

A Microscopic Study of Power Management in IEEE 802.11 Wireless Networks

Chunyu Hu[†], Rong Zheng, Jennifer C. Hou and Lui Sha

Abstract—IEEE 802.11 power saving mode (PSM) has been proposed in wireless LANs and multi-hop wireless networks to coordinate power states of wireless devices. In IEEE 802.11 PSM, power management decisions to wake up wireless devices or put them to sleep states are made periodically in every beacon interval. In this paper, we demonstrate via a rigorous, analytical model (the result of which is corroborated by simulation results) that such a periodic structure together with its signaling overhead leads to both energy and bandwidth under-utilization. We then devise SIMPA, a new power management protocol based on IEEE 802.11 PSM, to decouple the power management decision points and the beacon intervals, so as to allow fine grained control. In SIMPA, wireless devices can switch to the sleep state inside a beacon interval or extend their active states beyond one beacon interval. A comprehensive simulation study in both single hop wireless LANs without the AP support and multi-hop wireless networks demonstrates that as compared to IEEE 802.11 PSM, SIMPA can effectively reduce energy consumed under light to medium traffic loads and retain the network capacity for data transport at high traffic loads.

I. INTRODUCTION

With the proliferation of portable computing platforms and small wireless devices, wireless networks have received more and more attention as a means of data communication among untethered devices. As wireless devices usually rely on portable power sources such as batteries and the energy cost of devices in idle states is very significant [5], it is in general desirable to turn the radio off when it is not in use.

Unlike wireless LANs with the access point (AP) support, single hop or multi-hop wireless networks need to coordinate power management decisions in a fully distributed fashion. In particular, transmissions from a wireless node are subject to the wakeup schedule at the receiver (in contrast, a wireless node can transmit at any time to an always-on AP in wireless LANs). Packets destined for a receiver that is currently in the sleep state are delayed. This makes the trade-off between energy and performance in multi-hop networks a more pertinent and challenging problem.

To systematically study this problem, we develop a theoretical model to quantify the energy-performance trade-off of IEEE 802.11 power saving mode (PSM). In IEEE 802.11 PSM, power management decisions are made periodically at the

beginning of every beacon interval; a node can switch to the sleep state for the entire beacon interval to save power when the interface is idle. Recently, IEEE 802.11 PSM has also been applied in mobile ad hoc networks (MANET) to coordinate power management states in multi-hop communications [20], [4]. The analytical study, corroborated by simulation results, reveals that IEEE 802.11 PSM has low energy utilization under light to medium traffic loads and low bandwidth utilization under high traffic loads. It is mainly attributed to the periodicity of the instants when power management decisions are made and the signaling overhead incurred in waking up power-saving stations.

To address the aforementioned problems, we propose *Sleep In the Middle and Prolonged Activeness* (SIMPA), a new power management protocol based on IEEE 802.11 PSM, which decouples power management decision instants with beacon intervals to allow finer granularity of control. In SIMPA, wireless devices can switch to the sleep state inside a beacon interval or extend their active state beyond one beacon interval. The former significantly reduces the energy consumption incurred by wireless devices in the idle state, while the later reduces the signaling overhead to wake up power-saving nodes and expedites delivery of data packets in congested networks. In dense networks, SIMPA further decreases the number of wake-up messages by snooping transmissions in the wireless medium if possible. State maintenance in SIMPA is resilient to packet losses and wireless errors; it does not require any out-band signaling.

To study the performance of SIMPA, we conduct simulation study in both single hop and multi-hop wireless networks and demonstrate that SIMPA can effectively reduce energy consumption under light to medium traffic loads and increase the network capacity to accommodate high traffic loads. Consequently, the network lifetime is prolonged as compared to IEEE 802.11 operated networks with and without PSM. As indicated in one set of the simulation study, SIMPA can effectively prolong the network lifetime by 100% and 94% as compared to no PSM and PSM, respectively.

The rest of the paper is organized as follows. We first provide in Section II a succinct review of existing power management solutions. In Section III, we develop a theoretical model that quantifies the energy-performance trade-off of IEEE 802.11 PSM. Details of the SIMPA protocol are presented in Section IV, and are followed by a simulation study in Section V. Finally, we conclude the paper in Section VI.

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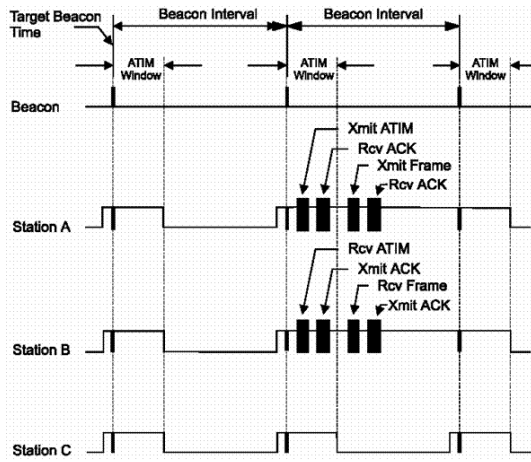


Fig. 1. Basic Operation of IEEE 802.11 PSM in IBSS

II. BACKGROUND

In this section, we first give an overview of IEEE 802.11 PSM. Then we categorize existing power management protocols and provide a qualitative comparison.

A. Overview of IEEE 802.11 PSM

In IEEE 802.11 PSM, a node can be in one of the two power modes, that is, the *active mode* when a node can receive and transmit frames at any time, and the *power-save mode* (PS) when a node is mainly in the sleep state and transits to the full powered state subject to the rules described next. The sleep state usually consumes at least an order of magnitude less power than in the active state [5].

In the power-save mode, all nodes in the network are synchronized to wake up periodically to listen to beacon messages. Broadcast/multicast messages or unicast messages to a power-saving node¹ are first buffered at the transmitter and announced via an ad hoc traffic indication message (ATIM) inside a small ATIM window at the beginning of the beacon interval. All the nodes are required to be active during the ATIM window. If a node receives a directed ATIM frame in the ATIM window (i.e., it is the designated receiver of a unicast message), it sends an acknowledgment and stays awake for the entire beacon interval, waiting for data packets to be transmitted. Otherwise, the node switches to the sleep state to conserve energy. Immediately after the ATIM window, a node can transmit buffered broadcast/multicast or unicast data frames addressed to nodes that are known to be active (e.g., by reception of acknowledgments to ATIM frames). The behavior of IEEE 802.11 PSM is illustrated in Fig. 1.

¹A power-saving node in this paper is referred to a node operated in the power-save mode and being in the sleep state.

B. Other Power Management Protocols

In recent years, tremendous research efforts have been made to improve energy efficiency at various layers of the wireless network protocol stack [15], [17], [9], [19], [14], [4], [20], [11], [2], [6]. In this paper, we are primarily interested in power management techniques that reduce energy consumption incurred in the idle state, by putting wireless interfaces to the sleep state. Based on the granularity of power management decisions in the time domain, we classify existing solutions into three categories, i.e., packet level power management, micro-power management and macro-power management solutions.

Packet-level power management approaches: Packet-level approaches make power management decisions on a per-packet basis.

The PAMAS power-saving medium access protocol [17] turns off a node's radio when it overhears a packet that is not addressed to it and thus operates at the packet level. As a node must remain on all the time for potential incoming transmissions, this approach is better-suited for radios in which processing a received packet is more expensive as compared to listening to an idle medium. Therefore, the effectiveness of PAMAS is limited to reducing the power consumed in processing unnecessary packets.

The wake-on-wireless technique proposed by Shih *et al.* [16] uses a separate control channel with low-power radio operating at a frequency band that is different from the one used for the data channel. With separate control channel for wakeup, power management decisions can potentially be made at per packet level. The main concern of this type of approaches is that the transmission range of radios operating at different frequency bands or using different modulation schemes are usually different. For example, in [16] the low-power radio operates in 915MHz ISM band with a transmission range of about 332 ft in free space and 30 ft indoor while the IEEE 802.11 cards operates at 2.4 GHz with transmission range up to 1750 ft. (Static or dynamic) power control is required to ensure the consistency among two channels.

Micro-power management: Micro-power management approaches control the transition between the sleep state and the active state when nodes are in the *power-save mode*.

