Power-Saving Strategy for Balancing Energy and Delay Performance in WLANs

Daewon Jung, Ryangsoo Kim, and Hyuk Lim

Abstract

In wireless local area networks (WLANs), power conservation for mobile devices is considered as one of the most important issues because it effectively prolongs the battery life of mobile devices. The IEEE 802.11 standard specifies a power-saving mode that allows mobile nodes to adaptively operate in sleep and wake modes to reduce the overall energy consumption. In the IEEE 802.11 power-saving mode, the access point (AP) can adjust the number of nodes in wake mode at every beacon interval. In this paper, we first investigate how the number of nodes in wake mode affects both energy consumption and delay performance in WLANs. We then propose a balanced power-saving strategy, which determines an appropriate number of nodes in wake mode based on a trade-off between energy consumption and packet delay. Through a performance analysis and extensive simulations, we show that our proposed scheme effectively reduces overall energy consumption while retaining low packet delay.

Index Terms

Energy efficiency, Packet delay, IEEE 802.11 PSM, WLANs.

I. Introduction

Driven by the increasing popularity of hand-held devices with wireless networking interfaces such as smart phones, personal media players, and e-book readers, wireless local area networks (WLANs) are rapidly growing and are widely deployed in hotels, airports, and community areas.

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In those places, WLAN hotspots provide wireless internet connectivity to mobile users with Wi-Fi enabled laptop and portable devices. Since hand-held devices are generally powered by a limited battery supply, minimizing energy consumption is a critical factor in prolonging the operation time of these wireless devices.

As specified in the IEEE 802.11 standard, IEEE 802.11-based wireless devices can choose one of two modes: (i) continuously active mode, and (ii) power-saving mode (PSM) [1]. In continuously active mode, a wireless radio is always powered on so that wireless users can perform data transmission or data reception at any time. However, this mode may be inefficient in terms of energy conservation. To prevent inefficient energy usage, the IEEE 802.11 wireless LAN standard specifies a power-saving mode called IEEE 802.11 PSM. A node in PSM can adjustably turn on and off its wireless radio to improve the energy efficiency; a wireless radio is turned on in *awake* state and off in *sleep* state. In PSM, staying in sleep state consumes much less battery power than staying in awake state. Note that the sleep state consumes at least an order of magnitude less power than in the active state [2].

In the PSM of IEEE 802.11 wireless networks, the access point (AP) buffers all incoming data frames destined to any of its associate nodes that are in the IEEE 802.11 PSM mode. At every beacon interval, which is typically set to 100 ms, if the AP has buffered frame for the nodes, the AP informs the nodes whether it has data buffered in the buffer through a traffic indication map (TIM) in a beacon message. During an association process between the AP and nodes, a unique association ID (AID) code is assigned to each node. Each bit of the TIM represents the AID code of a node. For example, if the bit for a specific node is not set to 1 in the TIM, then the node switches to sleep mode to reduce power consumption. Otherwise, the node has to stay in wake mode to download the buffered frames from the AP. In order to check the existence of data frames in the AP buffer, each PSM node periodically wakes up and listens to beacon messages. We emphasize here that the number of nodes in wake mode depends on how to set the AID field in IEEE 802.11 PSM. Unfortunately, the IEEE 802.11 standard does not specifically address how to decide the set of nodes in wake mode at each beacon interval. [1] When a node decides to stay in wake mode, it prepares to send a power-save poll (PS-POLL) frame by means of the IEEE 802.11 Distribution Coordination Function (DCF) procedure. After the AP successfully

[1] The maximum number of awake nodes indicated in the TIM field is 2008 [1].

receives the PS-POLL frame, it responds to the PSM node with a data frame. Once the data frame is received without errors, the node sends an acknowledgement to the AP.

Consider a WLAN hotspot where an AP serves a high volume of data traffic for many client nodes. If the AP fails to transmit all the pending packets within a limited beacon interval time, a set of nodes indicated in a TIM message should stay in wake mode, but do not receive the data frames from the AP. Because staying in wake mode requires a high level of energy consumption, a number of nodes in wake mode unnecessarily consume their battery power.

In the context of IEEE 802.11 PSM-based networks, we consider the effect of the number nodes staying in wake mode on energy consumption and MAC service delay performance. On the basis of the performance analysis, we propose a balanced power-saving mechanism that determines the appropriate number of nodes in wake mode based on a trade-off between energy consumption and MAC service delay performance.

The remainder of this paper is organized as follows. In Section II, we provide a summary of related work in the literature. Section III includes an overview of IEEE 802.11 PSM and the power consumption operation of an IEEE 802.11 PSM node. We then introduce our analytical model for power consumption and packet delay in IEEE 802.11 PSM. In Section IV, we propose a power-saving strategy to determine the appropriate number of nodes in wake mode by considering a trade-off between power consumption and packet delay. This is then followed by a performance evaluation in Section V. Finally, we conclude this paper in Section VI.

