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無線LAN環境におけるTCP Delayed ACKによる省電力効果の解析

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あらまし　無線通信の省電力化には無線デバイスの無通信時のスリープ動作が有効である．無線端末のパケット送受信タイミングは物理層及びデータリンク層プロトコルの挙動だけでは決定されず，アプリケーションが利用するトランスポート層プロトコルの挙動に強く依存する．効果的に消費エネルギーを削減するには，そのような上位層プロトコルの挙動を把握することが重要である．本報告では，Delayed ACK を利用して TCP レベルにおいて複数のパケットをまとめて転送 (バースト転送と呼ぶ) する方式を実現し，その省電力効果を明らかにする．消費エネルギーモデルを用いた解析により，Delayed ACK を利用したバースト転送によって消費エネルギーを 3/5 程度削減できることを示す．さらに，消費エネルギーを効果的に削減するために必要な無線 LAN デバイスの要素について議論し，スリープからの状態遷移にかかる電力を 0.1 W，その遷移時間を 100 μs 程度にできれば消費エネルギーを十分削減できることを示す．

キーワード　Transmission Control Protocol (TCP), 無線 LAN, 消費エネルギーモデル, 省電力

Energy Efficiency Analysis of TCP with Delayed ACK in a Wireless LAN Environment

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Abstract　The common strategy for energy saving of wireless network devices is to stay in sleep mode when no data is being transmitted or received. For effective energy saving, it is important to understand the relationships between the behaviors of the transport-layer protocols and energy efficiency. From the transport-layer viewpoint, it is effective to lengthen the idle interval by transmitting and receiving multiple packets successively in an RTT, which is called as *the burst transmission*. In this report, we analyze the energy consumption in TCP data transfer with the burst transmission of TCP over a wireless LAN. Through numerical results of our analysis, we reveal the burst transmission can reduce the energy consumption in TCP data transfer by an approximately three-fifth. We also discuss factors of WLAN devices for effective energy saving based on the analysis results.

Key words　Transmission Control Protocol (TCP), wireless LAN, energy consumption model, energy efficiency

1. Introduction

With recent developments in wireless network technologies, it is becoming increasingly common to access the Internet with such mobile devices as cellphones, smartphones, laptops and tablet PCs through IEEE 802.11-based wireless LANs (WLANs). As it is reported in [1–3], the wireless communications of a mobile device can account for approximately 10 % up to 50 % of its total energy consumption. Therefore, there is much interest in reducing the energy consumed by wireless communications, particularly because most mobile devices are battery-driven.

With regards to energy saving at MAC layer protocols, the IEEE 802.11 standard identifies a Power Saving Mode (PSM), whereas a normal mode referred to as the Continuously Active Mode (CAM). While in CAM, a wireless client always keeps its radio devices on. Thus, while network performance is high, the energy efficiency is low. In contrast, a wireless client in PSM enters sleep mode when no data is being transmitted or received and periodically wakes up to receive a beacon transmitted from an Access Point (AP). Although PSM can significantly reduce energy consumption, it can degrade network performance such as throughput and latency [4].

Several researchers have constructed energy consumption models for wireless clients in WLANs [5–7]. However, they mainly focus

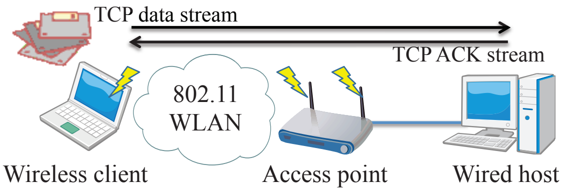


図 1 WLAN environment

on the behaviors at the MAC level and do not consider detailed TCP behaviors, even though TCP congestion control mechanisms mainly determine the timings of packet transmission and reception, which have a large impact on the energy efficiency of sleeping behaviors.

Therefore, for assessing the impact of TCP on energy consumption, we constructed a model for energy consumption in TCP data transfer over a WLAN, which is based on the detailed behaviors of TCP congestion control mechanisms [8]. One of the results of the analysis based on our model is that entering sleep mode at the inter-packet transmission/reception intervals at the sender successfully reduces roughly 40 % of the total energy consumption when the round trip time (RTT) is 100 ms and the probability of packet drop events in the wired networks is 0.01. We also pointed out that there is a possibility that the energy consumption is further reduced by changing the behaviors of transport-layer protocols. This means the modifications so that the wireless network interface (WNI) can the timings of TCP's packet transmission and reception to easily enter sleep mode at idle intervals.

In this report, we introduce *the burst transmission* of TCP-level behaviors, which lengthens each idle interval by transmitting multiple data segments successively in an RTT, to further reduce energy consumption in TCP data transfer. The burst transmission is achieved by changing parameters in the TCP delayed ACK [9]. As the first contribution of this report, we construct the mathematical model for energy consumption of TCP data transfer with burst transmission by extending the model in [8]. From the numerical results, we show the energy efficiency of the burst transmission and discuss the trade-off between energy efficiency and TCP performance. As the second contribution of this report, we discuss the factors of wireless network devices for efficient energy saving. Through the discussion, we present a design guideline for energy-efficient WNIs.

