Energy Conservation in Wireless Sensor Networks

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COST Action IC0804 Training School – Palma de Mallorca, Spain, April 24-27, 2012

Overview

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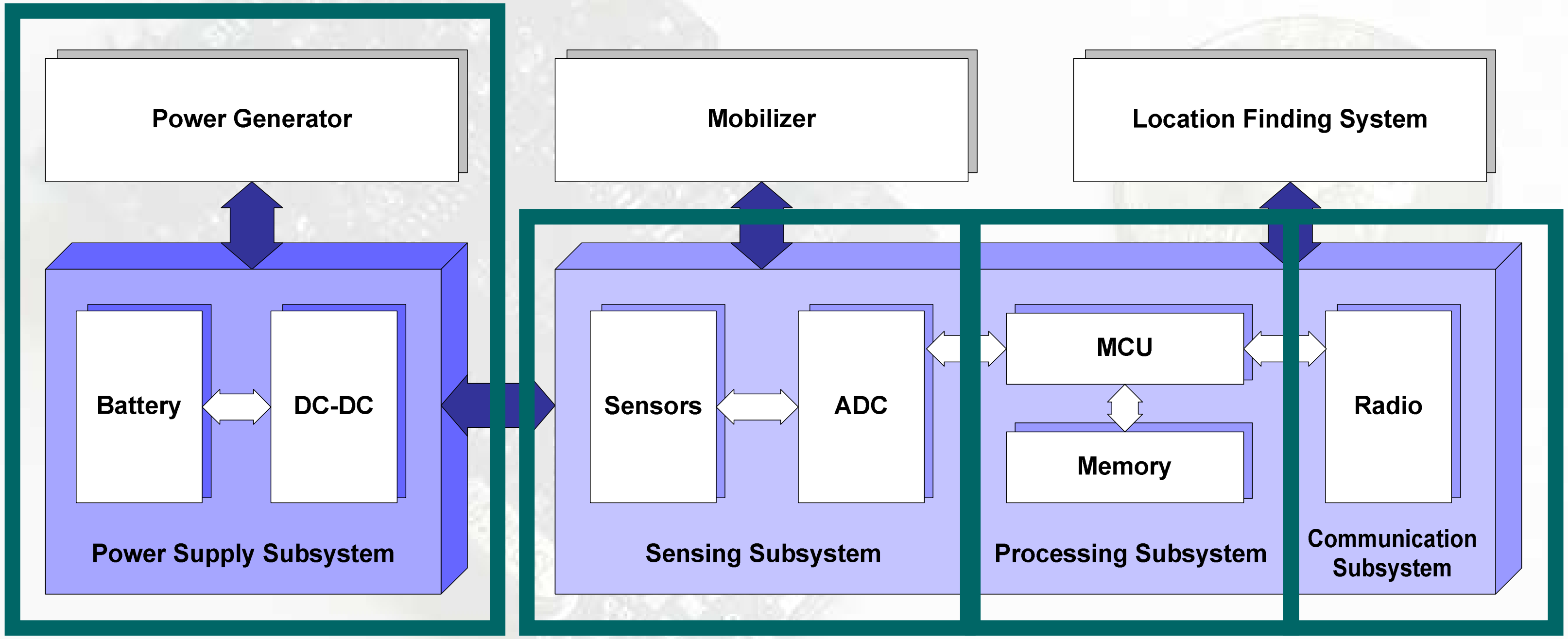
- Introduction
- The Energy Problem in WSNs
- Energy Conservation in static WSNs
  - Data-driven approaches
  - Topology Management
  - Power Management
- Energy Conservation in WSNs with Mobile Nodes
  - Power Management & MN Discovery
- WSNs for Energy Efficiency
  - Energy Efficiency in Buildings
  - Adaptive Lighting in Tunnels

Introduction

Sensor Node Architecture



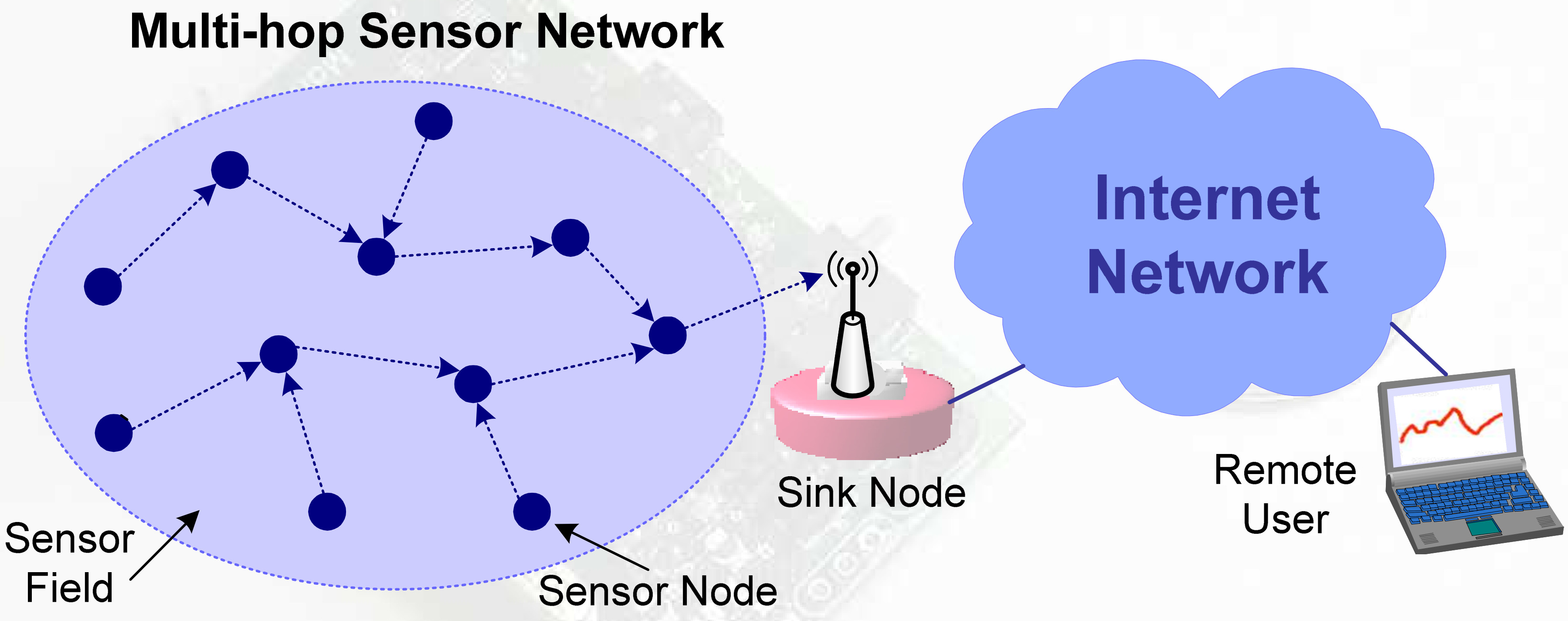
Battery powered devices
Batteries cannot be changed nor recharged

Usually negligible power consumption

Local data processing and data storage

Short range wireless communication
Radio is the most power hungry component

Wireless Sensor Networks



WSNs with Mobile Nodes

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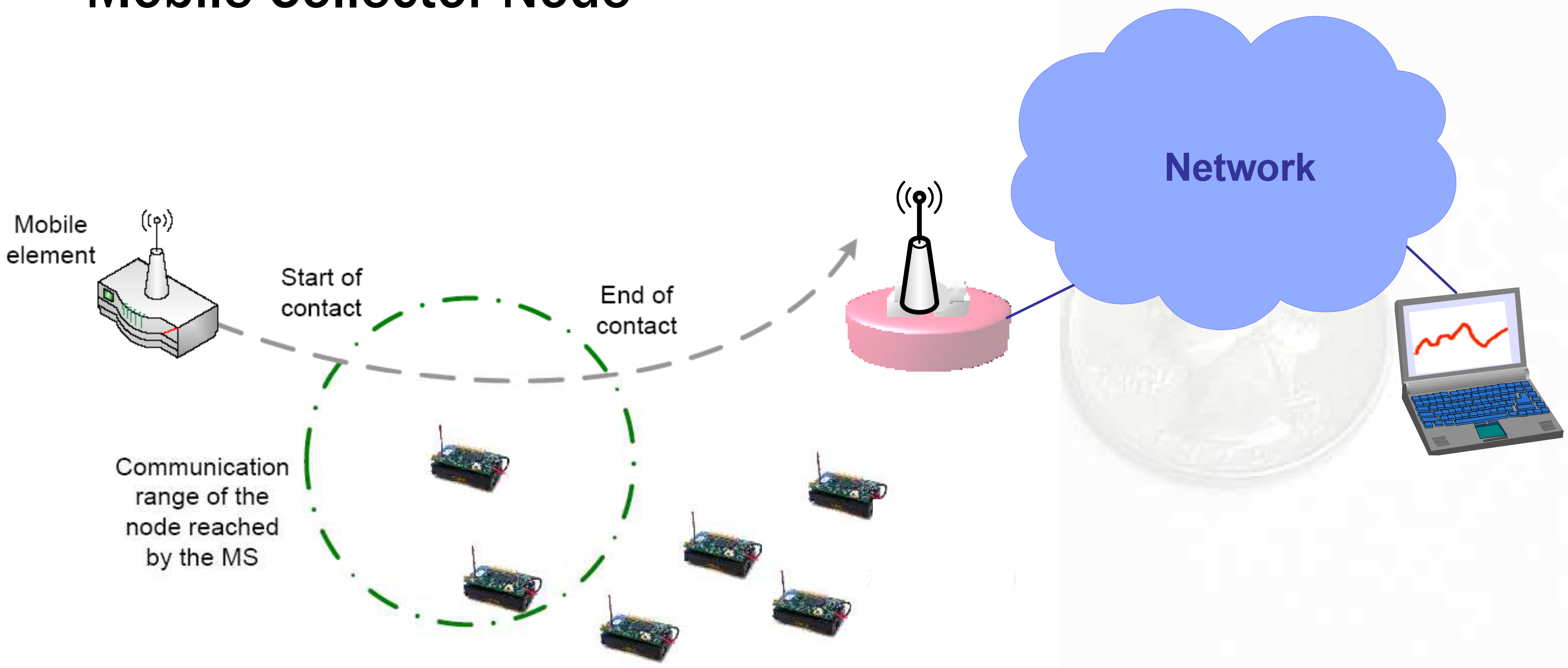
- Mobile Collector Node



