Optimization of Transceiver Energy Consumption in Wireless Sensor Networks

Presented by
Tianqi Wang
Introduction

• Motivation:
  • Minimizing Energy Consumption is a very important design consideration when frequent battery replacement is impractical (such as in wireless sensor networks (WSN))

• Given the difficulties of joint optimization of all layers, a pair-wise PHY-layer optimization is considered.

• In short-distance wireless communication systems (such as densely distributed WSN), circuit energy consumption and transmission energy consumption should both be considered.
Introduction

• Target
  • Minimize energy consumption per information bit considering the impacts of overhead and retransmission;

• Adjustable Parameters
  • Packet length
    • Tradeoff between overhead and retransmission probability;
  • Target bit error probability
    • Tradeoff between transmission power consumption and retransmission probability;
  • Modulation Schemes (Constellation Size)
    • Tradeoff between bandwidth efficiency and energy efficiency;
System Model

- Fig. A typical transmitter architecture
System Model

- Fig. A typical receiver architecture
System Model

- Total energy required to transmit/receive one packet

\[ E = P_{on} T_{on} \]
\[ = (P_t + P_{amp} + P_c)T_{on} \]
\[ = (P_t + \beta P_t + P_c)T_{on} \]

- The energy consumption when the transceiver is in active mode (modulation/demodulation, filter, power amplifier, ADC/DAC, mixer, frequency synthesizer)
Packet Structure

- Fig. Packet Structure
Energy Consumption per Information Bit

- The energy consumption of transmitting/receiving one packet

\[ \gamma = \frac{P_r}{P_{\text{noise}}} \]

\[ P_{\text{noise}} = 2BN_0 \]

\[ P_r = P_t / G(d) \]

\[ E = (1 + \beta)2BN_0G(d)f(P_b)T_{on}/G_c + P_cT_{on} \]

\[ T_{on} = (T_L + T_{UH} + T_H)/R_c + T_p \]
Energy Consumption per Information Bit

- Bit Error Probability w.r.t. SNR per Symbol

<table>
<thead>
<tr>
<th>Modulation</th>
<th>$P_b(\gamma)$</th>
<th>$\eta$ (bits/Hertz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>$P_b = Q(\sqrt{2\gamma}) \leq \frac{1}{2} e^{-\gamma}$</td>
<td>$\eta = 1$</td>
</tr>
<tr>
<td>MPSK</td>
<td>$P_b = \frac{2}{\log_2 M} Q(\sqrt{2\gamma \sin(\frac{\pi}{M})})$</td>
<td>$\eta = \log_2 M$</td>
</tr>
<tr>
<td>MQAM</td>
<td>$P_b \approx \frac{4}{\log_2 M} Q(\sqrt{\frac{3\gamma}{M-1}})$</td>
<td>$\eta = \log_2 M$</td>
</tr>
<tr>
<td>MFSK</td>
<td>$P_b \approx \frac{M-1}{\log_2 M} Q(\sqrt{\gamma})$</td>
<td>$\eta = \frac{2 \log_2 M}{M}$</td>
</tr>
</tbody>
</table>
Energy Consumption per Information Bit

Fig. The procedure to transmit one packet with $m$ transmissions
Energy Consumption per Information Bit

- The Energy Consumption during Each Time Period
  \[
  E_{tr} = P_{syn}T_{tr},
  \]
  \[
  E_{IFS} = P_{syn}T_{IFS},
  \]
  \[
  E_{LN} = (P_{cr} - P_v)T_{ACK},
  \]
  \[
  E_{ACK} = P_{cr}T_{ACK},
  \]
  \[
  E_{tx} = \left[(1 + \beta)2BN_0G(d)f(P_b)/G_c + P_{ct}\right]T_{on}.
  \]

- The Transmit Energy Consumption of m transmissions
  \[
  E_t(m) = (2E_{IFS} + E_{tx} + E_{LN})(m - 1) + 2E_{tr}
  + 2E_{IFS} + E_{tx} + E_{ACK}.
  \]
Energy Consumption per Information Bit

\[ E_{\text{tr}} \quad E_{\text{rx}} \quad E_{\text{IFS}} \quad \text{OFF} \]

\[ m - 1 \text{ retransmissions} \quad m^{th} \text{ transmission} \]

Fig. The procedure to receive one packet with m transmissions
Energy Consumption per Information Bit

- The Energy Consumption during Each Time Period
  \[
  E_{tr} = P_{syn}T_{tr},
  \]
  \[
  E_{IFS} = P_{syn}T_{IFS},
  \]
  \[
  E_{ACK} = P_t' T_{ACK},
  \]
  \[
  E_{rx} = P_{cr} T_{on}.
  \]

- The Receiving Energy Consumption of \( m \) transmissions
  \[
  E_r(m) = (2E_{IFS} + E_{rx})m + 2E_{tr} + E_{tx}^{ACK}
  \]
Energy Consumption per Information Bit

- The Average Energy Consumption

\[
E_t = \sum_{i=1}^{\infty} E_t(i) \Pr\{m = i\}
\]

\[
E_r = \sum_{i=1}^{\infty} E_r(i) \Pr\{m = i\}
\]

- Packet Error Probability

\[
P_{pe} = 1 - (1 - P_b)^L
\]

- The Probability of Transmission Number = m,

\[
P_t(m = i) = P_{pe}^{i-1} (1 - P_{pe})
\]
Energy Consumption per Information Bit

