Modeling and Analysis of Power Consumption in TCP Data Transmission over a Wireless LAN Environment

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***Abstract*—Reduction of power consumption is one of an important issue in wireless communications because most mobile devices are battery-driven. There are many power saving techniques for use in a wireless LAN (WLAN) environment at the hardware level and at the MAC protocol level. Their common strategy for power saving is to stay in sleep mode, which consumes very little energy, for as long as possible when no data is being transmitted or received. For effective power saving, therefore, it is important to understand the behaviors of the transport layer protocols used by upper-layer applications, since packet transmission and reception timing are mainly determined by those behaviors. In this paper, we propose a power consumption model based on a treatment of detailed TCP behaviors within a WLAN environment. Our model considers both the TCP-level and MAC-level behaviors of a wireless client. Comparing the model with and without ideal sleeping, we analyze the power consumption of a single wireless client as it sends data to a wired host by TCP. From the numerical results of our analysis, we show the lower-bound for power consumption in upstream TCP data transfer with ideal sleeping. We also discuss the trade-off between power saving and network performance in TCP data transfer.**

I. 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 that the wireless communications of a mobile device can account for approximately 10 % up to 50 % of its total power consumption with in an IEEE 802.11 WLAN [1]–[3], there is much interest in reducing the power consumed by wireless communications, particularly because most mobile devices are battery-driven.

With regards to power saving at MAC layer protocols, the IEEE 802.11 standard identifies a Power Saving Mode (PSM), as opposed to a normal active mode referred to as the Continuously Active Mode (CAM). Several researchers have constructed power consumption models for wireless clients in WLANs [4]–[6]. In [5], the authors model a single wireless client in the PSM downloading a file from a server in the presence of multiple wireless clients. [6] presents the results of an analysis of power consumption in different MAC operations at a wireless client with multiple clients in a WLAN. There the authors revealed that wasted energy accounts for 80 % of total energy in saturated situations. In [4], the authors model the power consumption of TCP transfers in CAM and in PSM in the presence of TCP background traffic. Note, however, that [4]–[6] mainly focus on the behaviors at the MAC level and do not consider detailed TCP behaviors, even though it is mainly TCP congestion control mechanisms that determine the timing of packet transmission and reception, timing which has a large impact on the power-saving effectiveness of sleeping behaviors.

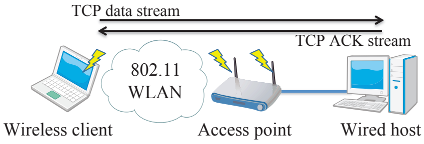

Fig. 1. WLAN environment

As the first contribution of this paper, we propose a new model for power consumption in TCP data transmission over a WLAN environment. The proposed model consists of a mixture of two layer models; a MAC-level model and a TCP-level. In the MAC-level model, power consumption is calculated on the basis of the frame exchanges in CSMA/CA mechanisms. Likewise, in the TCP-level model, which is based on detailed TCP behaviors, power consumption is determined on the basis of transmission and reception depending on the growth of the TCP congestion window size. We then analyze the power consumption of a single wireless client sending data to a wired host. We derive a power consumption model with CAM and with ideal sleeping to reveal the potential effectiveness of sleep strategy considering detailed TCP behaviors. From the numerical results, we show a lower-bound of power consumption in upstream TCP data transfer with ideal sleeping. We also discuss the trade-off between power saving and network performance in TCP data transfer.

II. POWER CONSUMPTION MODELS

A. Network Model and Assumption

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. More specifically, we derive the power consumed after 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. Our modeling 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 p 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.
- The delayed ACK option is disabled.
- Unless otherwise noted, we apply the same assumptions as in [7], [8] for our TCP-level model.

