The MAC Unreliability Problem in IEEE 802.15.4 WSNs

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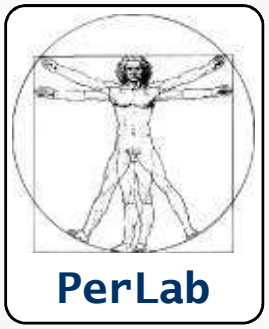

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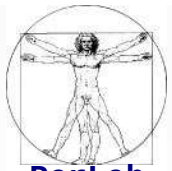
Acknowlegment

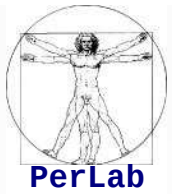
- Based on joint work with
  - Vincenzo Neri, University of Pisa
  - Marco Conti, IIT-CNR
  - Mario Di Francesco, University of Texas at Arlington
  - Sajal K. Das, University of Texas at Arlington

Overview

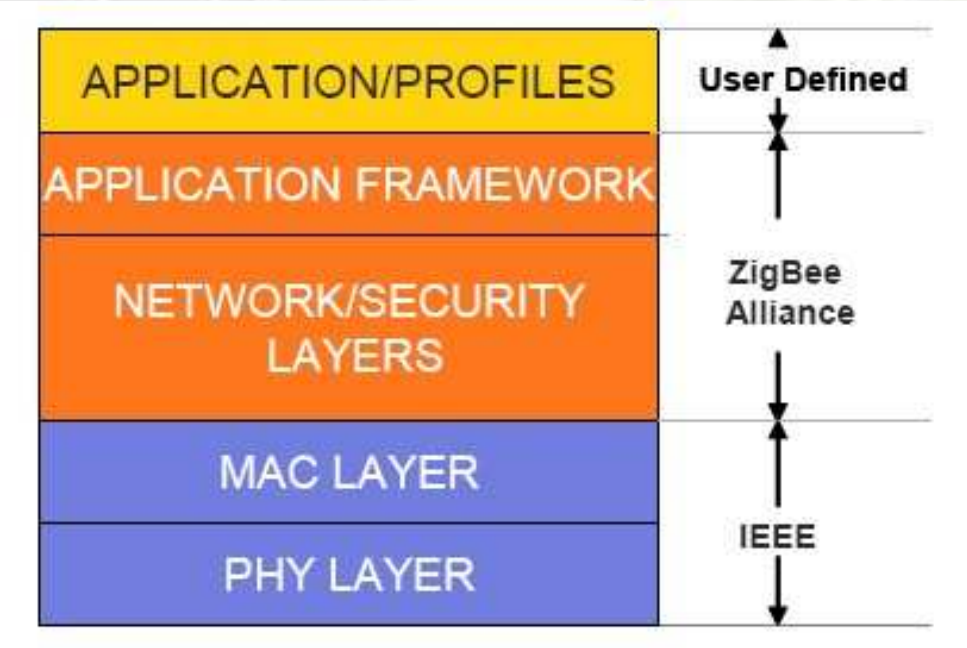


- IEEE 802.15.4 MAC
- MAC Unreliability Problem
- Causes
- Possible Solutions
- Conclusions

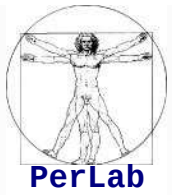
IEEE 802.15.4 and ZigBee



- IEEE 802.15.4 standard
  - Low-rate, Low-power, Low-cost Personal Area Networks (PANs)
  - PHY and MAC layers
- ZigBee Specifications
  - Upper Layers



IEEE 802.15.4 components



- Full Function Device (FFD)
  - implements the full set of standard functionalities
  - PAN coordinator
  - coordinator
    - ⇨ broadcasts beacons
    - ⇨ clock synchronization
- Reduced Function Device (RFD)
  - implements a minimal set of standard functionalities
  - cannot be a (PAN) coordinator
  - can only communicate with a FFD

IEEE 802.15.4/ZigBee Network Topologies

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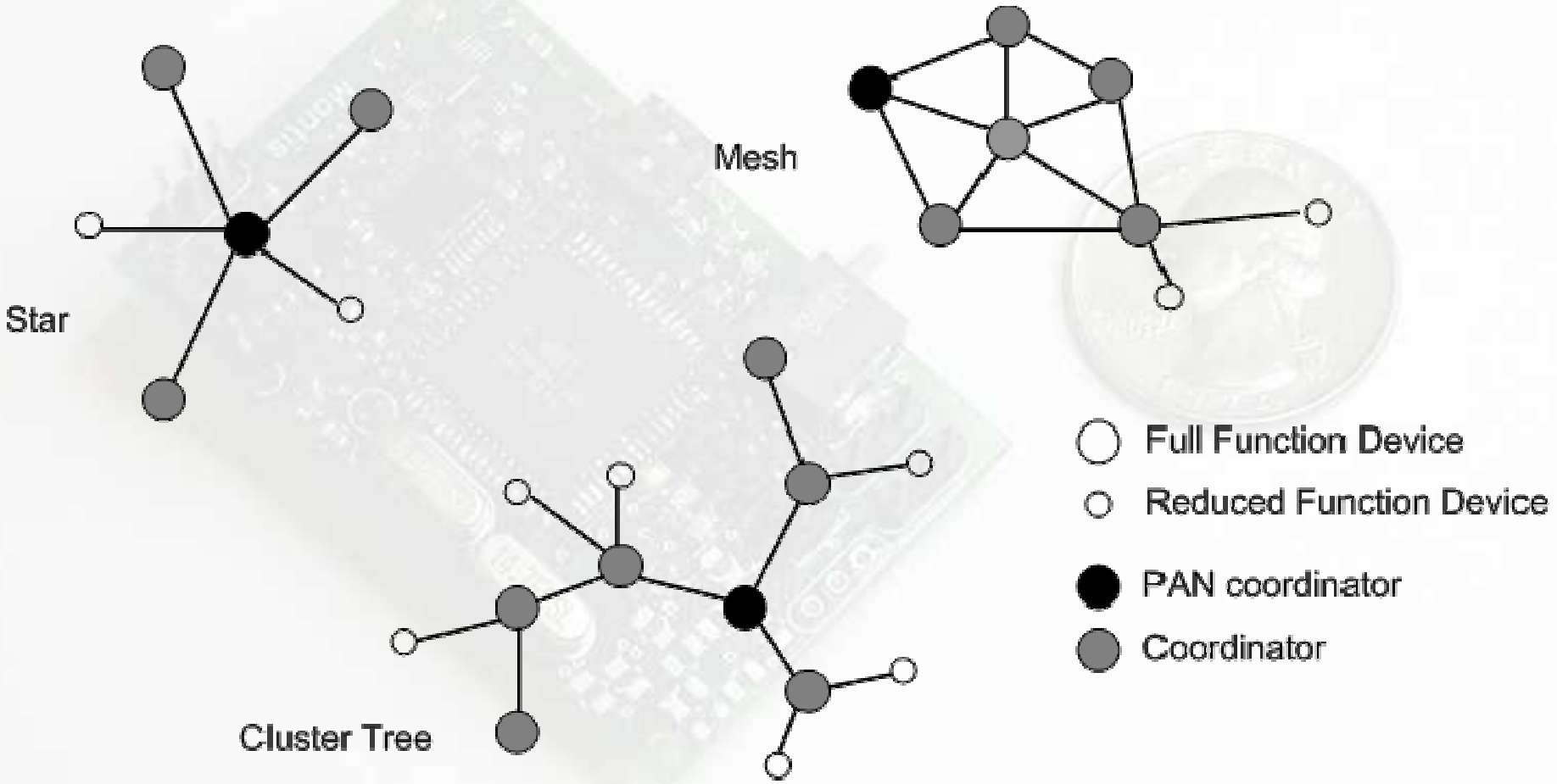
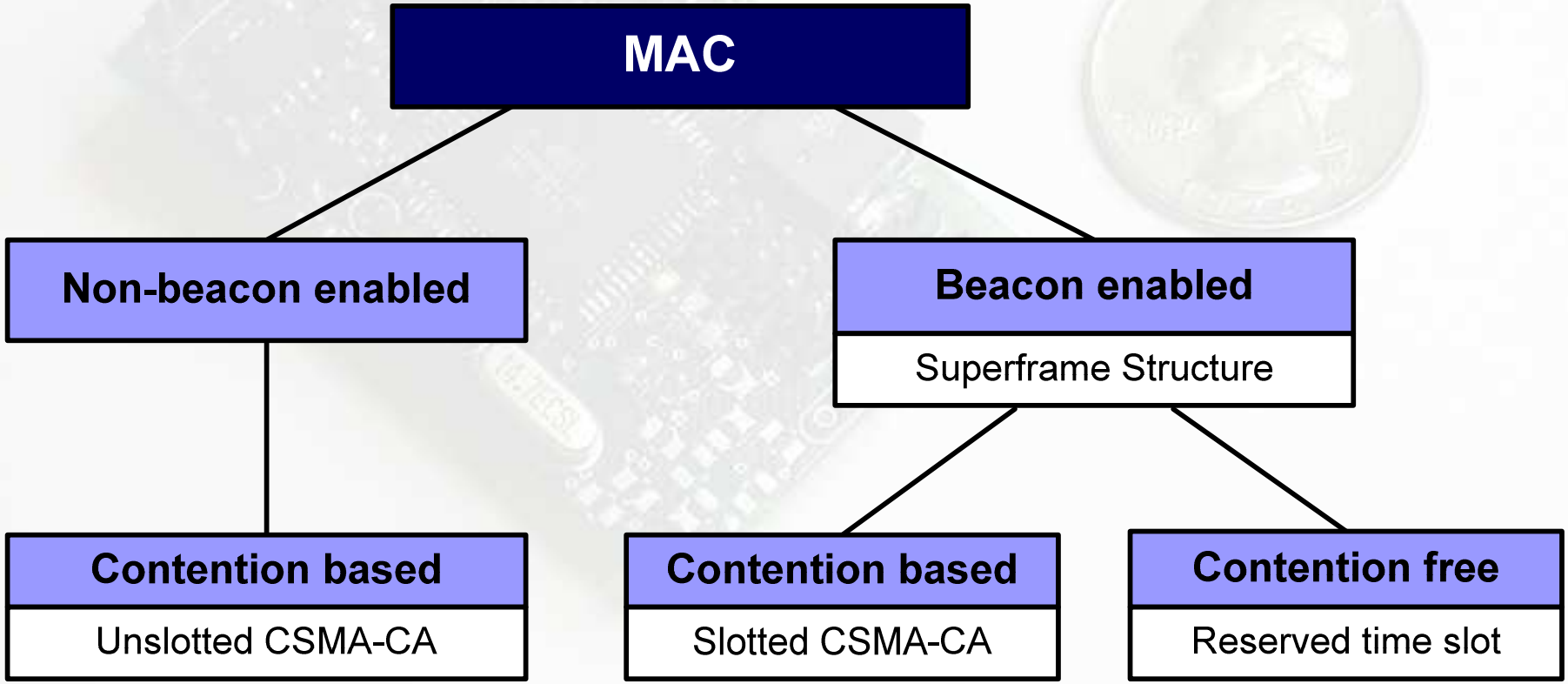
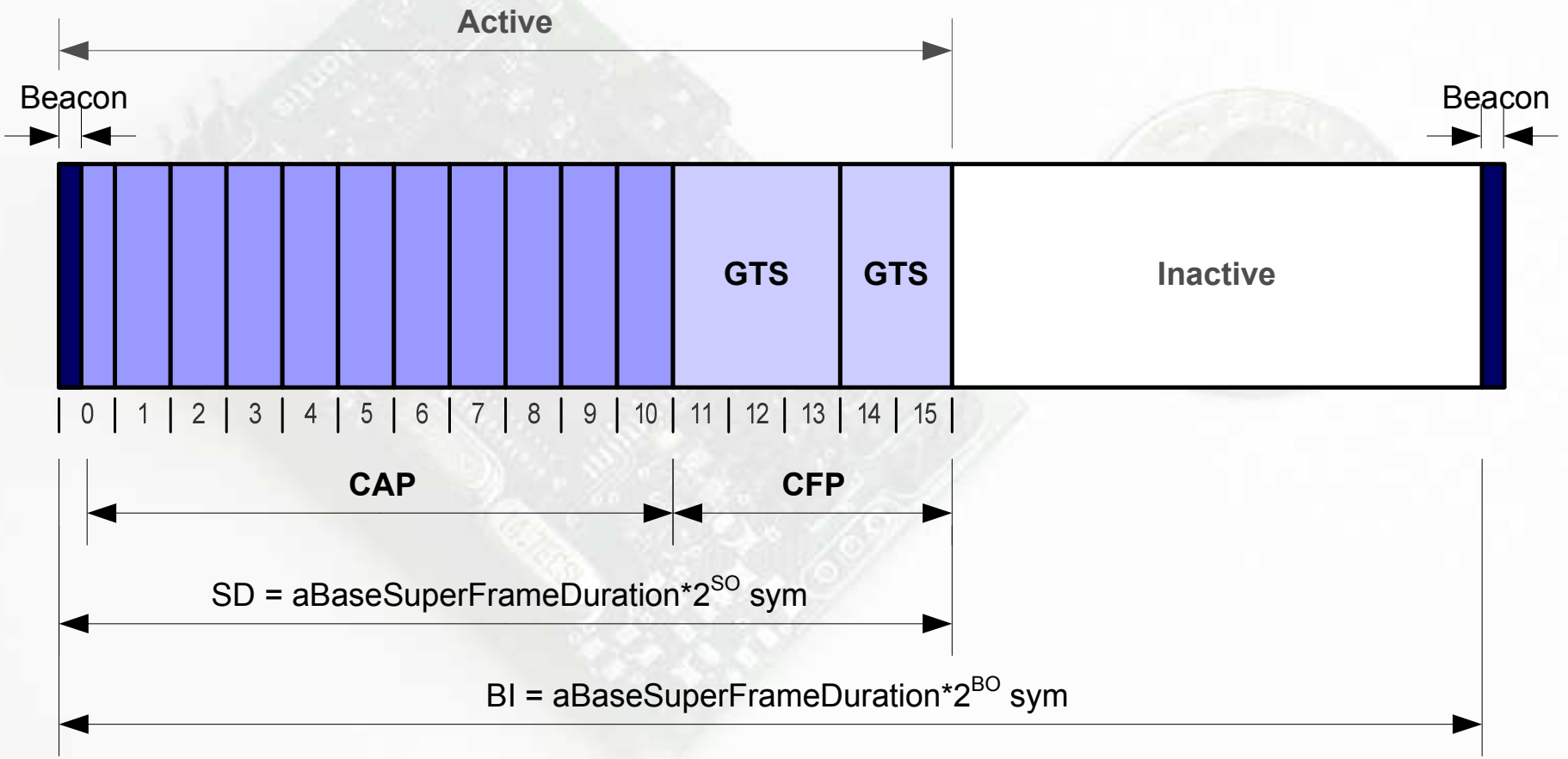