Potential Application Areas

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- Military Applications
- Environmental Monitoring
- Precision Agriculture
- Health Monitoring
- Smart Home/Office
- Intelligent Transportation Systems
- Industrial applications
- …

The Energy Problem

The energy problem

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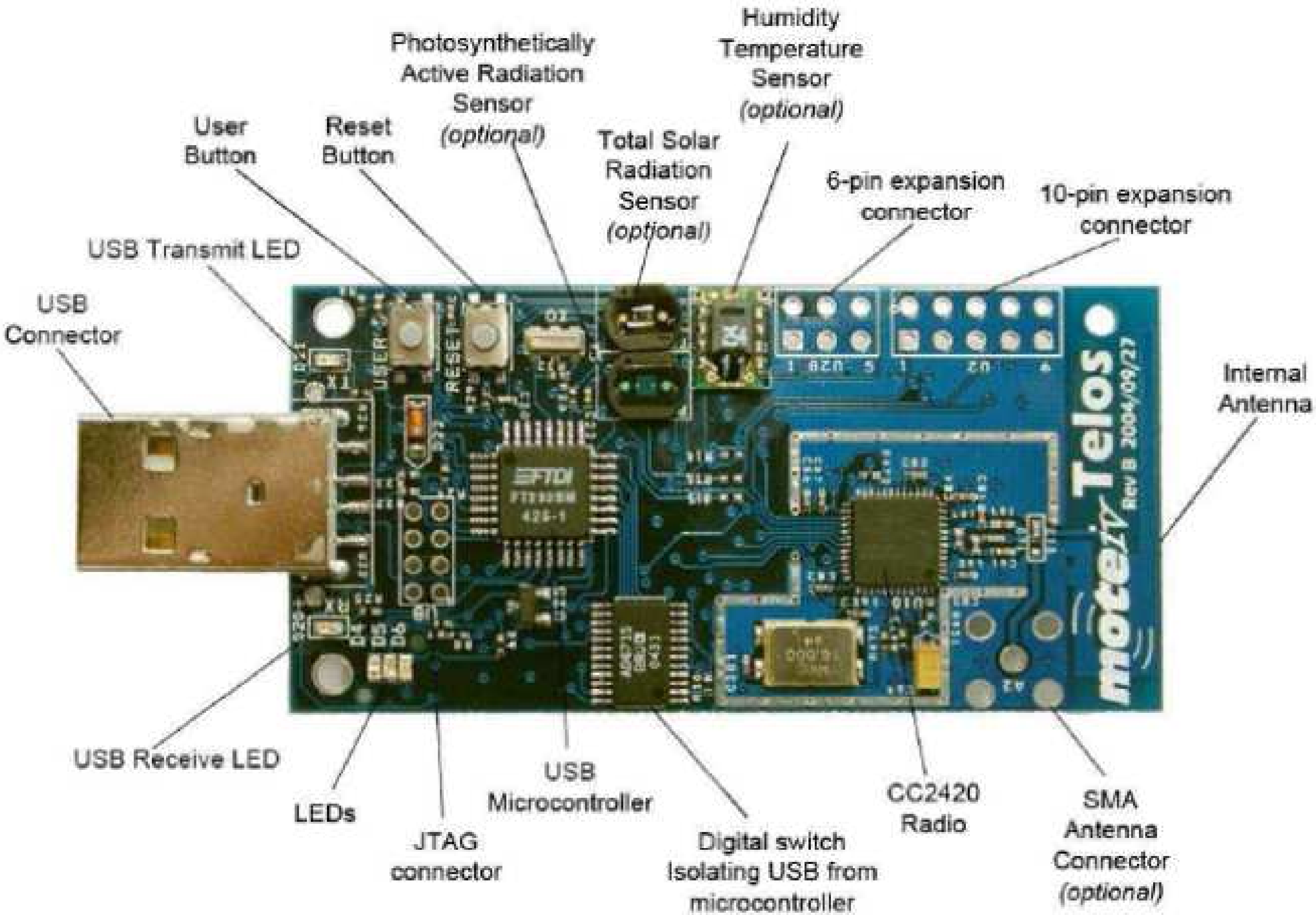
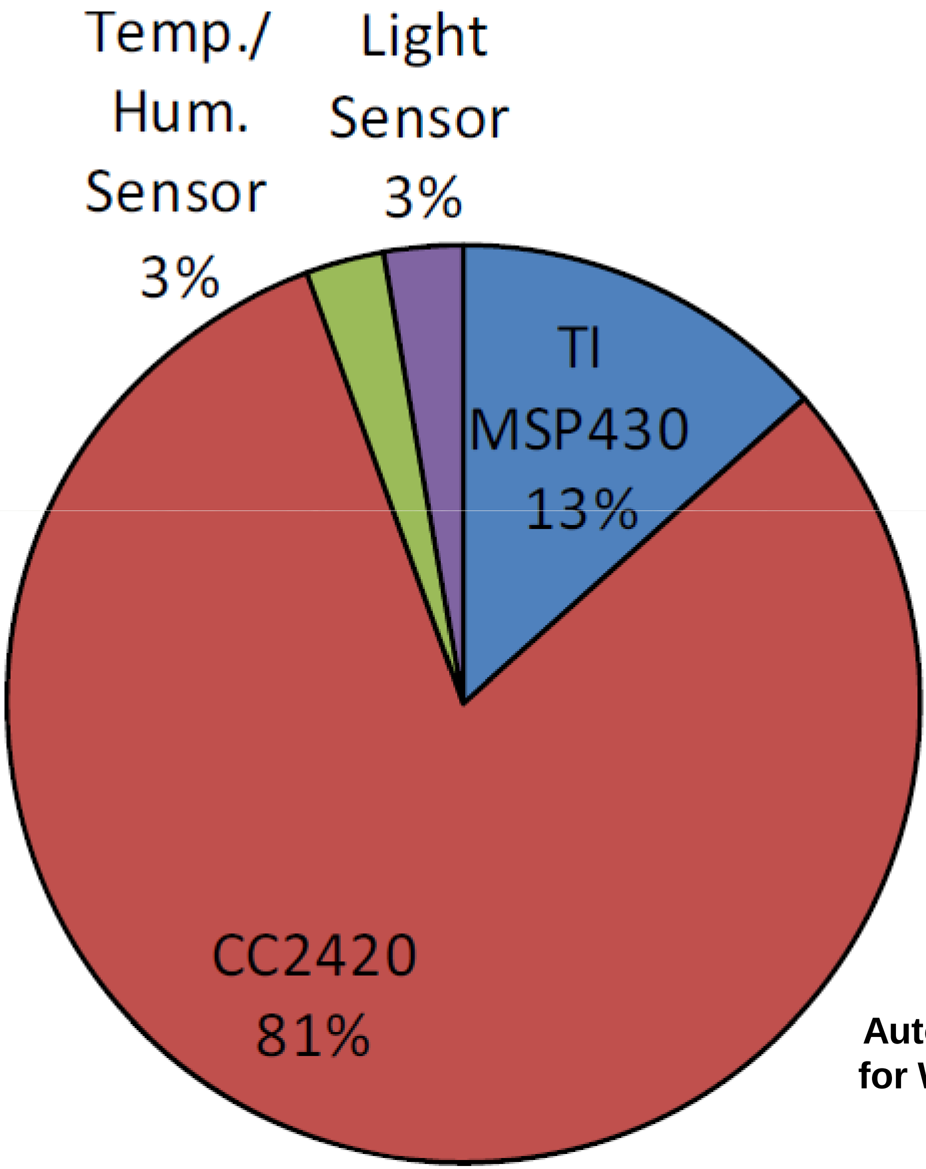
- Energy is the key issue in the WSN design
  - Applications may require a network lifetime in the order of several months or even years
  - If always active, sensor nodes deplete their energy in less than a week

- Possible approaches
  - Low-power sensor nodes
  - Energy harvesting
  - Energy conservation
  - Energy efficient protocols/applications
  - Cross-layering
  - …

TmoteSky Mote



Breakdown of TmoteSky Energy Consumption



Nakyoung Kim, Sukwon Choi, Hojung Cha, **Automated Sensor-specific Power Management for Wireless Sensor Networks**, Proc. IEEE MASS 2008, Atlanta, USA, Setp. 29 – Oct. 2, 2008

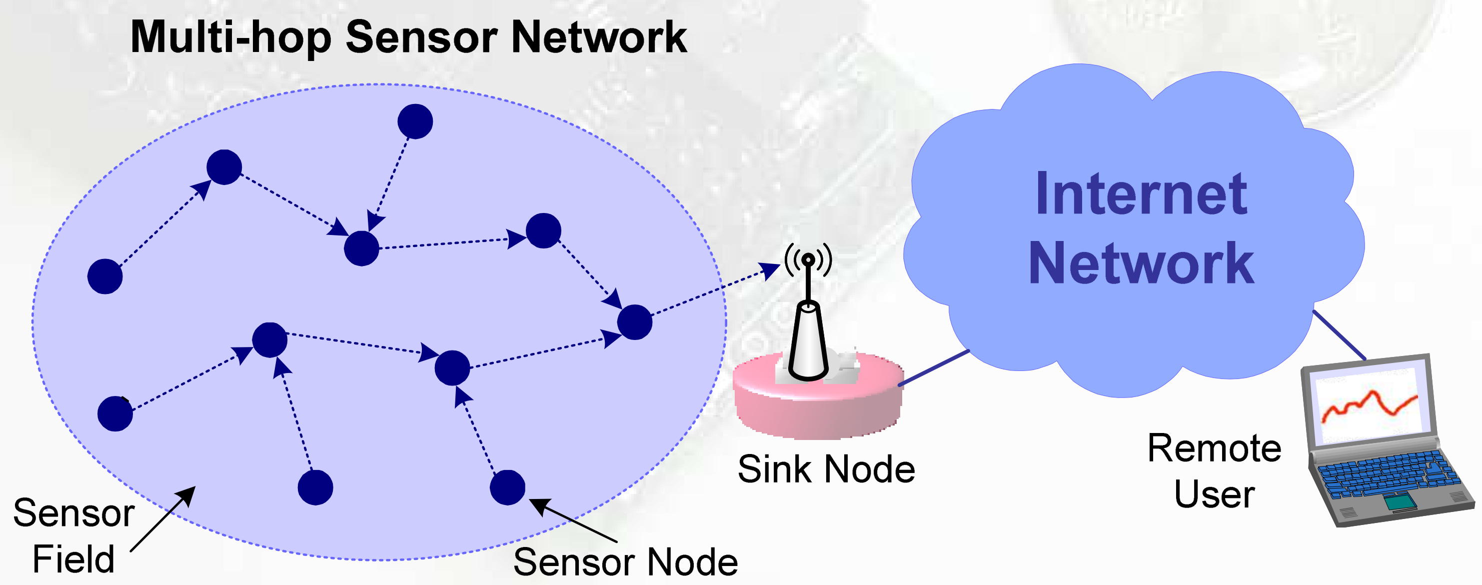
Power Consumption of CC2420

Supply Voltage: 1.8 V

Mode	Current	Power Consumption
Reception	19.7 mA	35.46 mW
Transmission	17.4 mA	31.32 mW
Idle	0.426 mA	0.77 mW
Sleep	20 μA	36 μW

