# Centralizing the Power Saving Mode for 802.11 Infrastructure Networks

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## 1. Introduction

With the rapid development of wireless networks, efficient energy management for wireless LAN (WLAN) has become an important problem, because mobile devices' availability is determined by their stringent batteries power. Quite a few sources of energy consumption have been identified (Narseo et al., 2010), among which the wireless communication component uses up a significant amount of energy. For instance, the Motorola Droid phone consumes around 200mW with the backlight off, close to 400mW with the backlight on, and over 800mW when the Wi-Fi radio is active (Zeng et al., 2011). This chapter focuses on improving the energy efficiency of wireless communication component, because they may consume up to 50% of the total energy.

Various mechanisms have been proposed to balance between communication quality and energy consumption for wireless devices, for example, power saving mode (PSM) that puts an idle client into a low-power mode (Gast, 2005), transmission power control (Nuggehalli et al., 2002), packet transmission scheduling (Qiao et al., 2003; Tarello et al., 2005), and some cross-layer methods (Anastasi et al., 2007). They investigate the trade-off between energy consumption and throughput (Gao et al., 2010; Zhang & Chanson, 2003), delay (Guha et al., 2010; Nuggehalli et al., 2002; 2006), or network utility (Chiang & Bell, 2004). In this chapter, we propose a centralized PSM (C-PSM), an AP-centric deployment of the IEEE 802.11 PSM, to optimize power saving and multiple performance metrics for infrastructure networks which are widely deployed in enterprise, campus, and metropolitan networks. In these networks, wireless clients (e.g., laptops, PDAs and mobile phones) using the IEEE 802.11 infrastructure mode connect to the Internet through an access point (AP). The experiment results show that significant improvements can be obtained from the new deployment of C-PSM.

The IEEE 802.11 PSM, widely used in WLAN, allows an idle client to go into a sleep mode. Hereafter, we use PSM to refer to the IEEE 802.11 PSM. The clients save energy by sleeping while wakes up periodically to receive beacon frames from AP. The beacon frame, sent by an access point (AP) every *beacon interval* (BI), indicates whether clients have frames buffered at the AP. Each client's wake-up frequency is determined by a PSM parameter *listen interval* (LI). Both BI and LI are configurable, and their settings directly influence the PSM's performance shown by the analysis of section 4. Unfortunately, the protocol does not prescribe how the BI and LI should be configured in PSM; therefore, default values are often used. Obviously, the PSM using default settings cannot adapt to the traffic and configuration dynamics inherent in typical wireless networks. Worse yet, the PSM was reported to have adverse impact on application performance, such as short TCP connections (Krashinsky & Balakrishnan, 2005).

To address these shortcomings, a number of new power-saving schemes that put idle clients into sleep have been proposed. A class of them (e.g., (Nath et al., 2004); (Qiao & Shin, 2005); (Krashinsky & Balakrishnan, 2005)) enables each client to save energy by reducing the number of unnecessary wake-ups ( i.e., design an optimal wake-up schedule). These user-centric schemes, however, do not address energy consumption due to channel contention which, as we will show in section 3, is another major source of energy wastage. Another class adopts an AP-centric approach which exploits AP to improve the energy efficiency of all clients in the network. Within this class, some schemes design a packet transmission schedule to minimize channel contention (e.g., (Lin et al., 2006); (He et al., 2007); (Zeng et al., 2011)). Others redesign beacon frame and poll clients one by one, which totally avoids channel contention (Lee et al., 2006). However, most AP-centric schemes are not compatible with the standard PSM scheme or difficult to implement, because they employ precise transmission schedule.

Unlike the previous works on the power saving mode (PSM), our C-PSM optimizes the beacon interval, listen interval, minimal congestion window, and sequence of first wake-up time for each device according to the traffic characteristics. Firstly, the AP chooses the optimal BI and LIs for clients based on the pattern of arriving packets to reduce energy consumption due to both unnecessary wake-ups and channel contentions. Especially, the energy wasted in channel contentions could be very significant, because all clients involved cannot go to sleep throughout the contention period which could be very long. Secondly, the AP assigns congestion windows to the clients which are involved in collisions, such that a client that wakes up less frequently will be able to retransmit earlier. Finally, C-PSM provides an additional wakeup schedule to further reduce simultaneous wakeups of clients.

Having the AP control the PSM parameters, C-PSM is therefore able to maximize the total energy efficiency for all clients and facilitates various aspects of network management and operations. Our extensive simulation results show that the C-PSM is very promising under four traditional distributions of inter-frame arrival times: deterministic, uniform, exponential, and Pareto. For example, under exponential traffic, the C-PSM can reduce power consumption by at least 50% compared with the standard PSM (S-PSM). At the same time, C-PSM also decreases the frame buffering delay at the AP by 30%. The wake-up schedule can further save the energy consumption by another 22%. Moreover, the C-PSM's advantage of energy saving is robust in a wide range of operational scenarios. For example, the C-PSM's energy saving remains effective for a large number of clients, heavier network workloads, and other configuration settings. In contrast, a client randomly selecting PSM parameters cannot obtain any long-term benefit in terms of performance or energy consumption.

Our C-PSM is different from other AP-centric schemes in three important aspects. First, C-PSM conforms to PSM, whereas other AP-centric schemes, such as (Belghith et al., 2007), do not. The only additional mechanism required for C-PSM is to notify the clients of their optimal LIs which could be accomplished through the beacon transmission channel. Second, C-PSM does not rely on computational-expensive packet scheduling which is employed in (He et al., 2007); (Lin et al., 2006); (Lee et al., 2006). Instead, the AP in C-PSM simply observes the statistics of the packet arrival patterns. Third, C-PSM is designed independent of the upper-layer protocols. Therefore, it could be used for any mix of network protocols. However, some AP-centric schemes, such as (Anastasi et al., 2004), are designed only for TCP traffic.

The rest of this chapter is organized as following. In section 2, we summarize previous energy-saving schemes for IEEE802.11 infrastructure networks. The system models and a PSM simulator are described in section 3. We motivate C-PSM by discussing the impacts of BI and LIs on energy efficiency and other performance metrics in section 4. Next, section 5 presents the design of C-PSM, and section 6 evaluates the performance of C-PSM based on extensive simulation experiments. The results lend a strong support to the efficiency of C-PSM. For example, compared with PSM, C-PSM reduces significantly more energy (up to 76%), achieves higher energy efficiency (up to 320%), and reducing AP buffering delay (up to 88%). The results also show that the improvements of C-PSM over S-PSM mainly depend on the wake-up energy consumption and the ratio of idle power to sleep power. Finally, section 7 concludes this chapter with future work.

## 2. Related work

Several enhancements adopt a user-centric approach to let each client determine when it will sleep and wake up. For example, Nath et al. (Nath et al., 2004) proposed a dynamic wake-up period in which each client chooses its LI according to the round-trip time of its current TCP connection. The Bounded Slowdown Protocol (Krashinsky & Balakrishnan, 2005), another user-centric method, allows a client to increase its LI when the period of idleness increases. In Smart PSM (Qiao & Shin, 2005), each client determines whether it will enter into the PSM depending on the traffic condition. After the client enters into the PSM, the LI can be dynamically adjusted. Although the user-centric methods are quite effective in reducing a client's energy, they do not address the power consumption due to channel contention. Moreover, it is not clear whether these schemes remain effective when some other clients do not employ them.

An AP-centric approach, on the other hand, lets the AP deploy the PSM operations. The power-saving management proposed in (Anastasi et al., 2004) saves a client's energy by extending its sleep period and reducing unnecessary wakeups when the AP and the single client communicate using Indirect-TCP. Most AP-centric schemes support multiple clients, and try to totally eliminate channel contention. For example, the wake-up schedule proposed in (Lin et al., 2006) redesigns the TIM to let only one client to retrieve its buffered frame. The AP in the scheduled PSM (He et al., 2007) assigns slices of a BI for the clients' buffered frames. The scheme proposed in (Lee et al., 2006) computes an optimal BI and design an energy-efficient scheduler for frame transmissions within one BI. Network-Assisted Power Management (NAPman) (Rozner & Navda, 2010) for WiFi devices leverages AP virtualization and uses a new energy-aware fair scheduling algorithm to minimize client energy consumption and unnecessary retransmissions. It is also helpful of ensuring fairness among competing traffic. Although these schemes generally perform well, their computation-intensive scheduling algorithms introduce high cost. In contrast, our C-PSM computes optimal BI and LIs jointly to reduce unnecessary wake-ups and channel contention, and optionally uses a wake-up schedule to further decrease the energy consumption.

Other powers-saving schemes based on sleeping even abandon the frame retrieving process of PSM. In the Once Poll PSM (Belghith et al., 2007), the frames buffered at the AP are forwarded upon the reception of a single PS-Poll. In the PSM-throttling (Tan et al., 2007), which does not use beacon frames, a wireless client wakes up at the beginning of each traffic burst, because it can identify bandwidth throttling connections and reshape the TCP traffic into periodic bursts. A power-saving multi-channel MAC protocol (PSM-MMAC) (Wang et al., 2006) was designed to reduce the collision probability and the waiting time in the 'awake' state of a node. The medium access probability is optimized by estimating the number of active links, queue lengths and channel conditions, such that PSM-MMAC results in improved throughput, delay performance, and energy efficiency.

