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On Energy Saving in IEEE 802.11ax

YANG HANG[1], DER-JIUNN DENG[2], (Member, IEEE), AND KWANG-CHENG CHEN[3], (Fellow, IEEE)
[1]Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan
[2]Department of Computer Science and Information Engineering, National Changhua University of Education, Changhua 500, Taiwan
[3]Department of Electrical Engineering, University of South Florida, Tampa, FL 33620, USA
Corresponding author: Der-Jiunn Deng (djdeng@cc.ncue.edu.tw)

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ABSTRACT Wi-Fi access has become a fundamental technology for smart building as reliable and efficient Wi-Fi is the foundation that effectively enable indoor smart devices in smart buildings. Recently, the IEEE 802.11ax standards were introduced to facilitate high-bandwidth wireless transmission in high-density environment as the new generation wireless local area network technology. In the IEEE 802.11ax, for the sake of energy-efficient smart devices, power saving mechanisms were included to further reduce Wi-Fi power consumption beyond the existing Wi-Fi power saving mechanisms. In this paper, a power saving design designated on the uplink multi-user system in 802.11ax is proposed. Additionally, an analytical analysis is developed to evaluate the effectiveness of the proposed power saving mechanism with further computer simulations to verify.

INDEX TERMS IEEE 802.11ax, Wi-Fi, energy consumption, smart building, high efficient WLAN.

I. INTRODUCTION

Wi-Fi has a distinct advantage of cost efficiency over other indoor wireless technologies due to wide deployment on unlicensed bands, and in many buildings usually Wi-Fi already exists as a built-in option or a *de facto* standard providing fast and reliable connectivity as a part of the indoor communication infrastructure avoiding expensive and time-consuming infrastructure deployment [1]. In smart buildings people rely more and more on Wi-Fi connections, and Wi-Fi will fuel the future intelligent information infrastructure to serve big data transportation and diverse smart application scenarios [2], [3].

To save energy consumption in WLAN, the Institute of Electrical and Electronics Engineers (IEEE) introduced the IEEE 802.11 standards in 1997, providing a definition of power save mode (PSM), which enables a station (STA) to enter sleep mode and wake up the STA at a specific time for data transmission or reception, thus achieving power saving [4]. As IEEE 802.11 standards evolve with smart battery-operating portable devices, the corresponding power save mechanism (PSM) adopted by legacy IEEE 802.11 standard must be improved as well. In the IEEE 802.11e standard [5], automatic power save delivery (APSD) is used in the access point (AP) to save energy consumption during direct link (DL) data transmission. APSD can be scheduled or unscheduled. IEEE 802.11n standard [6] defined power save multi-poll (PSMP) mechanism, in which the station (STA) is generally in sleep mode except while data being transmitted or received. IEEE 802.11ac standard [7] introduced the transmission opportunity power save mode (TXOP PSM) mechanism. That is, when the AP transmits data to an STA, other STAs could enter sleep mode. IEEE 802.11ah standard [8] introduced the target wake time (TWT), in which the AP and STA coordinate in waking up the STA at a specific time for transmission, and the STA can remain in sleep mode until the TWT, thereby achieving energy saving.

The IEEE 802.11ax standard emerged in response to mitigate the operating challenges in high-density WLANs. In March 2014, the IEEE Standards Association (SA) committee approved the IEEE 802.11ax, which aims at providing stable and high-bandwidth wireless transmission in high-density WLANs while achieving reduction of energy consumption during communication.

The UL-MU is a new technology adopted in the IEEE 802.11ax, targeting at power saving as well as high-bandwidth for each user. Besides, the IEEE 802.11ax equips various generic power save designs, including the TWT, cascade indication, opportunistic power save, intra-PPDU power save, and operation mode indication (OMI).

In this study, a novel power save mechanism has been developed taking advantage of the UL-MU mechanism in IEEE 802.11ax. The designed mechanism is simple and

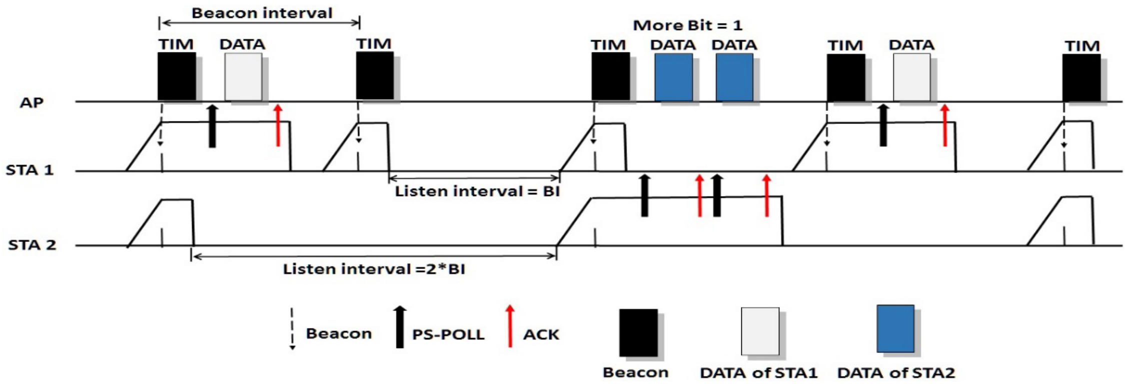

FIGURE 1. Legacy power save mode.

efficient. Furthermore, mathematical analysis is proposed to evaluate the effectiveness of the designated mechanism, and the analytical analysis is verified by computer simulations.

The rest of the paper is organized as follows. Section II provides a survey of the PSM in the legacy 802.11 standard. Section III briefly introduces the power management schemes proposed in IEEE 802.11ax. Section IV provides literature reviews on passive power saving and power save with random access. In Section V, we propose a power save mechanism based on the UL-MU mechanism in IEEE 802.11ax WLAN. A simple analytical analysis of the proposed scheme is provided in Section VI. Simulation results are given in Section VII to verify the accuracy of the analytical analysis, followed by Section VIII, which concludes this paper.

II. ENERGY SAVEING IN LEGACY IEEE 802.11

The 802.11 standard [4] introduced the PSM for power management [9] in WLAN. When AP has frames to send in PSM, it cannot send the frames at any time; it must store these frames first and then transmit them at a specific time. The traffic indication map (TIM) in the beacon frame documents the STAs with frames stored by the AP, and STAs in PSM should wake up at a fixed time point to receive beacon frames. After obtaining the TIM, STA can determine whether there are any frames for itself stored by the AP. If there are no frames stored in AP and no frames are to be transmitted, the STA returns to sleep mode.

