DCOSS

ZeroCal: Automatic MAC Protocol Calibration

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joint work with

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ETH
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NCCR MICS
National Competence Center in Research
Mobile Information and Communication Systems

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
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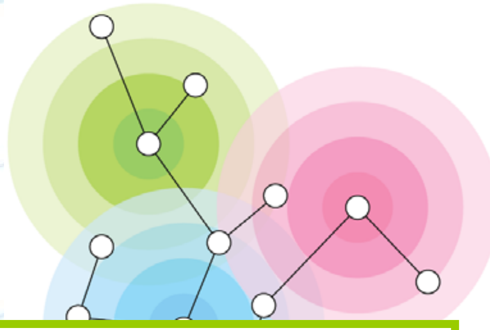
Swiss National Science Foundation

Data gathering in wireless sensor networks

- Sensor nodes sample data regularly
  - The data is sent to a common sink node requiring forwarding



How can we ensure that the configuration of the MAC protocol is optimized?

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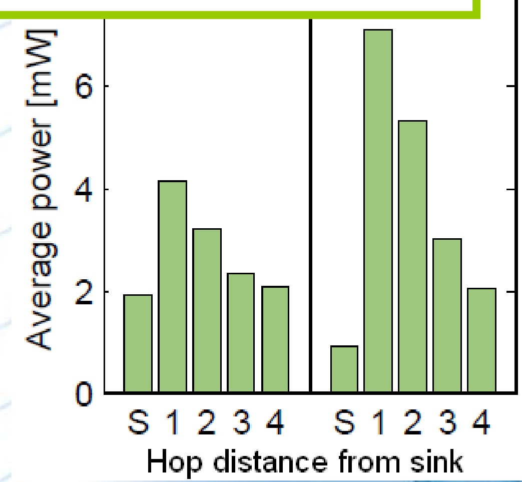
  - The energy consumption is not evenly distributed
  - Nodes closest to the sink spend the most energy
  - The energy consumption depends on the MAC parameterization (T_s)
  - Impacts network lifetime

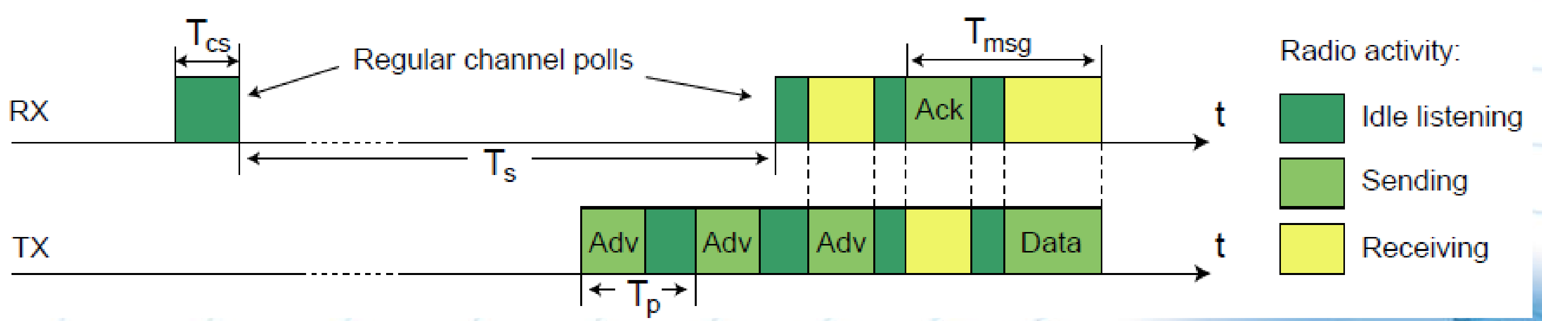


Related work

- Polastre et al. [SenSys'04]
  - Analytical model for adapting B-MAC for a certain traffic
  - Implementation of adaptation service is deferred to upper layer
- Buettner et al. [SenSys'06]
  - Optimize single sender-receiver pair
  - Cannot be used for general networks (e.g. mesh and trees)
- Jurdak et al. [TMC vol. 6, 2007]
  - Energy optimization through greedy local decisions
  - We show that it is beneficial not to make greedy decisions but to consider both parent and child nodes
- Merlin et al. [MASS'08]
  - Control theoretic approach
  - Only suitable for single-hop topologies

