Energy-Efficient Multi-Polling Scheme for Wireless LANs

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***Abstract*—In the past few years, IEEE 802.11 wireless LANs (WLANs) has rapidly gained large popularity for broadband wireless access. With the growing of various applications, users are demanding features such as higher throughput while keeping respectable operation time for their devices. To provide higher system bandwidth utilization, multi-polling mechanisms are often employed to reduce protocol overhead. However, they require wireless stations (STAs) to spend much time in overhearing which tends to waste energy and reduce battery lifetime. In this paper, we propose an energy-efficient multi-polling mechanism which combines power management strategy with a low overhead Medium Access Control (MAC) protocol. The main idea is to put STAs into the Doze state and determine a suitable wake-up time schedule to statistically achieve desirable guarantee of bandwidth utilization. From both analysis and simulation results, we found that, compared with the original ordered-contention multi-polling scheme, our proposed mechanism saves up to 80% of energy for a network consisting of 20 polled STAs with 5% loss of system bandwidth utilization as tradeoff. The significant saving of energy is a consequence of alleviating the overhearing problem with well scheduled wake-up times for STAs.**

***Index Terms*—WLAN, power management, multi-polling, bandwidth utilization.**

I. INTRODUCTION

BECAUSE of its friendly price, ease of deployment and flexibility, the IEEE 802.11 *wireless local area network* (WLAN), has become a prevailing technology in the broadband wireless access networking. The IEEE 802.11 standard document [1] defines the *medium access control* (MAC) layer and the *physical* (PHY) layer specifications. The mandatory *distributed coordination function* (DCF) uses contention-based scheme to provide easy and robust wireless access.

Due to high protocol overhead, however, the throughput performance of 802.11 WLAN is much worse than the underlying PHY transmission rate. It has been proved in [3] that there is theoretical upper limit of achievable throughput for IEEE 802.11 protocol. The upper limit depends on payload length and is about 75 Mbps for 802.11a with 1500-byte payload length. To increase system throughput, the IEEE 802.11n task group [17] is initiated to achieve a maximum throughput of at least 100 Mbps, as measured at the MAC data service access point, by both PHY layer and MAC protocol enhancements. Despite the goal to provide *quality of service* (QoS) in WLAN, IEEE 802.11e [2] defines some features which also improves the *system bandwidth utilization* (BU). The introduction of *transmission opportunity* (TXOP), Block ACK (*acknowledgement*), and direct link protocol can be utilized to reduce some MAC overhead. To further improve BU, multi-polling schemes [4]-[6] and [19] were proposed to reduce overhead caused by possibly constant polling frames.

Since most wireless devices are battery powered and the battery technology has no significant advances for decades [8], reducing energy consumption of wireless network interface cards is also a very important issue. In [7], the major sources of energy waste of shared medium wireless networks were listed: ***collision***, ***overhearing***, ***control packet overhead***, and ***idle listening***. Transmission collision obviously is a source of energy waste because frames involved in a collision are destroyed. Overhearing means that a *wireless station* (STA) receives and decodes packets that are not destined to it. Control (packet) overhead such as ACK frame and *inter-frame space* (IFS) are necessary to maintain MAC operations normally. Unfortunately, they increase the active time and energy consumption of STAs when transmitting, receiving control frames or experiencing some backoff deferral to facilitate distributed coordination. Finally, idle listening represents useless energy consumption of an STA waiting for possible frames destined to it. It is clear that the battery lifetime can be extended if these sources of energy waste can be eliminated.

For the ordered-contention multi-polling schemes proposed in [4]-[6], transmission collision can be eliminated. The multi-poll frame is the only control packet overhead to coordinate transmission. Moreover, idle listening can be avoided if the *access point* (AP) buffers data for STAs in the Doze state and notifies an STA before sending data to it. However, since their operations require STAs to monitor channel status continuously so that they can access the medium in proper time instant, overhearing is still a source of energy waste to these schemes.

In this paper, we propose an MAC scheme called EE-Multipoll (Energy-Efficient Multi-polling) which generally retains the merits of high BU as the ordered-contention multi-polling scheme while effectively lower energy consumption. Given traffic characteristics, a *wake-up time schedule* (WTS) is derived to statistically guarantee the BU. Since the overhearing problem is largely mitigated, the energy conservation for an STA of later access order is effectively improved. It is also

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good for energy saving for STAs not involved in the schedule since they can check the announcement at the beginning of the scheduled period when compared with the legacy polling scheme. Through analysis and simulation, when compared with previous ordered-contention multi-polling schemes, the proposed EE-Multipoll mechanism achieves significant energy saving with only slight degradation in BU.

The remainder of this paper is organized as follows. Section II describes the background of energy-saving and literature review of bandwidth efficient multi-polling schemes. Section III develops the framework and details of our proposed energy-efficient multi-polling protocol. In Section IV, we formally define the problem of optimal WTS subject to a pre-defined loss of BU and present a near-optimal feasible solution. Analyses of the wake-up times and energy saving are also presented in this section. Performance evaluation is provided in Section V. Finally, we draw conclusion in Section VI.

II. BACKGROUND AND RELATED WORKS

A. Power Management of WLANs

The IEEE 802.11 standard document defines two *power management* (PM) modes - Active mode and *Power Save* (PS) mode. In the Active mode, STAs stay in the Awake state and are fully powered to receive frames. On the other hand, STAs in the PS mode shall be in the Doze state and awake to listen to selected beacons. An STA in the Doze state consumes much less power than in the Awake state by turning off the RF circuitry. The switchover in between the states takes about 250μs [12].

An STA in the PS mode uses the *power-save polling* (PS-Poll) scheme to retrieve data buffered in AP to improve energy efficiency. However, the performance of downlink packet latency and BU may not be satisfactory when this scheme is implemented because of the dependency on beacon interval, access contention, and additional signaling load by PS-Poll frames. The 802.11e also includes some optional extension of power save functionality defined as *Automatic Power Save Delivery* (APSD). The *unscheduled APSD* (U-APSD) is a distributed mechanism for STAs to decide when to awake to receive buffered frames at the AP while *scheduled APSD* (S-APSD) is a centralized mechanism for the AP to determine some fixed intervals that STAs should periodically awake to receive the frames. These frameworks can reduce the signaling load and are, as stated, mainly designed for downlink usage.