- The Average Energy Consumption to Transmit/receive \( K \) information bits

\[
\bar{E}_{total} = \frac{K}{L_L}(\bar{E}_r + \bar{E}_t)
\]

\[
\bar{E}_t \approx \frac{(2E_{IFS} + E_{tx} + E_{LN})}{1 - P_{pe}} + 2E_{tr} + P_v T_{ACK}
\]

\[
\bar{E}_r \approx \frac{(2E_{IFS} + E_{rx})}{1 - P_{pc}} + 2E_{tr} + E_{tx}^{ACK}
\]
Energy Consumption per Information Bit

• To minimize the energy consumption of transmitting/receiving K information bits (consider retransmission and overhead)

\[
\hat{\partial} \frac{\partial E_{\text{total}}(B, d, L_L, P_b)}{\partial P_b} = 0
\]

\[
\hat{\partial} \frac{\partial E_{\text{total}}(B, d, L_L, P_b)}{\partial L_L} = 0
\]
Generics Model of Energy Consumption per Bit

- To minimize the energy consumption of transmitting/receiving $K$ information bits (consider retransmission and overhead)

$$L^*_L = \frac{-B_1 + \sqrt{B_1^2 - 4A_1C_1}}{2A_1}.$$  

$$P^*_b \approx \frac{1}{1 + (L_L + L_{UH})[\ln\left(\frac{2}{b}\right) + 10 + \frac{P_{cT_{on}} + 4E_{IFS} + E_{LN}}{\frac{2}{3}(2^b - 1)A_2}]}.$$
The impact of packet length and target bit error probability on energy consumption

Average Energy Consumption of successfully transmitting/receiving one information bit (16 QAM)
Simulation and Analysis

Fig. The Optimum Target Bit Error Probability v.s. distance

2008/7/1
Simulation and Analysis

Fig. Optimum Packet Length v.s. distance

Overall Optimized Packet length (in bits) with fixed overhead length = 160 bits

- BPSK
- QPSK
- 16QAM
- Coded BPSK
- Coded QPSK
- Coded 16QAM

d (meters)

Overall Optimized Packet length (in bits)

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

$5 \times 10^5$

2008/7/1
Simulation and Analysis

Fig. The optimized energy consumption of different modulation schemes v.s. distance.
Simulation and Analysis

Fig. The optimized receiver energy consumption of different modulation schemes v.s. distance
Simulation and Analysis

Fig. The Optimization Gain
Simulation and Analysis

- The Configuration as reference is $P_b = 10^{-4}$ $L_L = 128$ Bytes

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<tr>
<th>Modulation</th>
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<tr>
<td>BPSK</td>
<td>0.56 ~ 2.63 dB</td>
</tr>
<tr>
<td>Coded BPSK</td>
<td>0.61 ~ 2.04 dB</td>
</tr>
<tr>
<td>QPSK</td>
<td>1.10 ~ 3.74 dB</td>
</tr>
<tr>
<td>Coded QPSK</td>
<td>0.82 ~ 2.79 dB</td>
</tr>
<tr>
<td>16QAM</td>
<td>1.81 ~ 5.35 dB</td>
</tr>
<tr>
<td>Coded 16QAM</td>
<td>1.11 ~ 3.98 dB</td>
</tr>
</tbody>
</table>

Fig. The Optimization Gain
Conclusions

- An optimization over target bit error probability and packet length is proposed to minimize the energy consumption per information bit with the consideration of retransmission;
- Uncoded modulation with large constellation size is energy efficient at short transmission distance, while coded modulation with small constellation size is energy efficient at large transmission distance;
- lower target bit error probability and large packet size is preferred at short transmission distance, while higher target bit error Probability and small packet size is preferred at large transmission distance.
Current Research

- Application-aware/Energy-aware Link Cost
  - Assign weights to transmit/receive energy

\[
C_{\text{link}}(n_i, n_j)^* = (N_{n_i} + 1)C_{\text{total}}(n_i)E_t(n_i, n_j) \\
+ (N_{n_j} + 1)C_{\text{total}}(n_j)E_r(n_i, n_j).
\]

\[
C_{\text{total}}(n_i) = \frac{1}{E_{\text{res}}(n_i)} + \max_{(x, y) \in A(n_i)} \frac{1}{E_{\text{cov}}(x, y)}.
\]
Current Research

- Application-aware/Energy-aware Link Cost
Current Research

- Application-aware/Energy-aware Link Cost

```
N_{e3} = 0
C_{total}(n_i) = 1
16QAM
P_s = 2.5 \times 10^{-7}
L_L = 160000

N_{e5} = 2
C_{total}(n_i) = 30
Coded QPSK
P_s = 4.9 \times 10^{-5}
L_L = 10400

N_{e6} = 3
C_{total}(n_i) = 20
Coded QPSK
P_s = 1.2 \times 10^{-6}
L_L = 21600

N_{e7} = 5
C_{total}(n_i) = 10
16QAM
P_s = 6 \times 10^{-6}
L_L = 131200
```

Data Sink
Current Research

- Average Link Delay

\[
\bar{T}_b = \frac{1}{L_L} \left( \frac{T_{on} + 2T_{IFS} + T_{ACK}}{P_{pc}} + 2T_{tr} \right)
\]

- Packet Error Probability

\[
P_{pc} = \sum_{n_e=0}^{N_{max}} \left( \frac{L_L + L_{UH}}{n_e} \right) P_{n_e} \left( 1 - P_b \right)^{L_L + L_{UH} - n_e}
\]
Current Research
Current Research

- Problem Modeling

\[
\begin{align*}
\min & \quad f(b, P_b, L_L) \\
\text{subject to} & \quad P_{tx}(n_i) \leq P_{max}; (\text{Peak Power Constraints}) \\
& \quad \bar{R}_b \geq R_{min}; (\text{Throughput Constraints}) \\
& \quad P_t(n_i) \geq 0; P_r(n_i) \geq 0; (\text{Default Constraints})
\end{align*}
\]