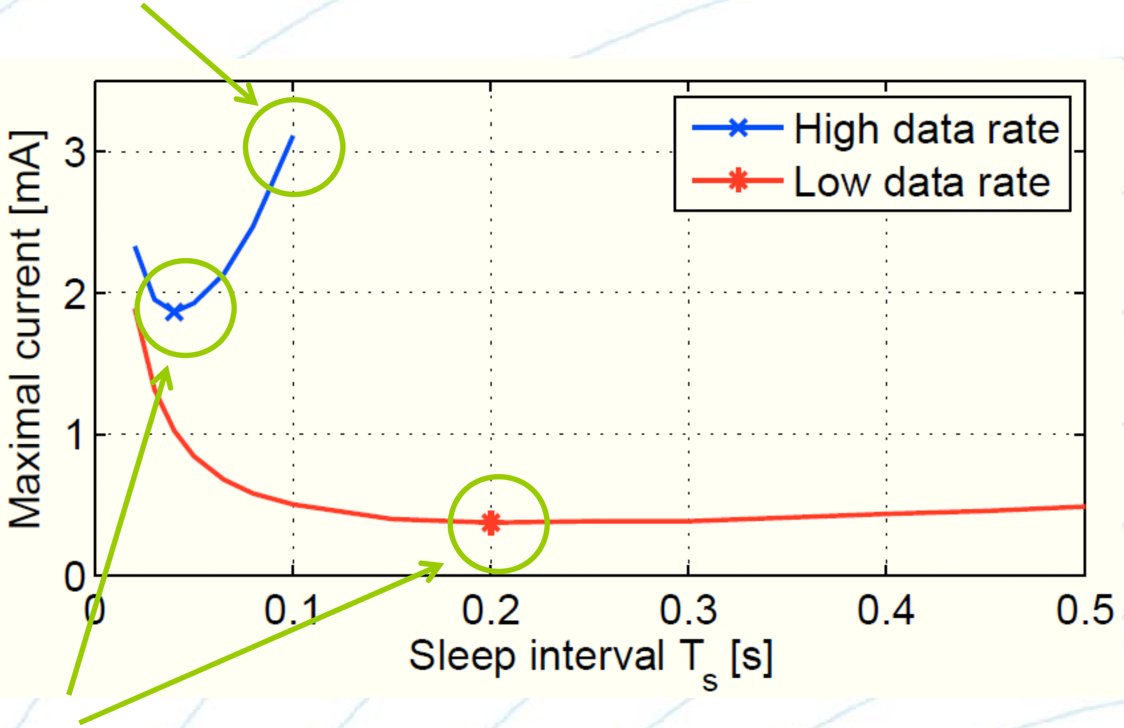
Background: Low-Power Listening MAC protocols (X-MAC)

- Receiver wakes-up every sleep interval T_s
  - The node keeps listening if the channel is busy
- The sender sends a long packet stream
  - The stream ends after $\sim T_s$ or after receiving an acknowledgment
- Increasing a parent node's T_s:
  - Decreases the parent's energy consumption for channel polling
  - Increases the child nodes' transmission energy



MAC parameters determine energy and bandwidth

- MAC parameterization dictates
  - Energy demands
  - Maximum data load



- Optimal MAC parameters
  - Depend on communication rate, traffic and link qualities

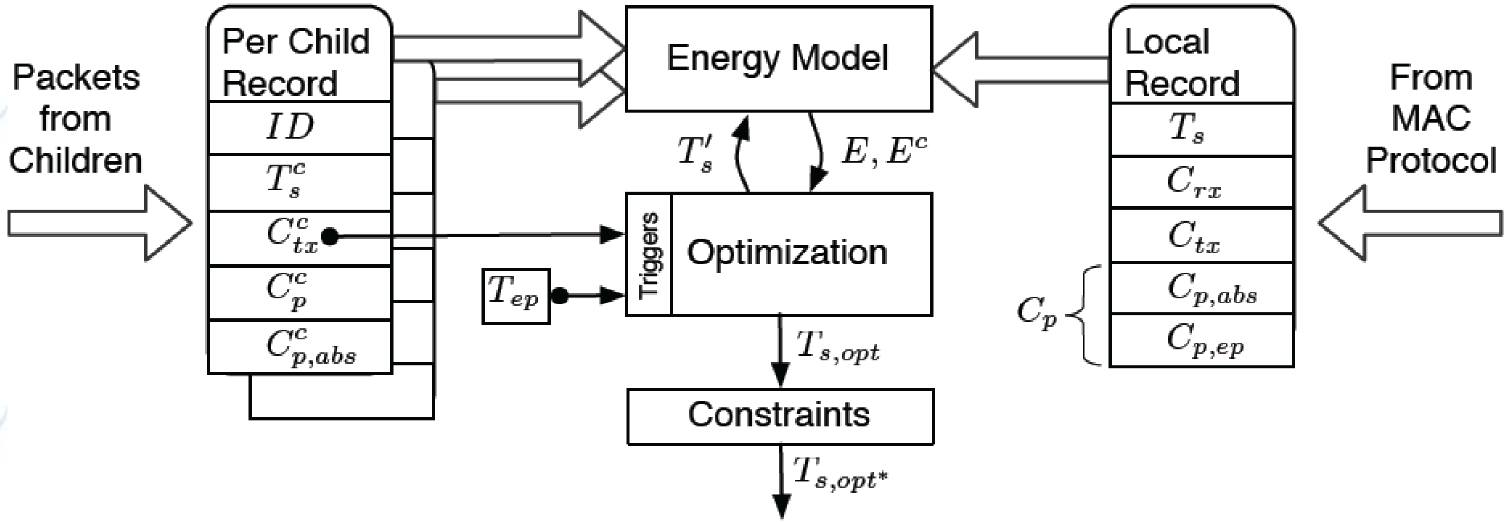
How to set the optimal MAC parameters?

