ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

RT-Link: A global time-synchronized link protocol for sensor networks

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Outline

- Introduction
- Design of the protocol
- Implementation
- Performance Evaluation
- Application Example
- Conclusion
- Questions

Introduction: Going wireless

- Wireless networks (radio-light transmission)
  - prone to interferences, collisions and errors => high BER
  - medium access, remote powering, security concerns
  - infrastructure required (base station, AP, etc...)
  - each end-station node only minds its own transmission

Introduction: Going wireless

- Wireless sensor networks
  - real-time (correctness depends not only on logical but also timing constraints behavior)
  - self organized, no infrastructure
  - small low cost node with low energy (battery-operated)
  - large number of nodes, multihop transmission at low data rate with information having temporal consistency

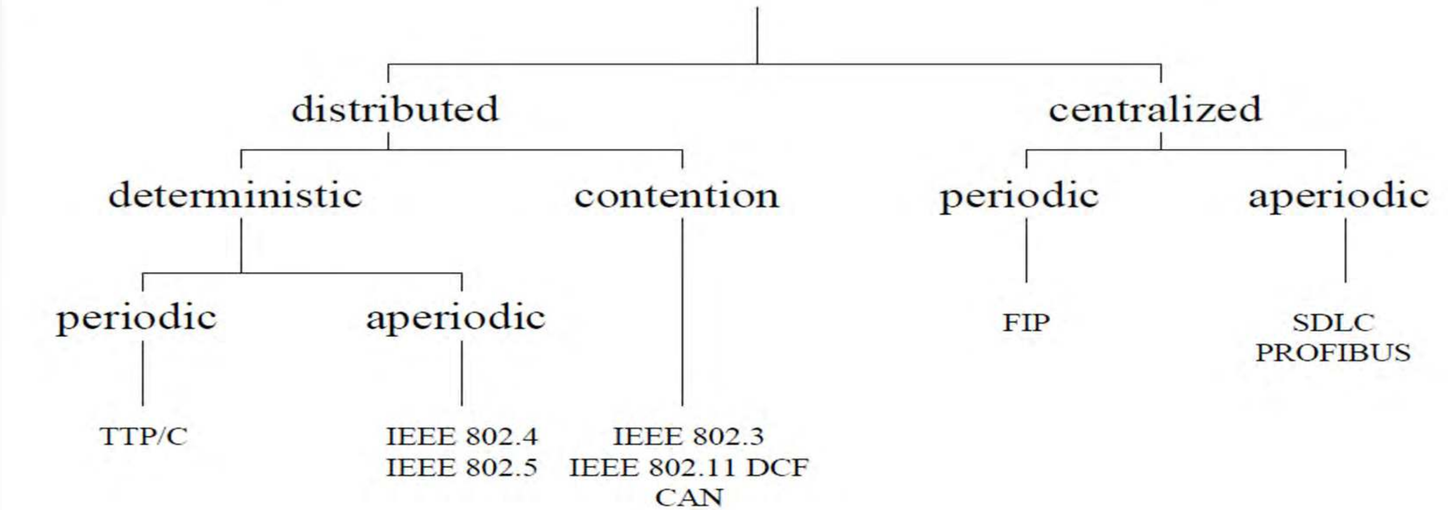
QoS: Impact on Tx/Rx properties

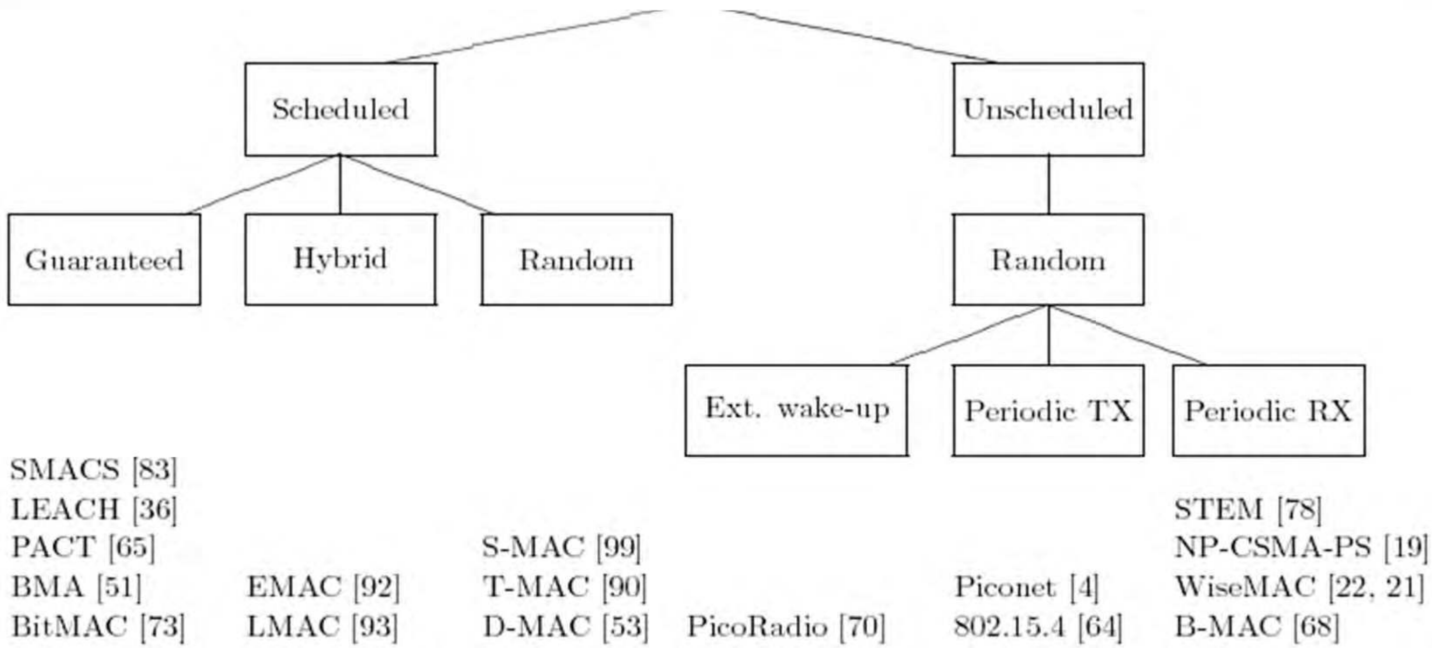
- Node lifetime, scalability, reliability
  - predictable bounded transfer delay, jitter, throughput
- Topology and physical limitations
  - BER, SNR, direct or multihop transmission
  - cost and energy effective operation
  - error detection/correction schemes
- Medium access, localization
  - fair access, low waiting time, high network usage

Tackling the problem

- Known issues?
  - Air medium: overhearing, errors, collisions of packets
  - Energy Saving: idle listening, dumb retransmissions
- ISO OSI model => Data link
  - can provide interference-, collision-free access to medium
  - can coordinate sleep intervals (no comm., no need to be awake)

Possible Solutions – MAC





Synchronization View Point

- Related link protocols
  - asynchronous (B-MAC)
  - loosely synchronous (S-MAC, T-MAC, WiseMAC)
  - fully synchronized (TRAMA, LMAC, Crankshaft)

