Energy Efficiency Analysis of TCP with Burst Transmission over a Wireless LAN

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***Abstract*—A common strategy for energy saving for wireless network devices is to stay in sleep mode for as long as possible when no data is being transmitted or received. The timings of packet transmission and reception are not determined only by the behavior at the physical and the data link layers; they strongly depend on the behavior of the transport-layer protocols used by upper-layer applications. For effective energy saving, therefore, it is important to understand the relationships between the behavior of the transport-layer protocols and energy efficiency. One effective method for lengthening the idle interval is by transmitting and receiving multiple packets in groups, which is called *burst transmission*. In this paper, we analyze the energy consumption of TCP data transfer with burst transmission over a wireless LAN. By comparing the energy consumption with and without burst transmission, we show that burst transmission can reduce the energy consumption in TCP data transfer by approximately 60 %. We also discuss which part of wireless LAN devices should be improved for effective energy saving.**

***Index Terms*—Transmission Control Protocol (TCP), wireless LAN, energy consumption model, energy efficiency**

I. Introduction

With recent developments in wireless network technologies, it is becoming increasingly common to access the Internet with mobile devices, such as cellular phones, smartphones, laptops, and tablet PCs, through IEEE 802.11-based wireless LANs (WLANs). The wireless communications of a mobile device can account for approximately 10 to 50 % of its total energy consumption [1]–[3]. 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 in MAC layer protocols, the IEEE 802.11 standard defines a Power Saving Mode (PSM), whereas the normal mode is referred to as the Continuously Active Mode (CAM). 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 characteristics, such as throughput and latency [4].

Several researchers have proposed energy-efficient methods in WLANs [4], [5]. The authors in [4] propose a Bounded Slow Down (BSD) protocol, which is a MAC-level method addressing the trade-off between reducing energy consumption and alleviating the increase in response delay. This protocol is aimed at situations where wireless clients spend a lot of time on idle state. In [5], the authors present a client-centered method in TCP over WLANs with burst transmission realized by manipulating the TCP receiver's window size. They show that the proposed method can save 21 % energy compared to PSM through some experiments where a WLAN environment is emulated.

Other researchers have constructed energy consumption models for WLAN clients [6]–[8]. However, they mainly focus on the behavior at the MAC level and do not consider detailed TCP behavior, 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 behavior.

We have constructed an energy consumption model for TCP data transfer over a WLAN, which is based on the detailed behavior of TCP congestion control mechanisms [9]. One of the results of the analysis based on our model is that entering sleep mode during the inter-packet transmission/reception intervals at the sender reduces the total energy consumption by roughly 40 % 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 discovered that changing the behavior of transport-layer protocols might further reduce energy consumption. This means modifying the timings of TCP packet transmission and reception so that the wireless network interface (WNI) can easily enter sleep mode during idle intervals.

In this paper, we introduce TCP-level *burst transmission*, which lengthens each idle interval by transmitting multiple data segments in groups, to further reduce energy consumption in TCP data transfer. Burst transmission is achieved by changing parameters in the TCP delayed ACK [10]. As the first contribution of this paper, a mathematical model is constructed of energy consumption for TCP data transfer with burst transmission by extending the model in [9]. Note that we present analysis results for energy efficiency of burst transmission based on the energy consumption models, which differ from [5]. Using numerical results from this model, we demonstrate the energy efficiency of burst transmission and discuss the trade-off between energy efficiency and TCP performance. As the second contribution of this paper, the factors contributing to efficient energy saving in wireless network devices are discussed. Based on this discussion, a design guideline for energy-efficient WNIs is presented.

