Wake-Up Latency Evaluation of IEEE 802.11ba WUR System

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***Abstract*— In this paper, we describe the coexistence technologies between legacy Wi-Fi and WUR Wi-Fi discussed in IEEE 802.11ba group, and perform a numerical evaluation of the wake-up latency considering the WUR signaling procedure and different load from co-existing legacy Wi-Fi devices. We consider two modes of operation for WUR capable devices, i.e. normal mode and duty cycle mode. The value of WUR ACK timeout does not critically affect the wake-up latency. Performance results also show that the duty cycle based operation mode is more preferable for low network load scenarios because it achieves similar delay performance with the normal mode, but requires less energy consumption. In contrast, the delay for duty cycle mode drastically increases with the load of co-existing legacy Wi-Fi network, but decreases more energy consumption.**

Keywords*— *wake-up radio, latency, coexistence

I. Introduction

The top priority to combine Wi-Fi with various Internet of Things (IoT) devices is low power consumption and coverage extension. The existing IEEE 802.11 standard specification already defines the power saving mechanism and the IEEE 802.11ah standard has been completed for the IoT service but it is still not enough in the market. To overcome the power consumption limitation of wireless LAN (WLAN), IEEE 802.11ba Wake-Up Radio (WUR) Task Group (TG) has been developing the WUR standard specification since January 2017. The IEEE 802.11ba WUR is the first IEEE 802.11 WLAN standard developed specifically for control without data transmission for power saving only. As an important performance indicator required for WUR, low power consumption, low latency, coverage extension, good detection/false alarm probability, and low cost/small size are considered. In addition, the legacy Wi-Fi and WUR Wi-Fi should coexist with each other without degrading performance. There are two modes of operation defined for WUR capable devices. One is the normal operation in which the main radio used for data exchange is in sleep state, while the secondary WUR interface is always in listening state waiting for the WU frame. In order to reduce the power consumption even more, a duty cycle based scheme is used, in which the secondary WUR interface performs periodic “ON/OFF” switching. This method is especially effective in term of energy consumption when the amount of wake-ups is minimal.

In this paper, we present the WUR basic concept of IEEE 802.11ba and the coexistence performance analysis of WUR Wi-Fi by evaluating the wake-up latency considering WUR signaling procedure and various network load from the coexisting legacy Wi-Fi devices. The evaluation results show that the WUR ACK timeout does not critically affect the latency. Performance evaluations also show that the duty cycle based approach is preferable when the load form the coexisting Wi-Fi network is low, while the latency increases critically when the level of contention increases.

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II. WUR Coexistence Technologies

Fig. 1 shows the structure of a WUR-enabled WLAN system. After the WUR receives a WUR frame, it transmits and receives WLAN frame by waking up a Primary Connectivity Radio (PCR). An IoT device without a WUR is periodically waked up to reduce power consumption, thus a long latency occurs because the user cannot connect to the IoT device until it wakes up. Reducing the sleep mode time can satisfy low latency, but shortens the battery life. The WUR is a technology that can satisfy low latency and long battery life of WLAN-based IoT devices at the same time.

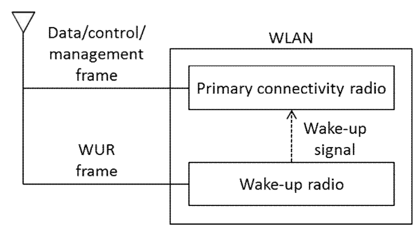

Fig. 1. WUR-enabled WLAN system

The IEEE 802.11ba Project Authorization Request (PAR) document specifies that the legacy Wi-Fi and the WUR Wi-Fi must be able to coexist without degrading performance by sharing radio resources effectively in the same band [1]. In order to coexist with legacy Wi-Fi, IEEE 802.11ba TG is discussing the topics such as the WUR frame structure, WUR EDCA parameter, and cooperation between legacy power saving mode and WUR mode, and so on.

As shown in Fig. 2, the WUR frame format consists of the legacy preamble and the WUR portion. The legacy preamble consists of L-STF, L-LTF, L-SIG and BPSK-Mark. The L-STF, L-LTF and L-SIG have the same structure as the IEEE 802.11a standard. This symbol is needed for legacy devices to protect the WUR frame with a carrier sense mechanism. On the other hand, the WUR portion modulated by OOK (On Off keying) is likely to be incorrectly detected as an 802.11n frame. The Cyclic Redundancy Check (CRC) failure occurs, and the level of the narrow-band WUR portion falls below the threshold. As a result, the Clear Channel Assessment (CCA) idle is determined and the WUR frame is not protected. To prevent this, a BPSK-Mark symbol is added after the L-SIG symbol. This is to spoof the 802.11n device to treat the WUR frame as an 802.11a frame. This is to allow the 802.11n device to recognize the WUR frame as an 802.11a frame. The WUR-Sync field is used by the WUR receiver to detect the WUR portion, recover the symbol timing, and determine the data rate of the WUR-Data field. The WUR-Data field has two data rates. The WUR-Sync field has a length of 128us for low data rate and the WUR-Sync field has a length of 64us for high data rate. The WUR supports two data rates for the WUR-Data field: low data rate of 62.5kbps and high data rate of 250kbps. More information can be found in the specification draft document [2].