## 3. Models and notations

### 3.1 The IEEE802.11 PSM

The PSM allows a wireless client to sleep instead of staying in active state all the time and asks the AP to buffer the frames for them. Let the AP's BI be $\beta$ millisecond (ms). The AP broadcasts a beacon frame every $\beta$ ms to announce the buffer status of all PSM-enabled clients in the *Traffic Indication Map* (TIM) that uses one bit to indicate empty or nonempty buffer for each client. On the other hand, each PSM-enabled client's LI is a multiple of BI; therefore, the BI actually determines the LI's granularity. Let the value of LI be $\gamma \times \beta$ ms, where $\gamma \geq 1$. For the PSM, the default settings are $\beta = 100$ ms and $\gamma = 1$.
Figure 1 (Gast, 2005) illustrates the PSM operation for two wireless clients $s_1$ and $s_2$. $s_1$ has a LI of 2 while $s_2$ has a LI of 3. The first (second) bit in the TIM indicates the buffer status for client $s_1$ ($s_2$). The shaded region shows that the client is in the active state. After waking up for the first time, $s_1$ is notified of its frames being buffered at the AP through the TIM. The client then sends a PS-Poll frame to retrieve the first frame. If the More Data bit in the received frame is not set, it will return to sleep; otherwise, it will send another PS-Poll frame. The same data exchange repeats until all buffered frames are sent and then the client goes to sleep. However, if a client wants to send data, it may wake up any time to transmit them. We will come back to this figure in section 4 to analyze the energy consumption sources.

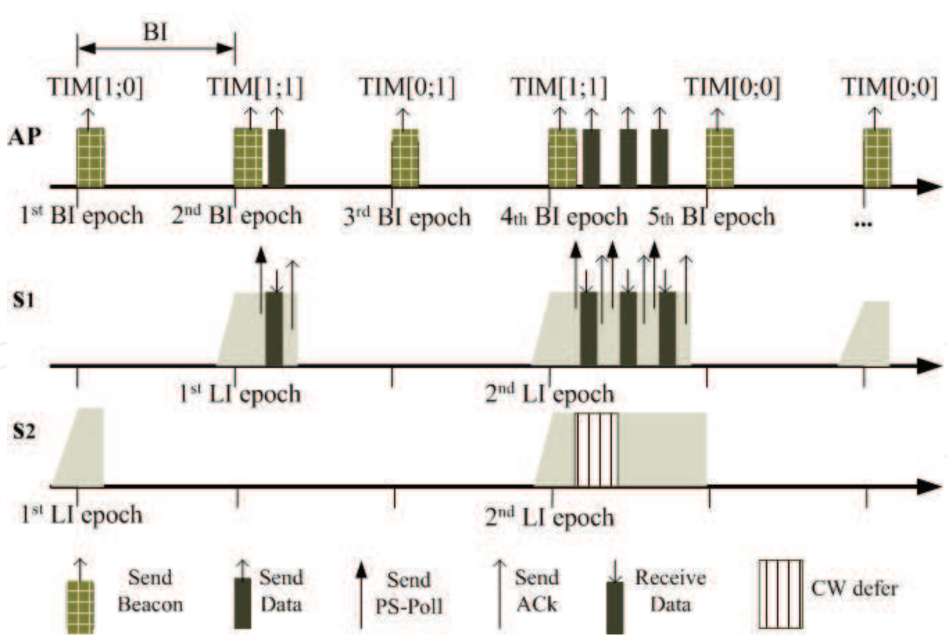



Fig. 1. An example of the PSM operation for two wireless clients.

### 3.2 System model

Our model consists of an AP and $c$ PSM-enabled wireless clients $s_j$, $j = 1, \ldots, c$, which run on IEEE 802.11b with a transmission rate of 11Mps. We have chosen IEEE 802.11b over

IEEE 802.11a/g for its less complex protocols. Moreover, IEEE 802.11a/g's rate adaptation algorithms will make the analysis much more difficult. The model considers only downlink traffic (i.e., those from the AP to clients). We do not consider the uplink traffic, because the PSM is effective only for downlink-dominant communication patterns. Furthermore, we model the traffic arriving at the AP from different sources, which are affected by applications, upper-layer protocols, and network path properties.

There are two random variables in our models: inter-frame arrival time and frame size. Let $T_j$ be the inter-frame arrival time for $s_j$'s traffic source and the mean of $T_j$ be $\delta_j$. Let the vector of the client's mean inter-frame arrival times be $\Delta = [\delta_1, \ldots, \delta_c]$. Our current study allows $T_j$ to take on four types of distributions: deterministic (DET), uniform (UNI), exponential (EXP), and Pareto (PAR). On the other hand, the frame size distribution is either deterministic and uniform. Besides $\beta$, the AP in C-PSM can also configure the LIs for all clients ($\Gamma = [\gamma_1, \ldots, \gamma_c]$) and the minimal congestion windows for all clients ($\Theta = [\theta_1, \ldots, \theta_c]$).

### 3.3 A simulator

We have adopted simulation as the major tool to study the problem, because simulation can capture many fine details than analytical models. Unfortunately, many publicly available simulators, such as J-SIM (Tyan, 2002), have not implemented most operations for infrastructure networks and the PSM, such as the beacon frames and PS-Poll frames. Even for the de facto simulator ns-2 (Berkeley et al., 1996), it is surprising that its PSM module (Krashinsky & Balakrishnan, 2005) supports only a single client. This prompted us to write our own simulator using MATLAB which provides an easy-to-use language and other supporting facilities to model the MAC sublayer accurately and effectively. There are also other MATLAB-based IEEE802.11 simulators, such as for IEEE802.11a (MATLAB Central, 2003) and the PHY layer of IEEE802.11b (MATLAB Central, 2009).

Our simulator implements the details of the IEEE 802.11b DCF with PSM, including the PS-Poll, beacon frames (with TIM), backoff algorithm, and congestion window. But we have excluded other nonessential elements (e.g., authentication and (de)association) and the RTS/CTS mechanism which is often turned off to increase the performance. We have used the simulation parameters in Table 1 for the experiments conducted in this chapter[1]. The values of power and energy consumption, which belong to the power consumption model $\mathcal{A}$ (shown in Table 10), have been widely used (Feeney & Nilsson, 2001; Margi, 2006)[2]. We will explain why the simulator selects these values in subsection 6.4.

The simulator produces detailed trace files which record frame exchanges, channel collisions, and clients' mode transitions. By carefully analyzing the trace files, we have validated the correctness of the PSM simulation. Moreover, we have obtained the following performance metrics from the trace files:

1. $P$: the total power consumed by the clients by watt (W).
2. $T$: the total client throughput by bits per second (bps).
3. $R_{T/P}$: $\frac{T}{P}$, the total energy efficiency metric by bits per joule (bpJ).

[1] The simulator uses only the long preamble, $192\mu s$. The transmission time of each frame is therefore equal to $192 + \frac{size*8}{transmission\ rate}\mu s$.

[2] The data for LUCENT IEEE 802.11 WAVELAN PC card were provided by the manufacturer and evaluated in (Feeney & Nilsson, 2001).

| Simulation parameters | Values |
|---|---|
| Number of clients | 1 to 20 |
| Data transmission rate (DTR) | 11 Mbps |
| Basic transmission rate (BTR) | 2 Mbps |
| Data frame size (DFS) | 512 bytes |
| Beacon frame size (BFS) | 28 bytes |
| PS-Poll frame size (PFS) | 14 bytes |
| ACK frame size (AFS) | 14 bytes |
| Transmission power | 1.4 W |
| Reception power | 0.9 W |
| Idle power | 0.7 W |
| Sleeping power | 0.060 W |
| Wake-up energy | 0.003 J |
| slotTime | 20$\mu$s |
| SIFS | 10$\mu$s |
| DIFS | 50$\mu$s |

Table 1. Simulation parameters used in this chapter.

4. $R_{c/t}$: $\frac{N_c}{N_t}$, where $N_t$ is the total number of transmission attempts by AP and all clients, and $N_c$ is the total number of collided frames by AP and all clients.
5. $R_{u/w}$: $\frac{N_u}{N_w}$, where $N_w$ is the total number of wake-ups by all clients, and $N_u$ is the total number of unnecessary wake-ups by all clients.
6. $R_{bB/B,k}$: $\frac{N_{bB,k}}{N_B}$, where $N_B$ is the total number of BIs, and $N_{bB,k}$ is the total number of BIs in which $k$ clients are involved in channel contention, $k \geq 2$.
7. $d_j$: the frame buffering delay of $s_j$'s frames at the AP by ms.

We have simulated for $c = 2, \ldots, 20$ in an increment of two. Each experiment was run for at least 20 seconds in simulation time after observing the time of convergence from several preliminary experiments. we have repeated for each simulation setting for 20 times and report their average values. All the results reported in the paper fall within a 95% confidence level.

