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How Was Your Journey? Uncovering Routing Dynamics in Deployed Sensor Networks with Multi-hop Network Tomography

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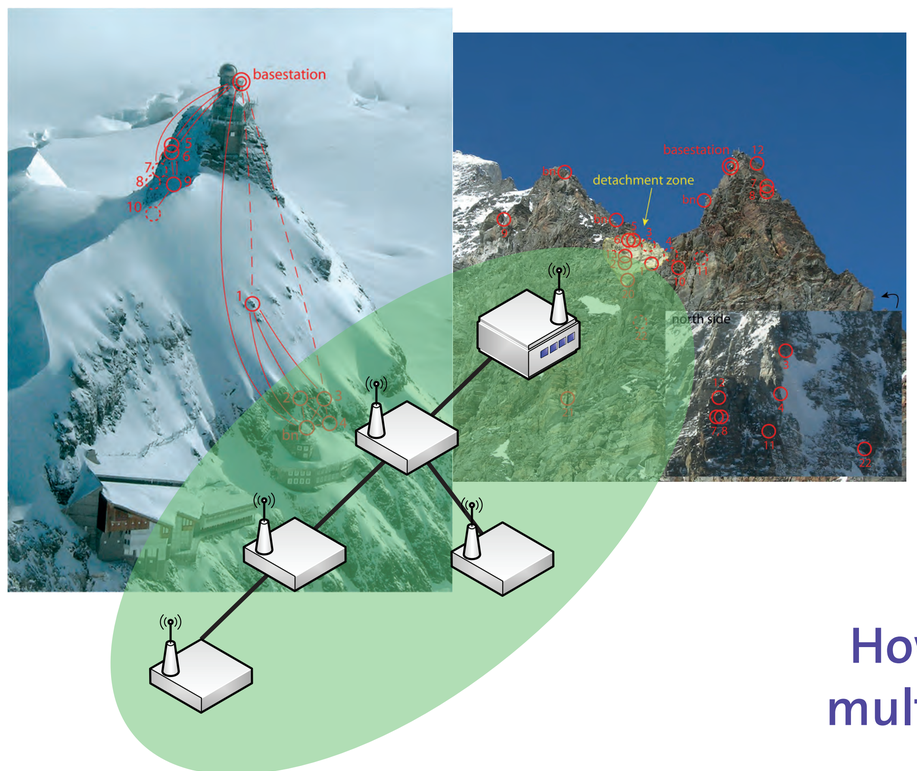


Deployed Multi-Hop Sensor Networks

- Battery-powered sensor nodes require low-power operation
- Low-power radio with small communication bandwidth
- Communication is limited to the wireless channel
- System health monitoring using end-to-end metrics

Root Causes of an Observed Performance

cannot be identified using

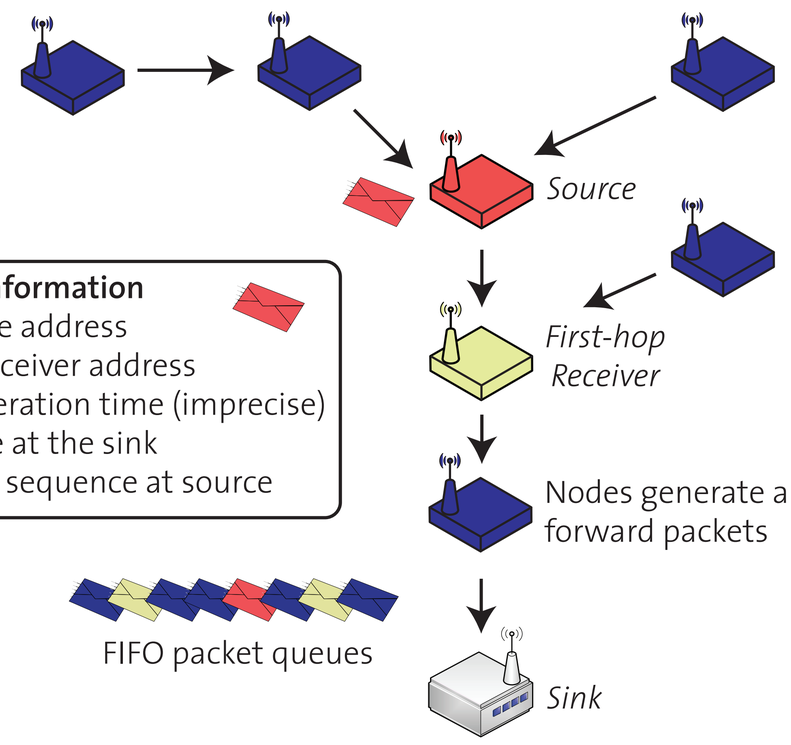
- End-to-end metrics, e.g., end-to-end delay
- Testbed experiments in a different environment
- Simulation

Two MSP430-based sensor nodes

How can we analyze the performance of a wireless multi-hop network in detail under these constraints?