Source: **Chipcon CC2420 Data sheet**
2.4 GHz IEEE 802.15.4/ZigBee-ready RF Tranceiver
http://focus.ti.com/docs/prod/folders/print/cc2420.html

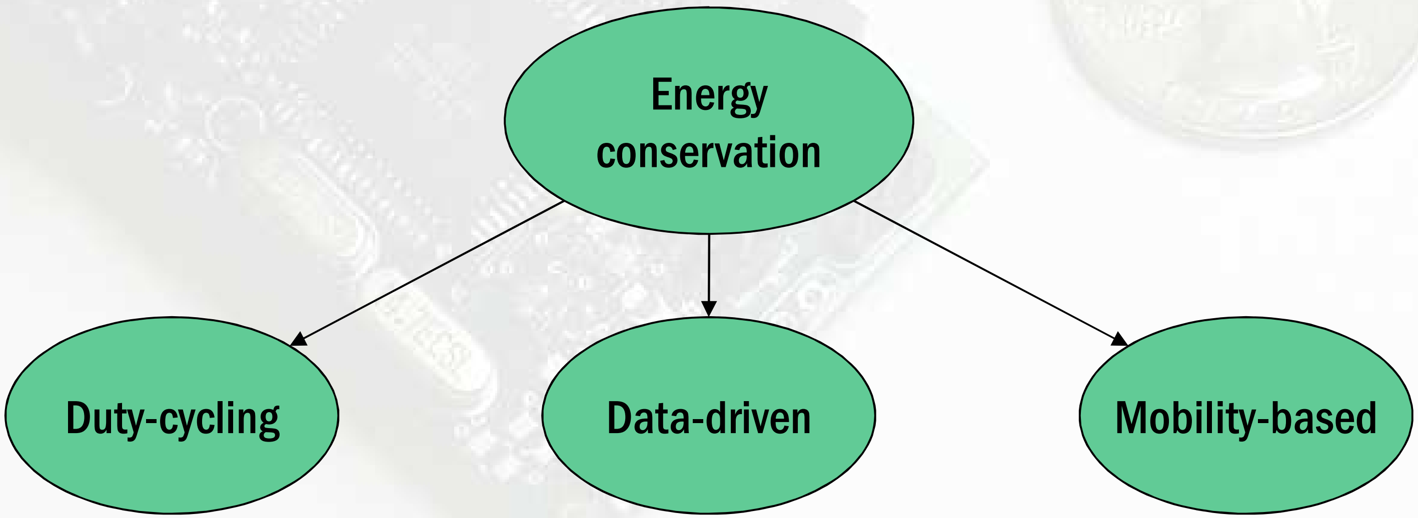
Energy Conservation in Static WSNs



Energy conservation

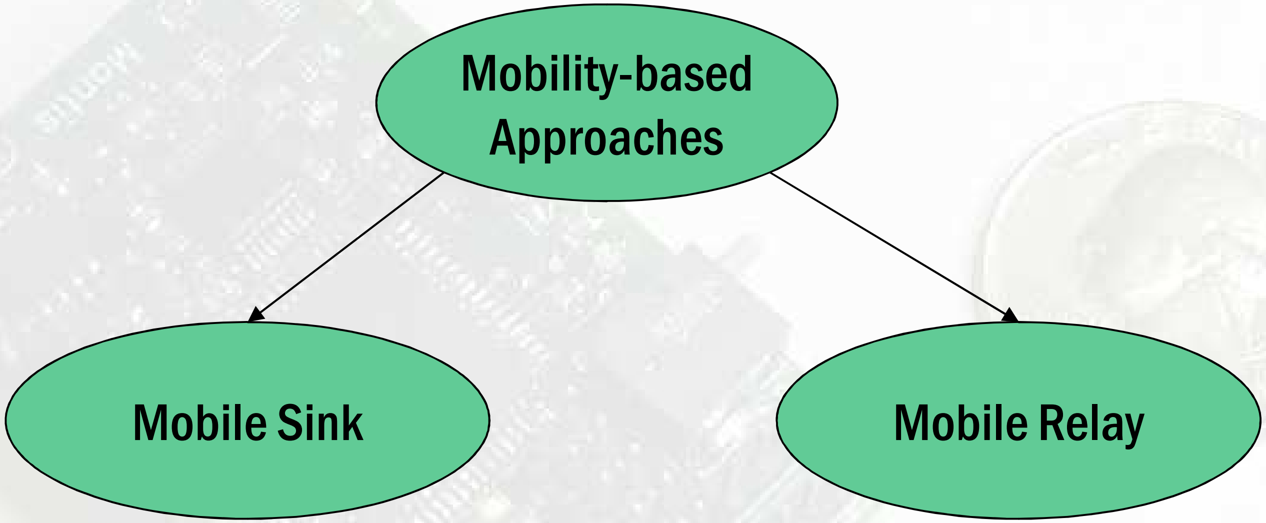
- Goal
  - Try to reduce as much as possible the radio activity, possibly performing local computations
    - ⇨ The radio should be in sleep/off mode as much as possible

- Different approaches



G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, **Energy Conservation in Wireless Sensor Networks: A Survey**, *Ad Hoc Networks*, Vol. 7, N. 3, May 2009. Elsevier.

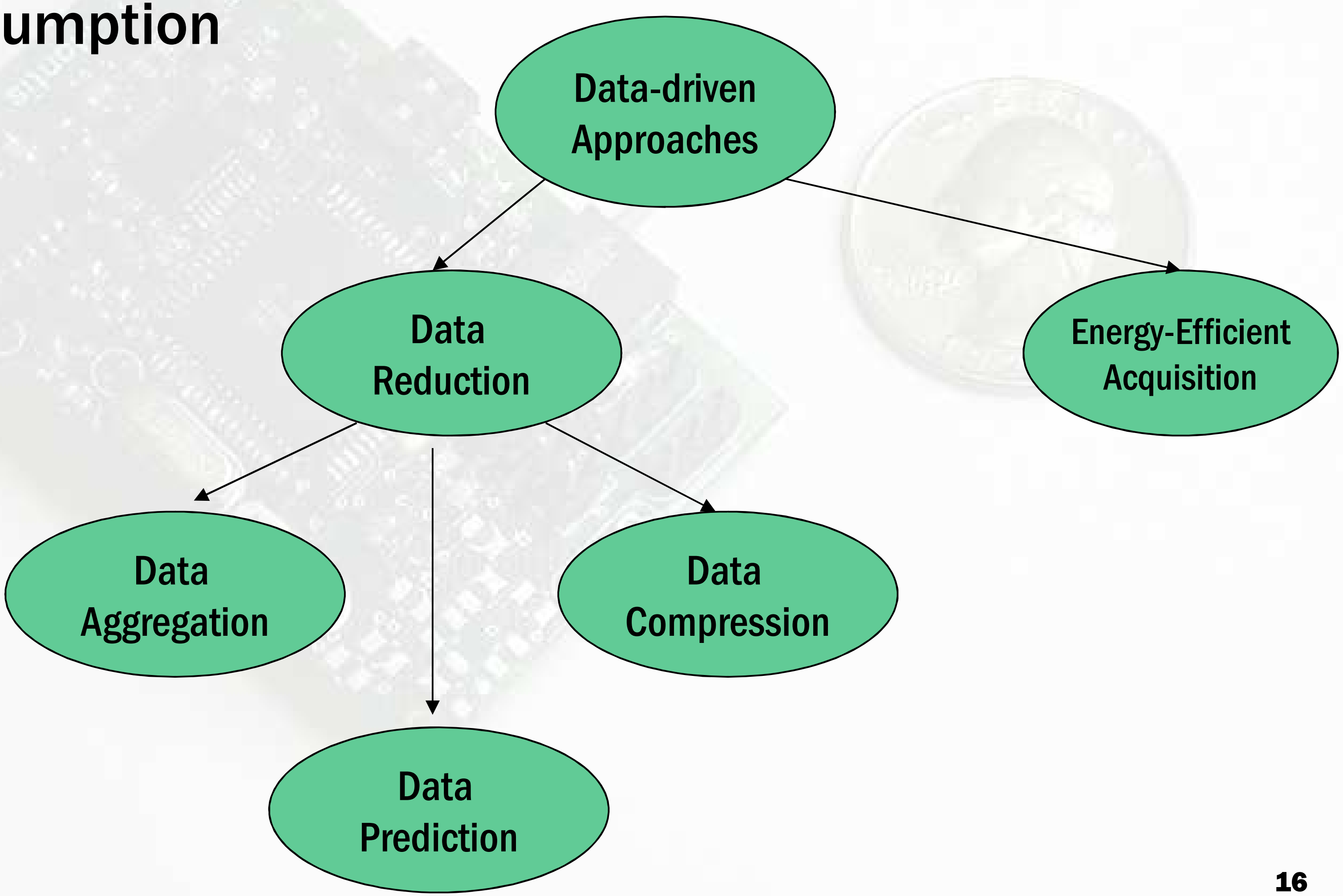
Mobility-based Energy Conservation



Mobility-based schemes will be re-considered in the framework of WSNs with Mobile Nodes