Jung and Vaidya [9] propose a scheme that adjusts the ATIM window size dynamically to accommodate varying traffic loads in wireless LANs. The number of pending packets destined for a receiver is piggy-backed in data packets. If this number is zero, the receiver can go to sleep; otherwise, if there are still packets to be transmitted at the end of a beacon interval, both the sender and receiver stay up in the next beacon interval. The major difficulty in realizing such a scheme is that it is non-trivial to adjust the ATIM window size individually and maintain consistent information among neighboring nodes. Also, as shown in later sections, switching to the sleep state as

soon as there is no buffered packet to a receiver can potentially lead to significant packet losses and higher delay.

Krashinsky and Balakrishnan [11] identify that using fixed beacon intervals leads to energy waste, while incurring large delay. They propose for wireless LANs with the AP support a bounded slow-down (BSD) scheme that essentially probes the round trip time between a HTTP request and its response progressively. The solution explores the dependency in two-way traffic but is only applicable to out-bound requests initiated by the wireless device.

Hu and Hou [6] propose a traffic prediction mechanism called *LISP*. *LISP* reduces the end-to-end delay in multi-hop communication by seeking the correlation between acknowledgments to direct ATIM frames and incoming traffic. Upon overhearing an ACK for an ATIM frame, nodes en route transmit a pseudo-ACK to notify downstream nodes to stay awake in the current beacon interval. For single hop connections, *LISP* essentially falls back to IEEE 802.11 PSM.

Macro-power Management: Macro-power management approaches operate on top of IEEE 802.11 PSM by controlling when a node enters *power-save mode*.

Zheng and Kravets [20] propose an on-demand power management framework for multi-hop wireless networks. In this framework, power management decisions are driven by data transmission in the network. Only nodes along the communication path from the source to the destination are kept active, while all other nodes can switch to the power-save mode. Specifically, transitions from the power-save mode to the active mode are triggered by communication events in the network, which set up/refresh a soft-state timer, called the *keep-alive timer*. Upon expiration of the keep-alive timer, a node switches from the active mode to the power-save mode.

The recent work by Anand *et al* [2] investigates the performance degradation of IEEE 802.11 PSM for latency-sensitive applications. They propose a self-tuning power management (STPM) scheme for wireless LANs with the AP support. STPM adapts the use of power-save mode to the patterns and intent of applications, the characteristics of the network interface, and the energy usage of the platform. STPM is implemented as a Linux kernel module and is shown to achieve better energy-efficiency for a wide range of network access patterns. STPM requires modification of applications to provide hints to the power management module.

The above approaches achieve different trade-offs between energy and performance. Table I summarizes the key differences of these schemes. The throughput performance refers to that under high traffic load. Several observations are in order: the smaller the granularity of power management decisions, the more energy saving can be achieved as the wireless devices can take advantages of idle periods between bursts of communications. On the flip side, keeping a wireless interface active for an extended period of time helps to accommodate bursty arrivals and expedites packet forwarding. In this paper,

TABLE I
COMPARISON OF ENERGY-PERFORMANCE TRADE-OFF

	Energy Saving	Delay	Throughput	Multi-hop?
PAMAS [17]	low	low	high	yes
IEEE 802.11 PSM	medium	high	low	yes
Jung et al.[9]	high	high	medium	no
BSD [11]	high	low	-	no
LISP [6]	medium	medium	low	yes
SIMPA	high	high	high	yes
On-demand [20]	low	low	high	yes
STPM [2]	low	low	high	no

we focus on the design of micro-power management for multi-hop wireless networks and treat packet-level and macro-power management as orthogonal techniques. The proposed scheme can be potentially combined with the latter to maximize the benefits.

III. ANALYSIS OF IEEE 802.11 PSM

To better understand the energy-performance trade-offs of IEEE 802.11 PSM, we first develop an analytical model using transient queuing analysis. Note that although the analysis is based on some simplifying assumptions such as Poisson arrival processes and exponential service times, observations drawn from the analytical study have been validated by simulation results under other traffic patterns and packet size distributions.

For ease of exposition, we refer to a beacon interval (BI) in IEEE 802.11 PSM in which a node is full-powered as an “active interval,” and a BI in which a node turns to the sleep state after the ATIM window as a “sleep interval.”

A. The Model

We consider a pair of transmitter and receiver nodes operating in the IEEE 802.11 distributed coordinating function (DCF) mode. The two nodes are synchronized using beacon messages. Therefore, they can be coordinated in the transition of power management states. For tractability of the derivation, we assume that packets arrive at the transmitter in compliance with a Poisson arrival process. The packet size follows an exponential distribution (and thus the service time is exponentially distributed). However, the analysis can be readily extended to other Markov regenerative processes such as Batch Markovian arrival process (BMAP).

For ease of analysis, a beacon interval is defined in this section as the time duration from the end of an ATIM window to the end of the next ATIM window, but defined in subsequent sections in the conventional way (i.e., from the beginning of an ATIM window to the beginning of the next ATIM window). The ATIM window size is δ . Packets destined for a receiver in the sleep mode are buffered at the transmitter, if there exists sufficient buffer at the transmitter; otherwise, they are discarded. As long as there are packets buffered at the end of an ATIM window, both the sender and receiver are active during the next beacon interval of size b . No data packets can be transmitted in an ATIM window.

We model the system with a finite buffer size K as a finite state Markov chain sampled at the boundary of beacon intervals². The system state at the end of the i th beacon interval is given by the number of packets buffered n_i at the sender side queue. Let $\zeta_i \in \{0, 1\}$ be the power management decision of the i th beacon interval, with “0” indicating a sleep interval and “1” an active interval. The power management decision of IEEE 802.11 PSM can be simply expressed as

- 1) if $n_i = 0$ then $\zeta_{i+1} = 0$;
- 2) if $n_i > 0$ then $\zeta_{i+1} = 1$.

Let A_i and D_i denote the number of arrivals and departures in the i th interval. Then the transition of n_i is given by

$$n_{i+1} = \begin{cases} \min\{n_i + A_{i+1} - D_{i+1}, K\}, & \text{if } n_i \geq 1, \\ A_{i+1}, & \text{if } n_i = 0. \end{cases}$$

We take the following steps to derive the quantities of interests:

- 1) Compute the one-step transition matrix $\mathbb{P}_{l,m} = \Pr\{n_{i+1} = m | n_i = l\}$ using the transient analysis method.
- 2) Derive the steady state probability $\pi_k = \Pr\{n_i = k\}$.
- 3) Derive the steady state blocking probability, the average power consumption and the average delay in the system.

B. Transient Analysis for One-step Transition Matrix

Traditional queuing analysis focuses, in general, on the steady state behavior of stationary processes. However, in the context of IEEE 802.11 PSM, the time-dependent behavior is of importance because the system cannot reach a steady state within an beacon interval under medium to high traffic load.

Let $N(t)$ be the number of packets in the system at time t , and $\mathbb{P}(\lambda, t)$ the time-dependent transient transition matrix within an (active/sleep) beacon interval for normalized load λ . For ease of presentation, we drop λ in $\mathbb{P}(\lambda, t)$ and simply write it as $\mathbb{P}(t)$. In particular, $\mathbb{P}_{0,m}(t) = \Pr\{N(t) = m | n_i = 0\}$, $m = 0, 1, \dots, K$ denotes the probability that there are m packets in the system at time t in a sleep beacon interval. $\mathbb{P}_{l,m}(t) = \Pr\{N(t) = m | n_i = l\}$, $l = 1, 2, \dots, K$ and $m = 0, 1, \dots, K$ denotes the probability that there are m packets in the system at time t in an active beacon interval i that starts with l packets. Lastly, $\mathbb{P} = \mathbb{P}(b)$ denotes the one-step transition matrix for beacon interval of length b .

Logothetis *et al.* [13] developed a computational technique for obtaining the time-dependent solution of the queue length distribution for a class for Markov regenerative process including M/G/1/K and GI/M/1/K queues. In the case that the service time is exponential, the transition matrix can be written simply as an exponential matrix. In the case of non-exponential service times, one has to resort to renewal theory on Markov regenerative process (MRGP) [12].

²In real implementation, buffer size is usually expressed in B bytes. Therefore, K can be approximated as $K = B/\bar{S}$, where \bar{S} is the average packet size.

