An Effective Power Conservation Scheme for IEEE 802.11 Wireless Networks

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***Abstract*—In IEEE 802.11 wireless networks, a mobile station (MS) can power down the transceiver to save energy. To achieve power conservation, an access point (AP) periodically broadcasts *beacons* to notify the associated MSs about their traffic indications, and the MSs periodically wake up to listen to the beacons. The MS awake time scheduling is an important issue, which affects the number of simultaneously awake MSs to compete for access. We propose a power conservation scheme to optimally schedule the awake times among the MSs, such that the number of MSs awaking at the same time is minimal. Our study indicates that the proposed scheme demonstrates good performance in terms of frame loss and delay time.**

***Index Terms*—Access point (AP), power conservation, power save mode (PSM), wireless local area network (WLAN).**

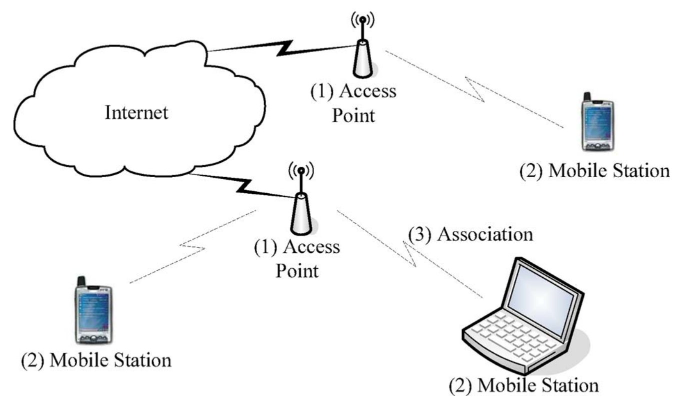

Fig. 1. WLAN architecture.

I. Introduction

THE IEEE 802.11 wireless local area network (WLAN) [1]–[3] has been widely deployed to provide low-cost broadband wireless Internet access. Fig. 1 shows the WLAN architecture, which consists of access points [APs; Fig. 1(1)] and mobile stations [MSs; Fig. 1(2)]. Each MS must associate with an AP to obtain the wireless access service [Fig. 1(3)]. An MS can be a personal digital assistant, a WiFi phone, or a notebook computer. Due to size restriction, the battery capacity of an MS is limited. Therefore, power conservation becomes an important issue in MS design [4], [5].

An MS can power down the transceiver to save energy [1], [4]. When the transceiver is on, it is said to be *awake or active*. When the transceiver is off, it is said to be *sleeping*, *dozing*, or in the *power-saving mode*. To achieve power conservation, the AP periodically broadcasts *beacons* to notify the associated MSs about their traffic indications (i.e., whether there are frames buffered for these MSs). In the IEEE 802.11 WLAN, a time line is partitioned into *beacon intervals*. Every beacon interval starts with a *beacon slot* to broadcast the beacon. To connect to an AP, an MS issues to the AP the *association request* containing a *listen interval* parameter. This parameter is used to specify when the MS should wake up to listen to beacons. Upon receipt of the association request, the AP may grant or deny access based on the content of the request (e.g., the listen interval). If the AP agrees with the listen interval that is specified by the MS, the MS is granted access to the AP. A connected MS issues the *disassociation* request to the AP when it wishes to exit the wireless access service. When there are frames that are buffered for the MS, the AP notifies the MS through the *traffic indication map* (TIM) contained in the beacon. Since the MS may sleep when the AP delivers the TIM, the AP must wait for at least one listen interval of the MS before discarding the frames. When the MS wakes up, and the TIM indicates that there are incoming frames, the MS will issue a power-saving (PS) poll (PS-poll) message to the AP to retrieve the buffered frames. To obtain the permission for issuing the PS-poll message, the MS may compete with other MSs in a time period called the *contention window*. During a contention window, only one MS is permitted to issue the PS-poll message (and then retrieve the frame). After frame transmission, other MSs may compete again in the next contention window. If the MS cannot issue the PS-poll message within the listen interval due to contention failure, the AP may discard the buffered frames without notification, which significantly affects the quality-of-service (QoS).

Power conservation significantly reduces the MS's power consumption at the cost of QoS degradation (e.g., frame loss, delivery delay, etc.). Previous studies [6]–[10] have addressed this problem. In [6], the adaptive power save mode (PSM) algorithm was proposed to estimate the current frame interarrival time to adapt the interval for issuing PS-poll messages. In [7],

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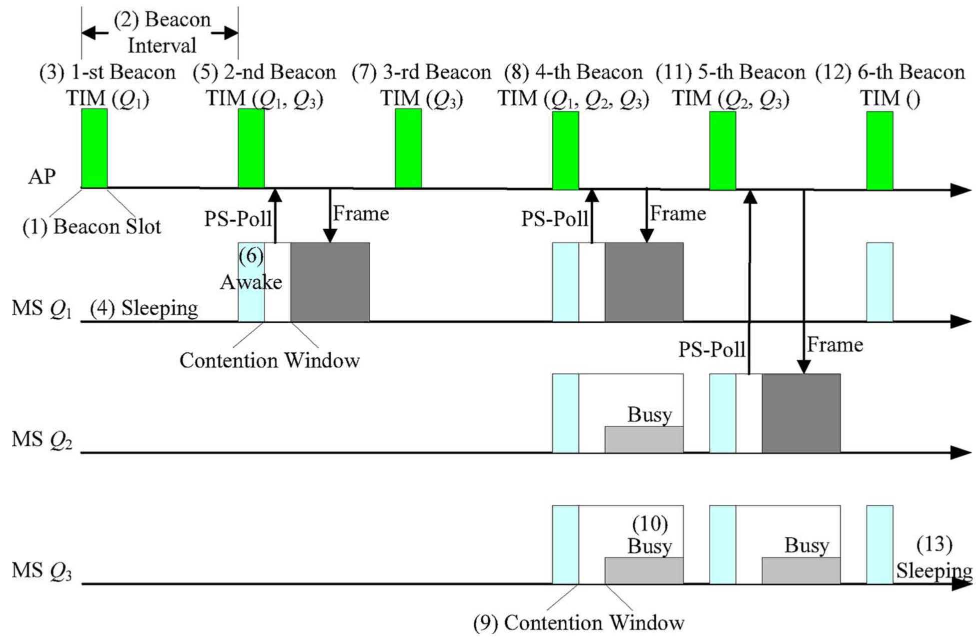