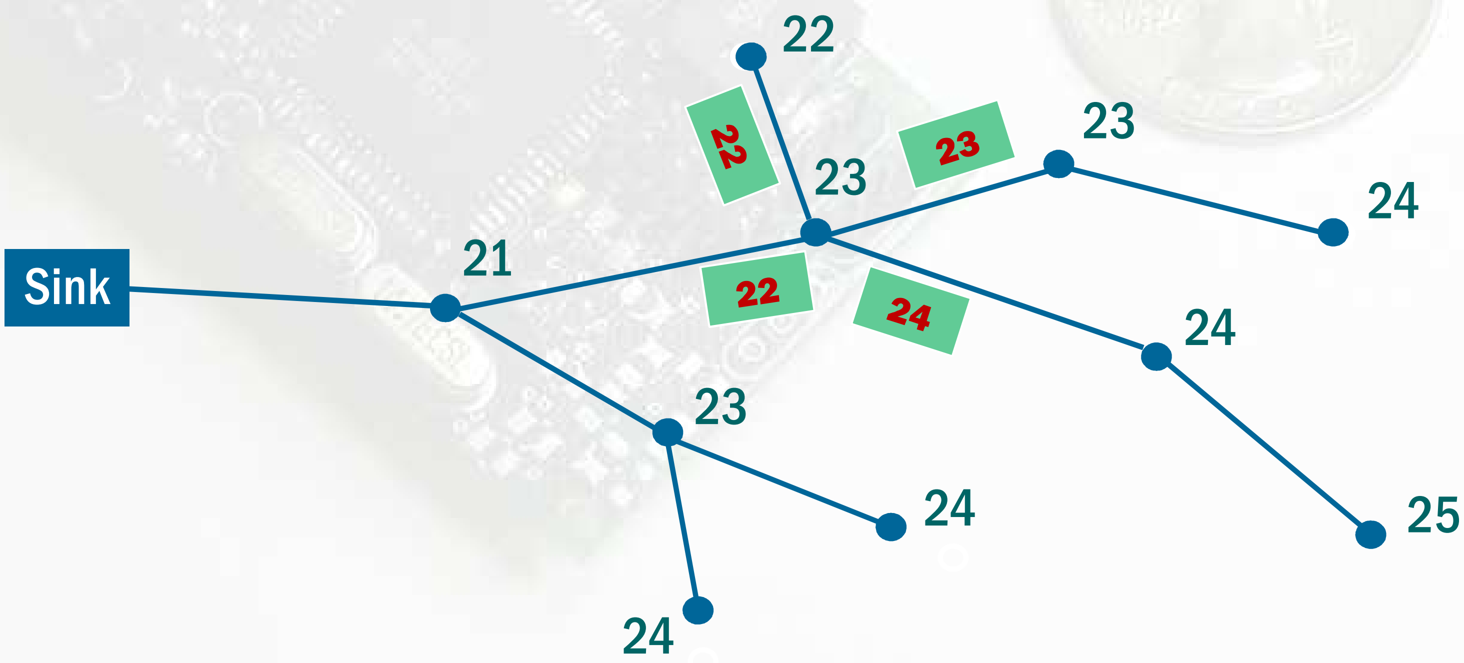
Data-driven approaches

- Reduces the amount of data to be transmitted
  - This reduces the radio activity and, hence, the energy consumption



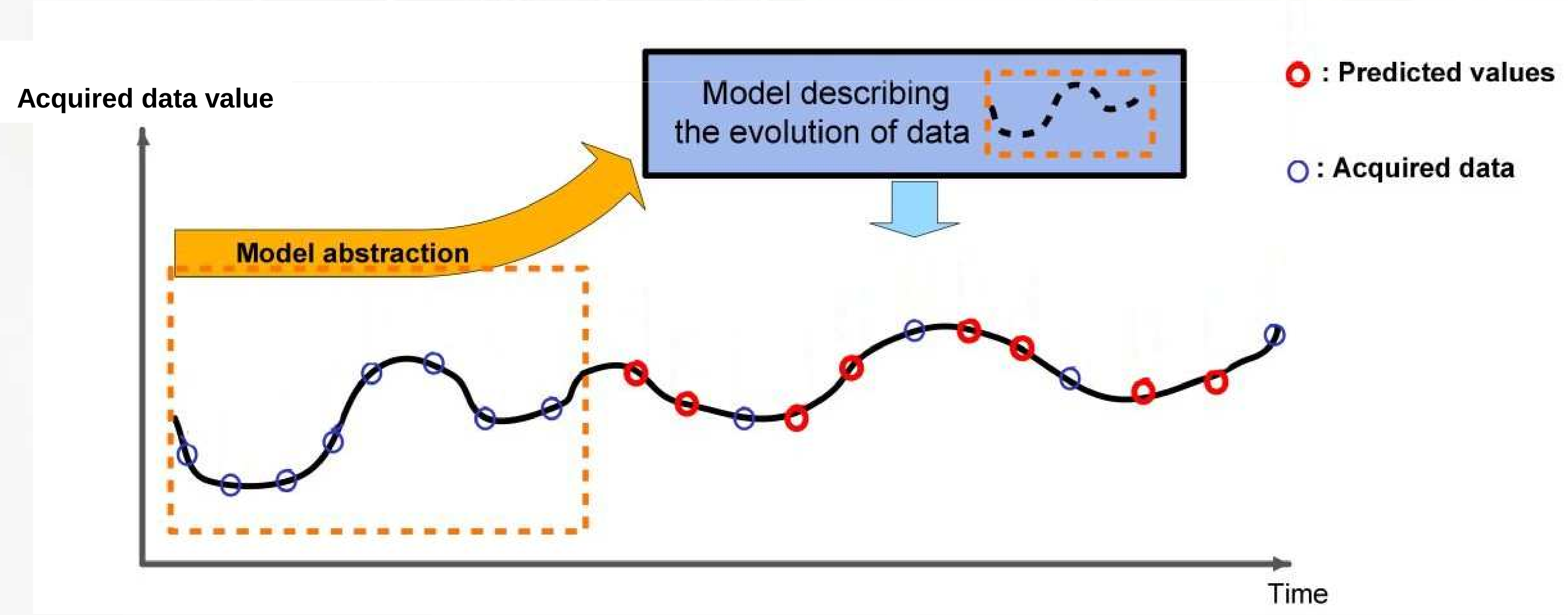
Data aggregation

- Data can be reduced as it flows through the network
  - E.g., which is the max/min temperature in sensing area?
    - ⇨ Each intermediate nodes forwards just one value to the sink
  - Also called in-network aggregation
  - Application-specific schemes



Model-driven Data Prediction

- Instead of reporting all data to sink, only sends the trend
  - only *if* and *when* it changes



Limitations of Data-driven approaches

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- Just reducing the amount of data does not necessarily result in energy consumption reduction
  - Transmitting a message requires approximately the same energy, irrespective of the message size
  - Energy costs for maintaining the sensor network cannot be avoided
  - Data reductions eliminates data redundancy → 100% communication reliability is required

How much energy-consumption reduction in practice?

Limitations of data-driven approaches

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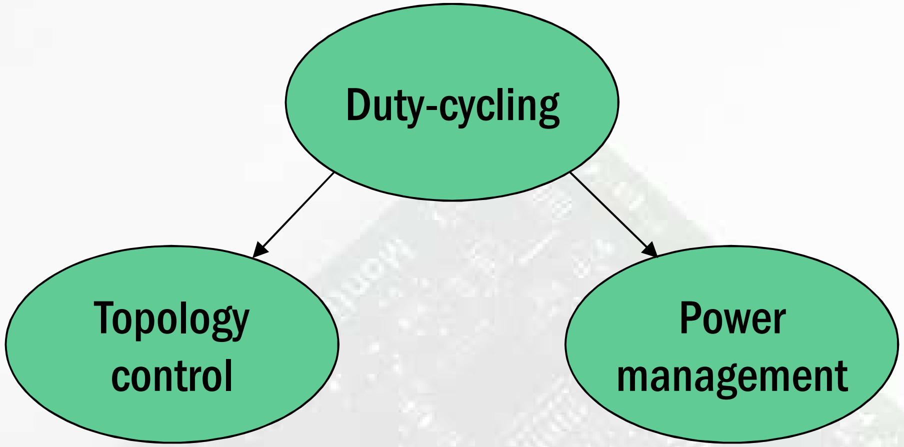
Usman Raza, Alessandro Camerra, Amy L Murphy, Themis Palpanas, Gian Pietro Picco, **What Does Model-Driven Data Acquisition Really Achieve in Wireless Sensor Networks?,** *Proc. IEEE PerCom 2012*, Lugano, Switzerland, March 19-23, 2012.

- WSN for adaptive lighting in road tunnels
- Model-driven data acquisition approach
  - Derivative-Based Prediction (DBP)
- The proposed technique suppresses 99.1% of reports
- However, lifetime “only” triples
  - Idle listening
  - Overhead introduced by the routing protocol
    - ⇨ Routing tree management
  - Need for reliable communication protocols

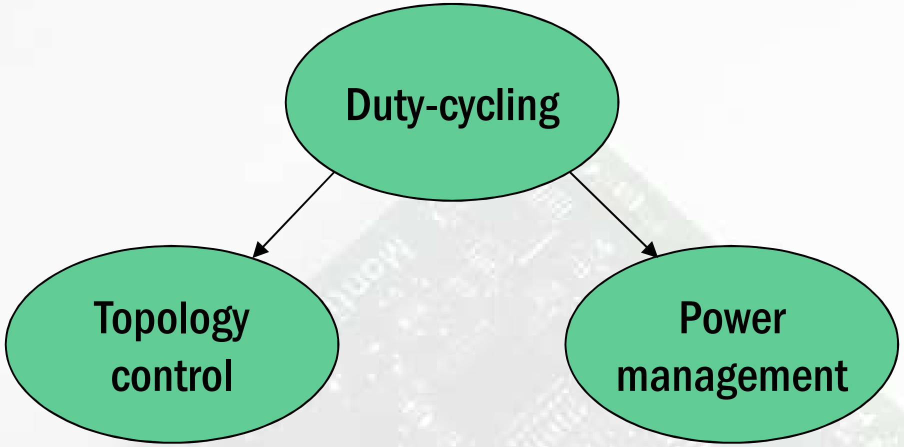
Duty-cycling



Node's components are switched off when not needed

- Topology Control
  - Exploits network redundancy
  - Selects the minimum set of nodes that guarantees connectivity
  - All the other nodes are kept in sleep mode to save energy
  - Increases the network lifetime by a factor depending on the degree of redundancy
    - ⇨ typically in the order of 2-3