In this paper, we discuss energy consumption of a WNI device only based on analysis models, assuming simple WLAN situation. Because our purpose for this paper is revealing how the TCP behavior affects energy efficiency, assuming simple situation is enough to make it clear and more complicated situations are not always necessary for the purpose. On the other hand, even though our models are not validated by any simulations or test-beds, we believe that our models have enough validity. This is because both the MAC-level and the TCP-level models are based on well-validated models; the MAC-level model considers different communication modes of a WNI which are considered in other analysis models [6]–[8] and the TCP-level model follows the detailed behavior in TCP analysis models [11], [12]. Note that our model is not appropriate to model energy consumption of TCP data transfer when RTT fluctuation is large, according to results

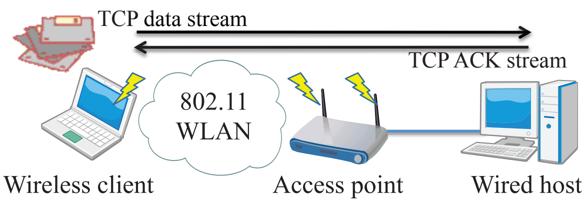


Fig. 1. WLAN environment

in [11], [12]. Of course, we are well aware the importance of realization of the cooperation from transport-layer protocols for further energy reduction and its validation in real wireless environments, which are subjects of future investigation.

The remainder of this paper is organized as follows. In Sect. II, the network model and assumptions are described. We introduce our model for energy consumption in a WLAN in Sect. III. Section IV contains the results of the numerical analysis based on our model. In Sect. V, we discuss factors contributing to energy efficiency. Finally, conclusions and a discussion of future research are presented in Sect. VI.

II. 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 assume that the wireless client sends a file of S_d bytes to the wired host by TCP: that is, we consider upstream TCP data transfer. Note that our model can be easily adjusted to deal with downstream TCP data transfer. In Sect. III, we derive the energy consumption from the transmission of the first segment of the file until the reception of the ACK segment for the last segment of the file. At the MAC level, we assume that the wireless client utilizes RTS/CTS mechanisms 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 modes, respectively. Furthermore, the WNI consumes some power when transiting from and to active and sleep modes, so we define P^{as} and P^{sa} as the 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 with a probability equal to that of packet drop events in the wired networks, whereas no ACK segments are lost.
- The retransmission of data segments is not considered.
- Fast recovery mechanisms of TCP are not considered.
- When the delayed ACK is utilized, it has been reported that the growth of the TCP congestion window is inhibited [13]. In this paper, we assume that this problem has been resolved.
- Unless otherwise noted, we apply the same assumptions as in [11] for TCP congestion control behavior.

III. Energy consumption models

In this section we describe an energy consumption model of TCP data transmission with *ideal sleeping* where the WNI enters sleep mode when no packet transmission or reception takes place. Here, ideal sleeping means that the WNI knows the timings of both the transmission of TCP data segments and the reception of TCP ACK segments, so that it can enter and leave sleep mode with exact timing. This means that, in order to enter the sleep mode without an additional delay, the idle interval needs to be larger than $(T^{as}+T^{sa})$, where T^{as} is the duration for transiting from active mode to sleep mode, and T^{sa} is the duration for transiting from sleep mode to active mode.

Based on the above discussion, in Subsect. III-A we briefly summarize the energy consumption model with ideal sleeping that was constructed in [9]. Then, we describe our model for energy consumption with both ideal sleeping and TCP burst transmission in Subsect. III-B. In Subsect. III-C we discuss the data transfer latency of TCP with burst transmission.

A. Modeling Energy Consumption in TCP Data Transfer with Ideal Sleeping

The model for energy consumption in [9] is a mixture of a MAC-level model and a TCP-level model. The MAC-level model derives energy consumptions for sending and receiving one data frame based on the frame exchange of CSMA/CA mechanisms. The energy consumptions of the transmission and reception of one data frame are denoted by J^t and J^r, respectively. We omit the detailed explanation of the MAC-level model due to limitations of space. 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 behavior 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 is the duration between two packet loss events detected by triple duplicate ACK segments. A TO period is the duration of a sequence of Retransmission TOs (RTOs).