Fig. 2. Buffered frame retrieval process.

the authors analyzed the integration of power conservation and IEEE 802.11 QoS enhancement (i.e., IEEE 802.11e [3]) and studied the impact of the PSM on the *enhanced distributed channel access* QoS mechanism. In [8], the authors proposed a self-tuning power management scheme that dynamically adjusts the power management mechanism for IEEE 802.11 devices based on access patterns of applications. In [9], the authors proposed a smart PSM scheme to adjust the active and sleeping modes according to the desired delay performance and energy consumption. In [10], the authors proposed a power saving backoff prediction to predict the time that the MSs will wait before accessing the IEEE 802.11 WLAN. The above approaches focus on the listen interval adjustment to reduce the power consumption of MSs, which do not address the PS-poll contention issues. In this paper, we propose a power conservation scheme to minimize the PS-poll contention among MSs. This scheme can complement the previous approaches to reduce the power consumption of MSs without significantly degrading the QoS.

In our previous study [11], [12], the shared channel assignment and scheduling (SCAS) algorithm was proposed to schedule connections for packet transmission in a shared channel. The SCAS algorithm periodically schedules the time slots in a shared channel for each connection, where period I_i is derived from its requested transmission rate. That is, if the first time slot scheduled to a connection is the kth time slot, then the $(k + nI_i)$th time slots (for $n > 0$) are also scheduled to the connection. In SCAS, I_i is assumed to be a two's-power number of a basic time unit. The SCAS algorithm schedules the connections with smaller periods first and schedules in any order if tie breaking is needed. By using the SCAS algorithm, we have shown that the connections can be scheduled into the time slots without conflict (i.e., any two connections will not be scheduled at the same time slot) if the total requested transmission rate does not exceed the supported transmission rate of the shared channel.

In this paper, we extend the SCAS algorithm to resolve PS-poll contention. We note that, in the IEEE 802.11 WLAN, more than one MS are allowed to listen to a beacon from the AP. On the other hand, SCAS only allows one MS to be scheduled at a time slot to listen to the beacon. Some MSs are blocked if they cannot be scheduled in the free slots (i.e., the slots that have not been scheduled for other MSs). Directly applying the SCAS algorithm in the IEEE 802.11 WLAN may restrict the number of MSs that are served by the AP. By enhancing the SCAS algorithm, we propose a new scheme to schedule the awake times of each associated MS. This scheme minimizes the possibility of PS-poll contention.

II. Power Conservation

An MS requesting longer listen interval consumes less battery energy at the cost of requiring more buffer space at the AP and longer frame delivery delays [4], [5]. The MS awake time scheduling affects the number of simultaneously awake MSs that compete for access. Fig. 2 illustrates how the simultaneously awake MSs affect the QoS in the IEEE 802.11 WLAN.

In this figure, three MSs Q_1, Q_2, and Q_3 are associated with the AP. The listen intervals that are specified by Q_1, Q_2, and Q_3 are 2, 4, and 4, respectively. The AP broadcasts the beacon at each beacon slot [see Fig. 2(1)] in every beacon interval [see Fig. 2(2)]. Depending on the design, multiple PS-poll messages can be issued without conflict within a beacon interval. In this example, we assume that at most one PS-poll message can be issued within a beacon interval. If an MS fails to issue the PS-poll message in this beacon interval, it will try to compete for the next beacon interval. If the MS cannot issue the PS-poll message within its listen interval, the buffered frame is discarded. At the first beacon slot, the AP broadcasts a beacon containing the TIM indicating that there is a frame that is buffered for Q_1 [see Fig. 2(3)]. Since Q_1 is sleeping [see Fig. 2(4)], it does not

List[1]	Q_1	Q_2	Q_3	Q_4	Q_1	Q_2	Q_5	Q_6	Q_1	Q_2	Q_3	Q_4	Q_1	Q_2	Q_5	Q_7
List[2]	Q_8	Q_9	Q_{10}	Q_{11}	Q_8	Q_9	Q_{10}	Q_{12}	Q_8	Q_9	Q_{10}	Q_{11}	Q_8	Q_9	Q_{10}	Q_{12}
List[3]	Q_{13}								Q_{13}							
Position	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Fig. 3. Example for element allocation in the scheduling lists ($C = 16$), where $I_1 = I_2 = I_8 = I_9 = I_{10} = 4$, $I_3 = I_4 = I_5 = I_{11} = I_{12} = I_{13} = 8$, and $I_6 = I_7 = 16$.

receive this indication. At the second beacon slot, the TIM indicates that there are frames for Q_1 and Q_3 [see Fig. 2(5)]. Since only Q_1 is awake to listen to the TIM [see Fig. 2(6)], it successfully issues the PS-poll message to retrieve the buffered frame. At the third beacon slot, the TIM indicates that there is a frame for Q_3 again [see Fig. 2(7)]. At this moment, Q_3 is sleeping and, thus, cannot retrieve the buffered frame. At the fourth beacon slot, the TIM indicates that there are frames that are buffered for Q_1, Q_2, and Q_3 [see Fig. 2(8)]. These three MSs are awake and compete to issue the PS-poll messages during the contention window [see Fig. 2(9)]. In our example, Q_1 is granted for access during the contention window and issues a PS-poll message to retrieve the frame. At this period, Q_2 and Q_3 are deferred to issue the PS-poll message [see the *busy* period; Fig. 2(10)]. Q_2 and Q_3 will keep awake until their frames are received or dropped. At the fifth beacon slot, the TIM indicates that there are frames that are buffered for Q_2 and Q_3 [see Fig. 2(11)]. Q_2 and Q_3 compete to issue the PS-poll messages again. Assume that Q_2 is granted to issue the PS-poll message and retrieve the frame. Q_3 still cannot retrieve its frame during this beacon interval. At the sixth beacon slot, the buffer time for Q_3's frame exceeds the listen interval (of Q_3). Therefore, the AP discards the frame, and the TIM indicates that no frame is buffered [see Fig. 2(12)]. In this case, the frame for Q_3 is lost, and Q_3 returns to sleep at this beacon interval [Fig. 2(13)].

It is obvious that if more MSs compete for the permission to issue PS-poll messages [e.g., the fourth beacon slot in Fig. 2(8)], the frame loss possibility will be increased. Therefore, the smaller the number of simultaneously awake MSs at the same beacon slot, the better the QoS (i.e., PS-poll contention can be reduced). Based on the above discussion, we make the following definition.

Definition 1: Let M be the maximal number of MSs that are allocated in the same beacon slot in an awake time scheduling scheme X. X is optimal in terms of potential PS-poll contention if the scheme satisfies the following two conditions.

1) M is minimal among all awake time scheduling schemes.
2) The number of the beacon slots that are allocated for M MSs is minimal.

The IEEE 802.11 standard does not specify how to schedule the awake times of each associated MS, and a typical scheduling scheme (called the basic scheme) for power conservation is defined as follows.

Definition 2—[The Basic Scheme]: Suppose that an MS Q_i associates with the AP at the time between $(k-1)$th and kth beacon slots. If Q_i has the listen interval I_i, then it is scheduled to awake at $(k + nI_i)$th beacon slots for $n > 0$.

Intuitively, the basic scheme is not "optimal." Now, we describe the conditions when the awake time scheduling satisfies Definition 1. We first note that the IEEE 802.11 standard only specifies the listen interval parameter to be a 16-bit value, which ranges from 0 to $2^{16} - 1$ [1]. For discussion purposes, we define k classes of the listen intervals: $2^1, 2^2, \ldots, 2^k$, where $k < 16$. Let S be the set of the MSs that are associated with the AP. Each MS $Q_i \in S$ requests a listen interval

$$I_i = 2^{r_i}, \quad \text{where } 0 \leq r_i \leq k. \tag{1}$$

It is clear that if $I_i = 2^{r_i}$ and $I_j = 2^{r_j}$, then

$$I_i = 2^r I_j, \quad \text{where } r = r_i - r_j. \tag{2}$$

We note that the constraint for the specified listen intervals (to be 2^{r_i} form) can be released to any positive integer by applying the scheme in our previous study [12]. Such details will complicate the discussion and are omitted.

For an MS Q_i with the listen interval I_i, if Q_i first wakes up to listen to the beacon from the AP at the jth beacon slot, then it must wake up to listen to the beacons at the $(j + nI_i)$th beacon slots for $n > 0$. Let C be the minimal common multiple of the requested listen interval ranges. Without loss of generality, define a *beacon cycle* as C consecutive beacon slots. Every MS will, at least, wake up once per beacon cycle. For description purposes, we introduce the concept of *scheduling list* to map the beacon slots that are assigned to the MSs in a beacon cycle. Assume that $C = 2^k$. The positions of elements in a scheduling list are sequentially labeled as $0, 1, 2, \ldots, 2^k - 1$. Element j records the identity of an MS that must wake up at the $(j + n2^k)$th beacon slots (for $n \geq 0$). If a beacon cycle cannot accommodate all MSs without conflicts, then a beacon slot in that cycle must be assigned to multiple MSs (and these MSs will compete for access at this slot). We use multiple scheduling lists (denoted by $List[1], List[2], \ldots$) to represent multiple MS assignment. When we say "element l," it means element l of all scheduling lists in a scheduling scheme. The number of scheduling lists is the maximal number of MSs that must wake up at the same beacon slot. Fig. 3 shows an example for element allocation in the scheduling lists. In this example, we assume that $k = 4$, and the positions of the elements in a scheduling list are labeled from 0 to 15.

Definition 3: An MS Q_i is said to have the listen interval I_i if element j in a scheduling list is first allocated to Q_i, and then, elements $j + nI_i$ (for $n > 0$ and $j + nI_i < C$) in the scheduling list are also allocated to Q_i.

Thus, Q_i will wake up at the $(j + nI_i)$th beacon slots for $n \geq 0$. Since C is a multiple of I_i, Q_i will also wake up at the $(j + nI_i + C)$th beacon slots, and the allocated positions (i.e., $j + nI_i$) for Q_2 during the current and the next beacon cycles are identical. Therefore, when the AP broadcasts at the lth beacon slot, all MSs that are assigned at element (l mod C) must wake up. For the scheduling lists shown in Fig. 3, if the AP broadcasts at the 16th beacon slot, the MSs Q_1, Q_8, and Q_{13} [assigned at element $(16 \bmod 2^4) = 0$] must wake up (see Fig. 3).

By utilizing the scheduling list concept, we show how to satisfy the optimal scheduling conditions in Definition 1.

Lemma 1: In a scheduling scheme X, the maximal number of MSs that are allocated in the same beacon slot (i.e., M) is minimal if the number of scheduling lists is $\lceil \sum_{Q_i \in S} 1/I_i \rceil$.

Proof: Since M is also the number of scheduling lists that are used in X, it suffices to prove that the minimal number of scheduling lists that can accommodate all MSs in S is $\lceil \sum_{Q_i \in S} 1/I_i \rceil$. Since the listen interval for Q_i is I_i, Q_i will consume a $1/I_i$ portion of a scheduling cycle. For all MSs in S, they will consume a $\sum_{Q_i \in S} 1/I_i$ portion of the cycle. Therefore, $\lceil \sum_{Q_i \in S} 1/I_i \rceil$ is the minimal number of scheduling lists that can accommodate all MSs in S (i.e., $M = L = \lceil \sum_{Q_i \in S} 1/I_i \rceil$). ■

Lemma 2: Consider a scheduling scheme X that uses L scheduling lists in scheduling a set of MSs. If each element l $(0 \leq l \leq 2^k - 1)$ has been allocated to at least $L - 1$ MSs, and at least one element is allocated to L MSs, then the number of beacon slots that are allocated to L MSs is minimal.