Duty-cycling



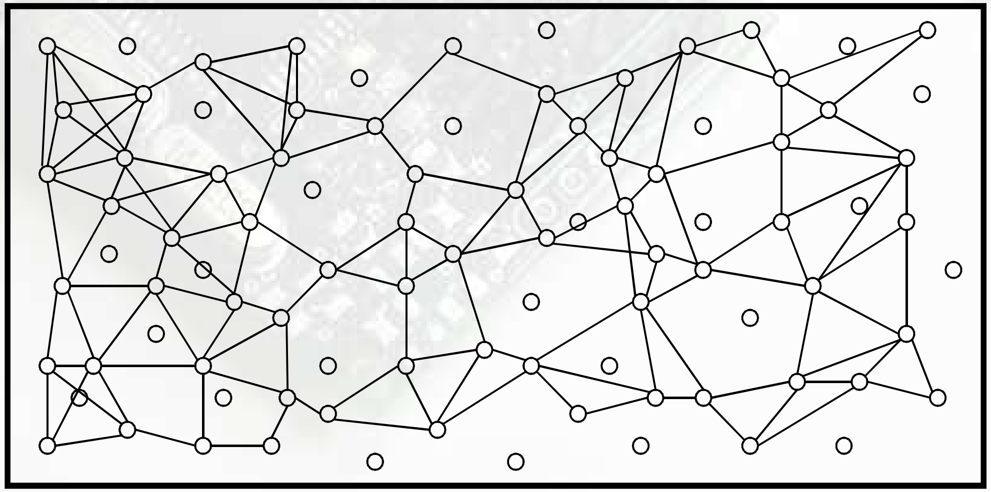
Node's components are switched off when not needed

- Power Management
  - Exploits idle periods in the communication subsystem
  - Switches off the radio during inactive periods
  - Extends the network lifetime significantly
    - ⇨ Duty cycles of some percents are quite common in WSNs

Topology Control

Topology Control

- How many nodes to activate?
  - ***Few*** active nodes:
    - ⇨ Distance between neighboring nodes high -> increase ***packet loss*** *and* higher ***transmit power and reduced spatial reuse***;
  - ***Too many*** active nodes:
    - ⇨ At best, ***expending unnecessary energy***;
    - ⇨ At worst nodes may ***interfere*** with one another by ***congesting*** the channel.

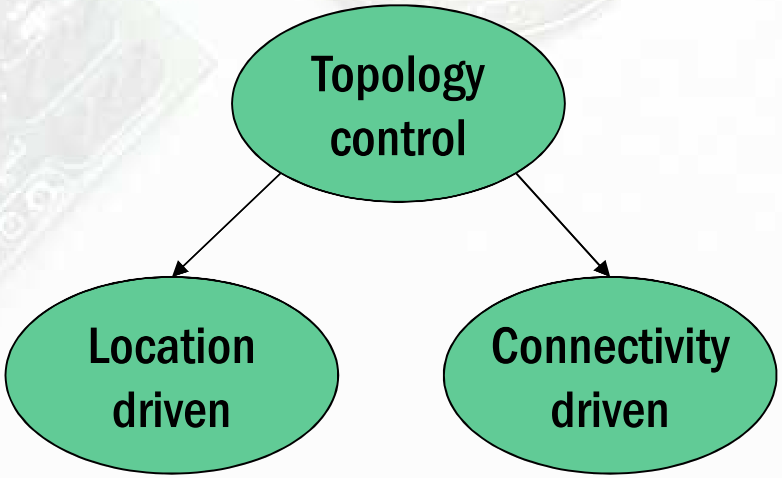


Topology control protocols

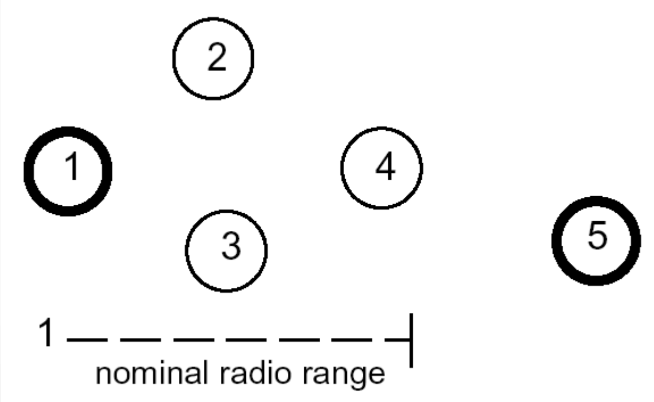
- Goal:

  Find out the minimum subset of nodes that is able to ensure network connectivity

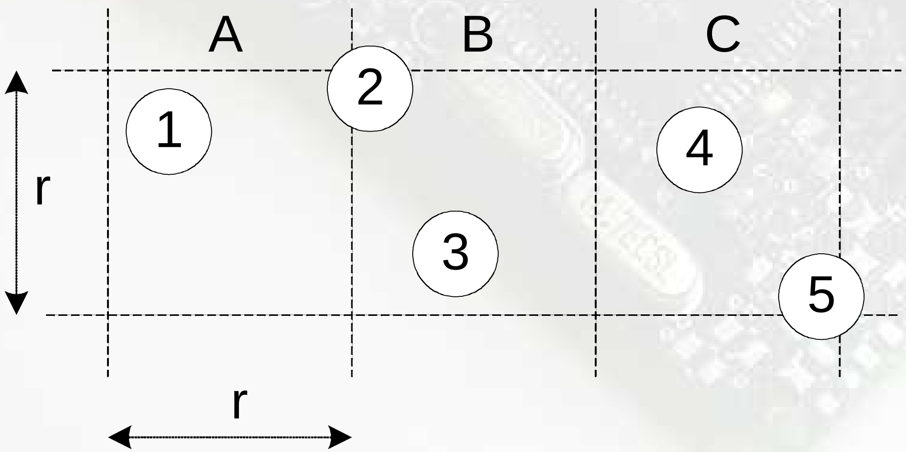
- Approaches
  - Location driven
    - ⇨ needs to know the exact location of nodes
    - ⇨ GAF
  - Connectivity driven
    - ⇨ more flexibility
    - ⇨ ASCENT, SPAN



Geographic Adaptive Fidelity (GAF)



- Each node knows its location (GPS)
- A virtual grid of size r is superimposed to nodes
- Each node in a grid is equivalent from a traffic forwarding perspective
- Keep **1 node awake in each grid** at each time



$$R \geq \sqrt{r^2 + (2r)^2}$$

$$r \leq \frac{R}{\sqrt{5}}$$

Y. Xu, J. Heidemann, D. Estrin, **Geography-informed Energy Conservation for Ad Hoc**, Proc. ACM MobiCom 2001, pp. 70 – 84. Rome, 2001.

Geographic Adaptive Fidelity (GAF)

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- Topology Management + Routing
- Clustering
  - Cluster-head election
  - Cluster-head rotation for uniform energy consumption
  - All nodes inside a cluster, but the cluster-head, are sleeping
- Routing
  - As soon as the cluster-head detects an event, it wakes up all the other nodes in the cluster
  - The cluster-head receives packets from cluster nodes, and forwards them to the sink node (no data aggregation)

ASCENT

- **A**daptive **S**elf-**C**onfiguring s**E**nsor **N**etworks **T**opologies
- Does not depend on the routing protocol
- Decision about joining the network based on *local measurements*
  - Each node measures the number of neighbors and packet loss *locally*.
  - Each node then makes an informed decision to *join* the network topology or to *sleep* by turning its radio off.

A. Cerpa, D. Estrin, **Ascent: Adaptive Self-Configuring Sensor Network Topologies**, Proc. IEEE INFOCOM 2002.

ASCENT

- Nodes can be in ***active*** or ***passive*** state
  - Active nodes are part of the topology (or stay awake) and forward data packets
  - Nodes in passive state can be sleeping or collecting network measurements. They ***do not*** forward any packets.
  - An active node may send *help* messages to solicit passive neighbors to become active if it is experiencing a low message loss
  - A node that joins the network (test state) sends an *announcement* message.
  - This process continues until the number of active nodes is such that the experienced message loss is below a pre-defined application-dependent threshold.
  - The process will re-start when some future network event (e.g. a node failure) or a change in the environmental conditions causes an increase in the message loss.

