An Experimental Evaluation of Selective Cooperative Relaying for Industrial Wireless Sensor Networks

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Quick Intro
Lots of theoretical work on cooperative relaying

Some experimental studies (40+ articles):

1. Software-Defined Radios: Mostly PHY Layer, few nodes
2. Wireless Sensor Nodes: MAC/Network layer, many nodes
Application in Industrial WSN

- Monitoring and control of production processes
- Harsh environment for wireless signal propagation
- Very strict requirements on link reliability and delay
- Standards: WirelessHART, ISA100.11a, Zigbee IA Profile
Which metrics to use for relay selection?
- Channel quality info, residual battery life, etc.

How selection is coordinated?
- Signaling messages, contention mechanism, etc.

How often a relay is updated?
- Update requirements and policy.
I. Periodic Relay Selection

A relay is selected strictly at periodic time intervals $T_{sel}$

- random contention of candidates in window $w$.
- based on current Link Quality Indicators $S - R$ and $R - D$. 

**selection**

- $S_{\text{RREQ}}$ (bc)
- rand(0, $w$)
- $S_{\text{RSEL}}$

**retransmission**

- $D_{\text{RSEL}}$
- $D_{\text{DATA}}$
- $T_{\text{ACK}}$
- err
- ACK (mc)
- $T_{\text{ACK}}$
- ACK
- ACK (mc)
II. Adaptive Selection

- A new relay selection when in a window $W_a$ more than $\varepsilon_a$ ACKs are lost.
- Selection and retransmission procedure same as periodic
III. Reactive Selection

Selection is performed after each missing ACK for direct S-D transmissions among nodes that

1. have received the packet correctly
2. have a good channel to the destination

**DATA delivery by S fails**

**DATA is delivered by S**
Test Environment
Hardware

- Crossbow TelosB
- TinyOS implementation
- Transmission: 2.4 GHz, 256 kbit/s, TxPower: -4 dBm
Two kind of experiments:

1. Trace-based analysis on individual link:
   Node 6 transmits to $D$ every 160 ms, other nodes retransmit

2. Explicit experimental comparison over all links
1. Periodic selection: every 200 packets
2. Adaptive selection: if error rate > 10% for last 50 packets.

![Graph showing delivery ratio vs. number of neighboring nodes for different node combination ids. The graph includes data for reactive, periodic, and adaptive methods. There are markers for direct transmissions only and time diversity.]
Periodic selection analysis

- Delivery ratio vs. selection period in data packets
- Number of selections per 100 data packets vs. selection period in packets

Graphs showing the impact of different relay configurations on delivery ratio and number of selections.
Performance Results: Trace-Based Analysis

Adaptive selection: Window

Adaptive selection: Error rate
Direct Comparison

Periodic
Adaptive
Reactive

Time division

Sample #

Delivery ratio per sample

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 500 1000 1500 2000

Exp.2. Test:3081

direct
periodic
adaptive
reactive

Sample #
Performance Results: Direct Comparison

- Measurements on 3 days, each 12 hours.
- Total 810K DATA packets sent by source nodes
- 33K on each link and each scheme, over 6 hours time.
- Periodic selection: $T_{sel} = 400 \cdot 160 \text{ ms} = 64 \text{ sec}$
- Adaptive selection: $W_a = 100$, $\varepsilon_a = 0.1$

Table: Mean Results over the Network

<table>
<thead>
<tr>
<th></th>
<th>direct</th>
<th>time div.</th>
<th>periodic</th>
<th>adaptive</th>
<th>reactive</th>
</tr>
</thead>
<tbody>
<tr>
<td>delivery ratio, %</td>
<td>81.2</td>
<td>85.7</td>
<td>96.9</td>
<td>97.9</td>
<td>98.9</td>
</tr>
<tr>
<td>selections per 100 pkts</td>
<td>-</td>
<td>-</td>
<td>1.08</td>
<td>1.11</td>
<td>22.7</td>
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<tr>
<td>number of candidates</td>
<td>-</td>
<td>-</td>
<td>3.69</td>
<td>3.86</td>
<td>3.43</td>
</tr>
<tr>
<td>selection success, %</td>
<td>-</td>
<td>-</td>
<td>94</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>relaying success,%</td>
<td>-</td>
<td>-</td>
<td>78</td>
<td>82</td>
<td>95</td>
</tr>
</tbody>
</table>
Performance Results: Direct Comparison

Delivery ratio in a sample

![Graph showing the cumulative distribution function (CDF) for delivery ratio in a sample for different transmission methods: single direct transmission, time diversity, periodic, adaptive, and reactive. The x-axis represents the delivery ratio in a sample, and the y-axis represents the CDF.]

Selections in a sample

![Graph showing the total delivery ratio over the delivery ratio by a single direct transmission in a sample for different transmission methods: time diversity, periodic, adaptive, and reactive. The x-axis represents the delivery ratio by a single direct transmission in a sample, and the y-axis represents the total delivery ratio.]

Selections in a sample
Performance Results: Direct Comparison

Delivery ratio in a sample

- time diversity
- periodic
- adaptive
- reactive
Conclusions

1. Cooperative relaying provides up to 99% delivery ratio
2. Short-term outages are also avoided
3. Adaptive selection provides best tradeoff between delivery ratio and selections overhead

Publications

Thank You for Your Attention!