## 4. A preliminary analysis

To motivate the design of C-PSM, we first analyze the impact of the BI and that of the LIs on the energy consumption of two wireless clients. There are two main sources of energy wastage: unnecessary wake-ups and channel contention. Clearly, the individual LI has a direct impact on the number of unnecessary wake-ups; an overly-frequent wake-ups will consume a significant amount of energy. For example, as shown in Figure 1, $s_2$ wakes up at the first epoch but finds no frames buffered for it.

Energy wastage due to channel contention, on the other hand, is more complicated. Back to Figure 1 again, $s_2$ wakes up the second time to find the frames buffered at the AP. However, it loses to $s_1$ after contending for the channel during the PS-Poll transmissions. Client $s_2$ then stays in the active mode during the backoff process which could take a long time. Therefore, rescheduling the active clients' wake-ups to nonoverlapping epoches will reduce such energy wastage. Note that reducing the BI value will also help, because, as mentioned before, the BI value determines the LI's granularity. Besides, the clients' congestion windows will also contribute to this energy consumption source.

### 4.1 Evaluating the impact of beacon and listen intervals

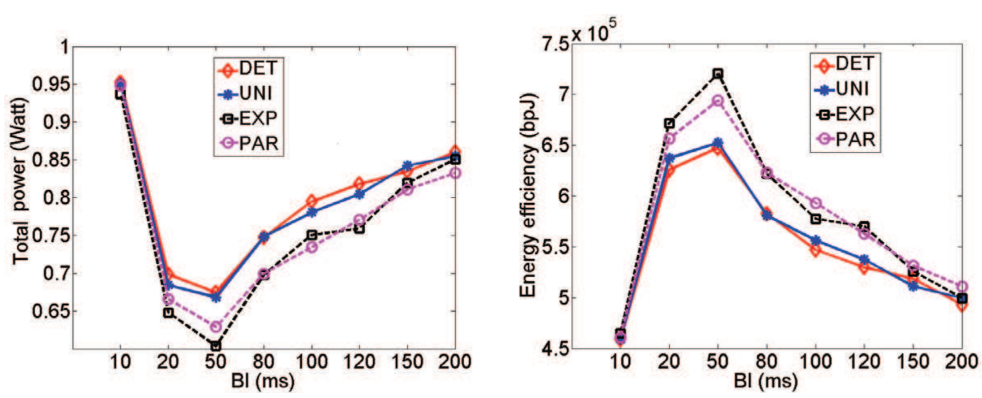
Since Nedevschi et al. (2008) has shown that the sleeping mechanism is valuable when the network utilization ($\rho$) is less than 30% , we select $\Delta$ to let the network be lightly loaded. More precisely, we consider only the $\Delta$s that satisfy

$$\rho = b_{min} \sum_{j=1}^{c} 1/\delta_j < 30\%, \quad where \tag{1}$$

$$b_{min} = \frac{DFS}{DTR} + \frac{PFS + AFS}{BTR} + DIFS + 2SIFS. \tag{2}$$

where $b_{min}$ is the minimum transmission time for one data frame (i.e., without using PSM or suffering from channel contention). According to the DCF and Table 1, $b_{min}$ is around 1.13ms when $c = 2$ and $\Delta = [15; 25]$ms (i.e., $\rho \approx 12\% < 30\%$).

**Impact of BI** We investigate the impact of $\beta$ when it changes from 10ms to 200ms with the default PSM settings: $\Gamma = [1; 1]$ and $\Theta = [31; 31]$. As shown in Figure 2(a), $P$ is high when $\beta$ is too small, because much energy is wasted on clients' frequent wake-ups. When $\beta$ is too large, many frames are accumulated at the AP. Consequently, energy is wasted on channel contention. The optimal $\beta$ in this example is 50ms, instead of the default value of 100ms. Moreover, since $R_{T/P}$ is inversely proportional to $P$, Figure 2(b) shows a similar trend as Figure 2(a).




(a) $P$ verses $\beta$, $\gamma_1 = \gamma_2 = 1$. (b) $R_{T/P}$ verses $\beta$, $\gamma_1 = \gamma_2 = 1$.

Fig. 2. Impact of BI for $c = 2$ and $\Delta = [15; 25]$ms.

**Impact of LIs** $\Gamma$ can also influence the clients' energy consumption and communication performance. Lei & Nilsson (2007) obtained optimal LIs to maximize energy efficiency based on M/G/1 and D/G/1 queuing models. However, the assumptions used in these models generally do not hold for the PSM. In our simulation study, we fix $\beta$ to 50ms and consider different $\Gamma$s for two clients. Table 2 for the EXP distribution clearly shows that the default case of [1; 1] is not optimal for the six performance metrics. The best value for each metric is underlined. Overall, the case of [1; 2] achieves the best performance. It is worth noting that $\frac{\gamma_1}{\gamma_2}$ is closest to $\frac{\delta_1}{\delta_2}$ for $\Gamma = [1; 2]$. We have observed similar results for the other three inter-frame arrival time distributions.

| $\Gamma$ | $R_{c/t}$ | $R_{u/w}$ | $R_{bB/B,2}$ | $P$(W) | $R_{T/P}$($10^5$bpJ) | $d_1$(ms) | $d_2$(ms) |
|---|---|---|---|---|---|---|---|
| [1; 1] | 1.54% | 11.51% | 81.37% | 0.6109 | 7.1578 | 37.4 | 32.3 |
| [1; 2] | 1.04% | 4.97% | 42.32% | 0.5487 | 7.9674 | 29.8 | 60.0 |
| [2; 1] | 1.07% | 12.24% | 46.79% | 0.6032 | 7.2316 | 81.0 | 28.0 |
| [2; 2] | 1.25% | 1.67% | 49.16% | 0.7470 | 5.8260 | 125.4 | 61.3 |

Table 2. Simulation results for different Γs under EXP inter-frame arrival distribution for $c = 2$, $\beta = 50ms$, and $\Delta = [15; 25]ms$.

## 5. Centralized PSM

### 5.1 The main algorithm

This section presents the centralized PSM (C-PSM) scheme that allows the AP to determine and deploy optimal PSM settings for itself and all clients. The AP first decides optimal $\beta$ (denoted by $\beta^*$) and optimal $\Gamma$ (denoted by $\Gamma^*$) based on the client's frame arrival patterns. These optimal settings are expected to bring significant improvement to the energy efficiency, because the intervals are selected to reduce the number of unnecessary wake-ups and channel contention. The AP also obtains a $\Theta$ (denoted by $\Theta^*$) to ensure that any client will not be denied channel access for too long.

The inputs to the main algorithm include $\Delta$, $\beta_{min}$, $\epsilon_\beta$, and $\epsilon_\Theta$. $\beta_{min}$ is a lower bound of $\beta^*$, and $\epsilon_\beta$ and $\epsilon_\Theta$ are the step sizes for searching $\beta^*$ and $\Theta^*$, respectively. The algorithm executes the following steps to yield $\beta^*$, $\Gamma^*$, and $\Theta^*$.

**Step 1** (Determining the candidates of $\beta^*$ and $\Gamma^*$) The purpose of this step is to obtain a number of $\beta^*$ and $\Gamma^*$ candidates for the second step.

We first consider a $\Gamma^*$ candidate: $[L_1; \ldots; L_c]$. Let $L_j = \alpha_j \times \delta_j$, where $\alpha_j \geq 1$, is an integer scaling factor. To reduce unnecessary wake-up, the probability that an awaken client finds an empty buffer at the AP (denoted by $Pr_0$) should be less than a given threshold $0 < \xi \leq 1$. The choice of this threshold reflects the tradeoff between the number of unnecessary wake-ups and the period of channel contention. If $\xi$ is too large, the LI may be short and a lot of unnecessary wake-ups will occur. If $\xi$ is too small, the frames buffered during the long LI may cause channel contention. After running a number of empirical simulations, we let $\xi = 0.05$. Then, $\alpha_j$ is the smallest integer which satisfies $Pr_0 \leq 0.05$. Table 3 shows examples of determining $\alpha_j$ under the four inter-frame arrival time distributions. For example, for the EXP distribution, $L_j$ is three times of $\delta_j$.

To determine the $\beta^*$ candidates, following the guideline in (Nath et al., 2004), we set $\beta_{min}$ to 10ms. To determine the upper bound of $\beta$, we note that BI should not be larger than any client's LI. Therefore, the upper bound of $\beta$ is given by $\min_{\forall j} L_j$. We then select $n + 1$ BI candidates uniformly within the range of $[\beta_{min}, \min_{\forall j} L_j]$, where $n = \lfloor (\min_{\forall j} L_j - \beta_{min})/\epsilon_\beta \rfloor$.

Moreover, for each $\beta^*$ candidate $\beta_i$, we consider three $\Gamma^*$ candidates:

1. $\Gamma_{i,1} = [\lceil L_1/\beta_i \rceil; \cdots ; \lceil L_c/\beta_i \rceil]$,
2. $\Gamma_{i,2} = [\langle L_1/\beta_i \rangle; \cdots ; \langle L_c/\beta_i \rangle]$, where $\langle x \rangle$ gives the round-off value of a real number $x$, and
3. $\Gamma_{i,3} = [\lfloor L_1/\beta_i \rfloor; \cdots ; \lfloor L_c/\beta_i \rfloor]$.