IEEE 802.15.4: MAC protocol

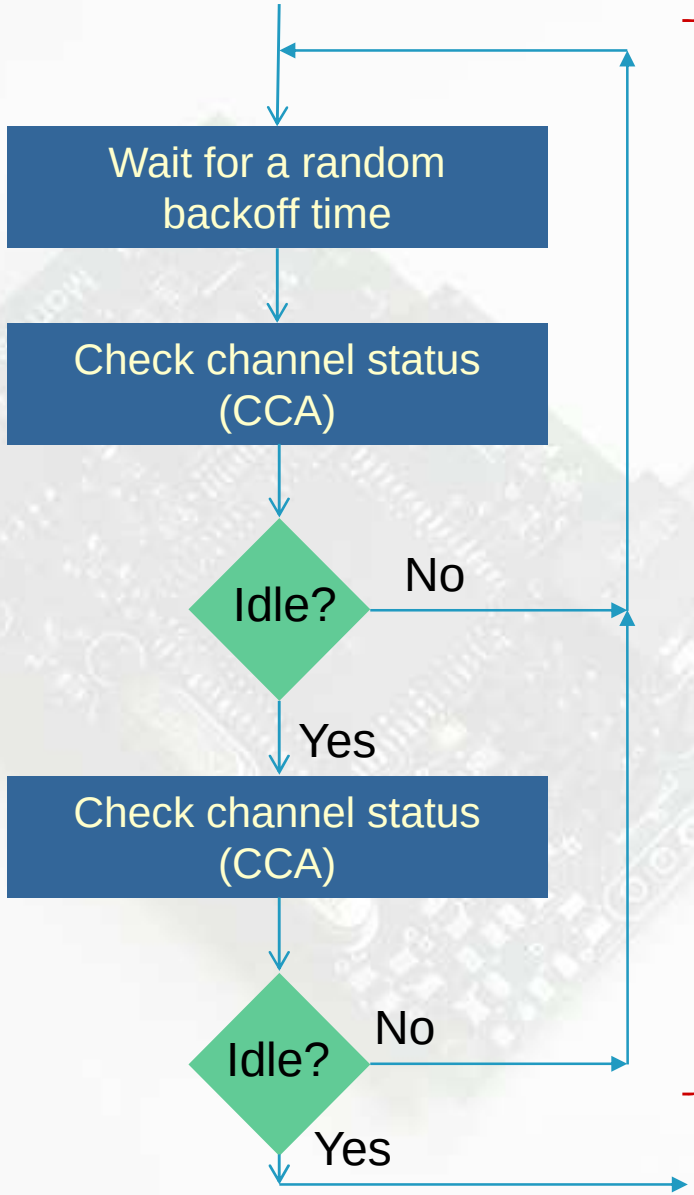
- Different operating conditions
  - duty-cycled beacon enabled mode
  - different channel access methods



IEEE 802.15.4: beacon enabled mode



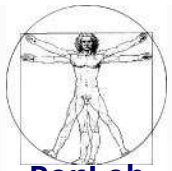
CSMA/CA: Beacon-enabled mode



At each trial the maximum backoff-window size is doubled

Only a limited number of attempts is permitted (***macMaxCSMABackoffs***)

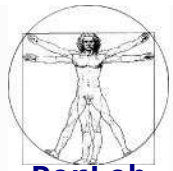
Acknowledgement Mechanism



- Optional mechanism
- Destination Side
  - ACK sent upon successful reception of a data frame
- Sender side
  - Retransmission if ACK not (correctly) received within the timeout
  - At each retransmission attempt the maximum backoff window size is doubled
  - Only a maximum number of retransmissions allowed (*macMaxFrameRetries)*

Performance of IEEE 802.15.4 Wireless Sensor Networks

Previous Work



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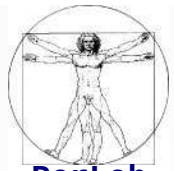
- K. Yedavalli, B. Krishnamachari, "Enhancement of the IEEE 802.15.4 MAC Protocol for Scalable Data Collection in Dense Sensor Networks", *Proc. International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt08),* Berlin, Germany, March 31 - April 4, 2008.

Previous Work (Cont'd)



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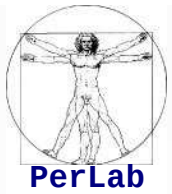
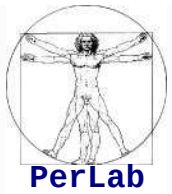
Simulation Setup



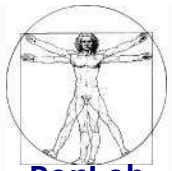
- NS-2 simulation tool
  - IEEE 802.15.4 module
- Scenarios
  - Single-hop (Star Topology)
  - Multi-hop (Cluster tree topology)
- Channel Conditions
  - Ideal
  - Non Ideal (Gilbert-Elliot Model for PER)

Traffic Generation Process



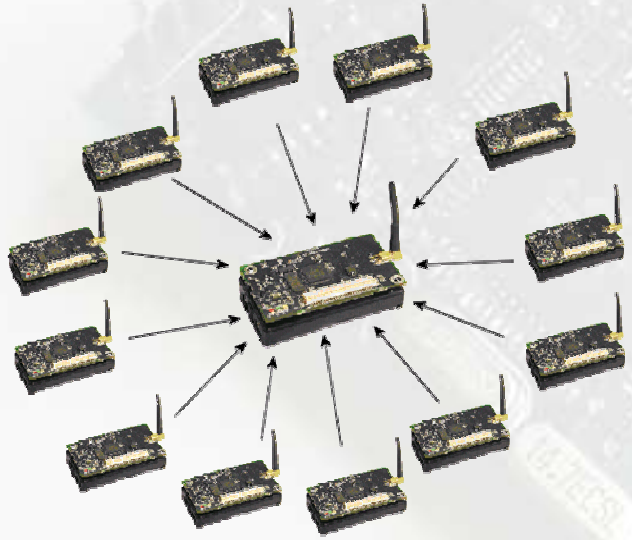
- Periodic
  - Power Management Enabled
  - Impact of Acknowledgement mechanism
- Poisson
  - Power Management Enabled/Disabled
  - Impact of Acknowledgement mechanism

Performance Indices



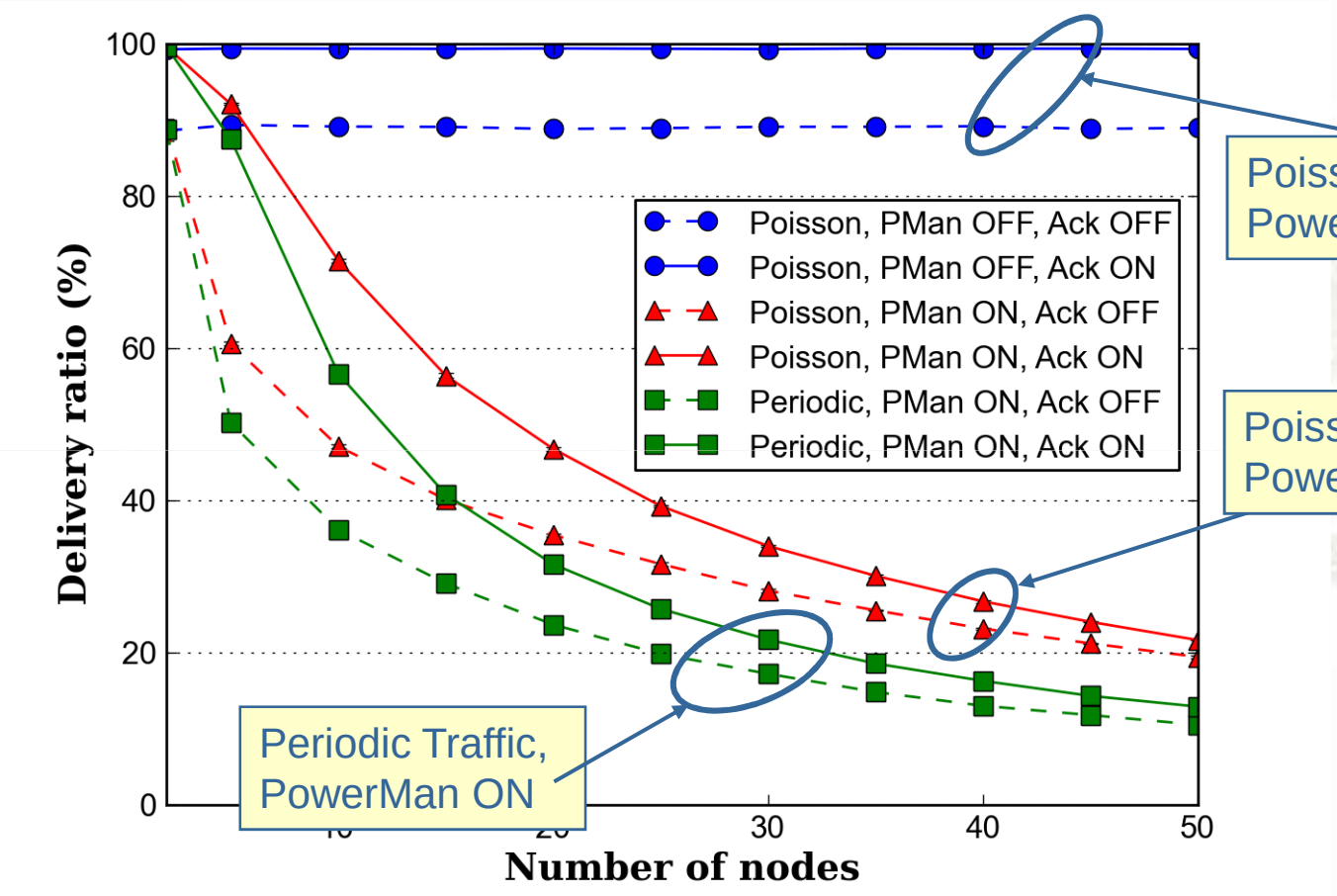
- Delivery ratio (Reliability)
  - ratio between the number of data messages correctly received by the sink and the total number of messages generated by all sensor nodes
- Average latency (Timeliness)
  - average time from when the message transmission is started at the source node to when the same message is correctly received by the sink
- Energy per message (Energy Efficiency)
  - average total energy consumed by each sensor node for each message successfully delivered to the sink

