This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE CCNC 2006 proceedings

Power Management in iBSS Wireless Networks: Selective Awakening of Doze Stations

Nicola Aste, Luigi Atzori, Luca Sanna Randaccio, and Alessandro Giua
DIEE, University of Cagliari, Piazza d'Armi, Cagliari 09123 Italy
Tel: +39-070-6755849, Fax: +39-070-675-5900
Email: N.Aste, L.Atzori, L.SannaRandaccio, Giua @ diee.unica.it

Abstract

Power Management mechanisms are widely adopted in Wireless LANs to achieve appreciable power saving. In DCF iBSS networks, all stations in doze mode with pending frames are awaken by the AP at the beginning of next beacon interval. Such stations then switch to the active mode for the reception of the frames. In this work, we propose a different power management technique based on giving the AP the power of deciding which stations with pending frames to wake up. Indeed, there are several circumstances with high channel traffic in which it is better to defer the transmission so as to reduce the expected energy consumption. The AP decision is taken in view of the energy consumption due to collisions and transmissions together with the introduced latency. Through simulations, we show the performance of the proposed method, which may lead to an overall energy saving of about 40% respect to the standard Power Management.

1. Introduction

In the last years, the wireless LANs (WLANs) are being widely employed for the great advantages in terms of mobility and achievable high data rates. The most widely used protocol in WLANs is the IEEE 802.11 [1]; it specifies two operating modes: the Independent Basic Service Set (IBSS) that is known as ad hoc mode, and the infrastructure Basic Service Set (iBSS). In the first mode, a BSS forms a self-contained network with no access to the Internet where stations communicate each other in a peer-to-peer fashion; in the second mode, the wireless stations within a BSS communicate only with an Access Point (AP) that usually acts as the gateway to the Internet. The main drawback of the wireless technology is the finite time battery power of mobile computers that negatively affects performance. Given that activities such transmission, reception and medium access are highly power consuming for mobile hosts, it is necessary to improve the efficiency of protocols that promotes Power Saving strategies to minimize power consumption. The IEEE 802.11 standard specifies a Power Management (PM) mechanism that allows a mobile station to enter in a state of low power consumption (*doze*) when its interface is idle. Much research has been conducted on PM and some inefficiencies and limitations of this mechanism have been revealed. Several solutions have been proposed to overcome such problems. Most of these refer to the IBSS mode; among these, in [2] the authors propose a Distributed Contention Control mechanism to guarantee the optimal power consumption, whereas a dynamic choice of the ATIM (Announcement Traffic Indication Map) window size in [3]. In [4] authors have addressed the power management in MANET (Multi Hop Ad Hoc Networks). On the contrary, only few works consider the iBSS system such as [5] and [6] where authors propose application dependent solutions to improve the efficiency in power management.

We believe that the PM algorithm used in iBSS may still be improved with a shrewd management of the stations status. We also think that these improvements should go towards an application-independent approach so as not to increase the algorithm complexity. Accordingly, in this work, we present a new strategy that introduces significant changes in the AP behavior, which acquires a high decisional power. We firstly investigate the total average energy consumption necessary to successfully receive a frame for the stations that, being in doze state, are woken up by the AP. This analysis puts in evidence that such energy strongly depends on the number of stations contending the channel: this means that in case of high traffic, the stations to be woken up could incur into long waiting times that can negatively affect the performance of the system, introducing delays and leading to waste of power. For this reason, we propose a simple but effective PM function aimed at minimizing these waiting times to reduce the power consumption of the overall system. It is based on giving the AP the authority to decide whether a station in doze mode with pending frames should be woken up or not, weighting the energy necessary to receive a frame and the latency of frames to be sent. In this way, the AP may defer the waking up of some stations to a subsequent interval so as to reduce the time spent in active mode for the woken stations and, as a direct consequence, the power waste.

The rest of the paper is organized as follows. In Section 2 we briefly describe the IEEE 802.11 standard, giving details on the MAC layer and the Power Management mechanism. In Section 3, we present the proposed approach to improve the PM efficiency. Last Section we provide numerical results and conclusions.

1-4244-0086-4/05/$20.00 ©2005 IEEE.