B. Modeling Power Consumption of Frame Exchanges in IEEE 802.11 MAC

The WNIC has four communication modes: *transmit*, *receive*, *listen*, and *sleep*, each of which has a different power consumption. Therefore, we introduce P^t, P^r, P^l, and P^s as the power consumption in transmit, receive, listen, and sleep mode, respectively. Due to space limitation, we omit the calculation process of power consumption of WNIC when one data frame is transmitted and received. As a result, we derive J^t and J^r, which represent the power consumption of the transmission and reception of one data frame, respectively. We can obtain J^t and J^r as follows:

$$\begin{aligned} J^t =& P^l\left(3T_{SIFS}+T_{DIFS}+T_{BO}+4\tau\right) \\ &+ P^t(T_{RTS} + T^{STA}_{DATA}) + P^r(T_{CTS} + T_{ACK}) \end{aligned} \quad (1)$$

$$J^r = P^l\left(T_{SIFS}+T_{DIFS}+T_{BO}+2\tau\right) + P^t T_{ACK} + P^r T^{AP}_{DATA} \quad (2)$$

where T_{BO} is the expected backoff time, τ is the radio propagation delay, T^{STA}_{DATA} is the transmission duration of a data frame from the client, and T^{AP}_{DATA} is the reception duration of data frame transmission from the AP.

C. Modeling Power Consumption of TCP Data Transfer in CAM

We construct a TCP-level model for power consumption in CAM. In a manner similar to [8], we construct the model by combining two phases: an *initial slow start phase* and a *steady phase*. We introduce J^{ss} and J^{ca}, which represent the expected power consumption in transferring data in the initial slow start phase and the steady phase, respectively. Using J^{ss} and J^{ca}, the expected power consumption J of whole data transfer can be calculated as follows:

$$J = J^{ss} + J^{ca}. \quad (3)$$

1) Initial Slow Start Phase: To derive J^{ss}, we further divide the initial slow start phase into two parts: data transfer before segment loss occurs, and data transfer after segment loss occurs. We then combine the two parts. Here, let J^{ss}_{data} denote the expected power consumption of the former part and J^{ss}_{loss} denote that of the latter part; i.e., $J^{ss} = J^{ss}_{data} + J^{ss}_{loss}$. Due to space limitation, we omit the deviation of J^{ss}_{loss}, which can be calculated in similar way to that of J^{ss}_{data} by using the deviations in [8].

We determine J^{ss}_{data}. The duration in listen mode of the wireless client in this part is equivalent to the total duration minus the duration over which data and ACK segments are transmitted and received. Therefore, we can obtain J^{ss}_{data} in CAM as follows:

$$J^{ss}_{data} = E[S^{ss}_d](J^t+J^r)+P^l\left\{E[T^{ss}]-E[S^{ss}_d](T^t+T^r)\right\} \quad (4)$$

where T^t is the the duration of the wireless client sending one data frame, T^r is the duration of the wireless client receiving one data frame, $E[S^{ss}_d]$ is the expected number of segments sent in the initial slow start phase, and $E[T^{ss}]$ is the total expected duration in the initial slow start phase. $E[S^{ss}_d]$ and $E[T^{ss}]$ are derived in [8].

2) Steady Phase: [7] analyzes the detailed TCP behaviors in the steady phase by considering a combination of 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 RTOs. We consider that one TO period occurs after experiencing multiple TD periods. We define this duration as a *cycle*. Let $E[M]$ denote the number of data segments transmitted during a cycle. It is given by [7] as follows:

$$E[M] = E[n] \cdot E[Y] + E[R] \quad (5)$$

where $E[n]$ is the expected number of TD periods in a cycle, and $E[Y]$ is the expected number of data segments sent in a TD period. $E[Y]$ is derived in [7].

In a similar way to Eq. (5), power consumption J^{cycle} in a cycle is calculated as follows:

$$J^{cycle} = E[n] \cdot J^{TD} + J^{TO} \quad (6)$$

where J^{TD} is the expected power consumption in a TD period, and J^{TO} is that in a TO period.

Since the number of segments transmitted in the steady phase is calculated by $S_d/S_p - E[S^{ss}_d]$ where S_p is the data segment size, we can obtain the number of cycles in the steady phase by dividing it by $E[M]$. Here, according to [7] $E[n]$ can be considered equal to $1/Q(w)$. Therefore, using Eqs. (5) and (6), J^{ca} can be calculated as follows:

$$J^{ca} = (S_d/S_p - S^{ss}_d)\frac{J^{TD} + Q(E[W]) \cdot J^{TO}}{E[Y] + Q(E[W])E[R]} \quad (7)$$

where $E[W]$ which represents the expected window size when the first segment loss occurs. Note that $E[W]$ is limited by the bandwidth of the WLAN because the excessive packets are accumulated at the WLAN buffer when the congestion window size is larger than the bandwidth-delay product of the wireless network.