In the unicast situation, every STA establishing a connection with AP is allocated an association identifier (AID) in the TIM. If an STA in PSM discovers that frames are stored by the AP, it sends a PS-Poll frame to the AP, which then transmits the frame to the STA as soon as possible. The STA confirms the reception of the frame through an acknowledgement (ACK) frame. The More Data field in this frame indicates the possibility of the frames stored by the coordinator. If there are more frames to be transmitted, the AP informs the STA by setting the More Data field in the data frame as ''1''. If there are more frames, then the STA returns the second PS-Poll frame. This process is repeated until the More Data field equals 0, as shown in Fig. 1.

In the broadcast/multicast (B/M) situation, an AP must first store the (B/M) frames to be transmitted until the (B/M) frame is behind the beacon frame with the TIM (DTIM) delivery. This is because the STA in sleep mode only wakes up at a specific time to receive the beacon frame, and after the beacon frame is transmitted, it enables the STA in sleep mode to more accurately plan the time at which to receive the (B/M) frame.

In contrast to the active mode, when AP does not store STA data, the STA in sleep mode closes its connection with the network interface to save power. When the network load is low, a conventional PSM can substantially reduce the energy consumption of the STA.

IEEE 802.11e standard [5] introduced the APSD power save mechanism to increase energy efficiency. APSD can be classified into scheduled APSD (S-APSD) and unscheduled APSD (U-APSD) [10]. Both APSD modes are used to facilitate power conservation for an STA. However, these two APSD modes operate differently as the S-APSD wakes up an STA through an AP at fixed time intervals to transmit or receive data, and it can close the circuit after completion of transmission to save energy. In U-APSD, an STA is in listening mode, and AP stores the DL packets for the STA. When the AP knows that the STA intends to transmit UL packets, it automatically releases and retains the packet for the STA. Once the STA receives all of the DL packets, it immediately returns to sleep mode.

IEEE 802.11n [6] defines the power save multi-poll (PSMP) mechanism [11], as an extension of APSD. Through AP, the PSMP manages the service period (SP) of an STA for UL/DL transmission or reception to decrease the wake time of an STA in sleep mode. An AP sends PSMP frames to all STAs in PSM, and the PSMP frames contain UL and DL scheduling information for each STA. An STA is awakened only at the scheduled SP to transmit and receive data.

IEEE 802.11ac standard [7] introduced the transmit opportunity (TXOP) PSM mechanism [12]. It is included in the medium access control (MAC) layer as an extension of the power save mechanism defined in the previous version of the standard. TXOP PSM mechanism permits the STA to switch between awake and sleep modes. In awake mode, the STA supplies power so that its radio transceiver can receive or transmit data at any time. In sleep mode, the STA switches off its radio transceiver to save power, but it cannot transmit or receive data.

IEEE 802.11ah standard [8] introduced the TWT mechanism. An AP and participating STA can coordinate the use of TWT functions, defining a specific time at which an individual STA can gain media access. The STA and AP exchange information, which includes the activity duration estimate. Thus, the AP can control the competition and superposition of the STA requiring media access in order to avoid collision between the STAs. The STA can use the TWT to reduce energy consumption, entering the sleep mode before the TWT.

III. POWER MANAGEMENT IN IEEE 802.11AX

Uplink Multi-user Multiple Input Multiple Output (UL MU MIMO), unique in the IEEE 802.11ax, allows multiple STAs to transmit simultaneously over the same frequency resource to the receiver with more than one antenna, wherein the receiver receives more than one space-time stream. An important difference from SU-MIMO in UL MU MIMO is that the transmitted streams originate at multiple STAs.

UL MU transmissions leverage a new control frame called a Trigger frame. As illustrated in Fig. 2, AP sends trigger frame to multiple STAs to trigger them to transmit frames in UL MU-MIMO when AP obtains the channel. The frame format of basic trigger frame is shown in Fig. 3. Common Info subfield carries the common information for all the triggered STAs, while User Info subfield carries the information for each of the triggered STAs independently [13].

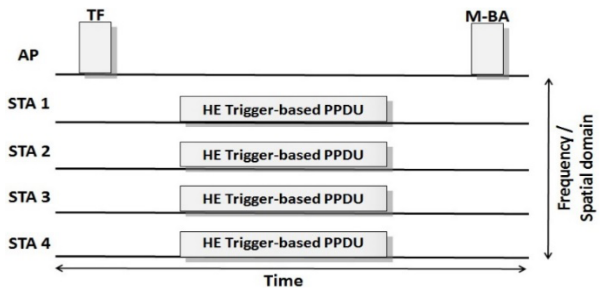

FIGURE 2. UL MU transmission.

According to [13], the Trigger frame is the frame used by AP to enable UL MU operation. AP transmits a Trigger frame to solicit UL frames from one or more STAs. Please note that only AP can transmit the Trigger frame. The Trigger frame allocates resources and carries other information required by the responding STA to send the UL frames in an HE trigger-based PPDU format [13].

The Trigger frame can carry information for a recipient via a user specific field. When a Trigger frame is intended for multiple recipients, the user specific field repeats with each instance carrying information specific to a particular recipient. Each User Info field carries information that uniquely identifies a particular recipient or an AID 0 to assign an RU for UL OFDMA random access. In addition, it carries information regarding the resource unit (RU) assigned to the recipient and other details such as Coding Type, MCS, DCM, Spatial Stream allocation and Target RSSI that the recipient uses for its HE Trigger-based PPDU response. The Trigger frame may carry optional per recipient fields based on the Trigger type [13].

After receiving the trigger frame, each of the triggered STAs needs to complete the following tasks in a fixed/specified time slot:

- Synchronize with the trigger frame, including pre-compensation for carrier frequency offset (CFO) error and symbol clock error.
- Check the CCA value (energy detection only) and NAV at the channels indicated by the trigger frame if channel sensing is required in trigger frame.

Pre-correction

- of its transmitted power based on the parameters in the trigger frame.
- Prepare PPDU as the PHY parameters indicated in the trigger frame.

All the HE Trigger-based PPDUs shall have the same length as indicated in their previous trigger frame. After receiving the HE Trigger-based PPDUs, AP has to send acknowledgement back in response to the triggered STAs. AP has two choices here: sends individual acknowledgement to each STA by using DL OFDMA BA or one frame incorporating the response to all the STAs (M-BA) [13].