2. Network model and Assumptions

We assume a WLAN environment where a single wireless client associates with an AP connected with a wired host (Fig. 1). In the WLAN, we consider the wireless client sending a file of S_d bytes to the wired host by TCP; i.e., we consider an upstream TCP data transfer. Note that our model can be easily accommodated to a downstream TCP data transfer. In Sect. 3., we derive the energy consumption from when transmitting the first segment of the file until receiving the ACK segment for the last segment of the file. At the MAC level, we assume that RTS/CTS mechanisms are utilized by the wireless client when transmitting a frame to the AP, whereas the AP does not utilize RTS/CTS when transmitting a frame to the wireless client.

At the hardware level, we assume that a WNI has four communication modes: *transmit*, *receive*, *listen*, and *sleep*, each of which has a different power consumption [1]. Let P^t, P^r, P^l, and P^s denote the power consumptions in transmit, receive, listen, and sleep mode, respectively. Furthermore, the WNI consumes some power when transiting from and to active and sleep mode, so we define P^{as} and P^{sa} as power consumption for transiting from active mode to sleep mode and that from sleep mode to active mode, respectively.

The other assumptions are as follows:

- Frame collision does not occur in the WLAN, so no frames are lost at the MAC level.
- At the TCP level, the data segments are lost at probability of packet drop events in the wired networks, whereas any ACK segments are not lost in the network.
- The retransmission of data segments is not considered.
- Fast recovery mechanisms of TCP is not considered.
- When the delayed ACK is utilized, it has reported the problem to slowdown the growth of the TCP congestion window [10]. We assume that the problem is resolved in this report.
- Unless otherwise noted, we apply the same assumptions as in [11] for TCP's congestion control behavior.

3. Energy consumption models

In this section we construct an energy consumption model with *ideal sleeping* of TCP data transmission where the WNI enters sleep mode when no packet transmission or reception takes place. Here, ideal sleeping means that the WNI knows both the timings of transmission of TCP data segments and reception of TCP ACK segments such that it can enter and leave sleep mode at the exact timing. This means that, in order to enter the sleep mode avoiding an additional delay, the idle interval needs to be larger than $(T^{as} + T^{sa})$ where T^{as} represents a duration time for transiting from active mode to sleep mode, T^{sa} represents a duration time for transiting from sleep mode to active mode.

Based on the above discussion, we briefly summarize the energy consumption model with ideal sleeping, which constructed in [8], in Subsect. 3. 1. Then, we construct the model for energy consumption with both ideal sleeping and the burst transmission of TCP in Subsect. 3. 2. Subsection 3. 3 shows the data transfer latency of TCP with the burst transmission.

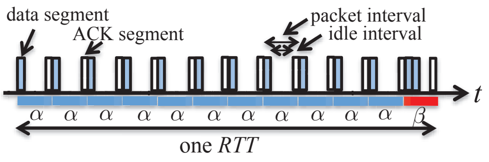
3.1 Modeling Energy Consumption in TCP Data Transfer with ideal sleeping

The model for energy consumption in [8] consists a mixture of a MAC-level and a TCP-level model. The MAC-level model derives energy consumptions in sending and receiving one data frame based on the frame exchange of CSMA/CA mechanisms. Consequently, we obtain J^t and J^r, which are the energy consumptions of the transmission and reception of one data frame, respectively. We omit the detailed explanation of the MAC-level model due to space limitation. On the other hand, the TCP-level model calculates the energy consumption in TCP data transfer by deriving inter-packet intervals of transmission/reception depending on the behaviors of the TCP congestion control mechanisms. It is constructed by combining two TCP phases: an initial slow start phase and a steady phase. The steady phase is further divided into two periods: a Triple Duplicate (TD) period and a TimeOut (TO) period. A TD period represents a duration between two packet loss events detected by triple duplicate ACK segments. A TO period represents a duration of a sequence of Retransmission TimeOuts (RTOs).

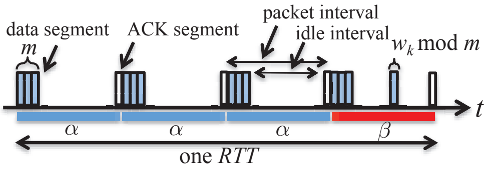
When the file size transmitted to the wired host is large enough, the data transfer in the initial slow start can be ignored. For this reason, we only explain the data transfer in the steady phase in this subsection. Let J^{ca} denote the energy consumption in the steady phase. By focusing on that TCP data transfer can be divided into *cycles* that consists of multiple TD periods and one TO period, J^{ca} can be calculated by multiplying the number of the cycles in the data transfer by the energy consumption in the cycle. J^{ca} is finally given by:

$$J^{ca} = (S_d/S_p - S_d^{ss}) \frac{J^{TD} + Q(E[W]) \cdot J^{TO}}{E[Y] + Q(E[W])E[R]} \qquad (1)$$

where S_p is the data segment size (bytes), S_d^{ss} is the expected number of segments sent in the initial slow start phase, $Q(w)$ is the probability of occurring TCP's timeout when a packet loss occurs. $E[W]$ is the expected window size (packets) with unlimited by the network bandwidth when the first segment loss occurs in a TD period. $E[Y]$ is the expected number of data segments sent in a TD period. $E[R]$ is the total number of data segment transmissions in a TO period. J^{TD} and J^{TO} are the expected energy consumption in a TD period and a TO period with ideal sleeping, respectively. Note that $Q(w)$, $E[W]$, $E[Y]$, and $E[R]$ are derived from TCP conges-



