Outline

- **Background**
  - Loss rate in WSNs
- **Application reliability requirements**
- **Where should reliability be implemented?**
  - MAC
  - Transport layer
- **Examples**
  - RMST, Wisden
- **Rate Control**
Loss rate in WSNs

- [GKW+],[ZG03] have shown that WSNs face harsh conditions
  - Loss rates can be up to 30%-50% between direct neighbors
  - Loss rates are variable
  - Loss rates cover a large range of values
Application Requirements

- Application requirements vary
  - Sample-and-collect: can tolerate errors
    - Scales to large networks? (cf. GDI report [ZG+04])
  - Network reprogramming: needs to reliably deliver a (fairly) large object over all the network nodes

- Related issues
  - Fragmentation/Reassembly
  - Fairness (next lecture)

- As always power consumption is the primary concern
Where to implement reliability? (1)

- MAC layer
  - ARQ mechanisms
    - No ARQ (Benefits?)
    - Unicast messages in 802.11, S-MAC use RTS/CTS/DATA/ACK mechanism for limited retransmissions (Stop-and-Wait)
    - Same mechanism can be extended to bcast/mcast (multiple copies)
    - Selective ARQ
Where to implement reliability? (2)

- **Transport layer**
  - End-to-End Selective Request NACK
  - Hop-by-Hop NACKs and local repair

- **Application layer**
  - End-to-End Positive ACK
RMST Overview

- Assumption: Works with Directed Diffusion
- Model: Eventual delivery of fragments to the destinations
  - No in-order delivery
  - No delay guarantees
- Receivers detect when fragment needs to be re-sent
  - Final destination or intermediate nodes can be receivers
- Receivers detect losses by “holes” in sequence numbers or by using timers
- After loss is detected, receiver send NACK to upstream node (using directed diffusion route)
  - Multiple requests can be sent in a single NACK
Analysis of MAC layer retries

- Assuming delivery probability $p$ and $R$ transmissions
  - Successful delivery probability across a single hop:
    $$p_h = 1 - (1 - p)^R$$
  - Successful delivery probability across $H$ hops:
    $$P_e = p_h^H$$

Probability of arrival across 40 hops with $p=0.1$ as a function of $R$
Effect of $p$

- ARQ with 3 retries operates well over large range of loss rates while performance of No ARQ deteriorates quickly
End-to-End Transport Layer performance

- Assuming large object is divided in $M$ fragments and transmitted across $H$ hops to destination. $\text{Prob}[\text{success}] = p_e$
- Expected number of fragments arriving at the destination:
  \[
  E[f(M,H)] = \sum_{m=1}^{M} m \cdot p_e^m \cdot (1 - p_e)^{M-m}
  \]
- Expected number of hops that failed packet will travel:
  \[
  E[f_h(H)] = \sum_{n=1}^{H} n \cdot p_e^{n-1} \cdot (1 - p_e)
  \]
- Approx cost of link-wise fragment transmissions with E2E transport layer:
  \[
  H \cdot E[f(M,H)] + E[f_h(H)] \cdot (M - E[f(M,H)])
  \]
Hop-by-Hop Transport Layer performance

- Data is cached at each hop and transport layer recovery happens on a per-hop basis.
- Expected number of retries to successfully transmit a fragment over single hop:
  \[ E[r(K)] = \sum_{k=1}^{\infty} k \cdot p_h \cdot (1 - p_h)^{k-1} \]
- Number of link-wise transmissions to send \( M \) fragments over \( H \) hops:
  \[ E[Tx(H, M)] = M \cdot H \cdot E[r(K)] \]
Comparison

Number of total transmissions to send $M$ Fragments over $N$ hops ($p=0.9$)

<table>
<thead>
<tr>
<th>Fragments</th>
<th>5 Hops</th>
<th>10 Hops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cache</td>
<td>No Cache</td>
</tr>
<tr>
<td>5</td>
<td>27.77</td>
<td>42.33</td>
</tr>
<tr>
<td>10</td>
<td>55.55</td>
<td>84.67</td>
</tr>
<tr>
<td>20</td>
<td>111.11</td>
<td>169.35</td>
</tr>
</tbody>
</table>

Effect of per hop success probability

If per-hop loss rate is > 1% then E2E requires many more retransmissions
Simulation Evaluation

- **Environment**
  - 802.11 MAC layer
  - Directed Diffusion
  - ns-2 simulation

- **Parameters**
  - Link Error Rate
  - Hop Count (6)
  - Number of MAC retries (4)
  - Message size (5K broken in 50 100-byte fragments)

- **Metric**
  - Ratio of total number of messages normalized to the cost of sending the message without ARQ or transport layer overhead
Simulation Results (1)

- **Baseline E2E positive ACK**
  - At low-loss rates MAC introduces overhead
  - Selective ARQ more efficient
  - When loss rate increases **No ARQ** requires many retransmissions

