Reducing Uncertainty in Wireless Sensor Networks

Network Inspection and Collision-Free Medium Access

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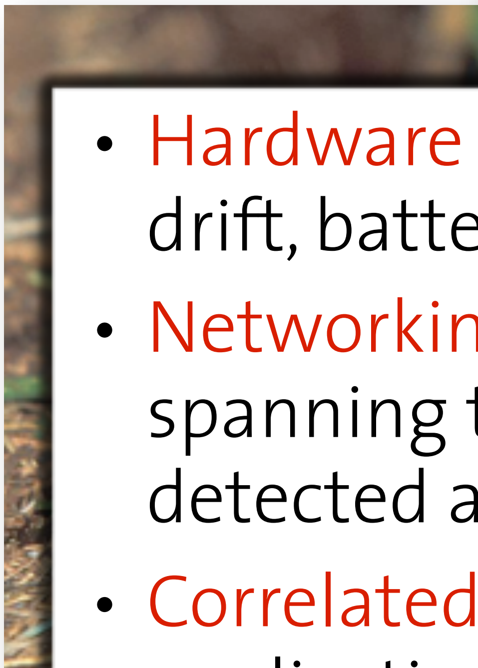
Wireless Sensor Networks

- Wireless Sensor Networks (WSN)
  - Wireless network of sensor nodes
  - Sensor nodes: sensing, processing, radio, power
- Monitoring and control of real-world phenomena
  - Scientific tool
  - Production and delivery
  - Health care
  - Military

BTnode Rev. 3 by TIK+DSG ETHZ

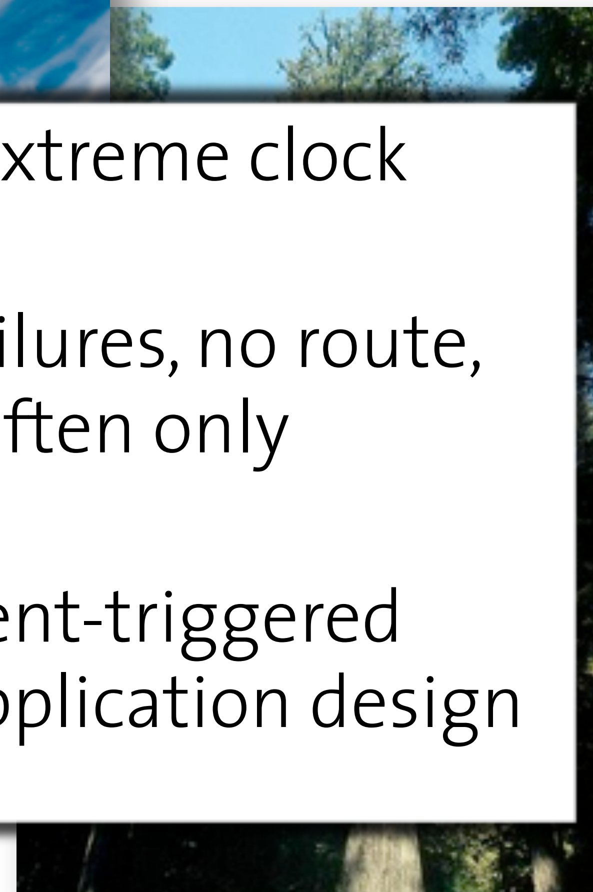
Deployment Problems

Great Duck Island [1]



Agriculture [4]

Redwoods [2]



Redwood Tree (Wikipedia)

- Hardware failures: moisture, extreme clock drift, battery depletion, etc.
- Networking problems: (link failures, no route, spanning tree construction), often only detected after deployment
- Correlated traffic bursts of event-triggered applications require special application design

[1] R. Szewcyk et. al. An analysis of a large scale habitat monitoring application. Sensys '04.

[2] G. Tolle et. al. A macroscope in the redwoods. SenSys '05.

[3] Geoff Werner-Allen et. al. Fidelity and yield in a volcano monitoring sensor network. OSDI '06.

[4] O. V. K. Langendoen et. al. Murphy loves potatoes: Experiences from a pilot sensor network deployment in precision agriculture. WPDRTS '06.

Thesis Statement

Deployment problems are caused by:
implementation and design defects.

- *Tools for inspection to detect faults in deployed WSN are inadequate. Passive inspection is an effective and interference-free way to inspect a deployed network.*
- *Energy-efficient probabilistic MAC protocols are inadequate to prevent faults caused by correlated traffic bursts typical for event-triggered applications. Collision-free schedule-based MAC protocols can handle traffic bursts well and be made energy-efficient, too.*

Main Contributions

- Fault Detection: Passive Inspection
  - Sensor Network Inspection Framework (SNIF) including novel time synchronization for Bluetooth Scatternets
- Fault Prevention: Collision-Free Medium Access
  - Cooperative transmission schemes as foundation for efficient coordination among a set of nodes
  - Two protocols: BitMAC and BurstMAC that handle co-related traffic bursts

Part I – Fault Detection: Passive Inspection

Problem

- Deployed WSN suffer from defects not detected during development.
- Existing tools (debugger, testbed, simulation, emulation) don't work for deployments.
- In-network monitoring: Sympathy[1], Memento[2]
  - "Heisenbugs"
  - Waste of resources
  - Monitoring suffers from network problems, too.