(a) $m = 1$



(b) $m = 3$

図 2　Packet sequences of TCP with the burst transmission in a TD period

tion control mechanisms [11].

J^{TD} can be calculated by adding all the energy consumed in each communication state of a WNI, including state transitions, in a TD period, which is finally derived in [8] as follows:

$$\begin{aligned} J^{TD} =& E[Y]J^t + (E[Y] - E[W]/2)J^r - P^l E[N^s_{td}](T^{as} + T^{sa}) \\ &+ P^l \left\{ E[A] - E[Y]T^t - (E[Y] - E[W]/2)T^r - E[T^s_{td}] \right\} \\ &+ P^s E[T^s_{td}] + E[N^s_{td}](P^{as}T^{as} + P^{sa}T^{sa}) \end{aligned} \quad (2)$$

where $E[A]$ is the expected total duration in a TD period, T^t is the duration of the wireless client sending one data frame, T^r is the duration of the wireless client receiving one data frame, $E[N^s_{td}]$ is the expected number of state transitions between active and sleep modes in a TD period, and $E[T^s_{td}]$ is the expected total duration of sleep mode in a TD period. $E[A]$, $E[N^s_{td}]$, and $E[T^s_{td}]$ are derived in [8].

$E[A]$ in [8] does not consider the case when the expected window size exceeds the bandwidth-delay product (BDP) of the wireless network. Since such situation usually occurs in a network where the probability of packet drop events is low, we extended the calculation of $E[A]$ to accommodate this problem. As a result, $E[A]$ can be derived as follows:

$$E[A] = \begin{cases} \left(\frac{E[W]}{2} + \frac{2E[W]-2}{E[W]} \right) RTT & \text{if } E[W] < W_{bdp} \\ \left(\frac{1-p}{pW_{bdp}} + \frac{E[W]}{W_{bdp}} + \frac{1}{8}(2W_{bdp} - E[W])^2 \right. & \\ \left. + 2\frac{E[W]-W_{bdp}}{E[W]} \right) RTT & \text{if } W_{bdp} \leqq E[W] < 2W_{bdp} \\ \left(\frac{1-p}{pW_{bdp}} + \frac{E[W]}{W_{bdp}} + 2\frac{E[W]-W_{bdp}}{E[W]} \right) RTT & \text{otherwise} \end{cases} \quad (3)$$

where RTT is the average round trip time of TCP without the delayed ACK, and W_{bdp} is the BDP (packets) of the network which is given by:

$$W_{bdp} = \min \left(\frac{RTT}{T^t + T^r}, \frac{W_{wire} \times 10^6}{8S_p} RTT \right) \quad (4)$$

where W_{wire} represents the bandwidth (Mbps) in the wired network.

3.2 Modeling Energy Consumption with the Burst Transmission

By extending the model in Subsect. 3.1, we derive a model for energy consumption with burst transmission. More specifically, we accommodate the burst transmission to the data transfer in TD periods of the steady phase. Note that the burst transmission is not utilized in a TO period because only one packet is transmitted at every occurrence of RTO.

We consider the packet sequence of TCP with the burst transmission where m packets are transmitted successively in the TD period, as depicted in Fig. 2. In a typical behavior of TCP congestion avoidance phase, a TCP sender sends new data segments when receiving ACK segments corresponded to unacknowledged data segments, as shown in Fig. 2(a), which means the data transmission when $m = 1$ without the burst transmission.

When the TCP's delayed ACK option is utilized, the TCP receiver sends an ACK segment after receiving multiple data segments. When receiving the ACK segment, the TCP sender can send successively new packets for the size of the acknowledged data segments. As a result, we obtain a sequence in packet transmissions and receptions, as depicted in Fig. 2(b), when m packets are transmitted successively with the burst transmission by using the delayed ACK. w_k is the window size in the k-th *round* in the TD period, which starts when the first segment of a window is transmitted and ends when the corresponding ACK segment is received. w_k can be calculated as follows based on the congestion avoidance phase in TCP behavior [11].

$$w_k = E[W]/2 + k - 1 \quad (5)$$

Note that we assume that the growth of w_k does not depend on the use of the delayed ACK. With the burst transmission, the TCP sends successively m packets $\lfloor w_k/m \rfloor$ times in the k-th round of the TD period when w_k can be divided by m. Otherwise, we assume that the TCP sends $(w_k \mod m)$ packets at the last transmission of the k-th round.

