mode, or called Independent Basic Service Set (IBSS), are quite

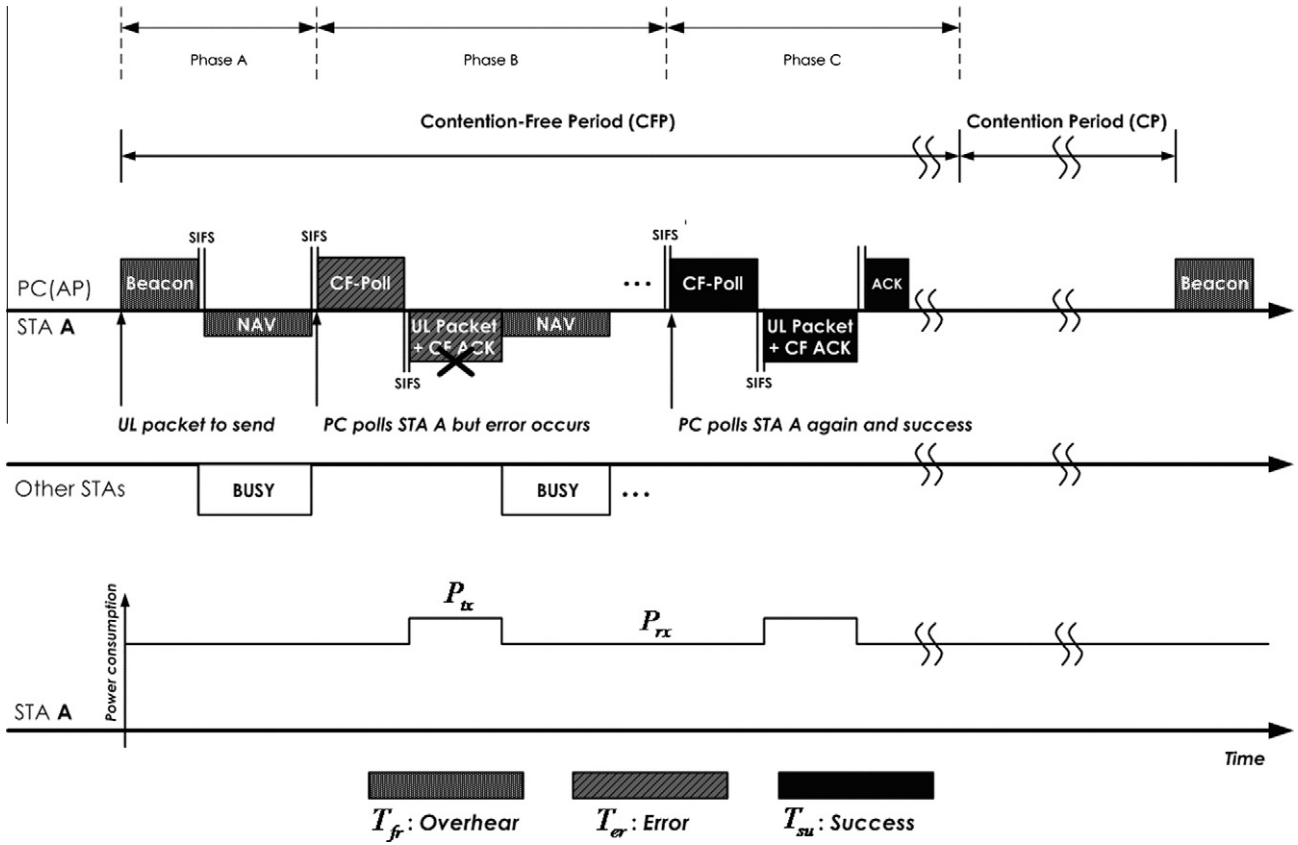


Fig. 2. PCF access and its energy consumption.

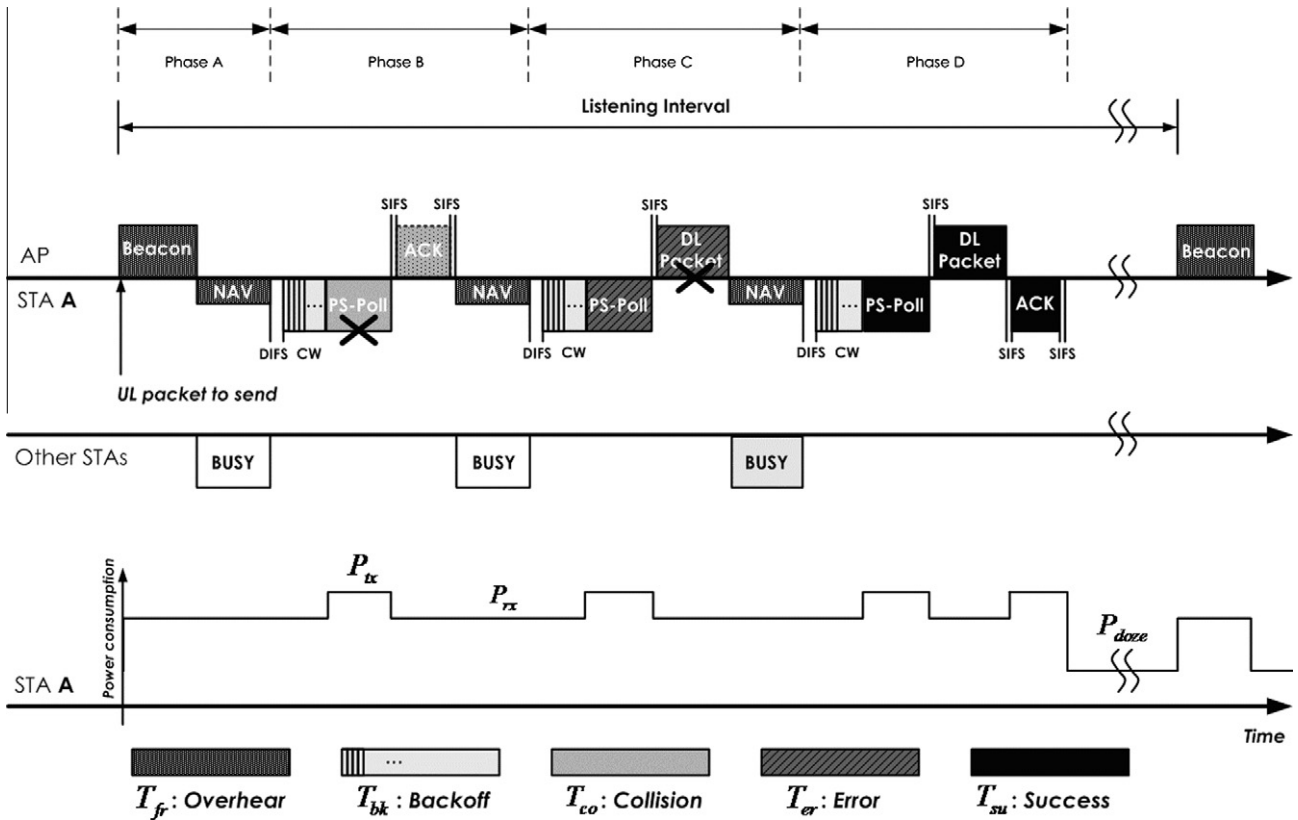


Fig. 3. PSM access and its energy consumption.

different. In IBSS PSM, all STAs in the ad hoc network must be synchronized. An STA in the ad hoc network broadcasts beacons periodically and each beacon initiates a period of a beacon interval. A beacon interval can be further divided into two periods. An ATIM (Announcement Traffic Indication Message) window is the period that ATIM frames are exchanged. The other period is for packet exchanges between STAs. The STAs that have packets to send must specify the destinations in the ATIM frames and transmit the ATIM frames during ATIM windows. Therefore, PSM STAs in ad hoc mode must stay awake for the entire ATIM windows for receiving ATIM frames. If an STA does not receive the ATIM frames indicating packets to be transmitted to the STA, the STA can go to sleep till the next ATIM window. Otherwise, the STA has to wake up during the data exchanging period to listen to the packets from other STAs. The exchanges of ATIM frames during ATIM windows and packet exchanges during packet exchange periods follow the same DCF access procedures. Since the STAs in ad hoc PSM must stay awake during the entire ATIM windows, the STAs consume more energy compared to the infrastructure PSM that the STAs only listens to beacons from the AP.