**Step 2** (Determining $\beta^*$ and $\Gamma^*$) The purpose of this step is to obtain the best $\beta^*$ and $\Gamma^*$ from a set of candidates identified in Step 1. The criterion is based on minimizing the number of simultaneous wake-ups. There are two sub-steps to achieving the goal.

In the first sub-step, we search for the best $\Gamma$ for each $\beta^*$ candidate obtained in Step 1. That is, for a given $\beta_i$ obtained in Step 1, we select the best $\Gamma$ from $\Gamma_{i,1}$, $\Gamma_{i,2}$, and $\Gamma_{i,3}$ that minimizes the

| Distribution | $Pr_0$ | | | | |
|---|---|---|---|---|---|
| | $\alpha = 1$ | $\alpha = 2$ | $\alpha = 3$ | $\alpha = 4$ | $\alpha = 5$ |
| DET | 0 | 0 | 0 | 0 | 0 |
| UNI | 0.5 | 0 | 0 | 0 | 0 |
| **EXP** | 0.3679 | 0.1353 | **0.0498** | 0.0183 | 0.0067 |
| PAR (k=1/3) | 0.2963 | 0.0787 | 0.0315 | 0.0156 | 0.0089 |

Table 3. Empty probability vs. scaling factor under different traffic distributions.

number of simultaneous wake-ups. Since $\gamma_j$s are integers, we can compute the least common multiple (LCM) for all the elements of each $\Gamma^*$ candidate. Note that the LCM gives the minimal number of BIs for which two or more clients wake up simultaneously. Therefore, a larger LCM means a smaller number of simultaneous wake-ups. We therefore choose the best $\Gamma$ based on the largest LCM and denote it as $\Gamma_i^*$.

In the second sub-step, given $(\beta_i, \Gamma_i^*)$, $i = 1, \ldots, n+1$, we select the best $\Gamma$ from the $\Gamma_i^*$s that minimizes simultaneous wake-up. The criterion is based on the largest spread of their elements from one another which is measured by the ratio of the standard deviation and the mean of the elements in $\Gamma_i^*$. Therefore, $\Gamma^*$ is given by the $\Gamma_i^*$ that gives the highest ratio, and $\beta^*$ is the corresponding $\beta_i$.

**Step 3** (Determining $\Theta^*$) The final step determines $\Theta^*$ based on the $\Gamma^*$ obtained in the last step. The motivation is to mitigate the possible unfairness in the frame buffering delay experienced by the clients. We assign a smaller $\theta_j^*$ to the client with a larger $\gamma_j^*$. In this way, the client that wakes up less frequently will have a higher priority to retrieve its frames during channel contention. To do so, we assign the default value to $s_j$ if its $\gamma_j^*$ is the largest (i.e. $\theta_j^* = 31$). We then increase other clients' $\theta_j$ by $\epsilon_\Theta$ when their $\gamma_j^*$ decrease. They are given by $\theta_j^* = 31 + \epsilon_\Theta(\max_{\forall j}(\gamma_j^*) - \gamma_j^*)$.

### 5.2 The optimal wake-up schedule

Besides the main algorithm, the AP in C-PSM may also obtain the optimal wake-up schedule (WS). This optional step is to schedule the first wake-up times of the clients, so that the maximal number of waking clients at one BI epoch is minimized. The optimization problem is given by

$$\min_{\mathbf{r}} : \max_{\nu=0,1,2,\ldots} N(\nu, \mathbf{r}, \Gamma^*). \tag{3}$$

The vector $\mathbf{r}$ presents the sequence of the first wake-up times where the client $s_j$ first wakes up at the $r_j$th BI epoch and $r_j \in [0, LCM(\Gamma^*) - 1]$ is an integer. The function $N(\nu, \mathbf{r}, \Gamma^*)$ is the number of waking clients at the $\nu$th BI epoch when the clients wake up according to $\mathbf{r}$ and $\mathbf{LI}^*$. WS consists of the optimal solution denoted as $\mathbf{r}^*$ which will further decrease the simultaneous wake-ups if two or more elements of $\Gamma^*$ are the same or have the same common factor.

Since the optimization problem (3) can be decomposed into a series of wake-up scheduling problems (WSPs) (Lin et al., 2006), we solve it by developing an algorithm based on the stepwise solving method for WSP.

When a new PSM-enabled client $s_j$ joins an infrastructure network (including a set of $m$ clients, $\mathcal{S}$) in the $\nu$th BI epoch, WSP is formulated to minimize the maximal number of wake-up clients in the following BI epoches. The optimization problem of WSP is given by

$$\min_{k_j(\nu)} : \max_{u=1,2,...} \{N(\nu+u)\} \tag{4}$$

where $N(\nu+u)$ is the number of waking clients at the $(\nu+u)$th BI epoch and the wake-up counter $k_j(\nu)$ records the remaining BIs that the client $s_j$ will wake up. Moreover, $N(\nu+u)$ equals to $\sum_{i \in \mathcal{S} \cup j} w_i(\nu+u)$ where the wake-up indicator $w_i(\nu+u)$ is 1 if $s_i$ wakes up at the $(\nu+u)$th BI epoch; otherwise, it is 0. Given the LI parameter of each client $\gamma_i$, $0 \le k_i(\nu) \le \gamma_i - 1$, $i \in \mathcal{S} \cup j$, the stepwise solving method (Lin et al., 2006) can calculate $k_j^*(\nu)$, the optimal wake-up counter of $s_j$. And $k_j^*(\nu)$ is a function $f(j, \gamma_j, m, w_i(\nu), k_i(\nu), \gamma_i)$, $i = 1, \ldots, m$. It is easy to see that $k_j^*(\nu)$ is the optimal first wake-up time of $s_j$ when $\nu = 0$, i.e. $r_j^* = k_j^*(0)$. According to $\Gamma^*$, our algorithm obtains $k_j^*(0)$ for each client at $\nu = 0$. Therefore, we determines WS as $\mathbf{r}^* = [k_1^*(0), \ldots, k_c^*(0)]$. The client $s_j$ first wakes up optimally at the $r_j^*$th BI epoch, $\forall j = 1, \ldots, c$. For example, if $r_j^* = 1$, $s_j$ will miss the first beacon frame at the beginning of simulation but wake up for the first time after $\beta^*$. The detail steps of our algorithm for obtaining $\mathbf{r}^*$ is given below:

1. Initialize the following variables: $\nu = 0$, $\mathcal{S} = \{s_1\}$, $m = 1$, $w_1(\nu) = 1$, $k_1(\nu) = 0$, $r_1^* = 0$ and $j = 2$.
2. If $j > c$, return $\mathbf{r}^*$ and exit; else, go to step 3.
3. Find the optimal wake up time of $s_j$, where

$$k_j^*(\nu) = f(j, \gamma_j^*, m, w_i(\nu), k_i(\nu), \gamma_i^*), i = 1, \ldots, m.$$

4. Update variables: $r_j^* = k_j^*(\nu)$, $m = m + 1$ and $\mathcal{S} = \mathcal{S} \cup s_j$.
5. If $r_j^* = 0$, then $w_j(\nu) = 1$; else, $w_j(\nu) = 0$.
6. Increase $j$ by 1 and go back to step 2.

## 6. Performance evaluation

We evaluate the performance of C-PSM and compare it with the PSM with default parameters (which is referred to as standard PSM or S-PSM). We do not compare C-PSM with other user-centric/AP-centric PSM schemes, because the design objectives and the study scopes are different. For example, C-PSM improves energy efficiency for all clients, whereas the user-centric PSM schemes consider only a single client. On the other hand, C-PSM is standard-compliant, but most AP-centric schemes are not compatible with the PSM scheme.

### 6.1 Evaluation methodology

In order to evaluate the effectiveness of different components of C-PSM, we examine three different versions. The first one is a "full version" which includes the optional optimal wake-up sequence discussed in the last section. The other two, Scheme-1 and Scheme-2, on the other hand, exclude this option and adopt the default congestion window size. Moreover, Scheme-2 adopts the default $\Gamma$ value. To sum up, we compare the following schemes in reference to S-PSM.

1. C-PSM: $\beta^*$, $\Gamma^*$, $\Theta^*$, $\mathbf{r}^*$;

2. Scheme-1: $\beta^*, \Gamma^*, \theta_j = 31, r_j = 0$;
3. Scheme-2: $\beta^*, \gamma_j = 1, \theta_j = 31, r_j = 0$;
4. S-PSM: $\beta = 100\text{ms}, \gamma_j = 1, \theta_j = 31, r_j = 0$.

We use the following four performance indices for comparing C-PSM, Scheme-1, and Scheme-2 against S-PSM: power saving (index $\eta_P$), throughput (index $\eta_T$), energy efficiency (index $\eta_{T/P}$), and frame buffering delay (index $\eta_D$). The notations with a superscript $S-PSM$ refers to S-PSM, whereas that without refer to C-PSM, Scheme-1, or Scheme-2. For easy comparison, a positive value indicates improvement over S-PSM.

