Performance Analysis of Power Saving Strategies for Power Line Communications

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***Abstract*—Power line communications (PLC) have become a viable solution in smart grid since most devices are connected to power lines. Although PLC stations can receive power through power lines, they also require efficient use of energy. To this end, recently published PLC standards define a power saving scheme. Since the current PLC power saving scheme only defines a simple constant sleep period strategy, two adaptive sleep period adjustment schemes are presented here. The delay performance and power consumption of the three power saving schemes are verified numerically and through simulations. The two adaptive schemes are confirmed to properly balance delay performance and power consumption for any traffic type.**

I. Introduction

One of the promising applications for the Internet of things (IoT) is the energy industry such as smart grid [1]. To connect elements in smart grid, diverse kinds of communication technologies as well as IEEE 802.15 based sensor network will be used [2]. Among them, power line communications (PLC) is in the spotlight as one of the core communication technologies for smart grid since most of the elements in smart grid are connected through power lines [3]. One important trend in PLC is increasing its transmission rate such as Gbps class PHY rate. On the other hand, another important trend in PLC is providing a longer transmission range in the cost of lowering transmission rate. The latter trend receives attention for the communication technology in the distribution network. For instance, a few kbps transmission rate is enough for some smart grid applications such as advanced metering infrastructure (AMI) and supervisory control and data acquisition (SCADA), but these applications require a long transmission range. Therefore, recently published PLC standards targets either high speed PLC or long range PLC [4].

Power consumption of a PLC station is unnoticed in comparison with that of wireless communications which generally operate with batteries since all PLC stations are connected to power line. However, power saving is also important in PLC to reduce power consumption. Some smart grid applications normally have an intermittent traffic arrival characteristic, so a significant power saving can be achievable by controlling the operation mode, i.e., power save mode. To this end, recently published PLC standards define a power save mode [5], [6].

In the power save mode, the communication module can be in one of four statuses: transmitting, receiving, idle listening, and sleeping statuses. When the communication module is turned on, its status is in one of the first three statuses. Otherwise, the status of the communication module is in sleeping status. When the communication module is on and the station does not transmit or receive a packet, it is called idle listening state. Experimental study reveals that the amount of consumed power according to the communication module's status is a big difference [7].[1] When the communication module is actually used (either transmitting or receiving status), their power consumptions are the two highest. The power consumption for idle listening status is not significantly different in comparison with that of receiving status and is much higher than that in sleep status. Therefore, to reduce power consumption of the communication module, PLC stations should turn the communication module off, i.e., sleeping status, when there is no packet to transmit or receive.

Much research on power saving has been conducted in wireless communication area. Performance analysis for power saving of each communication standard such as IEEE 802.11, IEEE 802.16, and LTE, has been done [8]–[10]. In [11], the authors have proposed a power saving improvement scheme in IEEE 802.11 that uses traffic information. Despite a number of enhanced power saving schemes, the basic concepts of them are the same. That is, remaining the communication module in sleeping state as long as possible. However, none of research has been done in PLC such as power saving analysis and improvement schemes.

In this paper, we firstly analyze the performance of the power save mode for PLC standards, i.e., HomePlug Green PHY and HomePlug AV2.[2] Since the current power saving scheme for PLC only provides a simple constant sleep period

This work was supported in part by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2015R1C1A1A02037774) and in part by Korea Electric Power Corporation (Grant number: R17XA05-62).

[1] In this work, 802.11n network interface card was used. When the communication module is in transmitting, receiving, idle listening, and sleep modes, its power consumptions is 1280 mW, 940 mW, 820 mW, and 100 mW, respectively.

[2] They use the same power saving scheme. Also, IEEE 1901 standard [12] can support the power save mode through software upgrade.

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strategy, two adaptive sleep period adjustment schemes are presented. The adaptive schemes change the sleep period according to the packet arrival behavior of the previous sleep period. The delay performances and power consumption are verified through numerical method and simulations. The two adaptive schemes balance well between delay time and power consumption in any arrival cases.

The rest of this paper is organized as follows. We first briefly overview the power save mode for PLC and present two adaptive sleep period adjustment scheme in Section II. Then, the performance of PLC power saving scheme is numerically analyzed in Section III. After evaluating our proposed schemes in Section IV, we conclude our paper in Section V.