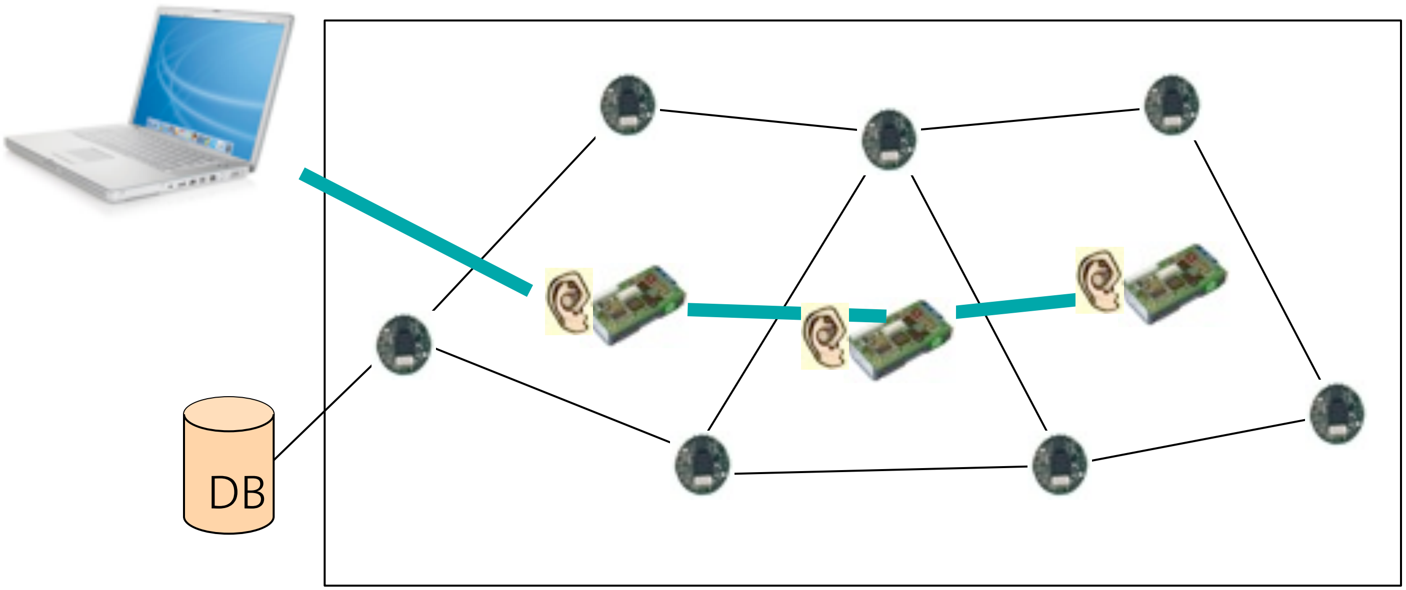
Active collection of network state as part of WSN application

[1] N. Ramanathan et al. Sympathy for the sensor network debugger. SenSys '05.

[2] S. Rost et al. Memento: A Health Monitoring System for Wireless Sensor Networks. SECON '06.

Approach

- **Passive inspection** of wireless sensor network with temporary sniffer network
- **Passive indicators** to detect problems



Example: Node Reboot Indicator

- Basic idea: observe sequence number in "hello" beacons send by link estimator

- Premise:
  - Sequence numbers are increasing
  - First beacon packet contains sequence number zero

- Passive node reboot indicator:

new sequence number $\neq$ last sequence number + 1

"But what happens:
• if not all packets are captured
• the sequence number counter overflows?"

Challenge (1): Incomplete Information

Incomplete Information due to:

- Packet loss: not all packets are received
- Black box observation: internal state unknown

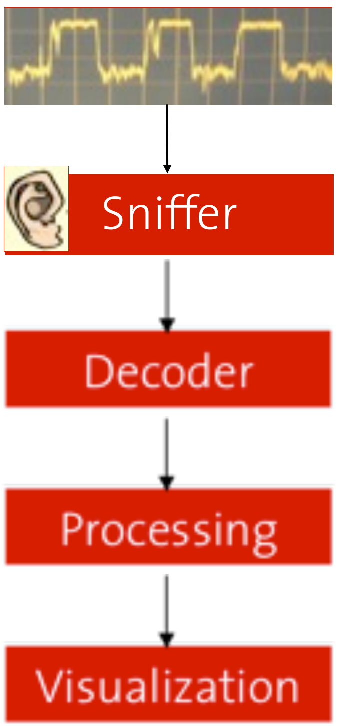
Example: Node Reboot Indicator

- Packet loss: not an issue for this indicator:
  - Updated rule: “new number < last sequence number => reboot”
- Black box:
  - Sequence counter could overrun internally: 0xffff=>0x0000
  - It is not possible to correctly distinguish overrun and reboot
  - Heuristic: use minimal time between beacons to calculate earliest expected time for received beacon packet

Challenge (2): Generic System

- No standard for WSN radio communication
  - Growing number of Media Access (MAC) Protocols: {B, S, T, SCP..}-MAC, WiseMAC, BitMAC, ...
  - Different packet formats: preamble length, start-of-packet symbol (SOP), packet size, CRC
- Non-standard protocols, message formats...
- Different types of faults to detect

SNIF: Sensor Network Inspection Framework



WSN radio communication

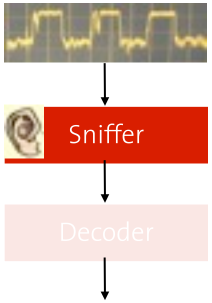
collects packets.

provides access to packet content.