A. Cerpa, D. Estrin, **Ascent: Adaptive Self-Configuring Sensor Network Topologies**, Proc. IEEE INFOCOM 2002.

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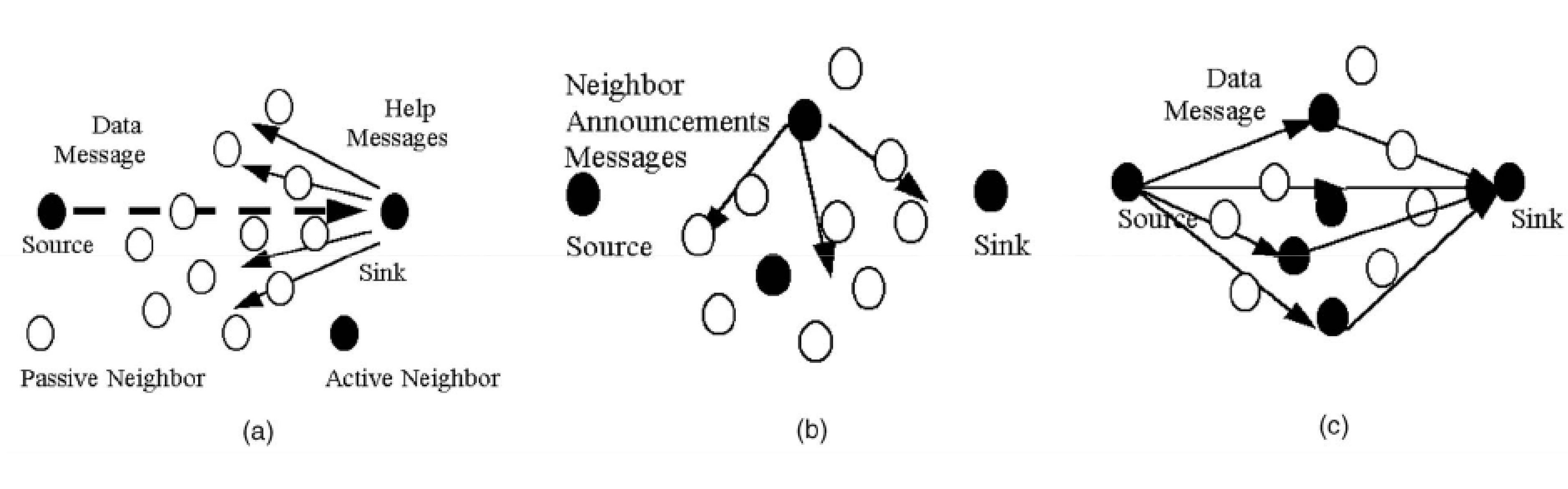
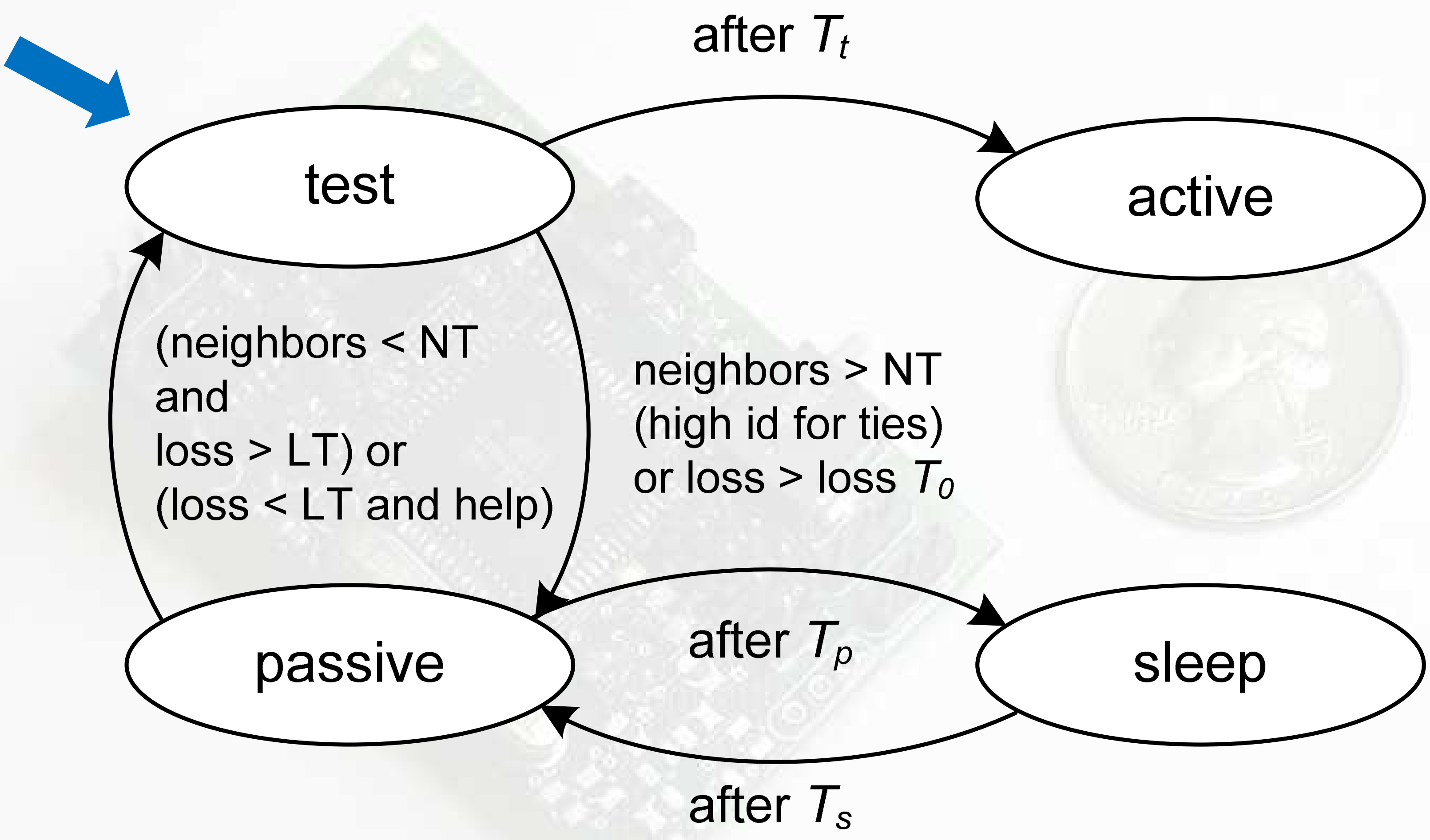
Network Self-Configuration - Example



(a) A communication hole is detected
(b) Transition from passive to active state
(c) Final State

A. Cerpa, D. Estrin, **Ascent: Adaptive Self-Configuring Sensor Network Topologies**, Proc. IEEE INFOCOM 2002.

ASCENT



A. Cerpa, D. Estrin, **Ascent: Adaptive Self-Configuring Sensor Network Topologies**, Proc. IEEE INFOCOM 2002.

ASCENT Performance

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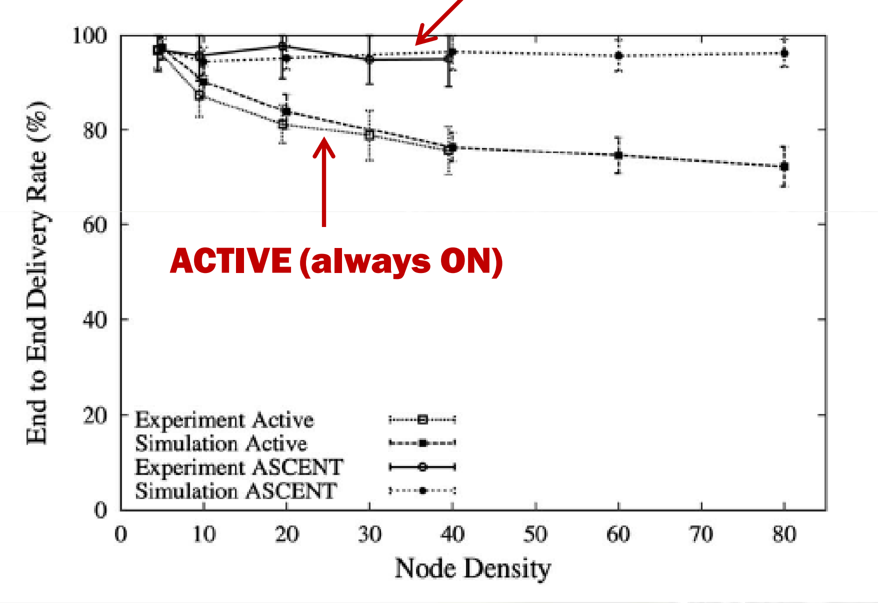
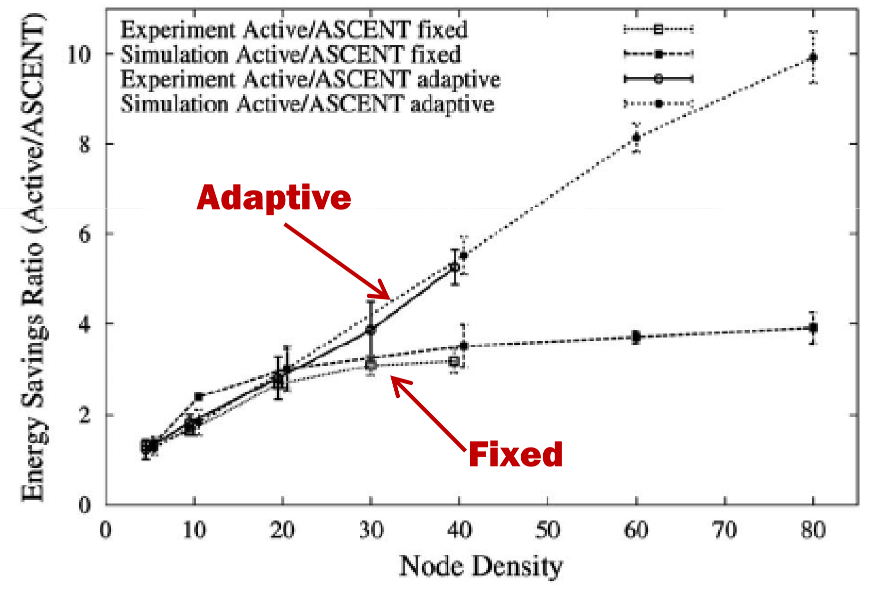
End-2-end Delivery Ratio