2. IEEE 802.11 DCF in iBSS

In this work, we consider the IEEE 802.11 MAC layer implemented with a Distributed Coordination Function (DCF), which is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol. With the DCF access method, an active station with frames to be transmitted senses the channel. If the channel is sensed idle for a period greater than the distributed interframe space (DIFS), the station transmits its frames; otherwise defers its transmission till the end of the ongoing transmission. Then, the station randomly selects a *backoff interval* used to initialize the *backoff timer*; this timer is decremented of a *backoff slot* as long as the channel is sensed idle, stopped when the channel is busy, and restarted when the channel becomes idle after a DIFS again. When the backoff timer expires, the station is allowed to transmit. Time is discretized by slot of length T_{slot}. When a station starts the collision avoidance mechanism, randomly selects the backoff counter (hereafter BC) included in the range $[0, CW(j)]$ where $CW(j)$ is the contention window after j unsuccessful transmission attempts. For the first attempt the contention window assumes the minimum value $CW_{\min}$; this value is doubled for each collision till the maximum value $CW_{\max} = 2^{w} CW_{\min}$ is reached. The entire BC has to expire before a station transmits. If another station uses the channel before the BC of the tagged station expires, the counter is stopped and restarted at the end of the next DIFS interval. The reference station is able to transmit after the residual value of the BC is decremented to zero. Then the frames exchange between the two stations finally begins: the IEEE 802.11 standard states that when a station receives a frame with no error, has to send an ACK frame after a short interframe space (SIFS). In this work, we neglect the hidden station phenomena assuming that all stations can hear transmissions of each other.

2.1. Power Management

In the following, we briefly describe the PM mechanism defined in the IEEE 802.11 standard for an infrastructure BSS with DCF [1]. A station can be in one of the two different power states: *awake* (the station is fully powered) and *doze* (the station cannot transmit or receive and consumes very low power). In an infrastructure BSS, the AP shall buffer all frames directed to the stations in doze mode and shall inform them for pending frames with a TIM (Traffic Indication Map) indicating their identities (IDs); this operation has to be done periodically for each interval named beacon interval, hereafter indicated with T_b. A station in doze mode must wake up at each beacon interval (or at an integer number of beacons called Listen Interval) to check its ID in the TIM: if its ID is present, the station sends a Power Saving (PS) Poll frame to the AP and remains awake until it receives the frames; otherwise it returns in doze mode. When multiple stations have buffered frames, i.e., more than one ID is set in the TIM, the PS-Poll shall be transmitted according to the random backoff algorithm. In this paper, we use the term "wake up" to referring to the situation in which the AP notifies the ID of a station in doze in the TIM. Once the AP receives a PS-Poll frame, it responds after a SIFS sending a single frame buffered for the station in exam; furthermore, the buffered frames must be positively acknowledged before being removed from the buffer. This operation has to be repeated for each frame in the AP buffer. Once this transaction successfully terminates, the station returns to the doze mode. In case neither an ACK frame nor a data frame is received from the AP in response to PS-Poll frame, the station retries the sequence, by transmitting another PS-Poll frame, at its convenience. Whenever the AP is informed that a station switches to the active mode, the AP shall send all the buffered frames to that station without waiting for a PS-Poll.

3. Proposed Approach

The proposed Power Management strategy acts as follows. At each beacon interval, the AP monitors the queues of the doze stations and, on the basis of a particular cost function, decides which stations with pending frames have to be woken up, putting their correspondent ID in the TIM. This means that, differently from the IEEE 802.11 protocol, some stations with pending frames could be not woken up, deferring the transmission of such frames to successive beacon intervals. Obviously, the cost function has to take into account the introduced latency: if the AP decides to keep in doze state a station with pending frames, this will suffer an additional latency equal to the length of a beacon interval. In an application-dependent environment, this latency plays a fundamental role that has to be considered ([5], [6], [7]).

Next subsection provides the description of the system and the notation used; subsection 3.2 provides the analysis of the average energy consumed by a woken station for the receipt of a frame as a function of the number of contending stations. The cost function is provided in the last subsection.

3.1. System Description

In this subsection, we describe a time-discrete model that will be adopted to evaluate the performance of our strategy and to define the cost function. Consider a wireless cell controlled by an AP with M stations implementing the PM. Let i and k index the stations and the beacon intervals, respectively. At the beginning of each beacon interval k, the AP lists in the TIM the ID's of the stations to be woken up. Let vector $\mathbf{\Lambda}_k = \{\lambda_k^i, i = 1,\ldots,M\}$ represent the PM decision of the AP at the beginning of interval k:

$$\lambda_k^i = \begin{cases} 1 \text{ if the AP wakes up station } i \\ 0 \text{ otherwise} \end{cases}.$$

