Energy Efficient Multi-polling Scheme for Wireless LANs

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Outline

• Introduction of Wireless LANs
• Power Saving issues
• The proposed scheme
• Performance evaluation
• Conclusion
Infrastructure WLANs

- AP to STA: downlink
- STA to AP: uplink

Shared medium, broadcast nature
IEEE 802.11 WLANs

- Medium Access Control Layer
  - Base on logical **coordination function** to determine **who** and **when** to access the wireless medium at any time

![Diagram showing different access control methods in IEEE 802.11e MAC extent]

- Distributed Coordination Function (DCF)
- Hybrid Coordination Function (HCF)
  - Point Coordination Function (PCF)
  - HCF Contention Access (EDCA)
  - HCF Controlled Access (HCCA)
IEEE 802.11 WLANs

• Medium Access Control Layer
  – Distributed Coordination Function (DCF)
    • Contention
    • CSMA/CA
IEEE 802.11 WLANs

• Medium Access Control Layer
  – Point Coordination Function (PCF)
    • Contention-free
      – Scheduling
  • Polling

[Diagram showing contention-free period and polling frames]
Enhancements for IEEE 802.11 WLANs

• Quality of Service
  – QoS differentiation
  – Enhanced Distributed Channel Access (EDCA)
  – HCF Controlled Channel Access (HCCA)

• Throughput
  – MIMO/OFDM
  – Reduce MAC layer overhead
    • TXOP, Block ACK
    • Multi-polling
Power saving Issue of Wireless Networks

• Mobile devices
  – Size and capacity of battery are limited

• Major sources of energy wastage of shared medium wireless networks
  – Collision
  – Overhearing
  – Control packet overhead
  – Idle listening

• Power Saving Method
  – Transmission Power Control
  – Power management
Power Management of WLANs

• Power management (PM) modes
  – Active mode
  – Power Save mode (PSM)
    • Awake state (transmit / receive / idle)
    • Doze state
    • The switchover takes 250 μs

• The PM schemes in 802.11/802.11e
  – Beacon(with TIM) / PS-Poll
  – Automatic Power Save Delivery (APSD)
    • Scheduled / un-scheduled
PSM of IEEE 802.11 WLANs

- **DTIM interval**
  - Beacon
  - PS-poll
  - ACK
  - Frame
  - ACK

- **TIM interval**
  - Beacon
  - PS-poll
  - ACK
  - Frame
  - ACK
  - Beacon

- **Beacon interval**
  - Beacon
  - PS-poll
  - ACK
  - Frame
  - ACK
  - Beacon

- **Active period**
  - STA 1
    - Receive DTIM = true
    - More data = 1
  - STA 2
    - Receive DTIM = false

- **Uplink transmission**
  - Frame
  - ACK
  - Busy
  - PS-poll
  - ACK
  - Busy
  - Frame
  - ACK

- **Receive DTIM = true**
  - Beacon
  - BC
  - MC
  - Beacon
  - Backoff
  - Frame
  - ACK
  - Beacon
  - BC
  - MC

- **Receive DTIM = false**
  - Beacon
  - BC
  - MC
  - Beacon
  - Backoff
  - Frame
  - ACK
  - Beacon
  - BC
  - MC
Motivation

• Bandwidth utilization

• Power Saving
  – CP-Multipoll is free from some energy wastage sources
    • Collision
    • Control packet overhead
    • Idle listening
  – However, it requires STAs to continuously monitor channel status before accessing the channel
    • Overhearing
CP-Multipoll: Ordered Contention [4]

- Backoff values are assigned by AP!
- Adapt well to Variable Bit Rate (VBR) traffic
Energy-Efficient Multi-Polling Mechanism

- The main idea is to
  - Put STAs into Doze state to alleviate overhearing problem
  - Determine a suitable wake-up time schedule (WTS)
  - Statistically achieve satisfactory bandwidth utilization

The framework of EE-Multipoll mechanism
Frame format and framework of EE-Multipoll