For exponential service times, the one-step transition matrix can be written as,

$$\mathbb{P}_{l,m} = \begin{cases} [e^{(b-\delta)\mathbb{Q}_{on}} e^{\delta\mathbb{Q}_{off}}]_{l,m}, & \text{if } l \geq 1, \\ e_{l,m}^{b\mathbb{Q}_{off}}, & \text{if } l = 0, \end{cases} \quad (1)$$

where \mathbb{Q}_{on} is the generation matrix of the corresponding M/M/1/K queuing system, i.e.,

$$\mathbb{Q}_{on} = \begin{bmatrix} -\lambda & \lambda & \cdots & & & \\ & \mu & -\lambda - \mu & \lambda & \cdots & \\ & & \mu & -\lambda - \mu & \lambda & \cdots \\ & & & \cdots & \cdots & \cdots \\ & & & & \cdots & \cdots \end{bmatrix},$$

and \mathbb{Q}_{off} is the generation matrix of the 0/M/1/K queuing systems (pure birth process), i.e.,

$$\mathbb{Q}_{off} = \begin{bmatrix} -\lambda & \lambda & \cdots & & & \\ & 0 & -\lambda & \lambda & \cdots & \\ & & 0 & -\lambda & \lambda & \cdots \\ & & & \cdots & \cdots & \cdots \\ & & & & 0 & 0 & 0 \end{bmatrix}.$$

The first expression in Eq. (1) results from the fact that according to IEEE 802.11 PSM, no packet can be serviced inside an ATIM window. The second expression comes from the fact that no packet can be serviced in a sleep interval.

C. Time-average Energy-Performance Metrics

In this section, we derive the time-average performance metrics of interest using the above result on the transition matrix \mathbb{P} and $\mathbb{P}(t)$.

Probability of the number of packets at the end of each beacon interval: Let $\pi_k = \Pr\{n_i = k\}$ be the probability that there are k packets at the end of the i th beacon interval. By solving the Chapman-Kolmogorov equation $\pi = \pi\mathbb{P}$, we can get the steady state distribution (i.e., the distribution of the number of packets) at the end of each beacon interval, where \mathbb{P} is given in Eq. (1) for exponential service times.

Blocking probability: Define $\mathbb{R}^{on} \triangleq \int_0^{b-\delta} e^{\mathbb{Q}_{on}t} dt$, $\mathbb{R}^{off} \triangleq \int_0^b e^{\mathbb{Q}_{off}t} dt$ and $\mathbb{R}^{atim} \triangleq \int_0^\delta e^{\mathbb{Q}_{off}t} dt$. The blocking probability in the sleep state is $\Pr\{B | \zeta = 0\} = \frac{1}{b} \mathbb{R}_{0,K}^{off}$. The probability that a packet arrives at an active interval that starts with j packets and sees K packets in queue is given by $\Pr\{B | \zeta = 1, n_i = j\} = \frac{1}{b} (\mathbb{R}_{j,K}^{on} + \sum_{m=0}^{m=K} \mathbb{P}_{l,m} \mathbb{R}_{m,K}^{off})$ since Poisson arrivals can be thought as a random point process on the time axis. Therefore, the total blocking probability is

$$P_B = \pi_0 \Pr\{B | \zeta = 0\} + \sum_{j=1}^{j=K} \pi_j \cdot \Pr\{B | \zeta = 1, n_i = j\}, \quad (2)$$

where π_0 gives the probability that a packet arrives at a sleeping system. Consequently, the throughput of the system is $\gamma = \lambda(1 - P_B)$. The carried load is defined as $\rho_c = \rho(1 - P_B)$.

Average power: Let $PW_{tx/rx}$, PW_{awake} , PW_{idle} be the power consumed in the transmission/receiving, awake and idle states, respectively. The average power at the sender and receiver can be computed as

$$\overline{PW}_{tx/rx} = Pr_{asleep}PW_{asleep} + \rho_c PW_{tx/rx} + Pr_{idle}PW_{idle}, \quad (3)$$

with $Pr_{asleep} = \frac{b-\delta}{b}\pi_0$, as a node has to be awake during ATIM windows. $Pr_{idle} = 1 - \frac{b-\delta}{b}\pi_0 - \rho_c$ gives the idle probability.

Average delay: The average number of packets in a sleep interval is $\overline{N}_{asleep} = \frac{1}{b}[1 \ 0 \ \dots \ 0] \cdot \mathbb{R}_{off} \cdot [0 \ 1 \ \dots \ K]'$. Similarly, if a packet arrives at an active system, the average number of packets it sees in a system that starts with j packets at the end of the last beacon interval is $\overline{N}_j|_{awake} = \frac{1}{b}(\mathbb{R}_{j,-}^{on} + \sum_{m=0}^{K-j} \mathbb{P}_{l,m} \mathbb{R}_{m,-}^{off}) \cdot [0 \ 1 \ \dots \ K]'$, where $\mathbb{R}_{j,-}^{on}$ and $\mathbb{R}_{m,-}^{off}$ are the j th and m th row of \mathbb{R}^{on} and \mathbb{R}^{off} . Therefore, the average delay is given by

$$\overline{N} = \pi_0 \overline{N}_{asleep} + \sum_{j=1}^{j=K} \pi_j \overline{N}_j|_{awake}. \quad (4)$$

Using Little's law, we can approximate the delay experienced by a packet in the system as $\overline{d} = \overline{N}/(\lambda P_B)$.

D. Numerical Examples

In this section, we present both analytic and simulation results for IEEE 802.11 PSM and demonstrate the energy-performance trade-offs. The simulation is conducted in *ns-2* [18] by modifying the CMU wireless extension [1] with support for IEEE 802.11 PSM. There are two static nodes within the wireless transmission range (≈ 250 m). The sender and receiver nodes communicate with half-duplex IEEE 802.11-based WaveLAN wireless radios with a bandwidth of 2Mbps. Simulation results show that the nominal capacity of the wireless link is around 1.6Mbps when the packet size is 1KB (with the overhead of MAC headers, RTS/CTS, ACK and random backoff) and 0.77Mbps when the packet size is 128B (without RTS/CTS). Both Poisson and constant bit rate (CBR) traffic (with deterministic packet sizes) are simulated. For CBR traffic, the inter-arrival time follows a uniform distribution within $\pm 50\%$ around the mean. Normalized load is defined as the actual traffic load divided by nominal wireless capacity. The link layer buffer size is set to 50 packets. The lengths of the beacon interval and the ATIM window are set to be 100ms and 10ms, respectively. Due to the page limit, we only present the results with packet size 128B.

Fig. 2 depicts the analytic and simulation results of the duty cycle³, delay and delivery ratio of a single hop connection under different loads. As shown in Fig. 2, the analytic results

³Duty cycle is defined as the proportion of time during which a node is in the active state by setting $PW_{tx} = PW_{rx} = PW_{idle} = 1$ and $PW_{asleep} = 0$ in Eq. (3).

agree well with the simulation results under Poisson arrivals, even though the packet size follows a different distribution (deterministic as opposed to exponential distributed assumed in the model). For CBR traffic, the differences between these two sets of results are more pronounced. Nevertheless, the analytic results still give the qualitative trend of the simulation results. This is attributed to the fact that CBR traffic is less “bursty” than the Poisson arrival process. When the average number of packet arrivals per beacon interval is no less than 15, with probability 1, there is a packet arrival within the ATIM window, as the packet inter-arrival time is always less than 10ms. This explains why when the normalized load is greater than 0.2, the percentage of time spent in the sleep state is zero. Consequently, the delay decreases sharply. In contrast, for the Poisson arrival process, the packet inter-arrival time is exponentially distributed and therefore, there is always a non-zero probability that no packet arrives in an ATIM window.

Fig. 3 depicts the percentage of time (obtained from the model) that a node spends in the idle, sleep and tx/rx state under different loads. Clearly, a significant amount of time is spent in the idle state. As the traffic load approaches the link capacity, the sleep time diminishes to zero and the idle time is close to the length of the ATIM window.

Next, we examine the effect of the ATIM window size on the energy-performance trade-off. The beacon interval is fixed at 100ms and the size of ATIM window is varied from 10ms to 30ms. As shown in Fig. 4, with a larger ATIM window, the link is saturated much earlier on as evidenced from the higher delay and packet loss rate. A larger ATIM window size puts a node to the active interval more frequently, thus consuming more power.