We first derive $J^{TD}(m)$ with the burst transmission. By using the delayed ACK, the number of ACK segments sent from the TCP receiver is smaller than that without the delayed ACK. More specifically, the number of the reductions of ACK segments in an RTT is calculated as follows. From Fig. 2, the number of the reductions is identical with the number of state transitions in an RTT. Here, according to [11], the average number of data segment discarded in a TD period is given by $E[W]/2$. Thus, the total number of ACK segments received in a TD period can be calculated by $(E[N^s_{td}] - E[W]/2)$. From the above discussion, we finally can obtain $J^{TD}(m)$ as follows:

$$\begin{aligned} J^{TD}(m) =& E[Y]J^t + (E[N^s_{td}] - E[W]/2)J^r - P^l E[N^s_{td}](T^{as} + T^{sa}) \\ &+ P^l \left\{ E[A] - E[Y]T^t - (E[N^s_{td}] - E[W]/2)T^r - E[T^s_{td}] \right\} \\ &+ P^s E[T^s_{td}] + E[N^s_{td}](P^{as}T^{as} + P^{sa}T^{sa}). \end{aligned} \quad (6)$$

We next derive $E[N^s_{td}]$ and $E[T^s_{td}]$ in Eq. (6). Here, we consider conditions for entering sleep mode at an idle interval. In order to derive this condition, we assume that packet intervals in an RTT are divided into two kinds of sub-intervals: multiple α intervals and a β interval, as shown in Fig. 2. Note that m data segments are sent and one ACK segment is received in each α interval, whereas $(w_k \mod m)$ data segments are sent and one ACK segment is received in the β interval.

By using α intervals and a β interval, we derive the conditions for entering sleep mode in the α interval and the β interval. In the k-th round of the TD period, the number of idle intervals is calculated by $\left\lceil \frac{w_{k-1}}{m} \right\rceil$. Assuming ACK segments are received equal intervals in an RTT, the length of an α interval and a β interval can be obtain as $RTT/\lceil w_{k-1}/m \rceil$. The idle interval in the α interval is calculated by $\left(RTT/\lceil w_{k-1}/m \rceil - mT^t - T^r \right)$ because m data segments are transmitted and one ACK segment is received in the α interval. We introduce $U^{\alpha}_{k,m}$, which is a unit function such that the value equals one when sleep mode can be utilized in the α interval.

$$U^{\alpha}_{k,m} = \begin{cases} 1 & \text{if } \frac{RTT}{\lceil w_{k-1}/m \rceil} - mT^t - T^r > T^{as} + T^{sa} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

On the other hand, $(w_k - m(\lceil w_{k-1}/m \rceil - 1))$ data segments are transmitted and one ACK segment is received in the β interval. Here, when the number of data segments sent in the β interval is larger than m, the data segments are transmitted $(\lceil w_k/m \rceil - \lceil w_{k-1}/m \rceil + 1)$ times. Note that, when $m = 1$, two data segments are transmitted successively in the β interval. From the above discussion, we introduce $U^{\beta}_{k,m}$, which is a unit function such that the value equals one when sleep mode can be utilized in the β interval.

$$U^{\beta}_{k,m} = \begin{cases} 1 & \text{if } m > 1 \text{ and} \\ & \frac{\frac{RTT}{\lceil w_{k-1}/m \rceil} - \left(w_k - m \left(\left\lceil \frac{w_{k-1}}{m} \right\rceil - 1 \right) \right) T^t - T^r}{\lceil w_k/m \rceil - \lceil w_{k-1}/m \rceil + 1} \\ & > T^{as} + T^{sa} \\ 1 & \text{if } m = 1 \text{ and} \\ & \frac{RTT}{w_{k-1}} - (w_k - w_{k-1} + 1)T^t - T^r > T^{as} + T^{sa} \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

By using Eqs. (7) and (8), we derive $E[N^s_{td}]$ with the burst transmission. Let $N^s_{k,m}$ denote the number of state transitions between active mode and sleep mode in the k-th round of the TD period, and r_{td} denote the round number where packet drop events occur in the TD period. By using $N^s_{k,m}$ and r_{td}, $E[N^s_{td}]$ can be obtained as $E[N^s_{td}] = \sum_{k=1}^{r_{td}+1} N^s_{k,m}$ where $r_{td} = E[W]/2$ which is derived in [8].

