# Understanding Packet Delivery Performance in Dense Wireless Sensor Networks

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## Experimental Setup

- 60 motes
- Three environments
  - Office Building
  - Open Parking Lot
  - Natural Habitat
- Two sets of experiments
  - Linear topology with one sender, to study the packet delivery performance at the PHY layer
  - Ad Hoc deployment with nodes generating traffic periodically for one of its neighbors, to study the packet delivery performance at the MAC layer

## Hardware & Software

- Mica motes
  - 4 MHZ Amtel Processor,
  - 128 K EEPROM, 4 K RAM, and 512 K flash
  - Amplitude Shift Keying 433 MHZ radio (throughput is 20 Kbps)
  - Omni directional whip antenna
- TinyOS
  - SECDED coding
  - MAC layer implements a simple CSMA/CA scheme with link-level acknowledgements

## Three Environments

- Office Building (*I*)
  - Long hallway (40 m X 2 m)
  - Higher multi-path effects
- Open Parking Lot (*O*)
  - 150 m X 150 m
  - No obstacles
- Natural Habitat (*H*)
  - 150m X 150 m in a state park
  - Downhill slope
  - Significant multi-path effect from rock and foliage

## Three Environments

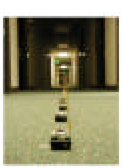

Figure 1: Experiments in an in-door environment *I*

Figure 2: Experiments in a habitat environment *H*

## PHY Experimental Setup

- 60 Motes
- Topology
  - 0.5 m separation (with 0.25 m spacing near the edge of communication range)
- Traffic Pattern
  - One node at the end of line transmits 1 packet/s and all other nodes just receive it and record it
- Experiment lasted 8 hours (data collected from hour 2 - hour 4) – 7200 packets for all receivers
- Transmission Power Setting
  - High, Medium and Low with potentiometer settings of 0, 50, and 90

## Coding Schemes

- SECDED
  - Default in TinyOS
  - Each Byte is encoded in 24 bits
  - 2 bit error detection and 1 bit error correction
- 4b6b
  - Encodes one byte into 12 bits
  - Detect 1 bit error out of 6 bits
- Manchester Encoding
  - Each byte is encoded in 16 bits
  - Detect 1 bit error out of 2 bits

## Packet Loss Characteristics

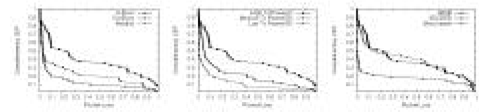

Figure 4: Packet Loss with 4b6b coding, high Tx power

Figure 5: Packet loss v.s. Tx power in J, 4b6b coding

Figure 6: Packet loss v.s. coding schemes in J, high Tx Power

## Packet Loss Analysis

- At least 20% of nodes had at least 10% packet loss
- At least 10% nodes had at least 30% packet loss
- Office building is the harshest environment
  - 33% nodes had a loss rate > 30%
  - 50% nodes had a loss rate > 10%

## Effect of Power Level on Packet Loss

- At low transmit power the loss rate is lower.
- Conjecture:
  - At low transmit power the reduced spatial extent of communication may reduce the likelihood of multi-path effect, contributing to better performance.

## Spatial Characteristics of Packet Delivery

Figure 7: Spatial profile of packet delivery for J, 4B6B, High Tx Power

Figure 8: Spatial profile for O, 4B6B, High Tx Power

Figure 9: Spatial profile for H, 4B6B, High Tx Power

## Analysis of Spatial Characteristics of Packet Loss

- The Inner Band
  - Upto a certain distance from the transmitter, the loss rate is uniformly low.
- The Gray Area
  - Loss rate varies dramatically, i.e. some nodes see 10% loss whereas some neighboring nodes see 50% loss
  - Gray area is 1/3rd of comm. range for office building and 1/5th of comm. range for the habitat resulting in 55% and 36% nodes in gray areas respectively.

## Explanation for the Existence of Gray Area

- Multi path propagation
  - Close to the transmitter, the direct signal is strong and scattered signals are attenuated
  - Further away from the transmitter, direct signal is weaker, and the reception rate depends on the exact placement of nodes
    - At some nodes the signals destructively combine to result in uniformly poor reception rate
    - At other nodes, they constructively combine to result in high reception rate.

## More to Come

- Spatial Correlation of Packets
  - How correlated are packet losses?
- Temporal Characteristics of Packet Loss
  - How much does the packet loss rate vary over time?
- MAC Layer Performance
  - Aggregate Packet Delivery Performance with different traffic load
  - Goodput variation with workload
  - Asymmetry in packet loss rate between two neighbors

## Spatial Correlation

- Are two receivers likely to see similar loss patterns?
- Can be useful information for modeling, simulation, and protocol design

We formally define the packet delivery correlation coefficient between between two receivers $i$ and $j$ as:

$$R_{i,j} = \frac{\sum_{k=1}^{n} x_{ik} x_{jk} - n\bar{x}_i \bar{x}_j}{[\sum_{k=1}^{n} x_{ik}^2 - n\bar{x}_i^2]^{1/2} [\sum_{k=1}^{n} x_{jk}^2 - n\bar{x}_j^2]^{1/2}} \quad (2)$$

where $x_{ik} = 1$ if the $k$th packet is successfully received by node $i$, otherwise $x_{ik} = 0$. $\bar{x}_i$ is the reception rate of $n$ pakcets. This metric reflects the correlation in packet deliv-