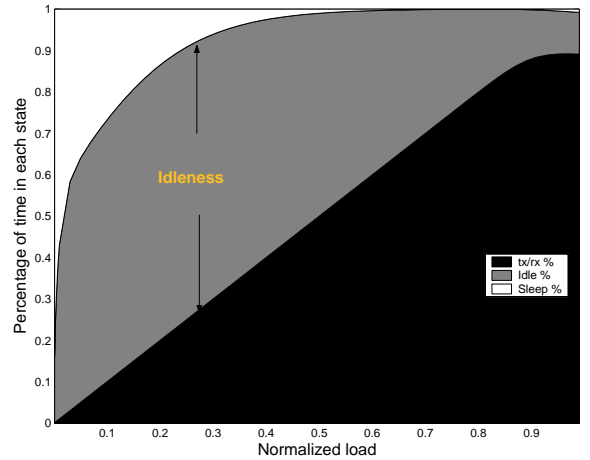


Fig. 3. Ratio of time spent in the idle, sleep and tx/rx state, packet size = 128B.

E. Observation Made from Analytic Results

As evidenced from the above discussion, IEEE 802.11 PSM achieves low energy utilization at light to medium traffic loads

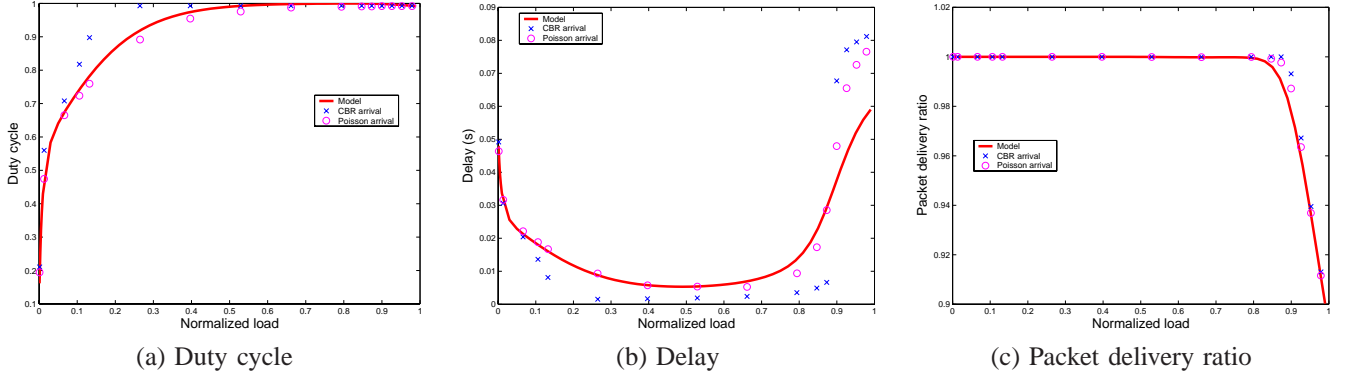


Fig. 2. Duty cycle and performance of IEEE 802.11 PSM between a pair of nodes, beacon interval = 100ms, ATIM window = 10ms, packet size = 128B.

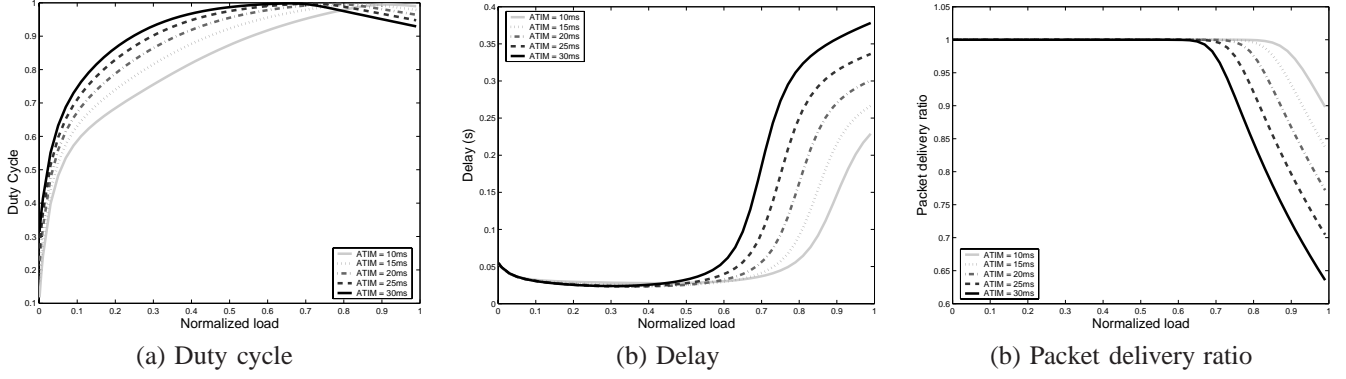


Fig. 4. Duty cycle and performance of IEEE 802.11 PSM between a pair of nodes, beacon interval = 100ms, packet size = 1KB

and low bandwidth utilization at high traffic loads due to the following reasons:

- **Periodic power management decision points.** Under low to medium traffic loads, nodes spend a significant amount of time in the idle state, as IEEE 802.11 PSM mandates a node to stay active for the entire beacon interval (the gray area in Fig. 3). This translates into high energy consumption, as the power consumed in the idle state is usually comparable to that in the tx/rx states. Note that reducing the length of the beacon interval does not suffice to tackle this problem. With a smaller beacon interval, more beacon messages will be transmitted, thus leading to higher energy consumption. Moreover, with a smaller beacon interval, the ATIM window should be reduced accordingly; otherwise, the energy wasted inside ATIM windows becomes dominant. However, a small ATIM window size limits the number of successful ATIM-ACK handshakes that can be carried out.
- **“Memoryless” property.** Power management decisions in IEEE 802.11 PSM is solely based on the information of buffered packets as opposed to the packet arrival history. Under highly bursty traffic, a node may prematurely go to sleep at the end of an ATIM window simply because no packets are buffered at that time. Packets

may arrive after the node goes to sleep, and hence have to wait for the next beacon interval to be transmitted. On the other hand, under high traffic load, even when data transmission is not complete by the end of the current beacon interval, the sender and receiver nodes still have to perform another run of ATIM-ACK exchange to announce pending packets.

- **Signaling overhead to wake up power-saving nodes.** First, an ATIM window is set aside in each beacon interval to announce pending packets. No data packets can be transmitted during this period. Second, in IEEE 802.11 PSM, ATIM frame-ACK hand-shake is limited to a pair of sender and receiver, i.e., it establishes a *link* state (in contrast, power management is a *nodal* state.) As a result, in the worst case when there exist n nodes in a single hop network, each of which has a packet to transmit to every other node, the total number of ATIM frames to be transmitted are $O(n^2)$.

IV. THE SIMPA PROTOCOL

To address the problems mentioned in Section III-E, we propose SIMPA, a micro-power management approach in IEEE 802.11 operated networks. SIMPA aims to minimize the energy consumed in the idle state, while keeping as much

bandwidth as possible for data transport (rather than signaling) at high traffic loads. It uses the packet arrival history to control transition of power management states in a beacon interval and judiciously extends the wake-up period beyond a single beacon interval. Data packets are allowed to be transmitted in the ATIM window in this extended interval, thus increasing the transport capacity.

Compared with other micro-power management schemes reviewed in Section II, SIMPA is designed to deal with various traffic patterns and channel conditions. It is not optimized for a particular type of applications, but instead targeted (with respect to both the energy consumption and performance) for general traffic settings with both unicast and broadcast transmissions. Caution has been used to evaluate the impact of different “components” to be incorporated in SIMPA on the energy and performance. For example, in the early design phase of SIMPA, we ruled out approaches that involve dynamic adjustment of ATIM window sizes or lengths of beacon intervals, because both require consistency of distributed states and can be counter-productive under certain scenarios.

A. Local States

IEEE 802.11 PSM requires that each node keeps two per-neighbor states *sent_atim* and *recvd_atim_ack* to indicate, respectively, whether a directed ATIM frame has been transmitted and acknowledged. SIMPA introduces three more non-negative integer states for each neighbor: $n2m$ (Neighbor to Me), $m2n$ (Me to Neighbor) and *pkt_inbuf_num*. Separate entries indexed by MAC broadcast and multicast addresses are introduced to store information related to broadcast and multicast messages.

$n2m$ ($m2n$) records future communication opportunities with a neighbor, with 0 meaning no packet will be received from (sent to) the corresponding neighbor, as it is (or has been requested to be) in the sleep state. The records are updated at the beginning of each beacon interval or upon receipt of a packet. For example, consider the records kept at node i .