We next determine $N^s_{k,m}$. Since there are no α interval and one β interval in an RTT when $\lceil \frac{w_{k-1}}{m} \rceil = 1$, sleep mode can be utilized $\lceil w_k/m \rceil$ times in an RTT. Otherwise, there are $(\lceil \frac{w_{k-1}}{m} \rceil - 1)$ α intervals and one β interval in the TD period. Therefore, $N^s_{k,m}$ can be calculated as follows.

$$N^s_{k,m} = \begin{cases} U^\beta_{k,m} \left\lceil \frac{w_k}{m} \right\rceil & \text{if } \left\lceil \frac{w_{k-1}}{m} \right\rceil = 1 \\ U^\alpha_{k,m} \left(\left\lceil \frac{w_{k-1}}{m} \right\rceil - 1 \right) & \\ +U^\beta_{k,m} \left(\left\lceil \frac{w_k}{m} \right\rceil - \left\lceil \frac{w_{k-1}}{m} \right\rceil + 1 \right) & \text{otherwise} \end{cases} \tag{9}$$

Note that, when $m = 1$, $N^s_{k,1}$ is given as follows.

$$N^s_{k,1} = \begin{cases} U^\alpha_{k,1} w_{k-1} & \text{if } w_{k-1} = 1 \\ (w_{k-1} - 1) U^\alpha_{k,1} + U^\beta_{k,1} & \text{otherwise} \end{cases} \tag{10}$$

When sleep mode can be utilized in the r_{td}-th round of the TD period, sleep mode also can be utilized in the $(r_{td} + 1)$-th round. In this time, sleep mode can be utilized $\lceil E[W]/m \rceil$ times in an RTT. Thus, $N^s_{r_{td}+1,m}$ can be obtained as follows:

$$N^s_{r_{td}+1,m} = U^\alpha_{r_{td},m} \lceil E[W]/m \rceil . \tag{11}$$

In the following we derive $E[T^s_{td}]$ with the burst transmission. We denote the total sleep time in the k-th round of the TD period by $T^s_{k,m}$. In the same way as the calculation of $E[N^s_{td}]$, $E[T^s_{td}]$ can be derived by $E[T^s_{td}] = \sum_{k=1}^{r_{td}+1} T^s_{k,m}$.

We derive $T^s_{k,m}$ as follows. When $\lceil \frac{w_{k-1}}{m} \rceil = 1$, there is one β interval in the k-th round of the TD period. In this time, when $U^\beta_{k,m} = 1$, sleep mode can be utilized in the β interval. Otherwise, there are $\left(\lceil \frac{w_{k-1}}{m} \rceil - 1 \right)$ α intervals and one β interval in an RTT. By adding sleep time in these intervals in the round, we can obtain $T^s_{k,m}$ as follows.

$$T^s_{k,m} = \begin{cases} U^\beta_{k,m} \left(RTT - w_k T^t - T^r \right) & \\ \quad -N^s_{k,m} (T^{as} + T^{sa}) & \text{if } \left\lceil \frac{w_{k-1}}{m} \right\rceil = 1 \\ U^\alpha_{k,m} (\lceil w_{k-1}/m \rceil - 1) \left(\frac{RTT}{\lceil w_{k-1}/m \rceil} - m T^t - T^r \right) & \\ +U^\beta_{k,m} \left(\frac{RTT}{\lceil w_{k-1}/m \rceil} - \left(w_k - m \left(\lceil \frac{w_{k-1}}{m} \rceil - 1 \right) \right) T^t - T^r \right) & \\ -N^s_{k,m} (T^{as} + T^{sa}) & \text{otherwise} \end{cases} \tag{12}$$

In the $(r_{td} + 1)$-th round, $E[W]$ data segments are transmitted and $\lceil E[W]/m \rceil$ ACK segments are received. Therefore, $T^s_{r_{td}+1,m}$ can be obtained as follows.

$$\begin{aligned} T^s_{r_{td}+1,m} = & U^\alpha_{r_{td},m} \left(E[T^{TD}_{loss}] - \frac{E[W]}{2} T^t - \left\lceil \frac{E[W]}{m} \right\rceil T^r \right) \\ & - N^s_{r_{td}+1,m} (T^{as} + T^{sa}) \end{aligned} \tag{13}$$

where $E[T^{TD}_{loss}]$, which is given as follows, represents a duration in the $(r_{td} + 1)$-th round of the TD period:

$$E[T^{TD}_{loss}] = \begin{cases} RTT \frac{2E[W]-2}{E[W]} & \text{if } E[W] < W_{bdp} \\ RTT \frac{2E[W]-W_{bdp}}{E[W]} & \text{otherwise} \end{cases} \tag{14}$$

3.3 Increase in Data Transfer Latency by Burst transmission

In this subsection, we consider the opposite effect of burst transmission. That is, we calculate the increase in the data transfer latency with the burst transmission. The most of the calculation is based on the TCP latency model in [12]. When TCP delayed ACK is utilized, the TCP receiver waits to send an ACK segment until m data segments are received or the delayed ACK timer expires. This means that the delayed ACK has the disadvantage of increasing delay. Because of this, the burst transmission achieved by the delayed ACK increases the data transfer latency in the whole data transfer. More specifically, the latency of the whole data transfer can be obtained as follows.

