Time-Sensitive Utility-Based Routing in Duty-Cycle Wireless Sensor Networks with Unreliable Links

Mingjun Xiao\textsuperscript{a,b}, Jie Wu\textsuperscript{b}, Liusheng Huang\textsuperscript{a}

\textsuperscript{a} University of Science and Technology of China
\textsuperscript{b} Temple Univeristy

SRDS 2012
Introduction: utility-based routing

- **Concept**: Utility-based routing
  - **Utility** is a composite metric
    \[
    \text{Utility} (u) = \text{Reliability} (\rho) \times \text{Benefit} (b) - \text{Cost} (c)
    \]
  - **Benefit** is a reward for a routing
    - succeed: a positive reward
    - fail: 0 reward
  - **Cost** is the total transmission cost for the routing
  - Benefit and cost are uniformed as the same unit
  - **Objective** is to maximize the utility of a routing
Introduction: utility-based routing

- **Motivation** of Utility-based Routing
  - **Valuable** package: FedEx (more reliable, costs more)
  - **Regular** package: Regular mail (less reliable, costs less)
Duty-cycle WSN

Each node has two working states:
- **active**: all functions (send/receive, etc.).
- **dormant**: can be waked up by a timer to send packets.

- Each sensor schedules its working states periodically
- There is a non-negligible delivery delay.
Introduction: duty-cycle WSN

Any duty-cycle WSN can be converted to a direct weighted graph

\[ \langle p \text{ (reliability)}, t \text{ (delay)}, c \text{ (cost)} \rangle \]

A duty-cycle WSN: \[ \langle V, W = \{\langle p, t, c \rangle \} \rangle \]
Utility-based routing

Duty-cycle WSN

delivery delay is an important factor for the routing design

Time-sensitive utility-based routing
Time-sensitive utility model

- **Benefit:** a linearly decreasing reward over time
  \[ b(t) = \begin{cases} 
  \beta - t \cdot \delta, & \text{successful delivery} \\
  0, & \text{failed delivery} 
  \end{cases} \]

- **Utility:** \( u = b(t) - c \)

- Remaining benefit \( b \) & Expected utility \( u(b) \)
• **Time-sensitive utility-based routing**
  - duty-cycle network $G = \langle V, W \rangle$,
  - source $s$, destination $d$, initial benefit $\beta$, benefit decay coefficient $\delta$,
  - **Objective**: maximize $u_s(\beta)$.

![Diagram of network with nodes and edges](image-url)
• Expected utility for a single path

\[ \beta = 45, \ \delta = 1 \]

\[
\begin{array}{ccc}
\text{benefit} & \text{cost} \\
\text{Succeed (} \rho \text{):} & 45 - 1 \times 5 = 40 & 10 \\
\text{Fail (} 1 - \rho \text{):} & 0 & 10 \\
\text{Expected} & 0.8 \times 40 + 0.2 \times 0 & 10 \\
\end{array}
\]

– Expected utility:

\[ u_s(\beta) = p_{s,d} \times (\beta - \delta \times t_{s,d}) - c_{s,d} = 0.8 \times 40 - 10 = 22 \]
Solution

- Expected utility for a single path

\[ u_s(\beta) = \prod_{i=0}^{n-1} p_{i,i+1} \left( \beta - \delta \sum_{i=0}^{n-1} t_{i,i+1} \right) - \sum_{i=0}^{n-1} c_{i,i+1} \prod_{j=0}^{i-1} p_{j,j+1} \]

Require the global information inefficient for multiple paths
• **Local iterative formula (Theorem 2)**

**Forward:**
\[ b_j = b_i - \delta^* t_{i,j} \]

**Backward:**
\[ u_i(b_i) = p_{i,j}^* u_j(b_j) - c_{i,j} \]
1. The number of $b_i$ needs to be calculated is limited. Especially for a well scheduled duty-cycle WSN, the number is a small value (an example in paper).