RT-Link protocol

- RT-Link (TDMA based) time synchronized link protocol using hardware global sync.
  - energy-efficient communication (all communicating nodes activity are packed)
  - bounded message latency, high throughput (collision-free operations and on-demand data rate with help of reservation)
  - deterministic lifetime (resources allocation/ reservation/ management in advance)
  - total event ordering (absolute time stamps assigned to distributed events for tracking)

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Protocol: Overview

- 2 node types:
  - Fixed nodes
  - Mobile nodes
- 2 types of operations
  - Indoors
    - AM/FM time synchronization module
  - Outdoors
    - Atomic clock receiver

Protocol: Overview

A finely slotted data communication period

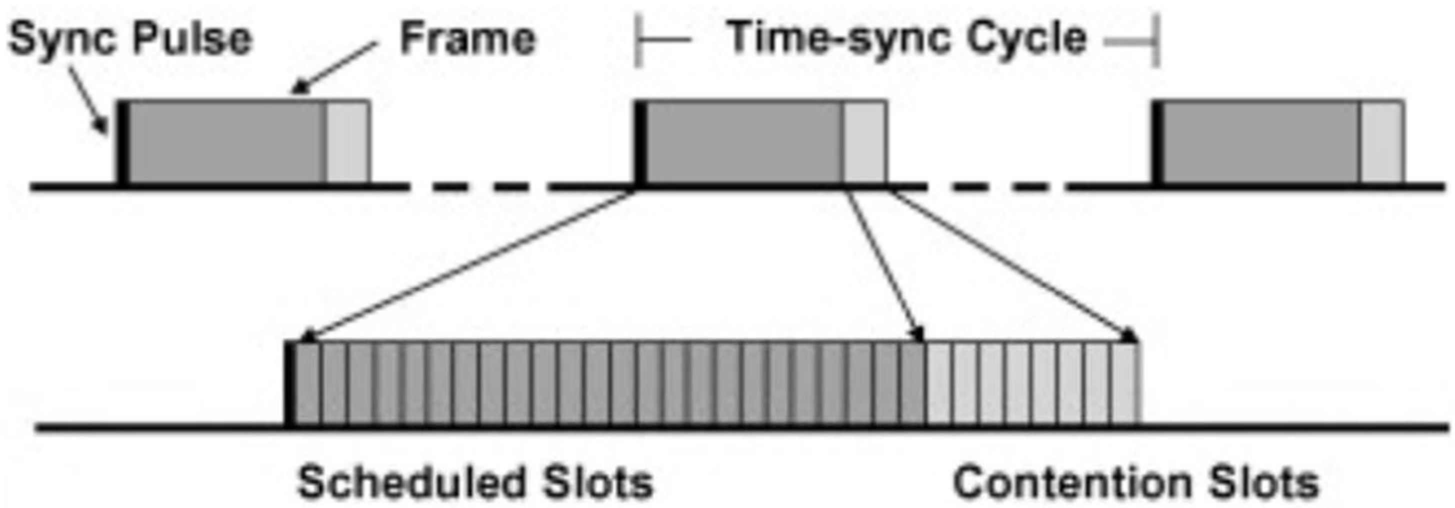


Fig. 2. RT-Link time slot allocation with out-of-band synchronization pulses.

Protocol: Overview

- 2 kind of slots
  - Scheduled Slots (SS)
    - Nodes are assigned specific transmit and receive time slots
  - Contention Slots(CS)
    - Nodes which are not assigned slots in the SS select slots at random as in slotted-Aloha

Protocol: Operation Procedure

3-state state machine

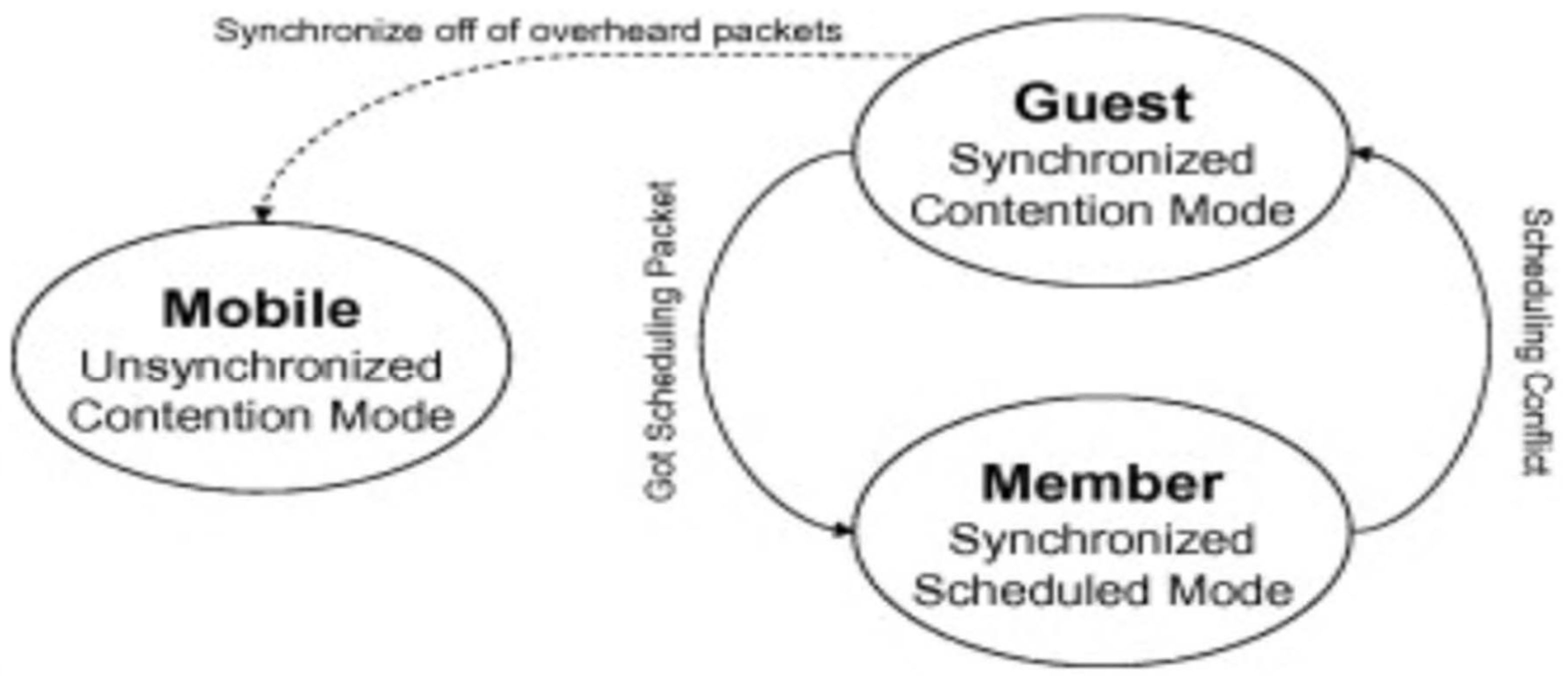


Fig. 3. RT-Link node state machine.