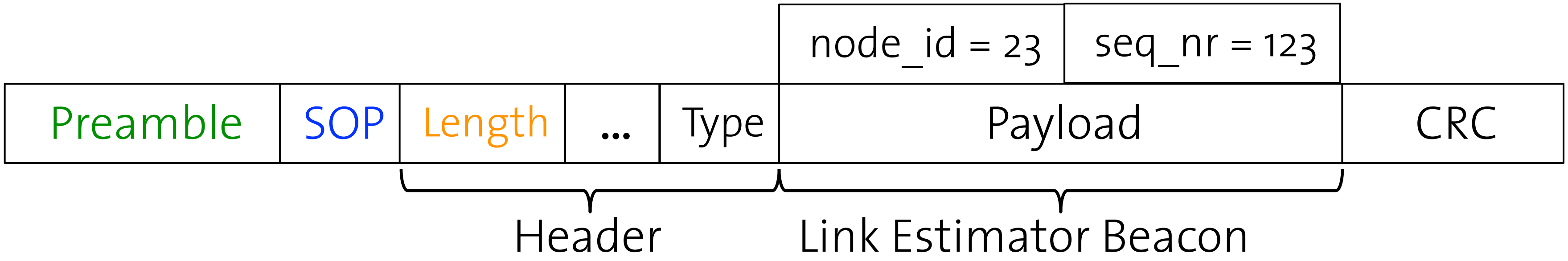
of packet contents.

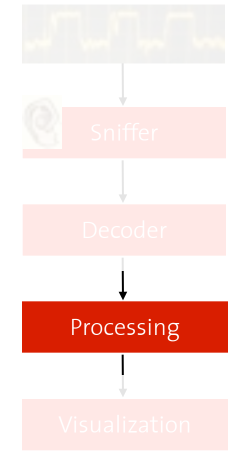
to represent node and network state.

Sniffer and Packet Decoder



- Generic sniffer
  - Always listening, waiting for Preamble and Start-of-Packet(SOP)
  - Packet size either fixed or variable using Length field
- Generic packet decoder
  - Packet format described by "Attributed C Structs"
  - Most WSN apps are written in C, easy copy & paste
  - Attributes allow to specify variable size arrays and encapsulated packets

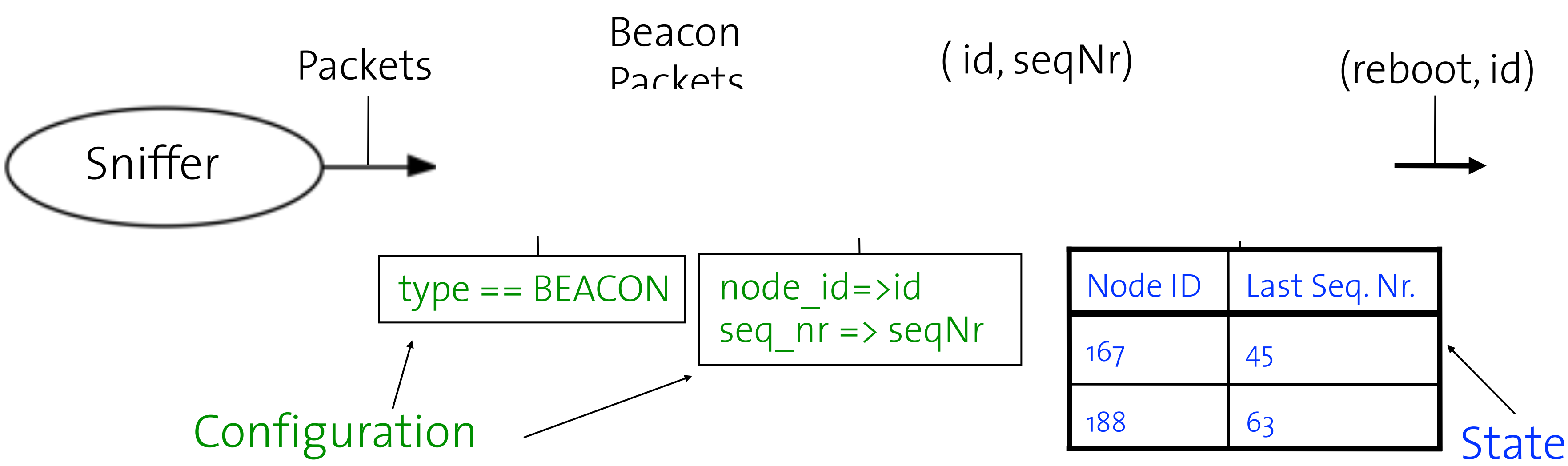




Online Packet Processing with Data Streams

Data stream processing:

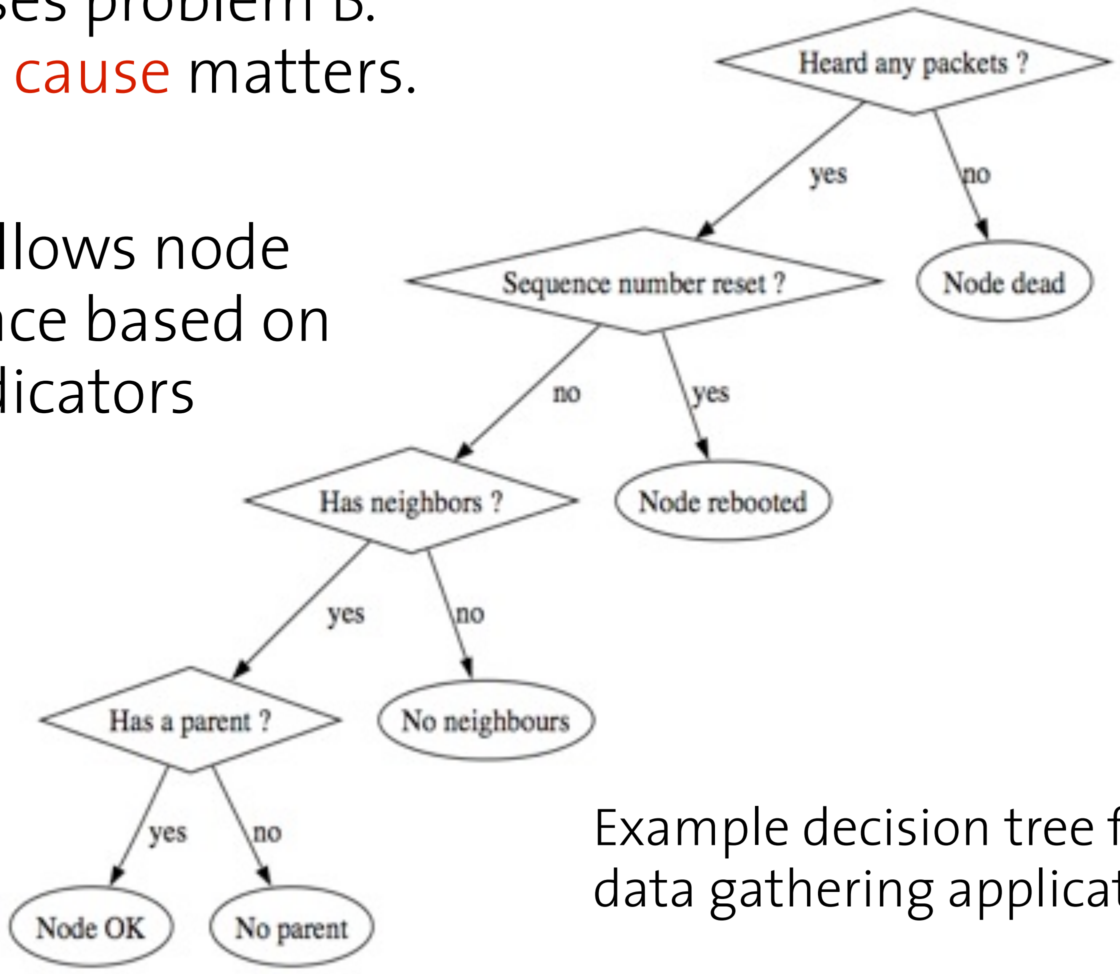
- Configurable operators
- Reusable operators and sub-graphs
- Online processing



Root Cause Analysis: Decision Tree

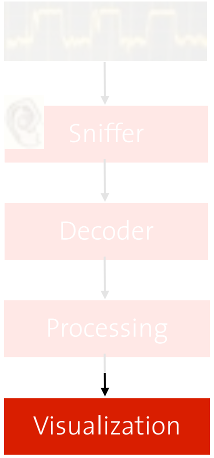
Problem A causes problem B.
=> Only root cause matters.