- Records $n2m$ and $m2n$ are initialized to 0.
- Each record is decremented by 1 till zero at the beginning of each beacon interval.
- $n_j \rightarrow n2m$ is set to 1 if node i receives a directed ATIM frame from node j .
- $n_{BCAST} \rightarrow n2m$ or $n_{MCAST} \rightarrow n2m$ are set to 1 if broadcast or multicast ATIM frames have been received.
- $n_j \rightarrow n2m$ is set to 2 (0) if node i receives a unicast DATA frame from node j and the *fc_more_data* bit in the MAC header is set (cleared).
- $n_j \rightarrow m2n$ is set to 0 if node i transmits a unicast DATA frame to node j , in which the *fc_more_data* bit in the MAC header is cleared.
- $n_j \rightarrow m2n$ is set to 2 if node i transmits a unicast DATA frame to node j , in which the *fc_more_data* bit in the MAC header is set and this DATA frame has been acknowledged.

- $n_j \rightarrow m2n$ is set to 1 if node i transmits a unicast ATIM frame to node j and has received an ACK for it; or if j is a broadcast/multicast address and node i transmits a broadcast/multicast ATIM; or node i overhears an ACK (for an ATIM frame) from node j .

Record $n_j \rightarrow \text{pkt_inbuf_num}$ reflects the number of packets buffered and destined (excluding the outstanding packet to be transmitted) for node j .

B. Power Management Policy

The power management policy in SIMPA consists of four components.

Transition from the active state to the sleep state:

Transition from the active to the sleep state is a local decision made by each node based on the information exchanged among neighbors. SIMPA allows a node to transit to the sleep state inside a beacon interval subject to the following conditions:

C.1 $n_k \rightarrow n2m = 0$ AND

$(n_k \rightarrow \text{pkt_inbuf_num} = 0$ OR $n_k \rightarrow m2n = 0)$,
 $\forall k \in \{N(i), BCAST, MCAST\}$,
 where $N(i)$ denotes the neighbor set of node i

C.1 implies that a node can **sleep in the middle** of a beacon interval as long as all its neighbors do not have packets destined to it (the first condition) and it has no more packets for any of its active neighbors (the second condition). Furthermore, it requires a node to remain awake for the entire beacon interval if it has received any broadcast/multicast ATIM frame. This is conservative but ensures broadcast messages (e.g. route discovery messages) can be forwarded in a more timely fashion.

Transition from the sleep state to the active state: Similar to IEEE 802.11 PSM, a node switches from the sleep state to the active state at the beginning of beacon intervals. When the ATIM window ends, the node will stay active if condition C.1 is not satisfied. In addition, a wireless interface that is previously in the power-saving state can be waken up by interrupts from its local applications subject to the following condition:

C.2 Interrupts from local applications to transmit to neighbor

k AND $n_k \rightarrow m2n > 0$,
 $\forall k \in \{N(i), BCAST, MCAST\}$.

Signaling mechanism: In SIMPA, we use two in-band mechanisms to wake up a power-saving node and to notify a neighbor of whether it should switch to the sleep state or remain awake. The first one uses, similar to IEEE 802.11 PSM, ATIM announcements with one difference. As all the nodes are active during ATIM windows, it is possible for a node to overhear ATIM-ACK handshake between other nodes. Since a single ATIM-ACK suffices to mandate a node to be awake for some time, no ATIM frames need to be sent to wake up the

corresponding receiver, if a node overhears that its intended receiver has been asked to stay awake by some other node. This reduces the number of ATIM frames. In summary, the rule to transmit ATIM frames is as follows,

For neighbor k ,

C.3 $n_k \rightarrow m2n = 0$ **AND** $n_k \rightarrow pkt_inbuf_num > 0$ **AND** $n_k \rightarrow recvd_atim_ack = false$

The second mechanism takes advantage of the *fc_more_data* bit in the MAC control field. Upon transmitting a unicast DATA frame to node j , the sender i needs to check its local state to decide whether the *fc_more_data* bit should be set. We first define the following conditions and then discuss how these conditions are used to determine the *fc_more_data* bit.

C.4 $n_k \rightarrow n2m > 0, \forall k \in N(i)$

C.5 $n_j \rightarrow pkt_inbuf_num > 0$

C.6 $n_j \rightarrow m2n > 0$

C.7 (Condition to avoid packet aging)

$S + \lambda(t_l + b) \leq C(b - \delta)$, where S is the size of the outstanding packet. t_l is the interval from the decision time instant to the beginning of the next beacon interval, and b and δ are, respectively, the length of a beacon interval and an ATIM window. λ and C are respectively the estimated arrival rate and the estimated available bandwidth. We will discuss how to estimate on-line the two parameters λ and C in Section IV-C.

The first two conditions mandate that a node can go to sleep only when it has no packets and is not required by others to remain awake. Condition (C.7) ensures that packets that arrive at the sender during the subsequent sleeping period of the receiver can be transmitted (under any service order) within the next beacon interval to avoid excessive delay or packet losses due to aging⁴. Let t be the time instant in the next beacon interval by which all new arrivals since t_l will have been transmitted. Therefore, t_l should satisfy the following inequalities:

$$\begin{aligned} S + \lambda(t_l + t) &\leq C(t - \delta), \\ t &\leq b. \end{aligned}$$

Finally, the *fc_more_data* bit is computed as follows.

$$fc_more_data = C.4 + \overline{C.4} \times (C.5 + \overline{C.5} \times \overline{C.7}) \times C.6 \quad (5)$$

Once node i receives a data packet from node j with field *fc_more_data* set in the MAC header, it sets its $n_j \rightarrow n2m$ to 2. By this mechanism the active state may be extended to the next beacon interval without additional ATIM-ACK handshakes. This is termed as *prolonged active mode*.

The sender node can transmit a data frame to its neighbor k as long as

C.8 $n_k \rightarrow m2n > 0$, and

C.9 not in the ATIM window **OR** in the ATIM window but in the *prolonged active mode*

⁴It has been recommended in [7] (11.2.2.4, page 135) that packets buffered for an excessive amount of time ($>$ beacon interval) may be discarded.

```

/* At the beginning of a beacon interval */
1.  wakeup();
   /* update m2n, n2m, pkt_inbuf_num, sent_atim
   and recvd_atim_ack */
2.  update_neighbor_table();
   /* purge aged packets from buffer */
3.  purge_PSM_buffer();

/* Inside the ATIM window */
1.  foreach k ∈ {N(i), BCAST, MCAST}
2.    if C.3
3.      send_ATIM(k);
4.    end
5.  end

6.  foreach k ∈ {N(i), BCAST, MCAST}
7.    if n_k → pkt_inbuf_num > 0 and C.8 and C.9
8.      send_DATA(k);
9.    end
10. end

/* In the active state, after the ATIM window */
1.  foreach k ∈ {N(i), BCAST, MCAST}
2.    if n_k → pkt_inbuf_num > 0 and C.8 and C.9
3.      send_DATA(k);
4.    end
5.  end

6.  if C.1
7.    goto_sleep(); /*may wake up later */
8.  end

/* In the sleep state, after the ATIM window */
9.  if recv_from_Local_app(k)
10.   if n_k → m2n > 0
11.     wakeup();
12.     send_DATA(k);
13.   else
14.     enqueue_PSM_buffer();
15.   end
16. end

```

Fig. 5. Pseudo code of the SIMPA protocol

The effect of the *prolonged active mode* is two fold. First, it allows transmission of data packets in the ATIM window at high traffic loads. Second, it can expedite forwarding of data packets in multi-hop connections by propagating power management states along a path. For example, consider a two-hop connection (1-2-3). As long as node 1 continues to transmit to node 2, node 2's $n_1 \rightarrow n2m$ field is non-zero. By Condition (C.4) and Eq. (5), node 2 sets the *fc_more_data* bit in the MAC header of messages to be forwarded to node 3. Consequently, node 3 is in the *prolonged active mode*. Thus, packets can be delivered without incurring wake-up delay.

The operations of SIMPA at node i are summarized in Fig. 5.