表 1 WLAN parameters

Name	Values
Data rate	54 Mbps
Slot time	9 μs
SIFS	16 μs
DIFS	34 μs

Name	Values
PLCP preamble	16 μs
MAC header	24 bytes
LLC header	8 bytes
CW_{min}	15

表 2 Power consumption of Atheros AR5004 [13]

P^t	P^r	P^l	P^s
1.4 W	0.9 W	0.8 W	0.016 W

When the delayed ACK is utilized, the receiver sends an ACK segment after receiving m data segments. When the sender receives the ACK segment, it sends new m data segments successively. Since we assume that packet drops occur in the wired network and RTT is the round trip time of TCP without the delayed ACK, the transmission rate in the wired network is calculated by $E[W]/RTT$ (packet/s). Thus, in the worst case, the average interval between data segments arriving at the receiver becomes $RTT/E[W]$ (sec). Because the receiver waits to send the ACK segment from receiving the first data segment of m to receiving the m-th data segment, the RTT observed at the TCP sender is increased by $(m - 1)RTT/E[W]$ seconds. Therefore, the average RTT of TCP with delayed ACK is obtained as follows.

$$R\hat{T}T(m) = RTT + (m - 1) \frac{RTT}{E[W]} \tag{15}$$

By using Eq. (15) and the TCP latency model in [12], the expected latency $E[T](m)$ to send the whole data transfer can be calculated as follows.

$$E[T](m) = \frac{R\hat{T}T(m) \left(\frac{E[W]}{2} + 1 \right) + \frac{Q(E[W]) G(p) T_0}{1-p}}{\left(\frac{1-p}{p} + \frac{E[W]}{2} + Q(E[W]) \right) / \left(S_d/S_p - S^{ss}_d \right)} \tag{16}$$

where p is the probability of packet drop events in the wired network, T_0 is the average duration of the first timeout in the TO period, and $G(p)$ is given by:

$$G(p) = 1 + p + 2p^2 + 4p^3 + 8p^4 + 16p^5 + 32p^6 . \tag{17}$$

4. Numerical Analysis

4.1 Parameter Settings and Evaluation Metrics

We consider TCP data transfer of a 1 MB file from the wireless client to the wired host of Fig. 1, assuming an IEEE 802.11a WLAN. The WLAN parameters of IEEE 802.11a are summarized in Table 1. From a data sheet for a WNIC implementing the Atheros AR5004 chip [13], we set P^t, P^r, P^l, and P^s as shown in Table 2. According to [4], in which are conducted measurements of power consumption in a specific WNIC to determine the power consumption of transiting from active mode to sleep mode and vice versa, we set $P^{as} = P^l$ and $P^{sa} = P^t$. T^{as} and T^{sa} are set to 1 μs and 1 ms, respectively, following [14]. TCP data segment size and TCP ACK segment size are set to 1500 bytes and 40 bytes, respectively. The other parameters of our model are set as same as [8].

In Subsect. 4. 2, we evaluate the performance of the burst transmission of TCP from the viewpoint of two metrics: energy efficiency and the trade-off between energy efficiency and TCP performance. In order to evaluate the energy efficiency, we use the following metric which is calculated by using the energy consumption model with CAM in [8] and that with the burst transmission derived in Subsect. 3. 2. The metric, which is called as *energy consumption ratio*, is defined as follows:

$$R_{energy} = J^{ca}(m) / J^{ca}_{CAM} \tag{18}$$

where $J^{ca}(m)$ is the energy consumption with the burst transmission in the steady phase, and J^{ca}_{CAM}, which derived in [8], is energy consumption with CAM in the steady phase.

For trade-off evaluation between energy consumption and data transfer latency, we consider *latency ratio* which is calculated by dividing the latency in Eq. (16) and that when $m = 1$ as follows:

$$R_{latency} = E[T](m)/E[T](1). \tag{19}$$

4.2 Numerical Results

Figure 3 presents the distribution of the energy consumption ratio when changing RTT and the packet drop events (p) of the wired network. The x-axis and the y-axis in these figures represent p and RTT, respectively. Figure 3 shows that the energy efficiency significantly improves when RTT and p are large. As RTT and p decrease, the energy consumption ratio increases and it becomes larger than one. After that, it finally approaches one. The following is the reason for this. When RTT and p are large, the average window size is small and idle intervals are large. Therefore, the energy consumption is significantly reduced. On the other hand, as RTT and p decrease, idle intervals become short and the energy consumption of state transitions increases, finally resulting in that the energy consumption of state transitions exceeds the energy reduction of sleeping. Thus, the energy consumption with sleeping is larger than that with CAM. When RTT and p are further large, there are no idle intervals such that sleep mode is utilized.

By comparing Figs. 3(a) and 3(b), the energy consumption with the burst transmission is extensively small. Especially, the energy consumption significantly improves when RTT is small. On the other hand, when RTT is large, the energy consumption is reduced slightly. The reason for this is as follows. When RTT is small, the energy consumption of state transitions is relatively large because that accounts for a large portion of the total energy consumption. In contrast, when RTT is large, the energy consumption of state transitions is relatively small because that accounts for a small portion of the total energy consumption. Therefore, the reduction of the number of state transitions by the burst transmission is effective for reducing the energy consumption when RTT is small. Furthermore, we can see that the energy consumption ratio without the burst transmission is larger that with CAM when p and RTT is small to some extent, whereas the burst transmission alleviates the excessive energy consumption. This is because the burst transmission can reduce the number of state transitions.