Proof: Let U_j be the set of elements that are allocated to exact j MSs. Denote the number of elements in U_j as $|U_j|$. Suppose that $|U_L| = m > 0$ and $|U_{L-1}| = C - m$ (where C is the length of the scheduling list) in X. The total number of MSs that are assigned at elements in U_{L-1} is $(C - m)(L - 1)$. Suppose that $|U_L|$ can be reduced (i.e., X is not optimal). Then, at least one MS that is assigned at an element in U_L must be reassigned to an element at U_{L-1} (to reduce $|U_L|$). Without loss of generality, consider that one MS that is assigned at an element in U_L is reassigned to an element in U_{L-1} (i.e., to reduce $|U_L|$ by one). Therefore, $(C - m)(L - 1) + 1$ MSs are assigned at elements in U_{L-1}. By pigeonhole principle [13], at least one element l in U_{L-1} will be allocated to L MSs. After the reallocation of the MS, element l will be moved to U_L, and $|U_L|$ is increased by one. In other words, $|U_L|$ cannot be reduced. ■

Theorem 1: Let L be the number of scheduling lists that are used in a scheduling scheme X. X is optimal if we have the following.

1) $L = \lceil \sum_{Q_i \in S} 1/I_i \rceil$.
2) each element l $(0 \leq l \leq 2^k - 1)$ has been assigned to at least $L - 1$ MSs, and at least one element is assigned to L MSs.

Proof: The proof can be directly shown from Lemma 1, Lemma 2, and Definition 1. ■

III. Proposed Power Conservation Scheme

This section proposes an optimal power conservation scheme for the MS awake time scheduling. Let S be the set of the MSs that are associated with an AP, and let L be the number of scheduling lists that are required in the scheme. Initially, $L = 0$ and $S = \emptyset$.

When an MS Q_i joins set S through the association request, it is assigned the awake beacon slots through the Join procedure, which is described as follows.

Procedure Join (Q_i)

Step J1 $S \leftarrow S \cup \{Q_i\}$.
Step J2 If $\lceil \sum_{Q_j \in S} 1/I_j \rceil > L$, a new scheduling list is added, and $L \leftarrow L + 1$.
Step J3 Let S_m be the set of all MSs that are scheduled in a scheduling list $List[m]$, where $\sum_{Q_j \in S_m} 1/I_j < 1$. Let $S_R = \emptyset$. For every $Q_j \in S_m$, if $I_j > I_i$, then $S_R \leftarrow S_R \cup \{Q_j\}$ and $S \leftarrow S - \{Q_j\}$. At this point, the elements in $List[m]$ that are occupied by MSs in S_R become vacant.
Step J4 Suppose that element l is the first vacant element in $List[m]$. Note that for all $I_j \geq I_i$, Q_j have been removed, and all elements $l + nI_i$ (for $n \geq 0$ and $l + nI_i \leq 2^k$) are vacant (to be proved in Lemma 3). These elements are allocated to Q_i.
Step J5 For all $Q_j \in S_R$, execute Join (Q_j).

After performing the Join procedure, the AP notifies Q_i about its awake beacon slots through the association response message. To efficiently execute the Join procedure, all Q_j in S_R with smaller listen intervals are selected earlier in Step J5 for execution. In this MS selection order, we ensure that $S_R = \emptyset$ in Step J3 when the Join procedure is invoked recursively. In Step J3, a list with least vacant elements (i.e., $List[m]$) is selected from the scheduling lists. This selection ensures that newly incoming MSs or MSs in S_R can always be scheduled in the same scheduling list until the list is allocated fully. The following fact and lemma show that the elements to be allocated to Q_i are all vacant after Step J3 is executed.

Fact 1: Let S_m be the set of MSs that are scheduled in $List[m]$, and let element l be the first vacant element in $List[m]$. Consider I_i for an MS $Q_i \notin S_m$. If $I_i \geq I_j$ for all $Q_j \in S_m$, then $l < I_i$.

Proof: See the Appendix. ■

Lemma 3: Suppose that a set S_m of MSs is scheduled in $List[m]$ using the Join procedure, where $\sum_{Q_j \in S_m} 1/I_j < 1$, and element l is the first vacant element in $List[m]$. Consider an MS $Q_i \notin S_m$ such that $I_i \geq I_j$ for all $Q_j \in S_m$. Let element x be the first allocated element for any $Q_j \in S_m$. Then, for all n and n' values

$$l + nI_i \neq x + n'I_j. \quad (3)$$

In other words, elements $l + nI_i$ in $List[m]$ are vacant, and, therefore, Step J4 of the Join procedure is justified.

Proof: See the Appendix. ■

Next, we prove that, by exercising the Join procedure, there is at most one scheduling list containing vacant elements.

Lemma 4: Consider a set S of MSs and any integer $r \geq -k$ (where $k \geq 0$ is an integer). For all $Q_j \in S$, if $2^{-k} \leq 1/I_j \leq 2^r$ and $\sum_{Q_j \in S} 1/I_j \geq 2^r$, then there exists a subset $S_m \subset S$ such that $\sum_{Q_j \in S_m} 1/I_j = 2^r$.

Proof: See the Appendix. ∎

Corollary 1: Consider a set S of MSs. For all $Q_j \in S$, if $1/I_j \leq 1$ and $\sum_{Q_j \in S} 1/I_j \geq 1$, then there exists a subset $S_m \subseteq S$ such that $\sum_{Q_j \in S_m} 1/I_j = 1$.

Proof: The proof can be directly shown from Lemma 4 with $r = 0$. ∎

Lemma 5: Consider a set S_n of n MSs. Label these MSs as $Q_1, Q_2, \ldots, Q_n$ such that

$$1/I_1 \geq 1/I_2 \geq \cdots \geq 1/I_n \tag{4}$$

$$\sum_{1 \leq j \leq n} 1/I_j \geq 1. \tag{5}$$

Then, there exists a subset $S_m = \bigcup_{1 \leq i \leq m} \{Q_i\} \subseteq S_n$ such that $\sum_{1 \leq j \leq m} 1/I_j = 1$.

Proof: See the Appendix. ∎

Lemma 6: Consider a set S_n of n MSs labeled as $Q_1, Q_2, \ldots, Q_n$, where

$$1/I_1 \geq 1/I_2 \geq \cdots \geq 1/I_n. \tag{6}$$

If

$$\sum_{1 \leq j \leq n} 1/I_j = 1 \tag{7}$$

then all MSs in S_n can be scheduled in one scheduling list by using the Join procedure.