According to the newly released IEEE 802.11ax draft, it includes a lot of Power Save schemes to further save power consumption besides the existing power saving mechanisms [13]. It includes:

- Target Wake Time (TWT)
- Cascade Indication
- Opportunistic Power Save

Intra-PPDU

- Power Save
- Operation mode indication (OMI)

Target Wake Time mechanism was originally designed in 802.11ah for STAs to stay in Power Save mode without listening to Beacon for a long time. It is a kind of scheduled transmission when STA wakes up in PS mode. The STAs can be scheduled in different times in order to minimize contention between them. There are two types of TWT in 802.11ax: Individual TWT and broadcast TWT. Individual TWT needs individual TWT agreements between two HE STAs, while broadcast TWT does not need to establish an individual TWT agreement between TWT scheduling STA and TWT scheduled STAs [13].

A STA can indicate to the AP its wake up patterns and traffic characteristics during individual TWT setup. The STA need not receive beacon frames after setting up an individual TWT but has to wake up at the start of the TWT to exchange

	Frame Control	Duration	RA	TA	Commom Info	User Info	...	User Info	Padding	FCS
Octets:	2	2	6	6	8 or more	5 or more		5 or more	variable	4

FIGURE 3. Trigger frame format [10].

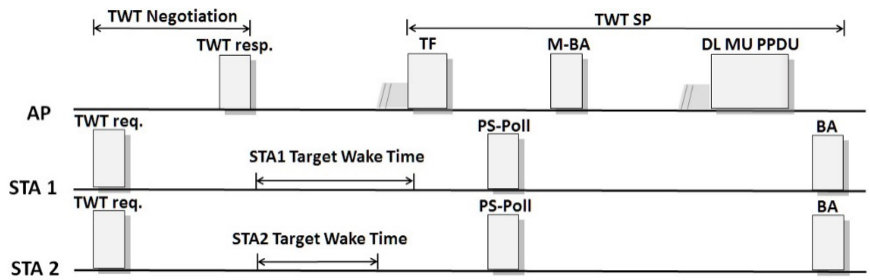

FIGURE 4. Individual TWT.

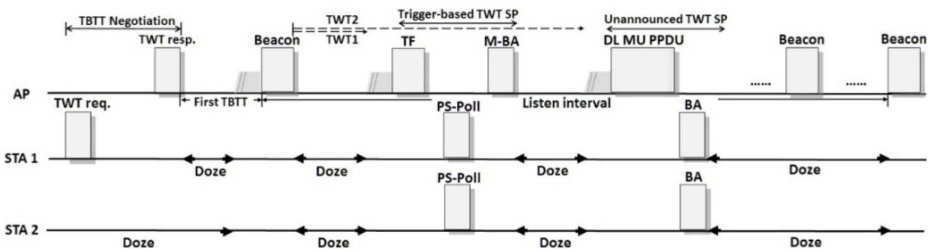

FIGURE 5. Broadcast TWT [13].

frames with the AP during the TWT SPs (e.g., receive a Trigger frame when the negotiated TWT is trigger-enabled TWT).

The HE non-AP STA may request scheduling of a TF at the start of each TWT. The AP confirms scheduling of a TF at the start of each TWT. AP schedules a TF at the beginning of each TWT SP. Non-AP STAs wake up at the TWT, wait for the TF and get ready for MU DL/UL exchange STAs are not supposed to contend during the TWT SP but rather wait for the TFs sent by the AP. During the TWT SP, STAs can exchange PS-Polls, DL data transmission, as shown in iFig. 4 [14].

During the broadcast of TWT, the STA in PS mode only needs to listen to the Beacon containing TWT IE, which can be negotiated at the beginning through TBTT negotiation. When the STA finds itself in the TWT IE, it needs to wake up at the indicated time to listen to the trigger frame of other downlink frames. Except those behaviors, the STA does not wake up until the next Beacon with TWT IE [13].

An AP can broadcast TWTs by including a broadcast TWT element in Beacon frames it transmits. The broadcast TWT element provides TWTs to STAs at which certain traffic is expected to be exchanged. STAs can wake at the start of the broadcast TWT to interact with the AP (e.g., receive a Trigger frames when the broadcast TWT is trigger-enabled TWT). The broadcast TWTs can be of the same type as the ones negotiated during individual TWT.

The AP can specify in the broadcast TWT IE whether it intends to schedule a TIM frame or FILS discovery at the TWT, whether it intends to schedule Trigger frames that contain resources for random access, etc. In addition, a STA can negotiate with the AP the target beacon transmits times at which it intends to wake for receiving the Beacon frame that contains the broadcast TWT element or it can negotiate the broadcast TWT ID(s) at which it intends to wake. The negotiation is done using TWT Setup frames.

AP can also indicate the start time of trigger frame with random access allocations in the TWT IE of Beacon frame. HE STAs in PS mode will wake up before the indicated start time after receiving the TWT IE. In case that there are more than one trigger frames in a sequence for random access, these trigger frames shall set their cascade indication field to 1 except the last trigger frame in this sequence, as shown in Fig. 5 [13].

The TWT Information frame is used by a STA to inform its TWT peer when it wishes to change the start time of the next TWT. The frame carries TWT Information field which contains information to temporarily suspend or resume a paused TWT session. The TWT session may be an individual TWT session or a broadcast TWT. Also, any STA can send a TWT information frame to a peer STA, when going to power save mode, to specify a TWT (which corresponds to a Broadcast TWT SP indicated by the peer STA or any time if Flexible TWT Schedule Support equal to 1). At this TWT,

	B0-B2	B3-B4	B5	B6-B8	B9-B11
	Rx NSS	Channel Width	UL MU Disable	Tx NSS	Reserved
Bits:	3	2	1	3	3

FIGURE 6. Operation mode indication [13].

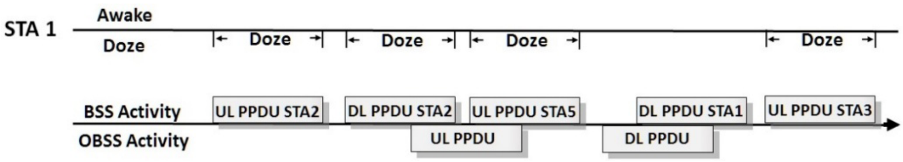

FIGURE 7. Passive power saving for 802.11ax.

the STA will recover the same PM mode as it is while sending the TWT Information frame.