Accordingly, the number of stations woken up is $n_k = \|\mathbf{\Lambda}_k\|_1$. Note that λ_k^i has to be zero for the active stations and for stations in doze state without pending frames. To take into account the state of stations at the beginning of interval k vector $\mathbf{B}_k = \{\beta_k^i, i = 1,\ldots,M\}$ has been introduced:

$$\beta_k^i = \begin{cases} 1 \text{ if station } i \text{ is in doze with pending frames} \\ 0 \text{ otherwise} \end{cases}.$$

The number of stations that the AP wakes up in the IEEE 802.11 PM is $m_k = \|\mathbf{B}_k\|_1$. In fact, the standard states that all the stations in doze with pending frames have to be woken up. Additionally, let $\mathbf{A}_k = \{\alpha_k^i, i = 1,...,M\}$ represent the evolution of the state during a beacon interval:

$$\alpha_k^i = \begin{cases} 1 \text{ if the AP receives frames for station } i \text{ in doze} \\ -1 \text{ if station } i \text{ wakes up by itself} \\ 0 \text{ if station } i \text{ maintains its state} \end{cases}.$$

To take into account the latency introduced by the proposed algorithm we also introduce vector $\mathbf{D}_k = \{d_k^i, i = 1,...,M\}$, which represents the number of beacon intervals during which the transmission of pending frames have been delayed. Based on the previous definitions, the system evolves according to the following expressions:

$$\mathbf{B}_{k+1} = \mathbf{B}_k + \mathbf{A}_k - \mathbf{\Lambda}_k \quad (1)$$

$$d_{k+1}^i = \begin{cases} d_k^i + \beta_k^i & \text{if } \lambda_k^i = 0 \\ 0 & \text{if } \lambda_k^i = 1 \,\middle|\, \alpha_k^i = -1 \end{cases}, \quad (2)$$

with the following constraints:

$$\begin{cases} \mathbf{\Lambda}_k \le \mathbf{B}_k \\ \mathbf{0} \le \mathbf{A}_k + \mathbf{B}_k \le \mathbf{1} \\ \mathbf{D}_k \le \mathbf{1} \cdot d_{\max} \end{cases}, \quad (3)$$

where $d_{\max}$ is an integer parameter to be chosen on the basis of the maximum tolerable latency (depending on the application) for frames and the AP buffers size. Finally, we denote with μ_k the number of active stations in the cell with frames to transmit.

3.2. Modeling

The scope of this subsection is to determine the total average energy necessary for the successful receipt of a frame for a station being woken up by the AP; this energy will be adopted to define the cost function that drives our power management strategy. In the following, we introduce the formulas that are necessary to draw this energy: we have substantially adopted the same modeling shown in [8] with some key differences that will be underlined. Consider a wireless cell with n contending stations with at least one frame to transmit/receive. Differently from [8], the reference of our analysis is focused on a doze station that, being woken up by the AP, has to contend the channel access with the other n-1 stations (among which some are active and some others that have been woken up) to receive the frames buffered at the AP. The total average energy is given by the sum of four main factors: the energy used during the backoff stages E_{BC}, the energy waste due to collisions E_C, the energy spent overhearing the other transmissions E_{fr}, and the energy necessary to successful receive a frame from the AP E_{tx}. To define these terms we firstly need to introduce some useful expressions. The probability that a transmission incurs collision p can be approximated as in [9] with $p = 1 - (1 - 1/E[BC])^{n-1}$, where $E[BC]$ is the expected value of the backoff counter:

$$E[BC] = 0.5 \cdot CW_{\min}\left(1 - p - p(2p)^w\right) \cdot (1 - 2p)^{-1}. \quad (4)$$

Furthermore, the probability that the reference station suffers a certain number N_C of collisions before successfully transmitting can easily be written as:

$$\Pr\{N_C = i\} = p^i(1 - p). \quad (5)$$

The expectation of such a probability is thus given by:

$$E[N_C] = \sum_{i=0}^{\infty} i \cdot p^i (1 - p) = \frac{p}{1 - p}. \quad (6)$$