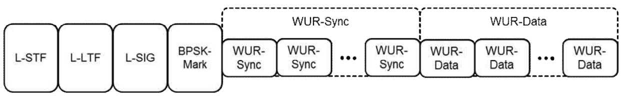

Fig. 2. WUR frame format

III. WUR Parameters and Signaling

In this paper, among the coexistence technologies of IEEE 802.11ba, we specifically evaluate the wake-up latency considering WUR signaling procedure and various network load from the coexisting legacy Wi-Fi devices.

Fig. 3 shows the basic Distributed coordination function (DCF) channel access method of WLAN system. If the medium is idle for DCF Inter-Frame Space (DIFS) time after the medium busy, the backoff procedure is activated. If the backoff timer is 0, the STA transmits the data frames or management frames [3]. The different interframe spaces are used to provide different level of priorities to different frame types and access schemes. Specifically, SIFS is used before some of the control frames transmission without requiring any subsequent backoff procedures, while PIFS is used by Point Coordination Function (PCF), which is controlled by AP for Quality of Service (QoS) demanded applications. This function, however, is not typically used by the commercial devices.

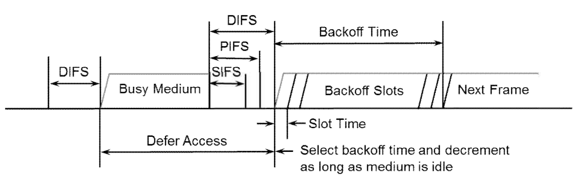

Fig. 3. Basic channel access method of WLAN system

Backoff time is generated randomly by (1).

$$Backoff\ Time = DIFS + Rand[0,CW] \times SlotTime \qquad (1)$$

Here *Rand[0,CW]* is selected as an integer value that is normally distributed in the interval of 0 and Contention Window (*CW*). The *CW* value starts from CW_{min}, and increases to CW_{max} exponentially if the transmission continuously fails. The *CW* never grows more than the CW_{max}. Fig. 4 shows an example in which *CW* increases exponentially with an exponent of 2. Since the exponent is set to 2 the procedure is called as Binary Exponential Backoff (BEB). *SlotTime* is the physical slot duration, which is set to 9us for OFDM based Wi-Fi devices. When performing station wake-ups AP also has to perform backoffs for before WUR frames transmission because WUR are transmitted on the same channel as the other legacy devices are using.

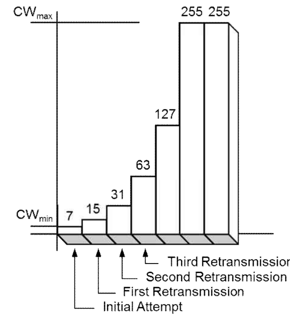

Fig. 4. Example of exponential increase of contention window

Fig. 5 shows an example of the WUR signaling procedure to wake up the PCR of the station (STA). Upon successful reception of the WUR frame transmitted from the access point (AP), the STA wakes the PCR and responds to the AP with the WUR-ACK frame. After confirming WUR-ACK frame, AP sends DATA frame and STA responds DATA-ACK frame and then switches to WUR mode again. The WUR frame and the WUR-ACK frame are also transmitted through the backoff method. Here, the latency required to wake up the STA is defined as the time from the start of the backoff of the WUR frame to the time of the successful reception of the WUR-ACK frame.

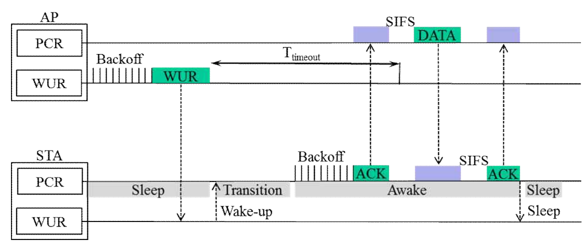

Fig. 5. Normal Wake-up signaling procedure

Fig. 6 shows an example of the WUR signaling procedure considering the duty cycle operation. The WUR actively listens to WUR frame only during the ON states. This operational mode can greatly reduce the power consumption and significantly increase the battery life. However, there is a tradeoff between the energy consumption and wake-up latency, since while being in OFF state AP is not able to wake-up the sleeping station.

