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

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## Background

- Accessing the Internet by using mobile devices is becoming common situations
  - Laptops, tablet PCs, smartphones, and so on
- Mobile devices are battery-driven
- Wireless communications of a mobile device can account for about 10% up to 50% of its total power consumption [1]

It is important for lengthening battery's lifetime to save power consumption in the wireless communications

[1] Atheros Communications, "Power consumption and energy efficiency comparisons of wlan products." In Atheros White Papers, May 2003.



## Power saving in wireless LAN (WLAN) environments

Power saving of a wireless network interface card (WNIC)

Power consumptions are reduced to about a one-tenth

Power consumption of a WNIC

| Product Name (Year) | Transmit | Receive | Listen | Sleep |
|---|---|---|---|---|
| Atheros AR5004 (2003) | 1.4 W | 0.9 W | 0.8 W | 0.16 W |
| Atheros AR6002 (2007) | 0.8 W | 0.5 W | 0.05 W | 0.002 W |

Power consumptions are reduced to about a half

Wistron NeWeb Corp., "CM9: WLAN 802.11 a/b/g mini-PCI Module." available at microcom.us/CM9.pdf.
Silex, "SX-SDCAG 802.11a/b/g SDIO card module datasheet." available at http://www. silexamerica.com/products/data sheets/sx-sdcag brief.pdf.



## Power saving in wireless LAN (WLAN) environments

Power saving in IEEE 802.11 MAC

- Power Saving Mode (PSM) can save energy in the wireless communication
  - PSM may degrade the network performance
    - Increase in the end-to-end latency
    - Decrease in the end-to-end throughput

How can we save power consumption effectively?

- Energy efficiency in sleep strategies is determined by sleep timing and the length of sleep time
  - Depend on the behaviors of applications and transport-layer protocols

We need to consider the behaviors of the upper-layer protocols for efficient power saving

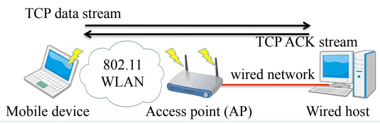


## Objectives of this work

1. Construct a model for power consumption in TCP data transmission over a WLAN environment, considering the detailed behaviors of the TCP congestion control
   – Power consumption model with continuously active mode (CAM)
   – Power consumption model with ideal sleeping
2. Discuss the trade-off between power saving and network performance in TCP data transfer



## Network model and assumptions

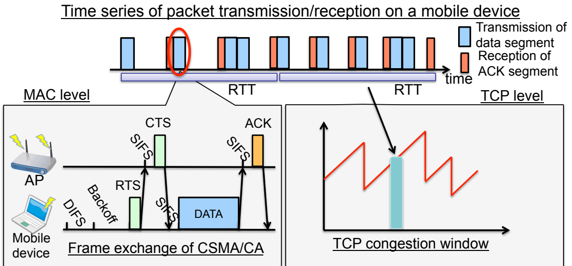



Model for power consumption of a mobile device in an upstream TCP data transfer over WLAN

Assumptions

- Consider TCP bulk data transfer
- Timings of packet transmission and reception are determined by the behaviors of TCP congestion control mechanisms, and TCP knows the timings
- Frame collision does not occur in the WLAN, so no frames are lost at the MAC level
- Data segments are lost by congestion in the wired networks, but ACK segments are not lost

## Structure of a power consumption model



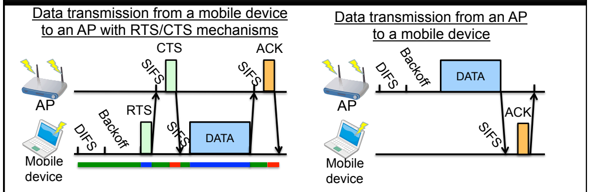

Based on frame exchanges of CSMA/CA, we calculate power consumption of transmission and reception of one data frame

The number of packet sent and received in an RTT is determined by the TCP congestion window size

Our model consists of a mixture of the MAC-level model and the TCP-level model.