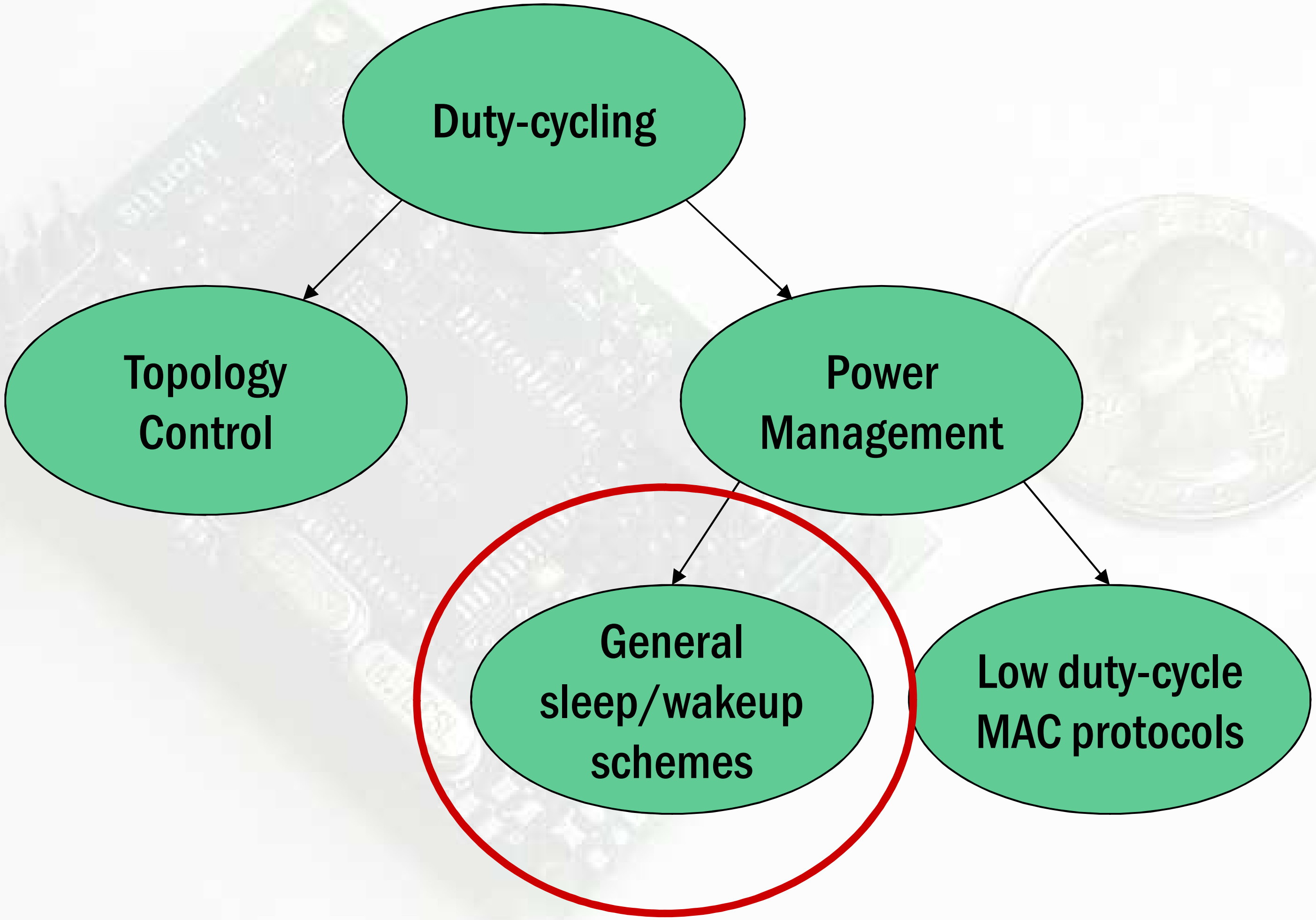
Energy Savings



A. Cerpa, D. Estrin, **Ascent: Adaptive Self-Configuring Sensor Network Topologies**, Proc. IEEE INFOCOM 2002.

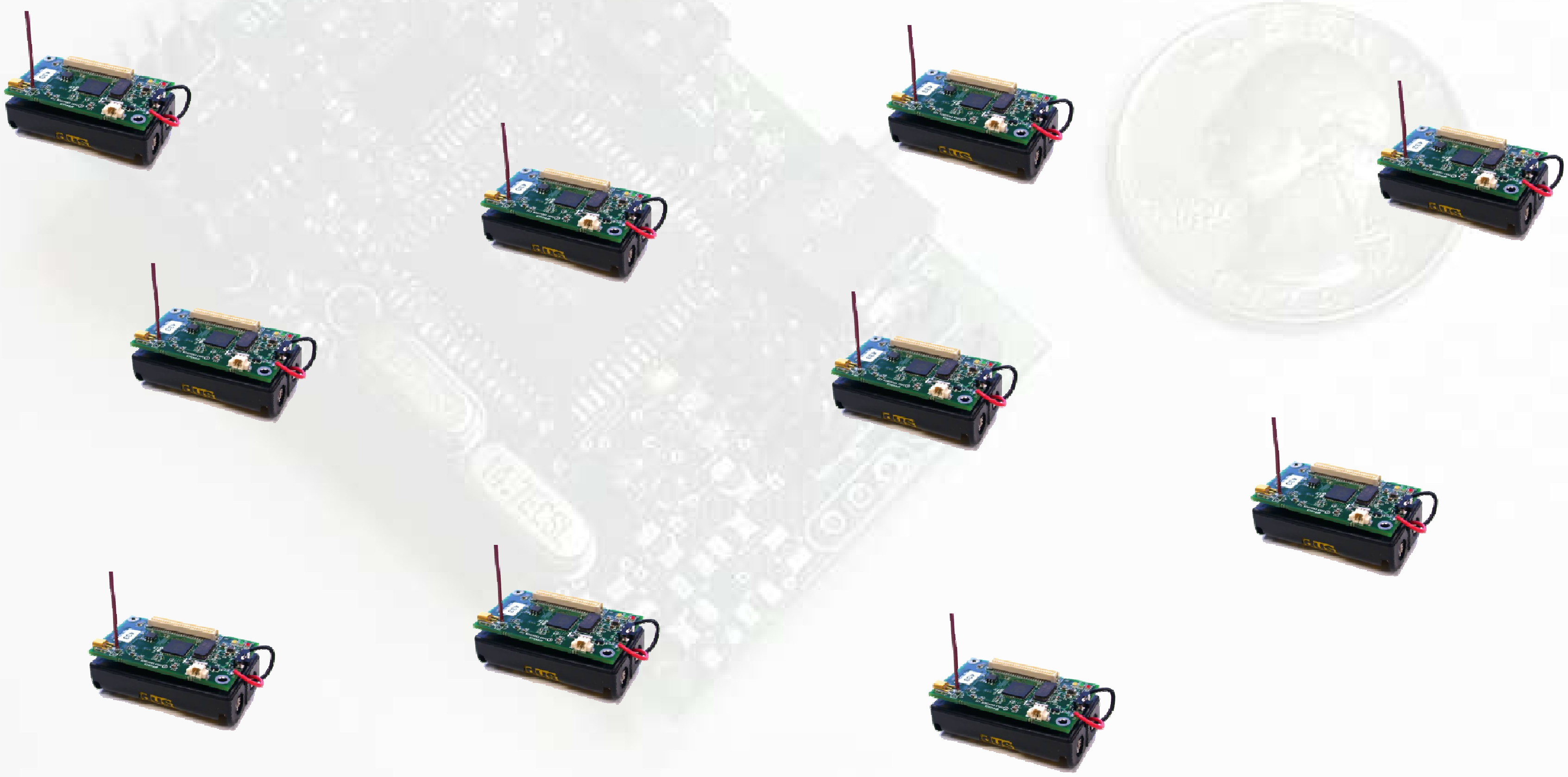
Power Management

Power Management



General sleep/wakeup schemes

- When should a node wake up for communicating with its neighbors?



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  - When another node wants to communicate with it (*on demand*)
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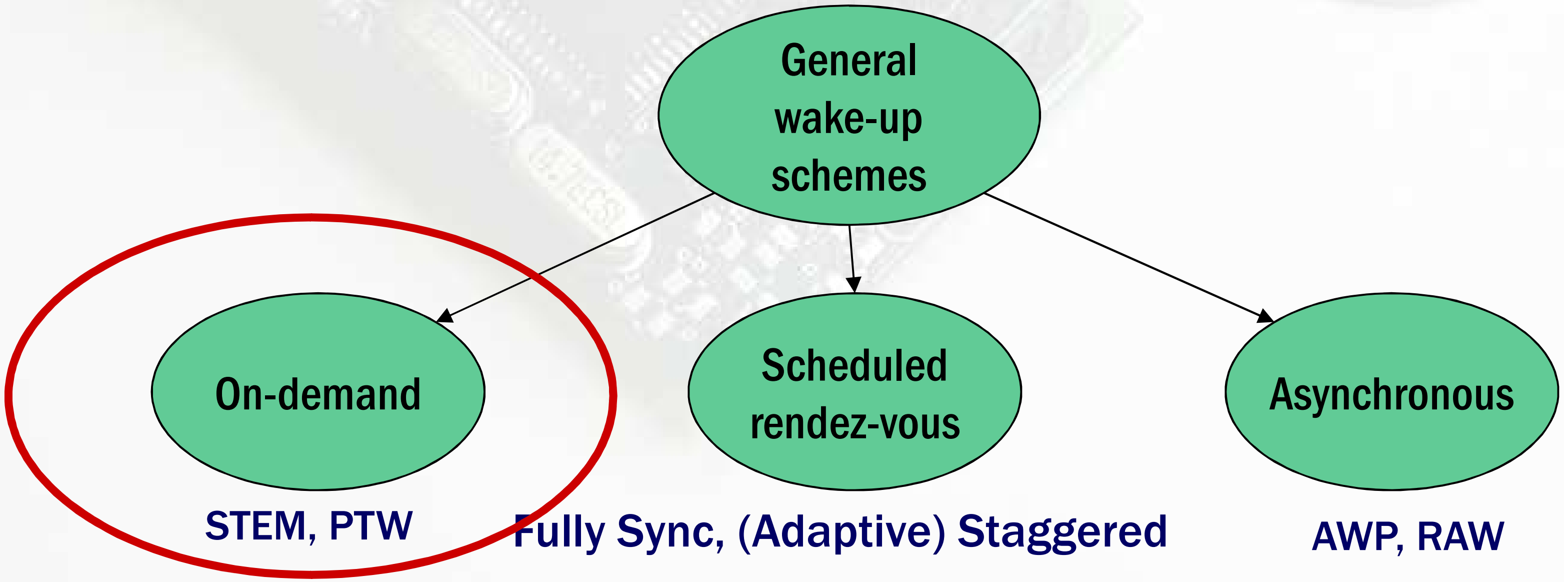
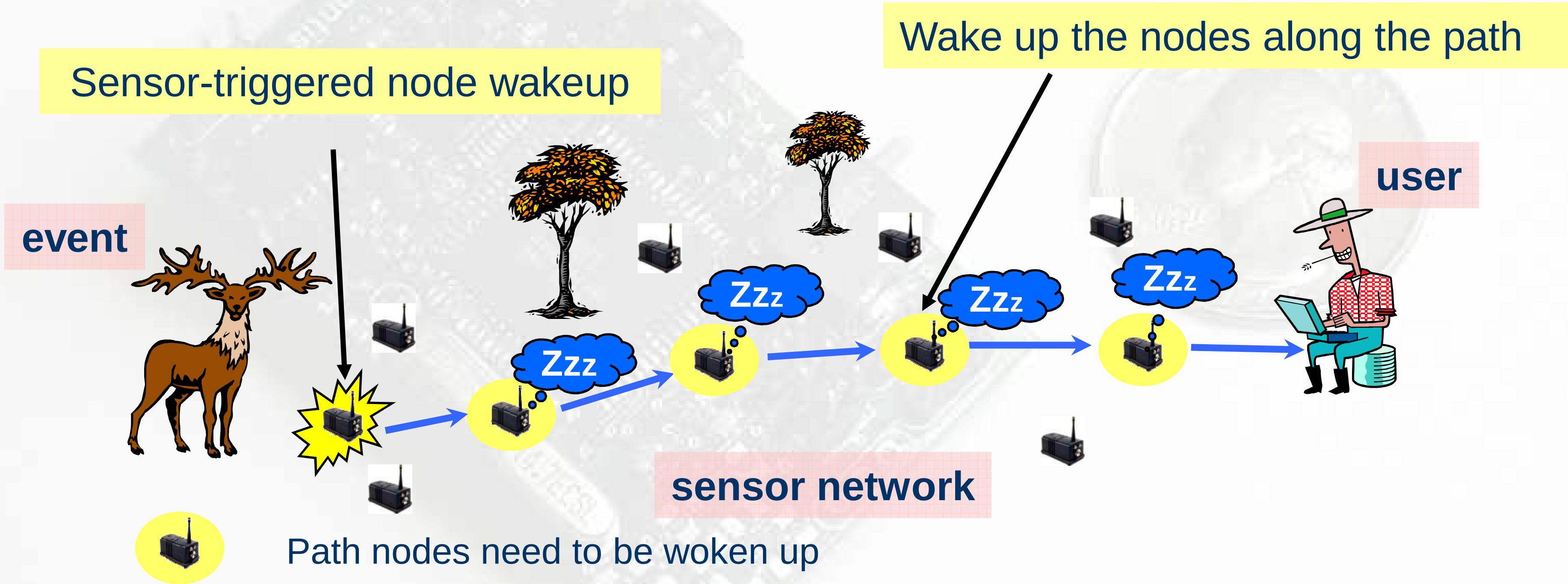
    - ⇨ Clock synchronization required
  - Whenever it wants (*Asynchronous*)



On-demand Schemes

Sparse Topology and Energy Management (STEM)



C. Schurgers, V. Tsiatsis, M. B. Srivastava, **STEM: Topology Management for Energy Efficient Sensor Networks**, *IEEE Aerospace Conference '02*, Big Sky, MT, March 10-15, 2002.