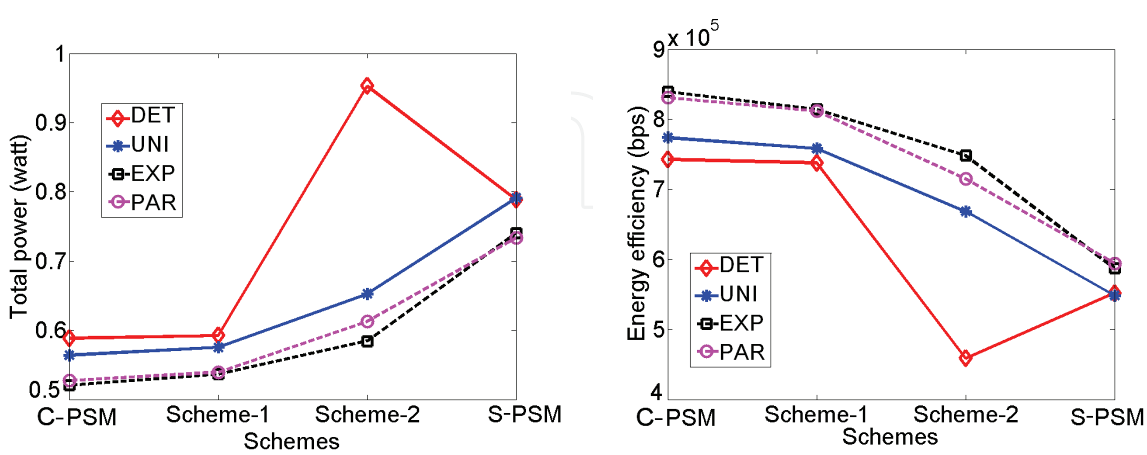
$$\begin{aligned}
\eta_P &= (P^{S-PSM} - P)/P^{S-PSM} \times 100\%, \\
\eta_T &= (T - T^{S-PSM})/T^{S-PSM} \times 100\%, \\
\eta_{T/P} &= (R_{T/P} - R_{T/P}^{S-PSM})/R_{T/P}^{S-PSM} \times 100\%, \\
\eta_D &= \frac{1}{c} \times \sum_{j=1}^{c} (d_j^{S-PSM} - d_j)/d_j^{S-PSM} \times 100\%.
\end{aligned}$$

### 6.2 Two clients

We first evaluate C-PSM in the two-client system. Given $\Delta = [15;25]ms$, the AP obtains the optimal parameters of C-PSM under different traffic distributions, as shown in Table 4.

| Δ(ms) | distribution | $\beta^*$(ms) | $\Gamma^*$ | $\Theta^*$ | **r*** |
|---|---|---|---|---|---|
| [15;25] | DET | 10 | [2;3] | [39;31] | [0;0] |
| | UNI | 26 | [1;2] | [39;31] | [0;0] |
| | EXP,PAR | 38 | [1;2] | [39;31] | [0;0] |
| [20;30;30] | DET | 16 | [1;2;2] | [39;31;31] | [0;0;1] |
| | UNI | 30 | [1;2;2] | [39;31;31] | [0;0;1] |
| | EXP,PAR | 46 | [1;2;2] | [39;31;31] | [0;0;1] |

Table 4. Optimal parameters of C-PSM ($\epsilon_\beta = 2$ms and $\epsilon_\Theta = 8$).




(a) Total power, $P$. (b) Total energy efficiency, $R_{T/P}$.

Fig. 3. A comparison of the four PSM schemes with $\Delta = [15;25]ms$.

Figure 3 depicts that C-PSM outperforms S-PSM on saving energy and improving energy efficiency under different distributions. C-PSM achieves lowest $P$ and highest $R_{T/P}$ among the four schemes. Scheme-1 performs a little worse than C-PSM, since it does not adopt $\Theta^*$. Comparing with scheme-1, scheme-2 increases power and decreases energy efficiency, since it does not use $\Gamma^*$. Adopting $\beta^*$, Scheme-2 still outperforms S-PSM under all traffic distributions except the DET distribution. Scheme-2 is the worst under deterministic traffic, because two clients wake up every $\beta^* = 10$ms and they both waste energy on the frequent unnecessary wake-ups. Note that, the WS is not adopted, since $\mathbf{r}^*$ is a zero vector when $\gamma_j$ $(\forall j)$ are relative prime. In this case, all clients wake up at the beginning of simulation.

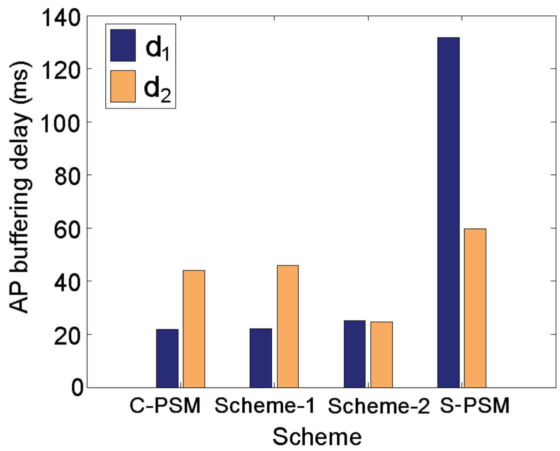
| index, % | scheme | DET | UNI | EXP | PAR |
|---|---|---|---|---|---|
| $\eta_P$ | C-PSM | 25.41 | 28.75 | 29.73 | 28.13 |
| | Scheme-1 | 24.91 | 27.28 | 27.53 | 26.47 |
| | Scheme-2 | -20.82 | 17.52 | 21.10 | 16.48 |
| $\eta_{T/P}$ | C-PSM | 34.63 | 41.18 | 43.01 | 39.76 |
| | Scheme-1 | 33.71 | 38.33 | 38.65 | 36.57 |
| | Scheme-2 | -16.88 | 21.95 | 27.38 | 20.30 |
| $\eta_D$ | C-PSM | 82.33 | 68.79 | 54.80 | 54.18 |
| | Scheme-1 | 82.08 | 68.15 | 53.07 | 53.56 |
| | Scheme-2 | 94.54 | 79.79 | 69.88 | 68.75 |
| $\eta_T$ | C-PSM | 0.41 | 0.59 | 0.50 | 0.45 |
| | Scheme-1 | 0.40 | 0.60 | 0.48 | 0.42 |
| | Scheme-2 | 0.43 | 0.58 | 0.50 | 0.47 |

Table 5. Indices of C-PSM, Scheme-1 and Scheme-2, $\Delta = [15; 25]ms$.

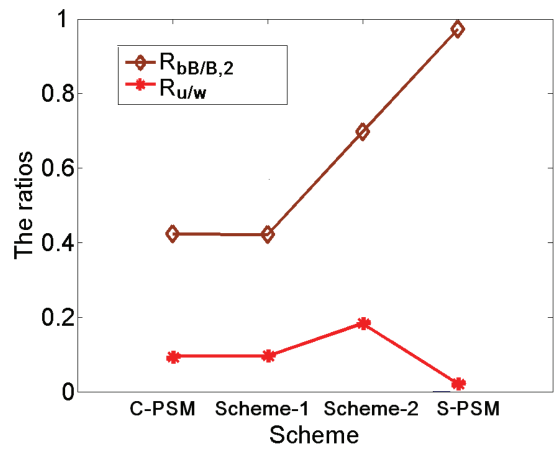
As shown in Table 5, all indices of C-PSM are positive and the improvements of C-PSM over S-PSM are significant under different distributions. For example, compared with S-PSM, C-PSM reduces power consumption by 29.37%, improves energy efficiency by 43.01% and reduces average buffering delay by 54.8% under the EXP distribution of traffic. We also find that C-PSM has largest $\eta_P$ and $\eta_{T/P}$. That is, C-PSM which employs $\beta^*$, $\Gamma^*$ and $\Theta^*$ together, performs the best in saving power and increasing energy efficiency.

In C-PSM, the benefit of adopting $\beta^*$ and $\Gamma^*$ is significant whereas the improvement due to $\Theta^*$ is minor. Scheme-1 using $\beta^*$ and $\Gamma^*$ has obtained large positive indices. Its indices are slightly less than C-PSM's indices. For example, the energy efficiency is improved by 38% while the $\eta_{T/P}$ of C-PSM is 43.01%. Therefore, the usage of $\Theta^*$ is helpful to save energy but not much. Moreover, $\beta^*$ and $\Gamma^*$ jointly play the major roles in improving PSM performance. In contrast, the PSM performance greatly degrades without using $\Gamma^*$. The $\eta_P$ and $\eta_{T/P}$ of Scheme-2 are much smaller than the ones of C-PSM and Scheme-1. Scheme-2 therefore is worse than these two schemes. It is even worse than S-PSM, because of its negative indices under the DET distribution of traffic.