- **RMST with Hop-by-Hop Recovery**
  - At medium loss rates transport recovery offers very little added benefit over MAC recovery
  - At $p=0.1$ **No ARQ** 15% better than **Selective ARQ**

<table>
<thead>
<tr>
<th>PHY Error Rate</th>
<th>No ARQ</th>
<th>ARQ All</th>
<th>Selective ARQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.93 (.07)</td>
<td>.57 (.03)</td>
<td>.65 (.03)</td>
</tr>
<tr>
<td>.01</td>
<td>.51 (.04)</td>
<td>.56 (.03)</td>
<td>.61 (.05)</td>
</tr>
<tr>
<td>.10</td>
<td>.21 (.05)</td>
<td>.47 (.09)</td>
<td>.54 (.06)</td>
</tr>
</tbody>
</table>

**Table 2: End-to-End Positive ACK**
Normalized byte transmissions required for diffusion to transfer 50 fragments of 100 bytes across 6 hops without any transport layer

<table>
<thead>
<tr>
<th>PHY Error Rate</th>
<th>No ARQ</th>
<th>ARQ All</th>
<th>Selective ARQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.99 (.05)</td>
<td>.60 (.06)</td>
<td>.68 (.06)</td>
</tr>
<tr>
<td>.01</td>
<td>.95 (.06)</td>
<td>.57 (.06)</td>
<td>.67 (.07)</td>
</tr>
<tr>
<td>.10</td>
<td>.76 (.07)</td>
<td>.48 (.07)</td>
<td>.61 (.07)</td>
</tr>
</tbody>
</table>

**Table 3: Hop-by-Hop Selective NACK and Caching**
Normalized byte transmissions required for diffusion to transfer 50 fragments of 100 bytes across 6 hops with hop-by-hop caching and repair
Simulation Results (2)

- **RMST with E2E recovery (NACK)**
  - At $p=0.1$ very high loss
    - Hop-by-Hop recovery mechanism at transport of MAC is necessary
  - Little difference between E2E and hop-by-hop NACKs on top of MAC-level recovery (cf. Table 3)

- **High Loss**
  - Compare schemes that performed best at $p=0.1$
  - No-ARQ breaks (routing protocol cannot create paths)
  - E2E-RMST and HBH RMST perform similarly over Selective ARQ

### Table 4: End-to-End Selective NACK
Total byte transmissions required for diffusion to transfer 50 fragments of 100 bytes across 6 hops with end-to-end repair.

<table>
<thead>
<tr>
<th>PHY Error Rate</th>
<th>No ARQ</th>
<th>ARQ All</th>
<th>Selective ARQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0 (.05)</td>
<td>.61 (.08)</td>
<td>.67 (.07)</td>
</tr>
<tr>
<td>.01</td>
<td>.90 (.06)</td>
<td>.60 (.10)</td>
<td>.66 (.07)</td>
</tr>
<tr>
<td>.10</td>
<td>n/c</td>
<td>.49 (.09)</td>
<td>.61 (.07)</td>
</tr>
</tbody>
</table>

### Table 5: High Error Rate Test
Total byte transmissions required for diffusion to transfer 50 fragments of 100 bytes across 6 hops with high error rates.

<table>
<thead>
<tr>
<th>PHY Error Rate</th>
<th>Hop by Hop RMST NoARQ</th>
<th>Hop by Hop RMST Sel ARQ</th>
<th>End to End RMST Sel ARQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>.20</td>
<td>.48 (.19)*</td>
<td>.40 (.18)</td>
<td>.40 (.17)</td>
</tr>
<tr>
<td>.30</td>
<td>n/c</td>
<td>.24 (.23)</td>
<td>.27 (.25)</td>
</tr>
</tbody>
</table>
Wisden

- A wireless multi-hop sensor network based data acquisition system for structural health monitoring.
  
  - Reliable data delivery over multiple hops.
  - Time-synchronized data delivery from multiple sensor nodes.
  - Data compression at the source node to relieve bandwidth bottleneck.
  - Ease and flexibility of deployment.

Wisden Overview (Software)

- **Reliability**
  - Application layer NACK mechanism
  - Hybrid hop-by-hop and end-to-end loss recovery over self-configured multi-hop tree topology

- **Data Synchronization**
  - Calculate residence time of a packet within each node.
  - Time-stamp data at the base station by estimating the generation time.

- **Data Compression**
  - Lossy run-length encoding for silence suppression
  - Required to reduce data rate and relieve the bandwidth limitations of the motes
Deployment Setup

- 14 MicaZ node network
- 2~4 hop: multi-hop network
- 200Hz, single-axis sampling
- 5 minute experiment with 40 seconds of forced vibration
System Evaluation

- Achieved 100% delivery
  - With 9.5% of the packets being retransmitted