To derive J^{TD}, we consider segments sent during a TD period. We define $E[\beta]$, which is derived in [7], by the number of segments sent in a window after detecting packet losses in the TD period. According to [7], the sender sends $E[Y]$ segments and receives $(E[Y]-(E[W]-E[\beta]))$ ACK segments in the TD period. Therefore J^{TD} in CAM is determined as follows:

$$\begin{aligned} J^{TD} =& E[Y]J^t + (E[Y] - E[W] + E[\beta])J^r \\ &+ P^l\left\{E[A]-E[Y]T^t-(E[Y]-E[W]+E[\beta])T^r\right\} \end{aligned} \quad (8)$$

where $E[A]$, which is given by [7], is the expected total duration in a TD period.

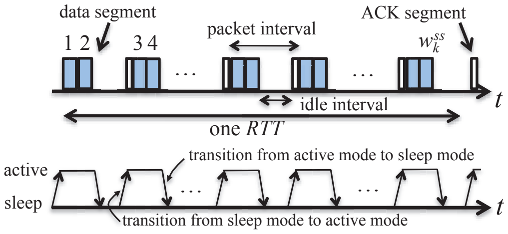

Fig. 2. Packet sequence of the k-th round in a slow start phase

On the other hand, J^{TO} in CAM is derived as follows. [7] gives $E[Z^{TO}]$ and $E[R]$, which represent the expected duration of successive packet retransmissions started by the first occurrence of RTO and the total number of data segment transmissions in the duration, respectively. Therefore, using $E[Z^{TO}]$ and $E[R]$, J^{TO} in CAM is calculated as follows:

$$J^{TO} = E[R]J^t + P^l \left(E[Z^{TO}] - E[R]T^r\right). \tag{9}$$

D. Modeling Power Consumption of TCP Data Transfer with Ideal Sleeping

In this section we construct a power consumption model with ideal sleeping where the WNIC enters sleep mode when no packet transmission or reception takes place. Here, ideal sleeping means that the WNIC knows both the transmission timing of TCP data segments and reception timing of TCP ACK segments such that it can enter and leave sleep mode at exact timing. The power consumption in ideal sleeping represents a lower-bound of power consumption in TCP data transfer. Thus, this is useful for developing practical sleeping methods. T^{as} and T^{sa} are duration time for transiting from active mode to sleep mode and duration time for transiting from sleep mode to active mode, respectively, and P^{as} and P^{sa} are power consumption for transiting from active mode to sleep mode and power comsumption for transiting from sleep mode to active mode, respectively. To avoid an increase in delay by sleeping behavior, we assume that the WNIC can enter sleep mode at idle intervals which are longer than $(T^{as} + T^{sa})$.

To derive a power consumption model with ideal sleeping, we introduce a *round* which starts when the first segment is transmitted in a window and ends when the corresponding ACK segment is received.

1) Initial Slow Start: In the following we derive a power consumption model with ideal sleeping in the initial slow start phase. To derive the difference from Eq. (4), we consider the packet transmission and reception sequence in the slow start phase, as depicted in Fig. 2. In the slow start phase, the congestion window increases by one segment after receiving an ACK segment. Therefore, when receiving an ACK segment, two data segments are transmitted successively. Thus, the number of packet intervals in the k-th round can be calculated by $w_k^{ss}/2$ where w_k^{ss} is a window size of the end of the k-th round in the initial slow start phase. Assuming ACK segments in a window are received at equal intervals in an RTT, sleep mode can be utilized when the following condition is satisfied:

$$2RTT/w_k^{ss} - (2T^t + T^r) > T^{as} + T^{sa}. \tag{10}$$

Let $E[T_{ss}^s]$ denote the expected total length of sleep mode in the initial slow start phase. To derive $E[T_{ss}^s]$, we consider r_{ss} which represents the maximum round number such that all idle intervals in the r_{ss}-th round satisfy Eq. (10). When sleep mode can be utilized in all idle intervals of the slow start phase, $w_{r_{ss}}^{ss}$ equals $E[W^{ss}]$, which is the window size achieved after sending $E[S_d^{ss}]$ segments, and r_{ss} is calculated by $\log_2(E[S_d^{ss}]/w_1 + 1)$ where w_1 is the initial window size according to [8]. Otherwise, r_{ss} is determined as follows. Here, let W_{ss}^{max} denote the maximum window size such that sleep mode can be utilized. It is given by:

$$W_{ss}^{max} = \left\lfloor 2RTT/(2T^t + T^r + T^{as} + T^{sa})\right\rfloor. \tag{11}$$

