Exploring Link Correlation for Efficient Flooding in Wireless Sensor Networks

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Design Challenges & The State of the Art

- Design challenges
  - Provide high reliability using unreliable wireless links
  - Reduce the number of redundant retransmissions

- Deterministic approaches
  - Dominating Set (MobiHoc ’02), DCB (INFOCOM ’04), Sprinkler (RTSS ’05)

- Probabilistic approaches
  - Predefined prob (MobiCom ’99), Gossip-based (ICDCS ’01), RBP (SenSys ’06)

  Assumption: Packet receptions are independent
  Empirical Study: Packet receptions are correlated!

Reduce redundant retransmissions  High reliability
Measurement of Link Behavior

Indoor

Outdoor

- Experiment setup
  - Hardware: 42 MICAz motes
  - Number of packets: 6000
Correlated Packet Reception

Packet receptions are NOT independent!

\[ P_s(N29 \mid N22) = 100\% \neq P_s(N29) = 47.29\% \]

\[ P_s(N23 \mid N22) = 100\% \neq P_s(N23) = 77.9\% \]
Packet receptions are highly correlated among receivers!
How to utilize the highly correlated packet receptions?

Collective acknowledgement (CA)

Dynamic Forwarder Selection

... details in the paper!
Traditional Reliable Flooding

<table>
<thead>
<tr>
<th>Node</th>
<th>Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>Yes</td>
</tr>
<tr>
<td>N2</td>
<td>?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>S</td>
<td>Yes</td>
</tr>
<tr>
<td>N2</td>
<td>?</td>
</tr>
</tbody>
</table>
CA: Utilizing Link Correlation

Conditional Packet Reception Probability

\[ P_s(N2|N1) = 100\% \]

Node | Covered
---|---
S | Yes
N2 | Yes

Provides high reliability with fewer transmissions!
CF Protocol Overview

- **Sender**
  - All Neighbors Are Covered
  - The uncovered node set
  - The coverage probabilities of its neighboring nodes

- **Receiver**
  - All Neighbors Are Covered

- **Maintenance**
  - Link Quality
  - CPRP

- **Initial Pseudostate**

**Flow:**
- Initial Pseudostate → Maintenance → Sender → Receiver → End
Passively maintain 2 pieces of information:
- Coverage probability $CP_u(k)$ for all its 1-hop neighbors $k \in N(u)$
- Estimated uncovered node set $U(u) \subseteq N(u)$

\[ CP_u(k) = X = P_v(k|u) \]

- If $CP_u(k) \geq \alpha$, $k$ is covered
- Else Set Timer
**Sender State**

- Actively maintain 2 pieces of information:
  - Coverage probability $CP_u(k)$ for all its 1-hop neighbors $k \in N(u)$
  - Estimated uncovered node set $U(u) \subseteq N(u)$

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<tr>
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<th>CP</th>
<th>Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>v</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>k</td>
<td>X</td>
<td>No</td>
</tr>
</tbody>
</table>

Uncovered probability before current transmission:

$CP_u(k) = X \leftarrow 1 - (1-X) \cdot (1-L(u, k))$

Probability that $k$ is covered either before or after current transmission:

- If $CP_u(k) \geq \alpha$, $k$ is covered
- Else Set Timer

End

Maintenance
CF Protocol

- Maintenance State

- Receiver State
  - **Passively** maintain 2 pieces of information
    - Coverage probability $CP_u(k)$ for all its 1-hop neighbors
    - Estimated uncovered node set

- Sender State
  - **Actively** maintain 2 pieces of information
    - Coverage probability $CP_u(k)$ for all its 1-hop neighbors
    - Estimated uncovered node set

- Back-off Timer

... details in the paper!
Evaluations

- Testbed implementation & large-scale simulations
  - Indoor: 37 MICAz motes
  - Outdoor: 48 MICAz motes (326-meter-long-bridge)

- Baseline solutions:
  - Standard Flooding (FLD)
  - RBP by F. Stann et al. in SenSys’06

- Evaluation Metrics:
  - Reliability
  - Message Overhead
  - Dissemination Delay
  - Load Balance
Outdoor Experiment Results

Reliability

Total Number of Packet Tx.

Packet Sequence Number

31.2%
Outdoor Experiment Results

Dissemination Delay

Packet Sequence Number

Dissemination Delay (s)

55.2%

Standard Deviation

Load Balance

RBP8 RBP4 FLD CF

RBP8 RBP4 FLD CF
System Insight Analysis

CDF of Neighbor Size

CDF of Dup. Packets Received
Conclusion

- Provided the first extensive study to exploit the link correlation for communication improvement through:
  - Collective acknowledgement
  - Dynamic forwarder selection

- Proposed collective ACKs
  - A new concept to improve the efficiency of reliable flooding
  - Transform traditional direct ACKs per receiver into correlated and accumulative ACKs

- CF design is simple, symmetric, and highly scalable.
  - Reduced total number of packet transmissions by 30~50%
Questions?

More at: www.cs.umn.edu/~tzhu

Acknowledgements: