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Performance enhancement and analysis for IEEE 802.16e/m sleep mode operations with unsolicited grant service/real-time variable-rate connections

C.-H. Hsu K.-T. Feng

Department of Electrical Engineering, National Chiao Tung University, Hsinchu, Taiwan
E-mail: ktfeng@mail.nctu.edu.tw

Abstract: The power saving class of type II (PSC II), one of the sleep mode operations in the IEEE 802.16e standard, is designed to reduce power consumption for unsolicited grant service (UGS) and real-time variable-rate (RT-VR) connections. However, the configuration of fixed-length listening windows in the PSC II incurs unnecessary energy consumption or packet loss for these types of connections. In order to enhance the performance of sleep mode operations, an approach with adaptive listening window (ALW) is proposed. The ALW scheme dynamically adjusts the length of each listening window based on the number of both arrival and retransmission packets as well as the delay constraint. Numerical analysis and simulation results show that the proposed ALW approach can effectively reduce the packet loss rate for UGS connections, whereas better energy conservation with reduced packet loss rate is achieved for RT-VR connections.

1 Introduction

The IEEE 802.16-2004 standard [1] for wireless metropolitan area networks is developed to support various demand for high capacity, high data rate and advanced multimedia services. The IEEE 802.16e amendment [2] enhances the original standard by addressing issues of mobility management and energy conservation for mobile stations (MSs). In order to support future advanced services with higher data rate and higher mobility, the next generation of IEEE 802.16 system is being developed in the IEEE 802.16m task group [3]. Since mobility is considered a key feature in wireless networks, how to prolong the battery lifetime of MSs has been recognised as one of the critical issues.

Several power-saving mechanisms are designed for conserving MSs energy in different wireless mobile networks. In IEEE 802.11 wireless local area networks [4], the access point (AP) periodically broadcasts beacons to notify the associated power-saving MSs regarding their traffic indications. The MS remains in sleep state most of time and wakes up to receive the beacons with a fixed wake-up interval. If the beacon received by the MS indicates the presence of buffered packets, the MS will keep awake and issue a power-saving poll (PS-poll) message to the AP in order to retrieve the buffered packets; otherwise it will return to the sleep state. After completely receiving the buffered packets in the awake state, the MS will go back to the sleep state immediately. On the other hand, the third-generation mobile cellular system universal mobile telecommunications system (UMTS) employs discontinuous reception (DRX) mechanism to conserve the power of MSs [5, 6]. An MS enters the power-saving mode while it has been idle for a period of time without data transportation in the power-active mode. In the power-saving mode, the MS is provided with a series of fixed-length DRX cycles wherein the MS stays in the sleep state. At the end of a DRX cycle, the MS will wake up and listen to the paging channel for upcoming messages. If a paging message indicates that there exists packets buffered at the base station (BS), the MS will terminate the power-saving mode and go back to the power-active mode for packet reception; otherwise it will return to the sleep state until the end of the next DRX cycle.

In IEEE 802.16e networks, power-saving mode is named sleep mode that is defined as a state in which the MS conducts per-negotiated periods of absence from the serving BS air interface. In the sleep mode, the MS is provided with a series of sleep cycles that consist of both sleep windows and listening windows. The sleep window is a time period in which the BS shall not transmit data or management messages to the MS. During the listening window, on the other hand, the MS is expected to transmit/receive data or management messages based on the same manner as in the state of normal operations. Three types of sleep mode operations, which correspond to the power-saving classes (PSCs), are specified in the IEEE 802.16e standard to support different types of traffic. It is noted that each PSC is defined as a group of connections that share the common demand properties. Different types of PSCs are differentiated by parameter sets, procedures of activation/deactivation and policies of MS's availability for data transmission. The difference among these PSCs mainly came from the way for determining the length of sleep windows.

The PSC of type II (PSC II) is defined by fixed period of sleep cycles that consist of fixed-length listening windows and sleep windows, which is recommended for serving connections of unsolicited grant service (UGS) and real-time variable-rate (RT-VR) types. According to the traffic characteristics of these connections, two potential problems can occur by adopting the PSC II as follows: (a) unnecessary energy consumption resulted from unutilised frames within the listening windows, and (b) packet loss because of the worse channel conditions. In this paper, an approach with adaptive listening window (ALW) is proposed for the PSC II in IEEE 802.16e networks. According to the delay constraints, the ALW scheme dynamically adjusts the length of each listening window based on the number of both buffered arrival packets and retransmission packets. It is worthwhile to mention that the concept of ALW approach has recently been proposed by the authors and is adopted in the IEEE 802.16m standard draft [7]. The performance of the proposed ALW scheme is evaluated and validated via both numerical analysis and simulation studies. The results show that the ALW scheme efficiently reduce the packet loss rate for both UGS and RT-VR connections in comparison with the PSC II mechanism. The energy conservation for RT-VR connections is also enhanced by adopting the ALW algorithm.

The remainder of this paper is organised as follows. Section 2 briefly describes the system model of packet transmission and sleep mode operations for the IEEE 802.16e networks. The proposed ALW approach is explained in Section 3, whereas its numerical analysis is carried out in Section 4. Both the performance evaluation and validation of the ALW approach are conducted in Section 5. Section 6 draws the conclusions.

2 Preliminaries

2.1 System model

The point-to-multipoint (PMP) mode, where the traffic controlled by the BS, is considered the well-adopted network configuration in IEEE 802.16e networks. In this paper, the PMP mode with time division duplexing (TDD) for a BS and an MS is considered as the system model to investigate the proposed ALW approach. In the PMP mode with TDD, each frame consists of a downlink (DL) subframe and a uplink (UL) subframe, which are exploited to deliver DL traffic (from BS to MS) and UL traffic (from MS to BS), respectively. Moreover, in order to preserve the quality of service (QoS) for the connections, the corrupted packets are considered to be retransmitted based on the corresponding delay constraint.