Since w_k^{ss} is calculated by $2^{k-1}w_1$ and from Eq. (11), r_{ss} to satisfy $w_{r_{ss}}^{ss} = W_{ss}^{max}$ is calculated as follows:

$$r_{ss} = \lfloor \log_2 (W_{ss}^{max}/w_1) + 1 \rfloor. \tag{12}$$

Combining the above deviations, we can obtain r_{ss} as follows:

$$r_{ss} = \min\{\lfloor \log_2 (W_{ss}^{max}/w_1) + 1 \rfloor ,\ \log_2(E[S_d^{ss}]/w_1 + 1)\}. \tag{13}$$

Note that $r_{ss} < 1$ means that sleep mode cannot be utilized in the slow start phase.

Using r_{ss}, we derive $E[N_{ss}^s]$, which represents the expected number of transitions to and from sleep mode. When sleep mode can be utilized at all idle intervals from the first round to the r_{ss}-th round, $E[N_{ss}^s]$ can be obtained as follows:

$$E[N_{ss}^s] = 1 + w_1(2^{r_{ss}-1} - 1). \tag{14}$$

Note that $E[N_{ss}^s]$ equals zero when $r_{ss} < 1$.

We next derive $E[T_{ss}^s]$ by using $E[N_{ss}^s]$. The total idle interval in the first round can be calculated by $RTT - w_1T^t - T^r$ since w_1 data segments are sent and the first ACK segment is received in the first round. In the k-th round, during one RTT, TCP sends w_k^{ss} data segments, and receives w_{k-1}^{ss} ACK segments. Then, the total idle interval in the k-th round can be calculated by $RTT - w_k^{ss}T^t - w_{k-1}^{ss}T^r$. From the above discussions, $E[T_{ss}^s]$ for $r_{ss} > 1$ can be obtained as follows:

$$\begin{aligned} E[T_{ss}^s] = {} & r_{ss} \cdot RTT - w_1T^t(2^{r_{ss}} - 1) \\ & - w_1T^r(2^{r_{ss}-1} - 1) - E[N_{ss}^s](T^{as} + T^{sa}). \end{aligned} \tag{15}$$

Note that $E[T_{ss}^s] = RTT - w_1T^t - T^r$ when $r_{ss} = 1$, and $E[T_{ss}^s] = 0$ when $r_{ss} < 1$.

Using Eqs. (4), (14) and (15), J_{data}^{ss} with ideal sleeping can be calculated as follows:

$$\begin{aligned} J_{data}^{ss} = {} & E[S_d^{ss}](J^t + J^r) + P^sE[T_{ss}^s] + E[N_{ss}^s](P^{as}T^{as} + P^{sa}T^{sa}) \\ & + P^l\Big\{E[T^{ss}] - E[S_d^{ss}](T^t + T^r) - E[T_{ss}^s] \\ & - E[N_{ss}^s](T^{as} + T^{sa})\Big\}. \end{aligned} \tag{16}$$

2) Steady Phase: We next derive a power consumption model in the steady phase. More specifically, we derive J^{TD} and J^{TO} in Eq. (7) with ideal sleeping.

Figure 3 shows the packet transmission and reception sequence in a TD period. In the TD period, TCP increases a data segment when receiving all ACK segment in the window. Thus, the number of packet intervals in the k-th round is calculated by $w_k - 1$ where w_k is the window size of the k-th round in the TD period. Assuming ACK segments are received at equal intervals during one RTT, to enter sleep mode in the idle interval of the k-th round, it is needed to satisfy the following condition:

$$RTT/(w_k - 1) - (T^t + T^r) > T^{as} + T^{sa}. \tag{17}$$

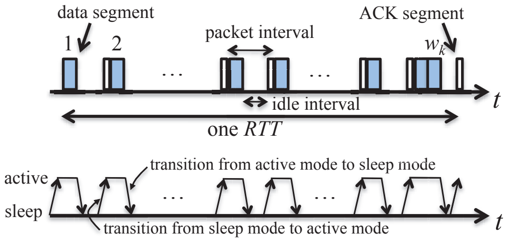

Fig. 3. Packet sequence of the k-th round in a TD period

On the other hand, since two data segments are sent successively after receiving the ACK segment for the (w_k-1)-th segment, the last idle interval of the k-th round is shorter than the others; i.e., $RTT/(w_k-1)-2T^t-T^r$. Therefore, to enter sleep mode at the last duration, it is necessary to satisfy the following condition:

$$RTT/(w_k-1)-(2T^t+T^r)>T^{as}+T^{sa}. \tag{18}$$

In the similar way to Subsect. II-D1, we consider r_{td} which represents the maximum round number such that all idle intervals in the k-th round satisfy Eq. (17). When all idle intervals in the TD period meet the condition, $w_{r_{ss}}$ equals $E[W]$. According to [7] the number of rounds where the window size is $E[W]$ is calculated by $E[W]/2$; i.e., $r_{td}=E[W]/2$. Otherwise, r_{td} is determined as follows. Let W_{td}^{max} denote the maximum window size where sleep mode can be utilized. It is given by:

$$W_{td}^{max}=\left\lfloor RTT/(T^t+T^r+T^{as}+T^{sa})\right\rfloor+1. \tag{19}$$

Since w_k is calculated by $E[W]/2+k-1$, from Eq. (19), r_{td} to satisfy $w_k=W_{td}^{max}$ is obtained as follows:

$$r_{td}=W_{td}^{max}-E[W]/2+1. \tag{20}$$

From the above deviations, r_{td} can be obtained as follows:

$$r_{td}=\min\left(W_{td}^{max}-E[W]/2+1,\ E[W]/2\right). \tag{21}$$

Note that $r_{td}<1$ means that sleep mode cannot be utilized in the TD period.

Here, r_{td} does not consider the fact that sleep mode cannot be utilized at the last idle interval while in sleep mode at the other idle intervals. Therefore, we derive N_{last}, which represents the total number of rounds of which sleep mode cannot be utilized at the last idle interval. Let W_{last}^{max}, which is calculated as follows, denote the maximum window size where sleep mode can be utilized in the last idle interval:

$$W_{last}^{max}=\left\lfloor RTT/(2T^t+T^r+T^{as}+T^{sa})\right\rfloor+1. \tag{22}$$

Using Eq. (22), N_{last} can be calculated as follows:

$$N_{last}=\max\left(E[W]-W_{last}^{max},\ 0\right). \tag{23}$$

We next derive $E[N_{td}^s]$ which is the expected number of transitions to and from sleep mode in the TD period. TCP sends $E[W]/2$ data segments in the first round. Assuming TCP sends data segments at equal intervals, the number of packet intervals is $E[W]/2$ in the first round. In the following rounds, the number of packet intervals in the k-th round is calculated by w_k-1. Therefore, from Eqs. (21) and (23), $E[N_{td}^s]$ for $r_{td}>1$ can be calculated as follows:

$$E[N_{td}^s]=\frac{r_{td}}{2}\left(E[W]+r_{td}-3\right)+1-N_{last}. \tag{24}$$

When sleep mode can be utilized in all idle intervals of the round where the window size equals $E[W]$, i.e., $r_{td}=E[W]/2$, sleep mode also can be utilized in all idle intervals of the $r_{td}+1$ round. Thus, the WNIC can sleep $2E[\beta]$ times further. Therefore, $E[N^s]$ finally can be obtained as follows:

$$E[N_{td}^s]=\begin{cases}0 & \text{if } r_{td}<1\\ 1 & \text{if } r_{td}=1\\ \frac{r_{td}}{2}\left(E[W]+r_{td}-3\right)-1+E[W] & \text{if } r_{td}=\frac{E[W]}{2}\\ \frac{r_{td}}{2}\left(E[W]+r_{td}-3\right)+1-N_{last} & \text{otherwise}\end{cases} \tag{25}$$