Protocol: Synchronization

- Initial status: Guest -> CS mode
  - Sync radio is on -> on sync pulse => wait for set of number of slots -> send “HELLO” message with node ID to gateway
  - Gateway eventually scheduled a slot in the SS
- Mobile node achieves sync by observing member’s slot and computes time until start of CS

Protocol: Synchronization

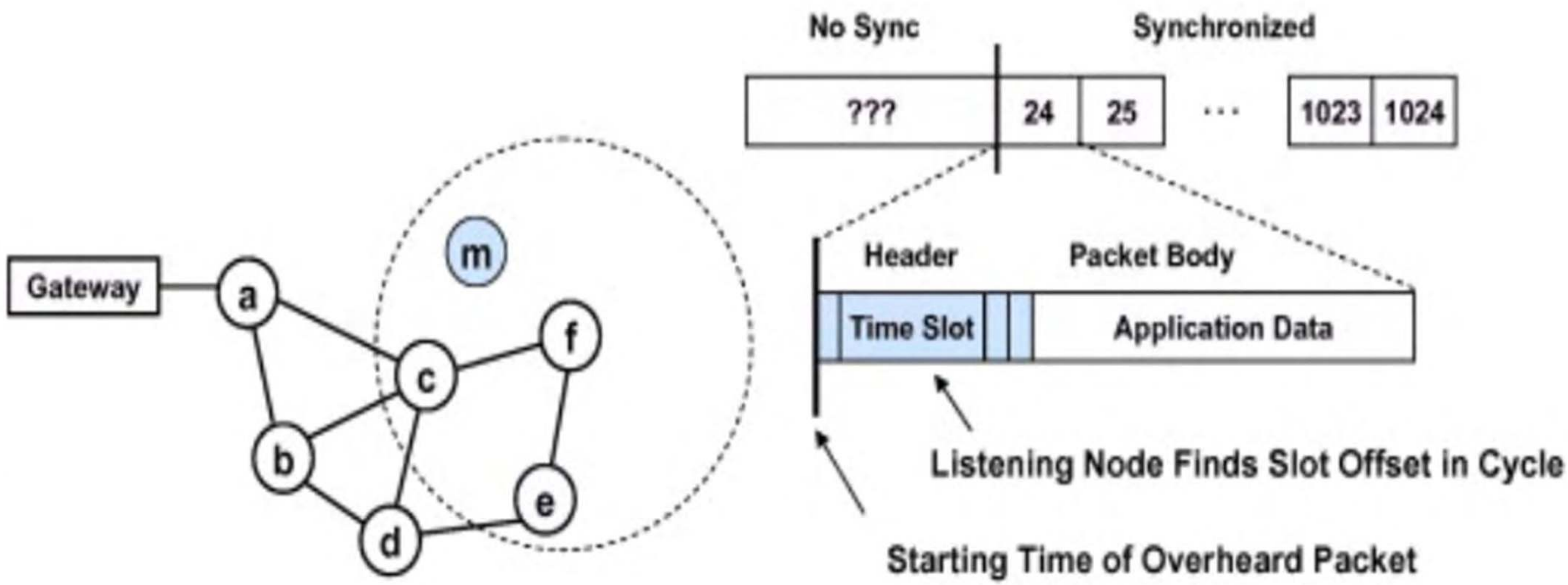
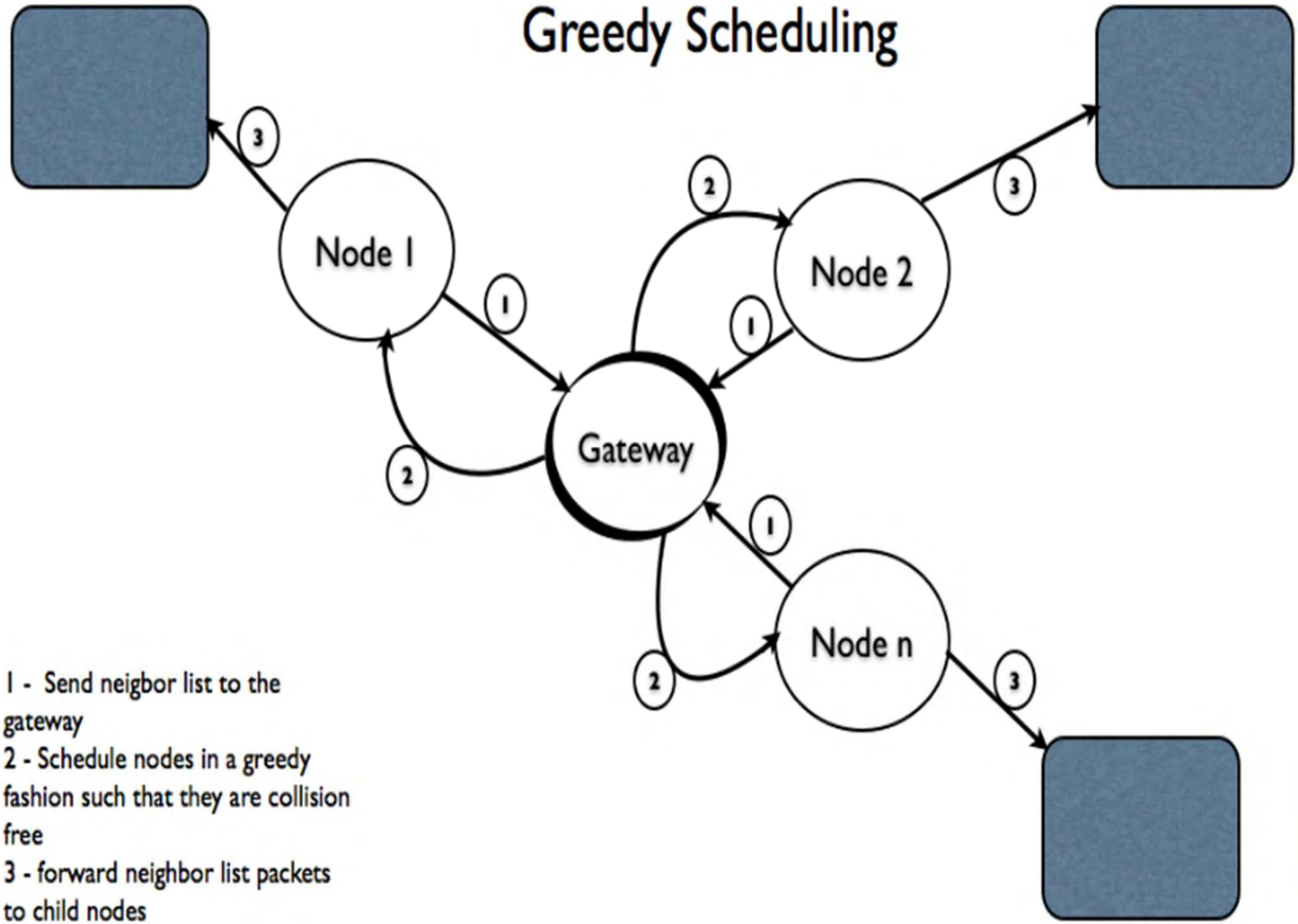