II. Related Work

There exist abundant research results on improving the energy efficiency of wireless networks including WLANs and wireless sensor networks (WSNs). In [3], Ting *et al.* showed that the idle listening time is very important for power conservation in IEEE 802.11 devices, and they tried to shorten this idle listening time. They proposed an idle listening and light sleeping mode, in which wireless devices wake up at the beginning and end of a DIFS interval, to alleviate energy consumption during the DIFS and back-off idle time. In [4], Lin *et al.* proposed a wake-up scheduling method, which arranges the wake-up nodes evenly in each beacon interval by scheduling the nodes to be waken up in sleep mode. This method can reduce overall energy consumption by reducing the collision probability of mobile nodes. In [5], He *et al.* proposed a scheduled PSM protocol based on time slicing, in which the STAs switch to wake mode at pre-defined slots. This protocol minimizes the channel idle time, thereby maximizing energy conservation. In [6], Krashinsky *et al.* presented the interaction between IEEE 802.11 PSM and TCP performance for Web data transfers, and proposed a bounded slowdown (BSD) protocol that guarantees bounded delay performance while reducing energy consumption. The BSD exploits past activities of each node to determine a sleep duration of network interface until there exists no activity.

The energy conservation is also one of the most important design goals in the WSNs. In [7], Fang *et al.* investigated the advantage of cooperative communication for energy conservation in WSNs. It has been shown that the cooperative communication against unreliable wireless links can improve the energy efficiency as well as data transmission performance. The proposed energy-efficient cooperative communication scheme in [7] exploits packet overhearing at nearby nodes and relays the overheard packets to its destinations in order to compensate with packet losses. In [8], He *et al.* presented an energy optimization framework for cognitive radio that can reduce energy consumption of wireless devices by adapting modulation, coding rate, coding gain, transmission power, and radio component characteristics such as power amplifier efficiency. This framework also considered quality of service (QoS) requirement of applications to minimize the energy consumption while guaranteeing a certain level of QoS performance. However, the proposed energy saving mechanism in [8] is adaptable only for cognitive communications with programmable radio components.

Recently, the use of IEEE 802.11 PSM for QoS-aware applications has been extensively studied in [9], [10]. In [9], Adams and Muntean proposed an adaptive-buffer power save mechanism (AB-PSM) for supporting mobile multimedia streaming. This method uses an extra application-layer buffer so that the nodes are able to sleep for a long period. In [10], Agarwal *et al.* devised an energy management architecture called Cell2Notify, which aimed to improve the power consumption efficiency of IEEE 802.11 PSM nodes while preserving QoS using the voice over internet protocol (VoIP). Cell2Notify turns on and off the Wi-Fi interface with respect to incoming VoIP service requests. However, the Cell2Notify power saving architecture requires each wireless node to be equipped with at least two wireless network interfaces for receiving service requests.

One of the most relevant work to our study was done by Lee *et al.* [11]. They proposed a beacon management scheme that restricts the number of nodes in wake mode in each beacon interval. In this scheme, the number of nodes in wake mode is set to the maximum number of packets to be delivered according to the transmission duration and beacon interval. Compared with [11], our proposed scheme mainly considers a trade-off between energy consumption and packet delay in congested WLANs. The main contributions of this paper are summarized as follows.

1) We provide an analytical model for the power consumption and packet delay of IEEE 802.11 PSM in WLANs.
2) We propose a power-saving strategy to determine the number of nodes in wake mode that efficiently balances energy consumption and packet delay performance. Our proposed balanced energy-saving strategy directly complies with IEEE 802.11 PSM.

III. Power-Saving Mode in IEEE 802.11 Infrastructure

A. Overview of IEEE 802.11 PSM

The IEEE 802.11 standard provides a PSM to reduce overall energy consumption. In infrastructure wireless networks, the AP transmits a beacon frame at every beacon interval. The TIM field in the beacon frame contains the buffering status, which indicates the nodes that are the destinations of data frames buffered by the AP. Furthermore, the IEEE 802.11 PSM nodes periodically wake up to obtain the buffering status through the beacon message. Whenever a node successfully receives the beacon message, it checks whether there are frames buffered by the AP destined for it. If the address of a node is included in the TIM field, the node should stay in wake mode to receive buffered data frames from the AP. In contrast, if the TIM message does not include the address of a node, the corresponding node switches to sleep mode, because the AP does not have any data frame destined for it. In other words, after receiving a beacon message from the AP, a node can determine whether it needs to stay in wake mode.

Once the nodes decide to stay in wake mode, they start to transmit PS-POLL frames to the AP by using the back-off mechanism of the IEEE 802.11 DCF protocol. The node with the smallest back-off number is the first to transmit a PS-POLL frame to the AP. After the AP successfully receives the PS-POLL frame, it transmits data frames to the node that successfully sent the PS-POLL frame. Whenever the AP transmits a data frame to the node, the AP indicates whether it has more data frames destined for the node by including a More-Data-Bit (MDB) in the data frame. By setting the MDB to 1, the AP signals that it has more buffered frames