Single-hop Scenario



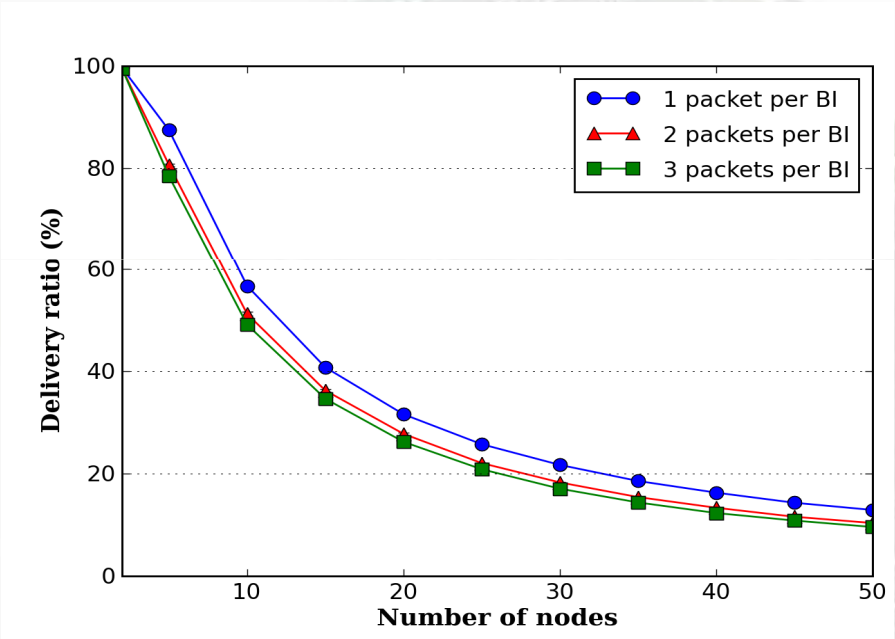
PHY layer	2.4 GHz
Bit Rate	250 Kbps
Sensor nodes	from 1 to 50
Distance from Coordinator Node	10m
CS range	30m
RX range	15m
Beacon Interval	125.8 s (BO=13)
Active Period	1.97 s (SO=7)
Duty Cycle (when enabled)	1.6%
Message Size	100 bytes
Message Arrival Process	Periodic
Message Loss Rate	10% (Gilbert-Helliot)
Coordinator node always ON	

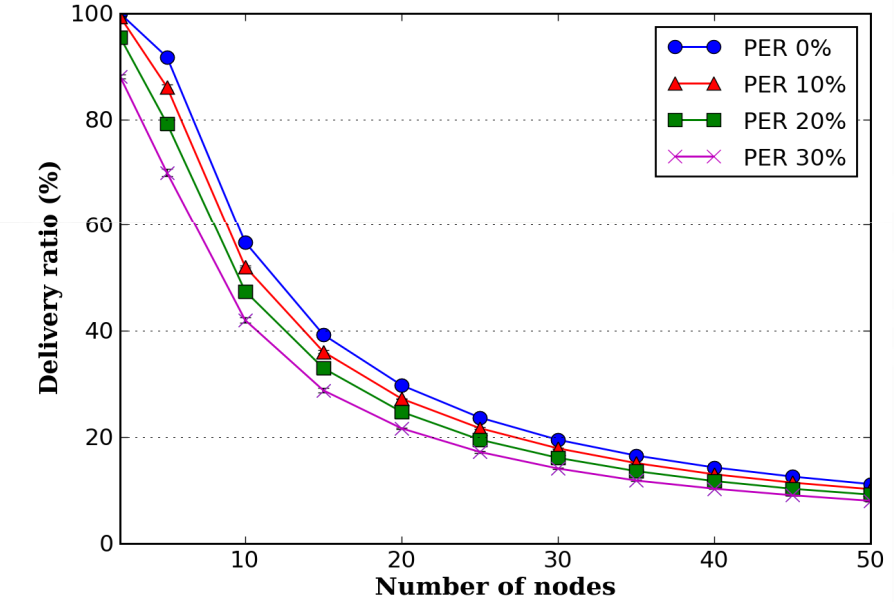
802.15.4 MAC Performance



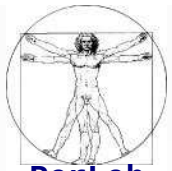
G. Anastasi, M. Conti, M. Di Francesco, A Comprehensive Analysis of the MAC Unreliability Problem in IEEE 802.15.4 Wireless Sensor Networks, *IEEE Transactions in Industrial Informatics,* Vol. 7, N. 1, Feb 2011.

802.15.4 MAC Performance



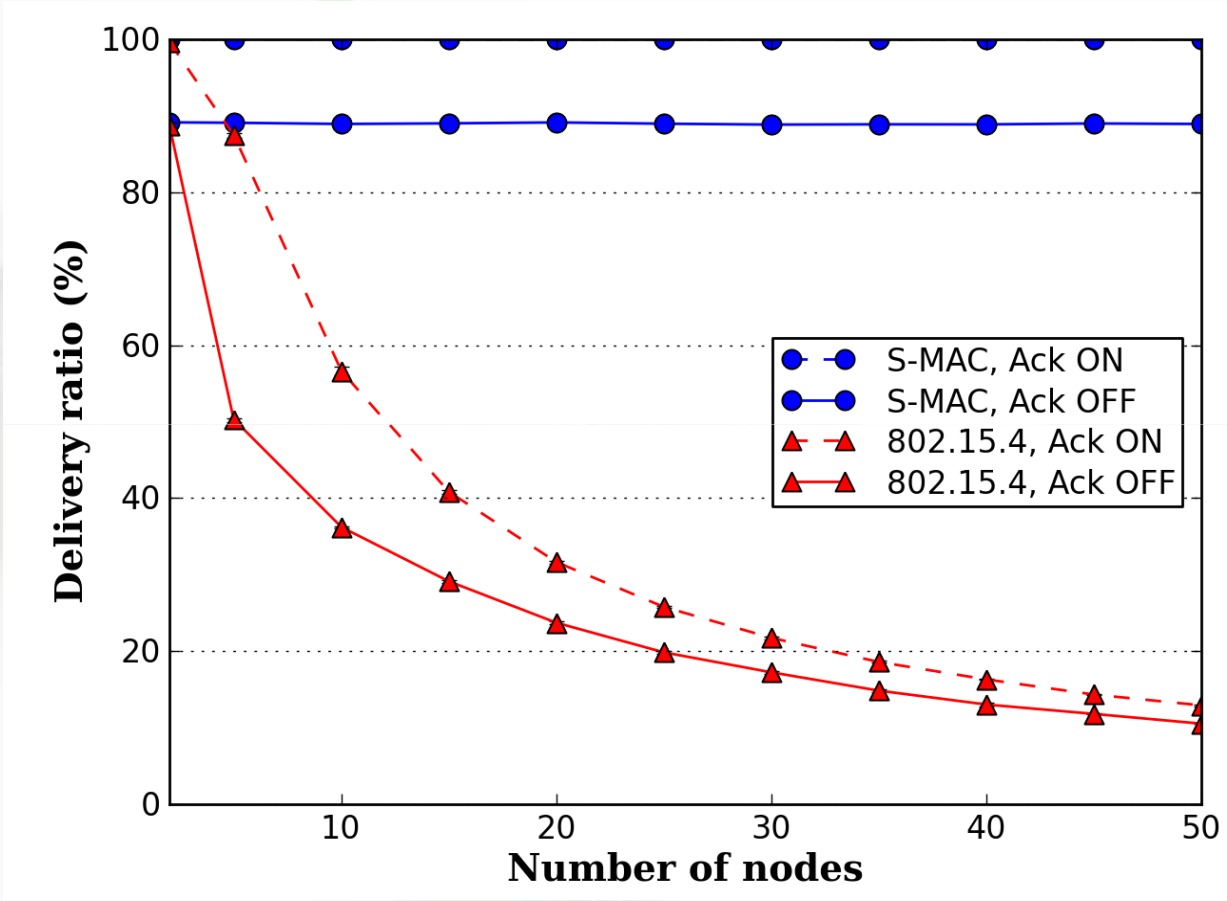


Key Question

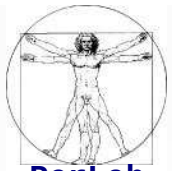


Why the 802.15.4 MAC Unreliability Problem Arises?

802.15.4 MAC vs. S-MAC



Influence of CSMA/CA parameters

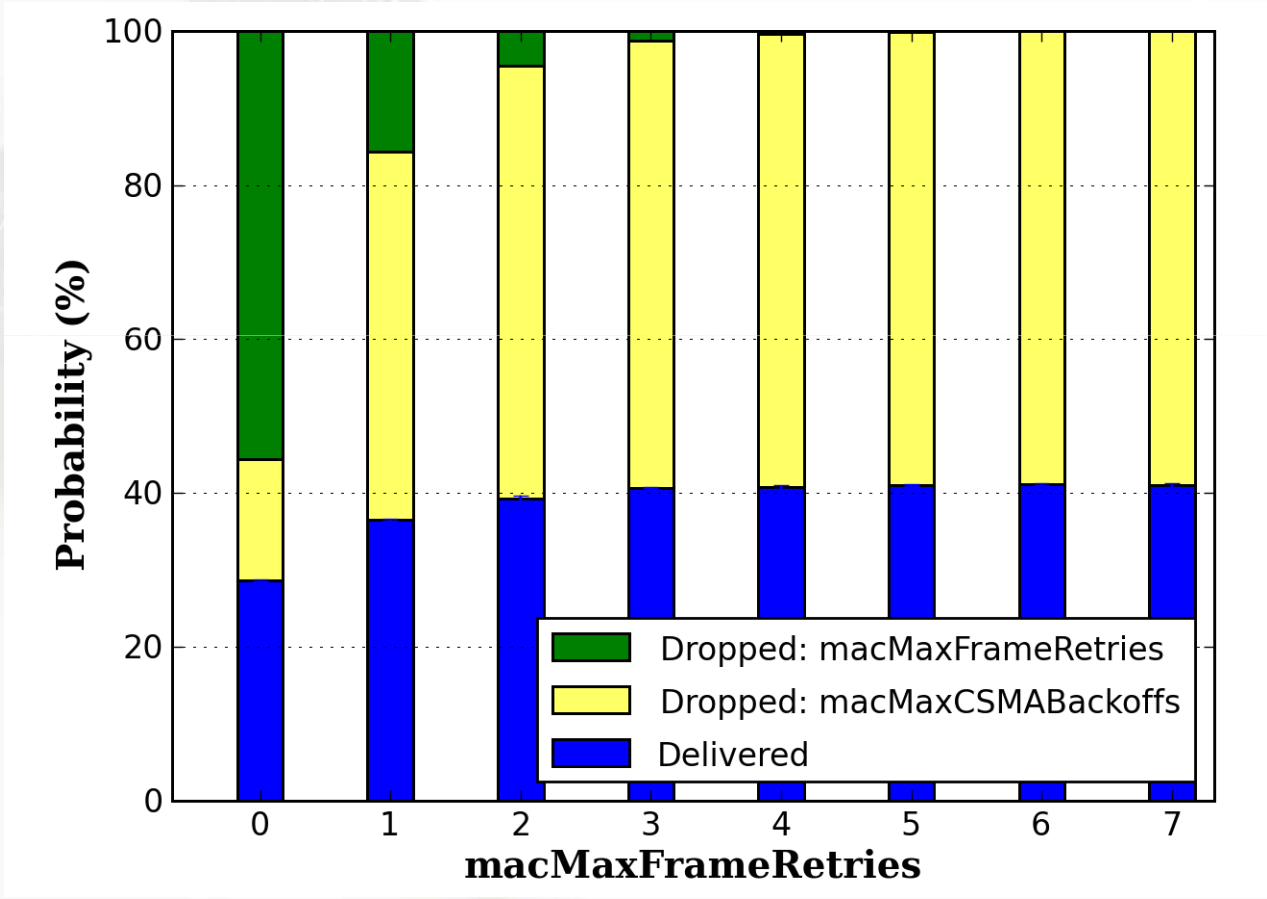


- Analysis of each single CSMA/CA parameter
  - 15 sensor nodes
  - Periodic Traffic
  - Power Management ON, ACK ON

Parameter	2003 release	2006 release	Notes
macMaxFrameRetries	3 (*aMaxFrameRetries*)	**0÷7** **Default: 3**	Max number of re-transmissions
macMaxCSMABackoff	**0÷5** **Default: 4**	**0÷5** **Default: 4**	Max number of backoff stages
macMaxBE	**5** (***aMaxBE***)	**3÷8** **Default: 5**	Maximum Backoff Window Exp.
macMinBE	**0÷3** **Default: 3**	**0÷7** **Default: 3**	Minimum Backoff Window Exp.