<table>
<thead>
<tr>
<th>Octets: 2</th>
<th>2</th>
<th>6</th>
<th>1</th>
<th>$6 \times \text{RecordCount}$</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frame Control</strong></td>
<td><strong>Duration /ID</strong></td>
<td><strong>BSSID</strong></td>
<td><strong>Record Count (0-255)</strong></td>
<td><strong>Poll Record (6 octets)</strong></td>
<td><strong>FCS</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>AID</strong> (2 octets)</td>
<td><strong>Backoff</strong> (1 octets)</td>
</tr>
</tbody>
</table>

- **Record count**: number of poll record
- **AID**: association ID
- **Backoff**: assigned backoff value
- **Wake-up time**: the WTS relative to the receiving time of this EE-Multipoll frame
- **TXOP Limit**: the maximal usable duration of an aggregated TXOP for a specified STA (in units of 32μs)
Illustration of EE-Multipoll
Energy-Efficient Multi-Polling Mechanism

• AP operation
  – Learn the type and number of traffic flows by join/leaving handshaking
  – Calculate WTS
  – Set up backoff numbers
  – Transmit EE-Multipoll frame every service interval (SI)
  – Announce the sequence of on-going transmitting STAs in the ACK frames
    • The initial backoff can avoid the possible collision situation when an STA wakes up
    • However, for the busy case, the backoff value can be reduced more effectively
Energy-Efficient Multi-Polling Mechanism

• STA operation
  – Periodically awake to check the EE-Multipoll frame
  – The assigned backoff value implies its access order
    • To reduce overhead, $bt_1 = 0$, $bt_j = bt_{j-1} + 1$ for $j \geq 2$
    • Count down when the channel is idle
    • When channel is busy, set NAV, check the access order of on-going STA by the overheard information, and adjust the backoff value
  – Transmit when backoff value reaches zero
    • Note that it is possible that there is no uplink frame for a polled STA in some polling round
Energy-Efficient Multi-Polling Mechanism

• Error Recovery Issue
  – In real environment, there could be transmission error
  – The EE-Multipoll frame should be delivered at base rate
  – The first STA listed in the multipoll frame should confirm the successful delivery of the multipoll frame by replying an ACK
  – To avoid failure of the first STA, the AP can change the polling order to let each STA take turn to be the first one
Energy-Efficient Wake-up Time Schedule

• Assumptions
  – Only finite number of different applications and the traffic characteristics are known
  – Traffic arrivals are assumed to be stationary and the AP can have pre-calculated traffic arrival distribution
    • The density function of required transmission time can be estimated
  – Assume that there are $n$ STAs with uplink traffic and the required transmission time for traffic arrivals in one SI are independent, identically distributed
    • $i.i.d.$ assumption yield more concise results
Energy-Efficient Wake-up Time Schedule

• For **VBR uplink traffic**, the AP does not know exact buffer statuses of STAs
  – High energy saving and high bandwidth utilization are in general conflicting goals

• Problem formulation
  – Determine $WT_1 \leq WT_2 \leq \ldots \leq WT_n$ to maximize energy saving subject to at most $x\%$ degradation of bandwidth utilization compared with the CP-Multipoll scheme
    • assume CP-Multipoll adopts the *shortest-job-first* policy as PM method: $WT_i = 0$ for all $i$
Energy-Efficient Wake-up Time Schedule

- **Proposed feasible solution**
  - An addition constraint of degrading exactly $x\%$ bandwidth utilization for the first $i$ STAs for all $i$

- Define the **BU for the first $i$ STAs** as the average time used for transmission by the first $i$ STAs over the access start time of STA $(i+1)$

$$
\frac{i(1-p)\overline{L}}{t_{MP}(i) + i(1-p)\overline{L} + i \cdot Slot + (i(1-p) + 1)SIFS} = (1) \times \frac{100 - x}{100}
$$