There are some other centralized PM schemes [11], [15] which achieve energy saving by adopting the *shortest-job-first* (SJF) policy to schedule transmissions. The SJF policy arranges the access orders of STAs according to their aggregate required time and STAs which finish their transmissions can switch to the Doze state. It can minimize the average waiting time after the announcement of schedule for STAs; however, the STAs of later orders tend to overhear more.

B. Ordered-Contention Multi-polling Mechanisms

In legacy 802.11 *point coordination function* (PCF), the AP maintains a polling list and a polled STA has the right to transmit one frame. Such policy may induce bandwidth hogging by low rate STAs. Therefore, the succeeding 802.11e introduces the notion of TXOP to limit the transmission time of an STA who may need to fragment a large frame into smaller ones to fit into the interval. The TXOP is a bounded interval during which the holder can initiate an uninterrupted frame exchange sequence. Moreover, if a TXOP holder does not have enough data to use up the allocated time, it can return the remaining time to the AP to do resource reallocation. (The join/leaving handshaking for the polling list of an STA can utilize the ADDTS (Add Traffic Stream)/DELTS (Delete Traffic Stream) frame defined in [2].) Nevertheless, the requirement of polling frames is kind of overhead lowering system BU. To reduce protocol overhead, multi-polling schemes are often employed.

The concept of ordered contention was first proposed in CP-Multipoll (Contention-Period Multi-Polling) [4] and slightly modified in [5] and [6]. The basic idea is that the AP announces the channel access order of STAs in the polling list via backoff value assignments. In other words, the carrier-sense multiple access with collision avoidance (CSMA/CA) access scheme is incorporated into the polling scheme except that the backoff value is controlled by the AP. After receiving the notification, all STAs set their backoff counters (in units of slot time) and start to count down after the medium is sensed to be idle for a period called Short IFS (SIFS), which is shorter than DCF IFS (DIFS) used by legacy STAs to prevent interruption. ($DIFS = SIFS + 2 \times SlotTime$ [1]) If the medium is busy, an STA freezes the counter and sets its network allocation vector (NAV) with the value carried in the duration field of the overheard frame for virtual carrier sensing. When the backoff counter reaches zero, an STA has the right to initiate its transmission for a duration as long as the allocated TXOP. The ordered-contention scheme adapts well to the *variable bit rate* (VBR) traffic.

Since the operations of the above multi-polling mechanisms require the scheduled STAs to monitor channel activity constantly, STAs which have not yet finished their transmission cannot enter the Doze state because they need to update their NAV values during others' transmission and decrease the backoff counters when the medium is idle. The overhearing problem exists in such scenario and would be more serious when there are many STAs to be polled. STAs of later orders tend to run out of their energy quickly since they spend more time to wait before accessing the medium. To the best of our knowledge, there is no PM scheme, except our previous work [16], which addresses the overhearing problem associated with the ordered-contention multi-polling mechanisms. In [16], the WTS is computed based on a heuristic algorithm and achieves satisfactory energy saving with slight sacrifice of BU. However, the proposed scheme does not maximize the energy saving under the constraint of a pre-determined loss of BU.

C. Two-Step Multi-polling Mechanism

The TSMP (Two-Step Multi-Polling) scheme [19] provides TXOP allocation with two multi-polling frames. The idea is to poll in the first step the STAs which are likely to have pending data to transmit with the *Status-Request Multipoll* (SRMP) frame to initiate the *Status Collection Period* (SCP). The polled STAs reply Status-Response frames one by one with their buffer statuses and the selected downlink rates from the channel estimation based on the received SRMP frame. After collecting the responses, the AP estimates the uplink rate for STAs. In the second step, the determined rates and the buffer statuses of STAs are used to derive an exact schedule which is then announced in the Data Transmission Multipoll frame. Since the time allocation for each STA in the *Data Transmission Period* (DTP) can be exactly derived, it seems very helpful for energy saving. However, the status collection process could bring significant time overhead since the handshaking frames should be sent with the base PHY rate.

III. ENERGY-EFFICIENT MULTI-POLLING MECHANISM

A. Network Model and Assumptions

An infrastructure *basic service set* (BSS) composed of m STAs which can hear each other within the BSS and an AP taking the responsibility of scheduling and having no energy concern as shown in Fig. 1 is considered. Assume that there are only a finite number of different applications and the traffic characteristics of all applications are known. Traffic arrival processes are assumed to be stationary, i.e., the probability distribution does not change when shifted in time. Note that the density function of required transmission time for traffic arrivals can be estimated offline via nonparametric density estimation methods such as histograms or the kernel estimator [20], or parametric methods to use a parametric pdf as an approximation. As a result, the AP can have pre-calculated traffic arrival distribution for each STA as long as it knows the applications that are admitted. We focus on protocol design of the EE-Multipoll mechanism and the scheduling strategy to maximize energy saving subject to the constraint of a pre-determined upper bound of BU loss. The related admission control is out of the scope of this paper.

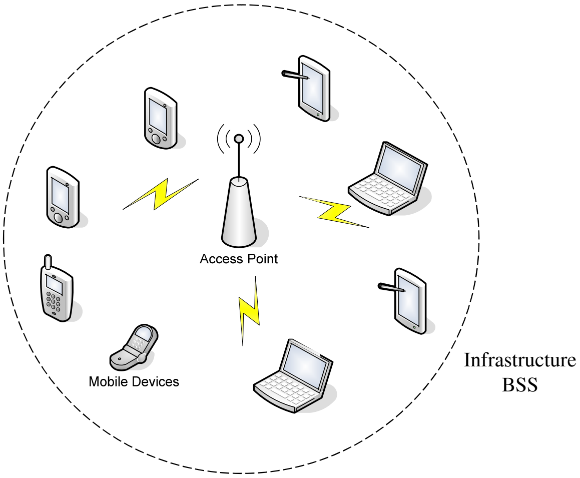

Fig. 1. The considered network scenario of the EE-Multipoll mechanism.

Octets: 2	2	6	1	6 × RecordCount				4
Frame Control	Duration /ID	BSSID	Record Count (0-255)	Poll Record (6 octets)				FCS
				AID (2 octets)	Backoff (1 octets)	Wake-up time (2 octets)	TXOP Limit (1 octets)	

Fig. 2. Suggested frame format of EE-Multipoll.