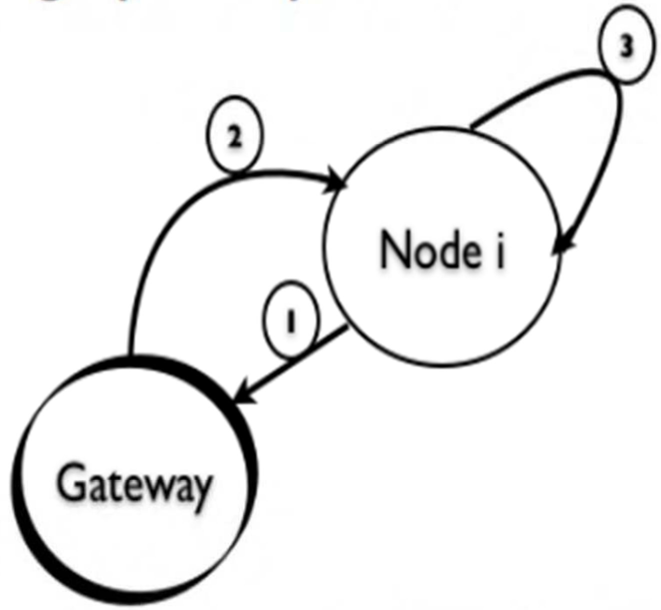
Fig. 4. Mobile node *m* synchronizes off of a packet overheard from node *f*.

Greedy Scheduling



1 - Send neigbor list to the gateway
2 - Schedule nodes in a greedy fashion such that they are collision free
3 - forward neighbor list packets to child nodes

Scheduling update packets

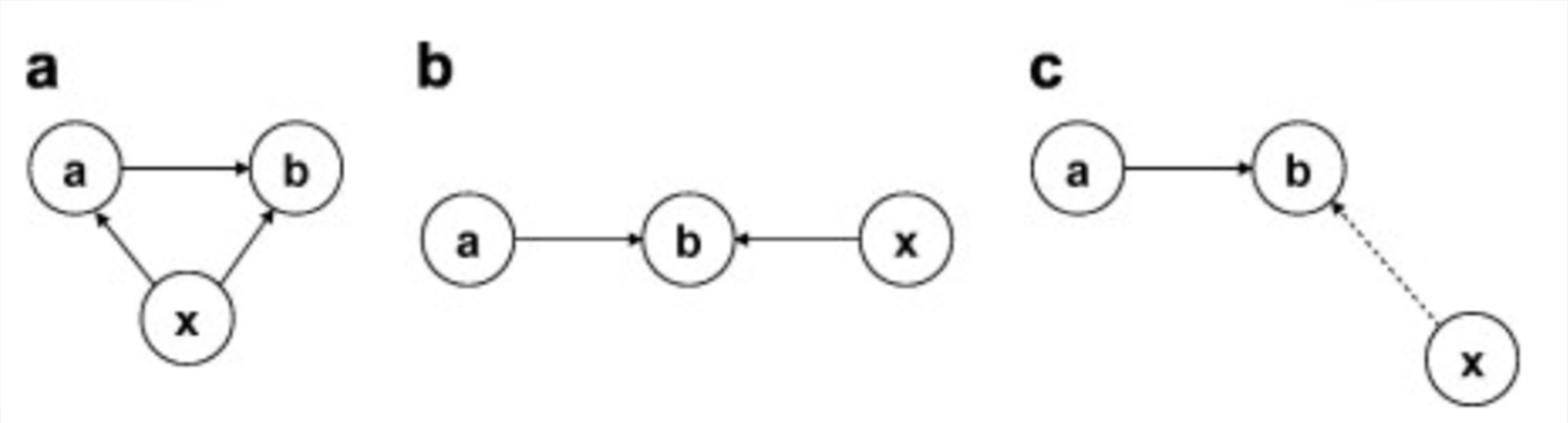


1 - Send shedule update packet to node
2 - Send ACK to gateway
3 - change to new schedule

Protocol: Conflict detection & resolution

- 2 mechanisms:
  - Active listener
    - Listen to transmit slot when no data to send
  - Active transmitter
    - Broadcast information packets

Protocol: Conflict detection & resolution



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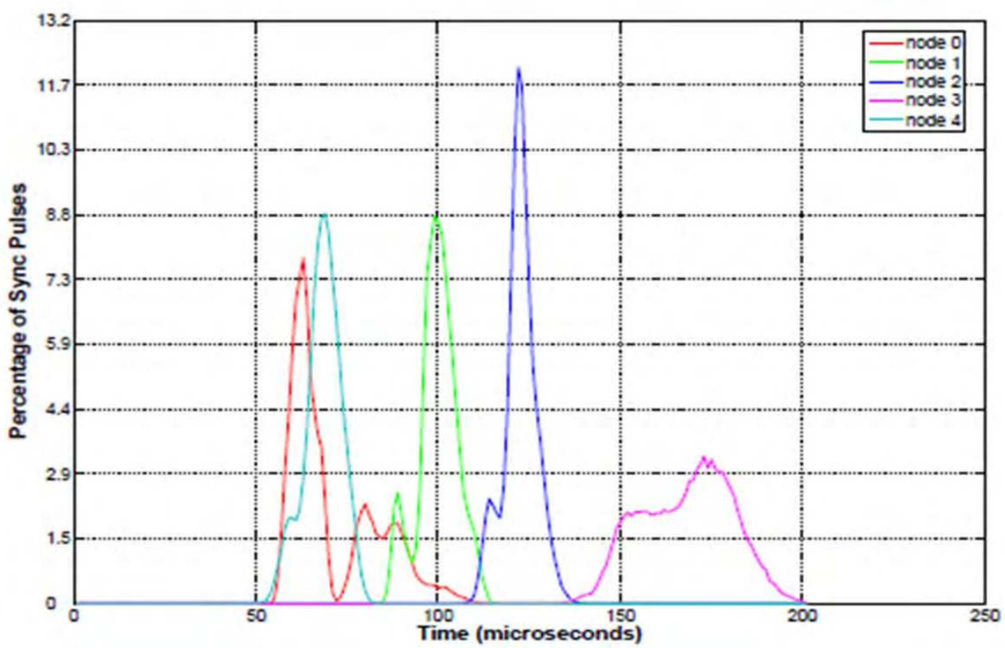
Infrastructure

- Hardware
  - FireFly sensor nodes
  - FireFly Jr. to forward packets
- Operating system: Nano-RK
  - Rate Monotonic Scheduling with Preemption
  - Enforces limits on:
    - Resources
    - Energy usage

Time Synchronization

- Open spaces : Atomic Clock Pulse WWVB
  - Detect edges to adjust internal clock
- Inside Buildings : Carrier-current
  - Use the power grid as AM - antenna
  - Jitter < 100 ~ 200 µs
    Clock drift < 10µs/s
    => update after 10 s
- Synchronization pulse every second
  - WWVB - bit
  - AM pulse



Time Synchronization

- Remarks
  - WWVB only in US and Southern Canada (60 kHz)
    - Need a different implementation in Europe: DCF broadcasts German Clock (77 kHz)
  - Global Synchronization bounded to 100µs
    - Slots of 5 ms
    - => 2 % synchronization loss
    - Difficult to reduce slot time

Communication

- Receiving strategy
  - Immediately start listening on listening-slots
  - If no preamble detected => Time-out (after 300µs)
  - If transit message, copy to transmit queue
- Sending strategy
  - Guard time before starting to send: 100 µs
    - Accounts for drifting between sender and receiver
- Provide configurable ISS (Inter slot spacing)