The value of 0 in the Next TWT sub-field in the TWT Information field indicates that the transmitting STA is requesting a suspension of the TWT session. A non-zero value in the Next TWT sub-field indicates the transmitting STA is requesting resumption of a paused TWT session for STAs with a TWT agreement, or is indicating the target time at which the STA will recover the same PM mode as it is while sending the TWT information frame for STAs without TWT agreements. The time when the TWT SP resumes is indicated in the Next TWT sub-field. A STA may indicate if it supports flexible scheduling, resumption at any arbitrary time (instead of being selected from existing TWT values) via the Flexible TWT Schedule Support field in the HE Capabilities element. A value of 1 indicates the STA supports flexible scheduling.

Opportunistic power save mechanism is based on broadcast TWT and splits a beacon interval into several periodic broadcast SPs. At the beginning of each SP, the scheduling information to all non-AP STAs is provided by transmitting a TIM frame or a FILS Discovery frame that includes a TIM element. That is, the TIM here provides the scheduling information [13].

Intra-PPDU Power Save is a mechanism for STAs to save power in a short time (shorter than PPDU length) but very frequently. When a HE STA finds that the received PPDU has a BSS color different from itself, or the received PPDU is not itself, the STA enter the doze state until the end of this PPDU. When the channel is busier, the more power will be saved in this mechanism [13].

Operation mode indication saves power in a dimension different from the power save mechanisms above. The common power save mechanism in WLAN is to let the WLAN chip shut down most of its elements and only keeps its clocking to operate a small part to ensure it is still synchronized with its associated BSS. That is, the common power save only happens when the STA does not transmit or receive signals.

However, OMI is to reduce the power consumption when the STA is transmitting or receiving signals. OMI can change some PHY parameters like bandwidth, number of spatial streams to reduce OMI is originated from Notification of operating mode changes in 802.11ac. Compared to Notification of operating mode changes, OMI is much faster because it is following the procedure of fast link adaptation.

OMI can be done at either receiver side (ROMI) or transmitter side (TOMI) or both sides, the format of OMI is defined in Fig. 6 [13]. The basic idea of ROMI is that the OMI initiator (receiver) indicate a change in receive operating mode by including OMI in a QoS frame that solicits an immediate acknowledgement from OMI responder (transmitter). The OMI indicates the maximum bandwidth value and maximum number of spatial streams of receiving PPDUs that the OMI initiator supports. TOMI initiator mostly indicates in OMI the changes in UL MU transmissions, e.g., suspension or resumption of UL MU operation, the maximum number of spatial streams the OMI initiator can transmit in response to trigger frames, the maximum channel bandwidth the OMI initiator can transmit in response to trigger frames, etc.

IV. RELATED WORKS

Although the PSM proposed in IEEE 802.11ax facilitated energy conservation of STAs, it cannot bring expected outcomes under many circumstances in the following. To date, schemes have been developed to strengthen the PSM mechanism from different dimensions [15].

Reference [16] introduced the passive power saving (PPS) scheme. The author examined the power saving feature by switching off the radio until other STAs in BSS have completed data transmission. In the same BSS color, AP is occupied in UL/DL transmission with an STA, and the remaining STAs enter doze mode until the end of transmission. During this time, the AP does not transmit frames to these STAs. If there are no STAs undergoing UL/DL transmission within BSS, then all STAs are in the awake mode, as shown in Fig. 7.

In [17], a trigger frame (TF-R) for random access was proposed for UL transmission. The beacon frame transmitted by an AP comprises a single or multiple TF-R start time. When the STA in sleep mode is awakened, it receives the beacon frame, and receives the TF-R start time from the beacon frame. The STA in sleep mode is in doze mode until the TF-R start time is indicated in the beacon. The STA

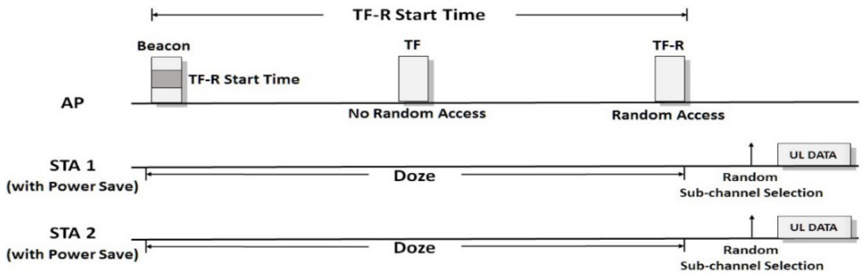

FIGURE 8. Power save with random access.

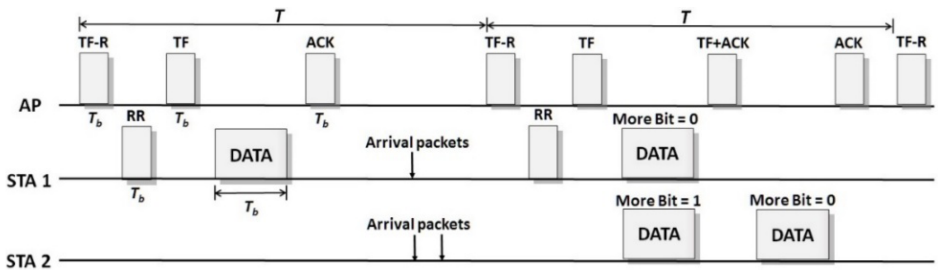

FIGURE 9. PSM for IEEE 802.11ax UL.

wakes up for UL transmission. The schedule message in the beacon facilitates reduction of energy wastage in the STA, thus reducing time in listening mode, as shown in Fig. 8.

The PPS helps PS by reducing energy wasted on listening. When traffic load is high, the STA frequently remains in doze mode, saving more energy. Conversely, when the traffic load is low, the STA remains in awake mode, achieving no power-saving effect at all. The power save method described in [17] is not complete; this method mentions only the power saving effect before UL transmission, but not the energy consumption status during UL transmission.

Based on the aforementioned discussions, several schemes have been proposed in studies regarding power save mechanism. The present study indicated that traditional PSM remains applicable for 802.11ax DL. However, this study focused on the power save mechanism of the uniquely new 802.11ax UL MU. The power save design proposed in this study, combined with the advantages of the aforementioned schemes, is simpler and more efficient, and can be easily realized in IEEE 802.11ax.