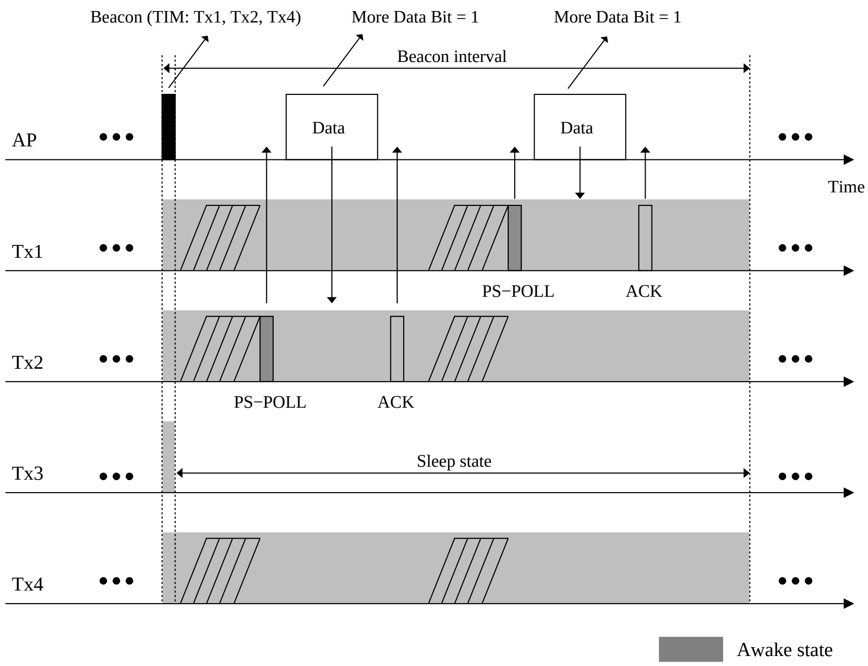


Fig. 1. Example of IEEE 802.11 PSM operation in infrastructure WLANs.

destined for the node, so that the node should stay in wake mode. Otherwise, the node goes into sleep mode to reduce energy consumption. After the node finishes receiving the data frame, it immediately sends an ACK frame to the AP.

Figure 1 shows an example of IEEE 802.11 PSM operation in infrastructure WLANs. Upon receiving the beacon frame, the IEEE 802.11 PSM nodes decide whether to stay in wake mode. In the example, Tx1, Tx2, and Tx4 decide to stay in wake mode, while Tx3 switches to sleep mode because it is not indicated in the TIM message. Consequently, Tx1, Tx2, and Tx4 remain in idle, receiving, and transmitting states, respectively, and hence they consume significant amounts of power. In contrast, Tx3 stays in sleep mode and rarely consume battery power.

B. Power consumption in IEEE 802.11 PSM

In Figure 1, Tx3 should stay in sleep mode while the other nodes (Tx1, Tx2, and Tx4) stay in wake mode for the beacon interval. In IEEE 802.11 PSM-based networks, the nodes switch to sleep, idle listening, and Tx/Rx states depending on the operation status. Detailed explanations of each state are as follows.

TABLE I

POWER CONSUMPTION OF WIRELESS INTERFACE CARDS.

Mode of NIC	Power consumption (mW)	
	Wavelan 2.4 GHz	Dell TrueMobile 1150
Sleep state	177	99
Idle listening state	1319	660
Receiving state	1425	759
Transmit state	1675	1089

- Sleep state: On receiving the beacon frame, the node checks whether the AP has buffered data frames destined for it through the TIM field. When the TIM frame does not indicate the existence of the buffered frames, the node is to sleep according to the PSM until the next beacon interval. In Figure 1, only Tx3 goes to the sleep state after it receives the beacon frame.
- Transmission and receiving states: The nodes that have decided to stay in wake mode perform the back-off mechanism in IEEE 802.11 PSM. The node with the smallest back-off number among the nodes in wake mode attempts to transmit its PS-POLL packet. Then, the AP sends the data frame, and consequently receives the corresponding ACK frame. In other words, each data frame is downloaded by means of PS-POLL-data-ACK frame sequences. In Figure 1, Tx1 and Tx2 consume transmitting power for modulating and sending packets to the air, and receiving power for detecting and demodulating the packets.
- Idle listening state: When the nodes are in an idle listening state, they continuously listen to the medium. This state includes the operations for checking whether the wireless channel is idle, waiting for incoming packets, and receiving packets not destined to itself. Therefore, the idle listening state consumes as much power as packet transmission and packet reception. In Figure 1, Tx4 consumes idle listening power during one beacon interval.

Table I lists the power consumptions of an off-the-shelf network interface cards (NICs) in sleep, idle, receiving, and transmitting states. Nodes that are not indicated in the TIM message of the beacon frame turn their radios off, and consume only the relatively small amount of power corresponding to the sleep state.

On the basis of the above observations, we evaluate power consumption and packet delay in IEEE 802.11 PSM-based wireless networks. Then, we formulate the problem of optimizing the number of nodes staying in wake mode to balance energy consumption and packet delay.

IV. Analytical modeling

In this section, we derive two important performance metrics for IEEE 802.11 PSM: power consumption and MAC service delay. We then show how the number of nodes in wake mode affects two performance metrics. In this model, it is assumed that each node always has pending data packets at the AP under a saturation condition, and all nodes operate on the IEEE 802.11 PSM mode. For simplicity, it is assumed that the buffer size of the AP is large enough to fully utilize the beacon interval and the wireless channel is error-free such that the transmission failures are only caused by packet collisions due to two or more simultaneous transmissions. In this paper, we consider a downlink case for one-hop network, where one AP is located at the center of the network and the other nodes are uniformly distributed around the AP. We also consider that the energy consumed in the sleep state is negligible, because the power consumed in the sleep state is considerably less than that consumed in the other states, such as the idle, transmission, and receiving states.

We now introduce the notations used in the analytical model derived in this study.