Communication

- Two nodes comunicating (request-response)

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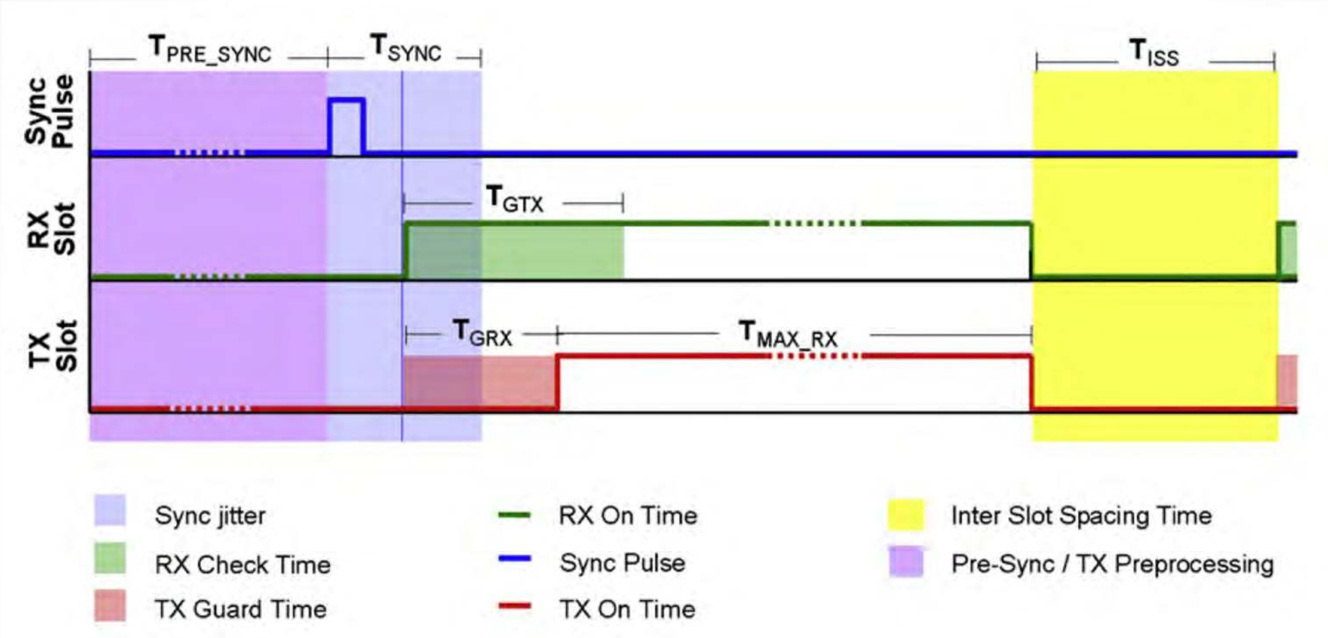
Set Up

- Comparison between the multi-hop performance of the RT-Link with that of a low-power-listen CSMA protocol (B-MAC)
- Implementation of a 10-node test-bed
- Used simulation to compare latency and lifetime

Energy consumption over a frame



Power consumption of the main components

Power parameters	Symbol	I (mA)	Power (mW)
Radio transmitter	$P_{\text{radio\_TX}}$	17.4	52.2
Radio receiver	$P_{\text{radio\_RX}}$	19.7	59.1
Radio idle	$P_{\text{radio\_idle}}$	0.426	1.28
Radio sleep	$P_{\text{radio\_sleep}}$	$1e^{-3}$	$3e^{-3}$
CPU active	$P_{\text{CPU\_active}}$	1.1	3.3
CPU sleep	$P_{\text{CPU\_sleep}}$	$1e^{-3}$	$3e^{-3}$
AM sync active	P_{sync}	5	15

Timing parameters for main components

Timing parameters	Symbol	Time (s)
Max packet transfer	$T_{\text{max\_payload}}$	$4e^{-3}$
Sync pulse jitter	T_{sync}	$100e^{-6}$
Sync pulse setup	$T_{\text{sync\_setup}}$	$20e^{-3} + (\rho * T_{\text{frame}})$
RX timeout	T_{GRX}	$300e^{-6}$
TX guard time	T_{GTX}	$100e^{-6}$
Inter-slot spacing	T_{ISS}	$500e^{-6}$
Clock drift rate	ρ	$10e^{-2}s/s$

Energy consumption over a frame

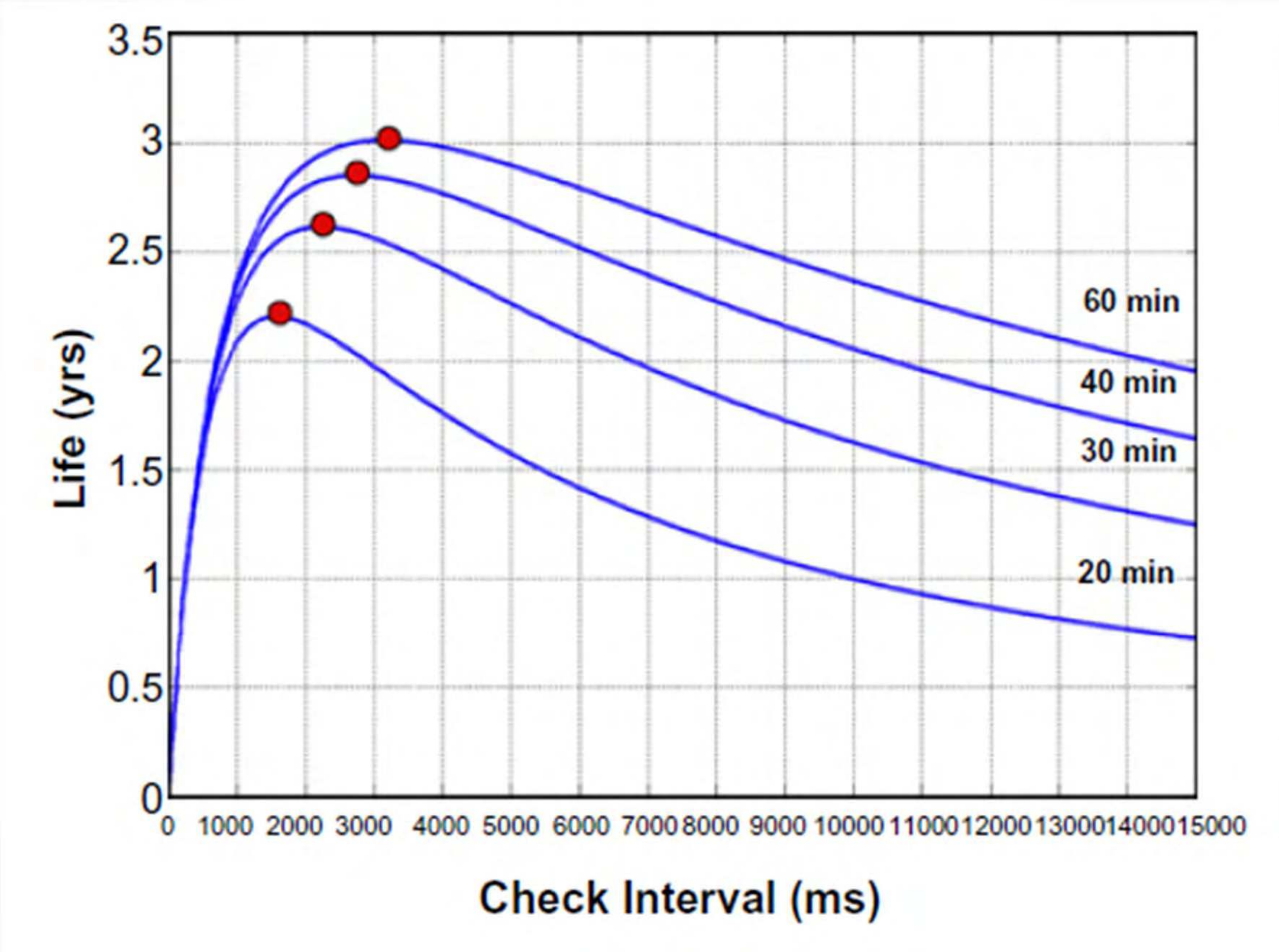
$$T_{\text{active}} = T_{\text{sync\_setup}} + T_{\text{sync}} + N_{\text{slots}} * (T_{\text{max\_payload}} + T_{\text{ISS}})$$