When a collision occurs, the contending stations will start decrementing their BCs again after a DIFS interval, which is the time T_C during which the channel remains busy for a collision. We are now able to define the first two contributes to the total average energy:

$$E_{BC} = P_{idle} \cdot (E[N_C] + 1) \cdot E[BC] \cdot T_{slot}, \quad (7)$$

$$E_C = P_{idle} \cdot E[N_C] \cdot T_C, \quad (8)$$

where P_{idle} is the power consumed by the station during the idle state. To derive E_{fr}, we need to define the average number of overheard transmissions by the tagged station during its backoff stages:

$$\overline{N}_t = (E[N_C] + 1) \cdot E[BC] \cdot P_{tr}, \quad (9)$$

where P_{tr} is the probability that any number of the n-1 occupies the channel for a transmission and is equal to p. Among these overheard transmissions, $\overline{N}_t \cdot P_s$ will be successful and $\overline{N}_t \cdot (1 - P_s)$ will be unsuccessful due to collisions, where P_s is the probability that any of these transmissions is successful:

$$P_s = P_{tr}^{-1} \cdot (n - 1) \cdot E[BC]^{-1}\left(1 - E[BC]^{-1}\right)^{n-2}. \quad (10)$$

The energy spent in overhearing the other transmissions is thus given by:

$$E_{fr} = \overline{N}_t \cdot [P_s T_s + (1 - P_s) T_C] \cdot P_{idle}, \quad (11)$$

where

$$T_s = \begin{cases} DIFS + T_{frame} + SIFS + T_{ACK} \\ \text{for an active station} \\ DIFS + T_{POLL} + 2SIFS + T_{frame} + T_{ACK} \\ \text{for a woken station} \end{cases} \quad (12)$$

is the duration of a successful transmission and T_{POLL}, T_{frame}, T_{ACK} are the transmission times for the PS-Poll frame, the data frame and the ACK frame, respectively. Differently from [8], in this work we keep also into account the duration of a successful transmission for a woken station that has to retrieve a buffered frame from the AP. The energy consumption for a successful transmission is then different from that adopted in [8]:

$$E_{tx} = P_{tx} \cdot T_{POLL} + P_{idle} \cdot (DIFS + 2SIFS) + \\ + P_{rx} \cdot (T_{frame} + T_{ACK}), \tag{13}$$

where P_{tx} and P_{rx} represent the power consumed by the woken station in transmission and receipt states, respectively.

We have now all the elements to define the total average energy necessary for the reference station to successfully receive a frame from the AP:

$$\overline{E} = E_{BC} + E_C + E_{fr} + E_{tx} \,. \tag{14}$$

This term strongly depends on the number of contending stations and, in an environment with high power constraints, has to be as low as possible. Figure 1 draws $\overline{E}$ as a function of the contending stations, whit system parameters set according to Table 1. It is worth noting that this curve has a linear behavior. Applying a least-squares regression to $\overline{E}$, we have obtained a straight line with slope $a = 0.0048$ and offset $b = 0.0028$, with very low norm of the residuals equal to 0.0011.

3.3. Cost Function

The objective of proposed PM algorithm is to find out a good compromise between energy consumption and frame latency. To this, we define a cost function as follows:

$$F = W_1 + \vartheta \cdot W_2 \,, \tag{15}$$

where W_1 and W_2 measure energy consumption and frame latency, respectively. The parameter $\vartheta > 0$ is a weight parameter whose importance will be discussed in the following. At the beginning of every interval *k*, the AP seeks for the solution $\mathbf{\Lambda}_k$ that minimizes (15) subject to the constraints in (3). The term W_1 measures the energy consumption of the woken stations at the beacon *k* according to equation (14). Clearly, this term weights the choice of the AP to wake up a certain number n_k of stations in doze. Accordingly, the used expression follows:

$$W_1 = n_k \cdot \overline{E}(n_k + \mu_k) \,. \tag{16}$$

As to W_2, it measures the latency of pending frames addressed to stations that have not been woken up by the AP:

$$W_2 = T_b \cdot \|\mathbf{D}_{k+1}\|_1 \,. \tag{17}$$

To make a comparison between our strategy and the standard one, the expression used to evaluate the performance of the PM implemented in the IEEE 802.11 protocol is:

$$F_k^{PM} = m_k \cdot \overline{E}(m_k + \mu_k) \,, \tag{18}$$

given that there are not deferred transmissions in the standard, the term W_2 is always equal to 0. The parameter ϑ controls the optimal balance between energy consumption and latency and its setting is a tricky task. When set to high values, the proposed algorithm converges toward the standard strategy, where the doze stations with pending frames are always awaken. Contrarily, low values bring to frequent postponements of frame transmissions with the aim of reducing station energy consumption. In order to understand the importance of the energy term with respect to the delay one, it should be considered one beacon interval latency per frame in terms of the energy dissipated by an active station during a beacon interval. The parameter ϑ should be set to $\overline{E}$ in case of equivalent importance. However, it is usually more appropriate to use lower values so as to give more importance to the energy.