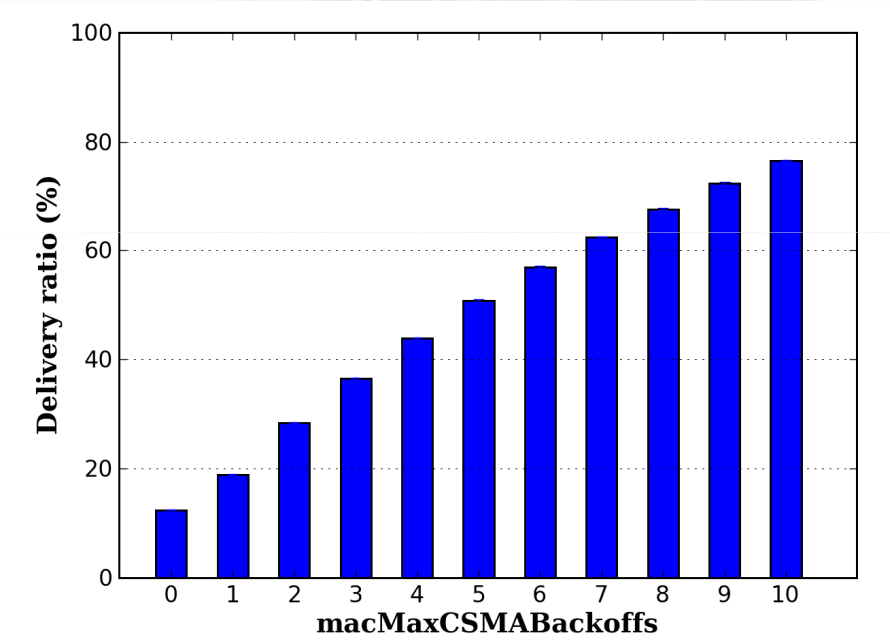
Influence of Number of Retransmissions

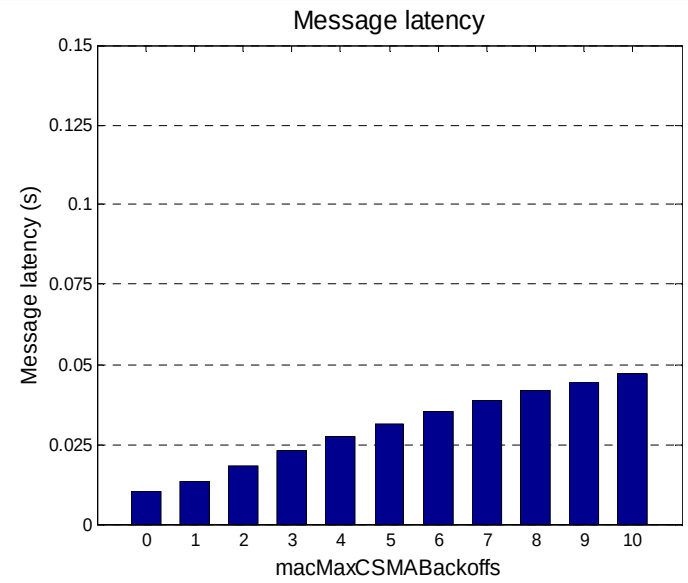
macMaxFrameRetries: 0-7 (default 3)

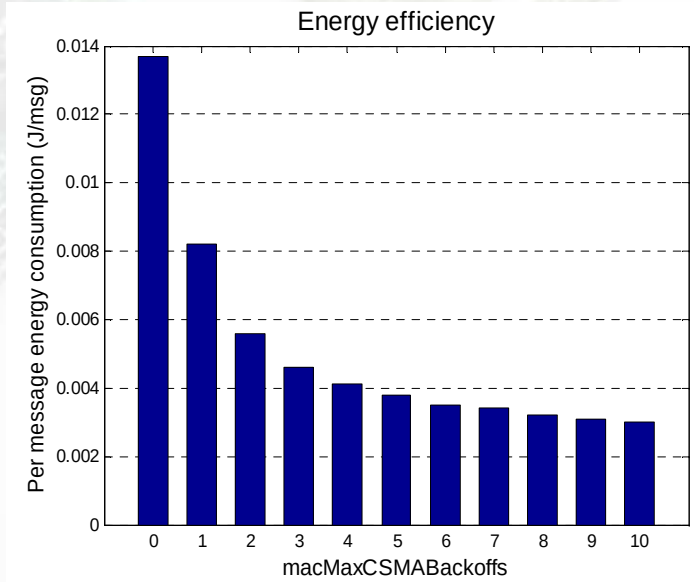


Influence of Number of Backoff Stages

macMaxCSMABackoffs: 0-5 (default 4)



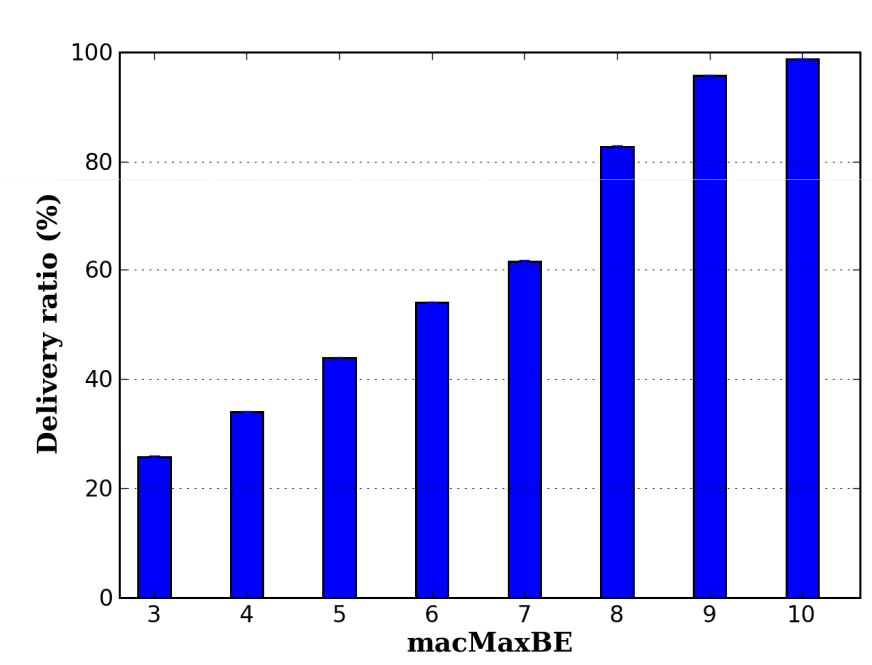


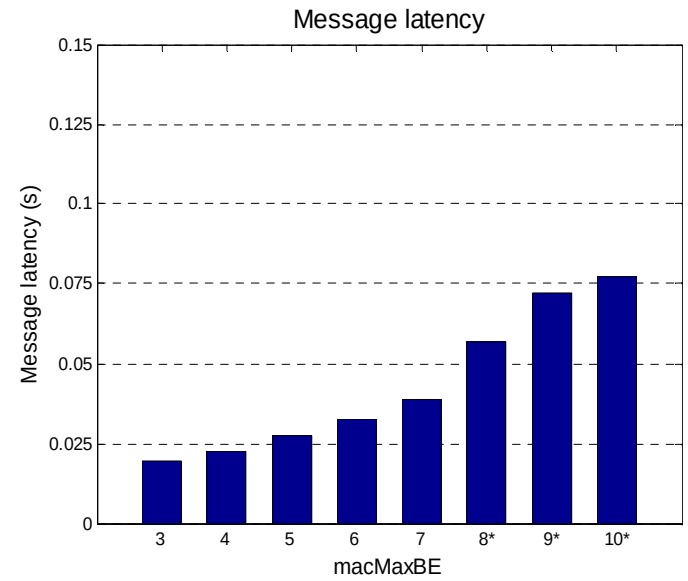


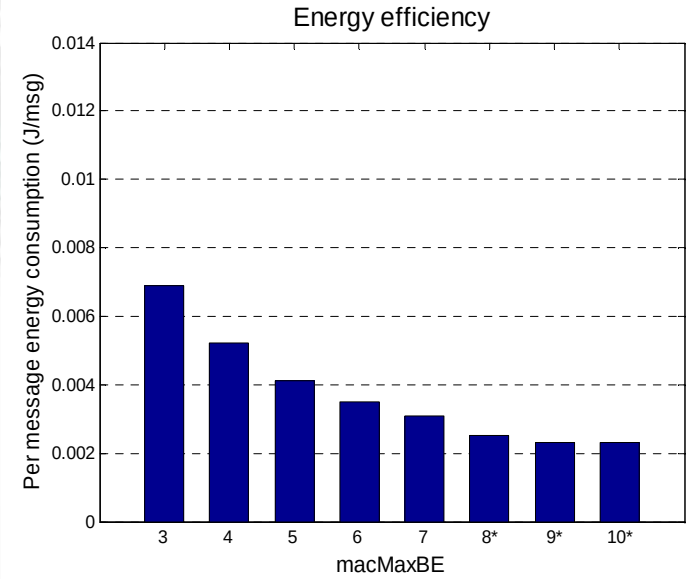
Influence of Maximum Backoff Window

macMaxBE: 3-8 (default 5)

macMaxCSMABackoffs ≥ *macMaxBE* – *macMinBE*



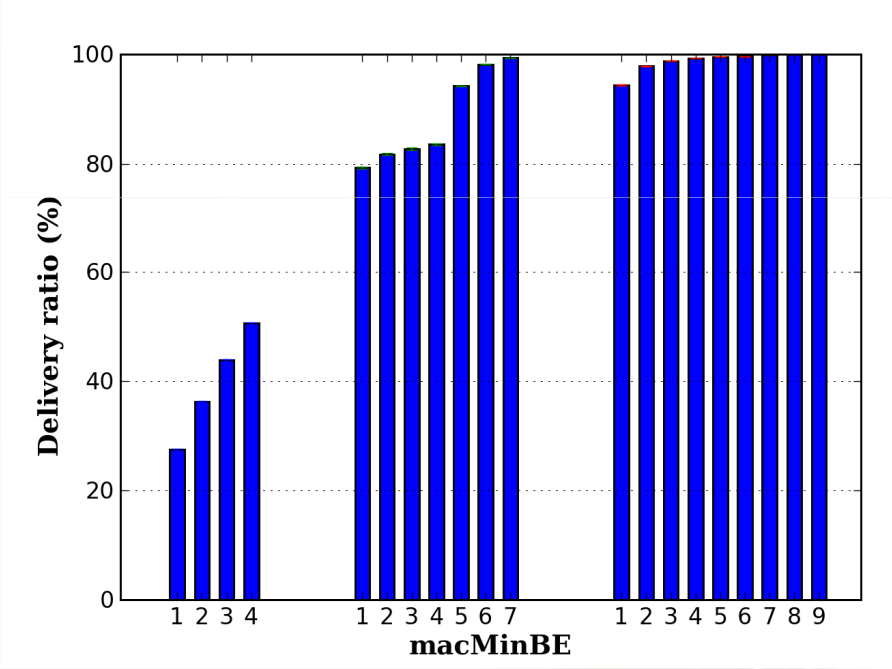


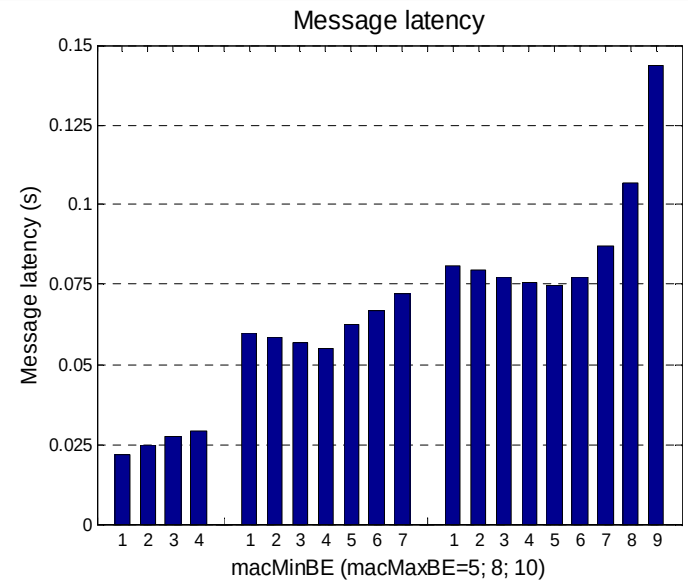


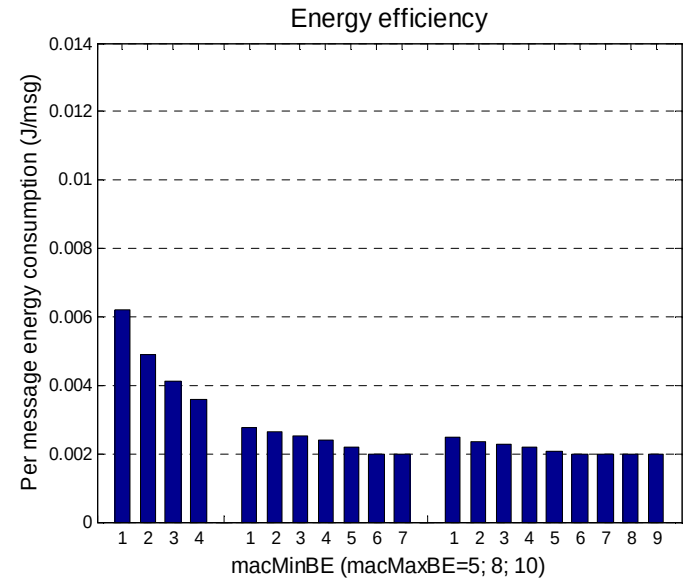
Influence of Minimum Backoff Window

macMinBE: 0-7 (default 3)

