Revisiting Multi-channel Communications to Mitigate Interference and Link Dynamics in Wireless Sensor Networks

António Gonga, Olaf Landsiedel, Pablo Soldati, Mikael Johansson

Automatic Control Lab - School of Electrical Engineering
KTH - Royal Institute of Technology, Sweden

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Interference and link dynamics degrade protocol performance

Temporal dynamics: mobility (of users, things), changes in environment

Link burstiness: spikes of consecutive packet losses
The ongoing debate how to mitigate the impact of link dynamics:

1. Frequency diversity, e.g., channel-hopping:
   - reduces burst losses at the expense of average throughput
   - implementation complexity

2. Adaptive routing:
   - can achieve high end-to-end throughput
   - high reliability by selecting consistently good links

Key observations:
- Channel-hopping adopted by more and more standards (WirelessHART, IEEE802.15.4e)
- Increasingly important to understand advantages and limitations
Contributions

- investigate how channel-hopping decreases burst loss duration
- investigate how channel-hopping increases statistical independence of losses in time
- quantify the benefits and limitations of frequency diversity and adaptive routing
Outline

1. Experimental Setup and Methodology

2. Single-Hop Study: link burstiness
   - maximum burst length
   - temporal correlation

3. Multi-Hop Analysis
   - in dense and medium-dense networks
   - in sparse networks

4. Conclusions
Experimental Setup: testbed environment

Testbed environment
- 32 TelosB motes, placed on ceiling of offices, corridors, and the kitchen (see Figure)
- Several days of experimental traces: richness of data

Sources of wide-band interference and fading
- Three 802.11 access points per floor, and other WSN deployments
- Microwaves, people moving, changes in humidity and temperature

Data traces collected for three scenarios: single-channel, 2-channel, N-channel
- N-channel: hopping sequences of increasing length: 4, 8, 12, 16
- Round robin, burst of 10640 consecutive packets, neighbors log received packets
- Inter-packet interval 10ms (used in WirelessHART)
Link burstiness: maximum burst length

WiFi-interference-free channels $C_{25}$ and $C_{26}$ and $S_1 = \{C_{25}, C_{26}\}$

WiFi-interfered channels $C_{13}$ and $C_{22}$ and $S_2 = \{C_{13}, C_{22}\}$

Four long hopping sequences

PRR is not sufficient:
- hides important performance indicator such as link burstiness
- link burstiness: maximum number of consecutive packets lost over a communication link

Key observations:
- channel-hopping: significantly reduces burst loss duration
- increasing hopping sequence length: no much benefit observed
Why study packet reception correlation?

- packet reception on links correlated
- opportunistic routing is useless
- no temporal or frequency diversity to exploit
Link burstiness: temporal correlation

If receptions in $R_x$ and $R_y$ correlated in time
Can channel-hopping improve link independence?

Use $\beta$-factor in single-channel and multi-channel communications

- to quantify temporal correlation of packet losses
- $\beta$-factor: based on conditional packet delivery function $C(n)$
- $C(n)$: describes conditional probability of successful packet reception given $n$ previous packets were received (for $n \geq 0$) or lost (for $n < 0$)

Computing $\beta$-factor for channel-hopping

- we consider the sequence of packets received between each transmitter-receiver pair
- $\beta$-factor will describe the link burstiness of a given transmitter-receiver pair for a given channel-hopping sequence.
Use $\beta$-factor to quantify temporal correlation of packet losses.

- $\beta = 0$ indicates a link with independent packet losses (following a Bernoulli process);
- $\beta = 1$ corresponds to bimodal link (either good or bad).

Key observations:

- multi-channel communications decorrelates packet losses in time
- 80% of links show roughly independent packet losses for hopping sequences with more than two channels
Multi-hop analysis: Channel-hopping vs. adaptive routing

Dense and medium-dense networks
- Evaluate the benefit of channel-hopping in multi-hop single-path routing
- Compare end-2-end performance in dense and medium-dense networks
- Explore the impact of network density on end-to-end reliability and delay

Sparse networks
- Show benefits of channel-hopping

Varying network density
- Eliminate links from experimental traces
- From best links in terms of PRR, till network becomes disconnected

Key observations:
- we build a routing three on top of our experimental traces
- we employ ETX as a routing metric
Channel-hopping vs. adaptive routing: multi-hop end-2-end performance

Case 1: two strongly interfered channels, and their channel-hopping

- routing on top of channel-hopping yields an average end-to-end delay that is essentially the average of the delay experienced when routing on each individual channel
- channel-hopping helps reduce the end-to-end delay
- channel-hopping increases reliability
Case 2: two interference-free channels, and their channel-hopping

- single-channel and channel-hopping have roughly the same end-to-end reliability
- while channel-hopping achieves lower delay spikes.

Key observations:

- when routing topologies can be adapted to link dynamics and interference, adaptive routing and channel-hopping achieve similar performance
- channel-hopping reduces the average end-to-end delay and the maximum delay
- to achieve the same with adaptive routing on a single-channel, one would need to know a priori which channels are in good conditions network-wide.
Channel-hopping vs. adaptive routing: sparse networks

Key observations:

- adaptive routing looses flexibility
- channel-hopping yields better average end-to-end delay and reliability
Conclusions

We addressed how to mitigate the impact of link dynamics in WSNs.

- adaptive routing vs. multi-channel communications

We compared adaptive routing vs. multi-channel communications

- maximum burst loss
- temporal correlation of losses
- frequency correlation of losses

Key observations:

- single-hop:
  - channel-hopping significantly reduces link burstiness
  - channel-hopping decorrelates packet losses both in time and frequency

- multi-hop: dense and medium-dense networks
  - adaptive routing and channel-hopping yield similar end-2-end reliability
  - channel-hopping reduces the average end-to-end delay and the maximum delay

- multi-hop: sparse-networks
  - adaptive routing loses flexibility
  - channel-hopping yields better average end-2-end delay and reliability
QUESTIONS ?
Link burstiness: frequency correlation

Receptions in $R_x$ and $R_y$ correlated in frequency
Can channel-hopping improve link independence?

Observations:
- packet reception on links correlation
- opportunistic routing is useless
- no frequency diversity to exploit
Use $\kappa$-factor to quantify frequency-correlation of packet reception on a link.

- $\kappa = 0$ indicates a link with independent receptions
- $\kappa = 1$ correlated receptions (positive)

**Key observations:**

- two well separated WiFi-free channels: 80% of links fully independent packet losses
References