II. Power Save Mode and Strategies

A. Power Save Mode

The power save mode in PLC defines awake window and sleep window. They are periods of times that the communication module of the PLC station is turned on and off, respectively. Power save period (PSP) is the sum of awake window duration and sleep window duration in the unit of beacon period.[3] According to the standard [6], PSP should be power of two, i.e., 2^k where $k \in [0, 10]$. To reduce the power consumption, a little awake window duration and large sleep window duration are needed.

Any station that wants to enter the power save mode should notice the awake window duration, sleep window duration, and PSP to the central coordinator (CCo). The CCo periodically broadcasts power save schedule through beacon. Power save schedule contains a list of stations in the power save mode, their awake window and sleep window durations, and PSPs. Therefore, all stations in the network share the power save mode information. To communicate between the stations in the power save mode which have different PSPs, at least one awake window is shared among them.

When a station tries to send a packet to another station, it first checks that the receiver is in the power save mode or not. If the receiver is not in the power save mode, the sender transmits the packet instantly. Otherwise, the sender should wait for its transmission until the awake window of the receiver. This additional delay for a transmission is an important side effect of the power save mode. Generally, the amount of saving power and additional delay are trade-off relationship with each other.

Fig. 1 shows an example of the power save mode in PLC. In this example, PSPs for STAs A, B, and C are 1, 2, and 4 beacon periods, respectively. All the three stations in the power save mode wake up at beacon period count (BPCnt) 1 and 5 to communicate between them. Any other station wants to be in the power save mode should start its awake window at BPCnt 1 + $4L$, where L is an integer variable. Among the three stations, power consumptions for STAs A and C are the greatest and lowest, respectively.

[3]One beacon period is the same as two AC line cycle. It is 33.33 msec in North America and Korea.

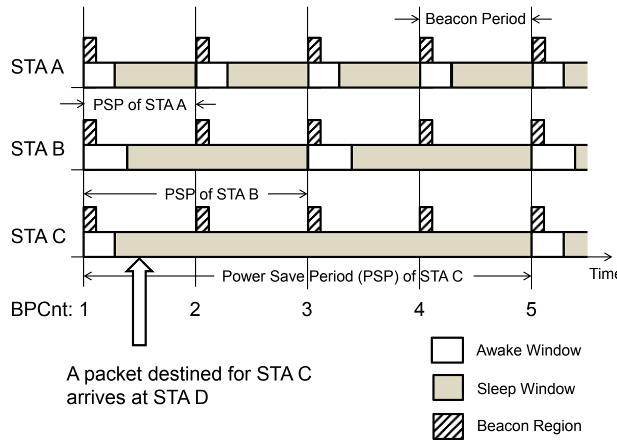


Fig. 1. An example of the power save mode.

In this example, a station (STA D) wants to transmit a packet to STA C at BPCnt 1. The station checks the receiver's status and awake window timing. STA D should wait until BPCnt 5, and then it can transmit the packet to STA C. If the packet's receiver is STA A, it can be transmitted at BPCnt 2, resulting in much smaller delay.

Choosing appropriate PSP for a station heavily depends on its quality of service (QoS) and power saving requirements. If a station wants to receive data quickly, such as less than few hundreds msec, its PSP should be set to a small one, such as 1 or 2 beacon period(s) or the station may not enter the power save mode. On the other hand, another station wants to minimize its power consumption and it does not care long delay, the station can set its PSP to a maximum value, i.e., 1024 beacon periods resulting in a delay of several tens of seconds.

B. Power Save Strategies

In the PLC standard, the only one operational strategy for the power save mode is constant sleep period strategy. In this section, we describe the constant sleep period strategy and two adaptive sleep period adjustment strategies in the PLC power save mode.

Constant PSP Strategy: The simplest strategy for choosing PSP is that PSP is set to a constant value regardless of the traffic pattern. In case the traffic regularly generates packets, and both the sender and receiver know the traffic generating period, this strategy is the most efficient strategy despite its simpleness. Possible candidate application is AMI since the metering data is generated regularly. However, if the traffic is not generated regularly, or either the sender or receiver does not know the traffic pattern, this strategy causes inefficiency in power saving and delay.