We next derive $E[T_{td}^s]$ which represents the expected total length of sleep mode in the TD period. In the first round, $E[W]/2$ data segments are sent and one ACK segment is received during one RTT. Therefore, the idle interval is calculated by $RTT-E[W]T^t/2-T^r$. In the k-th round, TCP sends w_k data segments and receives (w_k-1) ACK segments. Therefore, this idle interval is given by $RTT-w_kT^t-(w_k-1)T^r$. From the above discussions, $E[T_{td}^s]$ for $r_{td}>1$ is determined as follows:

$$\begin{aligned}E[T_{td}^s]=&r_{td}RTT-\frac{r_{td}}{2}(E[W]+r_{td}-1)T^t-E[N_{td}^s](T^{sa}+T^{as})\\&-\frac{1}{2}((r_{td}-1)E[W]+r_{td}(r_{td}-3)+4)T^r\end{aligned} \tag{26}$$

When $r_{td}=E[W]/2$, sleep mode can be utilized in all idle intervals. Furthermore, when $r_{td}=1$, $E[T_{td}^s]=RTT-E[W]T^t/2$. Therefore, $E[T_{td}^s]$ finally can be calculated as follows:

$$\begin{aligned}&E[T_{td}^s]\\&=\begin{cases}0 & \text{if } r_{td}<1\\ RTT-E[W]T^t/2-T^r & \text{if } r_{td}=1\\ E[A]-E[Y]T^t-(E[Y]-E[W]/2)T^r-E[N_{td}^s](T^{as}+T^{sa})\\ \qquad\qquad & \text{if } r_{td}=E[W]/2\\ r_{td}RTT-\frac{r_{td}}{2}(E[W]+r_{td}-1)T^t-E[N_{td}^s](T^{sa}+T^{as})\\ \quad-\frac{1}{2}((r_{td}-1)E[W]+r_{td}(r_{td}-3)+4)T^r & \text{otherwise}\end{cases}\end{aligned} \tag{27}$$

Using Eqs. (25) and (27), J^{TD} with ideal sleeping is given by:

$$\begin{aligned}J^{TD}=&E[Y]J^t+(E[Y]-E[W]/2)J^r-P^lE[N_{td}^s](T^{as}+T^{sa})\\&+P^l\left\{E[A]-E[Y]T^t-(E[Y]-E[W]/2)T^r-E[T_{td}^s]\right\}\\&+P^sE[T_{td}^s]+E[N_{td}^s](P^{as}T^{as}+P^{sa}T^{sa})\end{aligned} \tag{28}$$

On the other hand, J^{TO} with ideal sleeping is derived as follows. When detecting packet losses by RTO(s), the length of RTO is typically longer than one RTT, and so sleep mode can be utilized during RTO(s). Therefore, J^{TO} with ideal sleeping can be calculated as follows:

$$\begin{aligned}J^{TO}=&E[R]J^t+P^s\left(E[Z^{TO}]-E[R](T^r+T^{as}+T^{sa})\right)\\&+E[R](P^{as}T^{as}+P^{sa}T^{sa}).\end{aligned} \tag{29}$$

III. NUMERICAL ANALYSIS

A. Parameter Settings and Evaluation Metrics

We consider TCP data transfer of a 100 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. In calculating radio propagation delay in Eqs. (1) and (2), we assume that the wireless client is located four meters from the AP. Since we assume no frame loss in the WLAN, T_{BO} is calculated by $CW_{min}/2$.

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

From a data sheet for a WNIC implementing the Atheros AR5004 chip [9], we set P^t, P^r, P^l, and P^s to 1.4 W, 0.9 W, 0.8 W, 0.016 W, respectively. According to [10], 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 ms, respectively, following [11]. TCP data segment size and TCP ACK segment size are set to 1500 bytes and 40 bytes, respectively.

In Subsect. III-B, we evaluate the performance of sleep strategy from the viewpoint of two metrics: effectiveness of power saving and the trade-off between power saving and TCP performance. To evaluate the effectiveness of power saving, we use the power consumption models of Subsects. II-C and II-D.