V. PROPOSE SCHEME

Fig. 9 presents the proposed power save mechanism based on IEEE 802.11ax. The scheme combines trigger frame (TF) and UL-MU. The proposed design has two types of TF: TF-R for collection request and TF for resource allocation. The length of the TF-R period time is set as T. The duration of each control frame is T_b, and the duration of data transmission is T_p. Resource request (RR) is associated with two scenarios: 1) When the number of successful contending STAs is smaller than the number of resources, each successful contending STA receives resources from the AP; 2) When the number of successful contending STAs is higher than the number of resources, these successful contending STAs must contend for limited resources. Finally, STAs that succeeded in contending for resources have the chance to transmit data. When data packets arrive, they are stored temporarily in STAs until the next TF-R period which begins transmission.

When an STA has two sets of data that need to be transmitted, it informs AP as it transmits the first set of data by setting the More Data bit in the data frame as "1". After the AP receives the data, it issues an ACK to inform the STA that it has received the data, and then allocates resources to the STA for transmitting the second set of data. This process is repeated until the More Data bit is 0. Assume that the More Data field is "0" when the STA is transmitting the first set of data, then the second set of data would not be transmitted during this period. That is, this data is going to be stored in the STA until the next period begins. The STA needs to spend an extra $3T_b$ in order to transmit this set of data to the AP, thus increasing the energy consumption of the STA during transmission. Therefore, when the STA has more than two sets of data to transmit, simply setting the More Data bit in the data frame as "1" to shorten the time the STA spending in transmitting the data, which in turn reduces the amount of energy consumed.

VI. ANALYTICAL ANALYSIS

This section introduces an analytical model capable of accurately assessing the proposed power save design. Important symbols and variables are defined in TABLE I.

The mathematical model primarily considers the energy consumed during UL transmission. We ignore the competition between inter-frame space (IFS) and distributed

TABLE 1. Variables used in mathematical model

Variables	Meaning and explanation
D_{TX}^{s}	Duration of TX in successful Resource Request (RR)
D_{TX}^{f}	Duration of TX in failing RR
D_{RX}^{s}	Duration of RX in successful Resource Request (RR)
D_{RX}^{f}	Duration of RX in failing RR
p_s	Probability of successful RR
p_{sc}	Probability of successful contending
p_{ss}	Probability of obtaining resource
p_t	Transmit probability of STA
P_{TX}	Transmission power
P_{RX}	Receive power
P_{idle}	Idle mode power
P_{doze}	Doze mode power
N_s	Number of successful RR STAs
n_s	Number of successful contending STAs
n_c	Number of contending STA
n_{ch}	Number of channels
c_w	Contending window size
λ	New arrival STAs for this TF-R period
T_b	Time for transmitting a control frame
T_p	Time for transmitting a data frame
UL	Number of UL packets to be sent in the current TF period
R	Allocated resource (date rate)

coordination function (DCF), and we assume the STA knows when the TF-R arrives. The STA in sleep mode begins transmission only after it is awakened, indicating that the STA enters doze mode after it completes data transmission. On the other hand, when the STA is not in sleep mode, the duration of doze mode is replaced by idle mode. Assume that *E1* is the energy consumed in PSM and *E2* is the energy consumed in non-PSM. P_{TX}, P_{RX}, P_{idle}, and P_{doze} represent transmission power, receive power, idle mode power, and doze mode power, respectively. Δ_{idle} and Δ_{doze} denote the duration of idle mode and doze mode, respectively. Therefore, the following equation is obtained:

$$\text{without PS}: E1 = \Delta_{RX}P_{RX} + \Delta_{TX}P_{TX} + \Delta_{idle}P_{idle} \quad (1)$$

$$\text{with PS}: E2 = \Delta_{RX}P_{RX} + \Delta_{TX}P_{TX} + \Delta_{doze}P_{doze} \quad (2)$$

$$\text{without PS}: \Delta_{idle} = 1 - \Delta_{RX} - \Delta_{TX} \quad (3)$$

$$\text{with PS}: \Delta_{doze} = 1 - \Delta_{RX} - \Delta_{TX} \quad (4)$$

The duration of transmission (Δ_{TX}) is calculated as follows:

$$\Delta_{TX} = \frac{1}{T}\left[D_{TX}^{s}p_s + D_{TX}^{f}(1-p_s)\right]p_t \quad (5)$$

The duration of receiving (Δ_{RX}) is calculated as follows:

$$\Delta_{RX} = \frac{1}{T}\left[D_{RX}^{s}p_s + D_{RX}^{f}(1-p_s)\right]p_t \quad (6)$$

Here D_{TX}^{s} and D_{TX}^{f} stand for the duration of the time during transmission in successful RR and the duration of the time during transmission in failing RR. Thus, we have:

$$D_{TX}^{s} = \frac{UL}{R}T_p + T_b, \quad D_{TX}^{f} = T_b \quad (7)$$

Here D_{RX}^{s} and D_{RX}^{f} stand for the duration of the time during received in successful RR and the duration of the time during received in failing RR. Thus, we have:

$$D_{RX}^{s} = (UL+2)\,T_b + T_b, \quad D_{RX}^{f} = 2T_b \quad (8)$$

If UL packets are not transmitted successfully in current period T, then the transmission will be delayed until the next period T. Hence, the following equation is obtained:

$$UL = \lambda T\sum_{k=0}^{\infty}(1-p_s)^k = \frac{\lambda T}{p_s} \quad (9)$$

The resource indicated herein is the channel that can be used by STA during transmission. R denotes the probability that STA with successful RR can obtain resources from AP. That is, the following equation is obtained:

$$R = \frac{n_{ch}}{N_s} \quad (10)$$

where N_s denotes the successful contending STA that transmitted RR to AP and acquired resources from AP, and N_s is associated with two possibilities. When the number of successful contending STAs is higher than the number of resources, N_s depends on the number of resources; when the number of successful contending STAs is smaller than the number of resources, N_s depends on the number of successful contending STAs. The following equation is obtained:

$$N_s = \min\{n_s, n_{ch}\} \quad (11)$$

However, the value of probability p_s is still unknown. Since the probability of successful RR is defined as the probability that a STA successful contending and obtaining resource. The following equation is obtained:

$$p_s = p_{sc}p_{ss} \quad (12)$$

p_{ss} exhibits three scenarios: when $n_s > n_{ch}$, it means that the number of successful contending STAs is higher than the number of resources, and only some STAs can receive resources. When $1 \leq n_s \leq n_{ch}$, it means that the successful contending STAs receive resources from the AP. When $n_s = 0$, it means that none of the STAs succeeded possibly because the collision between the STAs leads to low probability of successful contention.