#### 2.4. EDCA/HCCA

The EDCA and HCCA schemes are enhanced MAC access mechanisms which are proposed in IEEE 802.11e [5]. These schemes support the quality of service (QoS) in WLAN. The EDCA scheme improves the DCF by assigning various sizes of IFSSs and contention windows to packets associated with different access classes. This approach differentiates the packets in different access classes during WLAN transmission. Therefore, the EDCA scheme makes it possible to achieve per-class QoS. The power consumption of the EDCA is similar to the DCF access. The main differences between the two access schemes are that the periods for overhearing the transmissions between other STAs and the AP ( $T_{fr}$ ) and the waiting back-off periods ( $T_{bk}$ ) vary when transmitting packets associated with different access classes in the EDCA. In other words, the power consumptions for transmitting packets associated with various access classes are different.

On the other hand, the HCCA scheme uses a hybrid coordinator (HC), which is usually an AP, as a centralized coordinator to allocate a time period, called the controlled access phase (CAP), during a contention-free period (CFP) or a contention period (CP). The HCCA scheme can fully manage radio resources during CAPs and grants transmission opportunities (TXOP) to STAs to access the WLAN channel. The power consumption of the HCCA scheme can be viewed as the PCF.

#### 2.5. Power saving enhancements in the latest IEEE 802.11 standards and Wi-Fi certifications

The APSD defined in IEEE 802.11e suggests two mechanisms, i.e., the Scheduled APSD (S-APSD) and Unscheduled-APSD (U-APSD). The APSD mechanism introduces a concept, called service period (SP). An SP is reserved for an STA to exchange data packets with the AP. Therefore, the STA does not have to contend the channels so that the power consumption of the STA is reduced. The S-APSD considers the characteristic of packets which are generated periodically. If an STA establishes the S-APSD with the AP, the AP allocates SPs to the STA periodically. Then, the STA only wakes up periodically, receives and sends packets with the minimal contentions. On the other hand, the AP does not offer SPs periodically to an STA in the U-APSD. In the U-APSD, the STA can send an up-link frame to trigger an unscheduled SP for exchanging the packets with the AP. Although, the STA has to contend the channel for sending the up-link trigger frame, the U-APSD method improves the IEEE 802.11 PSM by averting the PS-Poll procedure, and save

more STA energy. For example, an uplink voice packet can be configured as a frame to trigger a service period, which is used to transmit downlink voice packets.

As mentioned in Section 2.3, an AP broadcasts a TIM frame indicating the STAs to receive queued packets. An STA which receives a TIM frame must contend for the channel, and send a PS-Poll frame to the AP. However, WLAN contention becomes seriously if many STAs send PS-Poll frames to the AP at the same time. The WLAN resources are wasted, and the STAs also consume extra energy. To avoid this, the power save multi-poll (PSMP) scheme is defined in IEEE 802.11n. The AP could consider different QoS requirements, such as delay constraints and bandwidth constraints, and schedule the packet transmission of STAs using the multi-polling mechanism. The AP specifies the schedule information in the beacon frame so that the STAs can wake up and receive packets based on the AP schedule. The PSMP mechanism improves both energy efficiency of PSM STAs and WLAN utilization by minimizing PS-Poll contentions.

Wi-Fi peer-to-peer [65] which is defined by Wi-Fi Alliance facilitates Wi-Fi devices to connect to each other without a WLAN infrastructure. The specification defines two roles, i.e., P2P Group Owner and P2P Client. The P2P Group Owner is also an IEEE 802.11 STA but serves as an “AP-like” entity. The P2P Group Owner provides and uses connectivity between P2P Clients. Wi-Fi peer-to-peer defines procedure and allows P2P Group Owner to have opportunistic power save and notice of absence functions. For the opportunistic power save, the P2P Group Owner can go to sleep when it detects the P2P Clients are all in doze mode. For the notice of absence, the P2P Group Owner can notify P2P Clients that the P2P Group Owner is absent for a period. The P2P Clients could also perform the PSM and U-APSD procedures to conserve their energy.

### 3. Energy efficiency – MAC-layer improvement

Solutions to improve the energy efficiency of WLAN MAC can be categorized into MAC-layer approaches, which optimize MAC-layer parameters, and cross-layer approaches, which consider the characteristics of upper-layer packets transmitted in the WLAN. This section first discusses MAC-layer technologies.

#### 3.1. Active mode

Many factors influence the energy consumption of an STA in the active mode. MAC-layer technologies may reduce contentions by decreasing the back-off period and the period for overhearing the transmissions. Other approaches avoid packet losses, or speed up transmission. Solutions can be classified into three main categories. (1) Solutions in the first category try to minimize the back-offs, i.e., the length of  $T_{bk}$ , and overhears, i.e., the length of  $T_{fr}$ , or to conserve energy during contentions. (2) In the second approach, an STA must transmit packets to, or receive packets from, the AP at the associated speed. The faster the speed at which the STA can transmit a packet, the less time and energy it consumes in delivering the packet. However, higher link speeds imply less robust modulation and coding schemes, leading to an increase in the bit error rate (BER) and the potential loss of packets. In this situation, the energy required to transmit or retransmit a packet may increase. Therefore, the link adaptation schemes which decide the most energy-efficient speed, i.e., the modulation and coding schemes, are very important for the energy-efficient transmission. Other MAC-layer mechanisms, such as the fragmentation threshold, are also very important. Technologies in this category minimize collisions, errors, and transmissions, i.e., the length of  $T_{co}$ ,  $T_{er}$ , and  $T_{su}$ . (3) Third, the overhead for WLAN channel accesses, such as inter-frame spaces (IFSSs), contentions, and acknowledgments, waste

the bandwidth and energy resources of a WLAN device. Reducing the number of IFSSs, contentions, and acknowledgments increases both the bandwidth and energy efficiencies of WLAN. The following section summarizes energy-efficient technologies for WLAN MAC:

### 3.1.1. Conserving energy during contentions

An STA must contend for the channel before it can transmit a packet. The time that an STA must wait to transmit a packet is primarily determined by the contention window (CW) size and the time that the STA overhears other STAs' transmissions. Reducing the CW size may avoid extra waiting, but unfortunately, small CWs may cause collisions and retransmissions, and consume more energy [12]. Therefore, the CW size should be chosen carefully. Bruno et al. [13] presented an analytical model for evaluating the CW size, throughput, and energy consumption of IEEE 802.11 WLAN. The CW size that maximizes throughput and minimizes energy consumption can be obtained using their models. Also, previous studies show that the most energy-efficient CW size should consider the number of STAs contending for the channel, the amount of traffic that the STAs generate, and the average packet size that the STAs produce [13–16].