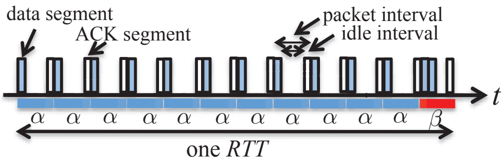
When the file size transmitted to the wired host is large enough, data transfer in the initial slow start phase can be ignored. For this reason, we only consider the data transfer in the steady phase in this subsection. Let J^{ca} denote the energy consumption in the steady phase. By focusing on the fact 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 cycles in the data transfer by the energy consumption in the cycle. So J^{ca} is finally given by

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

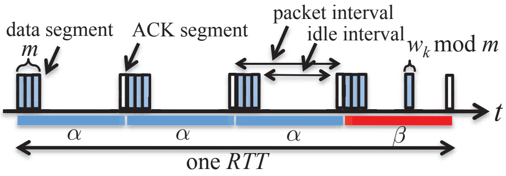
where S_p is the data segment size (bytes), S_d^{ss} is the expected number of segments sent in the initial slow start phase, $Q(w)$ is the probability of a TCP timeout when packet loss occurs, $E[W]$ is the expected window size (packets) for unlimited network bandwidth when the first segment loss occurs 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, and 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 the TCP congestion control mechanisms [11].

J^{TD} can be calculated by adding all the energy consumed in each communication state of a WNI, including state transitions, during a TD period, which is finally derived in [9] as follows.

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



(a) $m = 1$



(b) $m = 3$

Fig. 2. Packet sequences of TCP with burst transmission in a TD period

where $E[A]$ is the expected total duration of a TD period, T^t is the time it takes the wireless client to send one data frame, T^r is the time it takes the wireless client to receive one data frame, $E[N_{td}^s]$ is the expected number of state transitions between active and sleep modes in a TD period, and $E[T_{td}^s]$ is the expected total duration spent in sleep mode during a TD period. $E[A]$, $E[N_{td}^s]$, and $E[T_{td}^s]$ are derived in [9].

B. Modeling Energy Consumption with Burst Transmission

By extending the model in Subsect. III-A, we derive a model for energy consumption with burst transmission. More specifically, we incorporate burst transmission into the data transfer in TD periods of the steady phase. Note that 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 burst transmission where m packets are transmitted successively in the TD period, as depicted in Fig. 2. In a typical behavior of the TCP congestion avoidance phase, a TCP sender transmits new data segments when receiving ACK segments corresponding to unacknowledged data segments (see Fig. 2(a), which shows the data transmission when $m = 1$, that is, without burst transmission).

When the TCP 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 consecutive new packets that vary according the size of the acknowledged data segments. As a result, we obtain a sequence of packet transmissions and receptions like that depicted in Fig. 2(b). In this way, burst transmission can be realized by modifying the parameter of the delayed ACK of the TCP receiver. 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, is denoted by w_k. The window size can be calculated based on the congestion avoidance phase in TCP behavior [11]:

$$w_k = E[W]/2 + k - 1 \tag{3}$$

Note that we assume that the growth of w_k does not depend on the use of the delayed ACK. With burst transmission, the TCP consecutively sends 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 in the last transmission of the k-th round.

We first derive $J^{TD}(m)$ with 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. The reduction of ACK segments in an RTT is calculated as follows. From Fig. 2, the number of the reductions is identical with that of state transitions in an RTT. Here, according to [11], the average number of data segments discarded in a TD period is given by $E[W]/2$. Thus, the total number of ACK segments received in a TD period is given by $(E[N_{td}^s] - E[W]/2)$. From the above discussion, we finally can obtain

$$\begin{aligned} J^{TD}(m) =& E[Y]J^t + (E[N_{td}^s] - E[W]/2)J^r - P^l E[N_{td}^s](T^{as} + T^{sa}) \\ &+ P^l \left\{ E[A] - E[Y]T^t - (E[N_{td}^s] - E[W]/2)T^r - E[T_{td}^s] \right\} \\ &+ P^s E[T_{td}^s] + E[N_{td}^s](P^{as}T^{as} + P^{sa}T^{sa}). \end{aligned} \tag{4}$$

Next, we derive $E[N_{td}^s]$ and $E[T_{td}^s]$ in Eq. (4). In order to determine the conditions for entering sleep mode at an idle interval, we assume that packet intervals in an RTT are divided into two types 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.