(1)
<table>
<thead>
<tr>
<th>Notations</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WT_i$</td>
<td>The wake-up time of STA $i$, $1 \leq i \leq n$, relative to the end of the multi-poll frame.</td>
</tr>
<tr>
<td>$l(t)$</td>
<td>The probability density function (pdf) of required transmission time conditioning on there are traffic arrivals.</td>
</tr>
<tr>
<td>$\bar{L}$</td>
<td>The mean transmission time for the traffic arrival to an STA in one SI conditioning on there is something to transmit ($\bar{L} = \int_0^\infty tl(t)dt$).</td>
</tr>
<tr>
<td>$h(t)$</td>
<td>The pdf of the required transmission time for traffic arrivals to an STA ($h(t) = p \cdot \delta(t) + (1 - p)l(t)$, where $p$ is the probability of no traffic arrival in one SI and $\delta(t)$ represents the Dirac delta function).</td>
</tr>
<tr>
<td>$s_i(t)$</td>
<td>The pdf of the transmission start time for STA $i$ if it has data to transmit.</td>
</tr>
<tr>
<td>$\bar{S}_i$</td>
<td>The mean transmission start time for STA $i$, relative to the end of the multi-poll frame, if it has data to transmit ($\bar{S}_i = \int_0^\infty ts_i(t)dt$).</td>
</tr>
<tr>
<td>$u_i(t)$</td>
<td>The pdf of the total duration for STAs 1, 2, ..., and $i$ to finish their transmissions. $u_i(t) = p \cdot u_{i-1}(t) + (1 - p)(l(t) \otimes s_i(t))$</td>
</tr>
<tr>
<td>$U_i(t)$</td>
<td>The cumulative distribution function (CDF) of $u_i(t)$ ($U_i(t) = \int_0^t u_i(\tau)d\tau$).</td>
</tr>
<tr>
<td>$t_{MP}(i)$</td>
<td>The time for receiving and verifying a multi-poll frame which contains $i$ STAs.</td>
</tr>
</tbody>
</table>
Energy-Efficient Wake-up Time Schedule

• The process to calculate $WT_i$ can be depicted in two steps
  
  1. Find the target $\overline{S_i}$ satisfying the requirement of BU
  2. Solve for $WT_i$ making the $\overline{S_i}$ as expected by the relationship

• The derivation can be done iteratively from $i = 1$ to $i = n$
  
  – For $i = 1$

\[
\frac{t_{MP}(1) + (1 - p)L + Slot + (2 - p)SIFS}{t_{MP}(1) + \overline{S_2}} = (100 - x)\%
\]
Illustration of WTS calculation

\[
\overline{S}_i = U_{i-1}(WT_i)(WT_i + SIFS + (i - 1)\text{Slot}) + \int_{WT_i}^{\infty} (t + SIFS + \text{Slot}) u_{k-1}(t)dt
\]

\[U_i(t) = \text{The cumulative distribution function (CDF) of } u_i(t)\]

\[(U_i(t) = \int_0^t u_i(\tau)d\tau).\]
Energy-Efficient Wake-up Time Schedule

• Calculation for \( WT_2 \)

\[
\frac{t_{MP}(1) + (1 - p)\overline{L} + Slot + (2 - p)SIFS}{t_{MP}(1) + \overline{S}_2} = (100 - x)\%
\]

\[
\overline{S}_2 = U_1(WT_2)(WT_2 + SIFS + Slot)
+ \int_{WT_2}^{\infty} (t + SIFS + Slot)u_1(t)dt.
\]
Energy-Efficient Wake-up Time Schedule

• Calculate $u_2(t)$

$$s_2(t) = \begin{cases} 
0, & \text{if } t < WT_2 + SIFS + Slot. \\
U_1(WT_2)\delta(t - (WT_2 + SIFS + Slot)), & \text{if } t = WT_2 + SIFS + Slot. \\
u_1(t - (SIFS + Slot)), & \text{if } t > WT_2 + SIFS + Slot. 
\end{cases}$$

$$u_2(t) = p \cdot u_1(t) + (1 - p)(l(t) \otimes s_2(t))$$

Note that $h(t) = p \cdot \delta(t) + (1 - p)l(t)$
Energy-Efficient Wake-up Time Schedule