Reconstruction of the Path, the Per-Hop Order and the Per-Hop Timing of Individual Packets

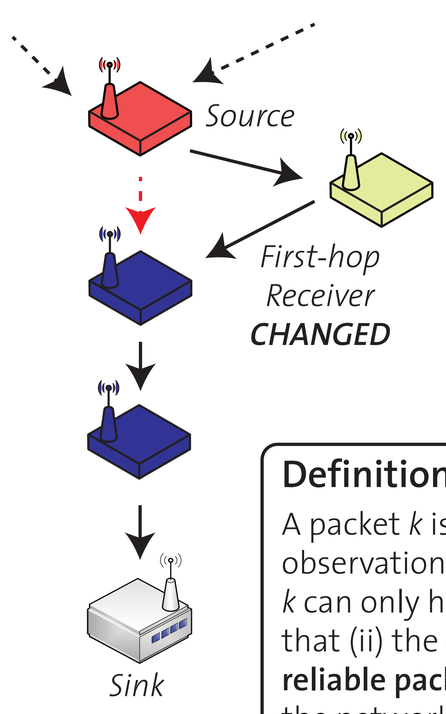
Packets of Different Sources Travel Together



Per-packet information

- Source node address
- First-hop receiver address
- Packet generation time (imprecise)
- Arrival time at the sink
- Generation sequence at source

The Problem of Path Changes



Problems

- Uncertainty in path observations right before and after a parent change
- Risk of inferring wrong information

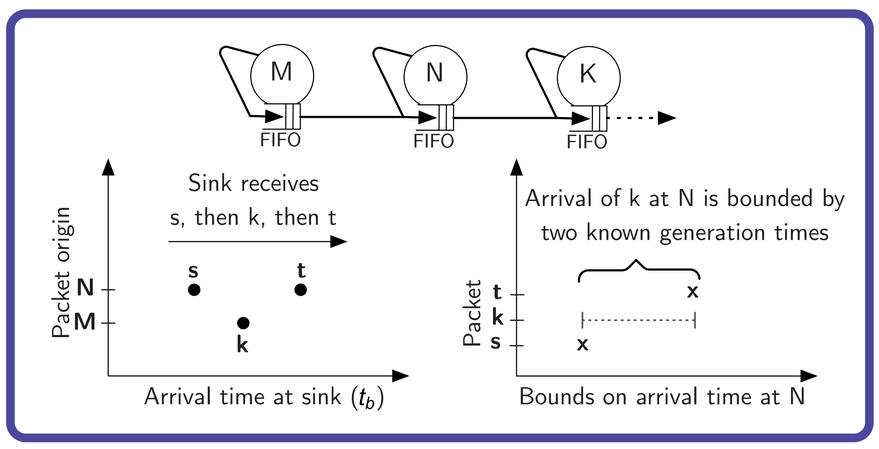
Solution

Limit packet analysis to subset of packet stream for which packet correlation is safe

Definition: *Reliable* Packet

A packet *k* is **reliable** if it fulfills two properties: From our observations at the sink, we can guarantee that (i) packet *k* can only have travelled along exactly one path *N*, and that (ii) the order relation between packet *k* and any other **reliable packet** *m* is consistent along all packet queues in the network including the sink.