Proof: See the Appendix. ∎

Theorem 2: By exercising the Join procedure, when there are L scheduling lists that are used in the scheme, there is at most one scheduling list containing vacant elements.

Proof: We prove by induction on L.

Basis: When $L = 1$, it is obvious that the hypothesis holds.

Induction step: Assume that the hypothesis holds for $L \geq 1$. We prove that the hypothesis also holds for $L + 1$. When there are L scheduling lists that are used in the scheme, from the induction hypothesis, there is at most one scheduling list containing vacant elements. Two cases are considered.

- Case 1) None of the L scheduling lists contains vacant elements. By Step J2 of the Join procedure, $List[L+1]$ is added when a new MS Q_i arrives, and Q_i is scheduled in $List[L+1]$. Therefore, only $List[L+1]$ contains vacant elements. The hypothesis holds.
- Case 2) One scheduling list $List[m]$ contains vacant elements. Let S_m be the set of MSs that are scheduled in $List[m]$. There are two possibilities when a new MS Q_i arrives.
  - Case 2.1) $\sum_{Q_j \in S} 1/I_j \leq L$. The MS Q_i will be scheduled in $List[m]$, which does not affect the fully allocated scheduling lists. Therefore, only one scheduling list $List[m]$ may contain vacant elements.
  - Case 2.2) $\sum_{Q_j \in S} 1/I_j > L$. This implies

$$1/I_i + \sum_{Q_j \in S_m} 1/I_j > 1. \tag{8}$$

At Step J2 of the Join procedure, a scheduling list $List[L+1]$ will be added. At Step J3 of the Join procedure, MSs $Q_j \in S_m$ (where $I_j > I_i$) will be rescheduled such that all MSs $Q_j \in S_m \cup \{Q_i\}$ can be scheduled into $List[m]$ in a nondecreasing I_j order. Since (8) holds, Lemma 5 ensures that a set S_n exists such that $S_n \subseteq S_m \cup \{Q_i\}$ and $\sum_{Q_j \in S_n} 1/I_j = 1$, and Lemma 6 ensures that all MSs in S_n can be scheduled in $List[m]$. Therefore, $List[m]$ will be fully allocated, and only $List[L+1]$ contains vacant elements.

From Cases 2.1 and 2.2, the hypothesis holds. ∎

When an MS Q_i leaves set S through the disassociation request, Q_i is removed through the Leave procedure, which is described as follows.

Procedure Leave (Q_i)

- Step L1 $S \leftarrow S - \{Q_i\}$, and Q_i is removed from its scheduling list $List[m]$ (i.e., the elements that are occupied by Q_i become vacant).
- Step L2 Let S_m be the set of MSs that are allocated in $List[m]$. If $S_m = \emptyset$, then $List[m]$ is removed, $L \leftarrow L - 1$, and the procedure exits. If $S_m \neq \emptyset$, then Step L3 is executed.
- Step L3 Let $S_R = \emptyset$. For all $I_j > I_i$, $Q_j \in S_m$ are removed from $List[m]$ and are added into S_R (i.e., $S_R \leftarrow S_R \cup \{Q_j\}$ and $S \leftarrow S - \{Q_j\}$). Let element x_i (x_j) be the first allocated element in $List[m]$ for Q_i (Q_j). For all $I_j = I_i$, if $x_i < x_j$, then $S_R \leftarrow S_R \cup \{Q_j\}$ and $S \leftarrow S - \{Q_j\}$.
- Step L4 If there exists $u \neq m$ such that the scheduling list $List[u]$ contains vacant elements, then all MSs of the set S_u that are scheduled in $List[u]$ are removed from the scheduling list and collected into S_R, i.e., $S_R \leftarrow S_R \cup S_u$ and $S \leftarrow S - S_u$. At this point, the MSs that are occupied by MSs in S_R become vacant and will be rescheduled in Step L6 to ensure at most one scheduling list containing vacant elements after rescheduling (to be proved in Lemma 7).
- Step L5 If $\lceil \sum_{Q_j \in S} 1/I_j \rceil < L$, $List[u]$ is removed, and $L \leftarrow L - 1$.
- Step L6 For all $Q_j \in S_R$, execute Join (Q_j).

Similar to Step J5 of the Join procedure, Step L6 executes the Join procedure for $Q_j \in S_R$ in the nondecreasing I_j order. Note that when an MS Q_i joins or leaves the set, the awake beacon slots of already scheduled MSs (i.e., the MSs in S_R) may be rescheduled. The AP will notify these MSs about their new awake beacon slots. Now, we justify the Leave procedure with the following lemma.

Lemma 7: After exercising the Leave procedure, there is at most one scheduling list containing vacant elements.

Proof: See the Appendix. ∎

We show that the power conservation scheme satisfies Definition 1.

Theorem 3: The proposed power conservation scheme is optimal.

Proof: In the power conservation scheme, the number of scheduling lists that are used in the scheme is $\lceil \sum_{Q_j \in S} 1/I_j \rceil$ (see Step J2 of the Join procedure and Step L3 of the Leave procedure). From Theorem 2 and Lemma 7, at most one scheduling list contains vacant elements. From Theorem 1, Definition 1 is satisfied (i.e., this scheme is optimal). ■

We note that the proposed power conservation scheme can be easily integrated with the IEEE 802.11 WLAN. To implement our scheme, we only need to add an indication of the first awake beacon interval at the standard association response message [1].

IV. Performance Evaluation

We develop a simulation model to investigate the performance of the proposed power conservation scheme. The simulation model follows the event-driven approach that is widely adopted in mobile network studies [14], [15]. In the simulation, the MSs are classified into k classes, where class i $(1 \leq i \leq k)$ has the listen interval $2^i \leq C$. We assume that only one PS-poll message can be successfully issued within one beacon interval, and a frame can be buffered in the AP within one listen interval (i.e., the frame is dropped after one listen interval).