- Traditionally the MAC parameters are set at compile time
  - Requires know-how from the application designer
  - Requires to anticipate the traffic of the network deployment
  - If the traffic is wrongly anticipated:
    - Energy is wasted
    - Packets are lost due to insufficient bandwidth

- ZeroCal: The parameter setting is observed regularly **at runtime** and updated if necessary
  - Every node tries to minimize **both** its own energy and the one of its children
  - This requires on-line **estimation of the energy** spent by the node itself and of if its children

ZeroCal Architecture

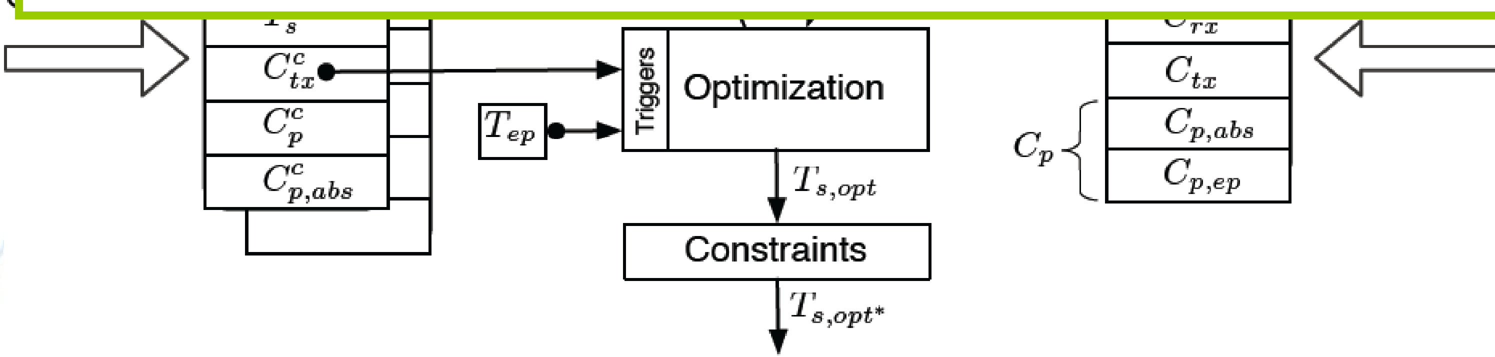
- Keep record of local and child statistics
- Optimization process is performed
  - Traffic based (or periodic if traffic is low)
- Compute a new optimal sleep interval
  - Using an energy model
  - Respect bandwidth and protocol constraints



ZeroCal Architecture

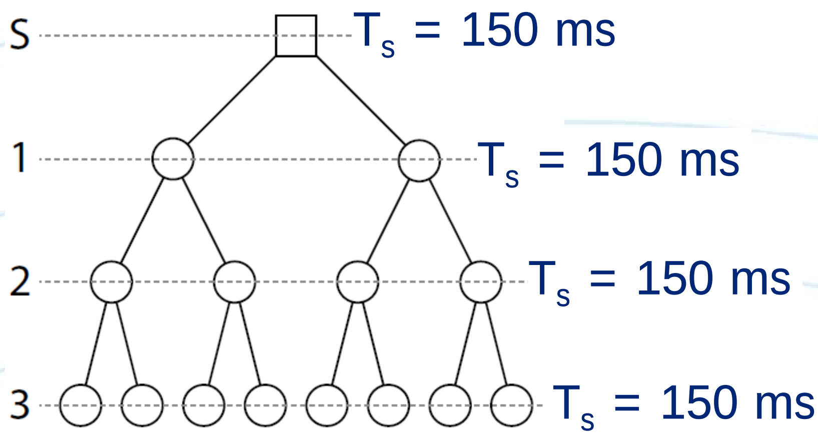
- Keep record of local and child statistics
- Optimization process is performed
  - Traffic based (or periodic if traffic is low)
- Compute a new optimal sleep interval

ZeroCal: Different nodes will have different parameter settings: A parent node will have a shorter T_s than its children

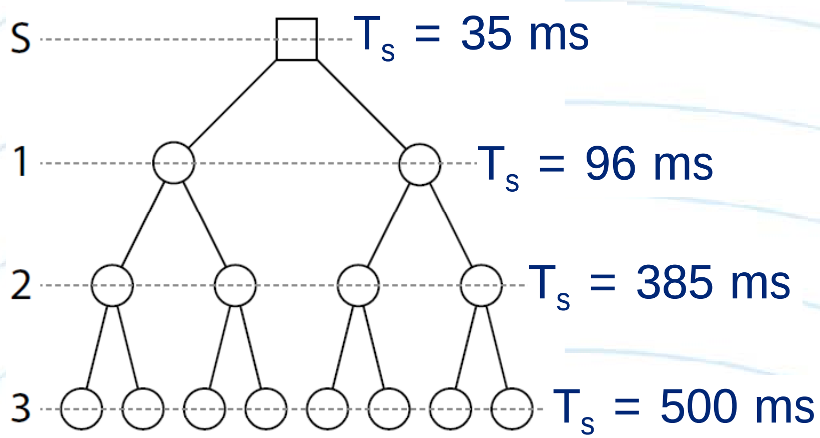


Identical vs. ZeroCals varying parameter setting

- Identical setting
  - Set at development time
  - Same setting for all nodes
  - Does never change



- ZeroCal
  - Different nodes will have different parameters
  - Optimize parameter setting at runtime
  - Adapt to changes in the traffic and environment



Estimate energy consumption with counters

- Energy estimation is based on our previous work
  - Analyzing MAC Protocols for Low Data-Rate Applications [Langendoen et al., ToSN to appear]
- Time for transmitting messages