An exemplified system model is illustrated in Fig. 1, wherein a single DL connection is considered. It is observed that all the arrival packets are queued into the arrival buffer of the BS before conducting its transmission services. The BS transmits the buffered packets to the MS in DL subframes and arranges corresponding opportunities for the MS to provide its reception status. If a packet is corrupted, a negative acknowledgement (NACK) message is sent back to the BS and the packet will be considered for retransmission based on the QoS constraint. On the other hand, in the case with successful packet transmission, a positive acknowledgement (ACK) message is returned to the BS and new packets will be consecutively transmitted to the MS. For the purpose of facilitating the explanation, the corrupted packets requesting for retransmission are retained in the retransmission buffer, which are considered to possess higher transmission priority over the packets stored in the arrival buffer. As shown in Fig. 1, two packets P_1 and P_2, stored in the arrival buffer, are transmitted in the DL subframe of the fth frame by the BS. The corresponding acknowledgement messages A_1 and A_2 are returned by the MS in the UL subframe of the same frame. Owing to the

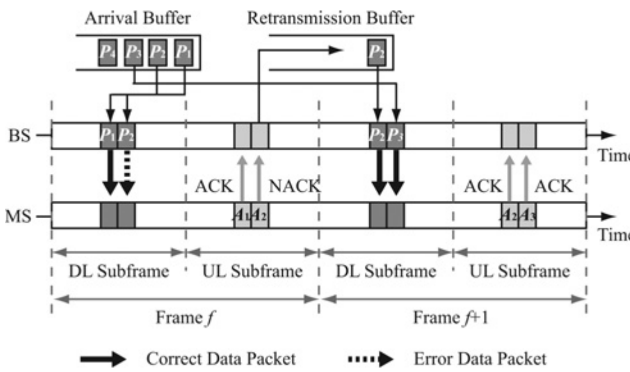

Figure 1 *Schematic diagram of packet transmission model in IEEE 802.16 PMP mode with TDD*

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transmission error reported via A_2, the packet P_2 is retained in the retransmission buffer and will be transmitted immediately in the DL subframe of the $(f+1)$th frame. It is noted that an intuitive and simple ACK/NACK scheme is exploited in this paper. However, other types of BS/MS negotiation schemes can also be applied in the considered networks.

2.2 IEEE 802.16e sleep mode operations

Fig. 2 depicts the operation of PSCs in IEEE 802.16e networks. For PSC of type I (PSC I) that is recommend for non-real-time traffic, the operation is similar to that of UMTS DRX mechanism by detecting the incoming traffic in the sleep mode and receiving the packets in the normal mode. The detection intervals (i.e. sleep windows) with length of binary-exponential increment is considered in the PSC I. As shown in Fig. 2*a*, the PSC I starts with a sleep window of length $T_{SW_0} = T_{min}$. The length of the next sleep window is double of the previous one if no traffic is addressed to the MS, for example, $T_{SW_1} = 2 \times T_{SW_0}$. This process is repeated as long as the length of the sleep window does not exceed T_{max}. As the length of the sleep window reaches T_{max}, the lengths of subsequent sleep windows will remain constant at T_{max}, for example, $T_{SW_4} = T_{SW_3} = T_{max}$. It is noted that the parameters T_{min} and T_{max} represent the minimum and maximum length of a sleep window, respectively, which are negotiated by the BS and MS before activating a PSC I. On the other hand, as shown in Fig. 2*b*, alternately fixed-length sleep windows and fixed-length listening windows are defined in PSC II, which is recommended for serving real-time traffic. With the operation of PSC II, the MS keeps staying in the sleep mode and receiving packets within listening windows until an explicit termination of the sleep mode is requested by the MS or BS. The lengths of sleep windows and listening windows are predefined according to the negotiation between the BS and MS. It is noted that the permission of data

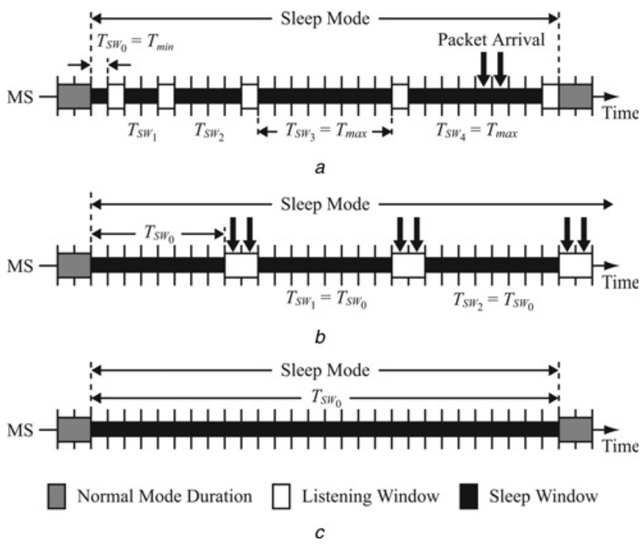

Figure 2 *Schematic diagram of PSCs in IEEE 802.16 system*
a PSC I
b PSC II
c PSC III

transportation within the sleep mode is the major difference between PSC II and UMTS DRX mechanism. Fig. 2*c* illustrates the configuration of PSC of type III, wherein only one sleep window is considered for multicast or management traffic.

In recent research studies, performance analysis of sleep mode operations in IEEE 802.16e networks have been investigated. The basic sleep mode operation for the PSC I in IEEE 802.16e networks has been analytically modelled and discussed in [8–18]. The work conducted in [8–10] only considers DL connection in the sleep mode, whereas both DL and UL connections are investigated in [11–14]. The power-saving performance that affected by queue behaviours based on different queueing models are studied in [15–18]. Moreover, enhanced sleep mode mechanisms for PSC I have been proposed and analysed in [19–23]. The work in [19, 20] dynamically enlarge the length of initial sleep window to reduce the total number of listening windows, whereas the probabilistic sleep windows is proposed in [21]. The adjustments of T_{min} and T_{max} are investigated in [22, 23]. On the other hand, the PSC II is analysed and discussed in [9, 14]. However, enhanced power-saving schemes for PSC II have not been studied and addressed in the existing literature.

2.3 Problem statement

As mentioned in the previous subsection, the PSC II is defined by fixed period of sleep cycles that consist of fixed-length listening windows and sleep windows. It is recommended for serving connections that require guaranteed data rate and delay, including both UGS and RT-VR types. The UGS connection is utilised to support fixed-rate data, whereas variable bit rates are supported by the RT-VR connection. According to the traffic characteristics of the connections, two potential problems can occur by adopting the PSC II, which are detailed as follows:

1. *Unnecessary energy consumption*. Since the UGS connection is designed to support real-time data stream with constant bit rate, the configuration of PSC II is considered appropriate for the UGS connection to conserve energy. As for the RT-VR connection, however, the length of listening window is generally set to achieve the required maximum bit rate. In such case, all the buffered arrival packets should be completely transmitted from the BS to the MS during the fixed-length listening window. However, with the nature of variable bit rate within the RT-VR connection, the design of fixed-length listening windows will result in the existence of unutilised frames, named *idle frames*, with full power-on mode. According to the current IEEE 802.16e standard, the MS will be kept awake until the end of each listening window, which incurs excessive energy consumption for the MS.