## Power consumption model in IEEE 802.11 MAC




Expected power consumption in sending a DATA frame from a mobile device to an AP

Power consumption in listen state

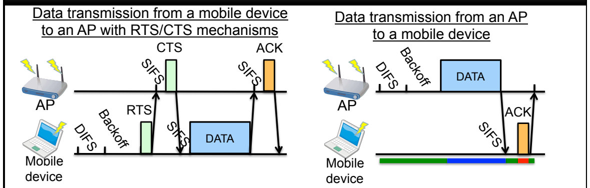
$$J^t = P^l\,(3T_{SIFS} + T_{DIFS} + T_{BO} + 4\tau) + P^t\,(T_{RTS} + T^{STA}_{DATA}) + P^r\,(T_{CTS} + T_{ACK})$$

Power consumption in transmit state

Power consumption in receive state



## Power consumption model in IEEE 802.11 MAC




Expected power consumption in receiving a DATA frame at a mobile device

Power consumption in transmit state

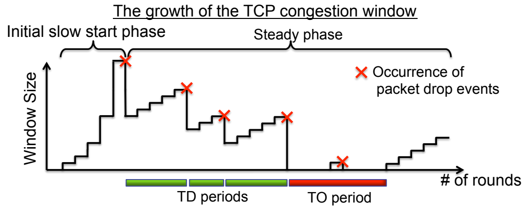
$$J^r = P^l\,(T_{SIFS} + T_{DIFS} + T_{BO} + 2\tau) + P^t T_{ACK} + P^r T^{AP}_{DATA}$$

Power consumption in listen state

Power consumption in receive state



## Power consumption model in TCP data transfer over WLAN

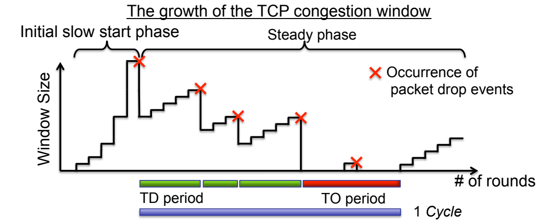



How to calculate the power consumption in TCP data transfer

1. Divide data transfer into blocks by packet drop events
2. Calculate the expected power consumption of each block
3. Obtain power consumption of the whole data transfer by adding all the power consumptions of the blocks



## Power consumption in the steady phase

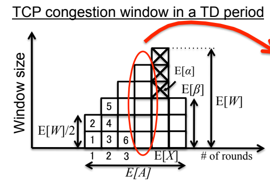


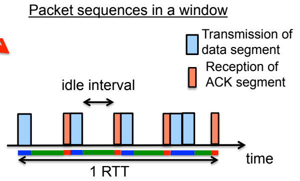

Power consumption in the steady phase

$J^{ca}$ = (the number of cycles in the steady phase)
x ((the number of the TD periods in a cycle)
x (power consumption in a TD period)
+ (power consumption in a TO period))



## Power consumption in a TD period with CAM




Power consumption in a TD period with CAM

Power consumption when data segments are sent

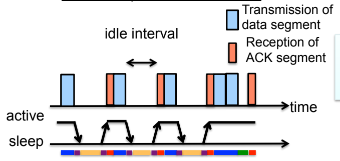
Power consumption when ACK segments are received

$$J^{TD} = E[Y]J^t + (E[Y] - E[W] + E[\beta])J^r + P^l\,\{E[A] - E[Y]T^t - (E[Y] - E[W] + E[\beta])T^r\}$$

Power consumption when no segment are sent and received

## Power consumption in a TD period with ideal sleeping

Packet sequences in a window




Condition for entering sleep mode

(idle interval) > (transition time to and from active and sleep modes)

Power consumption in a TD period with ideal sleeping

Power consumption when ACK segments are received

Power consumption in sleep mode

Power consumption of state transitions

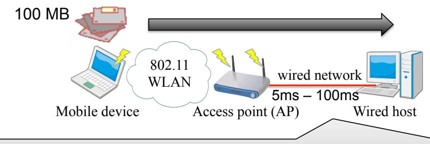
$$J^{TD} = E[Y]J^t + (E[Y]-E[W]/2)J^r + P^s E[T^s_{td}] + E[N^s_{td}](P^{as}T^{as} + P^{sa}T^{sa})$$
$$+ P^l\{E[A] - E[Y]T^t - (E[Y]-E[W]/2)T^r - E[T^s_{td}] - P^l E[N^s_{td}](T^{as}+T^{sa})\}$$

Power consumption when data segments are sent

Power consumption when no segments are sent and received



## Numerical analysis – parameter settings




We calculate power consumption when 100MB data transfer when changing in RTT and probability of packet drop events in the wired networks

Parameter settings

- Data size: 100 MB
- IEEE 802.11a
  - Data rate: 54 Mbps
  - $T_{backoff} = CW_{min}/2$
- Data segment size: 1500 bytes
- ACK segment size: 40 bytes