To evaluate the trade-off, we consider the latency of the whole data transfer. Since a large portion of the 100 MB file is transmitted in the steady phase, power consumption is negligible in the initial slow start phase. L, which is the latency of the data transfer, can be calculated as follows:

$$L = (S_d/S_p - E[S_d^{ss}])\,\frac{E[A] + Q(E[W])E[Z^{TO}]}{E[Y] + Q(E[W])E[R]}. \tag{30}$$

Note that in the power consumption model with ideal sleeping, we assumed that to avoid an increase in delays, the WNIC awakes before receiving ACK segments. However, in actual situations, it is difficult to estimate the transmission/reception timing of TCP segments since they depend on the behavior of TCP receivers and on network conditions. When the transition from sleep mode to active mode is delayed due to estimation failures, the timing of packet transmission and reception is delayed, resulting in the increase in the latency of the whole data transfer.

Therefore, to avoid delay increases in actual situations, we modify the conditions to enter sleep mode as follows. Specifically, we add the margin δ to determine whether or not the WNIC enters sleep mode in Eqs. (17) and (18). This is equivalent to the following equations transformed from Eqs. (19) and (22):

$$W_{td}^{max} = \lfloor RTT/(T^t + T^r + T^{as} + T^{sa} + \delta) \rfloor + 1 \tag{31}$$

$$W_{last}^{max} = \lfloor RTT/(2T^t + T^r + T^{as} + T^{sa} + \delta) \rfloor + 1. \tag{32}$$

Let N_{total}^s denote the expected total number of transitions to and from sleep mode. From the discussions in Subsect. II-D, N_{total}^s can be calculated with the following equation:

$$N_{total}^s = (S_d/S_p - E[S_d^{ss}])\,\frac{E[N_{td}^s] + Q(E[W])E[R]}{E[Y] + Q(E[W])E[R]}. \tag{33}$$

The delay increased by the sleep behavior is calculated by $N_{total}^s T^{sa}(1+\gamma)$ where γ is an adjusting parameter of delay. Therefore, L^s, which is the latency of the whole data transfer with sleeping, can be calculated as follows:

$$L^s = L + N_{total}^s T^{sa}(1+\gamma). \tag{34}$$

B. Numerical Results and Discussion

We show power consumptions with CAM and with ideal sleeping in Fig. 4 and the ratio of power consumption in Fig. 5.

These figures in x-axis denote the probability p of the packet drop events. Each line in these figures indicates the result for each RTT. Note that, to confirm the maximum potential of power saving, we plot the results when Eqs. (17), and (18) are utilized for the condition to enter the sleep mode. The ratio is calculated by dividing the power consumption with ideal sleeping by power consumption with CAM. Fig. 4 shows that power consumption increases as RTT increases regardless of whether or not sleep mode is utilized. This is because the transfer time for whole data becomes large as RTT increases. On the other hand, from the viewpoint of impact of p, Fig. 4 represents power consumptions for both modes are reduced as p decreases. The reason for this is as follows. When p is large, the transfer time for whole data of 100 MB increases due to the frequent occurrence of RTOs, and thereby power consumption increases. In contrast, when p is small, the number of segments sent per unit time increases because the congestion window size becomes large as p decreases. These results show that the total time for data transfer is one of an important factor to consider the power consumption.

From the viewpoint of power consumption with ideal sleeping, power consumptions are almost equivalent when $p < 0.2$ except for $RTT = 5$ ms whereas power consumption decreases significantly with CAM as p decreases regardless of RTT. This is because the power-saving effectiveness of the reduction of total time is small because of very little power consumption in sleep mode. On the other hand, when $RTT <$ 5 ms, power consumption with ideal sleeping decreases as p decrease as well as CAM. The following is the reason for this. In the power consumption with ideal sleeping, the number of idle intervals which satisfy Eqs. (17) and (18) decreases as p becomes small because the congestion window size increases and the packet intervals become short. Therefore, it is difficult to enter sleep mode, resulting in the number of transitions to and from sleep mode decreases. Thus, there are two factor for power consumption: a decrease in power consumption due to the reduction of the transitions to and from sleep mode and an increase in power consumption due to staying in listen mode. Because the former is larger than the latter, the power consumption consequently decreases with ideal sleeping.

In the terms of the relative effectiveness for power saving, we can observe from Fig. 5 that the effectiveness for power saving becomes large as p increases and when RTT increases. For instance, when $p = 0.01$ and $RTT = 100$ ms, the power consumption can be reduced by approximately 60 % with ideal sleeping. In contrast, when RTT is small and p is low, power consumption with ideal sleeping is larger than power consumption with CAM. This is because we can not ignore power consumption for transition to and from sleep mode and duration where sleep mode can be utilized becomes short.