$$p_{ss} = \begin{cases} \frac{n_{ch}}{n_s}, & n_s > n_{ch} \\ 1, & 1 \leq n_s \leq n_{ch} \\ 0, & n_s = 0 \end{cases} \tag{13}$$

where p_{sc} denotes the probability that STAs succeed in contending; c_w-1 represents a value randomly selected from the contending window of the STA; and n_c-1 indicates that the selected value cannot be the same as the value chosen by other STAs. The following equation is obtained:

$$p_{sc} = \left(\frac{c_w - 1}{c_w}\right)^{n_c - 1} \tag{14}$$

where $p\{n_s = k\}$ represents the probability that the number of successful contending STAs is k; when the number of contending STAs is bigger than the contending window value, k value depends on the contending window value. When the number of contending STAs is smaller than the contending window value, k value depends on the number of contending STAs. Please refer to the Appendix for details of the derivation.

$$p\{n_s = k\} = \sum_{j=k}^{n_c} (-1)^{k+j} \binom{j}{k} S_j, \quad 1 \leq k \leq \min\{n_c, c_w\}$$
$$S_j = \binom{c_w}{j} \prod_{i=1}^{k} \binom{n_c - i + 1}{1} \times \frac{1}{c_w - i + 1}\left(1 - \frac{1}{c_w - i + 1}\right)^{n_c - i} \tag{15}$$

where $E[p_t]$ represents the expected value of the probability of a packet arrival for the STA and that the STA is able to transmit it in the next TF-R period; and $e^{-\lambda T}$ represents the probability that no packet arrived within period T. The following equation is obtained:

$$E[p_t] = 1 - e^{-\lambda T} \tag{16}$$

According to (16), $E[n_c]$ represents the expected value of the number of contending STAs, and hence we have:

$$E[n_c] = \lceil (1 - e^{-\lambda T})n \rceil \tag{17}$$

According to (14), $E[p_{sc}]$ represents the expected value of the probability that the STA succeeds in contending, and hence we have:

$$E[p_{sc}] = \left(\frac{c_w - 1}{c_w}\right)^{E[n_c]-1} \tag{18}$$

According to (13), $p\{n_s = k\}$ indicates the number of successful contending STAs is smaller than or equal to the number of resources. $\frac{n_{ch}}{k} p\{n_s = k\}$ indicates the number of successful contending STAs is bigger than the number of resources. $E[p_{ss}]$ represents the expected value of the probability that successful contending STA receives resources, which can be expressed as follows:

$$E[p_{ss}] = \sum_{k=1}^{n_{ch}} P\{n_s = k\} + \sum_{k=n_{ch}+1}^{n_c} \frac{n_{ch}}{k} P\{n_s = k\} \tag{19}$$

According to (12), $E[p_s]$ represents the expected value of the probability that a STA successful contending and obtaining resource, which can be expressed below:

$$E[p_s] = E[p_{sc}]E[p_{ss}] \tag{20}$$

According to (11), $p\{n_s = k\}$ indicates the number of successful contending STAs is smaller than or equal to the number of resources. $p\{n_s > k\}$ indicates that the number of successful contending STAs is bigger than the number of resources. $E[N_s]$ represents the expected value of the number of STAs that succeeded in contending for and obtaining resources, which can be expressed as follows:

$$E[N_s] = \sum_{k=1}^{n_{ch}} kP\{n_s = k\} + P\{n_s > n_{ch}\} n_{ch} \tag{21}$$

According to (10), $E[R]$ represents the expected value of the probability that STA successfully transmits RR and receives resources from AP, and can be expressed as follows:

$$E[R] = n_{ch}/E[N_s] \tag{22}$$

VII. NUMERICAL AND SIMULATION RESULTS

In this section, the performance of the proposed power save mechanism is evaluated, and we will compare our analytical analysis and simulation results. The accuracy of the analytical analysis is well validated by the simulation results. TABLE II presents the default parameters used in the analytical analysis and simulation.

Assume that the fixed contention window size of the random access in the analytical analysis is 32. The contending process between IFS and TF is not considered. For this system, only the consumption of energy during transmission was considered, and throughput, delay, or other situations were not considered. This study mainly focused on the energy-saving effect of the system during the UL transmission of STA. Based on changes in 1 to 2 packets per second and when the number of STAs varied, the energy consumption during packet transmission was examined. The aforementioned assumptions are based on a preliminary introduction of mathematical analysis. Details are described in the subsequent section.

In Fig. 10, the vertical axis represents the percentage of energy saved, and horizontal axis represents the packet arrival rate. As the number of packets increase during UL transmission of a STA, energy-saving effect declines. Fig. 10 shows that when n = 1 (only one STA is contending), this STA can quickly gain access to the channel for data transmission, and

TABLE 2. Default attribute values used in the numerical results and simulation

Attribute	Meaning and Explanation	Value
T_b	Time for transmitting a control frame	50 µs
T_p	Time for transmitting a data frame	500 µs
n_{ch}	Number of channels	10
c_w	Contending window size	32
P_{TX}	Transmission power	1000 mW
P_{RX}	Receive power	600 mW
P_{idle}	Idle mode power	300 mW
p_{doze}	Doze mode power	150 mW

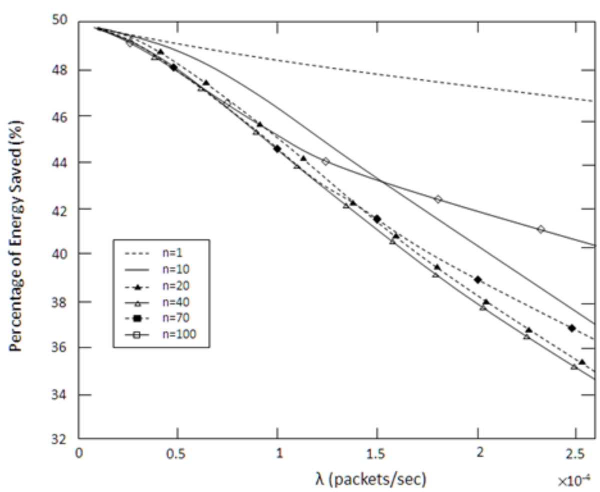

FIGURE 10. Percentage of energy saved versus arrival rate λ (c_W = 32).