In the k-th round of the TD period, the number of idle intervals is $\lceil \frac{w_{k-1}}{m} \rceil$. Assuming ACK segments are received at equal intervals in an RTT, the length of α or β intervals is $RTT/\lceil w_{k-1}/m \rceil$. The idle interval in the α interval is $(RTT/\lceil w_{k-1}/m \rceil - mT^t - T^r)$ because m data segments are transmitted and one ACK segment is received. We introduce $U_{k,m}^{\alpha}$, which is an indicator function whose the value equals one when sleep mode can be utilized in the α interval:

$$U_{k,m}^{\alpha} = \begin{cases} 1 & \text{if } \frac{RTT}{\lceil w_{k-1}/m \rceil} - mT^t - T^r > T^{as} + T^{sa} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

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 consecutively in the β interval. We introduce $U_{k,m}^{\beta}$, which is an indicator function whose value equals one when sleep mode can be utilized in the β interval.

$$U_{k,m}^{\beta} = \begin{cases} 1 & \text{if } m > 1 \text{ and} \\ & \frac{\frac{RTT}{\lceil w_{k-1}/m \rceil} - \left(w_k - m\left(\left\lceil \frac{w_{k-1}}{m} \right\rceil - 1\right)\right)T^t - T^r}{\lceil w_k/m \rceil - \lceil w_{k-1}/m \rceil + 1} \\ & > T^{as} + T^{sa} \\ 1 & \text{if } m = 1 \text{ and} \\ & \frac{RTT}{w_{k-1}} - (w_k - w_{k-1} + 1)T^t - T^r > T^{as} + T^{sa} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

By using Eqs. (5) and (6), we derive $E[N_{td}^s]$ with burst transmission. Let $N_{k,m}^s$ denote the number of state transitions between active mode and sleep mode in the k-th round of the TD period, and let r_{td} denote the round number in which packet drop events occur in the TD period. Then $E[N_{td}^s]$ is given by $E[N_{td}^s] = \sum_{k=1}^{r_{td}+1} N_{k,m}^s$ where we have used the relation $r_{td} = E[W]/2$, which is derived in [9].

Next, we determine $N_{k,m}^s$. Since there are no α intervals 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, $N_{k,m}^s$ can be calculated as follows.

$$N_{k,m}^s = \begin{cases} U_{k,m}^{\beta} \left\lceil \frac{w_k}{m} \right\rceil & \text{if } \left\lceil \frac{w_{k-1}}{m} \right\rceil = 1 \\ U_{k,m}^{\alpha} \left(\left\lceil \frac{w_{k-1}}{m} \right\rceil - 1 \right) & \\ + U_{k,m}^{\beta} \left(\left\lceil \frac{w_k}{m} \right\rceil - \left\lceil \frac{w_{k-1}}{m} \right\rceil + 1 \right) & \text{otherwise} \end{cases} \tag{7}$$

Note that, when $m = 1$, $N_{k,1}^s$ is given by

$$N_{k,1}^s = \begin{cases} U_{k,1}^{\alpha} w_{k-1} & \text{if } w_{k-1} = 1 \\ (w_{k-1} - 1)U_{k,1}^{\alpha} + U_{k,1}^{\beta} & \text{otherwise} \end{cases} \tag{8}$$