B. Mechanism Design

1) AP Operation: AP can learn the type and the number of traffic flows every STA intends to transmit/receive during the *contention-free periods* (CFP) after the join/leaving handshaking. It manages the polling list, computes the appropriate WTS from the built-in database for each STA, and periodically announces EE-Multipoll frame after beacon or at scheduled time in every scheduled *service interval* (SI). The SI represents the interval between two successive multipoll frames. To meet the QoS requirement of real-time traffic streams, the SI can be chosen such that every packet is served before its deadline. The guideline for SI selection can be found in [2] and [21].

The suggested frame format of EE-Multipoll is shown in Fig. 2. Each STA in the polling list has a corresponding poll record for its possible uplink traffic and another record for its downlink traffic, if AP has data buffered for the STA. The number of poll records is indicated in the Record Count field. The Poll Record field contains the information of the *association identifier* (AID) in the BSS, the assigned backoff value, the wake-up time (in units of slot time) relative to the receiving time of this EE-Multipoll frame, and the maximal usable duration of an aggregate TXOP for a specified STA (in units of 32μs [2]). The backoff filed is filled with the all-1s value for downlink usage. As for the uplink phase, the backoff value assignment should make sure that no two STAs have the same backoff value at any time to avoid collisions. To reduce overhead, the backoff value (in units of slot time) bt_j of STA with access order j in the uplink phase follows the rule: bt_1 = 0 and bt_j = $bt_{j-1} + 1$ for $j \geq 2$.

Fig. 3 depicts the framework of the proposed mechanism. Multipoll-capable STAs should remain awake to check the multipoll frame and update their NAVs. The AP should first serve the downlink traffic which can be exactly scheduled. Then it replies the uplink traffic with ACKs during the uplink phase. Since a polled STA can perform physical carrier sensing to determine the channel condition after it wakes up and collision can be avoided by the initial backoff assignment, the backoff value should be reduced more effectively for the busy case if the order of the ongoing transmitting STA can be learned. Hence, when AP replies ACKs to STAs, it should contain the order of the ongoing transmitting STA in the QoS Control field of the MAC header. After CFP, the remaining time of an SI will become contention period.

2) Scheduled STA Operation: Scheduled STAs should periodically awake to check the EE-Multipoll frame and achieve synchronization by listening to the beacon frames. They should keep awake to listen to the notification of EE-Multipoll frame and cannot fall back to sleep until any explicit information about their new wake-up time are successfully decoded. The announced information such as SI, backoff value, wake-up time and TXOP limit should be obeyed. To save energy, STAs not listed in the EE-Multipoll frame should enter the Doze state.

For an STA with downlink traffic, it should awake at the notified wake-up time to receive the buffered data and then back to sleep after its TXOP. As for the STA with uplink traffic, the assigned backoff value implies its access order during the uplink phase. When an STA wakes up at the assigned wake-

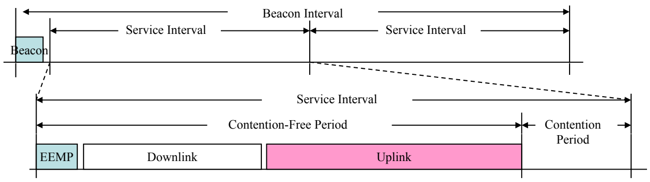

Fig. 3. The framework of the proposed EE-Multipoll mechanism.

up time, its backoff value count down process begins after the channel is sensed idle for an SIFS period. When the channel is busy, it sets the NAV and checks the access order of the ongoing STA from the overheard information. The obtained ongoing STA's order can be utilized to adjust the possessed backoff value according to the difference between the STA's access order and the obtained one. This adjustment keeps the possessed backoff values of awake STAs being unique and reduces the overhead. In case an STA cannot overhear a whole frame to identify the order of the ongoing STA or the medium is idle when the STA wakes up, it just keeps the original backoff value. Finally, when backoff value reaches zero, the STA transmits an uplink data frame to initiate its TXOP. When the frame exchanges are finished, the STAs can enter the Doze state till the transmission time of the next multipoll frame. Note that it is possible that there is no uplink frame for a polled STA in some polling round and it will remain in the Doze state till the next multipoll frame.

3) Error Recovery Issue: In a real environment, there could be transmission error and thus error recovery should be taken into account. For our scheme, the EE-Multipoll frame should be delivered at base rate to reduce error probability. Moreover, the *first STA* listed in the multipoll frame should take the responsibility of confirming the successful delivery of the multipoll frame. It should reply an ACK frame (or piggyback the confirmation on the uplink frame) when it receives the multipoll frame. In case the multipoll frame contains error and the first STA does not response as expected, the AP should retransmit the multipoll frame. To avoid failure of the first STA, the AP can change the order to let each STA take turn to be the first one. As for data frames, the immediate retransmission policy, i.e., retransmitting a data frame which is not correctly acknowledged after SIFS, can be adopted for error recovery.

IV. ENERGY-EFFICIENT WAKE-UP TIME SCHEDULE

Since the number of buffered downlink frames is completely known by AP, it can calculate the required time to derive an exact WTS. On the other hand, the latest buffer statuses of uplink traffic before polling are generally unknown to the AP. Therefore, it is challenging to estimate WTS for the uplink flows due to dynamic characteristics of VBR traffic.

In this section, we present a calculation of WTS for the proposed EE-Multipoll mechanism. Here we only address the uplink phase since the downlink WTS can be easily computed by the AP. In Part A, we first formally define the problem of optimal WTS subject to a predetermined BU loss and then provide a near-optimal feasible solution. The performance analysis is then provided in Part B. Finally, we provide the analysis about the impact of discrepancy between the real density function and the estimated one on BU performance in Part C.

TABLE I
NOTATIONS USED IN THE ANALYSIS

Notations	Descriptions
WT_i	The wake-up time of STA i, $1 \leq i \leq n$, relative to the end of the multi-poll frame.
$l(t)$	The probability density function (pdf) of required transmission time conditioning on there are traffic arrivals.
$\overline{L}$	The mean transmission time for the traffic arrival to an STA in one SI conditioning on there is something to transmit ($\overline{L} = \int_0^\infty tl(t)dt$).
$h(t)$	The pdf of the required transmission time for traffic arrivals to an STA ($h(t) = p \cdot \delta(t) + (1-p)l(t)$, where p is the probability of no traffic arrival in one SI and $\delta(t)$ represents the Dirac delta function).
$s_i(t)$	The pdf of the transmission start time for STA i if it has data to transmit.
$\overline{S_i}$	The mean transmission start time for STA i, relative to the end of the multi-poll frame, if it has data to transmit ($\overline{S_i} = \int_0^\infty ts_i(t)dt$).
$u_i(t)$	The pdf of the total duration for STAs 1, 2, ..., and i to finish their transmissions.
$U_i(t)$	The cumulative distribution function (CDF) of $u_i(t)$ ($U_i(t) = \int_0^t u_i(\tau)d\tau$).
$t_{MP}(i)$	The time for receiving and verifying a multi-poll frame which contains i STAs.