Figure 4 shows the energy consumption ratio as a function of p with various values of m, when $RTT = 100$ ms. We can observe from this figure that, when p is 0.005, the normal ideal sleeping with $m = 1$ reduces the energy consumption by approximately 40 %. Furthermore, the burst transmission with $m = 5$ reduces the energy consumption by further 20 %. Although the energy efficiency becomes large as m increases, the additional amount of energy saving becomes small. This implies that sufficient energy efficiency can be obtained with small value of m.

In order to evaluate the trade-off between the energy efficiency and the data transfer latency, we present the relationships between the energy consumption ratio and the latency ratio as a function of m in Fig. 5. From Fig. 5, as m becomes large, the latency ratio increases linearly, whereas energy consumption ratio converges to a certain value. From this result and results of Fig. 4, we can conclude that the excessive m does not make sense for effective energy saving, and we should choose the value of m within the range of one to five.

We can also observe that, when p is 0.005, the latency ratios when $RTT = 50$ ms and $RTT = 100$ ms are almost identical. The reason for this as follows. When p is large to some extent, the first term of numerator in Eq. (16) is very small compared with the second term of numerator. Consequently, the latency ratio nearly equals to $(1 - (m - 1)/E[W])$, which is only affected by m and $E[W]$. Therefore, the latency ratio becomes independent of RTT.

From the above discussion, we can conclude as follows. When the packet loss event frequency is small, sleeping without the burst transmission is effective for energy efficiency. When the packet loss event frequency is larger, the burst transmission becomes more effective. However, as m becomes larger than around five, the further reduction of energy consumption becomes small while the latency ratio increases linearly. Therefore, the users or applications need to decide the value of m within the range of one to five as their required energy efficiency and acceptable latency.

5. WNI factors for energy saving

In this section, we discuss on factors of WNI parameters for effective energy saving considering the TCP behaviors. For that purpose, we compare to the amount of energy reduction when changing the WNI parameters.

We first derive the amount of energy reduction with sleeping in an RTT. Let J_{CAM}^{TD}, which is derived in [8], denote the energy consumption with CAM in the TD period. By taking the difference between $J^{TD}(m)$ in Eq. (6) and J_{CAM}^{TD}, the amount of energy reduction with sleeping in the TD period is obtained as follows.

$$\begin{aligned} J_{CAM}^{TD} - J^{TD}(m) =& (P^l - P^s)E[T_{td}^s] \\ & - E[N_{td}^s]\left(\left(P^{as} - P^l\right)T^{as} + \left(P^{sa} - P^l\right)T^{sa}\right) \end{aligned} \tag{20}$$

Here, for the sake of simplification, we assume that all the packet intervals depicted in Fig. 2 are regarded as α intervals. Therefore, $T_{k,m}^s$ in Eq. (12) and $N_{k,m}^s$ in Eq. (9) are simplified as follows.

$$\begin{aligned} \tilde{T}_{k,m}^s =& U_{k,m}^{\alpha} \left\lceil \frac{w_{k-1}}{m} \right\rceil \left(\frac{RTT}{\lceil w_{k-1}/m \rceil} - mT^t - T^r \right) \\ & - \tilde{N}_{k,m}^s (T^{as} + T^{sa}) \end{aligned} \tag{21}$$

$$\tilde{N}_{k,m}^s = U_{k,m}^{\alpha} \left\lceil \frac{w_{k-1}}{m} \right\rceil \tag{22}$$

By substituting Eqs. (21) and (22) into Eq. (20), we finally obtain the amount of energy reduction by sleeping in an RTT as follows.

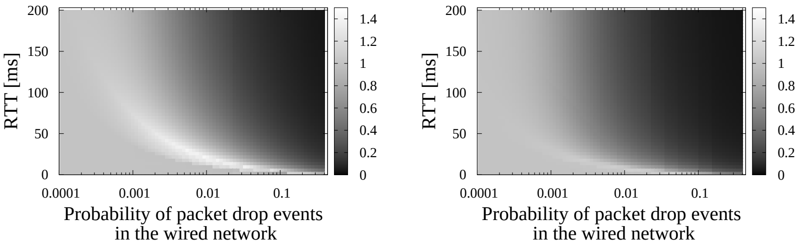
$$\begin{aligned} J^{cut} =& (P^l - P^s)\left(RTT - wT^t - \lceil w/m \rceil T^r\right) \\ & - \lceil w/m \rceil \left\{(P^{as} - P^s)T^{as} - (P^{sa} - P^s)T^{sa}\right\} \\ =& (P^l - P^s)T^{idle} - N^{st}\left\{(P^{as} - P^s)T^{as} - (P^{sa} - P^s)T^{sa}\right\} \end{aligned} \tag{23}$$

where w is the window size, T^{idle} is the total duration of idle intervals in an RTT, and N^{st} is the number of state transitions in an RTT.