Decision tree allows node state inference based on observed indicators

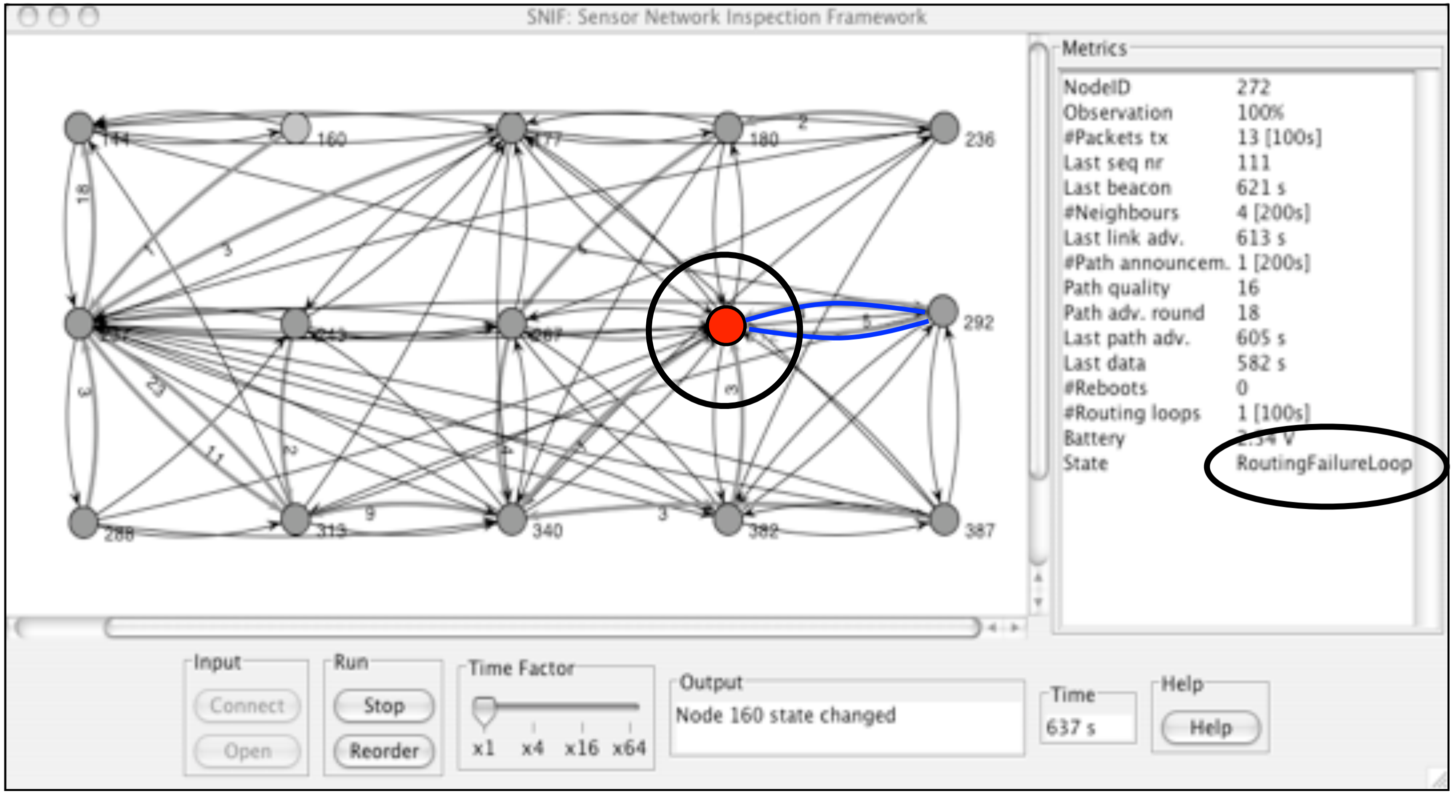


Example decision tree for data gathering application

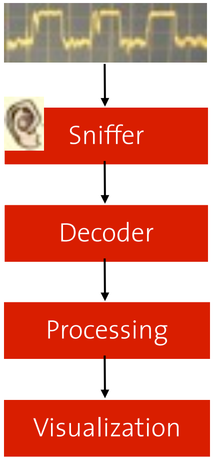
Visualization



- Indicators and node state can be inspected
- Replay of recorded sessions



Summary: Passive Inspection



- Passive inspection represents a valuable tool for deploying WSNs.
- Challenges: Incomplete information, generalization
- SNIF provides...
  - Distributed sniffer based on BTnode platform
  - Generic packet decoder
  - Data stream processing with WSN specific operators, sub-graphs are reusable
  - Basic network and state visualization

Part II – Fault Prevention: Collision-free Medium Access

Event-triggered Applications

```
On seismic activity:
   send seismographic trace of
   last minute (with 1 kHz
   resolution) to base station.


Otherwise:
   sleep and save energy.
```

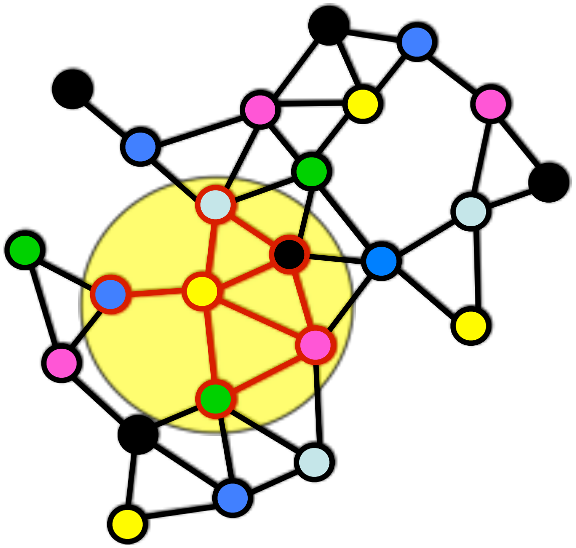
On seismic event, all nodes in a region start to communicate

Correlated Traffic Bursts

- **Problem**: Common probabilistic MAC protocols (WiseMAC, {B,S,T,X}-MAC) cannot handle such **correlated traffic bursts, resulting in:**
  - Collisions
  - Packet losses
  - Long latencies

- Schedule-based TDMA protocols can handle traffic bursts without collisions, but introduce coordination overhead.