$$E_{\text{max}} = E_{\text{min}} + (d + N_{\text{contention}}) * E_{\text{RX}} + N_{\text{TX\_slots}} * E_{\text{TX}}$$

$$E_{\text{min}} = E_{\text{sync}} + (d + N_{\text{contention}}) * E_{\text{GRX}} + E_{\text{CPU\_active}} + E_{\text{CPU\_sleep}} + E_{\text{radio\_idle}} + E_{\text{radio\_sleep}}$$

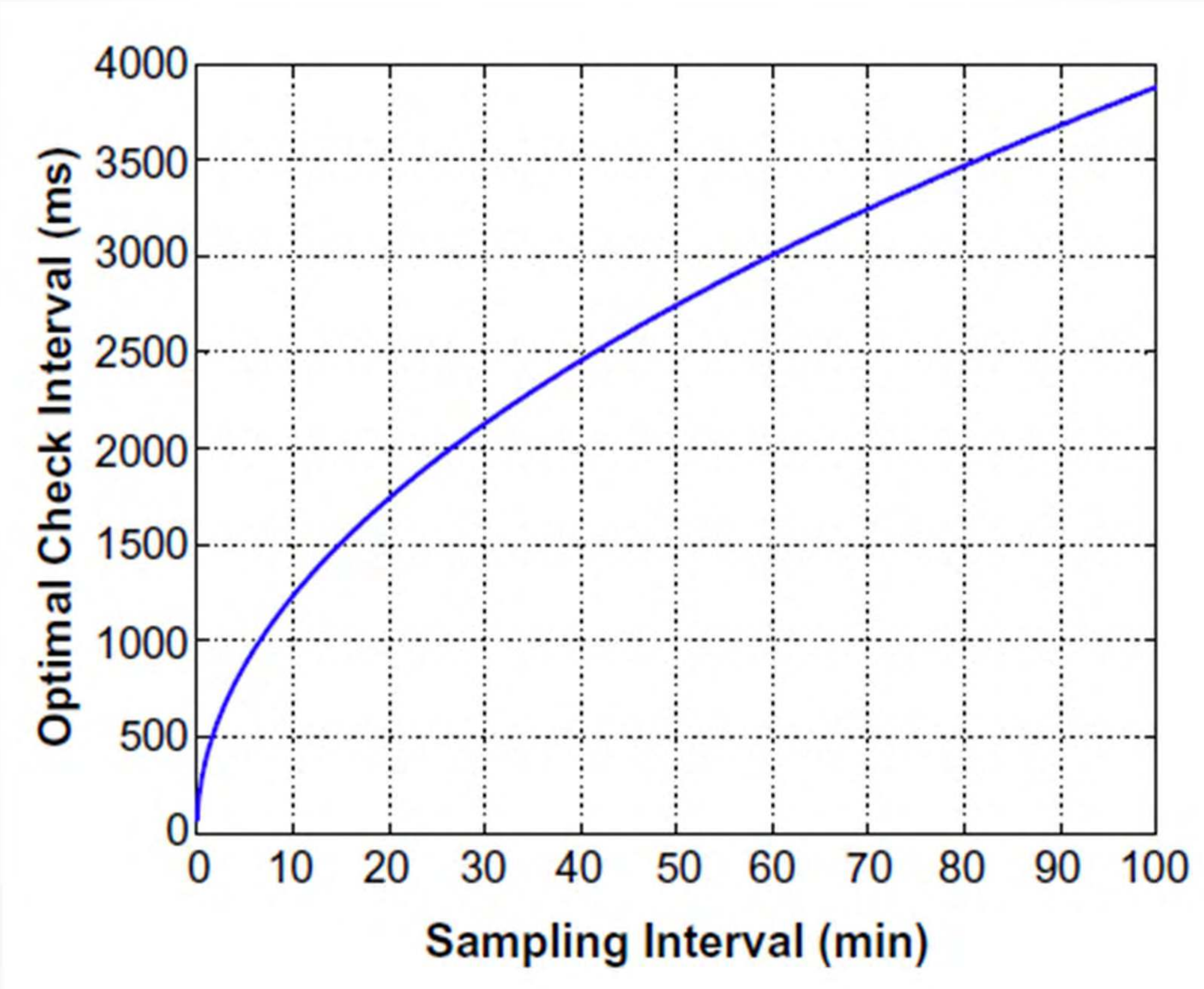
$$\text{Lifetime} = (E_{\text{capacity}}/E_{\text{max}}) * T_{\text{Frame}}$$