2. *Packet loss*. In order to improve the reliability of wireless links, retransmission mechanisms have been studied for real-time traffic [24, 25]. In general, packet retransmissions happen

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under the situations with worse channel conditions, which can resulted from either inter-cell interference or MS's mobility. With higher inter-cell interference or higher mobility of the MS, the frequency of packet retransmissions is required to be increased. Based on the predefined fixed length of listening window as described in PSC II, the buffered packets may not be completely transmitted from the BS to the MS. All the remained packets will violate the delay constraint and consequently be dropped. It is also noted that frequent transition between normal and sleep modes is not recommended in PSC II because of excessive handshakes between the BS and the MS. Therefore with the fixed length of listening window, the packet loss rate for both the UGS and RT-VR connections can be significantly increased as the quality of wireless channel becomes worse.

In order to overcome the aforementioned disadvantages of PSC II and consequently enhance the performance of sleep mode operation, a flexible and improved power-saving mechanism should be considered.

3 ALW approach

In this section, the proposed ALW approach is presented for the PSC II in IEEE 802.16e networks. According to the standard for an MS in the sleep mode, the packets arrived at the BS during the sleep window of the previous sleep cycle will be buffered, and consequently be transmitted within the listening window of the current sleep cycle. Owing to the characteristics of RT-VR connection, the total number of buffered packets can vary in different sleep cycles. Moreover, retransmissions for error packets that satisfy tolerable delay should also be considered owing to different channel conditions. In the design of the proposed ALW approach, the length of each listening window will be adaptively adjusted based on the total number of buffered packets that exist in both the arrival buffer and retransmission buffer as well as the delay constraint. It is noted that the arrival buffer is utilised to preserve the arrival packets in the previous sleep cycle, whereas the retransmission buffer keeps packets that are ready to be retransmitted within the current listening window. Compared with the PSC II, it is worthwhile to mention that the length of the listening window will be dynamically increased or decreased for each sleep cycle while adopting the proposed ALW approach, which can consequently reduce both the unnecessary energy consumption and packet loss rate.

Fig. 3 illustrates the schematic diagram of an exemplified PSC II with the proposed ALW scheme for an RT-VR connection, where the length of each predefined listening window (T_{L}) is selected as 2 frames. As mentioned above, the packets arrived at the BS during the $(k-1)$th sleep cycle are transmitted within the listening window of the kth sleep cycle. It is observed that all the buffered packets are completely transmitted in the first frame of the listening window within the kth sleep cycle and the second frame of that becomes idle. For the purpose of energy conservation, the MS decreases the length of the listening window and returns to the sleep state

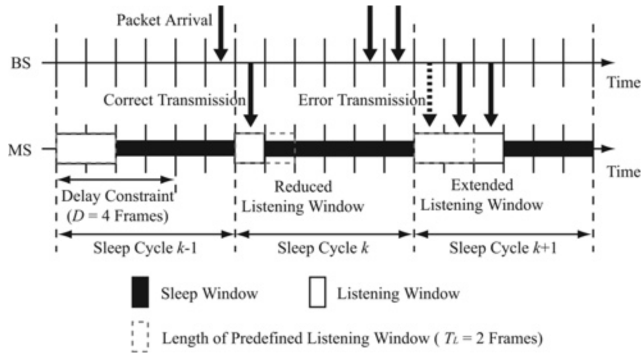

Figure 3 *Schematic diagram of PSC II with the proposed ALW approach for RT-VR connection with $T_L = 2$ frames and $D = 4$ frames*

early in the second frame of the kth sleep cycle. On the other hand, the length of the listening window in the $(k+1)$th sleep cycle is extended as 3 frames because of a transmission error occurred in the first frame. Since the delay constraint (D) for the packets is 4 frames in this example, retransmission for the error packet is required in order to preserve the QoS. It is noted that the maximum length for the extended listening window will be equal to D, which is the maximally tolerable packet delay for each connection.

Based on the concept as described above, an event-driven algorithm called 'Listening window adjustment algorithm' (refer to Fig. 4) is proposed for the BS to make an appropriate decision for adjusting the listening window lengths of an MS. The notations utilised in the algorithm are listed as shown in Table 1. The algorithm begins if one of the following events is occurred within the sleep cycle k:

1. $B_{\mathrm{A}}(t) = \text{empty}$ and $B_{\mathrm{R}}(t) = \text{empty}$: All the buffered packets are completely transmitted. In such case, the activities of the BS and MS can be found in lines 2 and 3 in Fig. 4. The BS will send an information to the MS in the (f_t+1)th frame for terminating the listening window, which consequently cause the MS to enter into the sleep state.

2. $t = (t_k + T_{\mathrm{L}} d_{\mathrm{f}})$: The current time is in the end of the predefined listening window. According to the IEEE 802.16e standard, the MS will terminate the listening window and return to the sleep state at $t = t_k + T_{\mathrm{L}} d_{\mathrm{f}}$. For the purpose of reducing packet loss rate while still satisfying the delay constraint, the statuses of both arrival buffer and retransmission buffer will be examined at this time instant. If both buffers are empty, the BS will do nothing and the MS will return to the sleep state (i.e. lines 6 and 7 in Fig. 4), which follows the original operations as specified in the standard. Otherwise, the BS will send an information to the MS in the (f_t+1)th frame for increasing the length of listening window, and the MS will keep awake until it receives a termination information from the BS (i.e. lines 9 and 10 in Fig. 4).

3. $t = (t_k + D d_{\mathrm{f}})$: The current time is in the end of the delay constraint. Following the QoS requirement, the BS will drop