A. An Energy-Efficient Scheduling Model

Assume that there are n STAs with uplink traffic and the required transmission time for traffic arrivals to the STAs in one SI are independent, identically distributed (*i.i.d.*). The derivation is not limited to traffic of identical distributions while *i.i.d.* assumption yields more concise results.

1) Problem Formulation: Without knowledge of exact buffer statuses of STAs, the AP can only estimate the transmission time required by each STA. As a result, the system BU might have to be sacrificed if STAs are put to sleep for energy saving because it is possible that the designated wake-up time of an STA is larger than the actual total transmission time of STAs assigned to transmit before it in some SI. As such, we define the scheduling problem of EE-Multipoll as follows. The notations and their definitions used in this section are listed in Table I. In the following description, CP-Multipoll represents the ordered-contention multi-polling scheme.

Determine $\mathbf{WT_1 \leq WT_2 \leq ... \leq WT_n}$ ***to maximize energy saving subject to at most*** $x\%$ ***degradation of bandwidth utilization compared with the CP-Multipoll scheme.***

Note that the original CP-Multipoll did not take PM into account. The access scheme, however, can function normally without modifications if the SJF policy is adopted. Therefore, to compare the performance on energy saving, we assume that

SJF policy is applied and thus an STA keeps awake till the end of its transmission and then enters the Doze state. As a result, the CP-Multipoll corresponds to $WT_i = 0$ for all i, $1 \leq i \leq n$, and $x = 0$. It seems difficult to solve the above optimization problem. In the following, we present a feasible solution with an additional constraint of degrading exactly $x\%$ BU for the first i STAs for all i. Since the first STA does not have the overhearing problem, it has $WT_i = 0$ and can start to transmit after SIFS of the EE-Multipoll frame. The i^{th} STA is assigned backoff value of $(i-1)$ slots.

Consider first the BU of the CP-Multipoll scheme. To simplify analysis, we assume that all traffic arrivals in one SI are served in the following polling period. To compute the BU for the first i STAs, we assume that there are i scheduled STAs and the AP is considered as STA $(i+1)$ with an assigned backoff value i. The BU for the first i STAs, which is defined as the average time used for transmission by the first i STAs over the access start time of STA $(i+1)$, can be obtained as

$$\frac{i(1-p)\overline{L}}{t_{MP}(i)+i(1-p)\overline{L}+i\cdot \mathit{Slot}+(i(1-p)+1)\mathit{SIFS}}. \qquad (1)$$

Let us now evaluate the BU of our proposed feasible solution. Since the required transmission time (with pdf $h(t) = p\cdot\delta(t)+(1-p)l(t)$) is independent of the transmission start time (with pdf $s_i(t)$), it is clear that $u_i(t) = p\cdot u_{i-1}(t)+(1-p)(l(t)\otimes s_i(t))$, where $\otimes$ represents the convolution operation and $u_0(t) = \delta(t)$. The BU for the first i STAs is also defined by $\frac{i(1-p)\overline{L}}{t_{MP}(i)+\overline{S_{i+1}}}$ to agree with that of CP-Multipoll.

2) Solution for the Defined Problem: The process to calculate WT_i can be depicted in two steps.
1. Firstly, find the target $\overline{S_i}$ satisfying the requirement of BU.
2. Secondly, solve for WT_i making the $\overline{S_i}$ as we expected by their relationship.
The derivation, which is shown below, is done iteratively from $i = 1$ to $i = n$.

Consider the first STA with $WT_1 = 0$. We have $s_1(t) = \delta(t-\mathit{SIFS})$, $u_1(t) = p\cdot\delta(t)+(1-p)l(t-\mathit{SIFS})$, and $\overline{S_1} = \mathit{SIFS}$ is the same as that for the CP-Multipoll scheme. Now consider the second STA. The BU for the first STA is given by $\frac{(1-p)\overline{L}}{t_{MP}(1)+\overline{S_2}}$. Since the BU is allowed to degrade by $x\%$ as compared with the CP-Multipoll scheme, we have

$$\frac{t_{MP}(1)+(1-p)\overline{L}+\mathit{Slot}+(2-p)\mathit{SIFS}}{t_{MP}(1)+\overline{S_2}} = (100-x)\%. \qquad (2)$$

Therefore, the target average transmission start time for STA 2, i.e. $\overline{S_2}$, can be derived. The next step is to find a suitable WT_2 resulting in the target $\overline{S_2}$.

Since STA 2 wakes up at time WT_2, we consider the duration spent by STA 1 as WT_2 if its actual finish time is shorter than WT_2. Therefore, the average transmission start time for STA 2 is given by

$$\begin{aligned}\overline{S_2} &= U_1(WT_2)(WT_2+\mathit{SIFS}+\mathit{Slot}) \\ &\quad + \int_{WT_2}^{\infty}(t+\mathit{SIFS}+\mathit{Slot})u_1(t)dt. \end{aligned} \qquad (3)$$

We can solve for WT_2 in (3) by using the obtained $\overline{S_2}$ from (2).

With the obtained WT_2 and $u_1(t)$, the pdf of the transmission start time for STA 2 if it has data to transmit, $s_2(t)$, is then given by

$$s_2(t) = \begin{cases} 0, & \text{if } t < WT_2+\mathit{SIFS}+\mathit{Slot}. \\ U_1(WT_2)\delta(t-(WT_2+\mathit{SIFS}+\mathit{Slot})), & \text{if } t = WT_2+\mathit{SIFS}+\mathit{Slot}. \\ u_1(t-(\mathit{SIFS}+\mathit{Slot})), & \text{if } t > WT_2+\mathit{SIFS}+\mathit{Slot}. \end{cases} \qquad (4)$$