Safe Correlation of *Reliable* Packets



Testbed Validation

- Two state-of-the-art data collection protocols
- Up to 92 real sensor nodes in a testbed
- More than 150 hours of testing
- Simulation of 100-node line topology for scaling tests

	N	D	IPI	H	PC	DY	Packets Received	Packets Reliable	Packets Full path	Packets Correct	Proc. Delay $p_{0.9}$	Proc. Delay $p_{0.98}$	Uncertainty $p_{0.9}$	Uncertainty $p_{0.98}$
CTP Noe/LPL														
A)	92	10 h	15 s	4	261	99.0%	217,078	99.0%	98.9%	100.0%	17 s	20 s	< 1 s	< 1 s
B)	85	9 h	30 s	3	123	98.3%	88,541	98.9%	98.9%	100.0%	32 s	40 s	< 1 s	1 s
C)	91	9 h	120 s	4	393	99.2%	54,143	98.4%	98.2%	100.0%	62 s	75 s	1 s	1 s
CTP (Simulation)														
D)	100	5 h	30 s	100	0	99.9%	60,150	96.5%	93.2%	100.0%	30 s	31 s	< 1 s	< 1 s
E)	100	20 h	120 s	100	0	99.9%	60,112	97.0%	94.3%	100.0%	120 s	121 s	< 1 s	< 1 s
Dozer														
F)	25	35 h	15 s	3	2,552	97.4%	101,479	91.5%	91.5%	100.0%	470 s	1834 s	16 s	140 s
G)	25	75 h	30 s	4	1,188	96.1%	99,611	90.2%	90.1%	100.0%	785 s	2623 s	31 s	381 s
H)	25	25 h	120 s	5	407	99.9%	19,529	97.2%	97.0%	100.0%	151 s	211 s	94 s	120 s
I)	10	60 h	120 s	3	37	99.5%	84,563	97.7%	97.7%	100.0%	122 s	212 s	74 s	118 s

Exemplary Application: Health Monitoring

Per-hop packet timing serves as a proxy for the occurrence of failure events at the network layer:

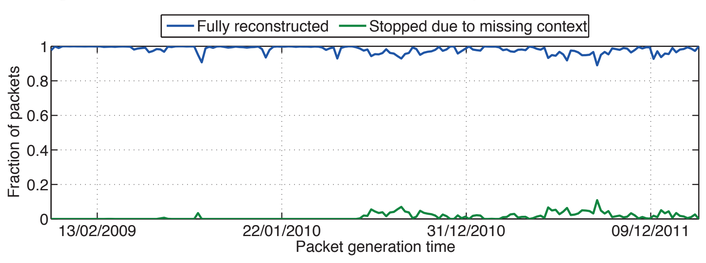
- Loss of a network announcement (beacon)
- Loss of a packet or a packet acknowledgment
- Incorrect state of radio resource

Detection accuracy of tomography-based method is significantly improved when sensor nodes transmit one extra bit per packet [2].

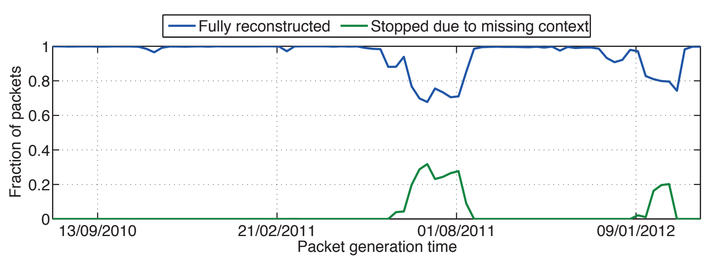
Real-World Deployment Data

Analysis of more than 140 million packets

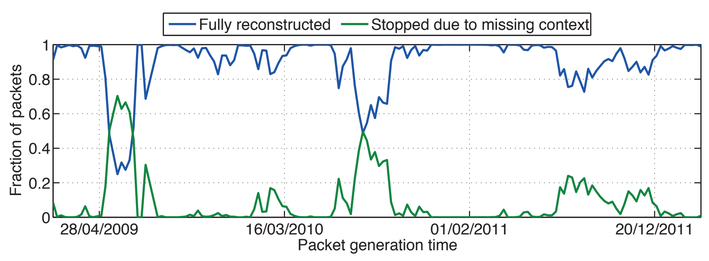
Full path including timing and ordering can be reconstructed for >92.6% of all packets



Matterhorn Site - 74 million packets



Dirruhorn Site - 39 million packets



Jungfraujoch Site - 19 million packets

[1] Matthias Keller, Jan Beutel, Lothar Thiele: *How Was Your Journey? Uncovering Routing Dynamics in Deployed Sensor Networks with Multi-hop Network Tomography*, p. 15-28, SenSys 2012

[2] Matthias Keller, Jan Beutel, Lothar Thiele: *The Problem Bit*, p. 105-114, DCOSS 2013