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    Input: t, t_k, d_f, f_t, D, T_L, B_A(t), and B_R(t)
    Output: A_BS(f_t + 1) and A_MS(f_t + 1)
1   if (t_k ≤ t < (t_k + T_L d_f)) or ((t_k + T_L d_f) < t < (t_k + D d_f)) then
2       A_BS(f_t + 1) ← send a termination information to the MS
3       A_MS(f_t + 1) ← return to the sleep state
4   else if t = (t_k + T_L d_f) then
5       if (B_A(t) = empty) and (B_R(t) = empty) then
6           A_BS(f_t + 1) ← do nothing
7           A_MS(f_t + 1) ← return to the sleep state
8       else
9           A_BS(f_t + 1) ← send an extension information to the MS
10          A_MS(f_t + 1) ← keep in the awake state
11      end
12  else
13      // t = (t_k + D d_f)
14      if (B_A(t) = empty) and (B_R(t) = empty) then
15          A_BS(f_t + 1) ← send a termination information to the MS
16      else
17          A_BS(f_t + 1) ← send a termination information to the MS and drop all the buffered packets
18      end
19      A_MS(f_t + 1) ← return to the sleep state
20  end
```

Figure 4 *Listening window adjustment algorithm*

Table 1 Notations for listening window adjustment algorithm

Notation	Description
t	initial time of algorithm execution
t_k	initial time of the kth sleep cycle
d_f	duration for a single frame
f_t	frame where time t is located
D	delay constraint in unit of frame
T_L	length of the predefined listening window in unit of frame
$B_A(t)$	status of the arrival buffer at time t
$B_R(t)$	status of the retransmission buffer at time t
$A_{BS}(f_t+1)$	activity of the BS in (f_t+1)th frame
$A_{MS}(f_t+1)$	activity of the MS in (f_t+1)th frame

all the buffered packets while the delay constraint is violated. In such case, a termination information will be sent by the BS to the MS in the (f_t+1)th frame and the MS will return to the sleep state. The activities of the BS and MS can be found in lines 14–19 in Fig. 4.

Since the complexity of the algorithm is O(1), the decision for adjusting the listening window length can be made by the BS immediately. Therefore it is expected that the proposed ALW approach, which is based on Fig. 4, can be implemented in practical systems.

4 Numerical analysis

In this section, a mathematical model is presented to analyse the energy consumption of the proposed ALW approach as well as the PSC II mechanism for an UGS/RT-VR connection. As mentioned previously, the packet arrived during the previous sleep cycle are stored in the arrival buffer at the BS. For the purpose of facilitating the analysis, it is assumed that the size of packets is constant for both UGS and RT-VR connections. Let the number of packets arrived during the previous sleep cycle denoted as N_A. For the UGS connection, N_A with the probability of n packets can be obtained as

$$P_r^{\mathrm{UGS}}(N_A = n) = \begin{cases} 1 & \text{if } n = \lambda T_C \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where λ is the packet arrival rate in unit of packet per frame, whereas T_C denotes the length of sleep cycle in unit of frame. On the other hand, the packet arrival process of the RT-VR connection is assumed to follow a Poisson process with rate λ, where the probability of N_A with n packets can be expressed as

$$P_r^{\mathrm{RT-VR}}(N_A = n) = \frac{(\lambda T_C)^n}{n!} e^{-(\lambda T_C)} \quad (2)$$

All the buffered packets are considered to be completely transmitted to the MS within the current listening window while the delay constraint is satisfied. In general, the value of the delay constraint is considered between the length of the listening window and the length of the sleep cycle, that is, $T_L \le D \le T_C$.

4.1 Analytical model

Fig. 5 shows the state transmission model of the ALW scheme for an MS. S_k (for $k \in \{1, 2, \ldots, D\}$) denotes the state that all the buffered packets are completely transmitted in successive k frames, named busy frames, within a sleep cycle. The transition probability from S_i to S_{i+1}, denoted as φ_i for $1 \le i \le D-1$, will be obtained based on the probabilities $P_r(\mathcal{C}_1)$, $P_r(\mathcal{C}_2)$ and $P_r(\mathcal{C}_3)$ that are defined as follows. Let δ indicates the service rate in unit of packet per frame for the connection. The state transition from S_i to S_{i+1} can occur while the number of packets stored in the arrival buffer is more than $i\delta$, where the probability $P_r(\mathcal{C}_1)$ can be acquired as

$$P_r(\mathcal{C}_1) \triangleq P_r(N_{\mathrm{A}} > i\delta) = 1 - P_r(N_{\mathrm{A}} \le i\delta) = 1 - \sum_{n=1}^{i\delta} P_r^{\varsigma}(N_{\mathrm{A}} = n) \quad (3)$$