Multiplicative Increase and Decrease to the Lowest PSP (MIDL) Strategy: MIDL strategy adaptively adjusts the PSP according to the packet arrival history. PSP in this strategy starts with the lowest PSP, i.e., one beacon period, and then it doubles when no packet received during the previous PSP. If more than or equal to one packet received during the previous

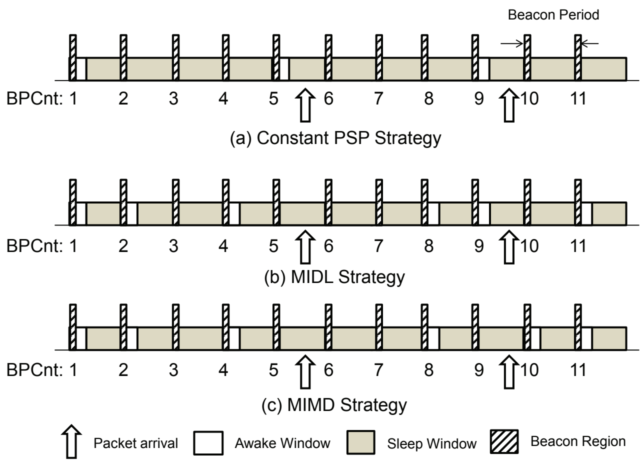


Fig. 2. Examples of the three power save mode strategies: constant PSP, MIDL, MIMD strategies.

PSP, the current PSP is initialized to the lowest one. Note that this strategy was proposed by IEEE 802.16e standard, i.e., power saving type 1 [13].

Multiplicative Increase and Multiplicative Decrease (MIMD) Strategy: Similarly to MIDL, MIMD strategy adjusts the PSP according to the packet arrival history. When one or more packets received during the previous PSP, the current PSP in MIMD is reduced half. Otherwise, it doubles. This strategy does not require any traffic information also. The advantage of the two adaptive adjusting strategies is that although they do not require any traffic information, they show good performance in any arrival pattern.

Fig. 2 shows example operations for the three power save strategies. In this example, constant PSP strategy has four beacon periods as its PSP. Packets arrive at BPCnt 5 and 9. Regardless of packet arrivals, PSP does not change in the constant PSP strategy. In MIDL and MIMD strategies, PSP becomes one and a half after a packet arrival, respectively. That is, PSPs for MIDL and MIMD strategies are set to one and two beacon periods at BPCnt 8, respectively.

III. Numerical Analysis for the PLC Power Save Mode

In this section, we analyze power consumption and delay time for the power save mode in the three power save strategies. Our analysis is an extension of the analysis on IEEE 802.16e [9].

A. System Model

We consider a simple scenario with two stations, i.e., one sender and one receiver, in the power save mode. Packets destined for the receiver arrives at the sender intermittently. It is assumed that the sender knows when the awake window of the receiver starts through the power save schedule contained in beacon. When a data packet arrived at the sender, the sender waits until the awake window of the receiver, and then it transmits the packet. We define the term delay time as the duration between a packet arrived at the sender and the packet delivered at the receiver.

The receiver begins its power save mode by the first PSP. After the PSP, the station wakes up and checks any packet destined for it at the awake window. If there is no packet to receive, the station enters the second PSP. Otherwise, after receiving the packet, the station starts the first PSP again. Let A and S denote the awake window duration and sleep window duration for ith PSP, respectively, in a unit of second. We assume that A is not changed with PSPs. P_i denotes ith PSP in unit of beacon period. Then, we have $P_i \cdot T_{BP} = A + S_i$ where T_{BP} denotes the duration of one beacon period in unit of second. It is assumed that A is long enough to receive all pending data destined for the station. Let E_A and E_S denote power consumption in awake and sleep windows per unit time, respectively. Packet arrival follows Possion arrival process with arrival rate λ, i.e. a number of packets per unit time. That is, inter packet arrival time follows an exponential distribution with mean $1/\lambda$. Let r_i denote the number of arrived packets in ith PSP.