Lifetime



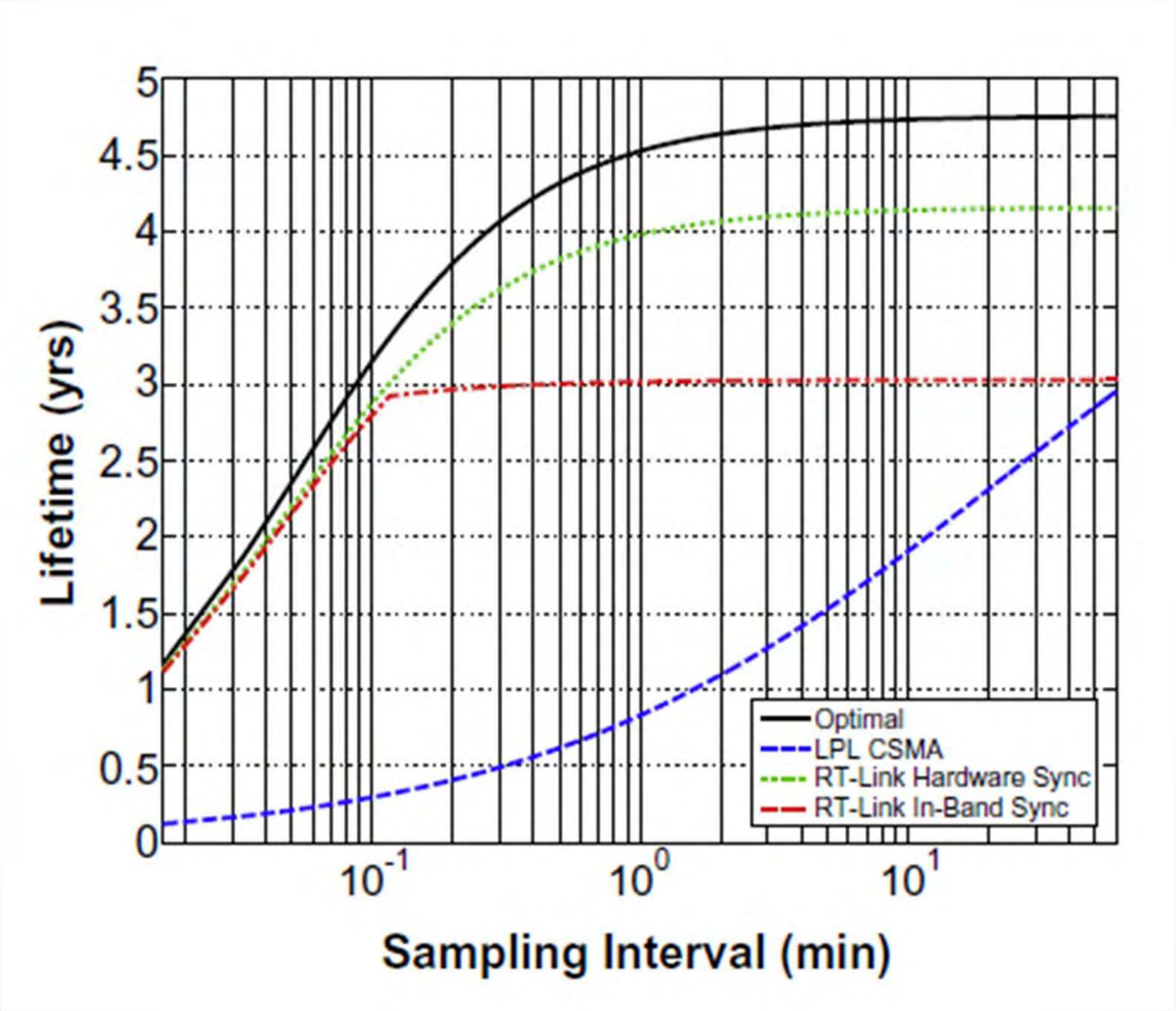
3.5
3
2.5
2
1.5
1
0.5
0
Life (yrs)
60 min
40 min
30 min
20 min
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000 15000
Check Interval (ms)

Lifetime



4000
3500
3000
2500
2000
1500
1000
500
0
Optimal Check Interval (ms)
0
10
20
30
40
50
60
70
80
90
100
Sampling Interval (min)

Lifetime


Lifetime (yrs)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
10^{-1}
10^{0}
10^{1}
Sampling Interval (min)
Optimal
LPL CSMA
RT-Link Hardware Sync
RT-Link In-Band Sync

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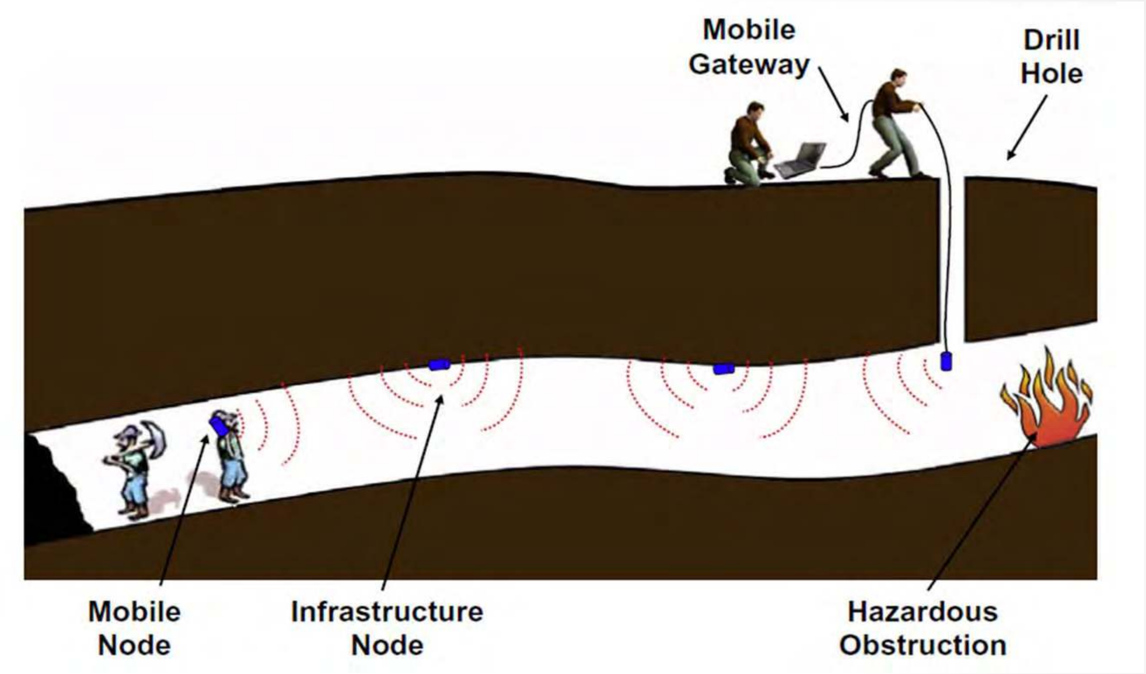
Application Example

1- All nodes are to be battery powered

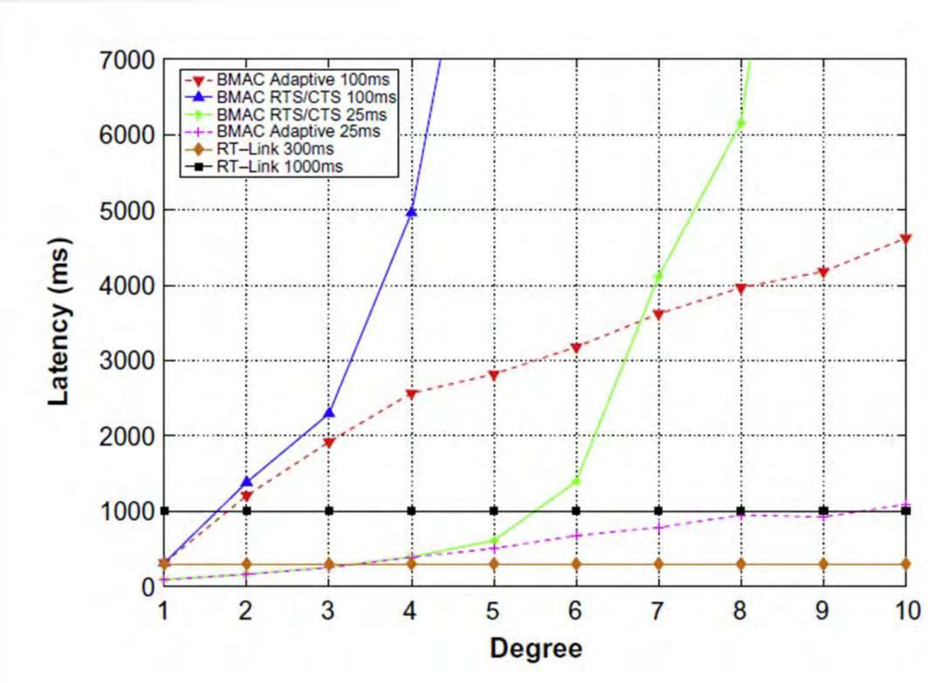
2- Nodes must have a predictable lifetime of at least one year under normal operation