The IEEE 802.11 standard mandates that STAs listen to the channel during the entire back-off period. When an STA overhears packet transmissions in this period, it sets the network allocation vector (NAV), stops counting down the back-off counter, and listens to the WLAN channel. Baiamonte and Chiasserini [17] suggested that the STA should switch to the doze state during the contention and not listen to the WLAN channel. After the back-off counter expires, the STA wakes up, listens to the channel for a period, and then transmits its packet if the channel is clear. Otherwise, if the STA wakes up but the channel is busy, the STA doubles the CW and generates a new back-off period. Although this mechanism may degrade throughput and increase delays, it significantly reduces energy consumption since the STA stays in the doze state rather than the receiving state during contentions.

### 3.1.2. Reducing power consumption for transmitting or retransmitting packets

There are several ways to reduce the energy consumption for transmitting packets. Packet compression is a way to reduce the transmission time, and therefore, energy consumption. Another approach to reduce the transmission time is to associate an AP at higher transmission rates. However, this implies the use of less robust modulation and coding schemes, which may result in a higher bit error rate (BER). If a packet is lost, retransmission also consumes energy. Therefore, identifying the most energy-efficient rate, also called link adaptation, which minimizes the packet loss rate and transmission time is a very important research topic. A number of studies have worked on this issue, selecting different energy-efficient rates under different assumptions and scenarios [20–24]. Physical-layer mechanisms, such as transmission power control (TPC), adaptive modulation and coding, and MAC-layer functions, such as fragmentation threshold and the number of retransmissions, should all be taken into consideration to solve this problem. For example, IEEE 802.11h [5] makes it possible for an STA to transmit a packet using different power levels. The STA can reduce the BER and avoid packet loss and retransmission by increasing the transmission power. Although increasing the transmission power consumes extra energy, the STA gains the benefits of better transmission quality. However, Gray and Vadde [25] reported that the TPC approach might not be able to improve energy efficiency since it may cause the hidden node problem and increase the number of collisions. Qiao et al. [18] suggested applying the TPC to the PCF access in which only one STA or the AP can transmit a packet at a time. The AP or the STA can use the most energy-

efficient rate and transmission power to transmit the packet. The MiSer approach proposed by Qiao et al. [19] combines TPC and physical layer rate adaptation to determine the most energy-efficient strategy for transmitting a packet. The idea is to pre-compute an optimal power and rate combination table which the STA then uses to determine the most energy-efficient strategy during transmission.

The RTS/CTS is a way to avoid the hidden node problem and packet collisions. Although this mechanism introduces extra energy costs for transmitting RTS/CTS frames, it guarantees no collisions during packet transmission. Therefore, the energy-efficient RTS/CTS threshold should be also considered for a WLAN suffering from serious hidden node problem [26].

IEEE 802.11n supports multiple transmitting antennas and receiving antennas, which can improve the WLAN transmission speed. Although this reduces the packet transmission time, the power consumption of the WLAN interface with multiple antennas increases significantly due to an increase in the silicon implementation area and the duplication of the transmitter and receiver radio frontends. An 802.11n system with multiple antennas is a high-performance, high-reliability solution, but is less efficient in terms of energy consumption [27].

### 3.1.3. Eliminating contentions, IFSSs, and acknowledgments

To transmit a uni-cast packet over WLAN, an STA must contend for the channel, transmit the packet and acknowledgment (ACK) frame, and spend time for waiting IFSSs. The overheads for contentions, IFSSs, and acknowledgments are serious, particularly for small packets. Therefore, researchers try to reduce the number of contentions, IFSSs, and acknowledgments for WLAN accesses. Block acknowledgment, which is defined in both IEEE 802.11e [5] and IEEE 802.11n [34], is an example of such an attempt. In this mechanism, an STA can send an ACK frame to acknowledge multiple packets, reducing the energy required to transmit multiple ACK frames. Packet aggregation is another approach to avoid multiple contentions, IFSSs, and acknowledgment frames. The basic idea behind the packet aggregation approach is to combine two or more small packets into one MAC frame which only requires one contention and one acknowledgment. The packet aggregation approach not only improves the energy efficiency of the WLAN MAC but also increases WLAN utilization. IEEE 802.11n defines two packet aggregation approaches, i.e., the aggregated MAC-level service data units (A-MSDU) scheme, and the aggregated MAC-level protocol data units (A-MPDU) scheme. The A-MSDU scheme aggregates several MSDUs into a MAC packet with only one MAC header. The A-MSDU packet must be dropped if any enclosed MSDUs contain bit errors. On the other hand, the A-MPDU scheme aggregates multiple MPDUs, and each has a separated MAC header. Any MPDU in the A-MPDU packet can be retransmitted individually if there is any bit error in the MPDU. Simulation results show that the A-MPDU aggregation scheme outperforms the A-MSDU aggregation scheme in both throughput and energy efficiency, especially under high packet error rates and high physical transmission rates [28].

Lorchat and Noel [29] presented several methods of aggregating two or more IP packets into one MAC frame. IEEE 802.11n and Otal and Habetha [30] further suggested aggregating and sending multiple packets from one source to different destinations using different modulation and coding schemes (MCSs). These mechanisms eliminate the overheads for IFSSs and contentions, and improve the energy efficiency of WLAN MAC.

## 3.2. Power saving mode (PSM)

An STA in the PSM must wake up and contend for the channel when it receives traffic-indicator-map (TIM) beacon frames. The energy consumption of an STA in the PSM involves all issues of

an active-mode STA using the DCF access. Besides the issues discussed in the previous section, two additional factors affect the energy consumption of an STA in the PSM. The first issue is how long an STA can successfully access the channel and retrieve all downlink packets. A number of researchers have investigated this issue, proposing various solutions to minimize the contention time of PSM STAs [31–38,55]. An STA which receives a TIM beacon frame must contend for the channel, send a *PS-Poll* frame to the AP, and retrieve all downlink packets before it can go to sleep. When many downlink packets must be sent to more than one STA in the PSM, the AP should consider the packet service sequence to minimize the total STA waiting time, i.e., the total energy consumed by all STAs. To minimize the time that STAs must wait to receive packets, solutions schedule downlink packets at the AP to minimize the contentions and energy consumption of STAs. For example, if the downlink transmission scheduling information can be sent in advance, the STAs can listen to the control messages and determine when to send the *PS-Poll* frame and avoid extra contentions.

Stine and De Veciana [31] proposed a solution that extends the TIM frame and embeds the scheduling information into the beacon frames. In this case, STAs can listen to the beacon, determine the service sequence, and receive packets in the pre-scheduled order. Obviously, if the AP schedules the long jobs first, other STAs may wait a long time and consume extra energy. Therefore, Stine et al. suggested that the AP should schedule the packets to STAs using a shortest-job-first algorithm to minimize the total waiting time of STAs. The length of a job includes the number of packets, the size of packets, and the association speed between an STA and the AP. Hsu et al. [32] suggested a short-job-first scheduler which gives the highest access priority to the STA that occupies the minimal duration of the WLAN channel. He and Yuan [38] further scheduled packet transmission for PSM STAs using precise timing slots. Their TDMA-like scheduling algorithm eliminates contentions and achieves near optimal power saving for the STAs. All of these studies assume that all downlink packets can be serviced within one beacon interval. Lee et al. [33] proposed a generic model in which packets may be queued for more than one beacon interval. They proved the downlink packet scheduling problem in the PSM is an NP-hard problem and proposed heuristic solutions.