B. Constant PSP Strategy

In this strategy, the duration of sleep window is constant, i.e. $S_i = S$ for all i resulting in constant PSP duration $P_i = P = (A+S)/T_{BP}$ for all i. The probabilities that no packet and more than one packet arrived in ith PSP are $\text{Prob}[r_i = 0] = e^{-\lambda P}$ and $\text{Prob}[r_i > 0] = 1 - e^{-\lambda P}$ for all i, respectively. We define N_{Const} as a discrete random variable that represents the number of PSPs before the station receives a packet. Then, we have probability mass function of N_{Const} as

$$\begin{aligned}\text{Prob}[N_{Const} = i] &= \prod_{j=1}^{i-1} \text{Prob}[r_j = 0]\,\text{Prob}[r_i > 0] \\ &= \prod_{j=1}^{i-1} e^{-\lambda P_j T_{BP}} (1 - e^{\lambda P_i T_{BP}}) \\ &= e^{-\lambda(i-1)PT_{BP}} (1 - e^{\lambda P T_{BP}}).\end{aligned} \tag{1}$$

Let X_{Const} denote a random variable representing the total consumed power for waiting a packet. The expected consumed power to transmit a packet with constant PSP strategy is

$$\begin{aligned}&E[X_{Const}] = \sum_{i=1}^{\infty} \text{Prob}[N_{Const} = i] \sum_{j=1}^{i} (AE_A + SE_S) \\ &= \sum_{i=1}^{\infty} e^{-\lambda(i-1)PT_{BP}} (1 - e^{\lambda PT_{BP}})(AE_A + SE_S) \cdot i.\end{aligned} \tag{2}$$

Similarly, let D_{Const} denote another random variable representing delay time for the packet to deliver to the receiver. Then, we have

$$\begin{aligned}E[D_{Const}] &= \sum_{i=1}^{\infty} \text{Prob}[N_{Const} = i] E[D_{Const} | N_{Const} = i] \\ &= \sum_{i=1}^{\infty} e^{-\lambda(i-1)PT_{BP}} (1 - e^{\lambda PT_{BP}}) \frac{PT_{BP}}{2},\end{aligned} \tag{3}$$

where $E[D_{Const}|N_{Const} = i]$ is the expected delay for the packet when the packet arrived at the sender at ith PSP. Simply, it is $E[D_{Const}|N_{Const} = i] = \frac{PT_{BP}}{2}$.

C. MIDL Strategy

The PSP duration in MIDL varies according to the packet arrival condition. The first PSP is always one, and it doubles when there is no packet to receive. Then, we have

$$\begin{aligned} P_i &= 2^{i-1}, \text{ if } P_i < P_{MAX} \\ &= P_{MAX}, \text{ otherwise,} \end{aligned} \tag{4}$$

for $i \geq 1$ where P_{MAX} is the maximum PSP duration. As a result, packet arrival probabilities are also changed according to the number of PSP cycle. That is, $\text{Prob}[r_i = 0] = e^{-\lambda P_i}$ and $\text{Prob}[r_i > 0] = 1 - e^{-\lambda P_i}$ for all i. Let N_{MIDL}, X_{MIDL}, and D_{MIDL} denote random variables for MIDL strategy that represent the number of PSPs before the station receives a packet, total consumed power, and delay time for the packet, respectively. We have the probability mass function of N_{MIDL} as

$$\begin{aligned} \text{Prob}[N_{MIDL} = i] &= \prod_{j=1}^{i-1} e^{-\lambda P_j T_{BP}}(1 - e^{\lambda P_i T_{BP}}) \\ &= e^{-\lambda \sum_{j=1}^{i-1} P_j T_{BP}}(1 - e^{\lambda P_i T_{BP}}). \end{aligned} \tag{5}$$

The expected consumed power and delay time for a packet are

$$\begin{aligned} E[X_{MIDL}] &= \sum_{i=1}^{\infty} \text{Prob}[N_{MIDL} = i] \sum_{j=1}^{i} (AE_A + S_i E_S) \\ &= \sum_{i=1}^{\infty} e^{-\lambda \sum_{j=1}^{i-1} P_j T_{BP}}(1 - e^{\lambda P_i T_{BP}}) \sum_{j=1}^{i} (AE_A + S_i E_S), \end{aligned} \tag{6}$$

where $S_i = P_i \cdot T_{BP} - A$ and

$$\begin{aligned} &E[D_{MIDL}] \\ &= \sum_{i=1}^{\infty} \text{Prob}[N_{MIDL} = i] E[D_{MIDL}|N_{MIDL} = i] \\ &= \sum_{i=1}^{\infty} e^{-\lambda \sum_{j=1}^{i-1} P_j T_{BP}}(1 - e^{\lambda P_i T_{BP}}) \frac{P_i T_{BP}}{2}, \end{aligned} \tag{7}$$

respectively.