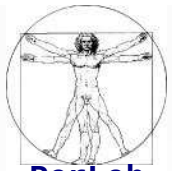
We varied *macMinBE* in [0, *macMaxBE*-1]





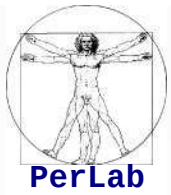


Learned Lesson



- The MAC unreliability problem is not intrinsic to the CSMA/CA algorithm
- It is originated by the default MAC parameter values
- The default parameter set is not appropriate for WSNs with power management enabled

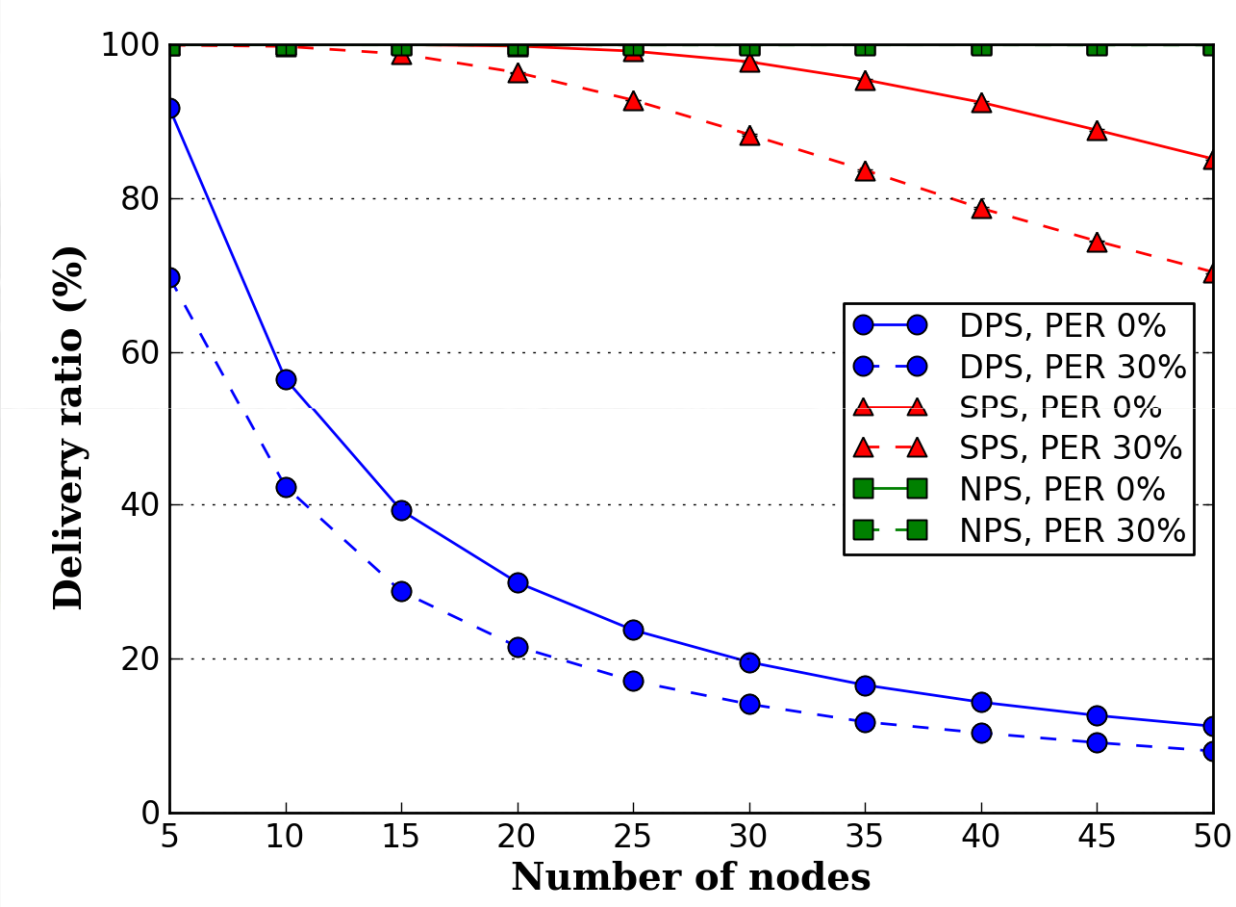
Possible Solutions



- *DPS (Default Parameter Set)*
  - Set di parametri con i *valori di default* previsti dallo standard
- *SPS (Standard Parameter Set)*
  - Set di parametri con i *valori massimi* previsti dallo standard
- *NPS (Non-standard Parameter Set)*:
  - Set di parametri con valori *oltre quelli consentiti* dallo standard

	macMinBE	macMaxBE	macMaxCSMABackoff	macMaxFrameRetries
DPS	3	5	4	3
SPS	7	8	5	7
NPS	8	10	10	10

Single-hop scenario: PDR vs. Offered Load



Single-hop scenario

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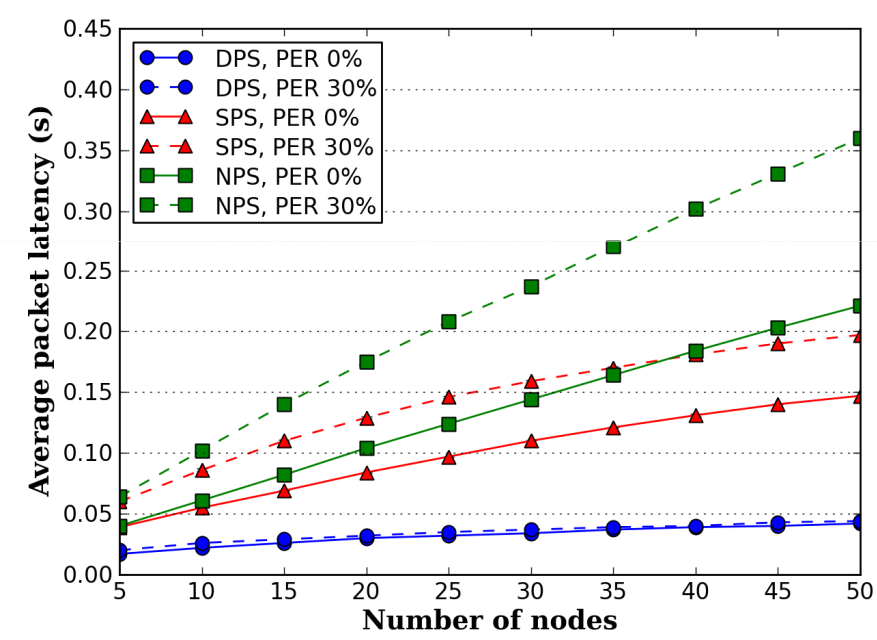
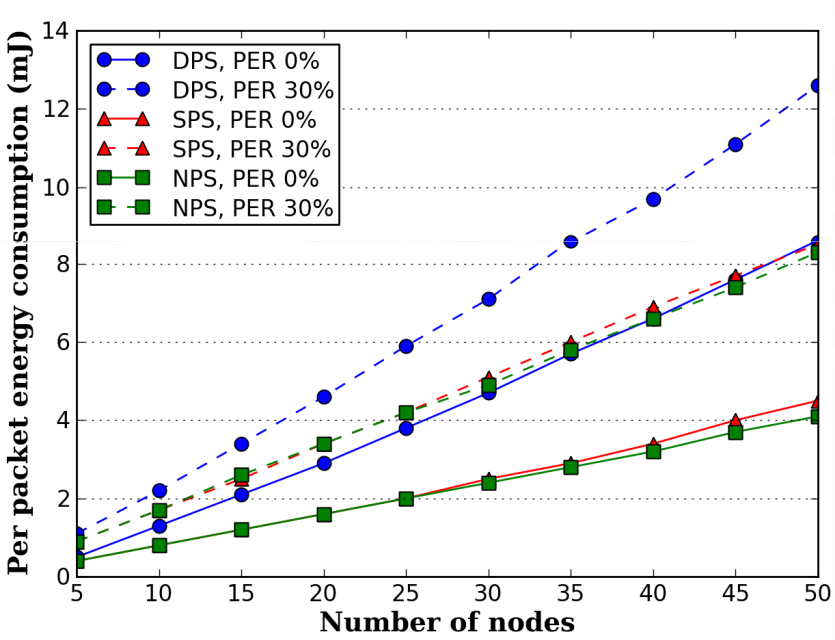
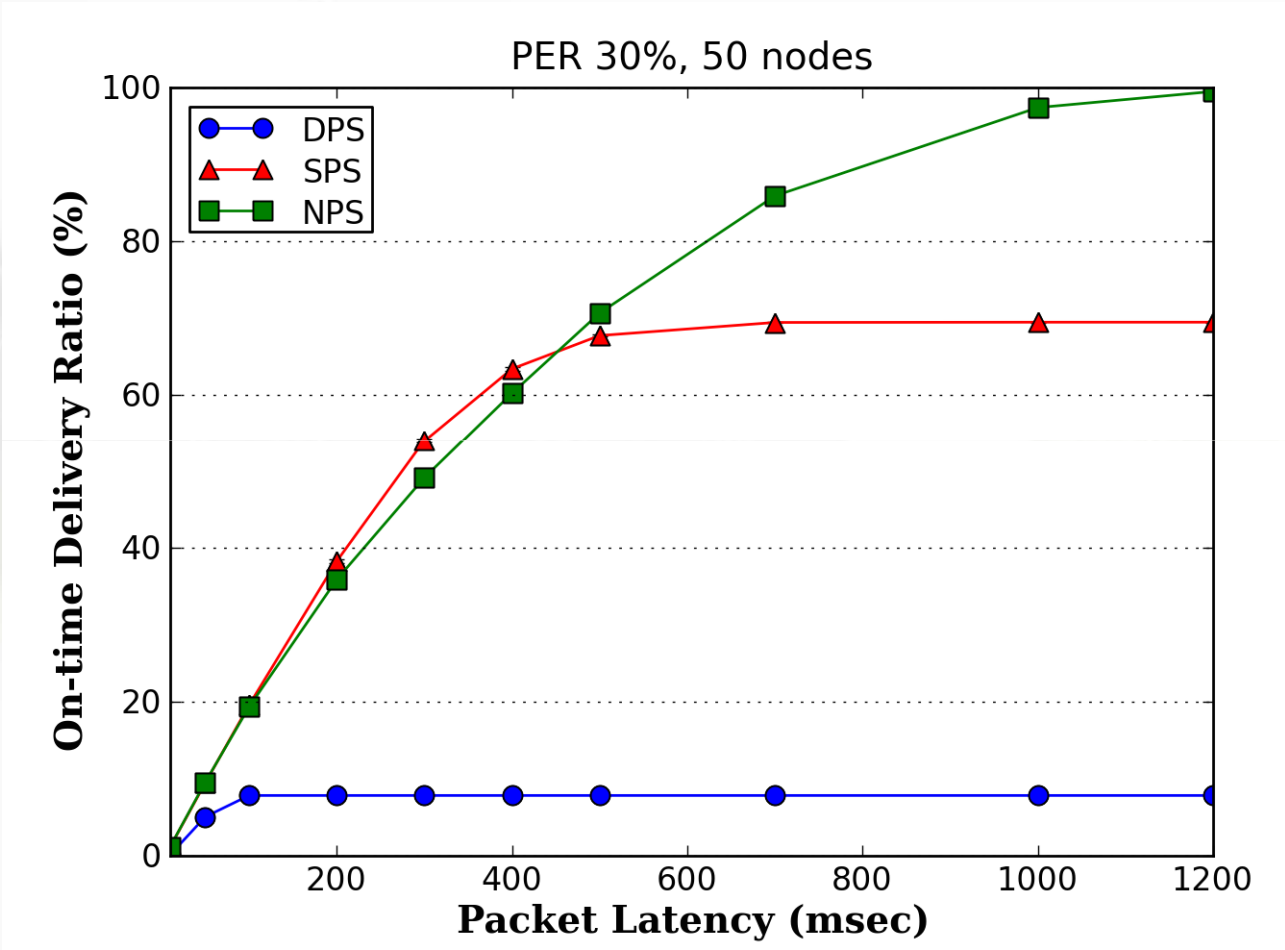
Avg. Latency



Energy/msg



Timeliness vs. Delivery Ratio



A Final Question

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Are Simulation Results Reliable?