C. Estimation of Packet Arrival Rate and Available Bandwidth

As SIMPA makes power management decisions based on incoming traffic load and available bandwidth (in addition to the information collected from neighboring nodes), these values have to be on-line estimated. The traffic load (generated locally or to be forwarded for other nodes) is estimated using an *Exponential Weighted Moving Average (EWMA)* estimator:

$$\lambda = \alpha\lambda + (1 - \alpha)\lambda_{cur}, \quad (6)$$

where λ_{cur} is the number of packets (or bytes) transmitted in the last beacon interval divided by the beacon interval length. λ is updated every beacon interval.

Accurate estimation of available bandwidth is more complicated, and requires, among other things, information such as the number of nodes with backlogged packets and/or the packet collision probability. [3], [10]. In SIMPA, we adopt the following simple mechanism to estimate the available bandwidth. Let Δt be the delay experienced in sending a backlogged data packet to an active receiver, i.e., the time interval from the time the data packet is dequeued from the PSM buffer till the corresponding ACK frame is received. The available bandwidth is then computed as

$$\tau = \alpha\tau + (1 - \alpha)\Delta t, \quad (7)$$

$$C = 1/\tau. \quad (8)$$

The effectiveness of the above simple mechanism will be demonstrated in the simulation study. More sophisticated schemes such as those proposed in [3], [10] can be adopted to further improve the estimation accuracy.

D. Discussion

In this section, we discuss several practical issues pertaining to the implementation of SIMPA.

Consistency of state information: In SIMPA, losses of data packets can potentially cause temporary inconsistency in neighbor states. However, since all neighbor records are decremented by 1 till zero in every beacon interval in the absence of data communication, any inconsistency can be resolved within two beacon intervals or until a successful message exchange, whichever occurs first. In the case of transient state inconsistency, SIMPA errors on the conservative side by keeping nodes (unnecessarily) active. Another source of inconsistency comes from the ACK snooping mechanism. When a third node snoops ATIM-ACK handshakes and determines that both nodes will be active for the rest of the current beacon interval, it is possible that one or both of the nodes switch to the sleep state in the middle of a beacon interval. Therefore, direct transmissions to the sleeping node are subject to losses. Upon detection of such events, a node resets its neighbor records to 0 and buffers packets till the beginning of next beacon interval (when ATIM frames can be transmitted).

Implementation complexity: SIMPA employs a signaling mechanism native to IEEE 802.11 MAC. No additional message format or MAC header field is introduced. The state maintenance in SIMPA only requires per neighbor accounting and involves simple logic and add/subtraction operations. It is our belief that such modifications can be readily implemented in practice.

V. SIMULATION STUDY

To evaluate the effectiveness of SIMPA, we have implemented it in the ns-2 [18] network simulator with the CMU wireless extension [1], and conducted a simulation study in both single-hop and multi-hop wireless networks under a wide variety of traffic loads. Though normally the wireless network shall not be operated in overloaded conditions, nodes in multi-hop networks may experience (temporary or/and local) overload due to traffic aggregation.

We are primarily interested in four performance metrics: energy efficiency, end-to-end delay, packet delivery ratio, and network lifetime. Energy efficiency is defined as,

$$\text{energy efficiency (bits/J)} = \frac{\text{total bit transmitted}}{\text{total energy consumed}}, \quad (9)$$

where the number of total bits transmitted is calculated for *application layer data packets* only. In essence, this metric captures the energy utilization of the network with all the control overheads considered. Efficiency of data delivery is characterized by the end-to-end latency and the packet delivery ratio. The latter is defined as the total amount of data received divided by the total amount of data transmitted. Network lifetime is defined as the time interval until the percentage, γ , of remaining forwarding nodes falls below a certain threshold. It is not only an index of energy consumption, but also how the energy is consumed among nodes. We compare SIMPA against IEEE 802.11 with and without PSM with respect to the above four metrics. Performance curves corresponding to IEEE 802.11 with and without PSM are labeled as *PSM* and *no PSM*, respectively.

A. Simulation Setup

In the simulations, all nodes communicate with half-duplex wireless radios with a bandwidth of 2Mbps and a nominal transmission radius of 250m. In all the simulation scenarios, the network is never partitioned and there are no error-induced losses. Dynamic source routing (DSR) [8] is used as the routing protocol.

The energy model assumed is based on the specification of Cisco Aironet 350 wireless cards. Power consumption in transmitting, receiving, idle and sleep states are 1480mW, 1000mW, 830mW and 50mW, respectively. The energy consumed for switching between the idle and sleep states is not considered in the simulation. The parameters for power management are chosen as follows. Beacon interval b is set to 100ms and the

ATIM window size δ is $20ms$. α for the EWMA estimator is chosen to be 0.9. Due to the page limit, we only report results with the use of long-lived CBR traffic. The long-lived CBR traffic is generated at data sources with packet inter-arrival times following a uniform distribution within $\pm 50\%$ around the mean value. All the packets are of length 128 bytes. Each simulation run lasts 500 seconds, and each data point is an average of 10 simulation runs.

B. A Single Pair of Sender and Receiver Nodes

We begin with the similar configuration given in Section III-D, and investigate the energy-performance trade-off of SIMPA in single hop networks. To be consistent with the results presented in Section III-D, we use power consumption (rather than energy efficiency) as the performance metric. We also experiment with an intermediate protocol with only the “sleep in the middle” component enabled. Performance curves corresponding to the intermediate protocol are labeled as “SI only.” The purpose of this comparative study is to understand the effect of the *prolonged active mode*.

As shown in Fig. 6(a), SIMPA achieves much higher energy saving as compared to PSM. In fact, the power consumption curve is close to be linear except at high traffic loads. This implies that the energy consumed in the idle state is small and is a constant in SIMPA (the offset of the power consumption curve from the origin is due to the energy consumed inside an ATIM window). Under high traffic loads, data packets can be transmitted inside ATIM windows. Therefore, the energy consumed in the idle state is further reduced (at the cost of higher delays, however, as shown in Fig. 6(b)). When the traffic rate is smaller than $5Kbps$ (or equivalently, 0.5 packet/BI), every packet experiences a wake-up delay of half a beacon interval in both PSM and SIMPA. As the load increases, the delay in PSM decreases till there are more than 7.5 packets/BI (or roughly at rate $75Kbps$). At this point, PSM keeps a node to be always active and thus the delay is close to that without power management. SIMPA, on the other hand, puts nodes to sleep inside a beacon interval and buffer packets that subsequently arrive till the next beacon interval. As the traffic load approaches the link capacity, PSM experiences significant packet losses. By enabling nodes to extend its active state beyond one beacon interval (i.e., the prolonged active mode), SIMPA saves more bandwidth for data transport (rather than for signaling), and maintains the packet delivery ratio comparable to that of no PSM. In comparison, with “SI only,” the power consumption is the same as that in SIMPA up to $500Kbps$, but the delay incurred is the highest among all schemes. Therefore, *sleep in the middle* alone is insufficient. The prolonged active mode indeed helps to improve the delay performance and preserve the transport capacity under high traffic loads. After justifying the need for the prolonged active mode, we only compare SIMPA with PSM and no PSM schemes in subsequent simulations.

C. A Single Hop Network

The above is an ideal case. Now we turn to a more realistic scenario, in which 50 nodes are randomly distributed in an area of $100m \times 100m$ and 20 pairs of sender and receiver nodes are randomly chosen. Each connection carries a CBR traffic with the same rate. All nodes are in the communication range of each other. To avoid the routing overhead and purely observe the effect of contentions from multiple-flow traffic, static routing is assumed.

Fig. 7 (a-c) illustrate the results obtained in the single-hop network with multiple connections as the traffic rate increases. The results present similar trends: SIMPA has the highest energy efficiency ($6.3Kb/J$ larger than PSM at the aggregated rate $\lambda_a \approx 400Kbps$ and $13.4Kb/J$ larger than no PSM at $\lambda_a \approx 650Kbps$); the delay is close to PSM at light traffic rate ($\lambda_a \leq 200Kbps$), larger than that of PSM under medium traffic load though not significantly, and less than that of PSM under high traffic load when PSM begins or is near to drop packets (around $\lambda_a = 500Kbps$); and SIMPA achieves higher capacity than PSM.

Differently from the previous scenario, in this scenario SIMPA does not trade off much delay for energy saving. An alternative interpretation of the traffic rate may help explain the reason. Take $\lambda_a = 100Kbps$ as an example. There are 20 flows in the network, and thus each connection carries a CBR flow of rate $5Kbps$, which can be translated into 0.5 packets/BI. Note that in Fig. 6 (a) the second vertical grid line is located at rate = $100Kbps$, which corresponds to 10 packets/BI. Compared to the performance and energy saving feature at the very low end in Fig. 6, it is not surprising to see in this single-hop multiple-connection scenario, the energy saving is not as dramatic as that in the previous scenario and associatively, the loss in delay, if any, is not so large, either.