1) N and N_{awake} : The total number of IEEE 802.11 PSM nodes, and the number of nodes in wake mode, respectively.
2) σ, T_s, and T_c: The durations of one idle slot, a successful transmission, and a collision, respectively.
3) PW_{idle}, PW_{tx}, and PW_{rx}: The power consumed in the idle, transmission, and receiving states, respectively.
4) E_{idle}, E_{succ}, and E_{coll}: The total energy consumption in the case of idle, success, and collision, respectively.

A. Power consumption modeling

In IEEE 802.11 PSM, each node decides whether to stay in wake mode or go into sleep mode after receiving the TIM message sent by the AP. On receiving the beacon message at every frame, N_{awake} nodes stay in wake mode, while $(N - N_{\text{awake}})$ nodes go into sleep mode to conserve their battery power. Then, each node in wake mode performs the back-off mechanism of IEEE 802.11 DCF to transmit its PS-POLL frame.

Given N_{awake} and the transmission probability of each node (τ), successful transmissions occur only when exactly one node in wake mode transmits and the other $(N_{\text{awake}} - 1)$ nodes defer their transmission as done in [14]. Under this condition, the probability that a transmission is successful (P_s) is readily obtained by

$$P_s = \frac{N_{\text{awake}}\tau(1-\tau)^{N_{\text{awake}}-1}}{P_{tr}}, \tag{1}$$

where P_{tr} is the probability that there is at least one transmission in a slot and is given by $P_{tr} = 1 - (1-\tau)^{N_{\text{awake}}}$. Further, the average length of one time slot in IEEE 802.11 PSM, denoted by l, is given in [14] by

$$l = (1 - P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1 - P_s)T_c. \tag{2}$$

In IEEE 802.11 PSM, the successful and collision times are given by

$$\begin{aligned} T_s &= T_{\text{POLL}} + T_{\text{DATA}} + T_{\text{ACK}} + 2 \cdot SIFS \\ T_c &= T_{\text{POLL}} + DIFS, \end{aligned} \tag{3}$$

where T_{POLL}, T_{DATA}, and T_{ACK} denote the transmission durations for PS-POLL, DATA, and ACK frames, respectively.

We now consider overall power consumption in a network where N_{awake} nodes (among a total of N nodes) stay in wake mode. In order to compute the power consumption, we consider the following three cases: energy consumption in the case of idling (E_{idle}), successful transmission (E_{succ}), and collision (E_{coll}).

(1) Energy consumption during a period of idle status (E_{idle}): When the channel is idle, all the nodes in wake mode consume the idle power (PW_{idle}) such the energy consumption of idle status in the network is expressed as

$$E_{\text{idle}} = N_{\text{awake}} \cdot \sigma \cdot PW_{\text{idle}}. \tag{4}$$

(2) Energy consumption during a period of the successful transmission (E_{succ}): When only one PSM node is transmitting in the network, the transmission is successfully performed. During this transmission time, $(N_{\text{awake}} - 1)$ nodes should stay in idle mode. The transmitter consumes

only the transmission power (PW_{tx}) and the reception power (PW_{rx}) for transmitting PS-POLL and ACK frames and receiving the data frame, respectively. Therefore, E_{succ} is computed as

$$\begin{aligned} E_{\text{succ}} &= (T_{\text{POLL}} + T_{\text{ACK}})PW_{\text{tx}} + T_{\text{DATA}}PW_{\text{rx}} \\ &\quad + (N_{\text{awake}} - 1)T_s PW_{\text{idle}}. \end{aligned} \tag{5}$$

(3) Energy consumption during a period of collision (E_{coll}): When two or more nodes in wake mode transmit their PS-POLL frames simultaneously, collisions occur. During this period, the transmitting nodes consume the transmission power to transmit the PS-POLL frames. In contrast, the rest of the nodes in wake mode consume the idle power. Hence, E_{coll} is given by

$$E_{\text{coll}} = N_{\text{coll}} T_c PW_{\text{tx}} + (N_{\text{awake}} - N_{\text{coll}}) T_c PW_{\text{idle}}, \tag{6}$$

where N_{coll} is the average number of colliding nodes when two or more nodes simultaneously attempt to access the channel under the collision condition. Hence, N_{coll} is given as

$$N_{\text{coll}} = \frac{\sum_{i=2}^{N} i \cdot \binom{N_{\text{awake}}}{i} \cdot \tau^i \cdot (1-\tau)^{(N_{\text{awake}}-i)}}{P_{tr} \cdot (1 - P_s)}, \tag{7}$$

where i denotes the number of simultaneously transmitting nodes.

We now derive the the average consumed power in IEEE 802.11 PSM-based networks (denoted by $E[P]$) as the ratio of the average amount of energy consumption for idle, successful transmission, and collision cases during a slot time to the average time duration of a slot time. Therefore, $E[P]$ can be computed as

$$E[P] = \frac{(1 - P_{tr})E_{\text{idle}} + P_{tr}P_s E_{\text{succ}} + P_{tr}(1 - P_s)E_{\text{coll}}}{l}. \tag{8}$$

B. MAC delay modeling

We now compute the MAC downlink delay (from the AP to a node) when there exist N_{awake} nodes at every beacon interval on average. In IEEE 802.11 PSM, the nodes that have not been selected to be in wake mode should wait for the next beacon interval to transmit their PS-POLL messages. This implies that if a small number of nodes in wake mode have been indicated in the TIM message, the average MAC delay significantly increases. On the other hand, if there are a large number of nodes in wake mode, these nodes may experience a long packet delay owing to severe congestion among themselves.