BurstMAC Approach



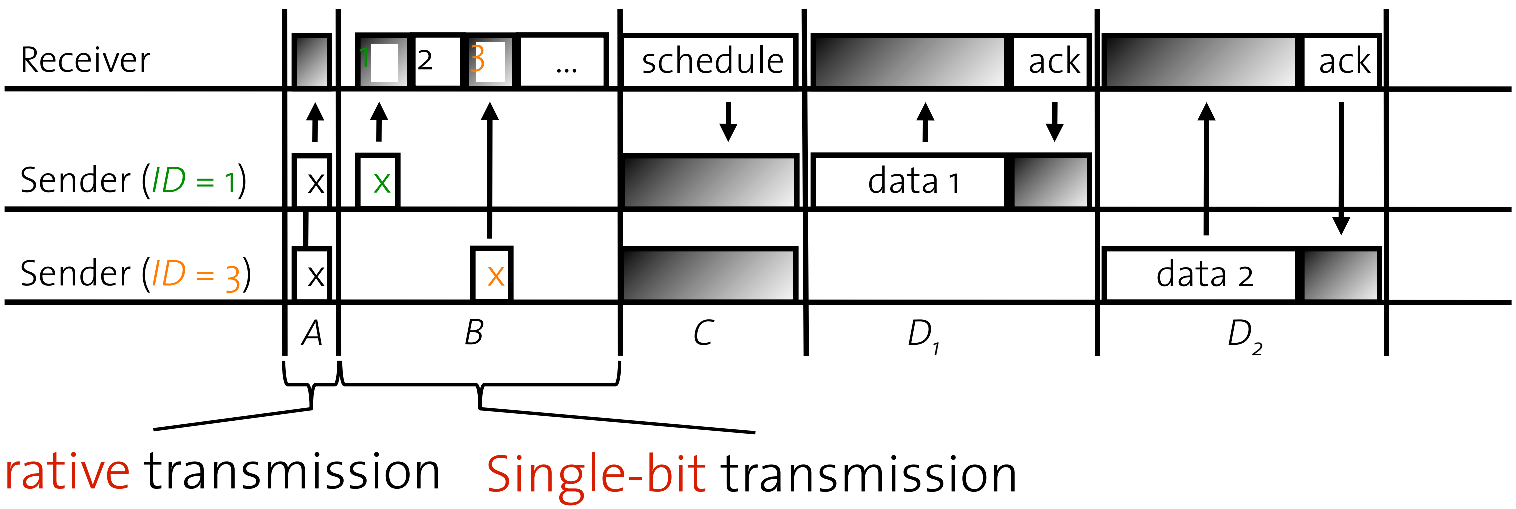
- Transform unstructured set of nodes into network of star networks.
- Each star network:
  - Communicates on interference-free radio channel assigned by 2-hop coloring.
  - Uses TDMA schedule.

- Challenge: Energy-efficient TDMA coordination

TDMA for Star Networks

Energy-efficient packet coordination and transmission

A. At least one sender?
B. Which nodes want to send?
C. Calculate and broadcast schedule
D. Send packets with acknowledgements

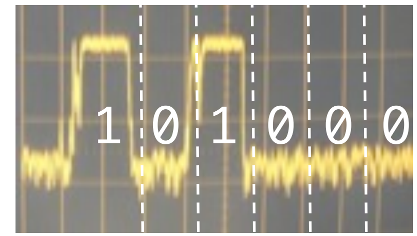


Cooperative Transmission:
Is collision-free concurrent access possible?

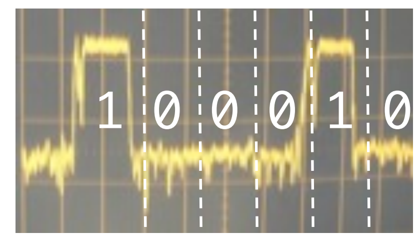
Experiment:

Two nodes A and B send different On-Off-Keying (OOK) modulated data.

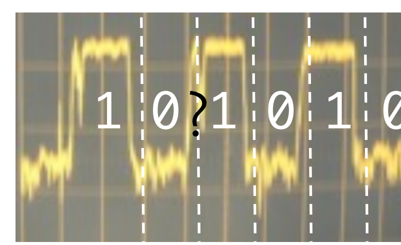
A



B



A + B



The OR channel characteristic of the broadcast medium allows for cooperative transmissions.

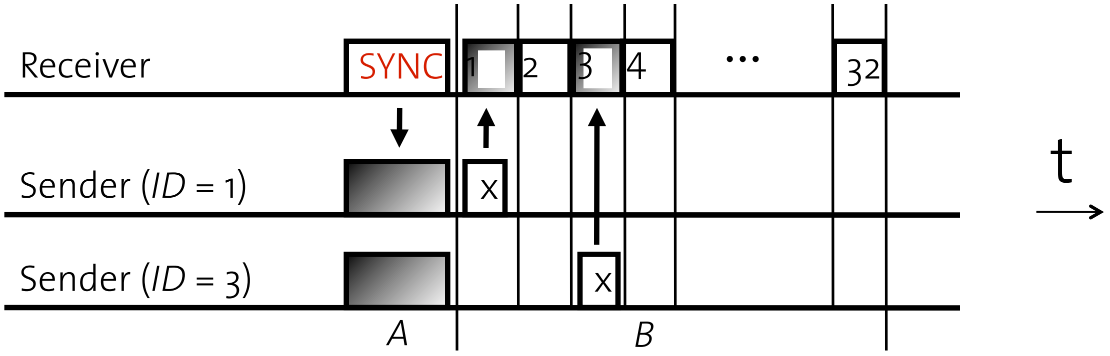
Single-Bit Transmission:
How-to transfer single bits of information?

Setup: One receiver, multiple sender, small IDs (5-bit)

A. [SYNC] packet synchronizes all senders (~ 10 us).

B_s. Sender encodes its ID *i* by sending carrier in mini slot *i*.

B_r. Receiver collects vector of single bits.