Note that STA 2 spends $\mathit{SIFS}+\mathit{Slot}$ to check the channel status before its transmission. Therefore, we have $s_2(t) = 0$ for $t < WT_2+\mathit{SIFS}+\mathit{Slot}$ because STA 2 cannot start its transmission before waking up and sensing the channel being idle for a duration of $\mathit{SIFS}+\mathit{Slot}$. For $t = WT_2+\mathit{SIFS}+\mathit{Slot}$, we have $s_2(t) = U_1(WT_2)\delta(t-(WT_2+\mathit{SIFS}+\mathit{Slot}))$ where $U_1(WT_2)$ represents the probability that the time used by STA 1 is less than or equal to WT_2. Finally, for $t > WT_2+\mathit{SIFS}+\mathit{Slot}$, it holds that $s_2(t) = u_1(t-(\mathit{SIFS}+\mathit{Slot}))$ because STA 2 starts to transmit $\mathit{SIFS}+\mathit{Slot}$ after STA 1 finishes its transmission. After $s_2(t)$ and $\overline{S_2}$ are obtained, the pdf of average total duration for STAs 1 and 2 to finish their transmissions can be derived as $u_2(t) = p\cdot u_1(t)+(1-p)(l(t)\otimes s_2(t))$. The acquired $u_2(t)$ can be used in the calculation of WT_3.

Consider now the derivation of WT_3. Since the BU for STAs 1 and 2 is given by $\frac{2(1-p)\overline{L}}{t_{MP}(2)+\overline{S_3}}$, the target $\overline{S_3}$ satisfies

$$\frac{t_{MP}(2)+2(1-p)\overline{L}+2\mathit{Slot}+(3-2p)\mathit{SIFS}}{t_{MP}(2)+\overline{S_3}} = (100-x)\%. \qquad (5)$$

Similar to the derivation of WT_2, we can obtain the average transmission start time for STA 3 as

$$\begin{aligned}\overline{S_3} &= U_2(WT_3)(WT_3+\mathit{SIFS}+2\mathit{Slot}) \\ &\quad + \int_{WT_3}^{\infty}(t+\mathit{SIFS}+\mathit{Slot})u_2(t)dt. \end{aligned} \qquad (6)$$

Similarly, we can solve for WT_3 in (6) by using the obtained $\overline{S_3}$ from (5).

Likewise, after the WT_3 is derived, the $s_3(t)$ is given by

$$s_3(t) = \begin{cases} 0, & \text{if } t \leq WT_3+\mathit{SIFS}+\mathit{Slot}. \\ u_2(t-(\mathit{SIFS}+\mathit{Slot})), & \text{if } t \in (WT_3+\mathit{SIFS}+\mathit{Slot}, \\ & \qquad WT_3+\mathit{SIFS}+2\mathit{Slot}). \\ U_2(WT_3)\delta(t-(WT_3+\mathit{SIFS}+2\mathit{Slot})), & \text{if } t = WT_3+\mathit{SIFS}+2\mathit{Slot}. \\ u_2(t-(\mathit{SIFS}+\mathit{Slot})), & \text{if } t > WT_3+\mathit{SIFS}+2\mathit{Slot}. \end{cases} \qquad (7)$$

For the first region, i.e., $t \leq WT_3+\mathit{SIFS}+\mathit{Slot}$, we have $s_3(t) = 0$ because STA 3 cannot start to transmit before waking up and sensing the channel for $\mathit{SIFS}+\mathit{Slot}$. The second region, i.e., $WT_3+\mathit{SIFS}+\mathit{Slot} < t < WT_3+\mathit{SIFS}+2\mathit{Slot}$, represents the situation that the total duration spent by STAs

1 and 2 is in between WT_3 and $WT_3 + \mathit{Slot}$. For the case that the medium is still busy after STA 3 wakes up, the sensing time for STA 3 actually depends on whether or not STA 2 has data to transmit. If it does not, then the ongoing one is STA 1 and STA 3 has to sense the channel for $\mathit{SIFS} + 2\mathit{Slot}$, the assigned backoff value plus the duration of one SIFS. On the other hand, if STA 2 has data to transmit, then STA 3 only needs to sense the channel for $\mathit{SIFS} + \mathit{Slot}$ before transmission. For simplicity, we assume that STA 2 has data to transmit in our analysis. For $t = WT_3 + \mathit{SIFS} + 2\mathit{Slot}$, we have $s_3(t) = U_2(WT_3)\delta(t - (WT_3 + \mathit{SIFS} + 2\mathit{Slot}))$ where $U_2(WT_3)$ denotes the probability that the total duration spent by STAs 1 and 2 is less than or equal to WT_3. Finally, for $t > WT_3 + \mathit{SIFS} + 2\mathit{Slot}$, we have $s_3(t) = u_2(t - (\mathit{SIFS} + \mathit{Slot}))$ because STA 3 starts its transmission $\mathit{SIFS} + \mathit{Slot}$ after STAs 1 and 2 finish their transmissions. Again, here we assume that STA 2 has data to transmit to simplify the analysis. We make similar assumption in deriving $s_k(t)$ for $k \geq 4$. In other words, we assume that STA $(k-1)$ has data to transmit if the medium is busy when STA k wakes up. In a real system, the sensing time of STA k, if medium is busy when it wakes up, is equal to $\mathit{SIFS} + (k-j)\mathit{Slot}$ if STA j is the last one to transmit before STA k does.

In general, to derive WT_k, we should first compute the target average transmission start time $\overline{S_k}$ for STA k by solving

$$\frac{t_{MP}(k-1) + (k-1)(1-p)\overline{L} + (k-1)\mathit{Slot} + (k-(k-1)p)\mathit{SIFS}}{t_{MP}(k-1) + \overline{S_k}} = (100 - x)\%. \tag{8}$$

The obtained value of $\overline{S_k}$ is then used to derive WT_k by solving

$$\begin{aligned} \overline{S_k} &= U_{k-1}(WT_k)(WT_k + \mathit{SIFS} + (k-1)\mathit{Slot}) \\ &\quad + \int_{WT_k}^{\infty} (t + \mathit{SIFS} + \mathit{Slot}) u_{k-1}(t)\,dt. \end{aligned} \tag{9}$$

Note that $u_{k-1}(t)$ and the obtained WT_k are needed to compute $s_k(t)$ as

$$s_k(t) = \begin{cases} 0, & \text{if } t \leq WT_k + \mathit{SIFS} + \mathit{Slot}. \\ u_{k-1}(t - (\mathit{SIFS} + \mathit{Slot})), & \text{if } t \in (WT_k + \mathit{SIFS} + \mathit{Slot}, \\ & \quad WT_k + \mathit{SIFS} + (k-1)\mathit{Slot}). \\ U_{k-1}(WT_k)\delta(t - (WT_k + \mathit{SIFS} + (k-1)\mathit{Slot})), & \text{if } t = WT_k + \mathit{SIFS} + (k-1)\mathit{Slot}. \\ u_{k-1}(t - (\mathit{SIFS} + \mathit{Slot})), & \text{if } t > WT_k + \mathit{SIFS} + (k-1)\mathit{Slot}. \end{cases} \tag{10}$$

The acquired $s_k(t)$ and $u_{k-1}(t)$ can be used to compute $u_k(t)$ as $u_k(t) = p \cdot u_{k-1}(t) + (1-p)(l(t) \otimes s_k(t))$ which is required in the calculation of WT_{k+1}.