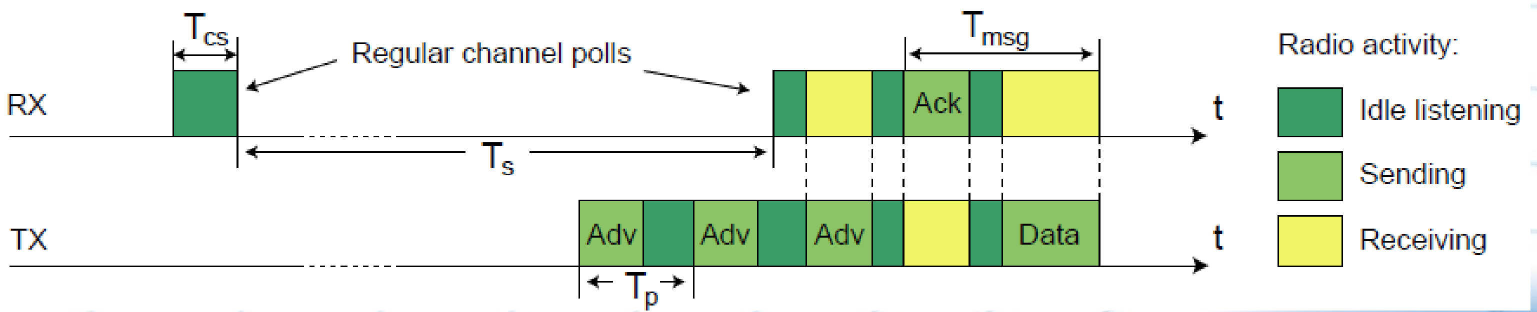
$$T_{tx} = C_p \cdot T_p + C_{tx} \cdot T_{msg}$$

- Time for receiving messages

$$T_{rx} = C_{rx} \cdot T_{msg}$$

- Time for idle listening

$$T_{cp} = (T_{ep} - T_{tx} - T_{rx}) \cdot T_{cs} / (T_s + T_{cs})$$

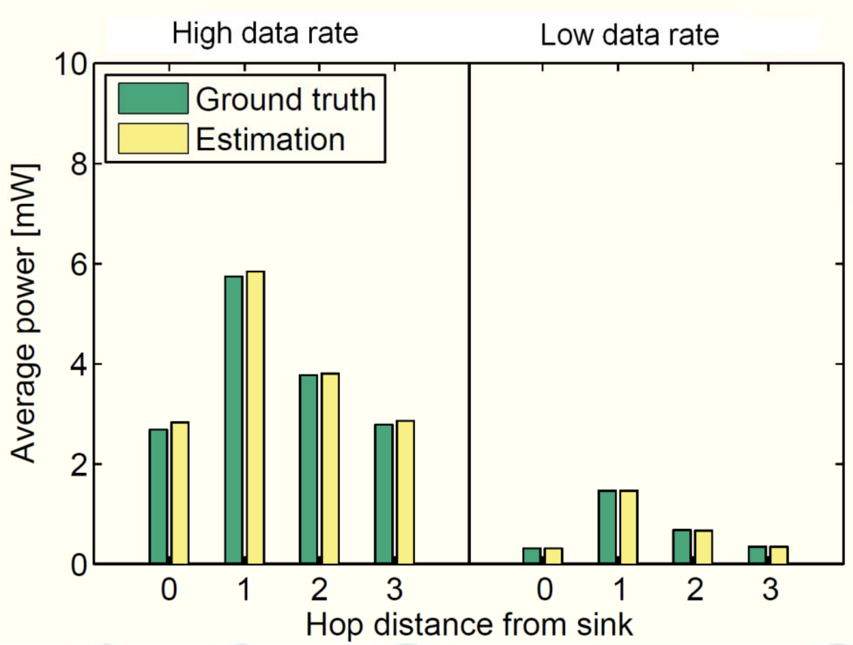


Energy estimation continued

- Calculate energy using the average power consumption for the different states:

$$E = T_{tx} \cdot P_{tx} + T_{rx} \cdot P_{rx} + T_{cp} \cdot P_{cp}$$

- Maximum estimation error:
  - 4.1% for high data rates
  - 1.8% for low data rates



Increasing a parent's sleep interval from T_s to T'_s

- Decreases the parent node's idle-listening time to:

$$T_{cp} = (T_{ep} - T_{tx} - T_{rx}) \cdot T_{cs}/(T'_s + T_{cs})$$

- Increases the child node's transmission time to:

$$T^c_{tx} = C^c_p \cdot T^c_p \cdot T'_s/T_s + C^c_{tx} \cdot T_{msg}$$

There is an optimal sleep interval $T_{s,opt}$:

$$T_{s,opt} = \operatorname*{argmin}_{T'_s \in [T_{s,min}, T_{s,max}]} \max\left[E, \max_{\forall \text{ children } c} (E^c)\right]$$

Two additional constraints for the sleep interval

1. Protocol constraint: The parent's sleep interval must not be longer than that of any child node

$$T_{s,opt*} \leq T_s^c, \quad \forall \text{ children } c$$

2. Bandwidth constraint: A message is sent or received in at most every n-th sleep interval

$$T_{s,opt*} \leq 1/(C_{tx} + C_{rx})/n$$

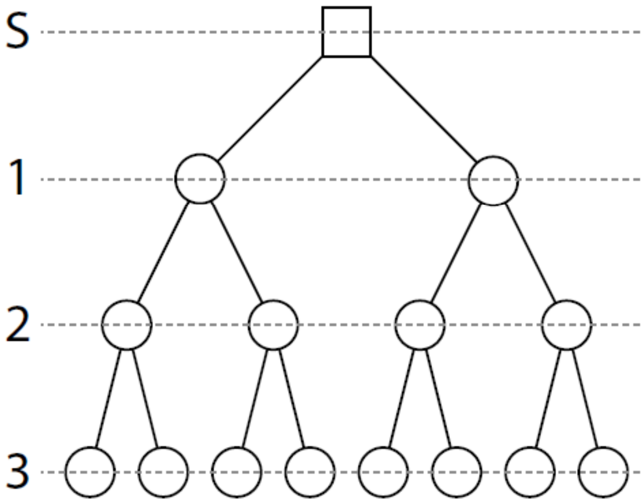
The optimal sleep interval $T_{s,opt*}$ is evaluated if either:

Periodic timeout: $T_{ep} > T_{ep,max}$

Traffic dependent: $C_{rx} > C_{eval}$

Evaluation in simulation

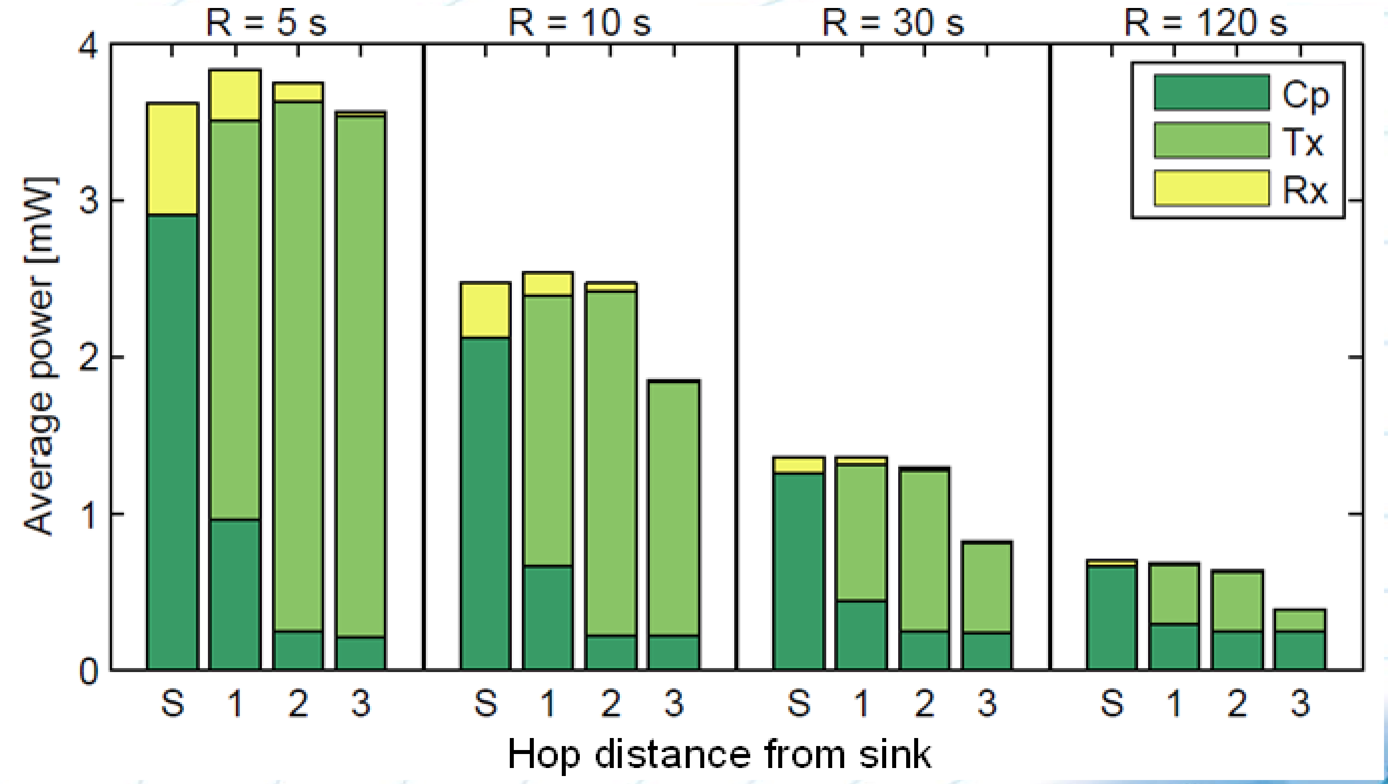
- Castalia simulator
  - X-MAC
- Complete binary tree
  - Height 3 (15 nodes)
  - Root is the sink
- Link Quality: PRR = 0.9
- Data rate: R = [5,120] s



Simulations with large and irregular topologies show the same trend as the binary tree.