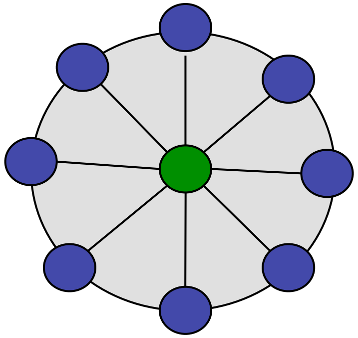


Evaluation

- Evaluation:
  - Idle energy vs. node density
  - Energy consumption comparison to:
    - SCP-MAC: Efficient probabilistic protocol
    - LMAC: Schedule-based protocol
  - Evaluated on BTnode rev. 3with Chipcon CC1000 radio transceiver, packet payload 32 bytes, further details can be found in dissertation.

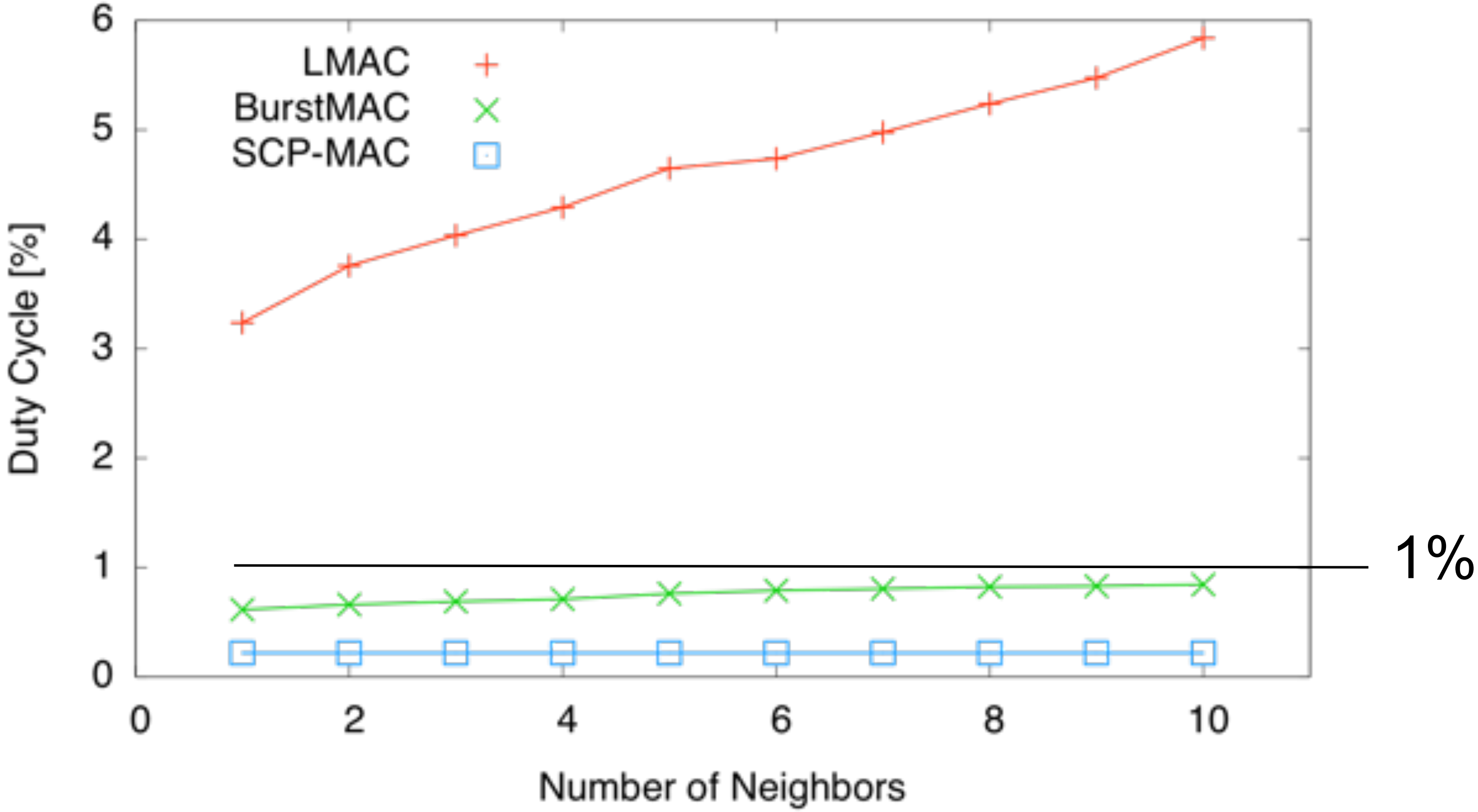
[1] L. van Hoesel: *A Lightweight Medium Access Protocol (LMAC} for Wireless Sensor Networks: Reducing Preamble Transmissions and Transceiver State Switches*, INSS '04

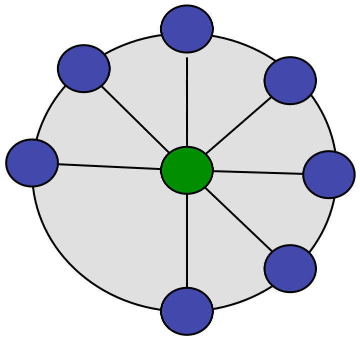
[2] W. Ye: *Ultra-low duty cycle MAC with scheduled channel polling*. Sensys '06.



