Title: Understanding Packet Delivery Performance in Dense Wireless Sensor Networks

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Overall Summary

- Studies packet delivery performance in sensor motes, using a 60-node network of Mica motes
- Study performed in three environments: indoor office building, habitat (state park), outdoor (parking lot; for experimental control)
- Study performed at PHY and MAC layers
- Main results:
  - There is a *long tail* in the distribution of error-rate; more than half the links had over 10% packet loss; one-third of the links had over 30% packet loss
  - Existence of *gray areas* in communication where the error rate is unpredictable and is also variable with time
  - CSMA/CA based MAC is quite inefficient and leads to 50-80% of energy being wasted in overcoming packet collisions
  - Nearly 10% of the links exhibit asymmetric packet loss
- The above results have implications on the design of sensor network protocols (mac, routing, transport, synchronization, etc.)
- *Topology control* may be useful: choosing the right set of neighbours to communicate

Related Work

- No such prior extensive study in a variety of environments
- Several studies of 802.11 networks exist with some results which are similar (asymmetry, variability in link performance); these are orthogonal to this study

Metrics and Methodology

- Primary metric: *packet loss rate* or its complement, the *reception rate*
- Motes are not calibrated, but are permuted to discount variability among motes
- Topology used is a chain topology
- Mica motes used with TinyOS: 4MHz Atmel (128KB EEPROM, 4KB RAM), 512 KB flash, ASK low-power 433MHz radio
- Omni-directional whip antenna
- MAC used is simple CSMA/CA: stable implementation in TinyOS available at that time; such implementation not available for S-MAC at that time

- Software modules: simple traffic generator, module to upload experimental parameters wirelessly (audible feedback was useful), logger component of TinyOS, precomputed intervals for exponential packet generation (to avoid collisions; TinyOS does not have any non-uniform random number generator)
- Questions at the PHY layer:
  - Packet loss in different environments
  - Temporal and spatial variation of packet loss
  - Dependence of packet loss on PHY coding
- Questions at the MAC layer:
  - How well does the CSMA/CA perform in terms of avoiding collisions?
  - What is the effect of link-layer retransmissions?
- What was the packet size used?

PHY Layer Experiments

- 60 motes in a linear chain, 0.5m apart from one another
- Nodes placed at finer granularity of 0.25m near the edge of communication range (for finer resolution)
- One end of the line transmit packets periodically once per second, with increasing sequence numbers
- All other nodes simply receive and store the received packets in local storage
- MAC level ACK mechanism disabled for this experiment
- Experiment in the three environments
- Experiments conducted on different days; node positions marked

PHY Layer Results

- Significant tail in the distribution of packet error (across the 60 nodes)
- Indoor environment worse than Habitat worse than Outdoor parking lot in terms of packet delivery performance
- Higher txpower is worse! Perhaps due to multipath? Unclear.
- 4BSB coding worse than Manchester; 4BSB almost same as Manchester, but Manchester coding has much more overhead.
- Plots in graphs not given in logical order (poorest performance to best performance: Fig 4 and Fig 6)
- Spatial pattern of loss indicates presence of *gray region* where some nodes have good performance and some have bad performance.
- Extent of gray area is about *one-third* of overall communication range for the indoor environment; and *one-fifth* for the habitat environment.
- The results are likely to be the same for low-power radios without frequency diversity (may be different with 802.15.4 in CC2420 chips).
- Existence of gray area means that 9/25 of the neighbours of a node are likely to be in the gray area: choose neighbours carefully for communication.
- High signal strength is a necessary but not a sufficient condition for good packet reception ratio.
- Spatial correlation high in mid communication range.
- Temporal variation high in mid communication range and in gray area.
- SECDED shows much lower temporal variation in packet error rate in most receivers.

MAC Layer Results

- Deployment seems too dense (neighbourhood size of 15-18 for indoor and parking lot environments)
- Deployment density seems different for habitat environments (6-8 nodes in neighbourhood)
- Poisson arrival of packets (to prevent synchronization): but seems quite far removed from any known sensor network data pattern

- Cannot distinguish between PHY layer packet error and packet error due to MAC layer collision
- Three packets per second is close to the nominal capacity (seems too high for periodic data, too small for continuous data transmission)
- CCDF for PHY layer and CDF for MAC layer data is confusing and makes direct visual comparison difficult
- 50-80% of energy spent in repairing lost transmissions
- Over 10% of links have over 50% asymmetry in packet delivery ratio

Positives

- First extensive measurements using actual implementation
- Well justified methodology, a variety of test cases, very useful results
- Well organized and well presented set of results

Negatives

- Some graph presentation can be better (CCDF in some graphs and CDF in others is confusing)
- Uses old radio (available readily at that time; shortcoming admitted in paper)
- MAC results are not that non-obvious (CSMA/CA without RTS/CTS is going to perform bad in multi-hop settings)
- High power transmission has worse performance, but many of the results are presented for this case (perhaps it was observed after data collection that surprisingly, high power transmission had worse behaviour)
- Poisson data arrival seems rather counter-intuitive
- Dense node deployment not really justified with citation of specific application/deployment

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