Based on simulation experiments, we compare the proposed power conservation scheme (scheme p) with the basic scheme (scheme b; see Definition 2) in terms of two output measures. The following input parameters are considered:

- T period of a beacon interval, which is assumed to be fixed;
- k number of MS classes;
- t_i inter-MS arrival time for class i MSs. We assume that t_i follows the gamma distribution with mean $1/\lambda_i$ and variance Λ_i;
- τ_i interframe arrival time for a class i MS. We assume that τ_i follows the gamma distribution with mean $1/\gamma_i$ and variance Γ_i;
- β probability that a frame arrival continues the MS session. In other words, the MS ends the session with probability $1-\beta$.

We note that the MSs are periodically awake to listen to the beacons from the AP; however, the traffic of the MSs can arrive in general form. We consider the gamma distribution in our traffic model, which has been widely used in telecom performance studies [5], [16]. It has been proven that any experimental data can be fit by a mixture of gamma distributions [17]. Therefore, one may measure the traffic data, fit them into a mixture of gamma distributions, and then use our performance model for analysis.

The following output measures are studied:

- P_l: the frame loss probability;
- T_w: the average waiting time between when the frame arrives and when the frame is delivered.

For discussion purposes, we introduce a "secondary" input parameter $U = \sum_{Q_i \in S} 1/I_i$, which is the average number of MSs that are scheduled to be awake at a beacon slot. The relation between U and the "primary" input parameters can be expressed as follows:

$$U = \sum_{i=1}^{k} \left(\frac{1}{I_i}\right) \left[\frac{\left(\frac{\beta}{1-\beta}\right)\tau_i + \tau_i}{t_i}\right] \tag{9}$$

where

$$\frac{\left(\frac{\beta}{1-\beta}\right)\tau_i + \tau_i}{t_i}$$

is the average number of class i MSs stayed in the network. Note that the term $(\beta/(1-\beta))\tau_i$ is the time period for generating $\beta/(1-\beta)$ frame arrivals, and the term τ_i is the time period between when the last frame occurs and when the MS disconnects from the AP. The impacts of the input parameters on the output measures are elaborated upon as follows.

Effects of U and γ_i: Fig. 4 plots P_l and T_w as functions of U and γ_i. We assume that the interframe arrival time τ_i follows the gamma distribution with mean $1/\gamma_i$ and variance $\Gamma_i = 1/\gamma_i^2$, and the inter-MS arrival time t_i follows the gamma distribution with mean $1/\lambda_i$ and variance $\Lambda_i = 1/\lambda_i^2$.

As U increases, more MSs will simultaneously wake up at a beacon slot, which increases the possibility of PS-poll contention. It also delays the time for retrieving the buffered frames, and, thus, more buffered frames are dropped due to buffer timeout (i.e., each frame is dropped after one listen interval). Consequently, P_l and T_w increase as U increases [see Fig. 4(a) and (b)].

As γ_i decreases, it is less likely that there is a frame to be delivered to an MS when the MS wakes up. Therefore, the possibility of PS-poll contention decreases. P_l and T_w decrease as γ_i decreases.

Effects of Γ_i: Fig. 5 shows the effects of variance Γ_i for interframe arrival time τ_i. P_l and T_w decrease as Γ_i increases. When Γ_i is large, more small and large τ_i intervals are observed, and either more frames for an MS arrive within a short period or no frame arrives within a long period [18]. These frames (that arrive within one listen interval) can be retrieved at the same time when the MS is granted to issue the PS-poll message. Therefore, more frames can be delivered when one PS-poll message is issued, and the waiting times for the delivered frames are reduced.

Comparison Between Scheme p and Scheme b: Fig. 4 shows that when U or γ_i are small (i.e., the traffic is not heavy), scheme p significantly outperforms scheme b. When U or γ_i are large (i.e., the traffic is heavy), scheme p performs slightly better than scheme b. In Fig. 5, when Γ_i is small, scheme p significantly outperforms scheme b. When Γ_i increases, the advantage of scheme p becomes less significant. These results indicate that scheme p demonstrates excellent performance when the traffic load is not heavy.

V. Conclusion

In this paper, we have proposed a power conservation scheme for IEEE 802.11 wireless networks to schedule the awake

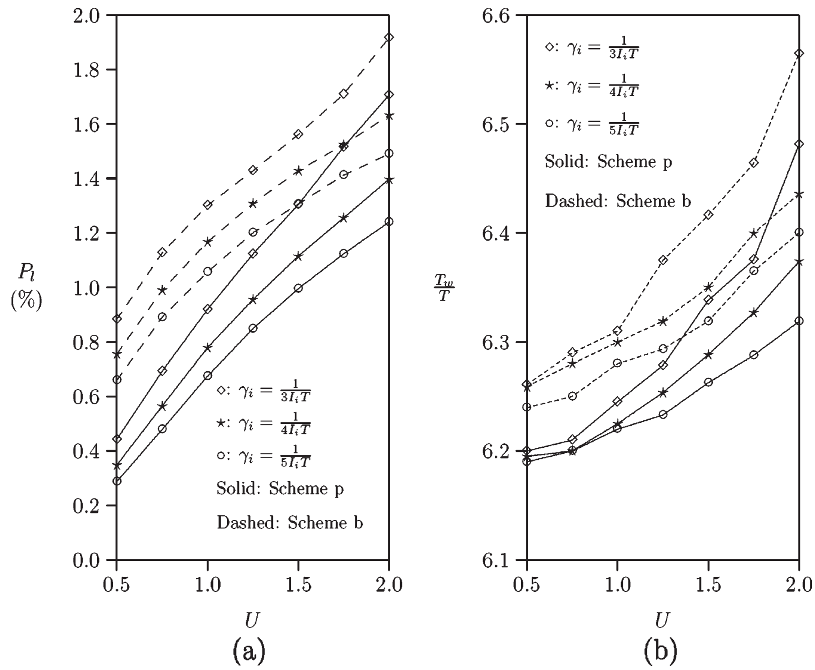

Fig. 4. Effects of U and τ_i. (a) P_l performance. (b) T_w performance.