4. Numerical Results and Conclusions

To evaluate the performance of the proposed strategy, we have carried out extensive simulations with Matlab. In this section, we refer to the results obtained with a wireless cell of *M*=40 stations, observed during *N*=1000 beacon intervals. Our aim was to make a comparison of the performance, during the same run, between the standard and the proposed PM. The main system parameters settings are listed in Table 1. The arrival process of packets addressed to each station is modeled with a Poisson point process with mean arrival rate equal to 5 packets per second; the probability for a station to switch from a state to another during a beacon interval is of 0.1. As to $d_{\max}$, it has to be set according to the delay tolerance of specific applications; in our simulations we have used a value of 5 beacon intervals, corresponding to 500msec. The number of active stations has been modeled as a birth-death model, with birth and death processes represented with poisson and erlang distributions, respectively [10], with an average number of active stations equal to 20. The term T_s in (12) is computed weighting the number of active and doze stations to be woken up. In the experiments, ϑ has been set to 0.25 unless otherwise stated; the aim was to give a more importance to energy saving than frame latency. In Figure 2, m_k and n_k are compared for the first 50 beacon intervals. As expected, our strategy tends to wake up a number of stations lower than that triggered by the standard PM for almost all the beacon intervals. Obviously, this difference is strictly linked to the choice of the tuning parameter ϑ. Figure 3 provides a comparison between the cost functions of the proposed and the standard PM as computed by means of expressions (15) and (18), respectively. Note that there is a significant mismatch between the two functions for almost all beacon intervals; in fact, we have obtained an average reduction of the cost function of about 17%, which brought to an overall energy saving of 40%. The drawback of this reduction is the increase in frame latency in the AP queues. To better evaluate this drawback, in Figure 4 we show the average latency obtained at different values of ϑ. As expected, the latency decreases as the parameter ϑ increases. In Figure 5 we have also compared the number of frames sent by the AP using our strategy and the standard one. It can be noted that the peaks of traffic towards awaken stations with the proposed strategy have been shifted respect to the standard approach so as to find the intervals of time with lower background transmissions. The average value is clearly the same and equal to 4. The resulting counterpart is higher buffer occupancy due to the deferred frames depicted in Figure 6. Note that there are no deferred frame transmissions when using the standard PM. These results underline that, depending on the requirements of the wireless cell, with an appropriate choice of the tuning parameter the proposed strategy can achieve an higher energy saving than the standard one at the expense of an higher delay.

5. References

[1] IEEE Computer Society. "IEEE standard 802.11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications," The Institute of Electrical and Electronics Engineers, New York, 1997.

[2] L. Bononi, M. Conti and L. Donatiello, "A distributed Mechanism for Power Saving in IEEE 802.11 Wireless LANs, " in ACM Mobile Networks and Applications (ACM MONET) Journal, Vol 6, 2001, pp 211-222.

[3] E.-S. Jung and N. Vaidya, "An Energy Efficient MAC Protocol for Wireless LANs," in Proc. IEEE INFOCOM 2002, Vol. 3, June 2002, pp. 1756-1764.

[4] Y. C. Tseng, C. S. Hsu and T. Y. Hsieh, "Power-Saving Protocols for IEEE 802.11-Based Multi-Hop Ad Hoc Networks," in Proc. IEEE INFOCOM 2002, Vol. 1, June 2002, pp. 200-209.

[5] Y. Chen, N. Smavatkul, and S. Emeott, "Power Management for VoIP over IEEE 802.11 WLAN," in Proc. IEEE Wireless Communications and Networking Conference (WCNC), Vol. 3, 21-25 March 2004, pp. 1648-1653.

[6] E. S. C. Takahashi, "Application aware scheduling for power management on IEEE 802.11," in Proc. IEEE International Conference on Performance Computing and Communications, IPCCC 2000, February 2000, pp. 247-253.

[7] A. Weissel, M. Faerber and F. Bellosa, "Application Characterization for Wireless Network Power Management," in Proc. Of the International Conference on Architecture of Computing Systems, ARCS 2004, March 2004, pp. 231-245.

[8] X. Wang, D.P. Agrawal, "Analysis and optimization of energy efficiency in 802.11 distributed coordination function," in Proc. IEEE International Conference on Performance Computing and Communications, IPCCC 2004, April 2004, pp. 707-712.