Let D_{awake} be the average MAC delay when the node has been chosen to be in wake mode together with other nodes. Under the assumption that the beacon interval is long enough, the average MAC delay of IEEE 802.11 PSM-operated nodes is the same as in normal IEEE 802.11 DCF operation. The only difference is that the number of active nodes is N_{awake} in IEEE 802.11 PSM, while all nodes are in a continuously active mode. In [12], the average packet delay for a successfully transmitted packet (defined by D_{awake}) is well defined, and given by

$$D_{\text{awake}} = \sum_{j=0}^{M} \{(T_s + jT_c + l \sum_{i=0}^{j} \frac{W_i - 1}{2}) \frac{p^j(1-p)}{1-p^{M+1}}\}, \tag{9}$$

where j, M, and W_i denote the transmission retrial number, the maximum retry limit, and the contention window size for the i^{th} transmission trial, respectively. Here, p denotes the probability that a transmitted packet collides, and is computed by $p = 1 - (1-\tau)^{N_{\text{awake}}-1}$. In addition, T_s, T_c, and l represent the successful transmission time, collision time, and the average length of one time slot in IEEE 802.11 PSM.

We now consider the probability that nodes are chosen to be in wake mode among N nodes. This selection probability (denoted by P_{select}) is the ratio of the number of nodes in wake mode indicated in the TIM message to the total number of nodes. This is given by $P_{\text{select}} = N_{\text{awake}}/N$. Suppose that a node has been selected to be in wake mode at the k^{th} beacon interval, which means that the packet destined for the node has been deferred during $(k-1)$ beacon intervals. Then, in the k^{th} beacon interval, this node has, on average, a delay of D_{awake} during the wake-up time. When the node switches to wake mode in the k^{th} beacon interval, the packet delay is expressed as $D_k = (k-1)T_{\text{beacon}} + D_{\text{awake}}$, where T_{beacon} is the beacon interval time.

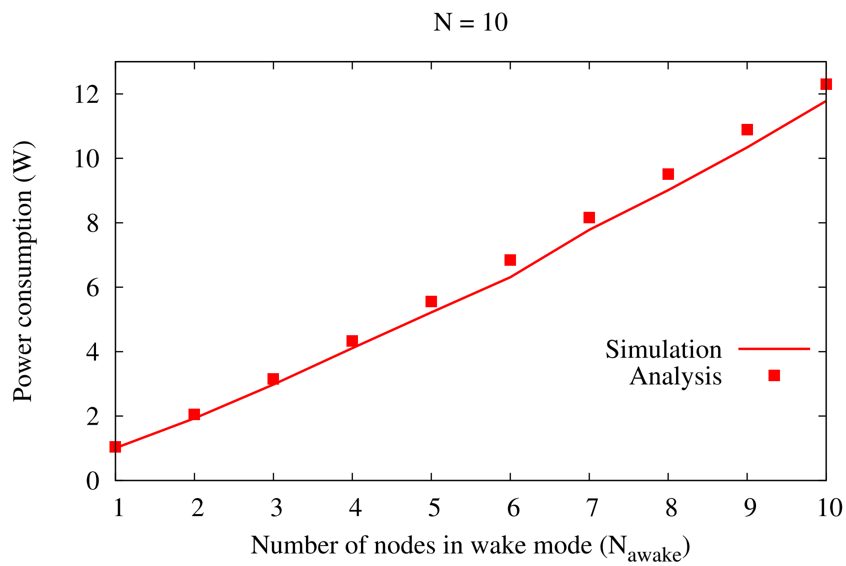
Because T_{beacon} is set to a large value (usually 100 ms), D_{awake} is assumed to be smaller than the beacon interval (T_{beacon}). On the basis of the computed values of P_{select} and D_{awake}, the average MAC delay (denoted by $E[D]$) for the successfully transmitted packets is obtained as

$$E[D] = \sum_{k=1}^{\infty} \{(1 - P_{\text{select}})^{(k-1)} P_{\text{select}}[(k-1)T_{\text{beacon}} + D_{\text{awake}}]\}. \tag{10}$$

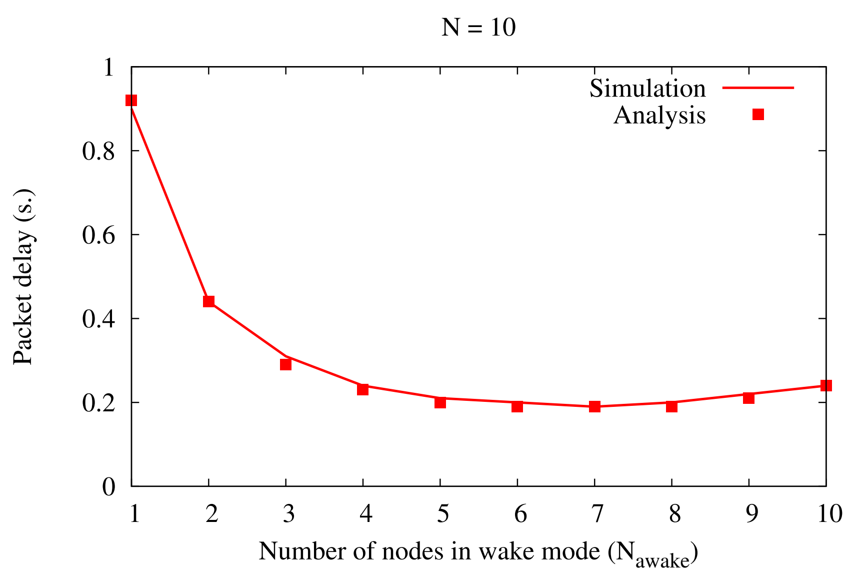
Note that the beacon frame is assumed to be reliably broadcast under the assumption that the wireless channel is error-free.