IEEE 802.11n also accommodates the concept of broadcasting the downlink transmission schedule to PSM STAs [34]. The power save multi-poll (PSMP) scheme in IEEE 802.11n avoids contentions in PS-Poll procedures and improves the energy efficiency of STAs in the PSM. The multi-polling scheme can be extended to support the QoS of an STA while minimizing its power consumption. The AP could consider different QoS requirements, such as delay constraints and bandwidth constraints, and schedule the packet transmission of STAs using the multi-polling mechanism. This approach achieves the QoS of STAs and also improves their energy efficiency [36].

Another strategy to improve the energy efficiency of PSM STAs is to differentiate packet transmission for PSM STAs and non-PSM STAs. Non-PSM STAs may not have power consumption constraints, but they compete for the channel accesses, forcing the PSM STAs to spend more time and energy in contending for the channel. Zhu and Niu [35] suggested assigning different channel access priorities to PSM STAs and non-PSM STAs to improve the energy efficiency of PSM STAs.

The second factor affecting the energy consumption of an STA in the PSM is how the STA should determine the length of each listening interval [39–41]. Obviously, an STA with a longer listening interval can stay in the doze state longer and conserve energy. However, a longer listening interval introduces packet delays, creating a trade-off between energy consumption and delays. Previous studies on this topic suggest changing the listening intervals dynamically to reduce energy consumption without increasing packet delays. Since packet delays depend on packet arrivals,

solutions usually have to consider cross-layer effects and the characteristics of packet arrivals, such as TCP and web accesses. The following section discusses these solutions.

#### 4. Energy efficiency – cross-layer improvement

Researchers also consider the different characteristics of upper-layer packets when designing WLAN transmission strategies [42]. If an STA can accurately predict the arrival of a packet, it sleeps during the period without packets, and wakes up to receive the packet when it arrives. Cross-layer approaches for improving WLAN energy efficiency explore the characteristics of upper-layer packets and predict packet arrivals. This section summarizes the cross-layer technologies commonly used to optimize the energy efficiency of WLAN MAC for transmitting TCP, web access, and voice over IP (VoIP) packets.

##### 4.1. TCP

Agrawal et al. [54] presented the analytical models of the energy consumption for transmitting TCP/IP traffic in an infrastructure WLAN. To minimize the energy consumption for TCP/IP sessions, a number of schemes have been proposed. TCP requires an STA to send a TCP acknowledgment (ACK) whenever the STA receives a TCP packet. The STA must also send a MAC acknowledgment when it receives a MAC frame. These duplicate acknowledgments for a TCP packet at both the network and link layers waste WLAN resources and energy. Pang et al. [43] proposed generating a TCP ACK at the AP on behalf of the STA to eliminate the overhead of duplicated ACKs.

An STA in the standard PSM wakes up at every fixed interval. If the STA wakes up frequently, it can reduce the round-trip delay (RTT) of a TCP connection [44]. However, in this situation, the STA must consume more energy listening to beacons. On the other hand, if the STA wakes up infrequently, the packet delay increases but energy can be saved. Lee et al. [45] considered the TCP slow start effect for an STA in the PSM, and proposed an adaptive beacon listening protocol for an STA when the STA initiates a TCP connection. Instead of using the fixed listening interval, their approach dynamically changes the lengths of the listening intervals based on the estimated RTT. The STA wakes up frequently when a packet is about to arrive. This approach reduces both the number of listening beacons and the delay.

Tan et al. [46] proposed a mechanism, called PSM-throttling, to minimize energy consumption in TCP transmission. Their idea is to reshape TCP traffic into periodic bursts so that an STA can stay in the PSM without affecting its TCP transmission. Compared with the conventional TCP transmission in the active mode, the same TCP throughput can be achieved with less power consumption by applying the PSM-throttling mechanism.

Anand et al. [58] indicated that when an STA is accessing data through WLAN, to set the STA into PSM degrades the performance and may even increase energy consumption. Therefore, they proposed the self-tuning power management (STPM) scheme to dynamically switch the STA between active mode and PSM depending on access patterns and user requirements for maximizing the performance and/or conserving energy. Experimental results demonstrate that the STPM can reduce the power consumption and improve the performance for a number of network access patterns. Anastasi et al. [59] further proposed a generic architecture, called Cross-Layer Energy Manager (XEM), to dynamically adjust the power-saving strategies of an STA depending on the application access patterns and network parameters. Their proposed mechanisms are able to save 20% and 96% energy compared with the standard PSM under different application behaviors.

### 4.2. Web

If the connection speed between the web and the STA is slow, an STA might have to stay active longer to retrieve the packets. Rosu et al. [47] proposed a power-aware web proxy between the STA and Internet servers. This proxy server caches and pre-fetches any objects in the web page that the STA may request. The STA can then retrieve the pages from the local proxy using higher transmission speeds, allowing the WLAN more opportunities to sleep.

Web packets have special characteristics because users usually request a page, read it, and then click uniform resource locator (URL) links embedded in the page. In this case, the packet arrival of web page accesses can be modeled using mathematical formulas. During inactive periods, the STA might switch to the PSM to conserve energy. However, if the STA applies the traditional fixed listening interval strategy, it may consume more energy and suffer from long delays. Krashinsky and Balakrishnan [44] proposed a bounded slow down protocol which dynamically determines the sleep mode operations and parameters for web accesses based on network conditions and web traffic models. Qiao and Shin [48] further developed a general model for this problem. Their objectives are to reduce the power consumption of a WLAN interface without introducing web access delays.

### 4.3. VoIP

The power consumption of a WLAN VoIP STA is a critical issue, as it determines the maximal talking time of a WLAN mobile device. Since voice packets arrive frequently, say every 20 ms, a straightforward implementation is to keep an STA always awake, i.e., set the STA in active mode. However, this design is inefficient since the STA may only need 2 ms to 5 ms to receive and transmit voice packets in every 20 ms. In this case, the STA can stay in the

doze state to conserve energy for the rest of the time between two voice packets. However, WLAN capacity may decrease when STAs go to sleep during VoIP sessions. This is because that the active-mode STAs can send packets immediately when there is an opportunity. The STAs give up transmission opportunities if they go to sleep. Zhu et al. [52] investigated this issue and proposed a dynamic sleep strategy to adjust sleep and packetization interval dynamically according to the collision probability of the WLAN. Namboodiri and Gao [53] also investigated the issues of sleep and wake-up intervals but from a different perspective. They proposed an algorithm to determine the sleep and wake-up schedules to conserve energy during VoIP sessions based on the observed end-to-end network delay and packet loss rate. They improve the energy efficiency of VoIP services over WLAN without sacrificing the quality of user experiences.

One approach to reduce the active-mode power consumption is to utilize the PSM design in IEEE 802.11. In this case, the STA can first notify the AP, and then goes to sleep. When an STA has an uplink (UL) voice packet to send, it wakes up to send the packet. After sending the UL packet, it immediately sends a *PS-Poll* frame to retrieve the downlink voice packets queued on the AP. Although downlink (DL) voice packets might be queued on the AP for a short period of time, the delay is less than the length of a voice frame (20 ms), and can therefore be tolerated. The advantage of this approach is that an STA only needs to wake up to send and receive DL/UL voice packets for a short period of time, and can then go back to sleep until the arrival of the next DL/UL packets. This approach significantly reduces power consumption by 50–80% [49]. Fig. 4 shows the PS-Poll approach for VoIP over WLAN.