Experimental Testbed

Sensor Nodes

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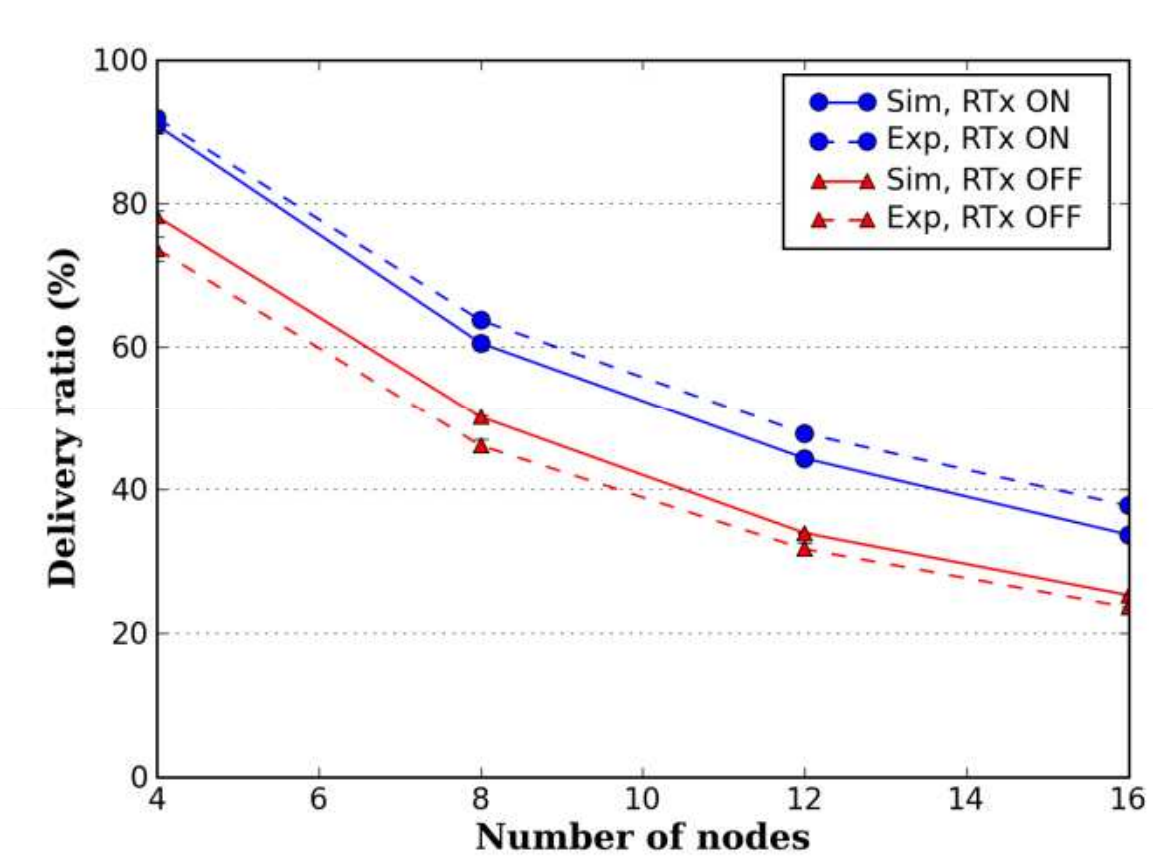
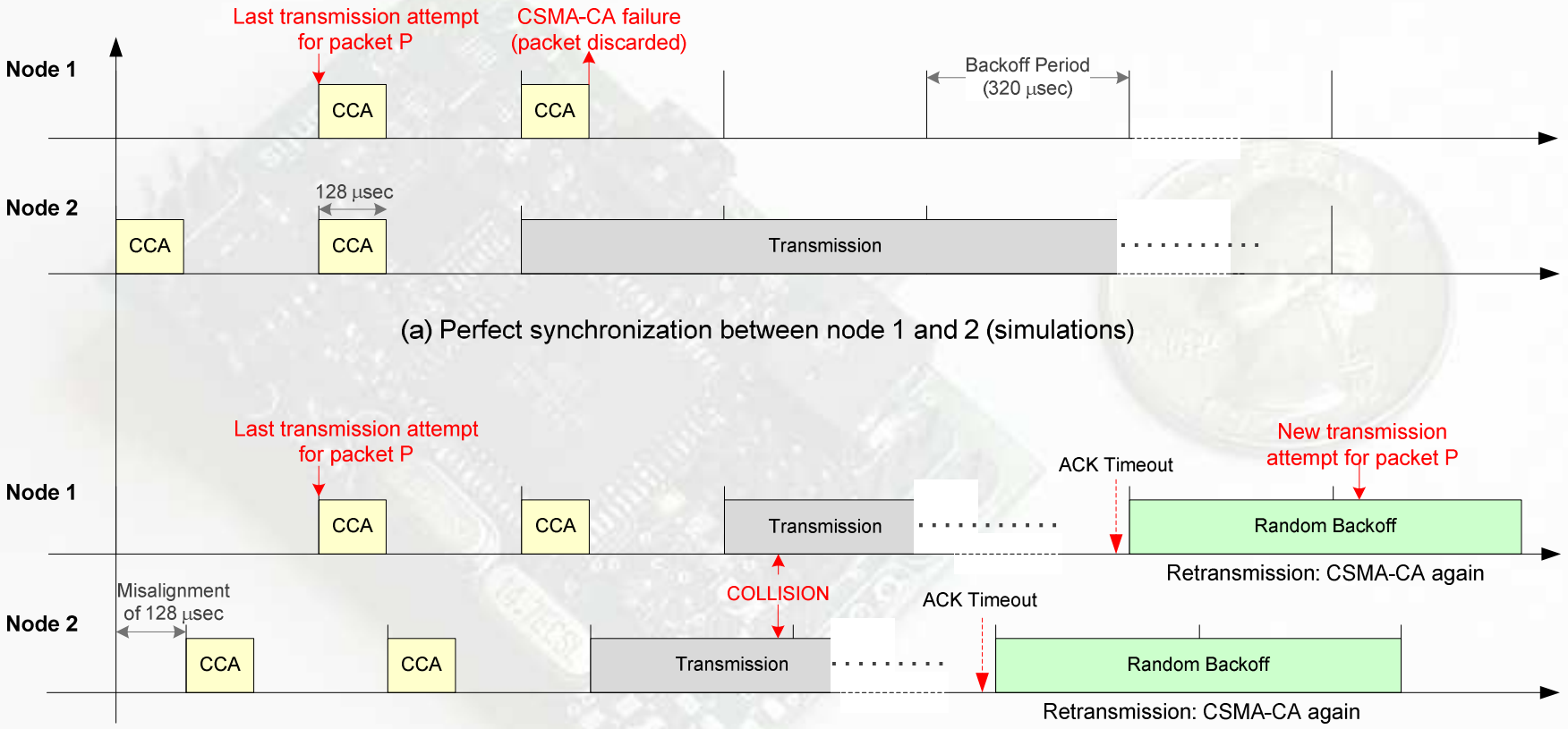
- T-mote Sky
  - TinyOS Operating System
  - IEEE 802.15.4 PHY
  - IEEE TKN15.4 MAC (TU-Berlin)
  - Power Management Enabled
  - Periodic Reporting Applications

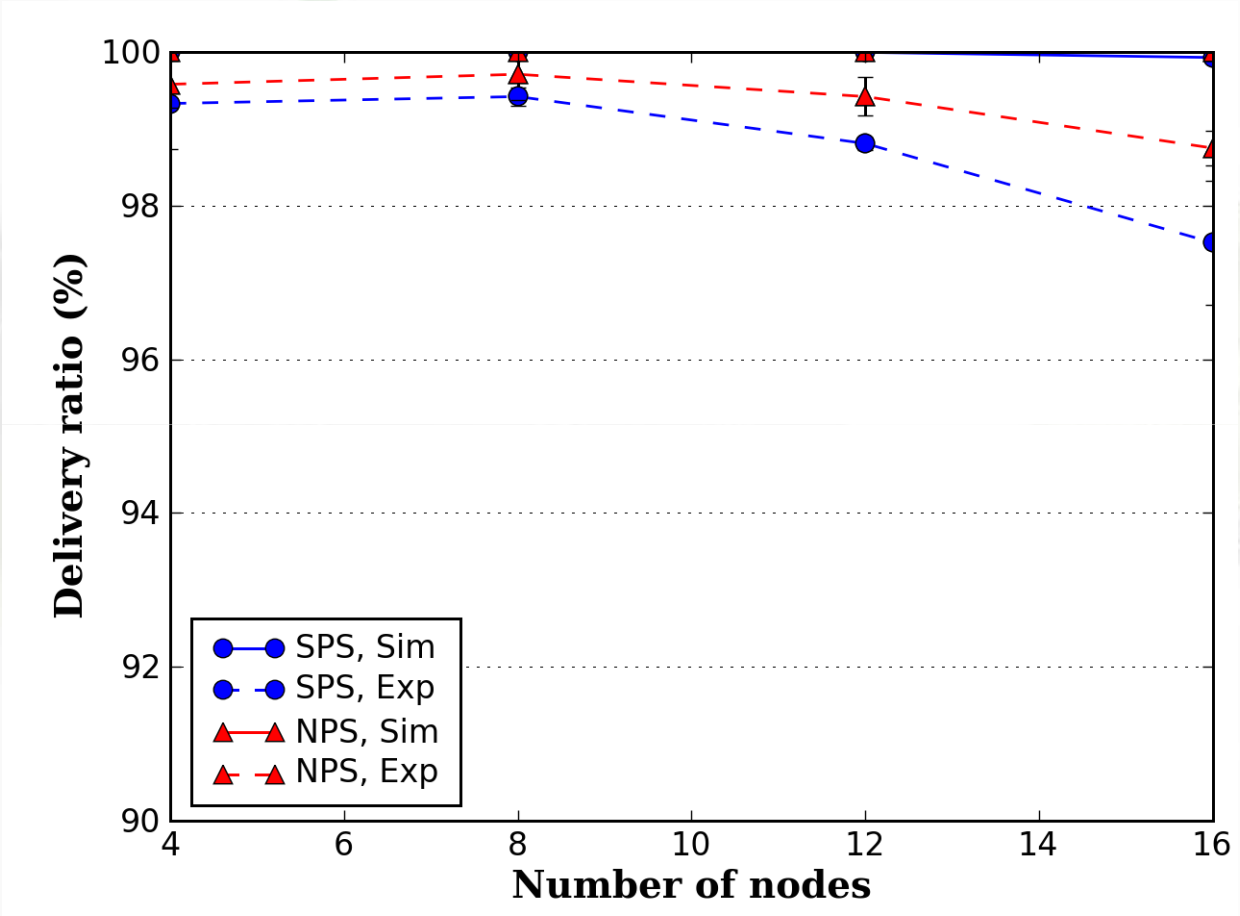
Simulation vs. Experiments (Default values)



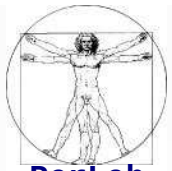
Effects of clock misalignment



Simulation vs. Experiments (SPS and NPS)



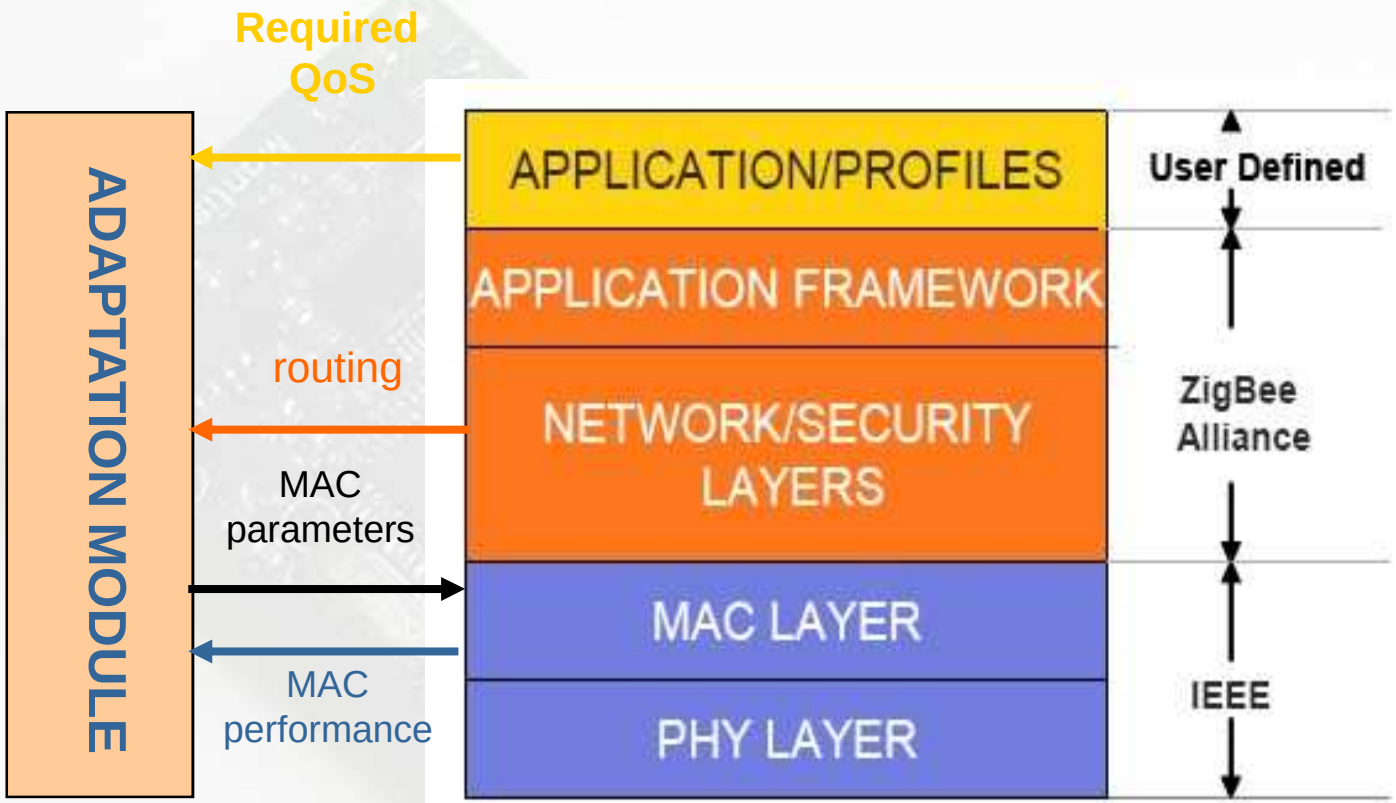
Key Question



- Lesson learned
  - A more appropriate setting can solve the problem
    - ⇨ Without modifying the MAC protocol
- However …
  - The best parameter set depends on
    - ⇨ Applications requirements
    - ⇨ Operating conditions
- Challenge

How to achieve the desired reliability level (e.g., 80%) with the minimum energy expenditure?