2. When we compute $b_i$ and $u_i (b_i)$ for the largest $\beta$, the $b_i$ and $u_i (b_i)$ for other $\beta$ are also calculated.
## Solution

- Example:

\[ \langle 0.8, 5, 1.0 \rangle \quad \beta = 5.0, \quad \delta = 1 \]

<table>
<thead>
<tr>
<th>Benefit</th>
<th>[ b_s = 5.0, \ b_1 = 4.5, \ b_d = 4.0 ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>directly computation</td>
<td>[ u_s = 0.8 \times 0.8 \times (5.0 - 1 \times (5+5)) - (1.0 + 1.0 \times 0.8) = 7.6 ]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Iteratively computation</th>
<th>[ u_d(b_d) = b_d = 4.0 ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ u_1(b_1) = p_{1,d} \times u_d(b_d) - c_{1,d} = 0.8 \times 4 - 1 = 2.2 ]</td>
<td></td>
</tr>
<tr>
<td>[ u_s(b_s) = p_{s,1} \times u_1(b_1) - c_{s,1} = 0.8 \times 2.2 - 1 = 7.6 ]</td>
<td></td>
</tr>
</tbody>
</table>
– Example:

![Graph with paths and benefits]

<table>
<thead>
<tr>
<th>path</th>
<th>benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 -t</td>
</tr>
<tr>
<td>s→1→d</td>
<td>7.6</td>
</tr>
<tr>
<td>s→2→d</td>
<td>4</td>
</tr>
<tr>
<td>s→2→1→d</td>
<td>2.5</td>
</tr>
<tr>
<td>s→1→2→d</td>
<td>1.6</td>
</tr>
</tbody>
</table>
## Simulation

**Settings**

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Default value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployment area S</td>
<td>$100m \times 100m$</td>
<td>-</td>
</tr>
<tr>
<td>Number of nodes $</td>
<td>V</td>
<td>$</td>
</tr>
<tr>
<td>Transmission probability</td>
<td>-</td>
<td>0.3-0.9</td>
</tr>
<tr>
<td>Transmission cost</td>
<td>-</td>
<td>1-10</td>
</tr>
<tr>
<td>Scheduling cycle</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Initial benefit</td>
<td>100</td>
<td>10-100</td>
</tr>
<tr>
<td>Benefit decay coefficient</td>
<td>0.02</td>
<td>0.02-0.2</td>
</tr>
<tr>
<td>Number of messages</td>
<td>10,000</td>
<td>-</td>
</tr>
</tbody>
</table>
Simulation

- Algorithms in comparison
  - MinDelay
  - MaxRatio
  - MinCost

- Metrics
  - Average utility
  - Average delivery delay
  - Average delivery ratio
  - Average delivery cost
Simulation

• Results
  – Average utility vs. initial benefit
• Results
  – Average utility vs. benefit decay coefficient
Simulation

• Results
  – Average utility vs.
    initial benefit & benefit decay coefficient
Simulation

• Results
  – Average delay vs.
    initial benefit & benefit decay coefficient
Simulation

• Results
  – Average ratio vs.
    initial benefit & benefit decay coefficient
Simulation

• Results
  – Average cost vs.
    initial benefit & benefit decay coefficient
Conclusion

• Our proposed algorithm outperforms the other compared algorithms in utility.

• The larger the initial benefit and the smaller the benefit decay coefficient are, the larger the average utility would be.

• Our proposed algorithm has achieved good performances with reliability, delay, and cost at the same time.
Thanks!

Q&A
Solution

• Example
Solution

• Example
Solution

• Example
Solution

- Example
Solution

- Example
Solution

• Example

\[ u_s(50) = 7.6 \]

\[ u_s(50) = P_{s,1} u_{1}(45) - c_{s,1} \]
\[ u_s(50) = P_{s,2} u_{2}(45) - c_{s,2} \]

\begin{align*}
& u_1(35) = 14 \\
& u_1(45) = 22 \\
& u_2(35) = 11 \\
& u_2(45) = 16 \\
& u_d(30) = 30 \\
& u_d(40) = 40
\end{align*}