In the following, we analyze the impact of the WNI parameters related to the energy consumption by varying one of them and the others are fixed. The WNI parameters except for the varied parameter are set as shown in Table 2.

Figures 6 and 7 present the amount of energy reduction when changing power consumption and transition time, respectively. The y-axis in these figures represent J^{cut} in Eq. (23) when the original value of the WNI parameter is increased by a factor of the value in x-axis. That is, when the value in x-axis is one, this figure shows the amount of energy reduction achieved with the original parameters of the AR5004 in Subsect. 4. 1. Note that T^{idle} and N^{st} are set to 100 ms and 20, respectively.

From Fig. 6, we can see that the amount of energy reduction is almost identical when changing P^s and P^{as}. This is because the original P^s is already small enough compared to P^l, and P^{as} hardly affects the energy reduction since 1 μs of T^{as} is very short. In contrast, as P^{sa} decreases, the energy reduction increases and it is almost identical when P^{sa} is smaller than one-tenth of the original value of P^{sa}. That is, the sufficient energy reduction can be obtained by reducing P^{sa} to one-tenth, which corresponds to around 0.1 W. Likewise, from Fig. 7, we can see that the energy reduction is almost identical as T^{as} decreases, whereas that increases as T^{sa} decreases and the sufficient energy reduction can be obtained when T^{sa} is smaller than one-tenth, which corresponds to around 100 μs, in common with P^{sa}. Furthermore, by comparing with Fig. 6 and 7, we can also see that the curves of P^{sa} and T^{sa} are almost identical. This is because the term $(P^{sa} - P^s)T^{sa}$ in Eq. (23) can be



(a) $m = 1$ (b) $m = 5$

図 3 Energy efficiency when changing RTT and probability of packet drop events

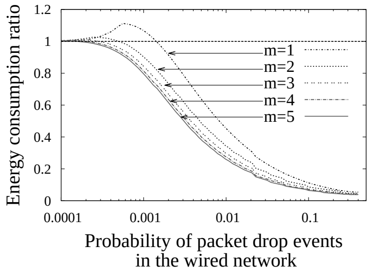


図 4 Energy efficiency of the burst transmission when $RTT = 100$ ms

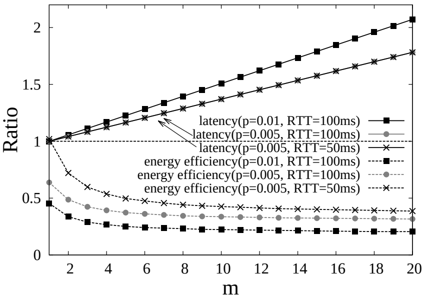


図 5 Trade-off between energy efficiency and latency

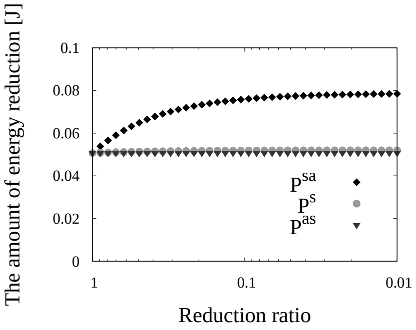


図 6 Energy reduction when changing power consumption

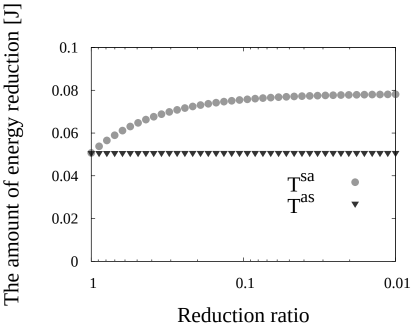


図 7 Energy reduction when changing transition time

regarded as $P^{sa}T^{sa}$ since P^s is very small. This means that, for further energy reduction, it is only necessary to reduce $P^{sa}T^{sa}$ to one-tenth by reducing P^{sa} and T^{sa}.

From the above results, we can conclude that WNIs which have similar parameters of AR5004 can save energy sufficiently by reducing the energy consumption of state transitions from sleep mode to active mode to one-tenth.

6. Conclusion

In this report we proposed a new model for energy consumption with the burst transmission in TCP data transfer over a wireless LAN environment. The burst transmission is realized by using the TCP delayed ACK. From the numerical results based on our model, we showed that, when packet loss event frequency is small, sleeping without the burst transmission is effective for energy saving. When the packet loss event frequency is larger, the burst transmission becomes more effective. Furthermore, even when RTT is small such that sleep mode without the burst transmission is ineffective for energy saving, the burst transmission can save the energy. We also reveled that WNIs which have similar parameters of AR5004 can save energy sufficiently by reducing the energy consumption of state transitions from sleep mode to active mode to one-tenth.

In the future, we plan to consider frame losses and collisions due to the existence of multiple wireless clients, and evaluate its impact for energy efficiency of the burst transmission. After that, we also plan to work out a transport architecture for energy saving based on the burst transmission.

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