Energy Efficient Protocols for Low Duty Cycle
Wireless Sensor Networks

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Environment Monitoring Sensor Network

Application Scenario: Factory machine monitoring

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Cell density</td>
<td>&lt; 300 in 5m x 5m</td>
</tr>
<tr>
<td></td>
<td>&lt; 3000 in 100m x 100m</td>
</tr>
<tr>
<td>Range of link</td>
<td>&lt; 10 meters</td>
</tr>
<tr>
<td>Packet rate (packet = 2 bytes)</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>20 packets/sec</td>
</tr>
<tr>
<td>max</td>
<td>100 packets/sec</td>
</tr>
<tr>
<td>min</td>
<td>2 packets/sec</td>
</tr>
<tr>
<td>Packet Error Rate</td>
<td>&lt; 10^{-6} after 5ms</td>
</tr>
<tr>
<td></td>
<td>&lt; 10^{-9} after 10ms</td>
</tr>
<tr>
<td></td>
<td>&lt; 10^{-12} after 15ms</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.725~5.875GHz ISM</td>
</tr>
</tbody>
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<courtesy of ABB research>

- Minimize the energy consumption of the sensors by efficient protocols based on energy models extracted from physical layer electronics
Average Power = $N_{tx-avg} \{P_{tx} (T_{transmit} + T_{start}) + P_{out} T_{transmit}\} + N_{rx-avg} P_{rx} (T_{receive} + T_{start})$

- $P_{rx/tx}$ dominates over $P_{out}$ ($<< 0\text{dBm}$) due to short distance

- Startup cost significant portion of overall power
Effect of Startup Transient

- Startup energy must be taken into account in protocol design

100bit packet, $P_{tx}=10\text{mW}$, $P_{out}=0\text{dBm}$
Low Power MAC

\[ T_{\text{collision}} = \frac{T_{\text{guard}}}{\delta} \]

\[ N_{rx} = \frac{\delta}{T_{\text{guard}}} \]

\[ P_{avg} = N_{tx} \cdot (P_{tx} \cdot (T_{\text{transmit}} + T_{\text{start}}) + P_{out} \cdot T_{\text{transmit}}) \]

\[ + N_{rx} \cdot P_{rx} \cdot (T_{\text{receive}} + T_{\text{start}}) \]

- Trade off between transmitter and receiver energy consumption
Hybrid TDM-FDM

- Higher receiver power prefers FDM, lower receiver power prefers TDM
Variable frequency band allocation

- Variable bandwidth allocation allows more average bandwidth per sensor
- Cochannel interference must be avoided
Energy vs Bandwidth

- Large bandwidth allows less synchronization & less energy consumption
By maintaining time synchronized network, time-frequency slots can be assigned to sensors such that co-channel interference is avoided.
Variable bandwidth allocation scheme achieves lower energy as the variance in spatial distribution of sensors gets large.
Modulation

\[ E_{\text{binary}} = P_{\text{tx-B}} (T_{\text{on}} + T_{\text{start}}) + P_{\text{out-B}} T_{\text{on}} \]

\[ E_{M\text{-ary}} = P_{\text{tx-M}} (T_{\text{on}} / n + T_{\text{start}}) + P_{\text{out-M}} T_{\text{on}} / n \]

\[ = \alpha P_{\text{tx-B}} (T_{\text{on}} / n + T_{\text{start}}) + P_{\text{out-M}} T_{\text{on}} / n \]

\[ \alpha = \frac{P_{\text{tx-M}}}{P_{\text{tx-B}}} \]
Energy comparison

\[ E_{M\text{-ary}} < E_{binary} \text{ if } \alpha < \frac{P_{tx-B} (T_{on} + T_{start}) + P_{out-B} T_{on} - P_{out-M} T_{on}/n}{P_B (T_{on}/n + T_{start})} \]

- Worth going to M-ary modulation only if overhead \( \alpha \) and \( T_{start} \) is small
Conclusion

❑ Low power MAC : hybrid TDM-FDM
  - Trade-off between energy consumption of transmitter and receiver

❑ Variable bandwidth allocation scheme
  - Exploit the wide spatial distribution of static sensor network

❑ Modulation scheme
  - M-ary more energy efficient if overhead and startup time is small

❑ Design of communication protocols must incorporate non-ideal behaviours of physical layer electronics.