it returns to the doze mode after transmission is completed. When $n = 10$, it means that 10 STAs are contending, and under the most ideal circumstance, all 10 STAs succeed in contending and gain access to the channel for transmission; therefore, the energy consumed is likely to increase. When $n = 20$, it means that 20 STAs are contending, but there are only 10 channels, implying that only 10 STAs can gain access to the channel for transmission, and the remaining 10 STAs will return to doze mode. However, all STAs will wake up after AP transmits TF-R and compete; regardless of the outcome of the competition, at least T_b of energy will be consumed. When $n = 70$ and $n = 100$, it is found that the power-saving efficiency is better than that when n = 20 and n = 40. This is because the $c_w = 32$, and it is unsuitable when the number of STAs is high, i.e., the possibility of collisions among STAs increases quickly. Whenever a collision occurs,

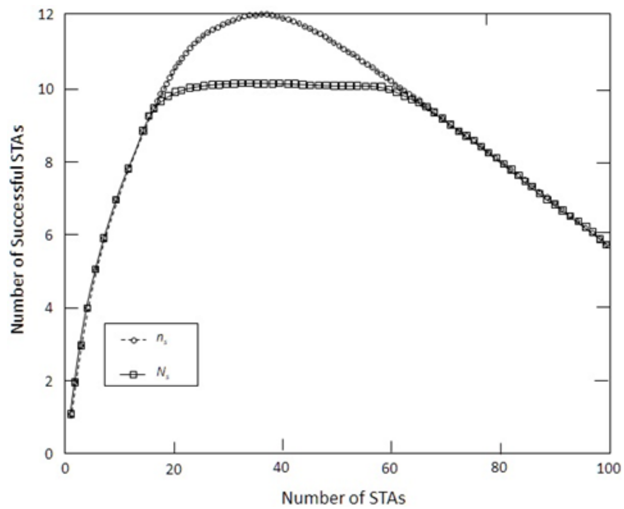

FIGURE 11. Number of successful STAs versus number of STAs.

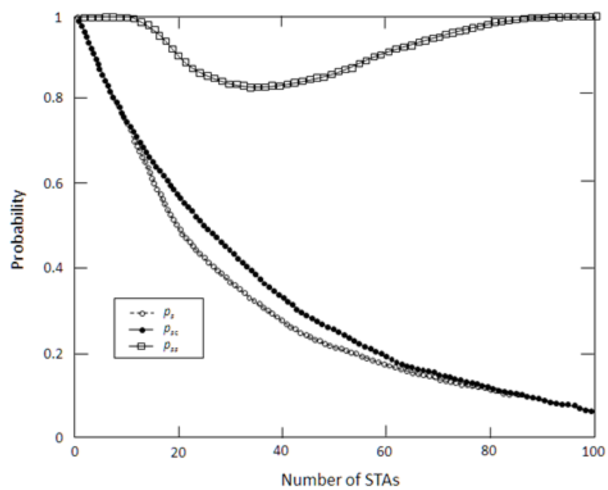

FIGURE 12. Optimal value of probability versus number of STAs.

STA enters doze mode directly and does not resend a packet, thus consuming considerably less energy than the STAs that successfully sent packets.

In Fig. 11, the vertical axis denotes the number of successful STAs and the horizontal axis denotes the number of STAs. Here, the packet arrival rate per second was set to $\lambda = 000.2$, the length of duration was $T = 10$ms, n_s represents the number of successful contending STAs, and N_s represents successful contending STAs transmitting RR to AP and gaining access to a channel from AP for transmission. Fig. 11 shows that when the number of STA is more than 35, both n_s and N_s decline. This is because the $c_w = 32$, and it is unsuitable when the number of STAs is high. For example, when the number of STAs > 40, the possibility of collisions among STAs increases quickly. Whenever a collision occurs, STA enters doze mode directly and does not resend a packet.

In Fig. 12, the vertical axis denotes the probability and the horizontal axis denotes the number of STAs. Here, the packet arrival rate per second was set to $\lambda = 000.2$, the length of duration was $T = 10$ms. p_{ss}represents the probability that successful contending STA will obtain resources from AP; p_{sc} represents the probability of successful contending STAs; and p_s represents the probability that successful contending STA will transmit RR to AP and receive resource from AP. Equation (12) shows that p_s increases with p_{ss} and p_{sc}. Fig. 12 shows that when the number of STA is more than 35, p_{ss} begins increasing. When n > 35, STAs are more likely to collide each other, which reduces the number of successful contending STAs, and the possibility of obtaining resources from AP increases. p_{ss} is dependent on these two situations. When $n_s \leq n_{ch}$, each STA can obtain resources from AP for transmission. When $n_s > n_{ch}$, n_s competes with n_{ch}, and the STA successfully obtaining resources will have the chance to transmit data.

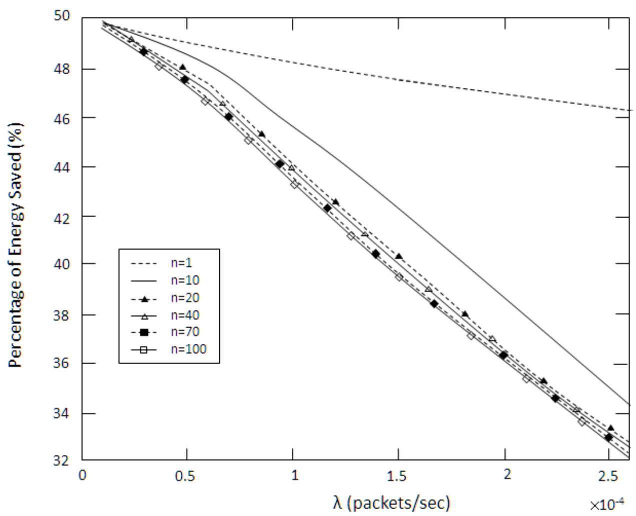

FIGURE 13. Percentage of energy saved versus arrival rate $\lambda(c_w = 64)$.