with $\varsigma \in \{\mathrm{UGS}, \ \mathrm{RT\text{-}VR}\}$ as the index to represent the probability from either the UGS connection or RT-VR connection. Furthermore, considering the scenario that the number of packets stored in the arrival buffer is less than $i\delta$, two other conditions will also cause the state transition to happen owing to the packet retransmissions. One of the conditions is that the number of packets from the arrival buffer and the error packets from the retransmission buffer counted from the previous $i-1$ frames are observed to be more than $i\delta$. For the purpose of facilitating the analysis, it is assumed that the error probability for each transmitted packet is equal to p. The corresponding probability $P_r(\mathcal{C}_2)$ can be obtained as

$$P_r(\mathcal{C}_2) \triangleq P_r(N_{\mathrm{A}} \le i\delta, N_{\mathrm{A}} + N_{\mathrm{R}}(i) - r_i > i\delta) = \sum_{n=1}^{i\delta} P_r^{\varsigma}(N_{\mathrm{A}} = n) \cdot P_r(N_{\mathrm{A}} + N_{\mathrm{R}}(i) - r_i > i\delta | N_{\mathrm{A}} = n) \quad (4)$$

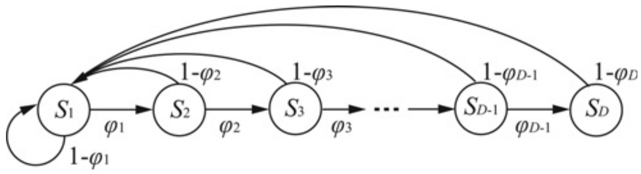

Figure 5 *State transition model of the proposed ALW approach*

where r_i denotes the number of packets with transmission error in the ith frame, whereas $N_{\mathrm{R}}(i) = \sum_{j=1}^{i} r_j$ indicates the total number of error packets from the first to the ith frame in the current sleep cycle. The conditional probability $P_r(N_{\mathrm{A}} + N_{\mathrm{R}}(i) - r_i > i\delta | N_{\mathrm{A}} = n)$ is denoted by $\Delta^{(i)}(n)$, which can be calculated as (see (5))

where $\mathbb{C}_j^{\delta} \triangleq C_j^{\delta} p^j (1-p)^{\delta-j}$ is defined as the error probability of δ successively transmitted packets with j packets that are corrupted. The other condition happens while the total number of buffered packets is less than $i\delta$; however, there exists transmission errors in the ith frame. The resulting probability $P_r(\mathcal{C}_3)$ can be acquired as

$$P_r(\mathcal{C}_3) \triangleq P_r(N_A \le i\delta, N_{\mathrm{A}} + N_{\mathrm{R}}(i) - r_i \le i\delta, r_i \ge 1) = \sum_{n=1}^{i\delta} P_r^{\varsigma}(N_{\mathrm{A}} = n) P_r(N_{\mathrm{A}} + N_{\mathrm{R}}(i) - r_i \le i\delta, r_i \ge 1 | N = n) \quad (6)$$

where the conditional probability $P_r(N_{\mathrm{A}} + N_{\mathrm{R}}(i) - r_i \le i\delta, r_i \ge 1 | N = n)$ denoted by $\Gamma^{(i)}(n)$ is obtained as (see (7))

With (3), (4) and (6), the transition probability from S_i to S_{i+1} can be obtained as

$$\Delta^{(i)}(n) = \begin{cases} 0 & \text{for} \quad 1 \le n \le \delta, 1 \le i \le D-1 \\ \displaystyle\sum_{j=2\delta-n+1}^{\delta} \mathbb{C}_j^{\delta} & \text{for} \quad \delta < n \le 2\delta, i = 2 \\ \displaystyle\sum_{j=\max\{0, 2\delta-n+1\}}^{\delta} \mathbb{C}_j^{\delta} \cdot \Delta^{(i-1)}(j+n-\delta) & \text{for} \quad \delta < n \le (i-1)\delta, 3 \le i \le D-1 \\ \displaystyle\sum_{j=0}^{i\delta-n} \mathbb{C}_j^{\delta} \cdot \Delta^{(i-1)}(j+n-\delta) + \sum_{l=i\delta-n+1}^{\delta} \mathbb{C}_l^{\delta} & \text{for} \quad (i-1)\delta < n \le i\delta, 3 \le i \le D-1 \end{cases} \quad (5)$$

$$\Gamma^{(i)}(n) = \begin{cases} \displaystyle\sum_{j=1}^{n} \mathbb{C}_j^{n} & \text{for} \quad 1 \le n \le \delta, i = 1 \\ \displaystyle\sum_{j=1}^{n} \mathbb{C}_j^{n} \Gamma^{(i-1)}(j) & \text{for} \quad 1 \le n \le \delta, 2 \le i \le D-1 \\ \displaystyle\sum_{j=0}^{\min\{\delta, i\delta-n\}} \mathbb{C}_j^{\delta} \Gamma^{(i-1)}(j+n-\delta) & \text{for} \quad \delta < n \le i\delta, 2 \le i \le D-1 \end{cases} \quad (7)$$

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$$\varphi_i \triangleq \Pr(S_{i+1}|S_i) = \Pr(\mathcal{C}_1) + \Pr(\mathcal{C}_2) + \Pr(\mathcal{C}_3) \quad (8)$$

$$= 1 - \sum_{n=1}^{i\delta} P_r^s(N_A = n)(1 - \Delta^{(i)}(n) - \Gamma^{(i)}(n)) \quad (9)$$

where $1 \leq i \leq D-1$. Let π_k be the steady-state probability of state S_k. Based on (9), the steady-state probability of state S_j is expressed as

$$\pi_j = \pi_1 \prod_{i=1}^{j-1} \varphi_i, \quad 2 \leq j \leq D \quad (10)$$

where π_1 is obtained by adopting the normalised condition $\sum_{l=1}^{D} \pi_l = 1$ as

$$\pi_1 = \frac{1}{1 + \sum_{j=2}^{D} \prod_{i=1}^{j-1} \varphi_i} \quad (11)$$

Therefore the average number of busy frames (T_B) can be acquired as

$$E[T_B] = \sum_{i=1}^{m} \pi_i i \quad (12)$$

It is worthwhile to mention that the proposed analytical model can also be applied to analyse the PSC II by replacing the number of state in Fig. 5 with T_L. In other words, the maximum number of busy frames is limited to the value of T_L in PSC II. It is because that all the buffered packets are dropped in the end of the predefined listening window regardless of the potential longer delay constraint.

4.2 Energy consumption