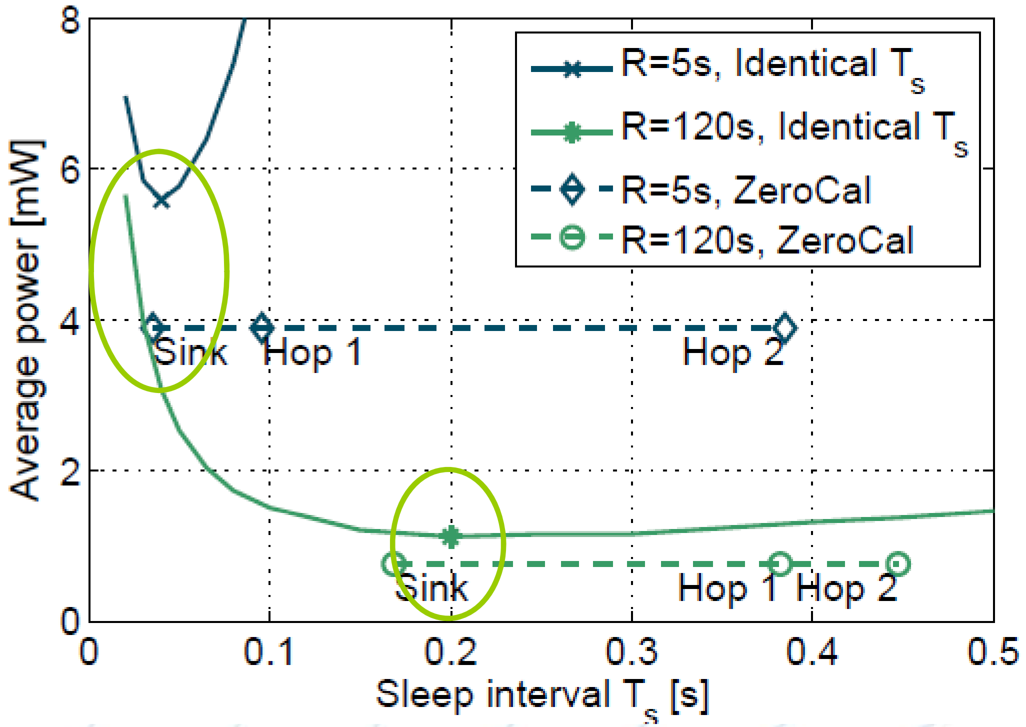
Simulation: Energy consumption using ZeroCal

- Well balanced energy consumption for low (R=120s) and high (R=5s) data rates
- The distribution of the energy consumption changes
  - Channel polling vs. transmission vs. reception



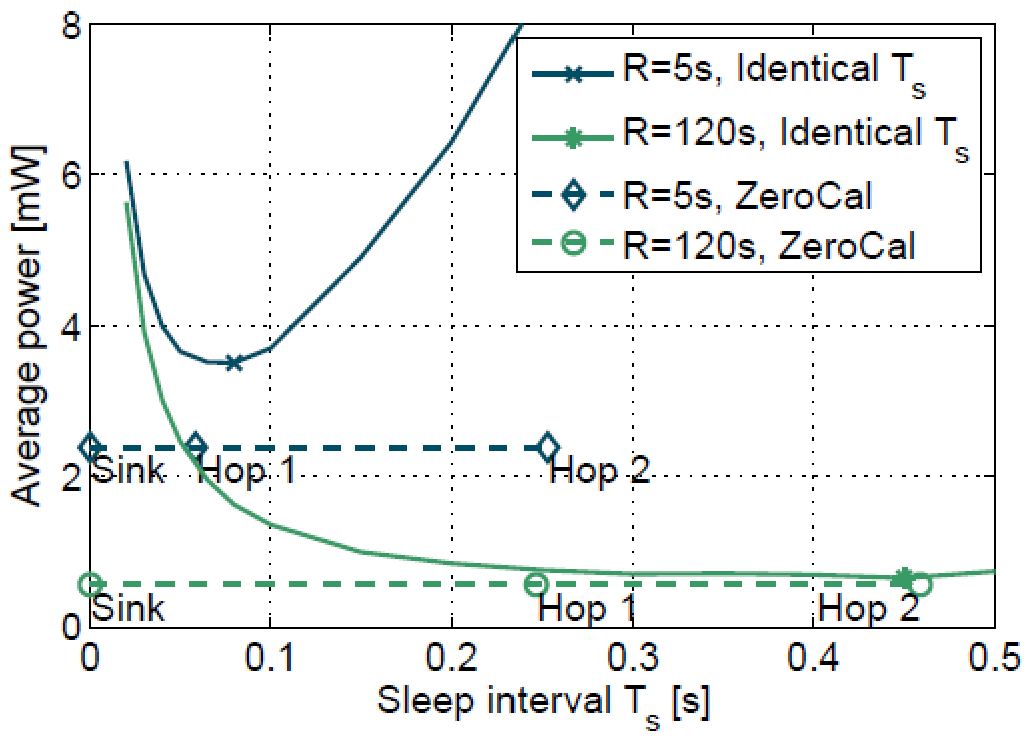
Simulation: ZeroCal vs. identical configuration

- ZeroCal outperforms the ‘hard-to-achieve’ optimal identical configuration by more than 30%
  - For low and for high data rates