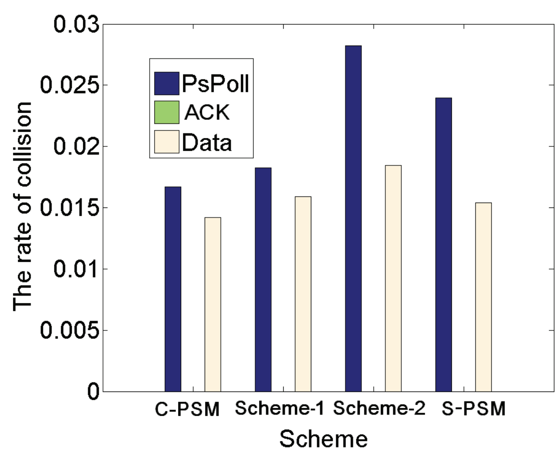
Next, we compare C-PSM and S-PSM under the EXP distribution of traffic. As shown in Figure 4(a), the AP buffering delay is shortest in C-PSM, whereas it is longest in S-PSM. Consequently, the clients using C-PSM can return to sleep mode earlier, because the frames with shorter buffering delay are retrieved faster than those in S-PSM. Moreover, C-PSM improves the fairness of clients, since it greatly decreases the delay difference of the two clients. C-PSM speeds up the retrieval of frames in the fast client, because the delay of $s_1$ is one sixth of that in S-PSM. At the same time, it does not degrade the slow client, since the




(a) The AP buffering delay.




(b) The ratios of unnecessary wake-ups and simultaneous wake-ups.




(c) The collision ratios.

Fig. 4. A comparison of the four schemes under the EXP distribution with $\Delta = [15;25]ms$.

delay of $s_2$ reduces a little. Figure 4(b) shows that C-PSM greatly reduces the chances that two clients simultaneously wake up to compete for channel, since its $R_{bB/B,2}$ is lowest. In contrast, S-PSM lets two clients wake up simultaneously at a large proportion of BI epochs, since its $R_{bB/B,2}$ is near 1. The clients using C-PSM spend less time on channel contention, consume less energy on idle mode and then achieve higher energy efficiency.

Figure 4 illustrates that C-PSM and Scheme-1 have similar performance metrics. The collision ratios of PS-Poll and data frames in C-PSM are less than those in Scheme-1. It means that $\Theta^*$ is useful for reducing channel collisions. That is why C-PSM performs better than Scheme-1 with slightly higher indices.

Scheme-2 outperforms S-PSM under the EXP distribution of traffic, since it achieves shorter AP buffering delay and less simultaneous wake-up ratio than S-PSM. Scheme-2 is less energy-efficient than C-PSM and Scheme-1, because it spends more energy on unnecessary wake-ups and channel contention. The clients in Scheme-1 frequently wake up every $\beta^*$ but nearly 20% of wake-ups are unnecessary while the unnecessary wake-ups ratio is less than 10% in C-PSM. Without using $\Gamma^*$, the clients in Scheme-2 spend more energy on idle mode when they simultaneously wake up to compete channel with a higher probability. Shown in Figure 4(b), they are involved in channel contention at 68% of BIs, i.e. $R_{bB/B,2} = 68\%$ while the $R_{bB/B,2}$ in C-PSM is only 40%. Furthermore, the collision ratios in Scheme-2 are higher than those in C-PSM and Scheme-1, shown in Figure 4(c). For example, the PS-Poll collision ratio in Scheme-2 is the highest, nearly 1.5 times of that in C-PSM. Therefore, the clients in Scheme-2 have to spend more energy to handle the collisions. On the other hand, Scheme-2 has shorter delay for the slow client $s_2$ than C-PSM and Scheme-2. However, its benefit is too small to affect the performance.

Additionally, the collision ratios of ACK are almost zero in Figure 4(c). The reason is that an awaken client always returns ACK after it has finished receiving a data frame and a SIFS has elapsed. The channel is rarely occupied by the other client or the AP within such a short SIFS. Therefore, ACKs rarely suffer from collisions especially when $c = 2$. If the number of clients increases, the probability of ACK collisions will increase as the channel contention intensifies.

### 6.3 More than two clients

We have applied C-PSM to a network with more than two clients. Firstly, we evaluate C-PSM when the number of clients is 3 and two clients have the same mean of inter-frame arrival times. According to $\Delta = [20; 30; 30]$ where $\rho = 13.18\% < 30\%$, the main algorithm obtains the optimal parameters of C-PSM, also shown in Table 4. Note that when the elements of $\Gamma^*$ are not relative prime numbers or even the same, C-PSM must adopt WS. In this case, $\gamma_2^*$ and $\gamma_3^*$ have a greatest common divisor 2, and then C-PSM uses WS, i.e., $\mathbf{r}^* = [0; 0; 1]$. $s_1$ and $s_2$ wake up at the beginning of simulation while $s_3$ defers the first wake-up time for one BI.

| index, % | scheme | DET | UNI | EXP | PAR |
|---|---|---|---|---|---|
| $\eta_P$ | C-PSM | 36.38 | 39.08 | 36.78 | 36.31 |
| | C-PSM not WS | 29.00 | 30.08 | 26.43 | 27.33 |
| $\eta_{T/P}$ | C-PSM | 59.86 | 65.92 | 59.11 | 58.00 |
| | C-PSM not WS | 43.22 | 44.56 | 36.73 | 38.41 |
| $\eta_D$ | C-PSM | 84.00 | 68.69 | 52.16 | 51.98 |
| | C-PSM not WS | 81.80 | 64.62 | 45.23 | 46.37 |
| $\eta_T$ | C-PSM | 1.71 | 1.08 | 0.60 | 0.63 |
| | C-PSM not WS | 1.69 | 1.07 | 0.59 | 0.58 |

Table 6. Indices of C-PSM with/without WS, $\Delta = [20; 30; 30]ms$.

The positive indices in Table 6 show that C-PSM outperforms S-PSM in terms of power saving, energy efficiency and AP buffering delay while keeping or slightly increasing throughput in the three-client network. For example, C-PSM reduces power consumption by 36.78%, improves the energy efficiency by 59.11% and shortens the average buffering delay by 52.16% under the EXP distribution of traffic while total throughput remains almost the same. On the other hand, the indices of C-PSM without WS are less than the ones of C-PSM under all traffic distributions. For example, without using WS, the $\eta_{T/P}$ Of C-PSM is decreased at most by 22% under the EXP distribution of traffic. Therefore, WS is much helpful to improve energy efficiency when the symmetric clients exist.

Next, we compare the simulation results of C-PSM, C-PSM without WS and S-PSM to explain the above findings. As an example, we study these three schemes under the EXP distribution of traffic.

| metrics | C-PSM | C-PSM not WS | S-PSM |
|---|---|---|---|
| $P$ (Watt) | 0.8242 | 0.9591 | 1.3037 |
| $T$ ($10^5$ bps) | 4.7538 | 4.7536 | 4.7257 |
| $R_{T/P}$ ($10^5$ bpJ) | 5.7675 | 4.9563 | 3.6248 |
| $d_1$(ms) | 34.4 | 36.3 | 234.2 |
| $d_2$(ms) | 55.8 | 63.2 | 84.5 |
| $d_3$(ms) | 54.9 | 64.7 | 87.4 |
| $R_{c/t}$ | 1.44% | 1.78% | 2.14% |
| $R_{u/w}$ | 10.06% | 10.66% | 4.86% |
| $R_{bB/B,2}$ | 83.83% | 10.47% | 7.64% |
| $R_{bB/B,3}$ | **0** | 39.05% | 92.29% |

Table 7. A comparison of three schemes under the EXP distribution with $\Delta = [20; 30; 30]ms$.

C-PSM saves energy by shortening the period of channel contention, shown in Table 7. All the clients' frame buffering delays of C-PSM are smaller than those of other two schemes. That is, each client can receive its buffered frames most quickly and then enter to sleep instead of spending much energy and time on idle mode during channel contention. C-PSM also saves energy by reducing channel contentions. It totally avoids all-client simultaneous wake-ups and $R_{bB/B,3}$ is zero. On the other hand, in S-PSM, three clients wake up together to receive data in almost all BIs and $R_{bB/B,3}$ is as high as 92.29%. At the same time, C-PSM consumes a small amount of energy on unnecessary wake-ups, since the total ratio of unnecessary wake-ups $R_{u/w}$ is near 10%. It also decreases the channel collisions where the total ratio of collisions $R_{c/t}$ is reduced by about one-third. From what has been discussed above, C-PSM outperforms S-PSM.

C-PSM without WS obviously outperforms S-PSM but is worse than C-PSM. Without using WS, the total power increases, the total energy efficiency decreases and three awaken clients compete for receiving data in 39.05% of BIs. However, C-PSM can totally avoid the situation of all-client simultaneous wake-ups. On the other hand, the $R_{bB/B,2}$ in the C-PSM without WS is smaller than the one in C-PSM. It is helpful to save energy but does not determine the energy consumption of all clients. The reason is that more energy is consumed on channel contention when all of three clients wake up simultaneously. In a global view, C-PSM saves more energy and achieves higher energy efficiency after using $\mathbf{r}^*$. Therefore, WS is helpful to improve energy efficiency, because the number of clients which wake up at the same beacon epoch has been minimized.

Furthermore, we find that C-PSM is applicable for a large scale network and saves more energy when the number of clients increases. These two sets of simulations evaluate the performance of our scheme when the number of PSM-enabled clients increases up to 20.