When sleep mode can be utilized in the r_{td}-th round of the TD period, sleep mode can also 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, $N^s_{r_{td}+1,m}$ is given by

$$N^s_{r_{td}+1,m} = U^{\alpha}_{r_{td},m} \lceil E[W]/m \rceil . \tag{9}$$

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

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 the sleep times in these intervals over the round, we obtain

$$T^s_{k,m} = \begin{cases} U^{\beta}_{k,m}\left(RTT - w_k T^t - T^r\right) \\ \quad - N^s_{k,m}(T^{as} + T^{sa}) & \text{if } \lceil \frac{w_{k-1}}{m} \rceil = 1 \\ U^{\alpha}_{k,m}(\lceil w_{k-1}/m \rceil - 1)\left(\frac{RTT}{\lceil w_{k-1}/m \rceil} - mT^t - T^r\right) \\ +U^{\beta}_{k,m}\left(\frac{RTT}{\lceil w_{k-1}/m \rceil} - \left(w_k - m\left(\lceil \frac{w_{k-1}}{m} \rceil - 1\right)\right) T^t - T^r\right) \\ -N^s_{k,m}(T^{as} + T^{sa}) & \text{otherwise} \end{cases} \tag{10}$$

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

$$\begin{aligned} T^s_{r_{td}+1,m} =& U^{\alpha}_{r_{td},m}\left(E[T^{TD}_{loss}] - \frac{E[W]}{2}T^t - \left\lceil \frac{E[W]}{m} \right\rceil T^r\right) \\ &- N^s_{r_{td}+1,m}(T^{as} + T^{sa}) \end{aligned} \tag{11}$$

where $E[T^{TD}_{loss}]$ is the duration of the $(r_{td}+1)$-th round of the TD period

$$E[T^{TD}_{loss}] = \begin{cases} RTT\frac{2E[W]-2}{E[W]} & \text{if } E[W] < W_{bdp} \\ RTT\frac{2E[W]-W_{bdp}}{E[W]} & \text{otherwise} \end{cases} \tag{12}$$

C. Increase in Data Transfer Latency by Burst Transmission

In this subsection, we consider a disadvantage of burst transmission—the increase in the data transfer latency. 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. Because of this, burst transmission achieved by the delayed ACK increases the latency in the whole data transfer.

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 m new data segments consecutively. 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 $E[W]/RTT$ (packet/s). Thus, the average interval between data segments arriving at the receiver becomes $RTT/E[W]$ (s). 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.

$$\hat{RTT}(m) = RTT + (m-1)\frac{RTT}{E[W]} \tag{13}$$

By using Eq. (13) and the TCP latency model in [12], the expected latency $E[T](m)$ for the whole data transfer can be calculated as follows.

$$E[T](m) = \frac{\hat{RTT}(m)\left(\frac{E[W]}{2} + 1\right) + \frac{Q(E[W])G(p)T_0}{1-p}}{\left(\frac{1-p}{p} + \frac{E[W]}{2} + Q(E[W])\right) / \left(S_d/S_p - S^{ss}_d\right)} \tag{14}$$

TABLE I
WLAN PARAMETERS

Name	Values	Name	Values
Data rate	54 Mbps	PLCP preamble	16 μs
Slot time	9 μs	MAC header	24 bytes
SIFS	16 μs	LLC header	8 bytes
DIFS	34 μs	CW_{min}	15

TABLE II
POWER CONSUMPTION OF ATHEROS AR5004 [14]

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

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

$$G(p) = 1 + p + 2p^2 + 4p^3 + 8p^4 + 16p^5 + 32p^6. \tag{15}$$

IV. NUMERICAL ANALYSIS

A. 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 I. From a data sheet for a WNI implemented using the Atheros AR5004 chip [14], we set P^t, P^r, P^l, and P^s to the values shown in Table II. Following [4], in which measurements of power consumption in a specific WNI were conducted 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 [15]. The 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 to the values given in [9].