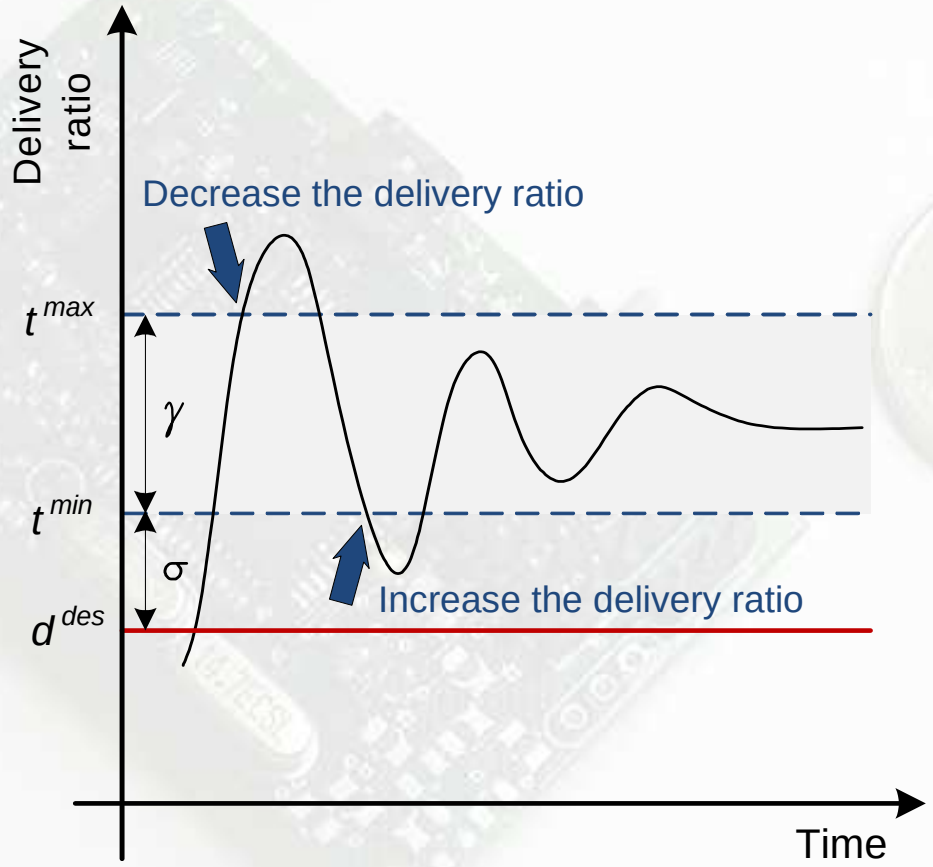
A Cross Layer Approach



Adaptive MAC Parameter Selection

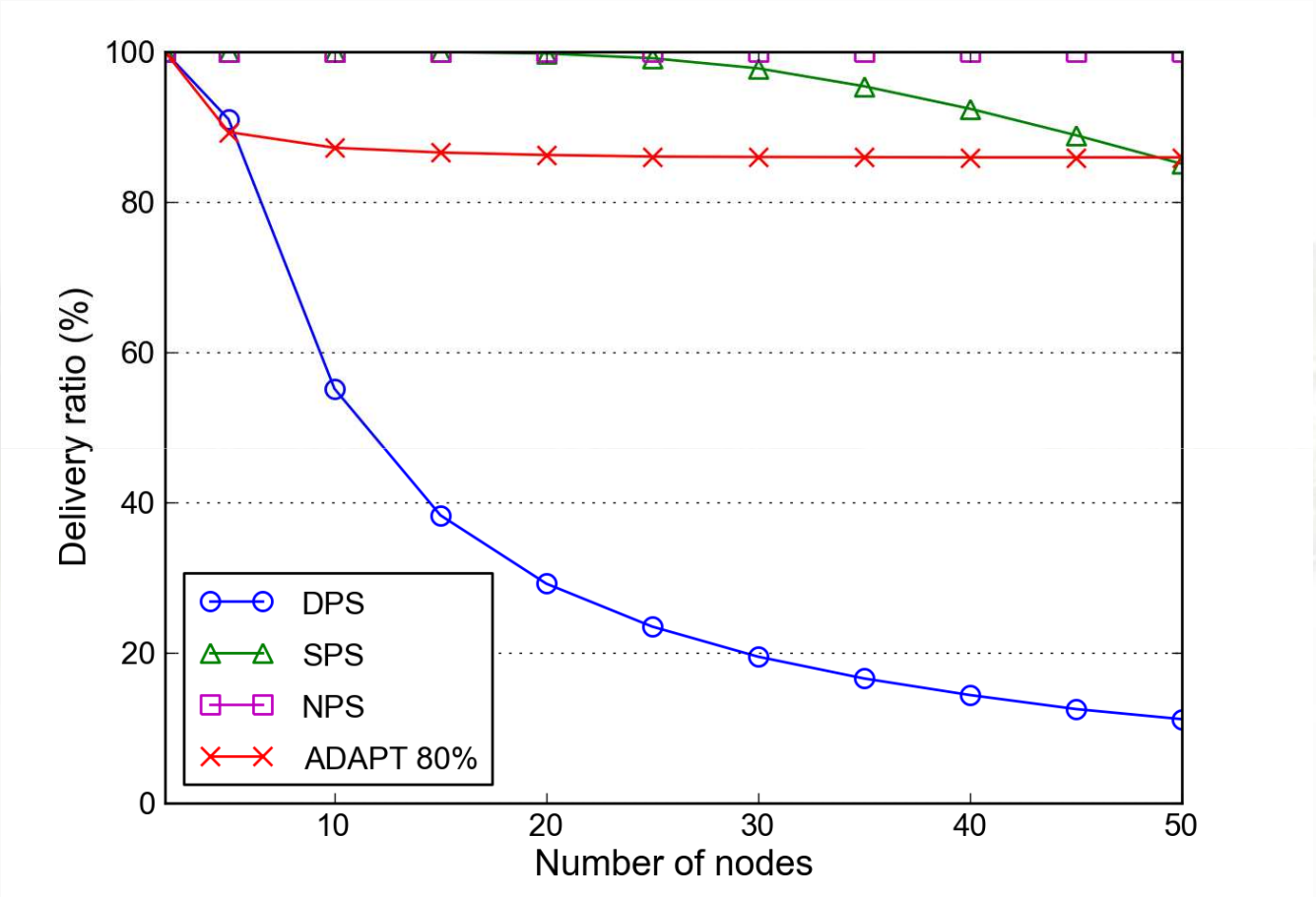
PerLab

- ADaptive Access Parameter Tuning (ADAPT)



M. Di Francesco, G. Anastasi, M. Conti, S. Das, V. Neri, An Adaptive Algorithm for Dynamic Tuning of MAC Parameters in IEEE 802.15.4/ZigBee Sensor Networs, Proc. *IEEE PerCom Workshops. International Workshop on Sensor Networks and Systems for Pervasive Computing (PerSeNS 2010)*, Mannheim, Germany, March 29, 2010.

Results in Stationary Conditions

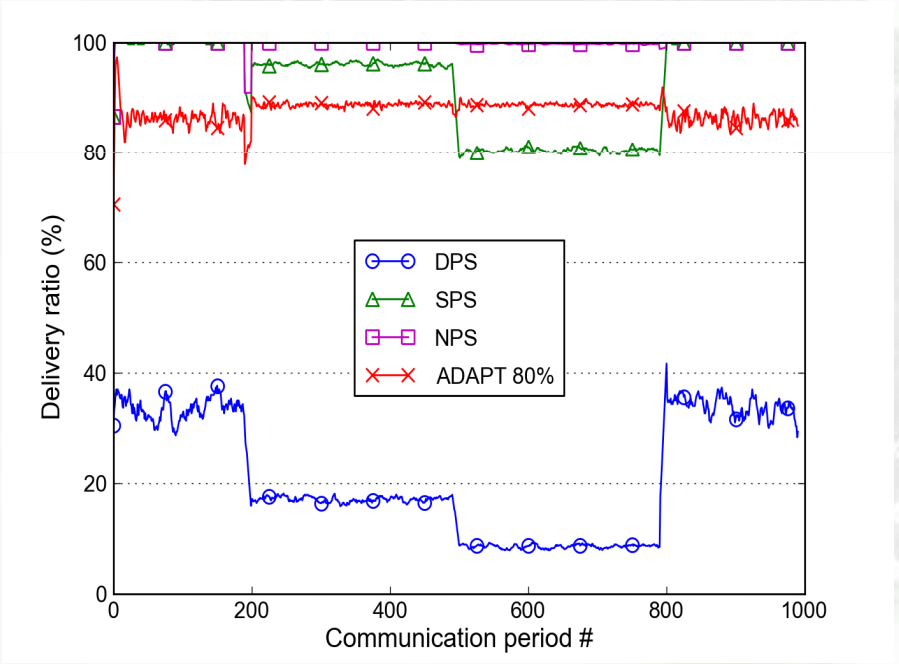


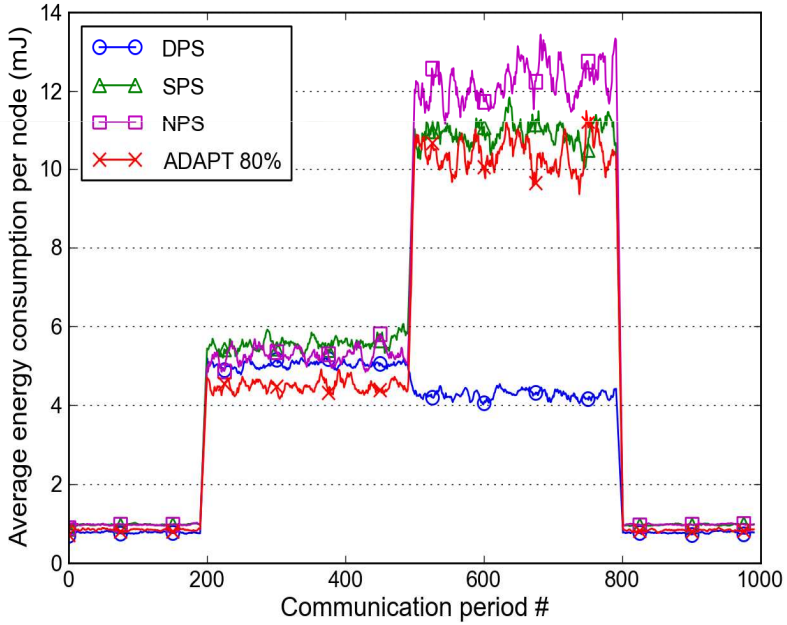
M. Di Francesco, G. Anastasi, M. Conti, S. Das, V. Neri, An Adaptive Algorithm for Dynamic Tuning of MAC Parameters in IEEE 802.15.4/ZigBee Sensor Networs, Proc. *IEEE PerCom Workshops. International Workshop on Sensor Networks and Systems for Pervasive Computing (PerSeNS 2010)*, Mannheim, Germany, March 29, 2010.