Let ε_B, ε_I and ε_S denote the energy consumption per frame under busy state, idle state and sleep state, respectively. As a result, the energy consumption for a connection can be obtained as

$$E_C = \varepsilon_B E[T_B] + \varepsilon_I E[T_I] + \varepsilon_S E[T_S] \quad (13)$$

where T_I and T_S denote the number of idle frames and sleep frames, respectively. For the proposed ALW approach, $E[T_I] = 0$ and $E[T_S] = T_C - E[T_B]$ since the MS immediately returns to the sleep state after the busy frames. The energy consumption of the ALW scheme (E_C^{ALW}) can be expressed as

$$E_C^{ALW} = (\varepsilon_B - \varepsilon_S)E[T_B] + \varepsilon_S T_C \quad (14)$$

For the PSC II, on the other hand, the average number of idle frames and sleep frames can be acquired as $E[T_I] = T_L - E[T_B]$ and $E[T_S] = T_C - T_L$, respectively. Therefore the energy consumption of PSC II (E_C^{PSC}) can be obtained as

$$E_C^{PSC} = (\varepsilon_B - \varepsilon_I)E[T_B^*] + (\varepsilon_I - \varepsilon_S)T_L + \varepsilon_S T_C \quad (15)$$

where $E[T_B^*]$ denotes the average number of busy frames for the PSC II.

5 Performance evaluation

In this section, the energy consumption of the PSC II and the proposed ALW approach derived from the analytical model are validated via simulations. Furthermore, extensive simulations with different traffic models are conducted to evaluate the performance of the proposed ALW approach in comparison with the PSC II mechanism for UGS connection and RT-VR connection, respectively. Single BS and one MS with a DL connection is considered in the simulation. In the PSC II, the length of the predefined listening window is generally set to achieve the transmission with required maximum bit rate. For the UGS connection, therefore, its value can be chosen as $T_L^U = \lceil(\lambda T_C)/\delta\rceil$, whereas $T_L^R = \lceil(2\lambda T_C)/\delta\rceil$ is considered for the RT-VR connection. The simulation is implemented via MATLAB even-driven simulator. Each obtained result is average from 100 simulation runs. The parameters adopted within the simulation are listed in Table 2, where the energy consumption parameters are acquired from an industrial manufactured mobile WiMAX chip [26].

Fig. 6 shows both simulation and analytical results of energy consumption over packet arrival rate for the proposed ALW approach and the PSC II mechanism. As illustrated in the figure, the analytical results are observed to coincide with the simulation outcomes. The detailed performance comparisons for the UGS connection and RT-VR connection are described as follows.

Table 2 Simulation parameters

Parameter	Value
frame duration	5 ms
energy consumption of busy frame	280 mW
energy consumption of idle frame	120 mW
energy consumption of sleep frame	10 mW
packet arrival rate (λ)	0.1, 0.2, 0.3, 0.4, 0.5 packets/frame
packet service rate (δ)	1, 2, 3, 4, 5 packets/frame
packet error probability (p)	0.01, 0.03, 0.05, 0.07, 0.09
length of sleep cycle (T_C)	30 frames
simulation time	10 min

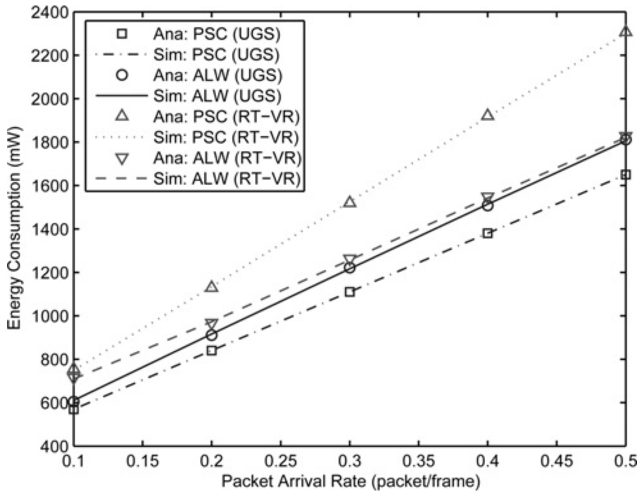

Figure 6 *Validation of analytical results: energy consumption against packet arrival rate*

5.1 Simulation results for UGS connection

Since the fixed-rate data are supported by UGS connections, the number of packet arrivals during each sleep cycle can be considered in the simulations as a deterministic value of λT_{C}. Figs. 7–9 show the performance comparisons of the UGS connection between the proposed ALW approach and the PSC II mechanism. The delay constraint for the UGS connection is shown within the parenthesis of each scheme. For example, ALW$(T_{\mathrm{L}}^{\mathrm{U}}+1)$ represents the ALW scheme for the UGS connection with delay constraint as the length of predefined listening window plus one frame. It is noted that same performance is obtained for the PSC II under different delay constraints because of the fixed-length listening window $T_{\mathrm{L}} \leq D$. Therefore the description of delay constraint for the PSC II is omitted.

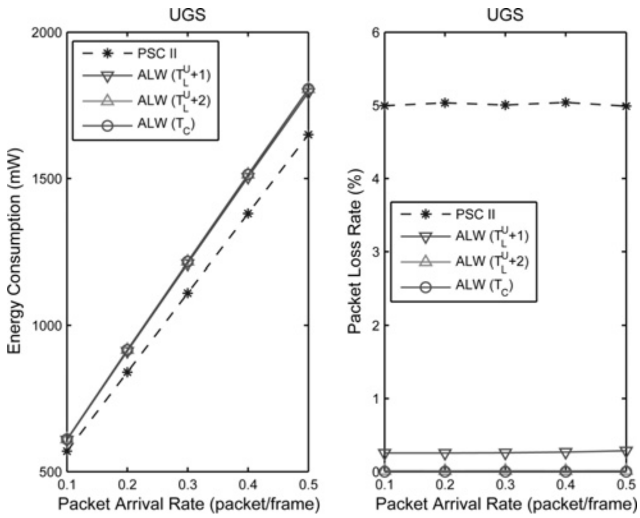

Figure 7 *Energy consumption and packet loss rate against packet arrival rate (λ) of UGS connection with p = 0.05 and δ = 3*

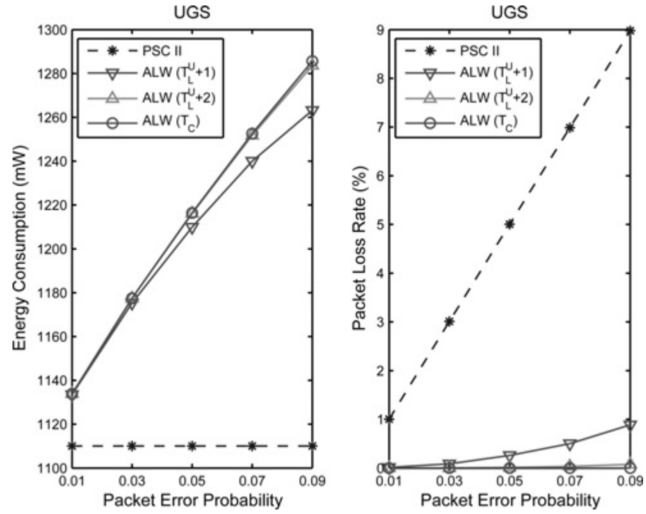

Figure 8 *Energy consumption and packet loss rate against packet error probability (p) of UGS connection with λ = 0.3 and δ = 3*

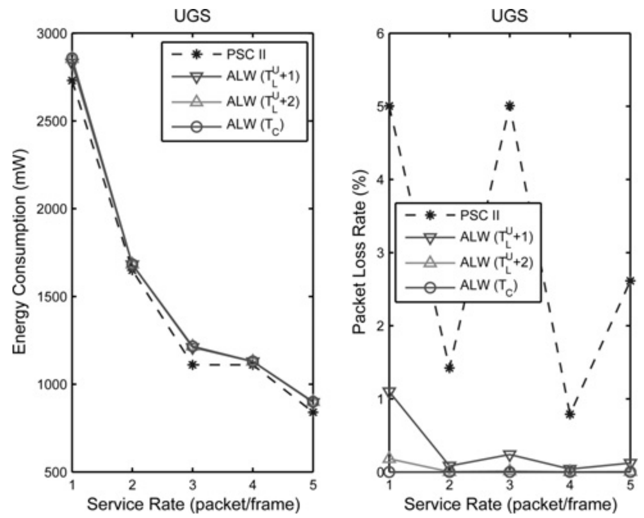

Figure 9 *Energy consumption and packet loss rate against packet service rate (δ) of UGS connection with λ = 0.3 and p = 0.05*