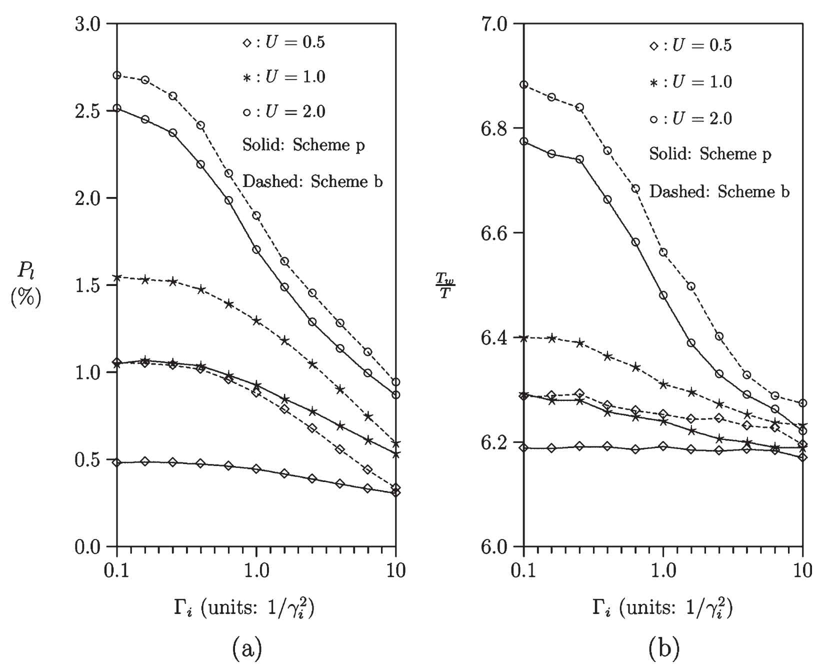

Fig. 5. Effects of the variance of the τ_i distribution. (a) P_l performance. (b) T_w performance.

times among the MSs that are served by an AP. We have formally proved that both the maximal number of MSs that are allocated in the same beacon slot and the number of the beacon slots that are allocated for the maximal number of MSs are minimal when the proposed scheme is executed. Simulation experiments have been developed to investigate the frame loss probability and frame waiting time measures. The results indicate that the proposed power conservation scheme outperforms an existing basic scheme and demonstrates excellent performance when the traffic load is not heavy.

APPENDIX

Fact 1: Let S_m be the set of MSs that are scheduled in $List[m]$, and let element l be the first vacant element in $List[m]$. Consider I_i for an MS $Q_i \notin S_m$. If $I_i \geq I_j$ for all $Q_j \in S_m$, then $l < I_i$.

Proof: We prove by contradiction. Suppose that $l \geq I_i$. It implies that all elements x (where $0 \leq x < I_i$) are allocated to MSs $Q_j \in S_m$. From (2), $I_i = 2^r I_j$ for $r \geq 0$. We have

$$x + nI_i = x + n2^r I_j, \quad \text{where } n \geq 0. \tag{10}$$

Since Q_j must wake up for every I_j beacon slot, all elements $x + nI_j$ (for $n \geq 0$) are allocated to Q_j. In other words, elements $x + n2^r I_j$ are allocated to Q_j. From (10), elements $x + nI_i$ must be allocated to Q_j. This implies that for all elements $y \geq I_i$, y have been allocated to MSs $Q_j \in S$, which contradicts the hypothesis that $l \geq I_i$. ■

Lemma 3: Suppose that a set S_m of MSs is scheduled in $List[m]$ using the Join procedure, where $\sum_{Q_j \in S_m} 1/I_j < 1$, and element l is the first vacant element in $List[m]$. Consider an MS $Q_i \notin S_m$ such that $I_i \geq I_j$ for all $Q_j \in S_m$. Let element x be the first allocated element for any $Q_j \in S_m$. Then, for all n and n' values

$$l + nI_i \neq x + n'I_j. \tag{11}$$

In other words, elements $l + nI_i$ in $List[m]$ are vacant, and, therefore, Step J4 of the Join procedure is justified.

Proof: To prove that hypothesis (11) holds, it suffices to prove that $(l + nI_i) \bmod I_j \neq (x + n'I_j) \bmod I_j$. From (2), $I_i = 2^r I_j$ for $r \geq 0$, and

$$(l + nI_i) \bmod I_j = (l + 2^r nI_j) \bmod I_j = l \bmod I_j. \tag{12}$$

For all $n' \geq 0$, since elements $x + n'I_j$ are allocated to Q_j, from Fact 1, we have $x \leq I_j$, and

$$(x + n'I_j) \bmod I_j = x. \tag{13}$$

Equation (13) implies that if $y \bmod I_j = x$, then elements y are allocated to Q_j. Since element l is vacant in the scheduling list, we must have

$$l \bmod I_j \neq x. \tag{14}$$

From (12)–(14), we have $(l + nI_i) \bmod I_j \neq (x + n'I_j) \bmod I_j$, and hypothesis (11) holds. ■

Lemma 4: Consider a set S of MSs and any integer $r \geq -k$ (where $k \geq 0$ is an integer). For all $Q_j \in S$, if $2^{-k} \leq 1/I_j \leq 2^r$ and $\sum_{Q_j \in S} 1/I_j \geq 2^r$, then there exists a subset $S_m \subset S$ such that $\sum_{Q_j \in S_m} 1/I_j = 2^r$.

Proof: We prove by induction on r.

Basis: We pick $r = -k$. From the hypothesis, for any $Q_j \in S$, we have

$$1/I_j = 2^{-k}. \tag{15}$$

Let $S_m = \{Q_j\}$. From (15), $\sum_{Q_j \in S_m} 1/I_j = 2^{-k}$. The basis step holds.