From the above results, we conclude that to effectively reduce power consumption, it is essential to reduce the number

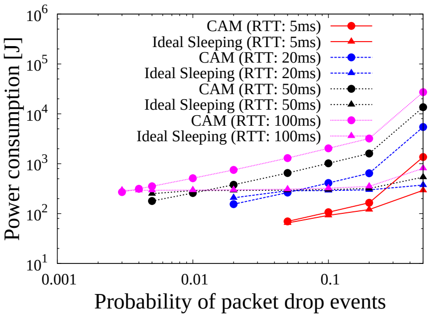

Fig. 4. Power consumption for the whole data transfer

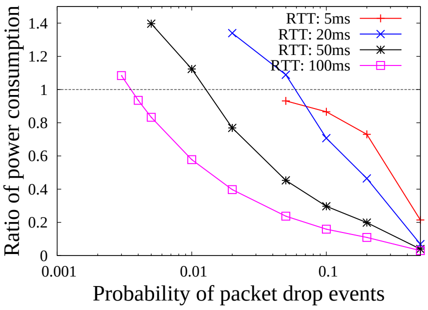

Fig. 5. Ratio of power consumption for the whole data transfer

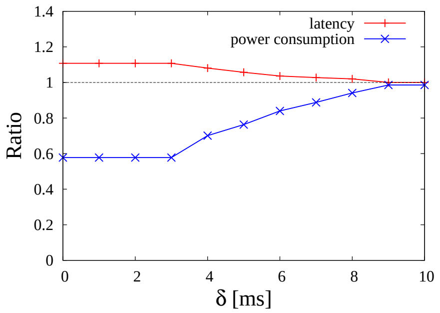

Fig. 6. Trade-off between power saving and latency

of transitions to and from sleep mode while maintaining the total duration in sleep mode because it is a large portion of power consumption. As a method for realizing that, there is a burst transmission technique, which lengthens idle intervals in one RTT by transmitting multiple data segments successively on the TCP level. Note that the tendencies of power consumption are dependent on percentages of the initial slow start phase and the stead phase for the whole data transfer. Therefore, when the file size is large, the ratio of power consumption is almost identical with Fig. 5. On the other hand, when the file size is small such that the whole data transfer ends in the initial slow start, the ratio of power consumption is totally lower than results in Fig. 5 because the number of transitions to and from sleep mode is low.

Next, to evaluate the trade-off between power saving and TCP performances, we represent the ratio of power consumption and that of latency in Fig. 6 when $p = 0.01$ and $RTT = 100$ ms. Note that power consumption with ideal sleeping is calculated by using Eqs. (31) and (32). On the other hand, the ratio of latency is calculated by using Eqs. (30) and (34) for conditions to enter sleep mode. δ is a margin to determine whether or not the WNIC enters sleep mode. Therefore, small δ means that sleep mode is utilized aggressively, whereas large δ means that sleep mode is utilized when idle intervals are large enough. From Fig. 6, we can see that power consumption is successfully reduced by around 60 % with sleeping while delay increases by a factor of approximately 1.1 when $\delta \leq 3$ ms. On the other hand, when $\delta \geq 9$ ms, power consumption is almost no reduction while experiencing no additional delay, because sleep mode is utilized only when RTOs occur. Otherwise, the ratio of power consumption increases linearly and the that of latency decreases linearly as δ increases. Thus, it is necessary to consider the trade-off between power saving and latency depending on the behaviors of upper layer applications.

IV. CONCLUSION

In this paper we proposed a new model for power consumption in TCP data transmission over a WLAN environment. We then analyzed the power consumption of a single wireless client sending data to a wired host. From the numerical results, we revealed that it is effective for power saving to reduce the number of transitions to and from sleep mode while keeping the total sleep time. We also presented that the trade-off between power saving and latency has liner relationships.

In the future, we plan to consider frame losses and collisions in a WLAN to MAC-level model and validate our model by measuring the power consumption of the WNIC. After that, we intend to extend the analysis model to accommodate multi-MAC and multi-path environments. We also plan to work out a transport architecture for power saving in WLANs based on our analytical model.

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