Fig. 7 illustrates the performance comparison for both energy consumption and packet loss rate over various packet arrival rate (λ). The energy consumption increases as the value of λ is augmented in both schemes. It is observed that the energy consumption of the proposed ALW scheme is slightly higher than that of the PSC II, which can be attributed to the lower packet loss rate of the ALW approach. In the PSC II, the length of the predefined listening window is set to consist with constant bit rate for the UGS connection. In case the transmission error is occurred, the corrupted packets will be dropped without consideration for retransmission, which leads to the high packet loss rate. On the other hand, the ALW approach increases the length of the listening window based on the number of buffered packets as well as the delay constraint.

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Therefore the energy consumption is slightly increased but the packet loss rate is significantly reduced. Furthermore, with the exploitation of the ALW scheme, lowered packet loss rate can be achieved if the delay constraint is increased.

In order to reflect the effect from various channel conditions resulted from either inter-cell interference or MS mobility, different packet error probabilities are considered in the simulations. The performance comparisons with an increasing probability of packet error (p) is shown in Fig. 8. As can be expected that the energy consumption of the PSC II is constant over various values of p, which is due to the fixed-length listening window. However, the packet loss rate of the PSC II increases significantly as the value of p is augmented. Comparing with the PSC II, the ALW approach incurs higher energy consumption, which primarily results from its lowered packet loss rate. Fig. 9 illustrates the performance comparisons with various values of service rate (δ). It can be observed that the energy consumption of the PSC II either decreases or remains constant as the value of λ is increased. The reason can be attributed to the length of predefined listening window $T_{\rm L}^{\rm U} = \lceil(\lambda T_{\rm C})/\delta\rceil$ determined by λ, $T_{\rm C}$ and δ. Given $\lambda = 0.3$ and $T_{\rm C} = 30$ in the simulation, for example, $T_{\rm L}^{\rm U} = 5, 3, 3$ can be derived under the cases of $\delta = 2, 3, 4$, respectively, which results in the same energy consumption of the PSC II for $\delta = 3$ and 4. On the other hand, more opportunities for packet transmission will lead to lower packet loss rate for a constant number of packets. Based on the example mentioned above, transmission opportunities $\delta T_{\rm L}^{\rm U} = 10, 9, 12$ are provided for the entire nine buffered packets under the case of $\delta = 2, 3, 4$, respectively. Therefore the packet loss rate of PSC II with $\lambda = 2$ is lower than that with $\lambda = 3$, and $\lambda = 4$ has the lowest one as shown in Fig. 9. As for the ALW scheme, it is expected that the energy consumption is slightly increased but the packet loss rate is significantly reduced in comparison with the PSC II.

5.2 Simulation results for RT-VR connection with Poisson distribution

In this subsection, the packet arrival process of the RT-VR connection is assumed to follow a Poisson process with rate λ. The performance comparisons between the proposed ALW approach and the PSC II mechanism are given in Figs. 10–12. The performance comparison with an increasing value of λ is shown in Fig. 10. In the PSC II, the length of the predefined listening window is set to achieve the transmission with required maximum bit rate for the RT-VR connection. Although it can provide opportunities for packet retransmission, the idle frames with unnecessary energy consumption is also produced in most cases. Moreover, packet loss can happen while the number of arrived packets is equal to the number of packets that can be served within the predefined listening window. On the other hand, the proposed ALW scheme will adaptively adjusts the length of the listening window based on the states of buffers as well as the delay constraint. Comparing with the PSC II,

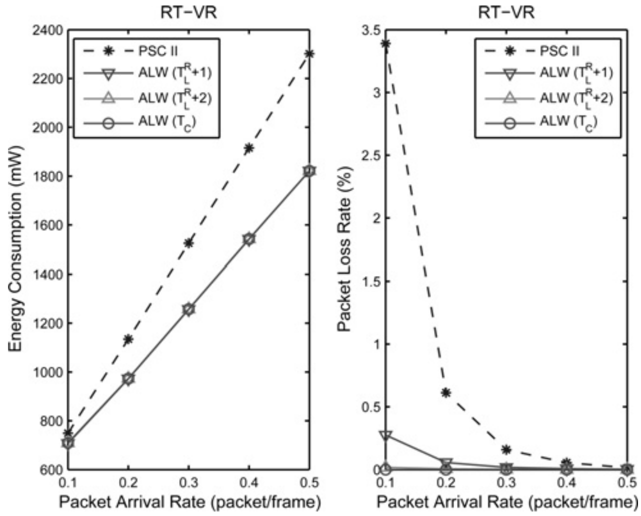

Figure 10 *Energy consumption and packet loss rate against packet arrival rate of RT-VR (λ) connection with $p = 0.05$ and $\delta = 3$*

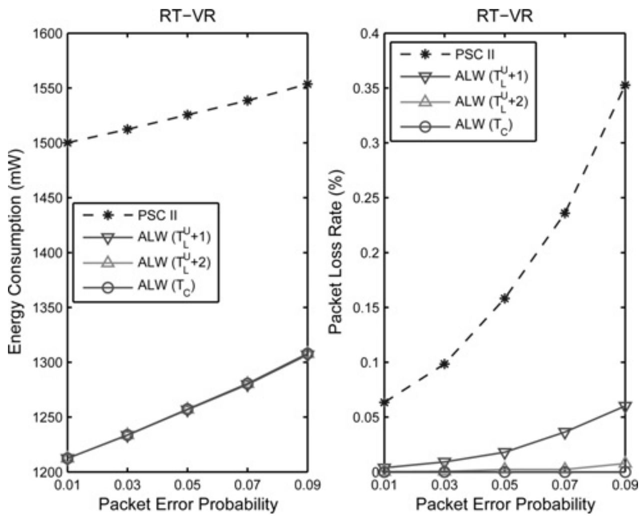

Figure 11 *Energy consumption and packet loss rate against packet error probability (p) of RT-VR connection with $\lambda = 0.3$ and $\delta = 3$*

lower energy consumption and lower packet loss rate are achieved by the ALW scheme. Figs. 11 and 12 illustrate the performance comparisons with various packet error probabilities and service rates, respectively. It can be expected that all the performance curves of the proposed ALW scheme outperform that of the PSC II mechanism, which can be explained by similar reasons as discussed in the previous subsection. The merits of the proposed ALW scheme can therefore be observed.