D. MIMD Strategy

In MIMD, the PSP duration varies according to previous PSP duration as well as the packet arrival conditions. The first PSP is $P_1 = P_{prev}/2$, where P_{prev} denote previous PSP duration. The other PSPs for $i > 1$ are

$$\begin{aligned} P_i &= P_1 2^{i-1}, \text{ if } P_i < P_{MAX} \\ &= P_{MAX}, \text{ otherwise,} \end{aligned} \tag{8}$$

Since the first PSP is not a fixed value but a random, we use a Markov chain model to get it as shown in Fig. 3. Each state in the figure represents the power number of the current PSP. That is, If a state is k, the current PSP duration is 2^k.

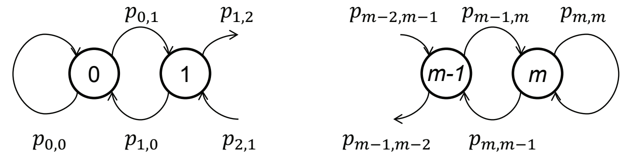


Fig. 3. Markov chain model for MIMD strategy. The number in the circle is the power number of the current PSP.

When no packet arrives in the current PSP k, the next state is $\min(k+1, m)$, where m is the maximum PSP state. Otherwise, the next state is $\max(k-1, 0)$. The state transition probabilities can be obtained as

$$\begin{aligned} p_{0,0} &= \text{Prob}[r_0 > 0] = 1 - e^{-\lambda T_{BP}}, \\ p_{i,i-1} &= \text{Prob}[r_i > 0] = 1 - e^{-\lambda 2^i T_{BP}} \text{ for } 1 \leq i \leq m, \\ p_{i,i+1} &= \text{Prob}[r_i = 0] = e^{-\lambda 2^i T_{BP}} \text{ for } 0 \leq i < m, \\ p_{m,m} &= \text{Prob}[r_m = 0] = e^{-\lambda 2^m T_{BP}}. \end{aligned} \tag{9}$$

Let $\mathcal{P}$ and π denote the transition probability matrix and steady state probability, respectively. We have

$$\mathcal{P} = \begin{bmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,m} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m,0} & p_{m,1} & \cdots & p_{m,m} \end{bmatrix} \tag{10}$$

and

$$\pi = \pi \cdot \mathcal{P}, \tag{11}$$

where $\pi = [\pi_0 \quad \pi_1 \quad \cdots \quad \pi_m]$. With (11), and $\sum_{i=0}^{m} \pi_i = 1$, the steady state probabilities π_i for $0 \leq i \leq m$ can be obtained.

Let N_{MIMD}, X_{MIMD}, and D_{MIMD} denote random variables for MIMD strategy that represent the number of PSPs before the station receives a packet, total consumed power, and delay time for the packet, respectively. The probability mass function of N_{MIMD} is the same as that of N_{MIDL}. In MIMD, the first PSP duration is a random variable, and its probability is the same as the steady state probabilities π_i. That is,

$$\text{Prob}[P_1 = i] = \pi_i. \tag{12}$$

To get the expected consumed power to transmit a packet, one additional expectation operator is needed. That is,

$$E[E[X_{MIMD}|P_1]] = \sum_{i=0}^{m} \text{Prob}[P_1 = i] E[X_{MIMD}|P_1 = i], \tag{13}$$

where

$$\begin{aligned} &E[X_{MIMD}|P_1 = i] \\ &= \sum_{j=1}^{\infty} \text{Prob}[N_{MIMD} = j] \cdot \sum_{k=1}^{j} (AE_A + S_{k+i} E_s) \\ &= \sum_{j=1}^{\infty} e^{-\lambda \sum_{k=1}^{j-1} P_k T_{BP}}(1 - e^{\lambda P_j T_{BP}}) \sum_{k=1}^{j} (AE_A + S_{k+i} E_S). \end{aligned} \tag{14}$$

TABLE I
EVALUATION PARAMETERS.