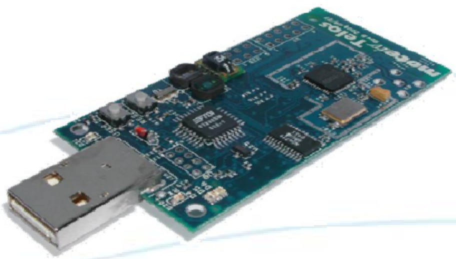
Simulation: Always listening sink

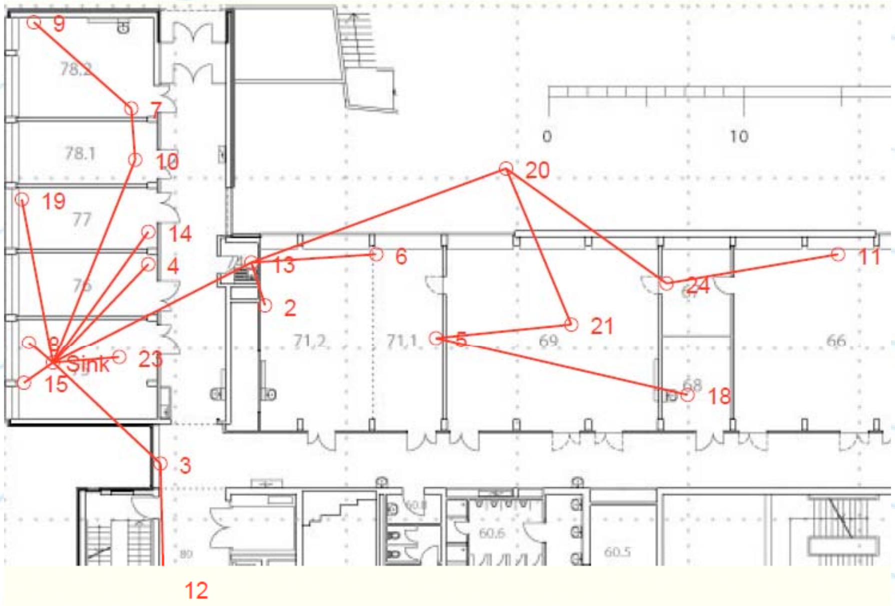
- The sink node has often an unlimited power supply
  - Allows for always listening (T_s=0 s)
- The adaptive duty cycling automatically adapts to this new scenario without any changes in the code



Testbed evaluation

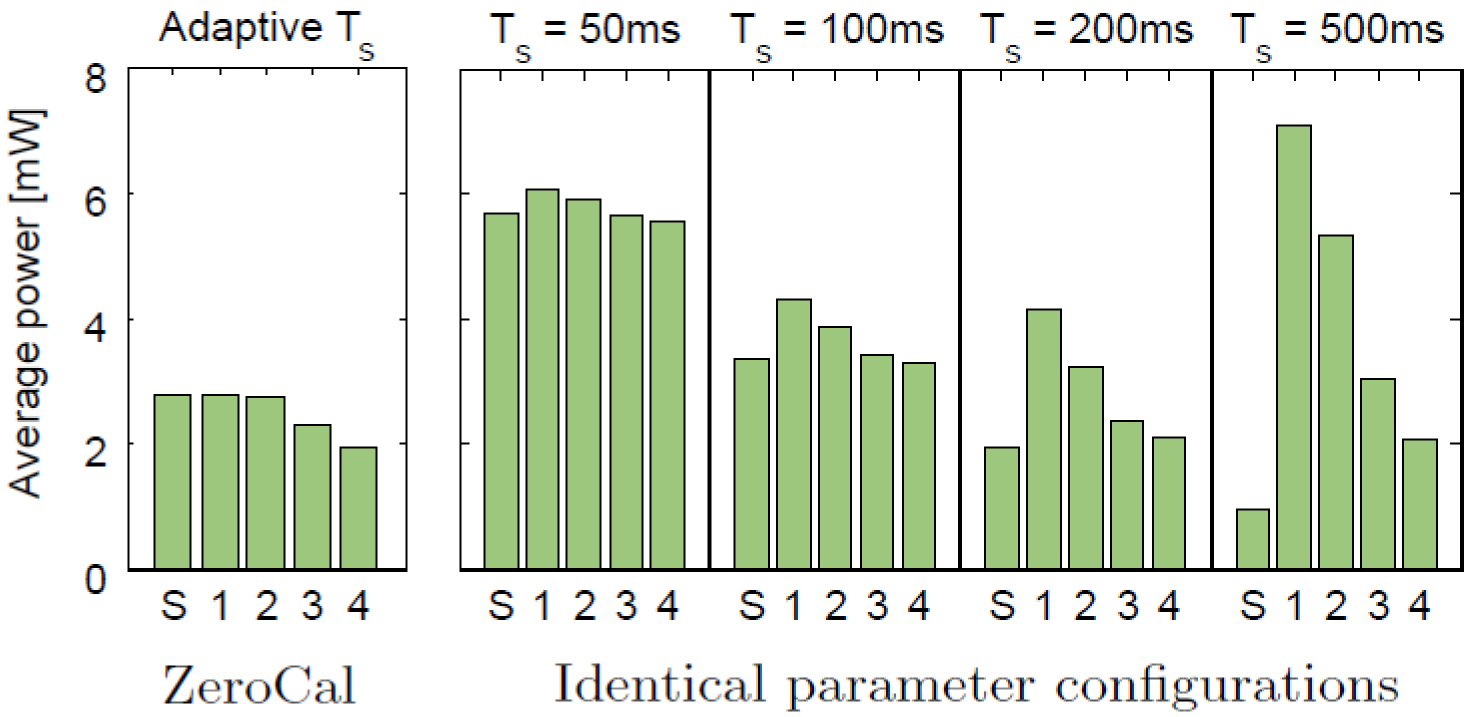
- 21 Tmote sky nodes
- Contiki operating system
  - X-MAC protocol
- Static topology
  - Up to 5 hops
- Data rate:
  - R = {10, 30, 120} s





Testbed: Zerocal vs. identical parameterization

- ZeroCal's energy consumption is
  - Largely reduced compared to the identical parameterization
  - Well balanced among all the hops