C. Validation

In this section, we numerically compute the power consumption and delay performance of IEEE 802.11 PSM with a predefined value for N_{awake}, and compare it with simulation results to



(a) Power consumption.



(b) Packet delay.

Fig. 2. Analytical and simulation results for power consumption and packet delay with respect to the number of nodes in wake mode (N_{awake}) when N=10.

validate our power consumption and delay analysis by using MATLAB. For this validation, we consider a WLAN hotspot where the AP is located at the center of region, and all nodes are randomly distributed within the region. All the important parameters are given in Table II. In a network containing 10 nodes, all the contending nodes are assumed to be fully backlogged, and the beacon interval is set to 100 ms. Here, we vary the number of awake nodes indicated in the list of the TIM field from 1 to 10 to verify the effect of the nodes in wake mode on the power consumption and packet delay performance.

First, we investigate the power consumed in the network with respect to the number of nodes in wake mode. Figure 2(a) depicts the analytical and simulation results for the power consumption of the network. In Figure 2(a), it is seen that the total power consumption gradually increases as the number nodes in wake mode (N_{awake}) increases from 1 to 10. This is because the nodes staying in sleep mode rarely consume battery power, so that the power consumed in the network is relatively low when there are a small number of nodes in wake mode. We also observe that the simulation and analysis results of our model are almost the same; this means that the analytical model for power consumption is very accurate.

We now study the effect of N_{awake} on the packet delay in the network. As shown in Figure 2(b), when the number of nodes in wake mode is set to 1, the average packet delay is very high, and is approximately 10 times the beacon interval. The reason is that only one node among 10 nodes is in wake mode and that this node attempts to transmit the frame during one beacon interval, resulting in a long packet delay. As N_{awake} increases from 1 to 7, the packet delay gradually decreases. This is because the nodes in wake mode may have a chance to transmit their frames without causing significant packet collisions. In contrast, when the number of nodes in wake mode exceeds 8, the packet delay increases because of the congestion. Here we also observe that the packet delay obtained by our simulations is very close to the analytical results.

V. Proposed Power-Saving Strategy for Balancing Energy and Delay Performance

A. Energy-delay product

Low power consumption and low packet delay are two of the most important objectives in designing a power-saving mechanism in wireless networks. Therefore, in 802.11 PSM as well as other power-saving mechanisms, it is desirable to simultaneously reduce the power consumption and packet delay. However, as shown in Figure 2, these two performance metrics (power consumption and packet delay) are often in conflict. For example, reducing power consumption of battery-powered devices leads to a long packet delay in the network. The presence of this trade-off relationship makes it impossible to improve both performance metrics simultaneously.

In order to determine the appropriate level of operating point in IEEE 802.11 PSM by considering the aforementioned trade-off relationship, we propose to use an Energy-Delay Product as a performance metric. From the derivations of (8) and (10), an Energy-Delay Product is expressed as $EDP = E[P] \cdot E[D]$. As shown in Figure 2, power consumption is viewed as an increasing function of N_{awake}, while the packet delay is a convex function of N_{awake}. Therefore, the multiplication of these two metrics (i.e., EDP) is also convex such that the optimal point can be uniquely computed.

B. Balanced power saving mechanism

The main objective of our proposed power-saving strategy is to minimize EDP in order to balance the energy consumption and packet delay performance. Because the number of nodes in wake mode affects both power consumption and packet delay performance, we use the number of nodes in wake mode as a control knob parameter. As indicated in (8) and (10), both performance metrics are a function of N_{awake} when τ and N are given at the AP. Note that it has been shown in previous studies the channel access probability of τ is approximately given as a function of the contention window size (CW) of IEEE 802.11 DCF protocol. For example, a simple estimation of τ reported in [13], [14] is $\tau = 2/(\text{CW}+1)$ when $\text{CW} = \text{CW}_{\text{min}}$ in an average sense. Hence, τ is readily available at the AP. Note that the approximation accuracy of τ is an important factor that affects the MAC service delay and power consumption because the collision probability depends on τ. If τ is overestimated, the MAC service delay would be larger. In contrast, if τ is under-estimated, the MAC service delay would be smaller due to a low collision probability.

Consequently, the AP can formulate the EDP minimization as follows:

$$\text{minimize}_{N_{\text{awake}} \in [1,N]} \quad EDP \tag{11}$$

We emphasize here that the integer programming problem can be solved by rigorously searching a sufficient range for N so that the optimal value of N_{awake} can be obtained. Once the optimal

TABLE II

SYSTEM PARAMETERS USED IN ANALYSIS AND SIMULATIONS.