Idle Duty Cycle

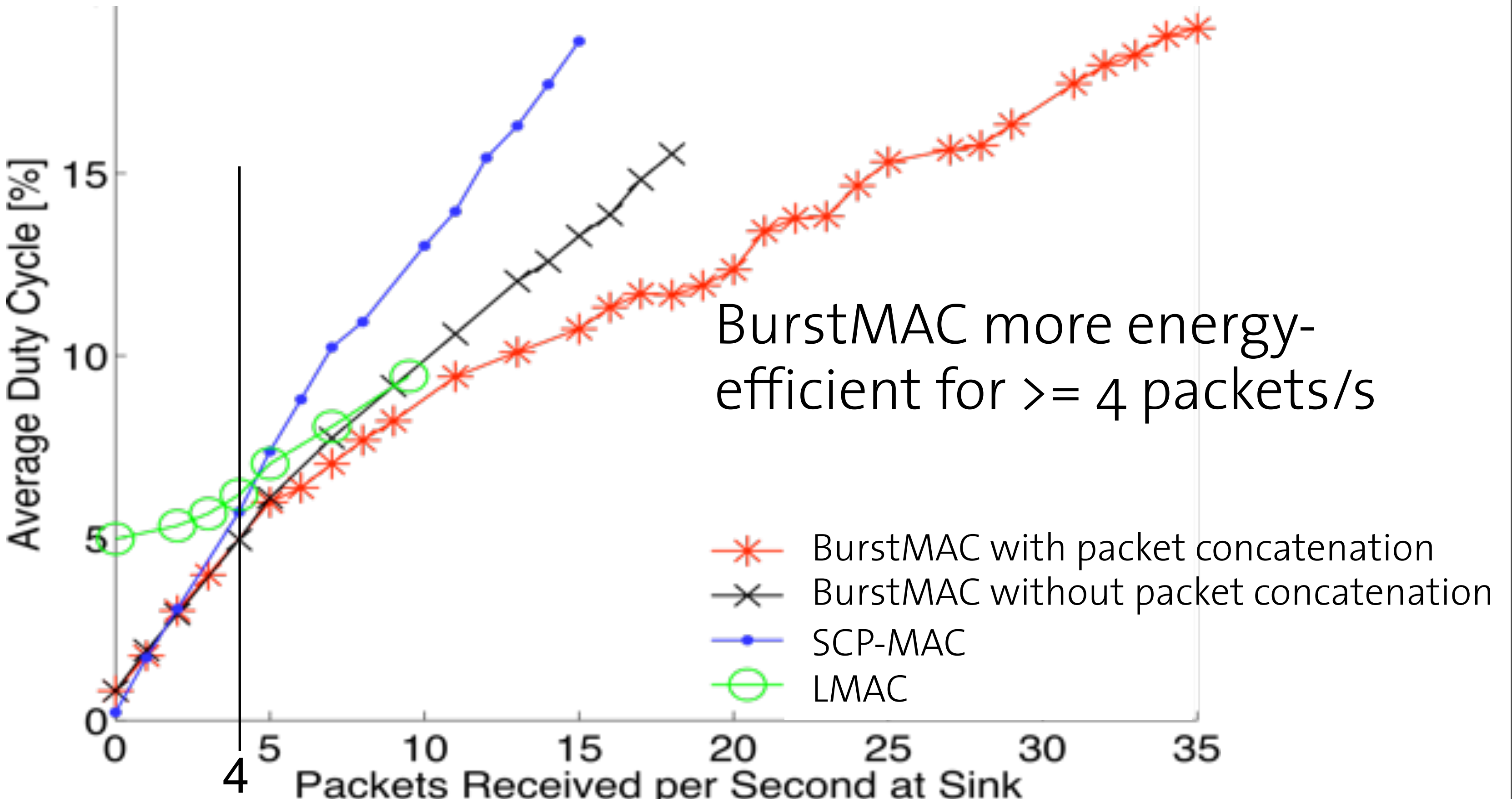
Experiment setup: 1 node and 1-10 neighbors





Traffic Burst

Experiment setup: 1 sink and 7 neighbors



Summary: BurstMAC

- Energy-efficient multi-channel TDMA protocol:
  - Efficient scheduling in star networks
  - Collision-free: handles correlated traffic bursts well
  - Duty cycle < 1.0% in idle situation
  - High throughput, up to 71% bandwidth usage

- Not shown:
  - Energy-efficient network startup
  - Inter-star communication coordination
  - Robust packet concatenation for packet bursts

Conclusions

Summary

- Main contributions:
  - Fault detection: Passive Inspection with Sensor Network Inspection Framework (SNIF)
  - Fault prevention: Collision-free BurstMAC protocol
- Other:
  - Generic sniffer and packet markup language
  - Bluetooth time synchronization for Scatternets
  - Single-bit transmission technique

Limitations and Outlook

- Passive Inspection
  - Limited insight
  - Multi-channel protocols
  - Semi-passive inspection

- Collision-free MAC Protocols
  - Packet-based radio transceivers
  - Dense networks

Questions?

- M. Ringwald, K. Römer. *BitMAC: A Deterministic, Collision-Free, and Robust MAC Protocol for Sensor Networks*. EWSN 2005.
- M. Ringwald, K. Römer, A. Vitaletti. *Passive Inspection of Sensor Networks*. DCOSS 2007.
- M. Ringwald, Kay Römer. *Deployment of Sensor Networks: Problems and Passive Inspection*. WISES 2007.
- M. Ringwald, K. Römer. *Practical Time Synchronization for Bluetooth Scatternets*. BROADNETS 2007.
- M. Ringwald, K. Römer. *BurstMAC – A MAC Protocol with Low Idle Overhead and High Throughput (Work in Progress)*. DCOSS 2008.