In the first set of simulations, we let $\delta_j = 10c$(ms), $j = 1, \ldots, c$. The total amount of traffic of all symmetric clients will not change with $c$, and the total arrival rate of frames $\lambda$ always equals 100 frames per second. The traffic workload is light, when $\rho = 11.3\% < 30\%$. Under light traffic, S-PSM can save energy, since the average power of each client is always lower than its idle power. For example in Figure 5, $P^{S-PSM}$ is much less than the $c$ times of client's idle power under the EXP distribution of traffic. C-PSM scheme can further reduce energy consumption, since the power difference between $P^{S-PSM}$ and $P^{C-PSM}$ is always larger than zero. Moreover, this power difference increases with $c$. Therefore, C-PSM saves more energy when the number of clients increases.

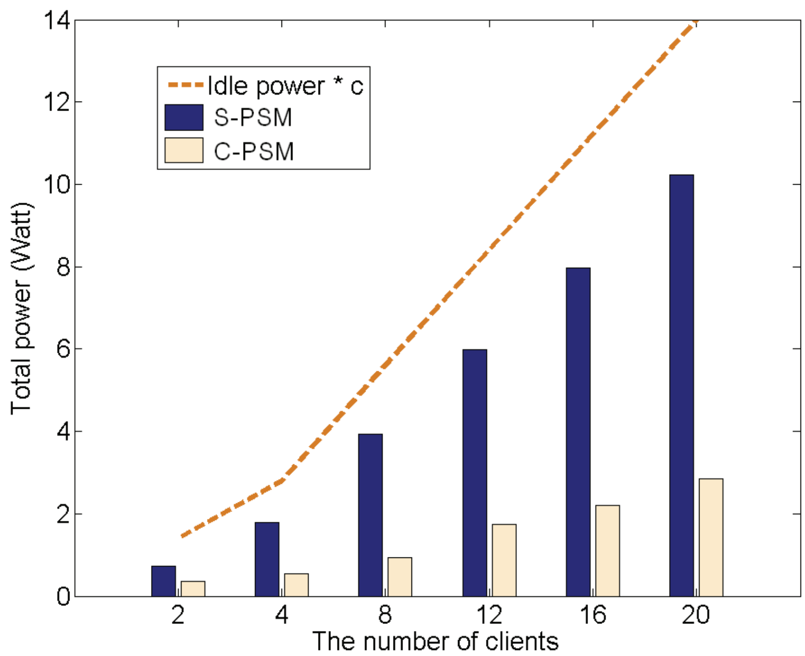



Fig. 5. Total power verses $c$ under the EXP distribution with $\delta_j = 10c$(ms).

| Index,% | $T_j$ | c=2 | c=4 | c=8 | c=12 | c=16 | c=20 |
|---|---|---|---|---|---|---|---|
| $\eta_P$ | DET | 22.30 | 63.75 | 79.20 | 71.54 | 75.52 | 72.98 |
| | UNI | 45.37 | 72.52 | 78.82 | 70.58 | 71.74 | 72.22 |
| | EXP | 51.09 | 70.33 | 76.07 | 70.98 | 72.27 | 72.14 |
| | PAR | 50.76 | 70.43 | 76.68 | 69.77 | 70.91 | 70.33 |
| $\eta_{R_{T/P}}$ | DET | 29.07 | 177.76 | 396.05 | 263.65 | 325.31 | 286.14 |
| | UNI | 83.50 | 265.28 | 384.96 | 251.95 | 270.96 | 281.65 |
| | EXP | 105.04 | 238.69 | 327.07 | 257.23 | 277.64 | 281.02 |
| | PAR | 103.89 | 239.39 | 338.50 | 241.89 | 260.80 | 255.76 |
| $\eta_D$ | DET | 92.35 | 87.63 | 85.78 | 87.47 | 90.18 | 89.21 |
| | UNI | 73.94 | 70.37 | 84.07 | 85.57 | 87.28 | 88.11 |
| | EXP | 64.09 | 70.89 | 82.68 | 85.02 | 87.04 | 88.43 |
| | PAR | 62.93 | 69.48 | 82.25 | 85.78 | 87.10 | 88.19 |
| $\eta_T$ | DET | 0.29 | 0.70 | 3.17 | 3.51 | 4.10 | 4.32 |
| | UNI | 0.24 | 0.40 | 2.72 | 3.55 | 4.83 | 6.02 |
| | EXP | 0.29 | 0.48 | 2.19 | 3.68 | 4.73 | 6.14 |
| | PAR | 0.40 | 0.37 | 2.27 | 3.36 | 4.94 | 5.55 |

Table 8. The indices of C-PSM verses the number of clients when $\delta_j = 10c$(ms), $j = 1, \ldots, c$.

Table 8 has shown that C-PSM achieves significant improvements of four main metrics in a large network. For example, the indices of $\eta_P$, $\eta_{T/P}$ and $\eta_D$ in are as high as 76.07%, 327.07% and 82.68% individually when $c = 8$ under the EXP distribution of traffic. C-PSM scheme also improves clients' throughput in a large network, since $\eta_T$ increases slightly with the number of clients.

In the second set of simulations, we let $\delta_j = 10 + 5j$(ms), $j = 1, \ldots, c$. The total packet arrival rate $\lambda$ increases with the number of clients where $\rho$ increases from 13.18% to 49.51%. When $c \geq 8$, the traffic is not light any more, since $\rho \geq 32\%$.

We firstly find that C-PSM has a wider applicability than the standard PSM. It is effective to save energy when the network supports many clients whose workload is not light. For

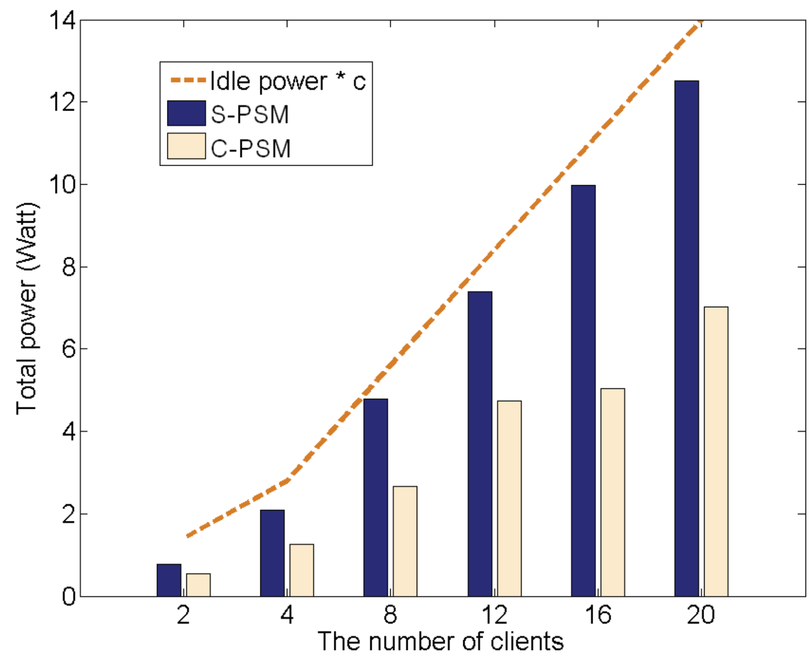



Fig. 6. Total power verses $c$ under the EXP distribution with $\delta_j = 10 + 5j$(ms), $j = 1, \ldots, c$.

example in Figure 6 under the EXP distribution of traffic, $P^{S-PSM}$ is much close to the total power of $c$ idle clients, when $c \geq 8$. It is obvious that these clients are too busy to sleep and S-PSM cannot save much energy. After using C-PSM, $P^{C-PSM}$ is much less than the total power of $c$ idle clients even when $c$ increases to 20. That is, C-PSM is still effective to save energy even when the network workload is as high as $\rho \approx 50\%$. Moreover, C-PSM saves more energy when the number of clients increases, since that the power difference $P^{S-PSM} - P^{C-PSM}$ increases with $c$. Although not shown here, the similar simulation results are obtained under other traffic distributions.

| Index,% | $T_j$ | c=2 | c=4 | c=8 | c=12 | c=16 | c=20 |
|---|---|---|---|---|---|---|---|
| $\eta_P$ | DET | 1.01 | 29.04 | 42.17 | 44.31 | 51.49 | 52.71 |
| | UNI | 21.93 | 37.81 | 44.29 | 37.34 | 51.98 | 50.97 |
| | EXP | 28.98 | 39.73 | 44.20 | 36.01 | 49.44 | 43.89 |
| | PAR | 25.64 | 37.59 | 44.19 | 35.65 | 48.85 | 43.49 |
| $\eta_{R_{T/P}}$ | DET | 0.55 | 55.54 | 132.72 | 174.52 | 248.45 | 286.48 |
| | UNI | 28.79 | 76.14 | 138.29 | 137.83 | 245.38 | 255.72 |
| | EXP | 41.51 | 75.73 | 124.41 | 115.23 | 201.97 | 172.88 |
| | PAR | 35.07 | 71.90 | 126.80 | 114.65 | 203.60 | 173.49 |
| $\eta_D$ | DET | 96.60 | 94.98 | 95.59 | 93.39 | 94.00 | 91.36 |
| | UNI | 76.05 | 79.90 | 85.27 | 85.56 | 86.88 | 85.72 |
| | EXP | 66.12 | 69.74 | 77.41 | 77.21 | 79.52 | 76.21 |
| | PAR | 65.05 | 69.82 | 77.69 | 77.10 | 79.66 | 76.30 |
| $\eta_T$ | DET | 0.45 | 10.38 | 34.58 | 52.88 | 69.04 | 82.76 |
| | UNI | 0.55 | 9.54 | 32.75 | 49.03 | 65.84 | 74.41 |
| | EXP | 0.49 | 5.91 | 25.23 | 37.74 | 52.68 | 53.12 |
| | PAR | 0.43 | 7.29 | 26.58 | 38.13 | 55.28 | 54.56 |

Table 9. The indices of C-PSM verses the number of clients when $\delta_j = 10 + 5j$(ms), $j = 1, \ldots, c$.