D. Chain Topologies

Next, we evaluate the various power management schemes in a 3-hop chain network.

As shown in Fig. 8(a), SIMPA achieves higher energy efficiency than PSM. The improvement in terms of energy efficiency can be as high as 153% and 93% when the traffic rate is 10Kbps and 50Kbps, respectively. At low traffic loads, the delay performance of both SIMPA and PSM is simply an additive effect of that in a single hop network, i.e., the end-to-end delay for a three-hop chain is roughly three times of the single hop delay. In this regime, SIMPA incurs higher delay. As the traffic load increases, nodes are put to the *prolonged active mode* in SIMPA and thus the end-to-end delay drops drastically (Fig. 8(b)). For PSM, though the delay incurred at the first hop decreases as in the single-hop scenario, packets have to wait till the beginning of the next interval to be transmitted, after they arrive at the second and third nodes. Therefore, the end-to-end delay is dominated by the wake-up latency at the second and third hops. Similar to the single-hop scenario, under high traffic loads, PSM experiences large

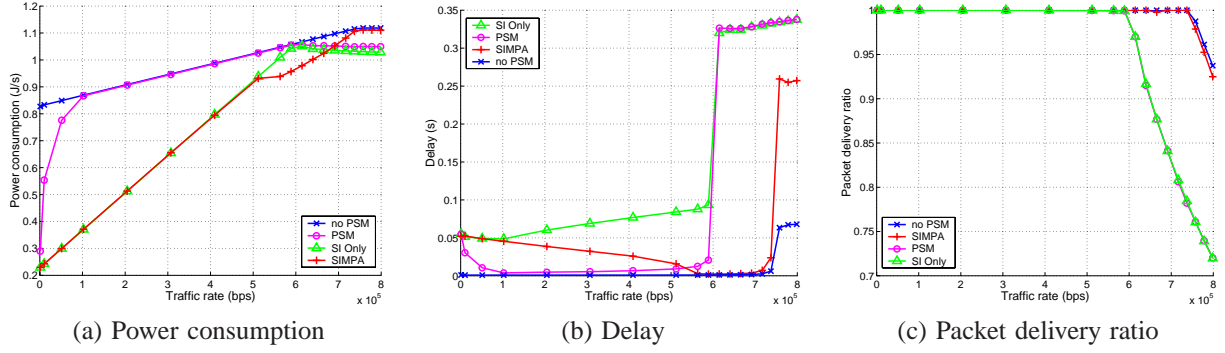


Fig. 6. Performance comparison for a single pair of sender and receiver nodes.

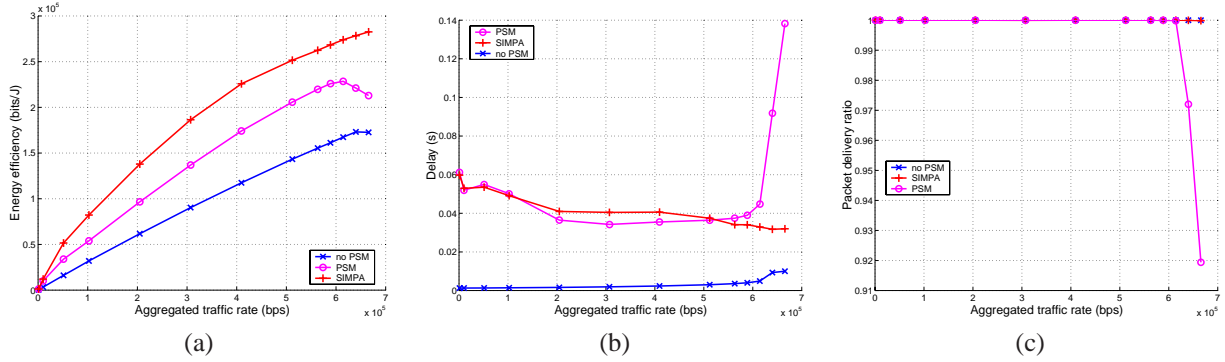


Fig. 7. A single hop network with multiple connections (Static Routing). Beacon interval = 100ms, ATIM window = 20 ms and packet size = 128B

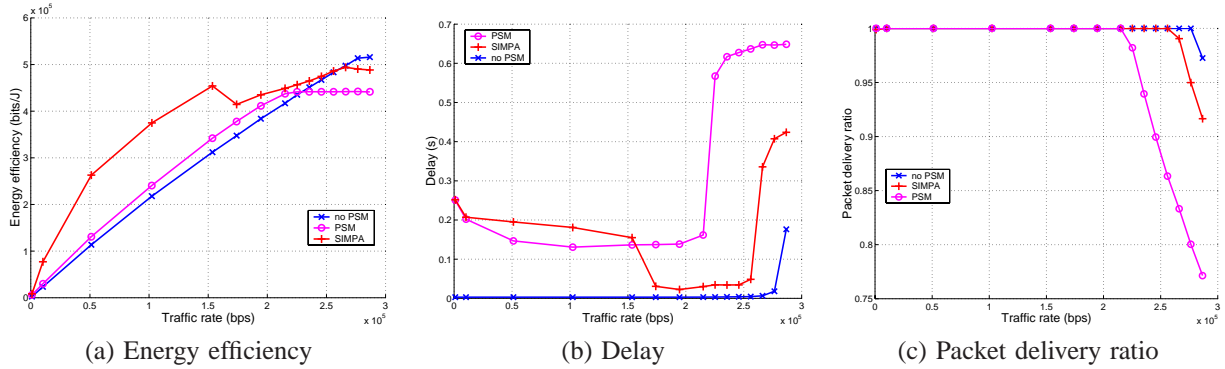


Fig. 8. Performance comparison in a 3-hop chain topology with a single connection.

packet losses. As shown in Fig. 8(c), SIMPA indeed better retains the transport capacity and incurs smaller packet losses at higher traffic loads as compared to PSM. However, because of packet losses, the energy efficiency of SIMPA drops below that of no PSM under very high traffic loads.

E. Multi-hop Static Networks

Next we study two scenarios in a more general setting with 50 nodes randomly placed in a 2-D plane of 750m \times 750m. In the first scenario, we fix the number of connections and randomly choose 10 pairs of sender and receiver nodes,

each carrying a long-lived CBR connection at the same rate. The aggregated traffic rate varies from 10 – 500Kbps. In the second scenario, we fix the per connection traffic rate at around 15Kbps and change the number of connections from 1 to 15.

Figs. 9–10 depict, respectively, the energy efficiency, delay, and packet delivery ratio of different schemes with the number of connections fixed and with the number of connections varied. From Fig. 9, SIMPA achieves performance improvement of approximately 10-20% as compared with PSM. The improvement is less pronounced than in the single-hop scenario (Fig. 6 (a)), because the energy efficiency is

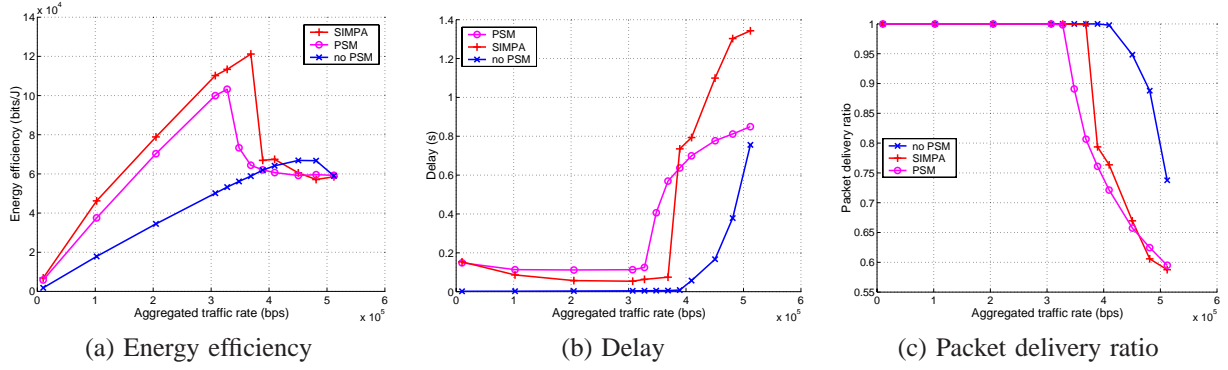


Fig. 9. Performance comparison in a random topology: 50 nodes randomly distributed in $750m \times 750m$, 10 connections.