5.3 Simulation results for RT-VR connection with Gamma distribution

The effect of different traffic models on the performance of PSC II and ALW approach is discussed in this subsection.

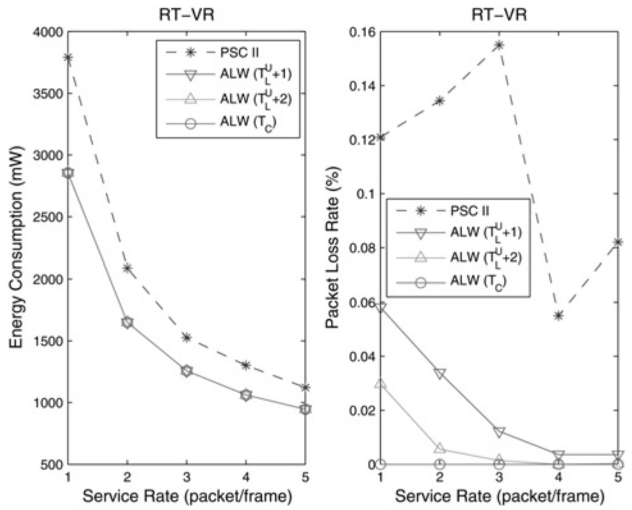

Figure 12 *Energy consumption and packet loss rate against packet service rate (δ) of RT-VR connection with λ = 0.3 and p = 0.05*

The Gamma distribution is considered as the distribution of packet inter-arrival time for the RT-VR connection since it has been well-adopted to model different types of random variables [27]. Let t_a denote the variable of packet inter-arrival time, whose probability density function with parameters $\alpha > 0$ and $\beta > 0$ can be defined as

$$f_{t_a}(t_a) = \frac{t_a^{\alpha-1}}{\Gamma(\alpha)\beta^{\alpha}} e^{-t_a/\beta} \quad \text{for } t_a \geq 0 \qquad (16)$$

where $\Gamma(\alpha)$ is the gamma function with shape parameter α, and β is the scale parameter to determine the mean packet inter-arrival time, that is, $1/\lambda = \alpha\beta$. It is noted that the Gamma distribution with $\alpha = 1$ presents the exponential distribution for packet inter-arrival time, which corresponds to the Poisson process for packet arrivals considered in the previous subsection.

Figs. 13–15 show the performance comparisons of the RT-VR connection with Gamma distribution between the proposed ALW approach and the PSC II mechanism. The performance comparison with the case of $\alpha = 0.5$ over various packet arrival rates and packet error probabilities is given in Figs. 13 and 14, respectively. As can be expected that all the cases by adopting the proposed ALW approach outperform the PSC II mechanism, which can be explained by similar reasons as discussed in the previous subsection. Fig. 15 depicts the performance comparisons with various α values. By observing the different cases using the ALW scheme, the energy consumption of $\alpha = 0.5$ is slightly lower than that from the other α values. However, relatively

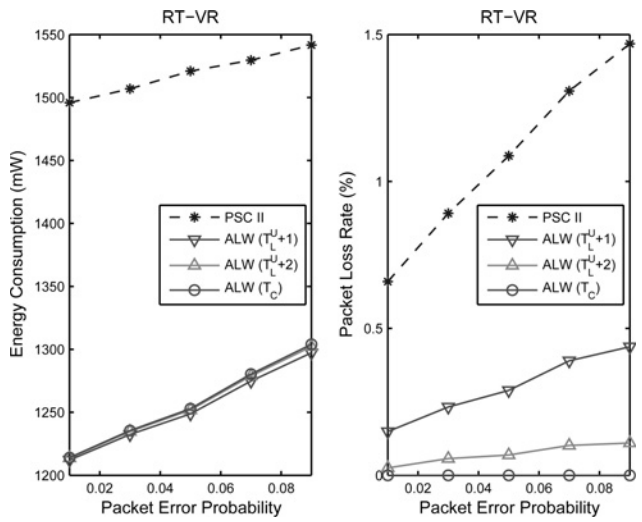

Figure 14 *Energy consumption and packet loss rate against packet error probability (p) of RT-VR connection with α = 0.5, λ = 0.3, and δ = 3*

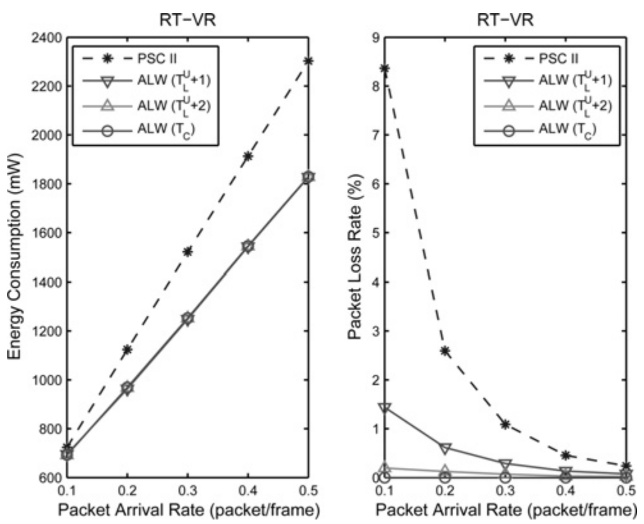

Figure 13 *Energy consumption and packet loss rate against packet arrival rate (λ) of RT-VR connection with α = 0.5, p = 0.05, and δ = 3*

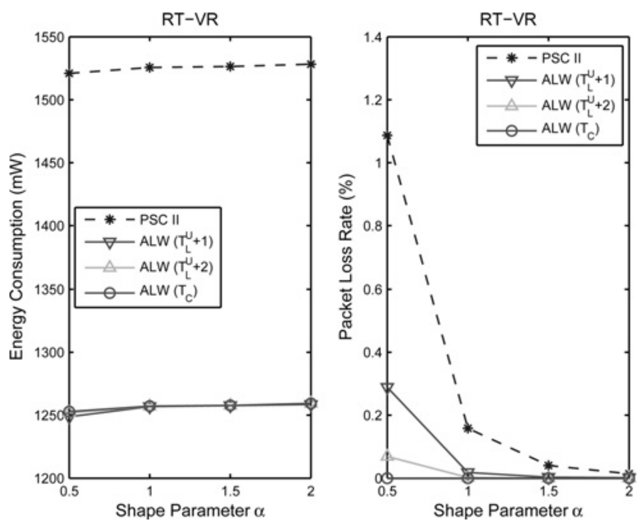

Figure 15 *Energy consumption and packet loss rate against shape parameter (α) of RT-VR connection with λ = 0.3, p = 0.05, and δ = 3*

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higher packet loss rate is obtained with the $\alpha = 0.5$ case, which can be attributed to the characteristics of Gamma distribution. For $\alpha < 1$, the traffic becomes non-smooth since the standard deviation of t_a is larger than its mean value. In this situation, larger variance in number of aggregated packets will be obtained from each sleep cycle. Since the maximum length of listening window is considered constant in each case, less energy consumption for the $\alpha = 0.5$ case will be acquired because of its potential small number of aggregated packets. On the other hand, higher packet loss rate will be obtained owing to the constant listening window size, which cannot accommodate the larger number of aggregated packets. For larger α values with the condition of $\alpha > 1$, the ratio of the standard deviation to the mean approaches zero, which results in the situation that t_a approaches a deterministic value $\alpha\beta$ and comparatively high energy consumption and low packet loss rate will be obtained. Finally, it can be observed that the performance of the ALW approach outperform that of the PSC II mechanism under different values of α. The merits of the proposed ALW scheme can therefore be observed.

6 Conclusions

In this paper, a power-saving mechanism with ALW is proposed for the power-saving classes of type II (PSC II) in IEEE 802.16e networks. The ALW scheme adaptively adjusts the length of each listening window based on both the buffered packets and delay constraint. Moreover, the concept of the ALW approach has recently been proposed by the authors and is adopted in the IEEE 802.16m standard draft. The energy consumption of the ALW and PSC II for UGS/RT-VR connection is evaluated and validated via both the numerical analysis and simulations. Simulation results show that the ALW scheme outperforms the PSC II for the RT-VR connection in terms of energy conservation. Furthermore, significant enhancement of packet loss rate for both the UGS and RT-VR connection is achieved by adopting the proposed ALW scheme.

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