[9] Y.C. Tay, K.C. Chua, "A capacity Analysis for the IEEE 802.11 MAC Protocol," in Wireless Networks Vol. 7, 2001, pp 159-171.

[10] C. H. Foh, M. Zukerman, "A New Technique for Performance Evaluation of Random Access Protocols," in Proc. IEEE International Conference on Communications, ICC 2002, Vol. 4, 28 April-2 May 2002, pp. 2284-2288.

Table 1. System Parameters

$T_b = 100$ msec	$T_{frame} = 4$ msec
Tx Rate = 2 Mbps	$SIFS = 10$ µsec
$T_{slot} = 20$ µsec	$T_{ACK} = 56$ µsec
$T_{POLL} = 80$ µsec	$CW_{\min} = 128$
$T_{frame} = 4$ msec	$CW_{\max} = 1024$
$DIFS = 50$ µsec	$P_{tx} = 1.65$ Watt
$P_{rx} = 1.4$ Watt	$P_{idle} = 1.15$ Watt

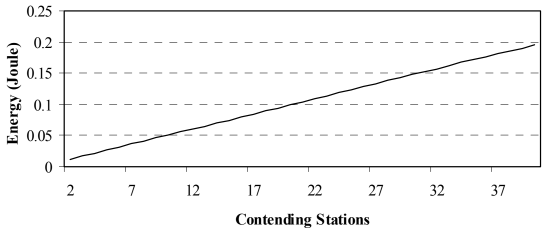

Figure 1. Total average energy $\overline{E}$, computed with settings parameters of Table 1.

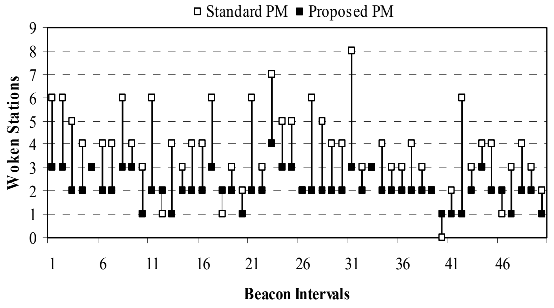

Figure 2. Comparison of the number of woken stations between the standard and proposed PM with $\vartheta = 1/4$.

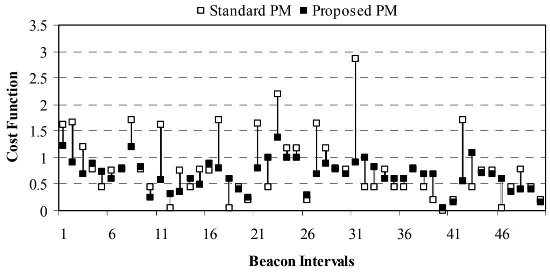

Figure 3. Performance comparison between the standard and the proposed PM with $\vartheta = 1/4$.

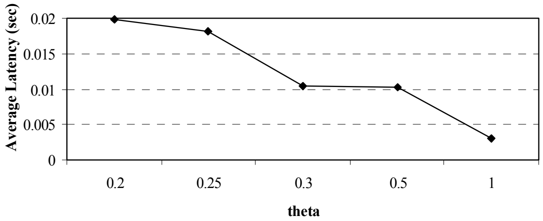

Figure 4. Mean latency vs ϑ .

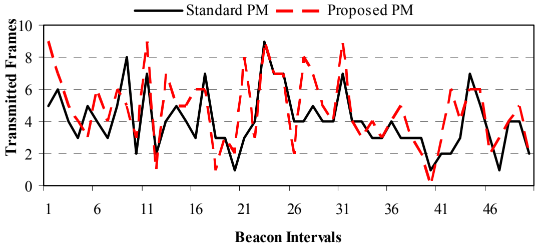

Figure 5. Comparison of the transmitted frames from the AP between the standard and the proposed PM with $\vartheta = 1/4$.

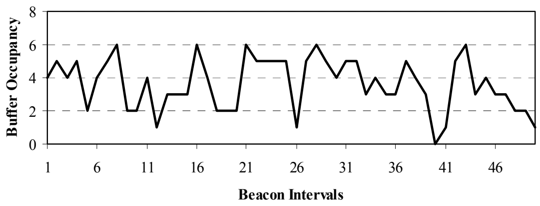

Figure 6. AP buffer occupancy in frames due to deferred transmissions using the proposed PM with $\vartheta = 1/4$.