• Calculation for $WT_3$

$$\frac{t_{MP}(2) + 2(1 - p)\overline{L} + 2\text{Slot} + (3 - 2p)SIFS}{t_{MP}(2) + \overline{S}_3} = (100-x)\%.$$  

$$\overline{S}_3 = U_2(WT_3)(WT_3 + SIFS + 2\text{Slot}) + \int_{WT_3}^{\infty} (t + SIFS + Slot)u_2(t)dt.$$
Energy-Efficient Wake-up Time Schedule

• Calculate \( u_3(t) \)

\[
s_3(t) = \begin{cases} 
0, & \text{if } t \leq WT_3 + SIFS + \text{Slot}. \\
u_2(t - (SIFS + \text{Slot})), & \text{if } t \in (WT_3 + SIFS + \text{Slot}, \ WT_3 + SIFS + 2\text{Slot}). \\
U_2(WT_3)\delta(t - (WT_3 + SIFS + 2\text{Slot})), & \text{if } t = WT_3 + SIFS + 2\text{Slot}. \\
u_2(t - (SIFS + \text{Slot})), & \text{if } t > WT_3 + SIFS + 2\text{Slot}.
\end{cases}
\]

\[
u_i(t) = p \cdot u_{i-1}(t) + (1 - p)(l(t) \otimes s_i(t))
\]
Energy-Efficient Wake-up Time Schedule

• Calculation for $WT_k$

$$
\frac{t_{MP}(k-1) + (k-1)(1-p) \bar{L} + (k-1) Sslot + (k-(k-1)p) SIFS}{t_{MP}(k-1) + \bar{S}_k} = (100 - x)\%.
$$

$$
\bar{S}_k = U_{k-1}(WT_k)(WT_k + SIFS + (k - 1) Sslot))
+ \int_{WT_k}^{\infty} (t + SIFS + Slot) u_{k-1}(t) dt.
$$
Energy-Efficient Wake-up Time Schedule

• Calculate $u_k(t)$

$$s_k(t) = \begin{cases} 
0, & \text{if } t \leq WT_k + SIFS + Slot. \\
 u_{k-1}(t - (SIFS + Slot)), & \text{if } t \in (WT_k + SIFS + Slot, WT_k + SIFS + (k - 1)Slot). \\
 U_{k-1}(WT_k)\delta(t - (WT_k + SIFS + (k - 1)Slot)), & \text{if } t = WT_k + SIFS + (k - 1)Slot. \\
 u_{k-1}(t - (SIFS + Slot)), & \text{if } t > WT_k + SIFS + (k - 1)Slot. 
\end{cases}$$

$$u_k(t) = p \cdot u_{k-1}(t) + (1-p)(l(t) \otimes s_k(t))$$
Energy-Efficient Wake-up Time Schedule

• Implementation Issue
  – Bisection method can be adopted to solve for $WT_i$
    • The initial lower bound and upper bound can be selected as $WT_{i-1}$ and $S_i – \text{SIFS – Slot}$
  – Retransmission caused by channel error can be incorporated in the computation of WTS
    • Calculate WTS according to the modified random variable as $B = (1+q)A$, where $q$ is the frame error probability
  – Switchover delay $D$ should be taken into account

• $WT_i = \begin{cases} WT_i, & \text{if } WT_i > D. \\ 0, & \text{if } WT_i \leq D. \end{cases}$
Energy-Efficient Wake-up Time Schedule

• Analysis of Energy Efficiency
  – The CP-Multipoll with SJF

\[
A_{CPMP}(i) = \begin{cases} 
(1 - p)(SIFS + \bar{L}), & \text{if } i = 1. \\
(1 - p)\left[\bar{L} + p^{i-1}(SIFS + (i - 1)\text{Slot})
+ \int_{0+}^{\infty} (t + SIFS + \text{Slot})u_{i-1}(t)dt\right], & \text{if } i > 1.
\end{cases}
\]

\[
E_{CPMP} = \sum_{i=1}^{n} E_i
= \left[\sum_{i=1}^{n} (A_{CPMP}(i) + t_{MP}(n))\right]P_A + \\
\left[ n \cdot SI - \sum_{i=1}^{n} (A_{CPMP}(i) + t_{MP}(n))\right]P_D.
\]
Energy-Efficient Wake-up Time Schedule