Induction step: Assume that the hypothesis holds for $r > -k$. We prove that the hypothesis also holds for $r + 1$. If S contains an MS Q_i, where $1/I_i = 2^{r+1}$, then let $S_m = \{Q_i\}$, and the hypothesis holds. Otherwise (i.e., S does not contain any MS Q_i, where $1/I_i = 2^{r+1}$), for all $Q_j \in S$

$$1/I_j \leq 2^r \text{ and } \sum_{Q_j \in S} 1/I_j \geq 2^{r+1} > 2^r. \tag{16}$$

From (16) and because the hypothesis holds for r, we can find a subset $S_{m1} \subset S$ such that

$$\sum_{Q_j \in S_{m1}} 1/I_j = 2^r. \tag{17}$$

From (16) and (17), for all $Q_l \in S - S_{m1}$

$$1/I_l \leq 2^r \text{ and } \sum_{Q_l \in S - S_{m1}} 1/I_l \geq 2^{r+1} - 2^r = 2^r. \tag{18}$$

From (18) and the hypothesis, we can find another subset $S_{m2} \subset S - S_{m1}$ such that

$$\sum_{Q_l \in S_{m2}} 1/I_l = 2^r. \tag{19}$$

Let $S_m = S_{m1} \cup S_{m2}$. From (17) and (19), $\sum_{Q_j \in S_m} 1/I_j = 2^r + 2^r = 2^{r+1}$. Therefore, the hypothesis holds for all $r \geq -k$. ■

Lemma 5: Consider a set S_n of n MSs. Label these MSs as $Q_1, Q_2, \ldots, Q_n$ such that

$$1/I_1 \geq 1/I_2 \geq \cdots \geq 1/I_n \tag{20}$$

$$\sum_{1 \leq j \leq n} 1/I_j \geq 1. \tag{21}$$

Then, there exists a subset $S_m = \bigcup_{1 \leq i \leq m} \{Q_i\} \subseteq S_n$ such that $\sum_{1 \leq j \leq m} 1/I_j = 1$.

Proof: We prove by contradiction. Suppose that for any m, where $1 \leq m \leq n$

$$\sum_{1 \leq j \leq m} 1/I_j \neq 1. \tag{22}$$

From (21) and (22), we have

$$\sum_{1 \leq j \leq n} 1/I_j > 1. \tag{23}$$

From (22) and (23), there exists $m \leq n$ such that

$$\sum_{1 \leq j \leq m} 1/I_j > 1 \tag{24}$$

$$\sum_{1 \leq j \leq m-1} 1/I_j < 1. \tag{25}$$

From Corollary 1, there exists a subset $S' \subset S_m$ such that

$$\sum_{Q_j \in S'} 1/I_j = 1. \tag{26}$$

Equations (24) and (26) imply that there exists a subset $S' \subset S_m$ such that

$$\left(\sum_{1 \leq j \leq m} 1/I_j\right) - \left(\sum_{Q_l \in S_m - S'} 1/I_l\right) = 1. \tag{27}$$

From (25) and (27), we have

$$\sum_{1\le j\le m-1} 1/I_j = \left(\sum_{1\le j\le m} 1/I_j\right) - 1/I_m < \left(\sum_{1\le j\le m} 1/I_j\right) - \left(\sum_{Q_l\in S_m-S'} 1/I_l\right) \Rightarrow 1/I_m > \sum_{Q_l\in S_m-S'} 1/I_l$$

which contradicts (20) because $1/I_m$ is minimal among those for MSs in S_m. ■

Lemma 6: Consider a set S_n of n MSs labeled as $Q_1, Q_2, \ldots, Q_n$, where

$$1/I_1 \ge 1/I_2 \ge \cdots \ge 1/I_n. \quad (28)$$

If

$$\sum_{1\le j\le n} 1/I_j = 1 \quad (29)$$

then all MSs in S_n can be scheduled in one scheduling list by using the Join procedure.

Proof: For all MSs in S_n, the Join procedure schedules these MSs into the scheduling list(s) in the nondecreasing listen interval order (i.e., $Q_1, Q_2, \ldots, Q_n$). We prove that $Q_m \in S_n$ can be scheduled in one scheduling list by induction on m, where $1 \le m \le n$.

Basis: For $m = 1$, since there is no other MS that is scheduled in the scheduling list, Q_m can be accommodated. The basis step holds.

Induction step: Assume that the hypothesis holds for $1 \le m < n$. We prove that the hypothesis also holds for $m+1$. From the induction hypothesis, $Q_1, Q_2, \ldots$, and Q_m have been scheduled in the scheduling list. From (29) and because $m < n$, we have

$$\sum_{1\le i\le m} 1/I_i < \sum_{1\le j\le n} 1/I_j = 1. \quad (30)$$

Since $\sum_{1\le i\le m} 1/I_i < 1$ [from (30)] and $I_{m+1} \ge I_j$ for $1 \le j \le m$ [from (28)], by Lemma 3, Q_{m+1} can be scheduled in the scheduling list. Therefore, the hypothesis holds for $1 \le m \le n$. ■

Lemma 7: After exercising the Leave procedure, there is at most one scheduling list containing vacant elements.

Proof: From Theorem 2, there is at most one scheduling list containing vacant elements before the Leave procedure is executed. Consider the following two cases when the Leave procedure is executed.

Case 1) The leaving MS Q_i is previously scheduled in the scheduling list $List[m]$ that contains vacant elements. In this case, Step L4 of the Leave procedure is not executed, which will not affect other scheduling lists. Therefore, after the Leave procedure is executed, only $List[m]$ contains vacant elements. Note that if $S_m = \emptyset$ (see Step L2 of the Leave procedure), then $List[m]$ is removed, and thus, no scheduling list contains vacant elements.

Case 2) The leaving MS Q_i is previously scheduled in a fully allocated scheduling list $List[m]$ (i.e., $\sum_{Q_j\in S_m} 1/I_j = 1$). If no scheduling list contains vacant elements, Step L4 of the Leave procedure will not be executed. Similar to case 1, only $List[m]$ contains vacant elements. Otherwise (i.e., there is a scheduling list $List[u]$ containing vacant elements), all the MSs that are scheduled in $List[u]$ must be rescheduled (see Step L4 of the Leave procedure). At Step L5 of the Leave procedure, if $\sum_{Q_j\in S_m\cup S_u} 1/I_j \le 1$ (i.e., $\lceil\sum_{Q_j\in S} 1/I_j\rceil < L$), $List[u]$ is removed, and thus, only $List[m]$ contains vacant elements. On the other hand, if $\sum_{Q_j\in S_m\cup S_u} 1/I_i > 1$, then Theorem 2 guarantees that, after Step L6 is executed, $List[m]$ will be allocated fully, and only $List[u]$ contains vacant elements. ■

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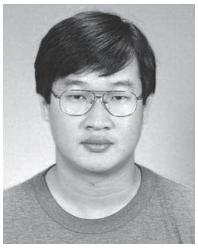

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