Scheduled automatic power-saving delivery (S-APSD), as defined in IEEE 802.11e, utilizes the characteristics of VoIP packets, which arrive periodically, to improve the energy efficiency of VoIP over WLAN [5,50]. This type of mechanism allows an STA to access

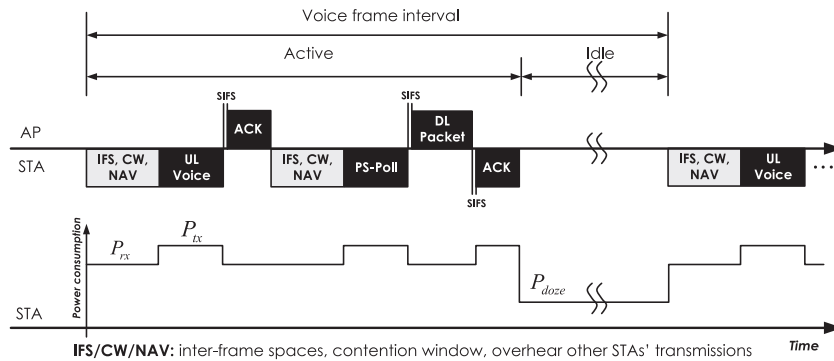


Fig. 4. PS-Poll mechanism for VoIP over WLAN.

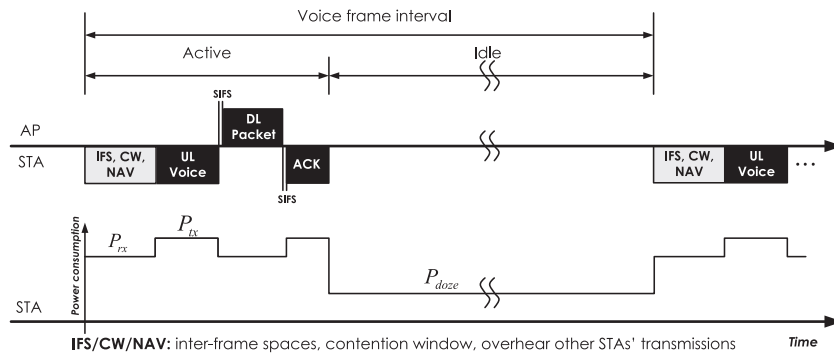


Fig. 5. U-APSD mechanism for VoIP over WLAN.



the WLAN channel using TDMA-like access methods. In this case, the STA only wakes up periodically, and receives and sends packets with minimal contentions.

The third approach is called *Unscheduled-APSD (U-APSD)*, which is also defined in IEEE 802.11e [5]. The U-APSD method improves the PSM by avoiding the PS-Poll procedure. An uplink voice packet can be configured as a frame to trigger a service period, which is used to transmit downlink packets. Fig. 5 shows an example of the U-APSD approach for transmitting voice packets over WLAN. In this case, the STA is initially in the doze state. Once the STA has an uplink voice packet to send, it wakes up and transmits the packet. The AP responds to the uplink voice packet by sending the downlink voice packet to the STA. This approach assumes that the AP can send the downlink packet to the STA immediately after receiving the uplink trigger packet. The other implementation is that the AP can first acknowledge the uplink frame, and send the downlink packet to the STA later. This approach avoids the PS-Poll procedure, shortens the length of each wake up period, and reduces the power consumption of an STA. Although the U-APSD method only avoids one *PS-Poll* frame, it improves energy efficiency by about 30–60% compared with the PS-Poll method [51]. This is because VoIP packets are normally small, and the overhead for contentions, PS-Poll, acknowledgment frames, and inter-frame spaces are significant.

Pérez-Costa and Camps-Mur [57] also evaluated the energy efficiency of the *Unscheduled-APSD (U-APSD)* and further proposed the *Adaptive U-APSD (AU-APSD)* that estimates downlink packet transmissions and determines the schedule of trigger frames. The power consumption of a WLAN STA by applying the AU-APSD can be further reduced without introducing too much packet delay.

## 5. Measurement and evaluation of energy consumption in WLAN MAC

The above two sections summarize different mechanisms to improve the energy efficiency of WLAN MAC. Some of them could be implemented based on the current standard but others may require changes in the IEEE 802.11 specifications. This section first presents the requirements for realizing these proposed ideas. To

evaluate the energy consumption of a WLAN interface, we created an experimental environment. This section then presents the design and setup of this evaluation environment, in which experiments were conducted to evaluate the energy consumption of a WLAN interface based on different MAC-layer parameters.

### 5.1. Requirements for realizing the energy efficient WLAN MAC designs

We categorize the mechanisms and/or protocols presented in the literature into two groups. The first group is related to these proposed designs that affect the other existing STAs and may introduce interoperability problems between STAs and APs. Therefore, the standard specification has to be modified. The other group is related to these schemes that only need to be implemented on some particular STAs and APs supporting the proposed functions. The proposed designs on these STAs and APs do not affect the other existing STAs or APs. Table 2 summarizes the mechanisms in the literature and their categories.

### 5.2. Evaluation environment

Fig. 6 shows the architecture of the experimental environment for evaluating the energy consumption of a WLAN interface. An AP provides the wireless access to all WLAN STAs. We observed the energy consumption, packet transmission, and reception rates of the target STA. Background STAs are installed to generate background traffics which contend for the WLAN channel with the target STA. A monitor STA is also installed in the experimental environment. This STA does not generate any packets, but only passively listens to activities on the wireless channel. The monitor STA records the timing and the other important information of packet exchanges over the air. Originally, we use a National Instruments Data Acquisition Card (NI DAQ) [60] to measure the voltage and current consumed by the WLAN interface. The NI DAQ can measure the voltage of the WLAN directly but must measure the current using an indirect approach. The indirect measurement approach connects a high resolution resistance to the WLAN interface, measures the voltage cross the resistance, allowing the current to be obtained. This approach can be used to measure large

**Table 2**  
Requirements to realize the energy efficient WLAN MAC designs.

Energy efficient WLAN MAC designs		Enhancements based on the current standard	Enhancements require changes in IEEE 802.11 standard
MAC-layer improvement	Optimize CW size [12–16]		✓
	Doze during back-off [17]	✓	
	TPC and link/rate adaptation [20–25,18,19]	✓	
	Optimize RTS/CTS threshold [26]	✓	
	Block acknowledgment [5,34]		✓
	Packet aggregation [28,30]		✓
	Standard enhancements such as U-APSD, S-APSD, PSMP [34]		✓
	PSM downlink service scheduling [31–33,35,36,38,55]		✓
Cross-layer improvement	Determine the length of listening interval [39–41]	✓	
	TCP ACK at AP [43]	✓	
	Optimize PSM for TCP accesses [44,45]	✓	
	PSM-throttling [46]	✓	
	Optimize PSM for web accesses [44,48]	✓	
	Power-aware web proxy for WLAN [47]	✓	
	TDMA-like access methods for VoIP [5,50]		✓
Dynamic sleep and wake-up intervals [52,53]	Dynamic sleep and wake-up intervals [52,53]	✓	
	Self-tuning power management (STPM) [58]		