• Analysis of Energy Efficiency
  – The EE-Multipoll and WTS

\[
A_{EEMP}(i) = \begin{cases} 
(1 - p) (SIFS + \overline{L}), & \text{if } i = 1. \\
(1 - p) (\overline{L} + \text{sensing}_i + \text{overhearing}_i + \text{hw\_delay}_i), & \text{if } i > 1.
\end{cases}
\]

\[
\text{overhearing}_i = \int_{WT_i}^{\infty} (t - WT_i) u_{i-1}(t) dt
\]

\[
E_{EEMP} = \left[ \sum_{i=1}^{n} (A_{EEMP}(i) + t_{MP}(n)) \right] P_A + \\
\left[ n \cdot SI - \sum_{i=1}^{n} (A_{EEMP}(i) + t_{MP}(n)) \right] P_D.
\]
Energy-Efficient Wake-up Time Schedule

• Impact of Estimation Discrepancy
  – Since there could be estimation error for the pdf, the actual degradation of BU is likely to deviate from the desired value
  – Estimation error
    \[ e_{i-1}(t) := u_{r,i-1}(t) - u_{i-1}(t) \]
  – The discrepancy of expected transmission start time
    \[
    ER_i := \bar{S}_{r,i} - \bar{S}_i \\
    = \int_0^{WT_i} (WT_i + SIFS + (i - 1)Slot)e_{i-1}(t)dt \\
    + \int_{WT_i}^{\infty} (t + SIFS + Slot)e_{i-1}(t)dt.
    \]
Energy-Efficient Wake-up Time Schedule

• Impact of Estimation Discrepancy
  – The relationship between the expected BU loss, $x$, and the actual one, $y$, by $ER_i$:

$$
 y = \frac{100(S_r,i - S_{CPMP,i})}{t_{MP}(i-1) + S_r,i} \\
 = \frac{100(ER_i + S_i - S_{CPMP,i})}{t_{MP}(i-1) + ER_i + S_i} \\
 = \frac{x(t_{MP}(i-1) + S_{CPMP,i}) + (100-x)ER_i}{(t_{MP}(i-1) + S_{CPMP,i}) + \frac{100-x}{100}ER_i},
$$

– $y$ will be close to $x$, if

$$
 x(t_{MP}(i-1) + S_{CPMP,i}) \gg ER_i
$$

• This tends to be true when $i$ is large and/or every STA transmit large amount of traffic
Performance Evaluation

• Three examples are studied for the proposed WTS strategy
• The PHY parameters conform to the IEEE 802.11a standard
• Since we made some simplification on sensing time in the analysis, we conduct computer simulations to verify our result
• The considered scenario is composed of $n$ STAs, $1 \leq n \leq 20$, with i.i.d. traffic
• $x$ is set to 5
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHY Data Rate</td>
<td>54 Mbps</td>
</tr>
<tr>
<td>PHY Control Rate</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>Transmission time for PHY header and preambles</td>
<td>20 $\mu$s</td>
</tr>
<tr>
<td>Transmission time for an OFDM symbol</td>
<td>4 $\mu$s</td>
</tr>
<tr>
<td>SIFS</td>
<td>16 $\mu$s</td>
</tr>
<tr>
<td>Slot Time</td>
<td>9 $\mu$s</td>
</tr>
<tr>
<td>MAC frame header</td>
<td>30 bytes</td>
</tr>
<tr>
<td>ACK frame</td>
<td>14 bytes</td>
</tr>
<tr>
<td>IP header</td>
<td>20 bytes</td>
</tr>
<tr>
<td>UDP header</td>
<td>8 bytes</td>
</tr>
<tr>
<td>RTP header</td>
<td>12 bytes</td>
</tr>
<tr>
<td>Service Interval</td>
<td>25 ms</td>
</tr>
<tr>
<td>Beacon Interval</td>
<td>100 ms</td>
</tr>
<tr>
<td>Power Consumption in Awake state</td>
<td>1.4 W</td>
</tr>
<tr>
<td>Power Consumption in Doze state</td>
<td>0.045 W</td>
</tr>
<tr>
<td>Hardware delay of switchover</td>
<td>250 $\mu$s</td>
</tr>
</tbody>
</table>
Performance Evaluation