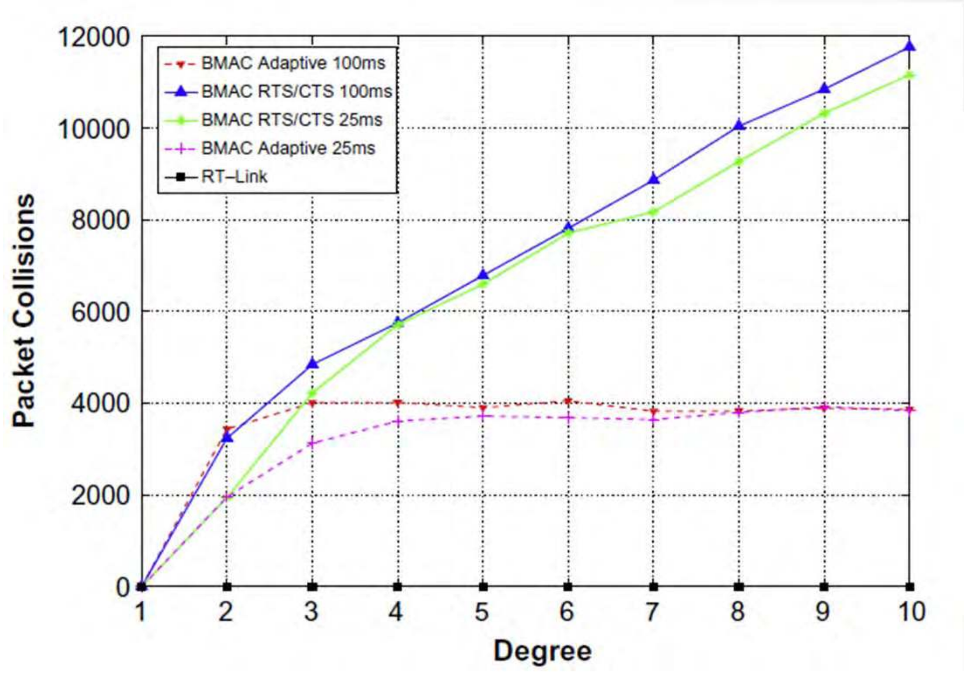
3-Nodes must provision continuous sensor sampling in an emergency

4- The network must be able to tolerate topology changes and self-heal to maintain connectivity after a partition.

Application Example



Impact on latency with node degree



Effect of node degree on collisions for B-MAC

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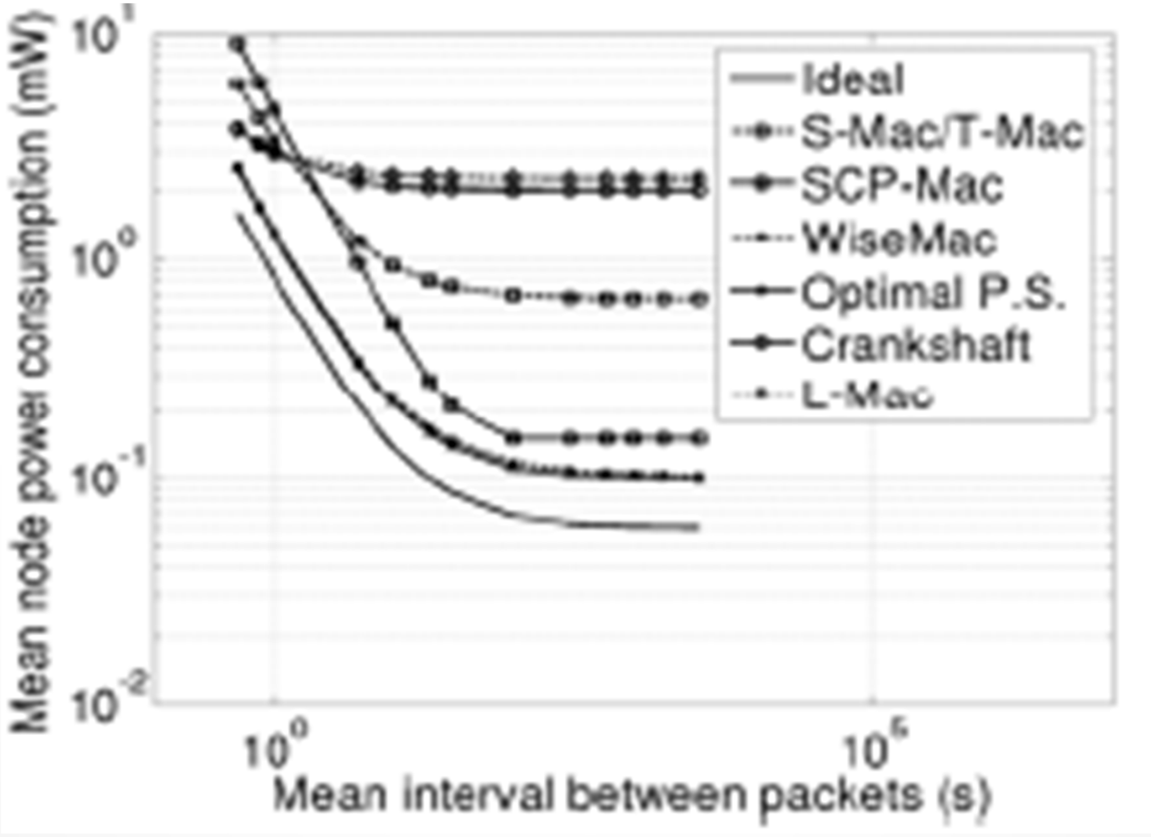
Remarks on the paper

- Protocol
  - Needs a lot of upfront calculations and estimations
  - Needs a centralized slot scheduler
- Time Synchronization works but
  - Introduces lower bound on slot-time to be efficient
- Performance
  - No information on performance in terms of throughput

Remarks on the paper

- Performance (cont'd)
  - easily coping with scalability in terms of latency, topology and node lifetime.



Conclusion

- Primary requirements for WSNs are met
  - energy efficient communication on scalable network having battery-operated nodes.
  - common sleep interval (via a sub-100 micron secs sync)
  - predictable maximal end-to-end throughput
  - bounded message latency
  - deterministic near-optimal lifetime for the network
  - total event ordering for inventory, logging or tracking

Conclusion

- Hardware-based TS is a robust and scalable option to in-band software-based techniques (such as RBS, TPSN and FTSP).
- Achieving global TS is economical and convenient for deployments.
- RT-Link achieves a practical lifetime of over 2 years

Questions

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