## Spatial Correlation Graphs

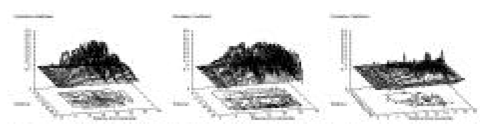

Figure 18: Correlation of packet loss for [illegible] Figure 19: Correlation of packet loss for [illegible] Figure 20: Correlation of packet loss for [illegible]

## Spatial Correlation Analysis

- Different correlation characteristics for different environments
  - Office building and parking lot show higher correlated packet loss than habitat
  - Correlations are strong everywhere in parking lot except those near the transmitter
  - Correlations are strong in the middle of the communication range for office building

## Spatial Correlation Inference

- The highest correlation coefficient is less than 0.7 indicating very moderate correlation (especially in the gray area).
- To a first order approximation, independent losses at the physical layer is a reasonable assumption.

# Temporal Characteristics

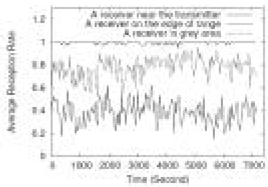


Figure 21: Packet reception rate over time (Window size=40 seconds)

# Standard Deviation of Reception Rate Variation

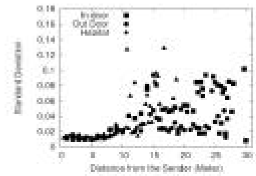


Figure 22: Standard Deviation in Reception Rate for different environments (4b6b, high Tx Power)

# Temporal Characteristics (Conclusion)

- There is sharp increase in link quality variation at the boundary of the inner band.
- If you are operating outside the Inner Band, measure the link continuously since the variation in link quality is high.
- If you are operating in the Inner Band, simple link estimators should work.

# MAC Layer Performance

# Topology

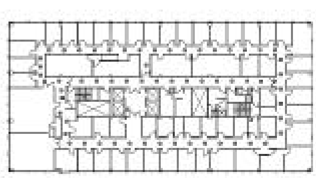

Figure 3: Illustration of node placement in multi-hop experiments $\mathcal{I}$

# Experimental Setup

- 62 motes deployed in the same topology for the office building and the parking lot.
- For the natural habitat which has a smaller communication radius, 4X12 grid was used with 0.75 m spacing.
- Medium (50) power was used
  - Node degrees of 15-18 for *I*, 17-20 for *O*, and 6-8 for *H*.
  - Network diameter is 3-4 hops in all cases.

## Traffic Pattern

- Each node sends *k* packets per second
  - Unicast to neighbors in round robin fashion
  - Periodically broadcast to all neighbors
  - Exponentially distributed inter-packet interval
  - At least 200 packets are transmitted to each neighbor
- Uses explicit ack and retransmission with a maximum of 3 transmissions.

## Packet Loss with Variation in Load

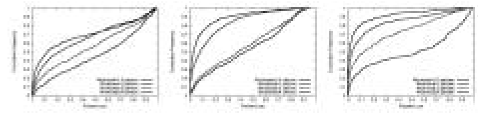

Figure 24: Packet loss distribution in I Figure 25: Packet loss distribution in O Figure 26: Packet loss distribution in H

## Observations

- Sources of Packet loss
  - Physical layer corruption
  - Collisions
- 3 pps is close to the nominal capacity of 20kbps for average degree of 15.
  - 36 *8*3*15*(12/8) = 17,280 bps
  - SECDED encoding reduces the capacity by 1/3rd
- More than 50% of links experience a packet loss of more than 50% under 2pps.

## Packet Delivery Efficiency Setup

- Efficiency = (Distinct Packets Received)/(Total Packets transmitted)
- Does not include overhead due to encoding
- Does not measure channel utilization
- But, it does indicate the amount of energy wasted due to retransmissions.

## Packet Delivery Efficiency

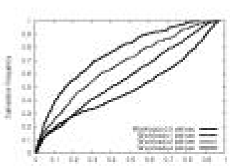

Figure 27: Delivery efficiency in I

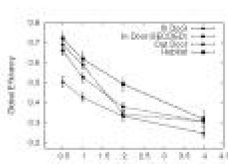

Figure 28: Average Efficiency

## Observations on Efficiency

- At light load, nearly 50% of the links have an efficiency of 70% or higher. (2.8 kbps)
- At heavy load, more than 40% of links have an efficiency of less than 20%. (11.52 kbps)
  - For these links 80% of energy is wasted in repairing perceived packet loss.

## Asymmetry in Packet Delivery

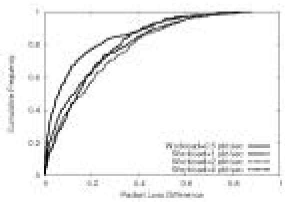

**Figure 29: Packet Loss difference distribution (*T*)**

## Observation on Asymmetry

- Even at light loads, more than 10% of links see a difference of more than 50% in their packet delivery ratio to each other.

## Summary

- Retransmission causes significant reduction in efficiency.
- It is better to operate in the Inner Band
  - How to find out the inner band?
- Stay well below theoretical capacity
  - Reduced density increases capacity.
  - Reduced power also leads to lower loss rate.
- For modeling, independent loss is a reasonable assumption.