3) Implementation Issues: The bisection method can be adopted to solve for WT_i. The initial values for the lower bound and the upper bound can be selected as WT_{i-1} and $\overline{S_i} - \mathit{SIFS} - \mathit{Slot}$, respectively. In real implementation, the WT_i can only be represented by finite precisions. Therefore, the solving process of WT_i is stopped when both the precision has been met and the resulted degradation of BU is smaller than the constraint of our defined optimization problem.

Retransmission caused by channel error can be easily incorporated in the computation of WTS. Let A be the random variable for the transmission time of an STA without channel error. Assume that frame error probability is q. All we need to do is to compute the WTS with the modified random variable $B = (1+q)A$. Moreover, since the hardware delay should be taken into account in a real system, WT_i will be compared with the *hardware delay* D once it is derived:

$$WT_i = \begin{cases} WT_i, & \text{if } WT_i > D. \\ 0, & \text{if } WT_i \leq D. \end{cases} \tag{11}$$

B. Analysis of Energy Efficiency

Let us now evaluate the energy saved by our proposed EE-Multipoll scheme with the WTS for the uplink phase. Let P_A and P_D denote the power consumption in the Awake state and the Doze state, respectively. Here we consider the energy consumption during each SI.

1) The CP-Multipoll with SJF: For the CP-Multipoll scheme corresponding to $WT_i = 0$ for all i, $1 \leq i \leq n$, STA i will stay in the Awake state for an average duration of

$$A_{CPMP}(i) = \begin{cases} (1-p)(\mathit{SIFS} + \overline{L}), & \text{if } i = 1. \\ (1-p)\Big[\overline{L} + p^{i-1}(\mathit{SIFS} + (i-1)\mathit{Slot}) \\ \qquad + \int_{0^+}^{\infty} (t + \mathit{SIFS} + \mathit{Slot}) u_{i-1}(t)\,dt\Big], & \text{if } i > 1. \end{cases} \tag{12}$$

For the case that $i > 1$, the term $p^{i-1}(\mathit{SIFS} + (i-1)\mathit{Slot})$ represents the time spent on waiting if all STAs before STA i do not have data to transmit, while the term $\int_{0^+}^{\infty} (t + \mathit{SIFS} + \mathit{Slot}) u_i(t)\,dt$ denotes the waiting time (with some simplification on sensing time) for the situation that at least one of the STAs has data to transmit. Therefore, the energy consumed by STA i, denoted by E_i, is given by $E_i = [t_{MP}(n) + A_{CPMP}(i)]P_A + [SI - t_{MP}(n) - A_{CPMP}(i)]P_D$. Consequently, the average total energy consumed by n STAs, denoted by E_{CPMP}, can be obtained as

$$\begin{aligned} E_{CPMP} &= \sum_{i=1}^{n} E_i \\ &= \Big[\sum_{i=1}^{n} (A_{CPMP}(i) + t_{MP}(n))\Big] P_A + \\ &\quad \Big[n \cdot SI - \sum_{i=1}^{n} (A_{CPMP}(i) + t_{MP}(n))\Big] P_D. \end{aligned} \tag{13}$$

2) The proposed EE-Multipoll with wake-up time schedule: Now consider the i^{th} STA in our proposed EE-Multipoll scheme. The average time staying in the Awake state equals

$$A_{EEMP}(i) = \begin{cases} (1-p)(\mathit{SIFS} + \overline{L}), & \text{if } i = 1. \\ (1-p)(\overline{L} + \mathit{sensing}_i + \mathit{overhearing}_i \\ \qquad + \mathit{hw\_delay}_i), & \text{if } i > 1. \end{cases} \tag{14}$$

The term $\mathit{overhearing}_i = \int_{WT_i^+}^{\infty} (t - WT_i) u_{i-1}(t)\,dt$ represents the average time for STA i to wait for STAs 1, 2, ..., and $(i-1)$ to finish their transmissions after it wakes up. The term $sensing_i = U_{i-1}(WT_i)[SIFS + (i-1)Slot] + \int_{WT_i^+}^{\infty} (SIFS + Slot)u_{i-1}(t)dt$ represents the average time STA i spent on sensing the channel. Additionally, the term $hw\_delay_i = D - (D - WT_i)^+$ stands for the required time of hardware delay for STA i which consumes roughly the same power as in the Awake state during this period [13]. The $(y)^+$ equals y if $y > 0$ or 0 if $y < 0$.

Let E_{EEMP} be the average total energy consumed by n STAs in one SI for our proposed feasible solution. Similar to the analysis of CP-Multipoll, we have

$$\begin{aligned} E_{EEMP} &= \Big[\sum_{i=1}^{n}(A_{EEMP}(i) + t_{MP}(n))\Big]P_A + \\ &\quad \Big[n \cdot SI - \sum_{i=1}^{n}(A_{EEMP}(i) + t_{MP}(n))\Big]P_D. \end{aligned} \tag{15}$$

Finally, compared with the CP-Multipoll scheme with SJF, the percentage of energy saved by our proposed feasible solution is equal to $100(E_{CPMP} - E_{EEMP})/E_{CPMP}$.

C. Impact of Estimation Discrepancy

Since there could be estimation error for the pdf ($h(t)$ and the corresponding $u_{i-1}(t)$), the actual degradation of BU is likely to deviate from the desired value. The impact of estimation discrepancy is analyzed below. Assume that we have derived the wake-up time WT_i for STA i from the expected $x\%$ loss of BU, the expected transmission start time $\overline{S_i}$, and the approximated pdf $u_{i-1}(t)$. Let $\overline{S_{r,i}}$ denote the actual expected transmission start time for STA i given WT_i and the actual traffic with pdf $u_{r,i-1}(t)$. Also, let the actual loss of BU be $y\%$.