Parameter	Value
T_{DIFS}	34 μsec
T_{SIFS}	16 μsec
T_{Slot}	9 μsec
PHY overhead	20 μsec
RTS frame	20 bytes + PHY overhead
CTS frame	14 bytes + PHY overhead
ACK frame	14 bytes + PHY overhead
Payload (l)	1000 bytes
Data transmission rate	54 Mb/s
Basic transmission rate	6 Mb/s
CW_{min}	15
CW_{max}	1023
PW_{idle}	1 W
PW_{tx}	2 W
PW_{rx}	1 W
T_{beacon}	100 $m$sec

value of N_{awake} is computed at the AP, the AP determines N_{awake} nodes among N nodes according to the queueing orders at every beacon interval. More specifically, when the AP sets the bitmap in the TIM field, it only sets the bits to 1 for only N_{awake} nodes. Therefore, only these selected nodes attempt to transmit their PS-POLL packets. An appropriate selection of nodes in wake mode can efficiently balance power consumption and packet delay performance in wireless networks. Note that in order to apply the proposed power-saving strategy, we only need to modify the procedure for setting TIM field at AP without any change at the client nodes.

VI. NUMERICAL RESULTS

To evaluate the performance of our proposed power-saving strategy and to compare it with that of continuously active mode and another existing power-saving method (Lee's method [11]), we carried out various simulations using MATLAB. In the simulations, we consider a downlink scenario of WLAN where the AP is located at the center of area, and all nodes are randomly distributed within the transmission range of the AP. In this scenario, all nodes are associated

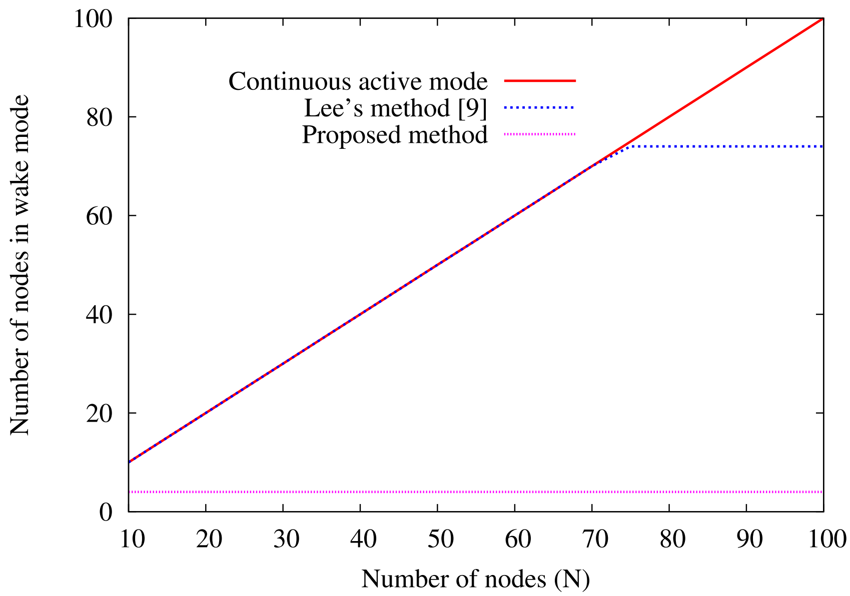


Fig. 3. The variation of the number of nodes in wake mode with respect to the changes in the number of nodes N.

with one AP and operate on the IEEE 802.11 PSM mode. It is assumed that the AP always has a number of pending packet for each node under a saturated condition. The parameter values used in the simulations are given in Table II. We first evaluate how many nodes in wake mode during one beacon interval are selected using the continuously active mode, Lee's method, and our proposed method. Second, we evaluate the effects of the number of nodes (N) on power consumption, packet delay, and EDP of IEEE 802.11 PSM.

A. *Number of nodes staying in wake mode during one beacon interval*

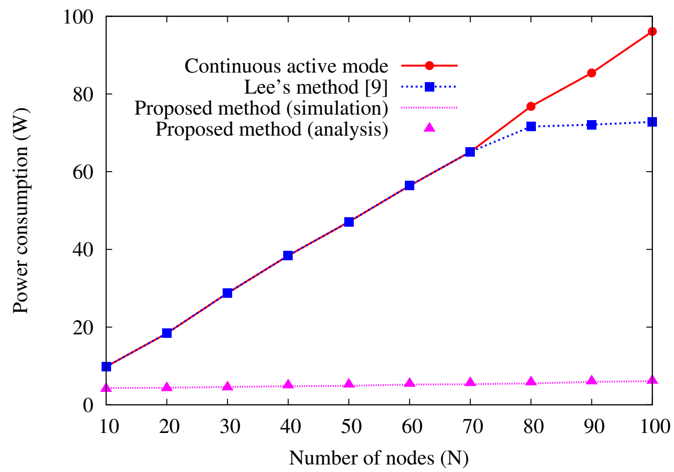
Figure 3 represents the number of nodes indicated in the TIM message (i.e., the number of nodes in wake mode) with respect to the total number of nodes N. In the continuously active mode, all the nodes are always powered on such that the number of nodes in wake mode also increases as N increases. In Lee's method [11], the number of nodes in wake mode is limited by the maximum value of the transmissions during one transmission duration. As shown in Figure 3, when N exceeds 11, the number of nodes in wake mode is limited to 11. When the number of nodes is less than 11, the number of nodes in wake mode is the same as N. In our proposed method, the number of nodes in wake mode is restricted to a small number as compared to the other two methods, because this small number of nodes in wake mode can minimize the EDP under IEEE 802.11 PSM.