Parameter	Value
T_{BP}	33.33 msec
P_{MAX}	1024 beacon periods
m	10
A	5.56 msec
λ	0.005 - 1 packets/beacon period
E_A	820 mW
E_S	100 mW

Similarly, we have the expected delay time in MIMD as

$$E[E[D_{MIMD}|P_1]] = \sum_{i=0}^{m} \text{Prob}[P_1 = i] E[D_{MIMD}|P_1 = i], \tag{15}$$

where

$$\begin{aligned} &E[D_{MIMD}|P_1 = i] \\ &= \sum_{j=1}^{\infty} \text{Prob}[N_{MIMD} = j] \cdot E[D_{MIMD}|N_{MIMD} = j] \\ &= \sum_{j=1}^{\infty} e^{-\lambda \sum_{k=1}^{j-1} P_k T_{BP}} (1 - e^{\lambda P_j T_{BP}}) \frac{P_j T_{BP}}{2}. \end{aligned} \tag{16}$$

IV. EVALUATIONS

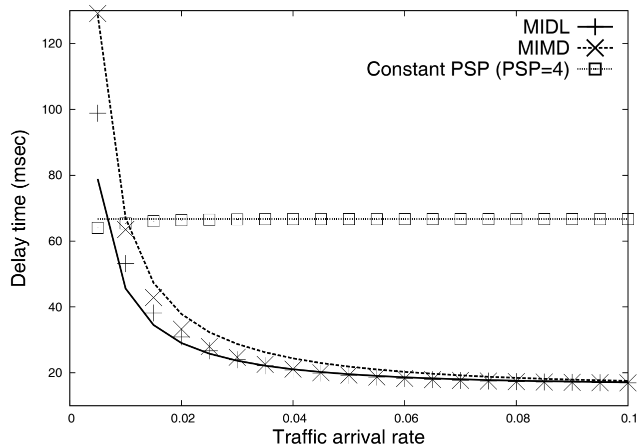
The performances of the three power save strategies (constant PSP, MIDL, and MIMD) between one sender and one receiver are evaluated in terms of delay time and power consumption through numerical method and simulations. In this study, the delay means the MAC delay, i.e. the delay from the sender's head-of-line queue to the receiver. The queueing delay is not taken account in here because all the three power save strategies show the same queueing delay.

A. Evaluation Settings

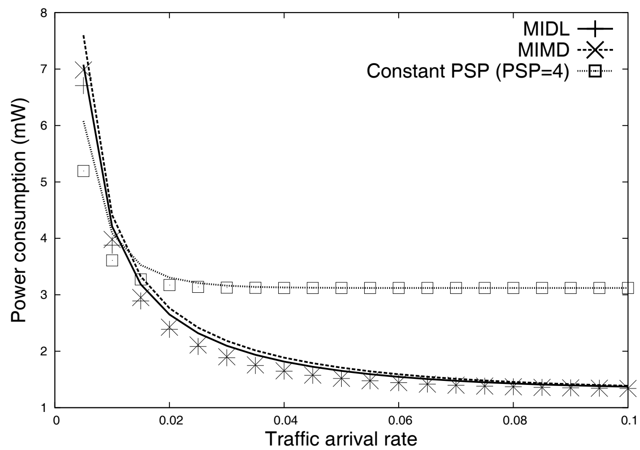
We consider three inter arrival time distributions that are fixed interval, exponential distribution, and Gaussian distribution. In case of periodic sensing applications, such as AMI or VAR control, their inter arrival times are fixed. On the other hand, some other applications, such as EV charging or non-periodic data acquisition, generate packets randomly which are modeled as exponential and Gaussian distributions. The evaluation parameters for the PLC power save mode [6] and power consumption [7] are presented in Table I.

B. Numerical and Simulation Results

Fig. 4(a) shows the delay performance for the three power save strategies under the exponential inter arrival time distribution. The lines and symbols represent numerical and simulation results, respectively. It is confirmed that the performance gap between numerical analysis and simulation results are small, i.e., about 4.4%. The results for both MIDL and MIMD strategies are similar tendency while the constant PSP strategy with PSP=4 shows almost the same delay time regardless of λ. Note that the other constant PSP strategies with different PSPs show horizontal lines with different delay time.