Denote the estimation error of pdf by $e_{i-1}(t) := u_{r,i-1}(t) - u_{i-1}(t)$. Then the discrepancy of expected transmission start time can be expressed as:

$$\begin{aligned} ER_i &:= \overline{S_{r,i}} - \overline{S_i} \\ &= \int_0^{WT_i} (WT_i + SIFS + (i-1)Slot)e_{i-1}(t)dt \\ &\quad + \int_{WT_i}^{\infty} (t + SIFS + Slot)e_{i-1}(t)dt. \end{aligned} \tag{16}$$

We can find the relationship between the expected BU loss and the actual one by ER_i.

$$\begin{aligned} y &= \frac{100(\overline{S_{r,i}} - S_{CPMP,i})}{t_{MP}(i-1) + \overline{S_{r,i}}} \\ &= \frac{100(ER_i + \overline{S_i} - S_{CPMP,i})}{t_{MP}(i-1) + ER_i + \overline{S_i}} \\ &= \frac{x(t_{MP}(i-1) + S_{CPMP,i}) + (100-x)ER_i}{(t_{MP}(i-1) + S_{CPMP,i}) + \frac{100-x}{100}ER_i}, \end{aligned} \tag{17}$$

where $S_{CPMP,i} = (i-1)(1-p)\overline{L} + (i-1)Slot + (i-(i-1)p)SIFS$. Clearly, if $x(t_{MP}(i-1) + S_{CPMP,i}) \gg ER_i$, then y is close to x. The condition tends to be true when i is large and/or every STA transmits a large number of frames.

TABLE II
SYSTEM PARAMETERS

Parameter	Value
PHY Data Rate	54 Mbps
PHY Control Rate	6 Mbps
Transmission time for PHY header and preambles	20 μs
Transmission time for an OFDM symbol	4 μs
SIFS	16 μs
Slot Time	9 μs
MAC frame header	30 bytes
ACK frame	14 bytes
IP header	20 bytes
UDP header	8 bytes
RTP header	12 bytes
Service Interval	25 ms
Beacon Interval	100 ms
Power Consumption in Awake state	1.4 W
Power Consumption in Doze state	0.045 W
Hardware delay of switchover	250 μs

V. PERFORMANCE EVALUATION

Three examples are studied for the proposed WTS strategy. System parameters are shown in Table II. The PHY parameters which conform to the IEEE 802.11a standard are available in [9]. More available non-overlapping channels in the 5 GHz band provide better flexibility to avoid interference. The power consumption in either state is according to [10]. Since the time spent on sensing is simplified in analysis, we conduct computer simulations using Matlab [18] as a comparison to reflect the real situation. The TSMP scheme is also studied in our simulations. An STA can enter the Doze state in both SCP and DTP, if it is worthy of energy saving. The considered scenario is composed of n STAs, $1 \leq n \leq 20$, with *i.i.d.* traffic in an infrastructure BSS with an AP. We allow 5% degradation of BU when deriving the proposed WTS for the examples.

A. Example 1

Assume that the pdf $h(t) = p \cdot \delta(t) + (1-p)\delta(t - \overline{L})$, where $\overline{L}$ represents the time for exchanging a constant-length Data frame. The case of $p = 0.6$ is considered because it is a typical model for an on-off voice connection [19]. The frame exchange time, denoted by $\overline{L}$, is chosen to be $200\mu s$ which is equivalent to the transmission time of a 200-byte VoIP frame. The mean and standard deviation of the traffic model are $\mu = 0.4\overline{L}$ and $\sigma = \sqrt{0.24}\overline{L}$, respectively. Fig. 4(a) shows the BU loss obtained from simulations for the first n STAs. As revealed in this figure, the analytical results are quite accurate since the maximum error is under 2.5%. The first 4 STAs have no loss of BU since the original wake-up times are smaller than the time of switchover and thus have wake-up time zero. The simulation result is slightly larger than the planned 5% for STAs after STA 5. The reason is that the sensing time of an STA is slightly underestimated for the busy channel

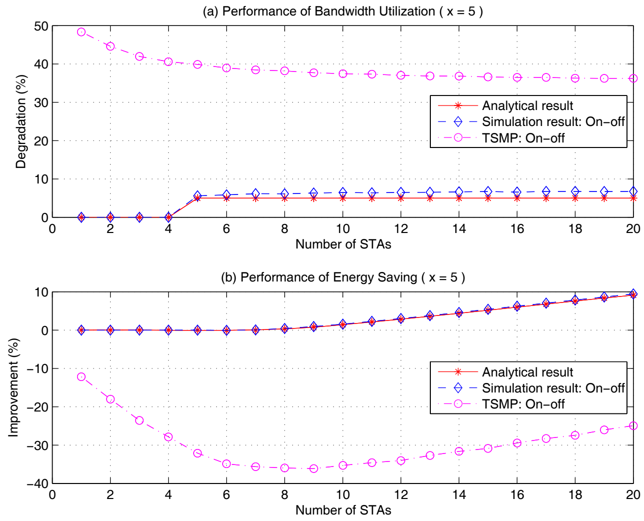

Fig. 4. Performances of the derived wake-up time schedule for Example 1.

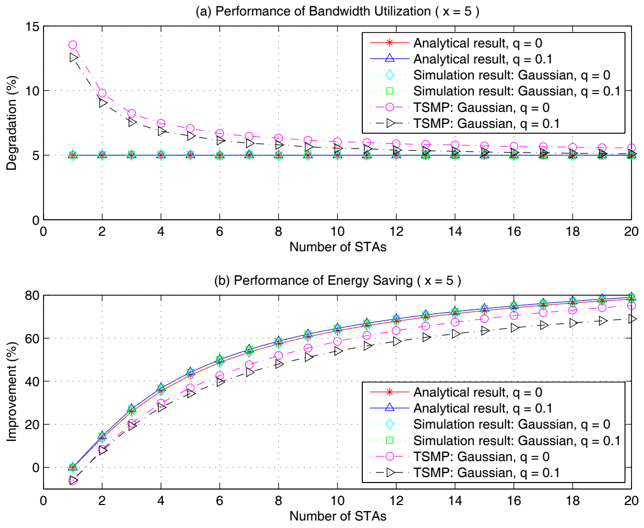

Fig. 5. Performances of the derived wake-up time schedule with different frame error rates for Example 2.

case and thus resulting in more optimistic wake-up time estimation. Fig. 4(b) shows the energy-saving performance of the proposed WTS compared with the CP-Multipoll. The energy saved increases as the number of STAs increases since the overhearing problem is getting severer for more STAs. As for TSMP, there is no trade-off between energy saving and BU because the transmission time of each STA is exactly known. However, the SCP represents a significant overhead to affect BU, especially when each STA only demands short transmission time as shown in this example. Note that the loss of BU decreases as the number of STAs increases because the effect of the fixed fields in the multipoll frame diminishes. The energy saving performance shown in Fig. 4(b) decreases initially since STAs need to spend more energy in the SCP. However, it is gradually improved when there are more than 9 STAs. The reason is that it becomes worthy for some STAs to switch states to save energy during the SCP.