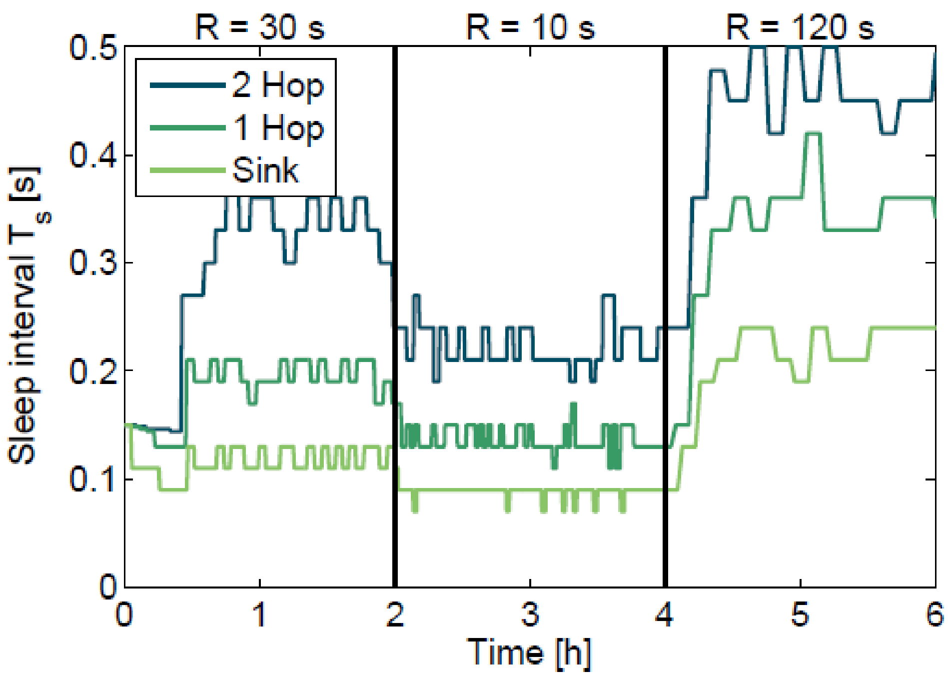


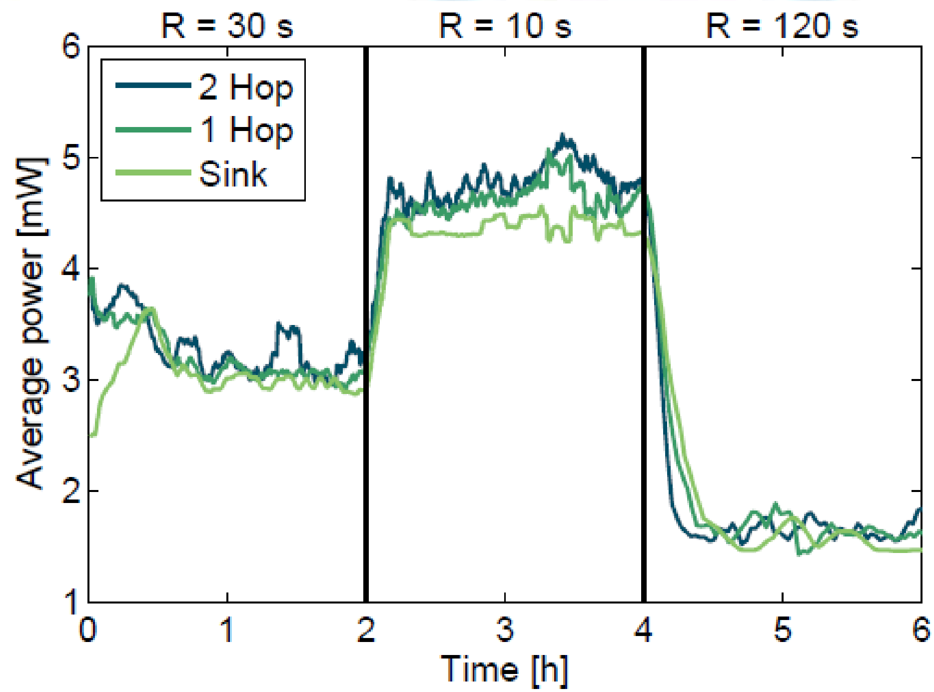
Datarate:

R = 30 s

Testbed: Adaptivity to network dynamics

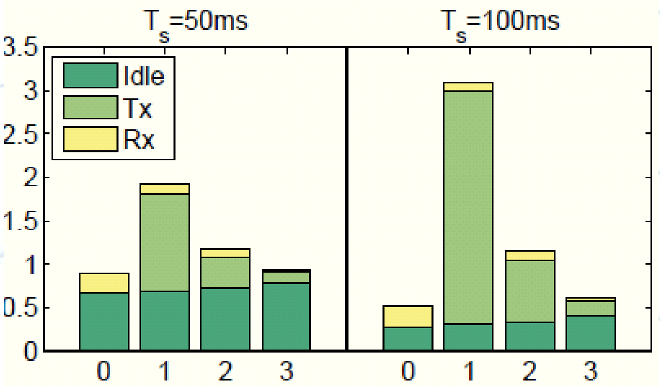
- The data rate R changes every two hours
  - R = [30, 10, 120] seconds
- The duty cycle adapts to the current setting
- The energy consumption is always well balanced





Conclusion

- It is difficult to find an <u>optimal</u> MAC configuration



- We showed an <u>adaptive</u> approach for optimizing the MAC parameters

$$T_{s,opt} = \underset{T'_s \in [T_{s,min}, T_{s,max}]}{\operatorname{argmin}} \max \left[E, \max_{\forall \text{ children } c} (E^c) \right]$$

- ZeroCal outperforms the optimal identic parameter setting.