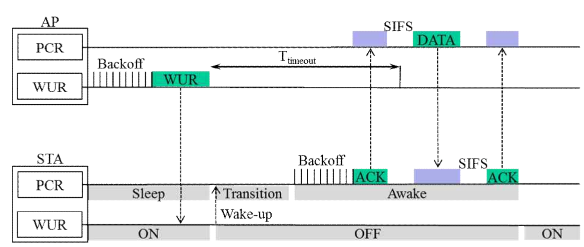

Fig. 6. Wake-up signaling procedure with duty cycle

IV. SIMULATION RESULTS

Table I shows the parameter values assumed in the simulation to evaluate the wake-up latency. It is assumed that there is always data to be transmitted in the transmission buffer of the STA, and a frame error occurs only by a collision. $T_{timeout}$ is defined as the time to wait for an WUR-ACK frame after transmitting the WUR frame. If the WUR-ACK frame is not received within $T_{timeout}$, it is determined that the WUR frame is collided and the CW of the WUR frame is increased. When the DATA frame is not received after Short Inter-Frame Space (SIFS), it is determined that WUR-ACK frame is collided and CW of WUR-ACK frame is increased.

TABLE I. SIMULATION PARAMETER VALUES

Parameter	Value
PSDU length of other STAs (Bytes)	500, 1000, 1500
Number of STAs	5 ~ 100
$T_{timeout}$ (ms)	15, 20, 30
Slot time (us)	9
SIFS (us)	16
DIFS (us)	34
CW_{min}	15
CW_{max}	1023
Antenna scheme	SISO
DATA rate (Mbit/s)	6.5
ACK rate (Mbit/s)	6
Guard interval (us)	0.4
WUR frame duration (us)	420
Transition time (ms)	10.01
TWT ON time (ms)	100
TWT OFF time (ms)	5000

Fig. 7 and Fig. 8 show the simulation results of the wake-up latency according to the number of STAs. Topology consists of multiple active STAs and one sleeping STA. To evaluate the wake-up latency, the average time to wake-up the sleeping STA is estimated. As shown in Fig. 7, the wake-up latency is more affected by the length of the PHY Service Data Unit (PSDU) of other STAs participating in the competition than $T_{timeout}$. However, despite the aggressive condition of a simulation, the wake-up latency does not exceed a maximum of 350 ms.

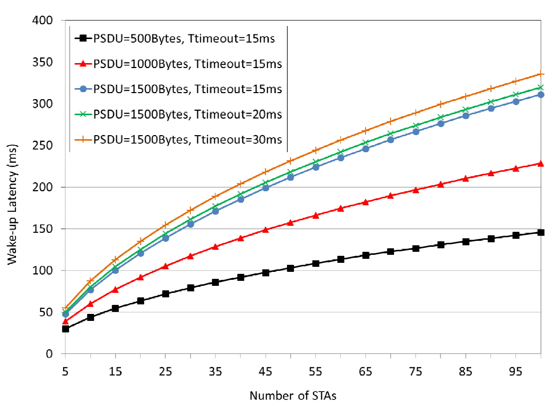

Fig. 7. Wake-up latency according to the PSDU length and $T_{timeout}$

Fig. 8 shows the simulation results of the wake-up latency considering the duty cycle operation. The duty cycle operation in the WLAN can be implemented using the Target Wake Time (TWT) function. The application of TWT can greatly reduce power consumption, but the wake-up latency is increased significantly. However, even in the worst case, the wake-up latency does not exceed a maximum of 1,200 ms. The results show that when the number of active legacy devices is small the usage of duty cycle mode is more preferable compared to the normal mode because with nearly similar latency energy consumption is much smaller [4]. However, as the level of contention is increasing the latency of wake-ups for duty cycle scheme rapidly increasing. This is because the wake-up cannot be accomplished during the one ON state and is postponed to the following ON states.

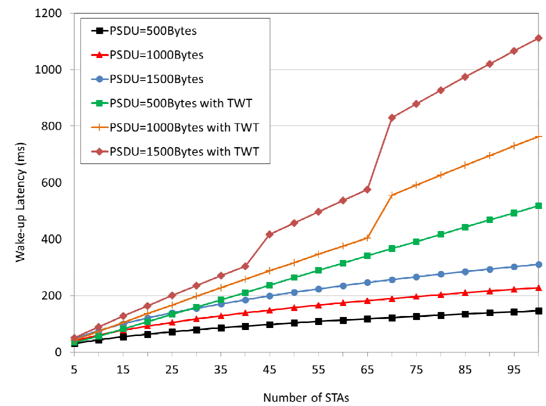

Fig. 8. Wake-up latency considering the duty cycle operation

V. CONCLUSIONS

In this paper, we described the coexistence technologies with legacy Wi-Fi being discussed in the IEEE 802.11ba task group. Specifically the wake-up latency is evaluated considering the WUR signaling procedure and the network load from the coexisting legacy Wi-Fi devices. By considering normal and duty cycle operational modes it has been found that duty cycle based approach is more preferable for the scenarios with low network load from the legacy Wi-Fi. This is because with the similar latency performance the duty cycle algorithm allows much less energy consumption. On the other hand with the increase of the network load of co-existing legacy devices the latency increases drastically making duty cycle approach less reasonable.

REFERENCES

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