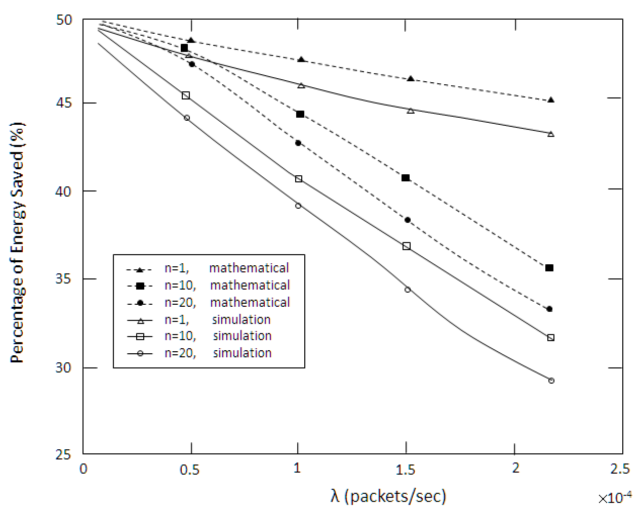

FIGURE 14. Analytical analysis versus simulation results.

In Fig. 13, the contention window size is changed to 64, which generated analysis results that more closely reflected the expected outcome. When $c_w = 64$, the simulation results and mathematical analysis results were almost identical, but noticeably, when $c_w = 32$, considerable difference was observed: using higher c_w reduces the probability of collision among STAs. The final result indicated that an increase in the number of STAs and data transmission considerably reduces energy-saving efficiency.

Fig. 14 presents a comparison of the analytical analysis and simulation results. The accuracy of the analytical analysis is well validated by the simulation results, as the difference between the simulation results and analytical analysis was less than 5%. Although the simulation results slightly less than the analytical analysis, they presented the same trend.

VIII. CONCLUSION

Since in WLANs STAs are battery-powered devices, turning the devices to low-power states when they are not in use is a very important technique. In this paper, we propose a pragmatic, practical, and yet more easy to implement power save mechanism to support energy saving in IEEE 802.11ax WLAN. In addition, to ascertain the effectiveness of the PSM in WLAN, this study introduced an analytical model to analyze the energy consumption status in the PSM. The model was used to examine the performance of the proposed power save mechanism in a high-density environment. Simulation results verified the validity of the proposed power saving scheme. According to our analytical analysis and simulation results, improvement in energy consumption during UL MU transmission primarily depends on energy consumed during awake mode and energy consumed between idle mode and sleep mode. In the future, we intend to continuously conduct research on the energy efficiency in IEEE 802.11ay standard as it utilize 60 GHz ultra-high frequency for transmission and adopt MU-MIMO beamforming technologies.

APPENDIX

The number of successful contending STAs in random access equals to a problem as follows. Given n buckets and m balls then put the balls into the buckets randomly. We want to know the distribution of number of buckets which contain only one ball. Let$X$ be the number of such buckets. Y_i denotes number of balls in bucket i. Then

$$X = \sum_{i=1}^{n} 1_{Y_i=1}$$

A_i: event that bucket i contains only one ball.

To begin, for $1 \leq k \leq m$, let

$$S_k = \sum_{i_i<\ldots<i_k} P\left(A_{i_1}\ldots A_{i_k}\right)$$

equal the sum of the probabilities of all the $\binom{n}{k}$ intersections of k distinct events. With above formulation, the distribution of X is given as follows [15]:

$$P\{X=k\} = \sum_{j=k}^{n} (-1)^{k+j} \binom{j}{k} S$$

$$= S_k - \binom{k+1}{k} S_{k+1} + \ldots + (-1)^{n-k} \binom{n}{k}$$

$$S_j = \binom{n}{j} \prod_{i=0}^{j-1} \binom{m-i}{1} \frac{1}{n-i} \left(1 - \frac{1}{n-i}\right)^{m-i-1}$$

The expected value is straightward to compute.

$$E[X] = E\left[\sum_{i=1}^{n} 1_{Y_i=1}\right] \sum_{i=1}^{n} E\left[1_{Y_i=1}\right]$$

$$= \sum_{i=1}^{n} \binom{m}{1} \frac{1}{n} \left(1 - \frac{1}{n}\right)^{m-1} \quad (23)$$

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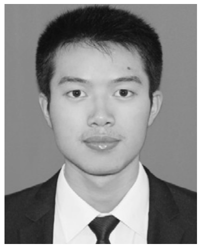

YANG HANG received the bachelor's degree in communication engineering from Chongqing University in 2014 and the master's degree in communication engineering from National Taiwan University in 2017. In 2017, he joined Hikvision, focusing on computer vision. His research interests include power saving and performance analysis of wireless communication, and computer vision.

DER-JIUNN DENG (M'10) received the Ph.D. degree in electrical engineering from the National Taiwan University in 2005. He is currently seconded as the Vice President of Overseas Chinese University for research and development for a period of one year. He joined the National Changhua University of Education as an Assistant Professor with the Department of Computer Science and Information Engineering in 2005 and then became a Distinguished Professor in 2016. His research interests include multimedia communication, quality of service, and wireless local networks. He has received a number of research awards, such as the Research Excellency Award and the Outstanding Faculty Research Award from the National Changhua University of Education, the ICS 2014 Best Paper Award, the NCS 2017 Best Paper Award, and the Chinacom 2017 Best Paper Award. He also served or is serving on several program chairs, symposium chairs, and technical program committees for IEEE and other international conferences. He is the Co-Editor-in-Chief of *EAI Endorsed Transactions on IoT* and the *Journal of Computers*. He serves as an Associate Editor for the *IEEE Network Magazine* and the *International Journal of Communication Systems*.

KWANG-CHENG CHEN (M'89–SM'94–F'07) received the B.S. degree from National Taiwan University in 1983 and the M.S. and Ph.D. degrees from the University of Maryland at College Park, College Park, in 1987 and 1989, respectively, all in electrical engineering. From 1987 to 1998, he was with SSE, COMSAT, IBM Thomas J. Watson Research Center, and National Tsing Hua University, where he was involved in mobile communications and networks. From 1998 to 2016, he was a Distinguished Professor and the Irving T. Ho Chair Professor with National Taiwan University, Taipei, Taiwan. He has been a Professor with the Department of Electrical Engineering, University of South Florida, FL, USA, since 2016. His recent research interests include wireless networks, artificial intelligence, cyber-physical systems, social networks and data analytics, and cybersecurity. He received a number of awards, such as the 2011 IEEE ComSoc WTC Recognition Award, the 2014 IEEE Jack Neubauer Memorial Award, and the 2014 IEEE ComSoc AP Outstanding Paper Award. He has been actively involving in the organization of various IEEE conferences as the general chair/TPC chair/co-chair. He actively participated and has contributed essential technology to various IEEE 802, Bluetooth, LTE and LTE-A, and 5G-NR wireless standards. He has served in editorships with a few IEEE journals.