(a) Delay performance

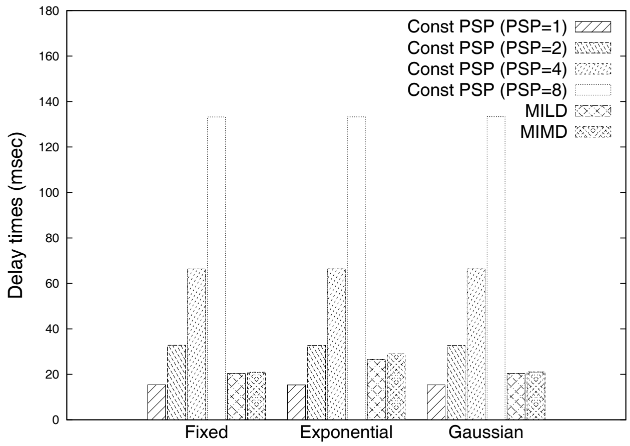


(b) Power consumption

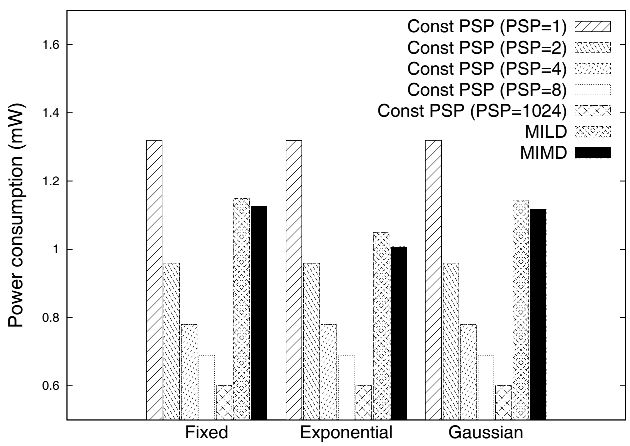
Fig. 4. Delay performance and power consumption for the three power save strategies according to λ under the exponential inter arrival time distribution. The lines and symbols represent numerical and simulation results, respectively.

Fig. 4(b) shows the power consumption to transmit a packet for the three power save strategies under the exponential inter arrival time distribution. Again, the results of the numerical analysis are very close to those of simulation, i.e., about 5.9%. Also, MIDL and MIMD strategies show similar trends. With $\lambda > 0.025$, the constant PSP with PSP=4 gives a horizontal line. It is because at least one packet arrives in each PSP when λ is greater than 0.025.

We also simulated two different packet arrival distributions: fixed packet arrival interval and Gaussian distribution. The results of average delay performance and power consumption shown in Fig. 5 are averaged values of λ from 0.005 to 0.1. The constant PSP with PSP=1 shows the smallest delay performance and the highest power consumption. The two adaptive strategies show good delay performance and moderate power consumption since the two strategies adjust the PSP according to the arrival rate. Between the two adaptive strategies, MIDL



(a) Delay performance



(b) Power consumption

Fig. 5. Average delay performance and power consumption for the three power save strategies under the three inter arrival time distributions.

has an advantage on the delay performance while MIMD does on the power consumption.

Note that results for the constant PSP with maximum beacon period, i.e., 1024, are not presented in Fig. 5(a). Regardless of different distributions, average delay performance is 17.1 seconds for the constant PSP with PSP=1024. If an application is not delay sensitive one, i.e., accept more than 17 seconds average delay, the use of constant PSP with maximum beacon period is the most energy efficient strategy. On the other hand, the two adaptive schemes show good energy efficiency with tens of millisecond delay without setting any parameters. MIMD strategy consumes 1.67 times higher power consumption than that of constant PSP with maximum beacon period. However, its delay time is much smaller than that of constant PSP with maximum beacon period, i.e., 1/500. We can conclude that the two adaptive strategies are a reasonable choice for any applications.

Even if a more general scenario such as many senders to many receivers scenario is considered, the same delay and power consumption results will be delivered. This is because performances of power save strategies only depend on the sender and receiver pair.

V. Conclusion

Recent power line communication standards, such as HomePlug Green PHY and HomePlug AV2, define a power save mode to reduce power consumption for the communication module. The standard only describes constant power save period strategy. In this paper, two adaptive power save period adjustment strategies as well as the constant power save period strategy are presented. Multiplicative increase and lowest decrease (MILD) and multiplicative increase and multiplicative decrease (MIMD) strategies increase and decrease power save period when no and any packet is received at the previous cycle, respectively. The delay performance and power consumption are numerically analyzed for the three strategies with the Poisson arrival traffic. They are also verified through simulations under three inter arrival time distributions that are fixed interval, exponential distribution, and Gaussian distribution. Constant PSP strategies have clear merits and demerits and the PSP duration should be set to a proper value of each application's characteristic. However, the two adaptive strategies, i.e., MIDL and MIMD, balance well between delay performance and power savings without setting any parameters.

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