In Subsect. IV-B, we evaluate the performance of TCP burst transmission using two metrics: energy efficiency and the trade-off between energy efficiency and TCP latency. In order to evaluate the energy efficiency, we use the *energy consumption ratio* defined as

$$R_{energy} = J^{ca}(m)/J^{ca}_{CAM} \tag{16}$$

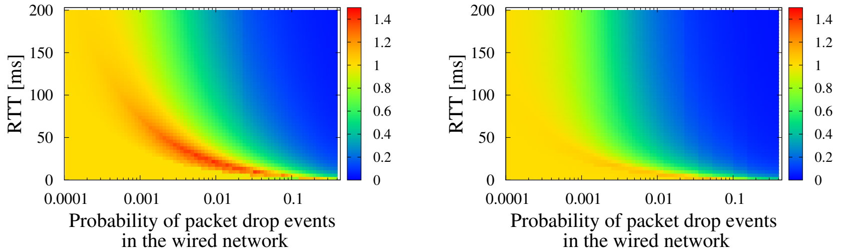
where $J^{ca}(m)$ is the steady-phase energy consumption with burst transmission in the model derived in Subsect. III-B and J^{ca}_{CAM}, which is derived in [9], is the steady-phase energy consumption with CAM.

For the evaluation of the trade-off between energy consumption and data transfer latency, we use the *latency ratio* that is calculated by dividing the latency in Eq. (14) by that when $m = 1$:

$$R_{latency} = E[T](m)/E[T](1). \tag{17}$$

B. Numerical Results

Figure 3 shows the distribution of the energy consumption ratio as a function of RTT and the probability (p) of packet drop events in the wired network. Figure 3 shows that the energy efficiency improves significantly when RTT and p are large. As RTT and p decrease, the energy consumption ratio increases and, eventually, it becomes larger than one. After that, it finally approaches one. The reason for this is that, 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 shorter and the energy consumption of state transitions increases, until the energy consumption of state transitions exceeds the energy reduction from sleeping. Thus, the energy consumption with



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

Fig. 3. Energy efficiency as a function of RTT and the probability of packet drop events

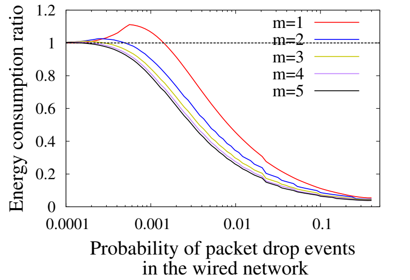


Fig. 4. Energy efficiency of burst transmission when $RTT = 100$ ms

sleeping is larger than that with CAM. When RTT and p are even larger, there are no idle intervals and sleep mode is not utilized.

By comparing Figs. 3(a) and 3(b), the energy consumption is reduced with burst transmission. In particular, the energy consumption is significantly improved when RTT is small. On the other hand, when RTT is large, the energy consumption is reduced only slightly. The reason for this is as follows. When RTT is small, the energy consumption of state transitions is relatively large and 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 and that accounts for only a small portion of the total energy consumption. Therefore, the reduction of the number of state transitions by burst transmission is effective for reducing the energy consumption only when RTT is small. Furthermore, we see that the energy consumption ratio with ideal sleeping but without burst transmission ($m = 1$) is slightly larger that with CAM when p and RTT are small.

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

In order to evaluate the trade-off between energy efficiency and 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, in contrast to the energy consumption ratio converges to a certain value. From this result and results of Fig. 4, we can conclude that very large values of m do 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 see that, when p is 0.005, the latency ratios when $RTT = 50$ ms and $RTT = 100$ ms are almost identical. The reason for this is as follows. When p is quite large, the second term of the numerator in Eq. (14) is very small compared with the first term. Consequently, the latency ratio nearly equals $(1-(m-1)/E[W])$, which is only affected by m and $E[W]$. Therefore, the latency ratio becomes independent of RTT.