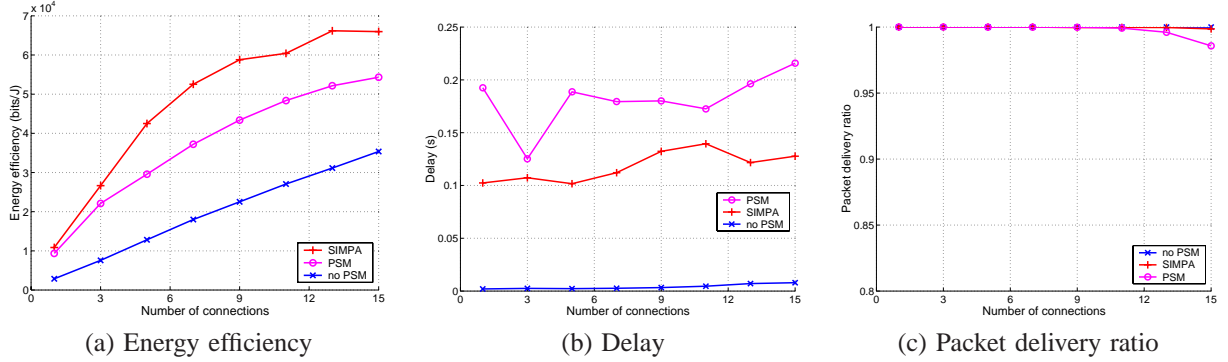


Fig. 10. Performance comparison in a random topology: 50 nodes randomly distributed in $750m \times 750m$, per connection traffic load is around 15Kbps.

computed as the average over all nodes. As some nodes do not participate in packet forwarding in multi-hop communications, they experience the same amount of power consumption in both schemes. In contrast, as shown in Fig. 10(a) when the number of connections increases and more nodes participate in communication, the energy efficiency of SIMPA compared to other schemes becomes more significant.

In both scenarios, SIMPA incurs less end-to-end delay than PSM (Fig. 9(b) and Fig. 10(b)). This is due to the use of the prolonged active mode in SIMPA (Section IV). Also, as shown in Fig. 9(c) and Fig. 10(c), SIMPA starts to drop packets later than PSM due to its capacity preserving capability. However, since packet losses are treated as indications of link failures in DSR, route discovery messages are broadcast across the entire network when packet losses occur. Transmissions of broadcast messages have to be announced in the ATIM window. Storms of such broadcast ATIM frames may collide with data frames (and other direct ATIM frames) transmitted inside ATIM windows, and cause more packet losses as observed in the tail of curves of Fig. 9(c). This effect is only partially alleviated by ATIM-ACK snooping in SIMPA. Investigating the impact of broadcast messages on power management is part of our future research work.

F. Study on Network Lifetime

The major objective of conserving energy is to prolong the network lifetime. Depletion of nodes' battery power is, on one hand, disruptive to network operations, e.g., impairing network connectivity and capability of transporting data, and on the other hand, incurs high maintenance cost to replace battery.

Power management techniques directly affect the energy consumed by nodes over the time. However, its impact on the network lifetime is less direct as the latter is also affected by how the energy is consumed among nodes. In this set of simulations, we investigate the effect of power management on the network lifetime in a network of 10×5 grid topology. Each grid is $150m \times 150m$. A total of 10 pairs of sources and sinks are carefully placed at the longer sides of the rectangular area. DSR is instrumented to disable packet forwarding at the source and sink nodes by not answering to route requests. All the forwarding nodes have an initial energy of 300J. The source/sink nodes are assumed to be equipped with wired power supply and hence will not deplete their energy. There are ten long-lived CBR connections transmitting at a rate of 10Kbps with distinctive sources/sinks. The simulation lasts 1000 seconds.

Fig. 11 (a) depicts the percentage, γ , of remaining forwarding nodes as time goes on, while Fig. 11(b) gives the number of packets delivered in every 10-second interval (recall

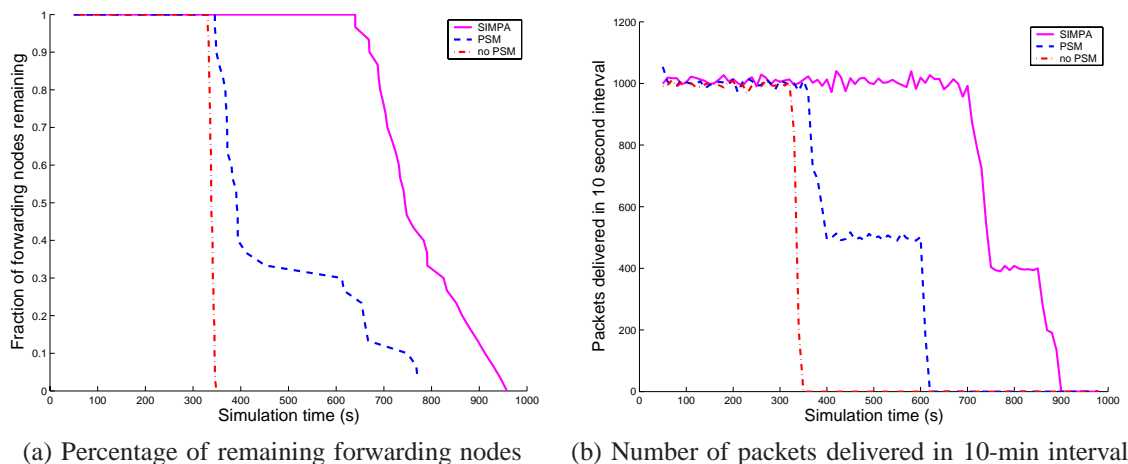


Fig. 11. Performance comparison in a grid topology: 10 x 5 grids with grid size 150mx150m. 10 connections with sources/sinks on either side of the grid. Per connection rate = 10Kbps.

the sources and sinks never run out of power and thus the number of packets transmitted remains the same). Initially, γ is 100% under all the three schemes and the throughput remains the same. Starting at time 330s, γ drops drastically to zero under no PSM, as all nodes are depleted of their energy roughly at the same rate. As a result, the network is partitioned and no packet can be delivered. In the case of PSM, the first node depletes its energy at time 345s. γ continues to decrease sharply till 749s, at which point only one node is still alive. From the traces we find that this node never forwards traffic for other nodes and hence is never depleted of energy during the simulation run. As more nodes die, the transport capacity of the network decreases. At around time 620s when only 20% forwarding nodes are alive, the number of packets delivered diminishes to zero. In contrast, under SIMPA the first node depletes its energy at time 640s. Afterward γ decreases steadily. The throughput starts to drop at time 710s. If the network lifetime is defined as the time interval until γ falls below 90%, then it is approximately 350s, 360s and 700s under no PSM, PSM and SIMPA. SIMPA effectively prolongs the network lifetime by 100% and 94% as compared to no PSM and PSM, respectively.

VI. CONCLUSION

In this paper, we have conducted a systematic study of micro-power management in IEEE 802.11 wireless networks. We first develop a theoretical model to quantify the energy-performance trade-off of IEEE 802.11 PSM. The analytical study reveals that the periodicity of the instants when power management decision are made and the signaling overhead incurred in waking up power-saving stations lead to both energy and bandwidth under-utilization. We then propose SIMPA to decouple the power management decision points with the beacon intervals in IEEE 802.11 PSM.

A comprehensive simulation study in both single hop wireless LANs without the AP support and multi-hop wireless networks demonstrates that as compared to the IEEE 802.11 PSM, SIMPA can effectively reduce energy consumption under light to medium traffic loads and increase the network capacity to accommodate high traffic loads. In one of the scenarios, the improvement of SIMPA in the network lifetime can be as high as 100% and 94% as compared to no PSM and PSM, respectively.

We envision SIMPA as one basic building block for comprehensive power management solutions in IEEE 802.11 wireless networks. In particular, macro-power management schemes proposed in [20], [2] can be laid on top of SIMPA in order to achieve a desirable design point in the energy-performance space determined by both application QoS specifications and network-wide optimization goals.

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