• Example 1

— Assume \( h(t) = p \cdot \delta(t) + (1 - p)\delta(t - \bar{L}) \)

— \( p \) is set to 0.6 for a typical On-off Voice model

— \( \bar{L} \), the time for exchanging a constant-length Data frame, is set to 200 \( \mu\text{s} \)

— The mean and standard deviation of the model

\[
\mu = 0.4\bar{L} \\
\sigma = \sqrt{0.24\bar{L}}
\]
Example 1

(a) Performance of Bandwidth Utilization (x = 5)

(b) Performance of Energy Saving (x = 5)
Performance Evaluation

• Example 2
  – Assume \( h(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} \)
    where \( \mu = 1000\mu\text{s}, \sigma = 200\mu\text{s} \)
  – It models the aggregated traffic of multiple connections from an STA
  – We also study the impact of channel error with \( q = 0.1 \) in this example
  – Better energy saving performance since the coefficient of variation \( (\sigma/\mu) \) of this model and the impact of overhead (sensing, switchover) is smaller than those of Example 1
  – The performance of the proposed WTS for this model with different standard deviations is studied
Example 2

(a) Performance of Bandwidth Utilization (x = 5)

(b) Performance of Energy Saving (x = 5)
### WTS for different standard deviation

<table>
<thead>
<tr>
<th>STA $i$</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{S_i} , (\mu s)$</td>
<td>1099</td>
<td>2179</td>
<td>3258</td>
<td>4337</td>
<td>5417</td>
<td>6496</td>
<td>7576</td>
</tr>
<tr>
<td>$WT_i , (\text{std} = 100 , \mu s)$</td>
<td>1051</td>
<td>2112</td>
<td>3180</td>
<td>4245</td>
<td>5318</td>
<td>6388</td>
<td>7465</td>
</tr>
<tr>
<td>Energy saved for the first $i$ STAs (%)</td>
<td>15.22</td>
<td>28.08</td>
<td>37.76</td>
<td>45.16</td>
<td>50.98</td>
<td>55.65</td>
<td>59.49</td>
</tr>
<tr>
<td>$WT_i , (\text{std} = 200 , \mu s)$</td>
<td>969</td>
<td>1998</td>
<td>3045</td>
<td>4100</td>
<td>5166</td>
<td>6225</td>
<td>7305</td>
</tr>
<tr>
<td>Energy saved for the first $i$ STAs (%)</td>
<td>13.57</td>
<td>25.89</td>
<td>35.41</td>
<td>42.80</td>
<td>48.66</td>
<td>53.40</td>
<td>57.34</td>
</tr>
<tr>
<td>$WT_i , (\text{std} = 300 , \mu s)$</td>
<td>866</td>
<td>1851</td>
<td>2871</td>
<td>3900</td>
<td>4955</td>
<td>5981</td>
<td>7030</td>
</tr>
<tr>
<td>Energy saved for the first $i$ STAs (%)</td>
<td>11.43</td>
<td>23.04</td>
<td>32.32</td>
<td>39.63</td>
<td>45.54</td>
<td>50.31</td>
<td>54.28</td>
</tr>
</tbody>
</table>
Performance Evaluation

• Example 3
  – We study the performance of using Normal distribution as an approximation of the density function of true traffic arrivals
  – The traffic arrivals are assumed to follow the Poisson and the Exponential distributions with identical means selected to be 1000μs
  – As the number of STAs increases, the losses of BU for both traffic models approach the desired value
    • Central Limit Theorem
Example 3

(a) Performance of Bandwidth Utilization (x = 5)

(b) Performance of Energy Saving (x = 5)
Conclusion

• Current ordered-contention multi-polling schemes significantly improve BU by reducing control overhead
• However, overhearing causes wastage on energy consumption
• This work provides a PM method which aims at achieving maximal energy saving subject to a pre-defined degradation on BU
• An interesting and challenging further research topic is to efficiently incorporate QoS guarantee into the proposed EEMP mechanism
References


Thanks for your attention!
Two-Step Multipoll