From the above discussion, we reach the following conclusions. When the packet loss event frequency is small, sleeping without burst transmission is effective for achieving energy efficiency. When the packet loss event frequency is larger, burst transmission becomes more effective. However, as m becomes larger than about five, the further reduction of energy consumption becomes small while the latency ratio increases linearly. Therefore, users or applications need to choose the value of m within the range of one to five according to their requirements for energy efficiency and acceptable latency.

V. WNI Factors for Energy Saving

In this section, we discuss the effects of WNI parameters on TCP energy saving behavior. For that purpose, we compare energy reductions achieved for various values of the WNI parameters.

We first derive the energy reduction in an RTT with sleeping. Let J^{TD}_{CAM}, which is derived in [9], denote the energy consumption with CAM in the TD period. By taking the difference between $J^{TD}(m)$ in Eq. (4) and J^{TD}_{CAM}, the energy reduction with sleeping is

$$J^{TD}_{CAM} - J^{TD}(m) = (P^l - P^s)E[T^s_{td}] - E[N^s_{td}]\Big(\big(P^{as} - P^l\big)\,T^{as} + \big(P^{sa} - P^l\big)\,T^{sa}\Big) \quad (18)$$

Here, for the sake of simplification, we assume that all the packet intervals depicted in Fig. 2 are regarded as α intervals. Therefore, $T^s_{k,m}$ in Eq. (10) and $N^s_{k,m}$ in Eq. (7) are simplified as follows.

$$\tilde{T}^s_{k,m} = U^{\alpha}_{k,m}\left\lceil \frac{w_{k-1}}{m} \right\rceil \left(\frac{RTT}{\lceil w_{k-1}/m \rceil} - mT^t - T^r \right) - \tilde{N}^s_{k,m}(T^{as} + T^{sa}) \quad (19)$$

$$\tilde{N}^s_{k,m} = U^{\alpha}_{k,m}\left\lceil \frac{w_{k-1}}{m} \right\rceil \quad (20)$$

By substituting Eqs. (19) and (20) into Eq. (18), we finally obtain the energy reduction achieved by sleeping in an RTT:

$$\begin{aligned} J^{cut} =& (P^l - P^s)\left(RTT - wT^t - \lceil w/m \rceil T^r\right) \\ & - \lceil w/m \rceil \{(P^{as} - P^s)T^{as} - (P^{sa} - P^s)T^{sa}\} \\ =& (P^l - P^s)T^{idle} - N^{st}\{(P^{as} - P^s)T^{as} - (P^{sa} - P^s)T^{sa}\} \end{aligned} \quad (21)$$

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 on the energy consumption by varying one of them and keeping the others fixed. The WNI parameters except for the varied one are set to the values shown in Table II.

Figures 6 and 7 present the energy reductions achieved when changing power consumption and transition time, respectively. The x-axes and y-axes in these figures represent the multiplier factor for the original value of the WNI parameter and J^{cut} in Eq. (21), respectively. That is, when the value in the x-axis is one, the energy reduction is that achieved with the original parameters of the AR5004 given in Subsect. IV-A. Note that T^{idle} and N^{st} are set to 100 ms and 20, respectively.

From Fig. 6, we can see that the energy reduction is almost unchanged when P^s and P^{as} are reduced. This implies P^s