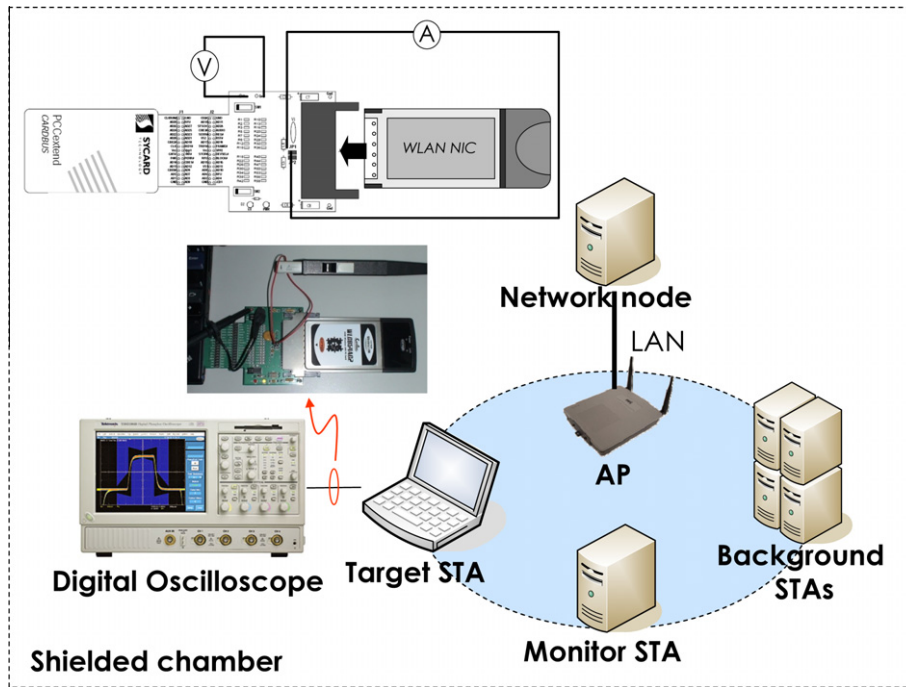


Fig. 6. Experimental environment for evaluating the energy consumption of a WLAN interface.

power consumption levels in transmission and receive states, but cannot be applied to measure WLAN interfaces that consume very little current in the doze state. When the current is very small, the resistance error may result in significant distortion of the measurement data. Therefore, we set up another measurement environment using a digital oscilloscope. In this setup, a Tektronix TD5104B [61] digital oscilloscope is connected to the target STA. We used one current probe TCP312 with a current amplifier TCPA300 and one voltage probe to connect to the WLAN interface of the target STA. Normally, a WLAN interface does not provide connectors for probing current and voltage, and therefore an extension card is required between the target STA and the interface. Universal Serial Bus (USB), CompactFlash (CF), Secure Digital Input Output (SDIO) and CardBus extension cards from Sycard [62] are adopted in our experimental environment. All STAs and AP are put in a shielded chamber to minimize interference in the WLAN channel during the experiments.

The digital oscilloscope used in this study accurately records the current and voltage that the interface consumes in every microsecond. The measurement results are downloaded from the digital oscilloscope to another PC for post processing. Software packages which monitor and generate packets are also required. WildPackets AiroPeek [63], a popular network monitor and analyzer for WLAN, is installed on the monitor STA. IxChariot [64] is installed on the target STA, all background STAs and network node. This tool generates UDP/TCP testing packets between the STAs and the network node. Packet exchange logs collected by the monitor STA, current and voltage logs obtained from the digital oscilloscope are fed into a program we developed to evaluate and analyze the energy consumption of the target STA. Timing synchronization of these data sets are required so that the energy consumption of every packet can be accurately estimated.

### 5.3. Measurement of energy consumption

First, we evaluate the power consumption of different WLAN chipsets and interface cards. IEEE 802.11b/g working on 2.4 GHz

is the most popular standard that WLAN products support. Therefore, we chose two IEEE 802.11b cards, two IEEE 802.11g cards, and one multi-standard IEEE 802.11a/b/g card in our experiments. Current IEEE 802.11n products which usually utilize Multi-Input/Multi-Output (MIMO) and emphasize high throughput are not considered in our power consumption measurements. Fig. 7 shows the power consumption of a WLAN interface in different configurations. Fig. 7(a) illustrates the power consumption of a Realtek RTL8180L in the active mode. The interface receives constant bit rate (CBR) UDP packets at 10 packets per second. This figure shows that the current consumed in the receiving state is about 150 mA, but the current consumed in the transmitting state is about 300 mA. Therefore, the power consumption of a WLAN interface during the transmitting state is much higher than that in the receiving state. On the other hand, Fig. 7(b) demonstrates the PSM and the listen interval is set to 100 ms. Experimental results indicate that the WLAN interface consumes about 25 mA during the doze state, which is much lower than that in the transmitting and receiving states. When the STA wakes up and listens to the beacon frames, it consumes 150 mA, which is similar to the receiving state. Fig. 7(c) and (d) further demonstrates the power consumption of a WLAN interface for transmitting packets with RTS/CTS and fragmentation enabled. Table 2 compares the power consumption levels for different WLAN chipsets and interface cards. The power consumption data in Table 1 includes the average results based on 10 experiments, where each experiment lasted for 5 min. This table shows that the transmitting power consumption is much higher than the receiving power consumption. The power consumption of the doze state can range from 10 mW to 100 mW. Experimental results indicate that the power consumption for receiving a packet is similar to the power consumption for listening to channels, or usually called the idle state in WLAN MAC. This is because that the target of conventional WLAN chipsets is usually to maximize data throughput rather than to optimize the idle state power consumption. The implementation of the idle state for these chipsets is similar to that of the receive state. The STA must process incoming signals when it stays idle. The STA has to listen to the