Results in Dynamic Conditions

PerLab

1-200	CP:	Low Traffic	(1 20-byte message per CP)
201-500	CP:	Moderate Traffic	(10 20-byte messages per CP)
501-800	CP:	High Traffic	(10 100-byte messages per CP)
801-1000	CP:	Low Traffic	(1 20-byte message per CP)





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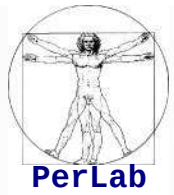
Optimal Algorithm

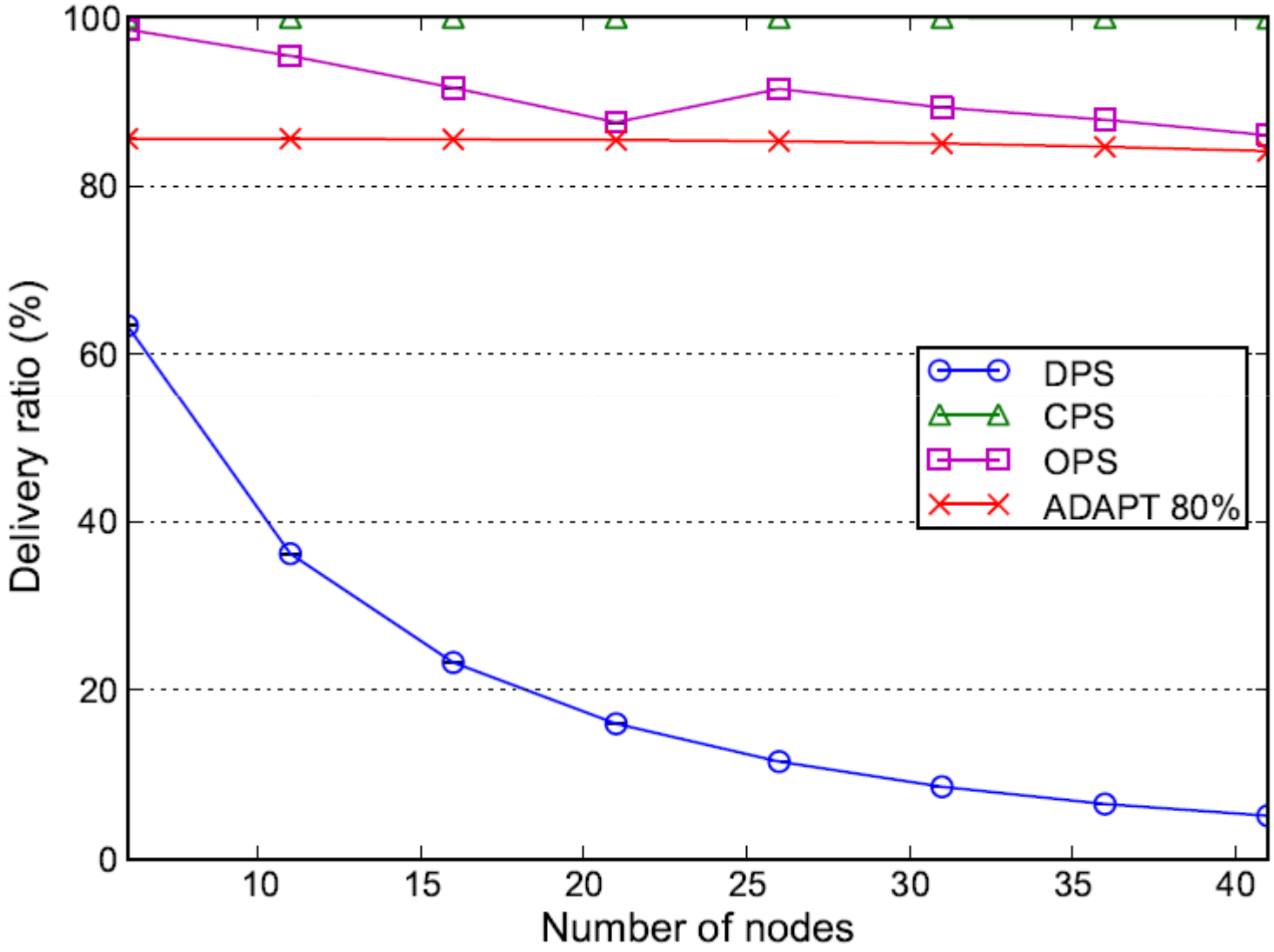


- Park et al. investigated the 802.15.4 MAC performance through an analytical model [Par09]
- Based on the model in [Par09], they proposed an optimal algorithm [Par10]
  - Guaranteed delivery ratio
  - Minimum energy consumption

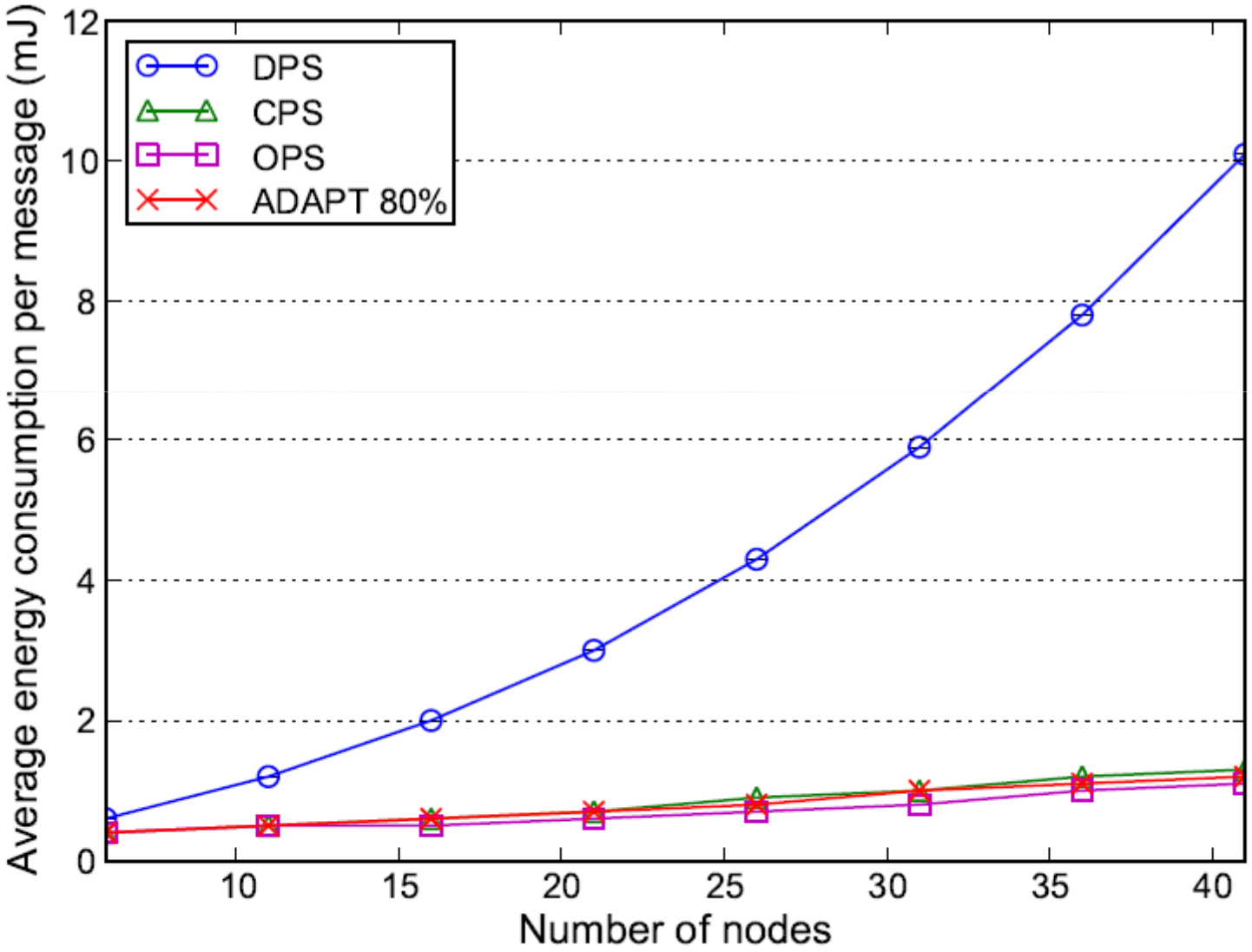
[Par09] P. Park, P. Di Marco, P. Soldati, C. Fischione, and K. Johansson, **A generalized markov chain model for effective analysis of slotted IEEE 802.15.4**, *Proc. IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS '09)*, October 2009, pp. 130 –139.

[Par10] P. Park, C. Fischione, and K. Johansson, **Adaptive IEEE 802.15.4 protocol for energy efficient, reliable and timely communications**, *Proc. International Conference on Information Processing in Sensor Networks (IPSN 2010)*, April 12-16 2010, pp. 327–338.

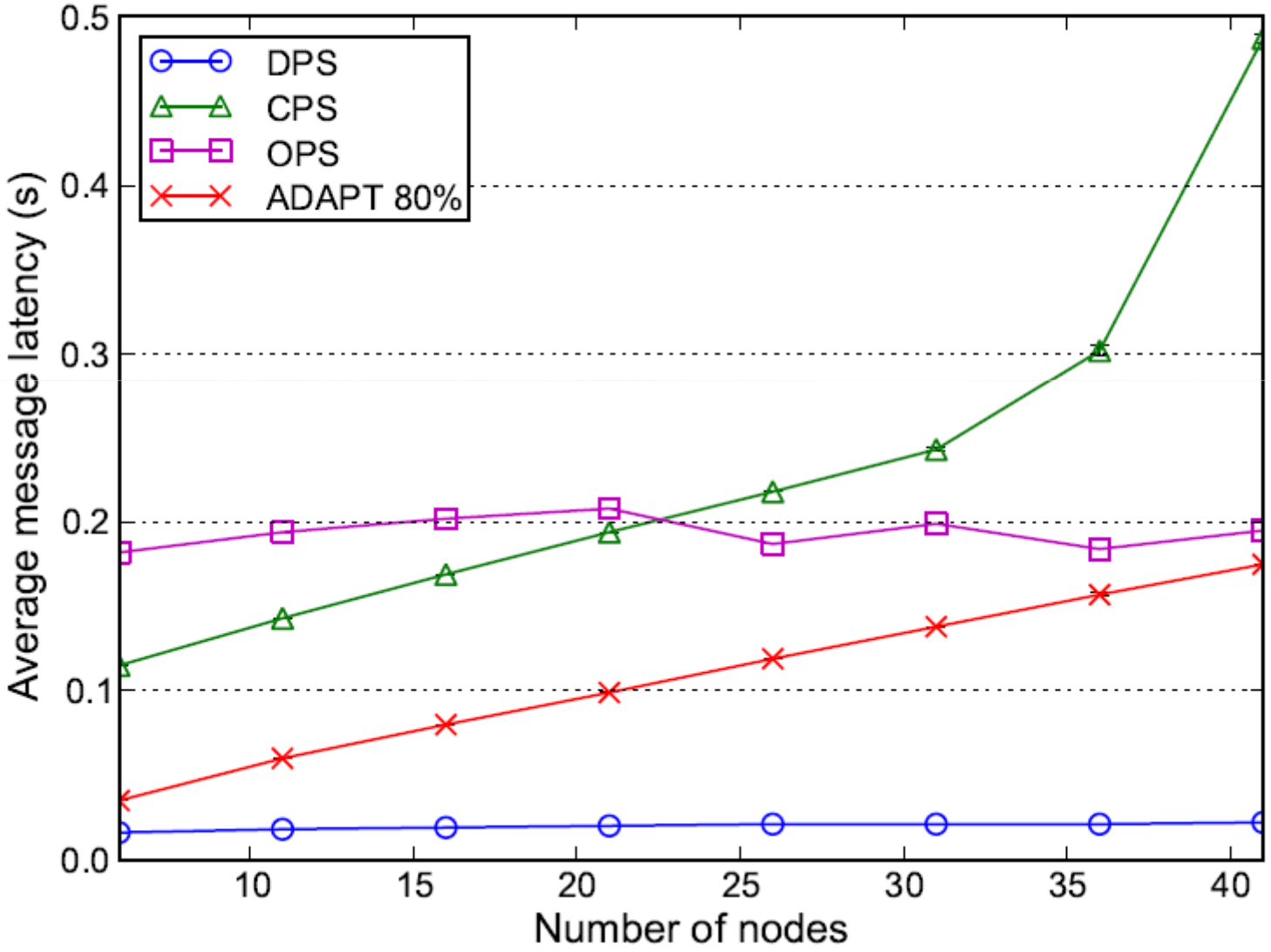
Comparison with an Optimal Algorithm



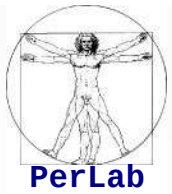
Comparison with an Optimal Algorithm



Comparison with an Optimal Algorithm

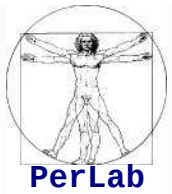


Conclusions



- IEEE 802.15.4 MAC has a serious unreliability problem
  - Due to non appropriate default parameter settings
- The reliability can be increased by using more appropriate parameter values
  - At the cost of increased latency
- Adaptive solution to guarantee reliability
  - with minimum latency and energy consumption

References



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Thank you!