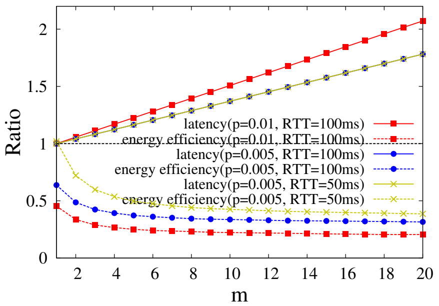


Fig. 5. Trade-off between energy efficiency and latency

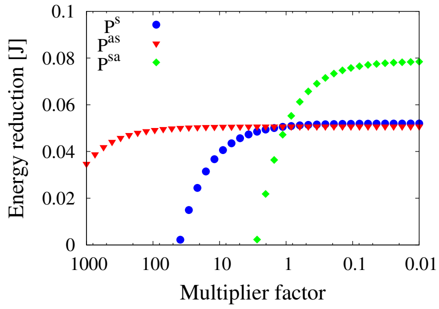


Fig. 6. Energy reduction when changing the power consumption of the WNI

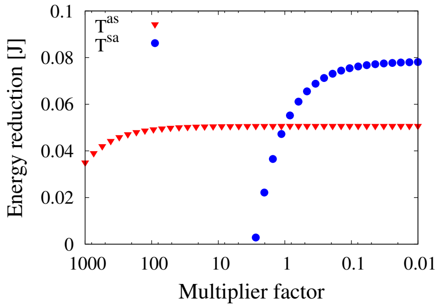


Fig. 7. Energy reduction when changing the transition time of the WNI

and P^{as} are already sufficiently small. In contrast, as P^{sa} decreases, the energy reduction increases until the multiplier factor is approximately one-twentieth. That is, the sufficient energy reduction can be obtained by reducing P^{sa} to approximately one-twentieth. Likewise, from Fig. 7, we can see that the energy reduction is almost constant as T^{as} decreases, whereas it increases as T^{sa} decreases. The energy reduction is approximately constant when the multiplier factor of T^{sa} is smaller than one-twentieth, in common with P^{sa}. This is because the power consumption of state transitions and the transition times affect the energy reduction to the same degree.

Thus, we see that there are critical multiplier factors for each WNI parameter, below which there is almost no further energy reduction when the multiplier factors are reduced. From Figs. 6 and 7, we can see that these critical multiplier factors for P^s, P^{as}, P^{sa}, T^{as}, and T^{sa} are around 1, 100, 0.05, 100, and 0.05, respectively.

We can use these critical multiplier factors to derive conditions on various WNI parameters for achieving a satisfactory energy reduction. We first derive a condition for P^s. According to Eq. (21), the energy consumption in sleep mode is determined by the difference between P^l and P^s. Using the ratio of the original values of P^l and P^s, and because the critical multiplier factor of P^s is around 1, the power consumption in the sleep state is sufficiently small if

$$P^s \leq \frac{0.016}{0.8} P^l = \frac{1}{50} P^l \tag{22}$$

On the other hand, because the energy reduction is affected to the same degree by power consumption of state transitions and transition time, we derive conditions for the product of power consumption and transition time. Using the ratio of the original values and the critical values, we find the conditions

$$P^{as} T^{as} \leq \frac{0.8}{0.8} P^l \times 10^{-6} \times 100 \approx P^l \times 10^{-4} \tag{23}$$

$$P^{sa} T^{sa} \leq \frac{1.4}{0.8} P^l \times 10^{-3} \times 0.05 \approx P^l \times 10^{-4} \tag{24}$$

For the above conditions, we can design energy-efficient WNIs for TCP data transfer by using WNI parameters that are small sufficiently compared with the power consumption in listen mode. More specifically, we can develop more efficient WNIs by reducing WNI parameters in descending order of the difference between the current value of WNI parameters and the values given in the conditions in Eqs. (22), (23) and (24).

VI. Conclusion

In this paper we have proposed a new model describing the energy consumption of burst transmission of TCP data transfer in a wireless LAN environment. Burst transmission is realized by using the delayed ACK. Numerical analyses based on our model showed that, when the packet loss frequency is small, sleeping without burst transmission is an effective mechanism for energy saving. When the packet loss event frequency is larger, burst transmission becomes more important. Furthermore, even when RTT is so small that introducing a sleep mode without burst transmission is ineffective for energy saving, burst transmission can save energy. We also determined conditions on each WNI parameter for designing energy-efficient WNIs.

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

Acknowledgments

This work is supported in part by the Ministry of Internal Affairs and Communications (MIC), Japan, under Promotion program for Reducing global Environmental loaD through ICT innovation (PREDICT).

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