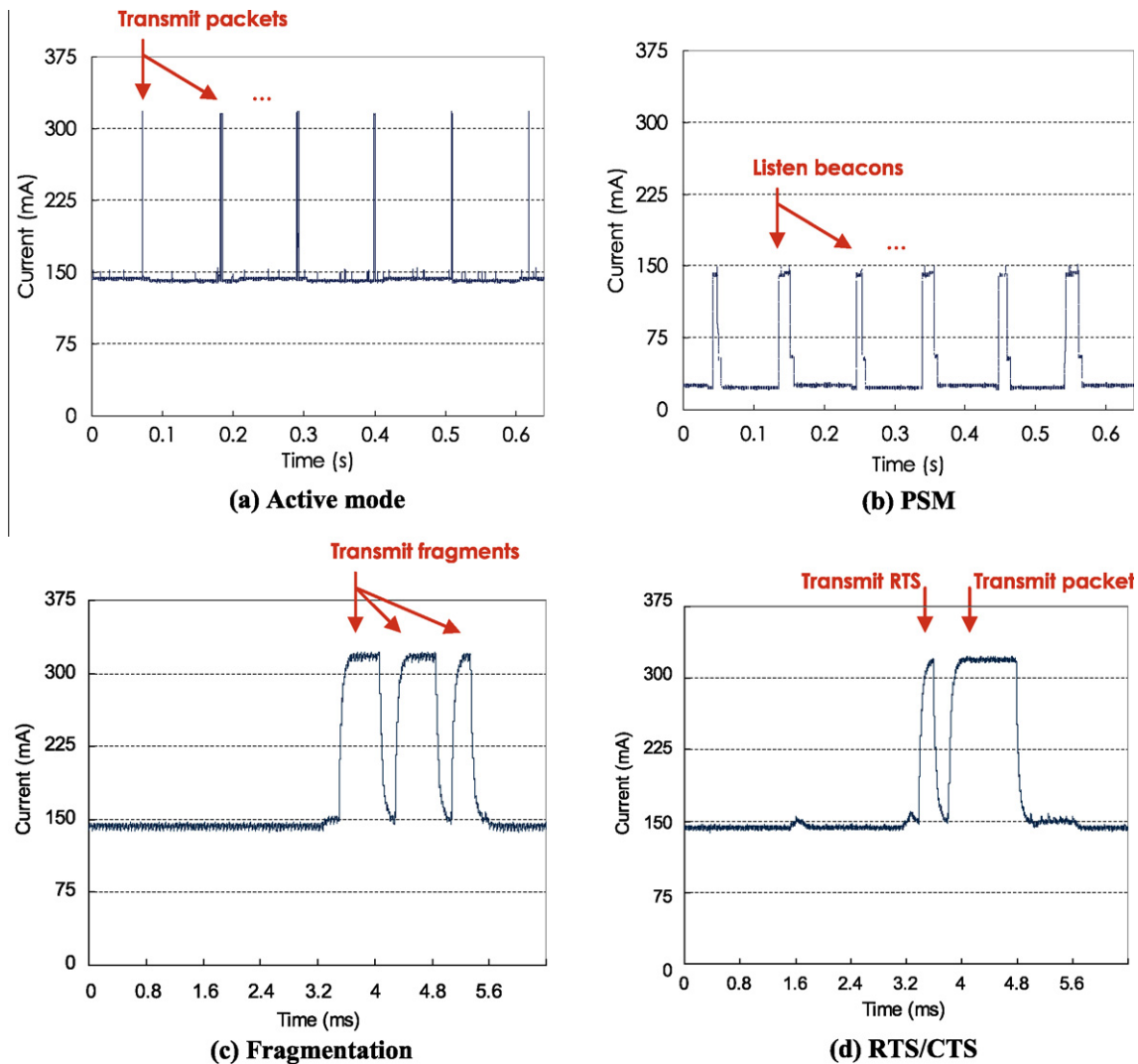


Fig. 7. Power consumption of a WLAN interface in different configurations.

channel and determine if the data is a MAC frame and if the frame is sent to the STA. Therefore, power consumption levels for listening to the WLAN channel, i.e., the idle state, and receiving packets are almost the same. The design of modern WLAN chipsets takes the power consumption issue into account. For example, chipsets could immediately stop processing incoming signals during IFSS and when they detect that the incoming packets are not sent to them. These WLAN chipsets can thus significantly reduce the idle state power consumption.

The interface standard also plays an important role in power consumption. Comparing two WLAN interface cards using the same chipset, USB 2.0 consumes much higher power than the CardBus interface. An SDIO WLAN module consumes much less power than USB and CardBus WLAN interfaces. This is because the SDIO WLAN module is usually designed for a PDA or smart phone and has to optimize its power consumption. The measurement results shown in Table 3 are slightly different from the product specifications of the WLAN chipsets. This is mainly because the power consumption shown in the product specification usually only considers the MAC/baseband chipsets. The power consumption of the entire WLAN interface includes other components, such as the radio frequency (RF) frontend/Power Amplifier (PA), peripheral interface controller, and power management controller, which all consume extra power.

#### 5.4. Analysis of energy consumption of WLAN MAC

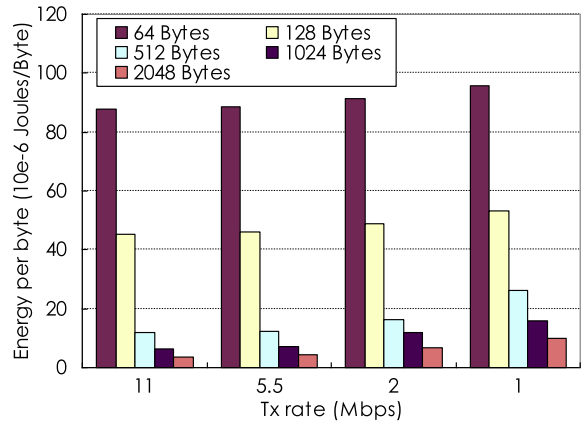
The following experiments evaluate factors such as channel contention, transmission speed, and channel error which influence the energy consumption of the WLAN MAC. These experiments are all based on the same measurement environment presented in Section 5.1. Each experiment ran 10 times, and each run lasted for at least 10 min. The results were collected and processed, and the average results are shown in Figs. 8–10. The WLAN interface with the Realtek RTL8180L chipset served as the experimental interface. The first experiment examines the energy consumption of a WLAN interface for transmitting packets under different contention situations. In other words, this experiment evaluates the energy consumption for overhearing other STA transmissions and staying in the back-off window period. The association speeds for all target and background STAs are 11 Mbps, and all STAs are in the active mode. The target STA generates 384 Kbps CBR UDP packets to the Internet node. Meanwhile, background traffics are UDP and TCP which simulate different level of contentions in the WLAN channel. In the first configuration, different numbers of background STAs generate 384 Kbps CBR UDP packets to the WLAN. In the second configuration, the background STAs generate FTP packets to the WLAN. The packet size of the 384 Kbps CBR stream is 800 bytes. Fig. 8 illustrates the experimental results. Fig. 8(a) shows the

**Table 3**  
Power consumption of different WLAN interface cards.

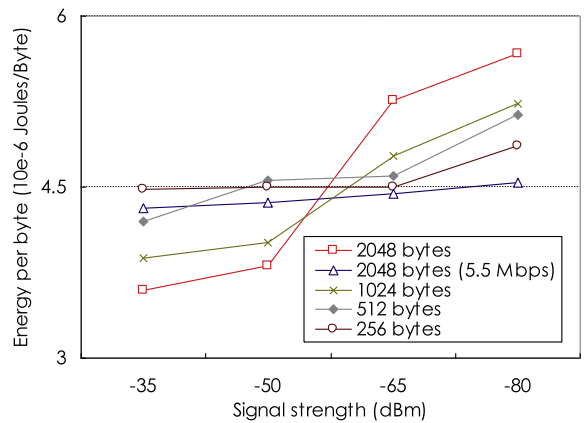
IEEE standard	Interfaces	Average power consumption in different states		
		Doze state	Rx state	Tx state
<i>Realtek RTL8180L</i>				
802.11b	CardBus	73 mW	462 mW	1053 mW
<i>Intersil Prism 3</i>				
802.11b	CardBus	116 mW	782 mW	884 mW
<i>Atheros AR5212 (2.4 GHz/5 GHz dual-band)</i>				
802.11b	CardBus	88 mW	728 mW	1056 mW
802.11a		96 mW	889 mW	1232 mW
802.11g		96 mW	880 mW	1224 mW
<i>Atheros AR5212 (2.4 GHz/5 GHz dual-band)</i>				
802.11g	USB 2.0	480 mW	1.68 W	3.1 W
<i>MediaTek MT5911</i>				
802.11g	SDIO	10 mW	424 mW	484 mW

average energy per byte when the WLAN interface of the target STA is set to the active mode. Fig. 8(b) depicts the energy per byte when the WLAN interface of the target STA is in the PSM. In the two experiments above, other background STAs are all in active mode. In Fig. 8(a), the WLAN interface consumes  $1 \times 10^{-5}$  Joules per byte without background traffics. While the number of background STAs increases, the energy per byte also increases. This figure shows that the energy per byte does not increase much when the number of background STAs increases. According to these experimental results, the difference in energy consumption per byte between an active-mode STA which does not need to contend for the channel and the STA which contends for a busy channel is only 3%. This is because an active-mode STA must stay awake, consumes the receiving power during idle. The energy per byte for an STA with or without contentions thus becomes similar.