Power consumption of a WNIC [9]

| Transmit | Receive | Listen | Sleep |
|---|---|---|---|
| 1.4 W | 0.9 W | 0.8 W | 0.16 W |

Transition time from sleep to active: 1ms

Power consumption from sleep to active: 1.4 W

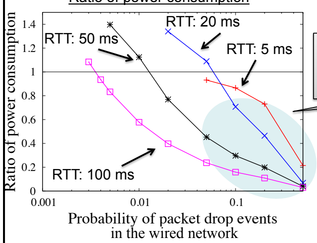
[9] Wistron NeWeb Corp., "CM9: WLAN 802.11 a/b/g mini-PCI Module." available at microcom.us/CM9.pdf.



## Numerical results – effectiveness of power saving

ratio of power consumption = power consumption with ideal sleeping / power consumption with CAM

Ratio of power consumption




Power-saving effectiveness increases as probability of packet drop events and RTT increase.

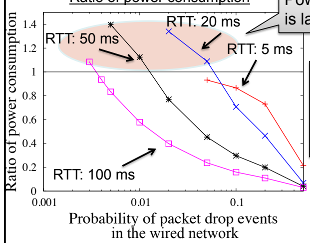
Effectiveness of power saving becomes large as the total time for the whole data transfer



## Numerical results – effectiveness of power saving

ratio of power consumption = power consumption with ideal sleeping / power consumption with CAM

Ratio of power consumption




Power consumption with ideal sleeping is larger than that without ideal sleeping

1. As probability of packet drops decreases, the average window size increases
2. This results in increasing the number of state transitions.

Power consumption in state transitions can't be ignored

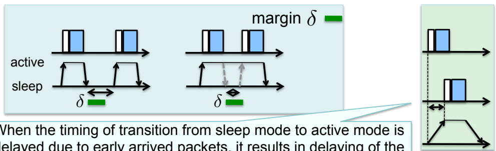
In order to effectively reduce power consumption, it is essential to reduce the number of state transitions to and from sleep mode and active mode



## Trade-off between power saving and data transmission time

- To evaluate trade-off between power saving and data transmission time, we consider latency of the whole data transfer

Margin $\delta$ is to determine whether or not the WNIC enters sleep mode
- Small $\delta$ means that sleep mode is utilized aggressively
- Large $\delta$ means that sleep mode is utilized when idle intervals are large enough



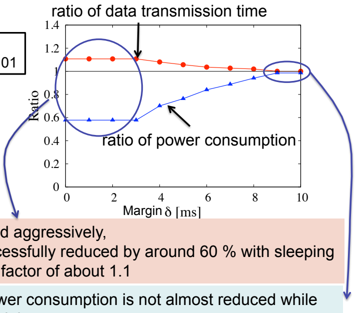

When the timing of transition from sleep mode to active mode is delayed due to early arrived packets, it results in delaying of the reception of the packets

We evaluate the whole delay increased due to the delay of the reception timing, assuming the delay of timings always occur regardless of the size of margin $\delta$



## Trade-off between power saving and data transmission time

RTT: 100ms
Probability of packet drops: 0.01




When sleep mode is utilized aggressively, power consumption is successfully reduced by around 60 % with sleeping while delay increases by a factor of about 1.1

When margin $\delta$ is large, power consumption is not almost reduced while experiencing no additional delay

## Conclusion and future work

Conclusion
- We proposed the model for power consumption in TCP data transfer over a WLAN
  - It is based on the behaviors of TCP congestion control mechanisms
- We analyzed the power consumption of a single mobile device sending data to a wired host
- From numerical results, it is effective for power saving to reduce the number of transitions to and from sleep mode while keeping the total sleep time

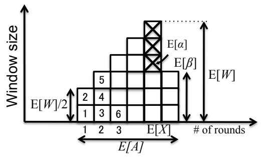
Future work
- We plan to consider frame losses and collisions in a MAC-level model and validate our model by measuring the power consumption of the WNIC



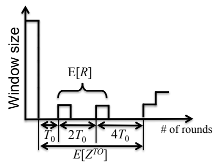


## Energy consumption in a TO period

TCP Congestion window in a TD period




TCP Congestion window in a TO period




Energy consumption in a TO period

Energy consumption when data segments are sent

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

Energy consumption when no segments are sent and received