B. Power consumption, packet delay, and energy-delay product performance with respect to the number of nodes N

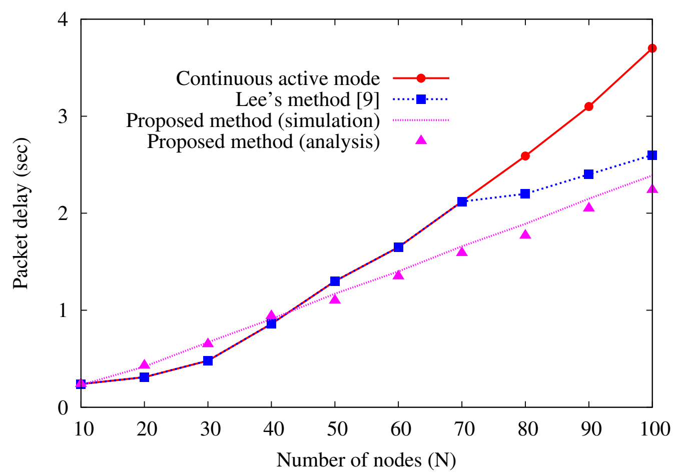
Figure 4 shows the analytical and simulation results of power consumption, packet delay, and EDP performances with respect to N. In the simulations, we vary N from 10 to 100 nodes. As shown in Figure 4(a), the consumed energy under the continuously active mode in the network significantly increases as N increases. This is because all the nodes stay in wake mode, which consumes a significant amount of energy. In contrast, the power consumption performance does not vary under our proposed method. The reason is that the AP restricts the number of nodes in wake mode in the proposed strategy. We also observe that our proposed power-saving mechanism consumes significantly less energy. The reason is that our proposed method is designed to minimize the EDP so that only a small number of nodes are allowed to stay in wake mode.

Figure 4(b) depicts the packet delay performance with respect to N. In all cases, the packet delay for the successfully transmitted packets gradually increases as N increases, because a large number of competing nodes leads to a longer packet delay. When the number of nodes is larger than 30, the packet delay in our proposed strategy is longer than that of Lee's method. The reason is that, in Lee's method, the number of nodes in wake mode is determined regardless of the number of nodes, while our proposed method considers the trade-off relationship between power consumption and packet delay. Therefore, our proposed method lets more nodes stay in sleep mode in order to minimize the EDP for a large number of N. In addition, the analytical results of the proposed method are very close to the simulation results for all the cases of N.

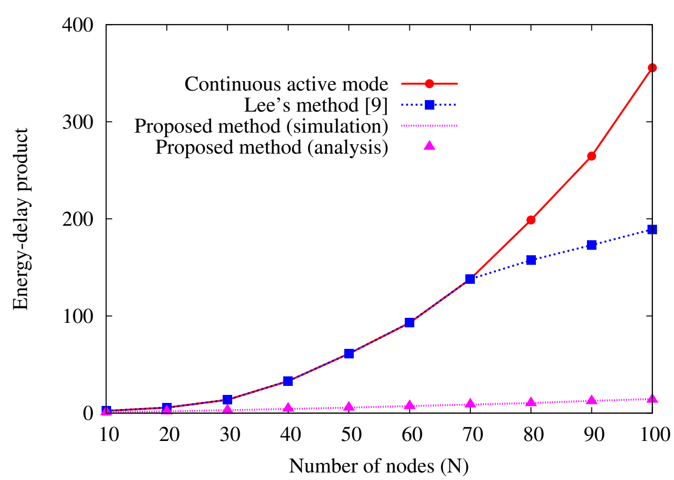
Figure 4(b) depicts the packet delay performance with respect to N. In all cases, the packet delay for the successfully transmitted packets gradually increases as N increases, because a large number of competing nodes leads to a longer packet delay. When the number of nodes is less than 40, the packet delay in our proposed strategy is longer than that of continuously active mode and Lee's method. The reason is that, our proposed method lets more nodes stay in sleep mode in order to minimize the EDP. In contrast, when the number of nodes is larger than 40, the packet delay in our proposed strategy is shorter than that of the other methods. In addition,



(a) Energy consumption.



(b) Packet delay.



(c) Energy-delay product.

Fig. 4. Power consumption, packet delay, and energy-delay product with respect to the number of node N.

the analytical results of the proposed method are very close to the simulation results for all the cases of N.

Figure 4(c) shows the EDP with respect to N. In the continuously active mode, as N increases, the EDP significantly increases, because a large number of active nodes results in high energy consumption and a long packet delay. However, under the proposed method, the EDP is considerably smaller than that of the other two methods for all the cases, as depicted in Figure 4(c).

VII. Conclusion

In this paper, we numerically derived the analytical model for energy consumption and packet delay in highly congested WLANs. In particular, we focused on how the number of nodes in wake mode affects energy consumption and packet delay performance. We then showed the trade-off relationship between energy consumption and packet delay in WLANs. On the basis of this observation, we proposed the adjustment of the number of nodes in wake mode in order to minimize the EDP. Through various simulations, we showed that the proposed strategy minimizes power consumption of IEEE 802.11 PSM nodes without causing a long delay.

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