The WLAN interface of the target STA is forced to stay in the PSM to allow the WLAN interface to remain in the doze mode when it has no packets to transmit or receive. Fig. 8(b) shows that the number of background STAs and the traffic generated by the background STAs significantly influence the energy per byte when the WLAN interface of the target STA is set to the PSM. This is because for a busy WLAN channel, the PSM STA must stay in the receiving state for a longer time to contend for the channel. Experimental results indicate that the difference in energy consumption per byte between a PSM STA which need not contend for the channel and

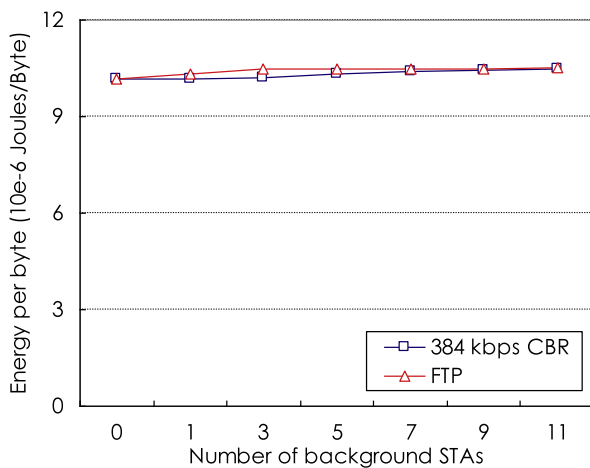


**Fig. 9.** The energy per byte under different transmission speeds and packet sizes.

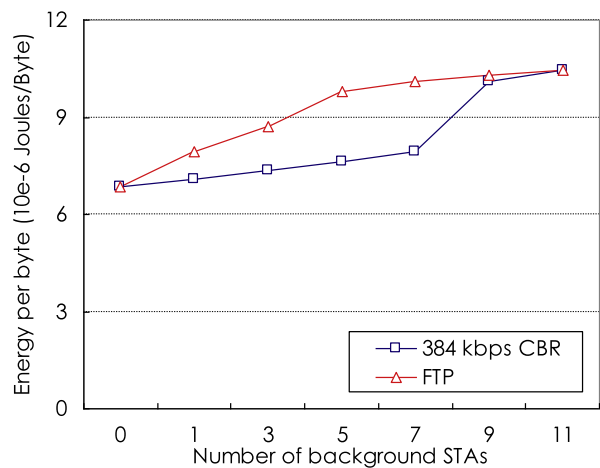


**Fig. 10.** The energy per byte under different channel qualities and fragmentation thresholds.

the STA contending for a busy channel is approximately 53%. Fig. 8(b) further shows that while the background traffic is FTP, five STAs generating FTP packets can saturate the WLAN channel. In this case, the target STA in the PSM must consume the same amount of energy to access the packet as it does in the active mode.



(a) Active mode



(b) PSM

**Fig. 8.** The energy per byte under different numbers of background STAs.

In the second experiment, the target STA is also set to the PSM, the listening interval is 100 ms, and the transmission speed is set to 11 Mbps, 5.5 Mbps, 2 Mbps, or 1 Mbps. There is no background traffic, and the packet sizes are 64 bytes, 128 bytes, 512 bytes, 1024 bytes, and 2048 bytes. The rate of packet generation from the network node to the target STA is 50 packets per second. The energy per byte under different transmission speeds and packet sizes is investigated. The results in Fig. 9 show that for small packets, such as 64 bytes, the energy per byte for the target STA accessing the packet using 11 Mbps is 1%, 4%, and 9%, less than that for 5.5 Mbps, 2 Mbps, and 1 Mbps, respectively. However, transmission speed does not play a significant role in the energy consumption of a WLAN interface when transmitting small packets. In this case, the inter-frame spaces, acknowledgment frames, and preambles which must be transmitted using the lowest speed become the most important factors. When the packet sizes increase, transmission speed becomes more important. For example, when the packet size is 1024 bytes, the energy per byte for the target STA accessing the packet using 11 Mbps is 16%, 48%, and 64% less than that for 5.5 Mbps, 2 Mbps, and 1 Mbps, respectively.

Finally, this study investigates the energy per byte under different channel qualities and fragmentation thresholds. In this experiment, the STA is also set to the PSM, and there is no background traffic. The listening interval is 100 ms, the packets are 2048 bytes, the packet arrival rate is 50 packets per second, and the target STA connects to the AP at 11 Mbps. The fragmentation threshold is set at 256 bytes, 512 bytes, 1024 bytes, or 2048 bytes. Fig. 10 shows that the small fragmentation threshold under good channel conditions is inefficient in terms of energy consumption. The 256-byte fragmentation threshold requires 25% more energy than 2048-byte fragmentation when the channel quality is good, such as  $-35$  dBm. On the other hand, 256-byte fragmentation requires only 15% more energy than 2048-byte fragmentation when the channel quality is poor, such as  $-65$  dBm. Therefore, channel quality should be considered when deciding the most energy-efficient fragmentation threshold. On the other hand, using a robust modulation and coding scheme, i.e., a low link speed, also reduces the bit error rate and packet loss. Fig. 10 shows that the target STA uses 2048-byte fragmentation and a 5.5 Mbps speed to connect to the AP. When the STA is under good channel conditions, its energy consumption when applying the low transmission speed is higher than that for the high transmission speed. On the other hand, when an STA suffers from poor channel conditions, its energy consumption when employing the low transmission speed is lower than that for the high transmission speed. Fig. 10 also shows that using a robust transmission scheme is more useful than changing the fragmentation thresholds when the STA is situated in poor channel conditions.

## 6. Summary

This article provides an overview of the energy consumption issues of MAC protocols for an IEEE 802.11 WLAN. The energy consumption of an STA for the DCF, PCF, PSM, EDCA, and HCCA access were first investigated. The energy efficiency of the WLAN MAC can be improved using MAC-layer improvements such as reducing channel contentions, avoiding inter-frame spaces and retransmission overheads, and optimizing the speeds for packet transmission. Recently, more and more studies have developed cross-layer designs that consider the characteristics of upper-layer packets, such as TCP, web accesses, VoIP, and multimedia streaming, in the design of the WLAN MAC. This paper also discusses these technologies. Finally, this study presents an experimental environment and study of the energy consumption of the WLAN MAC.

Since broadband WLAN technologies such as IEEE 802.11n focus on improving access speeds, studies should consider the trade-off between WLAN throughput and energy consumption from a cross-layer perspective. Moreover, more and more consumer electronic products, such as Digital Living Network Alliance (DLNA) devices, have built-in WLAN capabilities. WLAN power consumption for these consumer electronic devices becomes a critical issue. Energy efficient designs for such applications and devices should be further investigated and studied.

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