Table 9 also shows that C-PSM scheme outperforms S-PSM on saving power, improving energy efficiency, shortening delay and increasing throughput. When the traffic is not light (i.e. $c \geq 8$), C-PSM improves energy efficiency a lot, since it not only reduces power consumption but also increases throughput greatly. For example, compared with S-PSM, C-PSM saves 49.44% of power, increases 52.68% of throughput and then finally achieves 201.97% higher energy efficiency in the sixteen-client system under the EXP distribution of traffic.

### 6.4 Effects of power consumption model on C-PSM

The power profile of wireless device has a great impact on the performance of energy-saving scheme using sleeping (Nedevschi et al., 2008). This profile includes the power consumption of client in transmission, reception, idle mode, sleeping mode and mode transition (when the client wakes up from sleeping mode to active mode), as well as the wake-up time. Additionally, the energy consumed on client's wake-up is the product of wake-up power[3] and wake-up time. The set of these above parameters are defined as a power consumption model in this chapter.

We adopt model $\mathcal{A}$ (Feeney & Nilsson, 2001; Margi, 2006) in our simulator, which is widely used. Model $\mathcal{A}$ is comparable to the hardware characteristics of many popular wireless interface cards. The ratio of transmission power to reception power in model $\mathcal{A}$ is approximately 160% which is similar to the ratioes of ORiNOCO 11a/b/g ComboCard (Proxim Wireless Corporation, 2006a), ORiNOCO 11a/b/g PCI card (Proxim Wireless Corporation, 2006b), CISCO AIRONET 802.11A/B/G Wireless Cardbus adapter (Cisco Systems, Inc., 2004), CISCO AIRONET 350 Series Wireless LAN Client Adapters (Cisco Systems, Inc., 2005) and Aironet's PC4800 PCMCIA NIC (Ebert et al., 2002). The reception power is near to the idle power in model $\mathcal{A}$ which is the same in CISCO AIRONET 802.11A/B/G Wireless Cardbus adapter (Cisco Systems, Inc., 2004) and Aironet's PC4800 PCMCIA NIC (Ebert et al., 2002). Moreover, the sleep power is about an order of magnitude lower than the idle power in model $\mathcal{A}$. The ratio of idle power to sleep power denoted as $R_{I/S}$ equals to 1167% which is common in many popular wireless network interface cards.

| State | model $\mathcal{A}$ | model $\mathcal{B}$ | model $\mathcal{C}$ | model $\mathcal{D}$ | model $\mathcal{E}$ |
|---|---|---|---|---|---|
| Transmission power | 1.4W | 1.65W | 0.75W | 1.3W | 0.85W |
| Reception power | 0.9W | 1.4W | 0.75W | 0.95W | 0.85W |
| Idle power | 0.7W | 1.15W | 0.75W | 0.79W | 0.85W |
| Sleeping power | 0.06W | 0.045W | 0.05W | 0.17W | 0.005W |
| $R_{I/S}$ | 1167% | 2556% | 1500% | 468% | 17000% |
| Wake-up power | 0.7*2W | 1.15*2W | 0.75W | 0.51W | 0.85*2W |
| Wake-up Time | 2ms | 2ms | 2ms | 13ms | 2ms |
| Wake-up Energy | 0.003J | 0.005J | 0.0015J | 0.0066J | 0.0034J |

Table 10. Five power consumption models.

Next, we compare *model* $\mathcal{A}$ with other power consumption models *model* $\mathcal{B}$ (Jung & Vaidya, 2002; Simunic et al., 2000), *model* $\mathcal{C}$ (Anastasi et al., 2007; Krashinsky & Balakrishnan, 2005), *model* $\mathcal{D}$ (Jeong et al., 2004) and *model* $\mathcal{E}$ (C-Guys, Inc., 2004) listed in Table 10. In order to study

[3] During the mode transition, the client's power consumption is near or higher than transmission power (Stemm & Katz, 1997). It could be estimated as two times of idle power (Jung & Vaidya, 2002), for example the models $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{E}$.

the effects of power consumption model on the performance of C-PSM, we deploy S-PSM and C-PSM in the two-client network ($\Delta = [15;25]$ms) (shown in section 4) under the five different power consumption models.
The improvements of C-PSM over S-PSM mainly depend on the wake-up energy consumption and $R_{I/S}$. Comparing the power saving index $\eta_P$ and the energy efficiency index $\eta_{R_{T/P}}$ in Table 11, C-PSM outperforms S-PSM greatly with the highest indices in *model* $\mathcal{C}$, since the wake-up energy consumption is minimal and $R_{I/S}$ is as high as 1500%. *Model* $\mathcal{C}$ and *model* $\mathcal{A}$ has the similar $R_{I/S}$ over 1000%, the indices of $\eta_P$ and $\eta_{R_{T/P}}$ decrease with the wake-up energy consumption. When the energy consumption is the same like *model* $\mathcal{A}$ and *model* $\mathcal{E}$, the indices increase with $R_{I/S}$. That is, the advantages of C-PSM over S-PSM is more outstanding when the wake-up energy consumption decreases and $R_{I/S}$ increases. *Model* $\mathcal{D}$ achieves the worst performance, since it has the maximal wake-up energy consumption and the lowest $R_{I/S}$. For example, C-PSM is worse than S-PSM with negative indices under the DET distribution. Therefore, C-PSM is not efficient when clients consume much energy on waking up or the sleeping power is close to the idle power.

| Index | $T_j$ | $\mathcal{A}$ | $\mathcal{B}$ | $\mathcal{C}$ | $\mathcal{D}$ | $\mathcal{E}$ |
|---|---|---|---|---|---|---|
| $\eta_P$ | DET | 26.16 | 30.86 | 46.46 | -4.86 | 38.44 |
| | UNI | 27.72 | 32.32 | 42.12 | 5.65 | 38.73 |
| | EXP | 28.99 | 33.72 | 39.63 | 12.69 | 39.58 |
| | PAR | 29.56 | 34.37 | 40.31 | 13.02 | 40.30 |
| $\eta_{R_{T/P}}$ | DET | 36.25 | 45.52 | 87.91 | -4.05 | 63.44 |
| | UNI | 39.01 | 48.46 | 73.58 | 6.48 | 63.98 |
| | EXP | 41.29 | 51.37 | 66.17 | 14.91 | 66.04 |
| | PAR | 42.30 | 52.71 | 67.93 | 15.24 | 67.91 |

Table 11. Indices of C-PSM in different power consumption models when $c = 2$, $\Delta = [15;25]$.

## 7. Conclusions and future works

We propose the centralized PSM (C-PSM) to increase the energy efficiency of all wireless clients in an infrastructure wireless network. C-PSM is traffic-aware and inherits the operations of standard PSM except for using optimal parameters. According to the traffic characteristics, C-PSM instructs the AP to compute the optimal beacon interval, optimal listen intervals, optimal minimal congestion windows and optimal sequence of first wake-up times. C-PSM achieves the significant improvements over standard PSM because (1) the jointly optimized intervals can reduce unnecessary wake-ups and channel contentions which collectively translate into the energy saving and reduction in the buffering delay; (2) the optimal minimal congestion windows are effective to balance the delay among clients; and (3) the first wake-up times reduce the simultaneous wake-ups to alleviate channel contention. Moreover, C-PSM has a wider applicability than S-PSM. It is effective even when the workload of the network is not light. The improvements of C-PSM over S-PSM increases when the number of clients increases, the wake-up energy consumption decreases or the ratio of idle power to sleep power increases. In future works, we will further improve optimization algorithms and extend C-PSM to support more traffic models.

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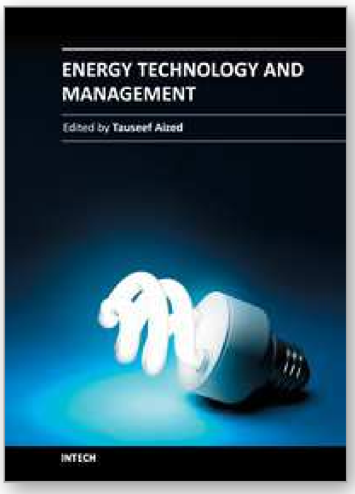


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The civilization of present age is predominantly dependent on energy resources and their utilization. Almost every human activity in todayâ€™s life needs one or other form of energy. As worldâ€™s energy resources are not unlimited, it is extremely important to use energy efficiently. Both energy related technological issues and policy and planning paradigms are highly needed to effectively exploit and utilize energy resources. This book covers topics, ranging from technology to policy, relevant to efficient energy utilization. Those academic and practitioners who have background knowledge of energy issues can take benefit from this book.