B. Example 2

In the second example, we assume that pdf $h(t) = \frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(t-\mu)^2}{2\sigma^2}}$ with $\mu = 1000\mu s$ and $\sigma = 200\mu s$ to model the aggregated traffic of multiple connections from an STA. Since the required transmission time cannot be negative, a new value is generated if a negative transmission time is obtained. We also study the impact of channel error in this example. The immediate retransmission scheme is adopted as the error recovery strategy. The frame error rate q is set to 0.1. Fig. 5(a) shows the BU degradation obtained with simulations. Note that the curves for analytical and simulation results cannot be distinguished clearly because they are almost identical. The situation of underestimated sensing time, as shown in Example 1, does not appear in this example. The reason is that the probability for an STA to have zero required transmission time is zero for continuous transmission time case. Fig. 5(b) illustrates the energy- saving performance of the proposed WTS, compared with the CP-Multipoll. The saved energy is about 80% for 20 STAs that is much higher than 10% obtained for Example 1. The reason is that the coefficient of variation (σ/μ) of the traffic model and the impact of overhead such as sensing and switchover time of this example are smaller than those for Example 1. The TSMP scheme performs much better in this example since the impacts of SCP on BU and energy saving are relatively smaller due to larger transmission time for each STA in this example. However, the proposed WTS with the EE-Multipoll scheme still outperforms TSMP for both comparisons due to less overhead. In Fig. 5(b), the energy saving performance of TSMP declines by 6.1% from $q = 0$ to 0.1 because retransmissions delay the original transmission schedule and become a new source of overhearing which cannot be exactly predicted. For the EE-Multipoll mechanism with WTS considering retransmission time in advance, the improvement in energy saving is slightly increased since the overhearing problem of CP-Multipoll is aggravated in erroneous situation.

We also investigated the performance of the proposed WTS for this traffic model with different standard deviations. Table III shows the wake-up times of STAs, the corresponding target average access start times, and the saved energy for a network consisting of 8 STAs. To meet the same constraint of BU loss, STAs have to wake up earlier if the standard deviation is larger. This is intuitively true since higher standard deviation results in more conservative estimates. The saved energy decreases by 5.21% as the standard deviation increases from 100 to 300.

C. Example 3

In this example, we study the performance of using Normal distribution as an approximation of the density function of true traffic arrivals. The traffic arrivals are assumed to follow the Poisson and the Exponential distributions with identical means selected to be $1000\mu s$. As shown in Fig. 6, using Normal distribution as an approximate traffic model yields satisfactory results. As the number of STAs increases, the losses of BU for both traffic models approach the desired value, i.e., 5%. We believe that it is a consequence of the Central Limit Theorem. Based on the observations, we suggest using Normal distribution as traffic model to reduce the complexity when

TABLE III
THE WTS FOR DIFFERENT STANDARD DEVIATIONS, THE TARGET TRANSMISSION START TIME, AND THE CORRESPONDING ENERGY SAVING PERFORMANCES.

STA i	2	3	4	5	6	7	8
$\overline{S_i}$ (μs)	1099	2179	3258	4337	5417	6496	7576
WT_i (std $= 100$ μs)	1051	2112	3180	4245	5318	6388	7465
Energy saved for the first i STAs (%)	15.22	28.08	37.76	45.16	50.98	55.65	59.49
WT_i (std $= 200$ μs)	969	1998	3045	4100	5166	6225	7305
Energy saved for the first i STAs (%)	13.57	25.89	35.41	42.80	48.66	53.40	57.34
WT_i (std $= 300$ μs)	866	1851	2871	3900	4955	5981	7030
Energy saved for the first i STAs (%)	11.43	23.04	32.32	39.63	45.54	50.31	54.28

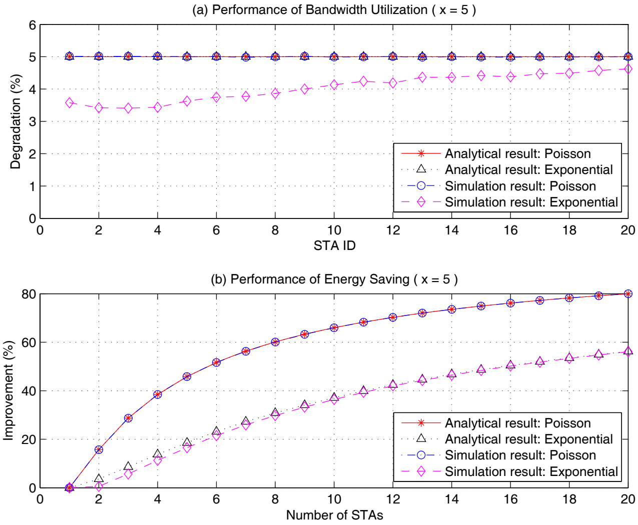

Fig. 6. The deviation of using Normal distribution as traffic model.

accurate estimation of pdf is difficult. For Normal distribution, only estimates of mean and variance are needed.

VI. CONCLUSION

Current ordered-contention multi-polling schemes significantly improve BU by reducing control overhead. However, they suffer from useless energy consumption caused by overhearing which may largely decrease battery operating time. To solve the overhearing problem, we provide a PM method which aims to achieve maximum energy saving subject to a pre-defined degradation on BU. The derivations of WTS and saved energy are verified with computer simulations. According to numerical results, the saved energy is significant as compared with the original ordered-contention multi-polling schemes, especially when there are a large number of STAs. Moreover, when compared with the TSMP scheme, the simulation results reveal that the TDMA-like access method may not guarantee to bring better energy-saving performance since the prior handshaking can cause significant overhead to STAs. An interesting and challenging further research topic is to efficiently incorporate QoS guarantee into the proposed EEMP mechanism.

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