On-demand Schemes

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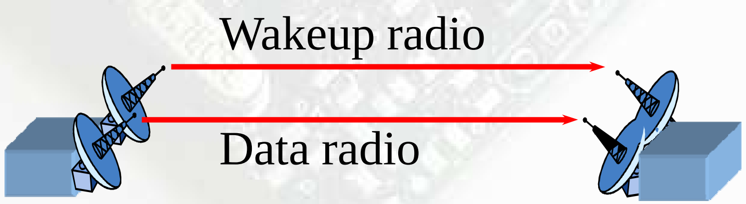
Sparse Topology and Energy Management (STEM)

- Can be used in combination with topology control
  - GAF + STEM can provide a duty cycle of about 1%
- STEM trades energy saving for path setup latency
- Two different radios
  - data transmissions
  - wakeups



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On-demand Schemes

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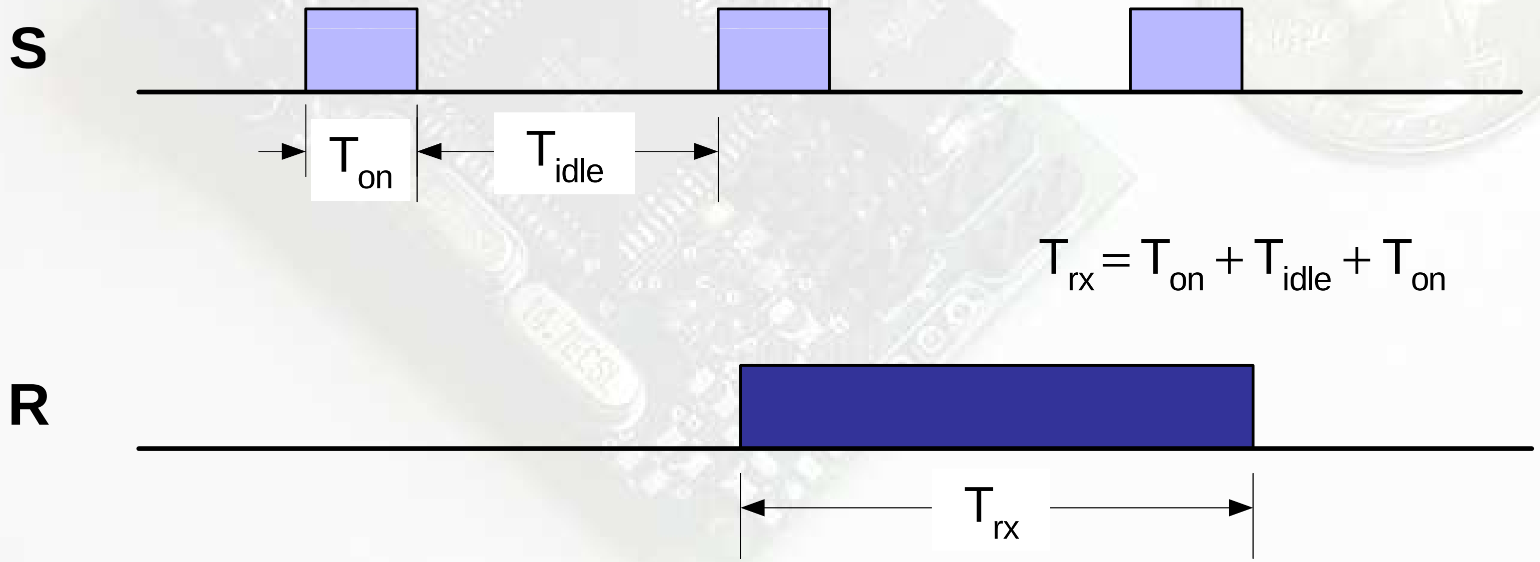
Sparse Topology and Energy Management (STEM)

- Wakeup Radio
  - Ideally, a low-power radio should be used
    - ⇨ It would result in a wakeup range shorter than the data transmission range
  - In practice, two similar radios are used for data and wakeup
    - ⇨ Similar power consumption, similar transmission range
  - Duty cycle on the wakeup radio, using an asynchronous approach
    - ⇨ A potential target node wakes up periodically
    - ⇨ The initiator node transmits a stream of periodic beacons (STEM-B) or a continuous wakeup tone (STEM-T)

C. Schurgers, V. Tsiatsis, M. B. Srivastava, **STEM: Topology Management for Energy Efficient Sensor Networks**, *IEEE Aerospace Conference '02*, Big Sky, MT, March 10-15, 2002.

Power Management on Wakeup Radio

- Asynchronous Initiator
  - Periodic beacon transmission
  - Busy tone
- Potential Target Nodes periodically listening



C. Schurgers, V. Tsiatsis, M. B. Srivastava, **STEM: Topology Management for Energy Efficient Sensor Networks**, *IEEE Aerospace Conference '02*, Big Sky, MT, March 10-15, 2002.

On-demand Schemes

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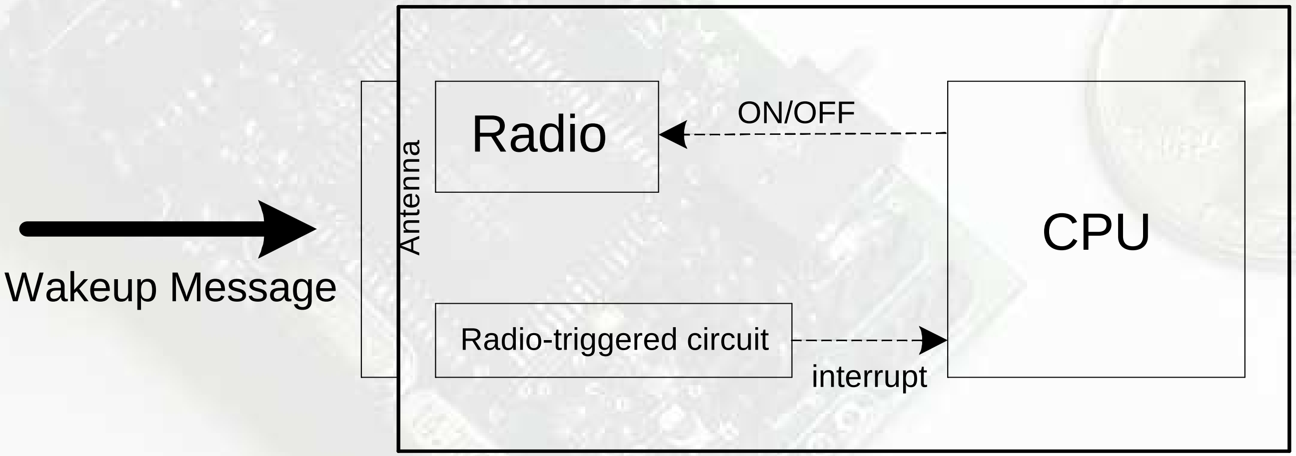
Radio-triggered Power Management



L. Gu, J. Stankovic, **Radio-Triggered Wake-up for Wireless Sensor Networks**, *Real-Time Systems Journal*, Vol. 29, pp. 157-182, 2005.

General sleep/wakeup schemes

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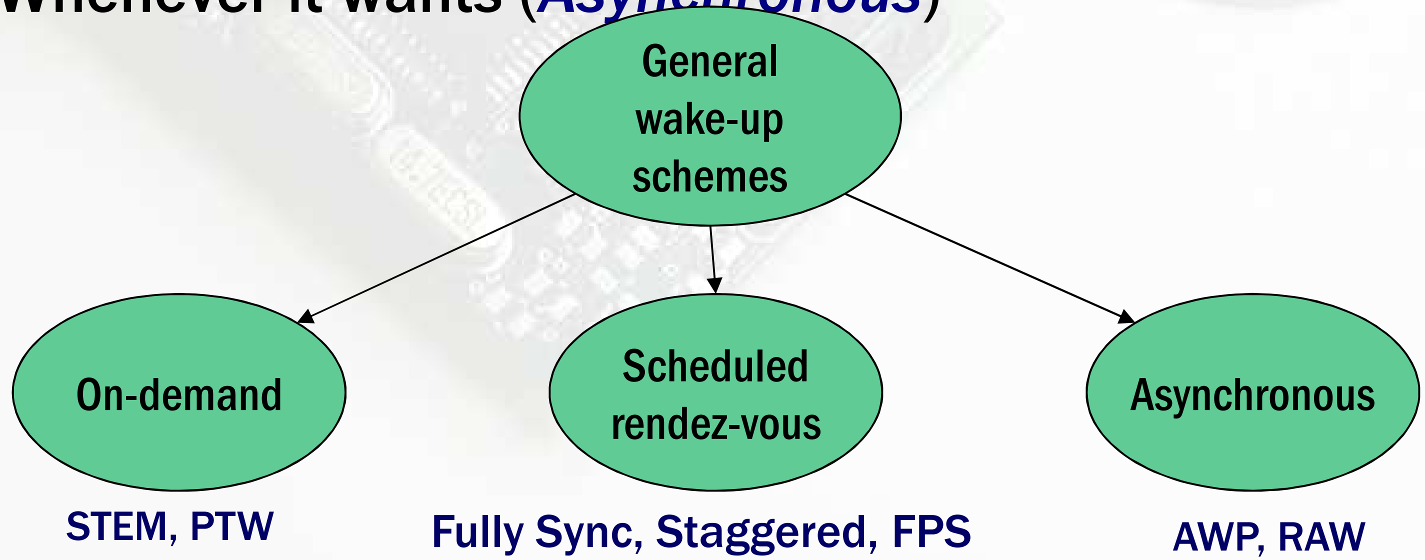
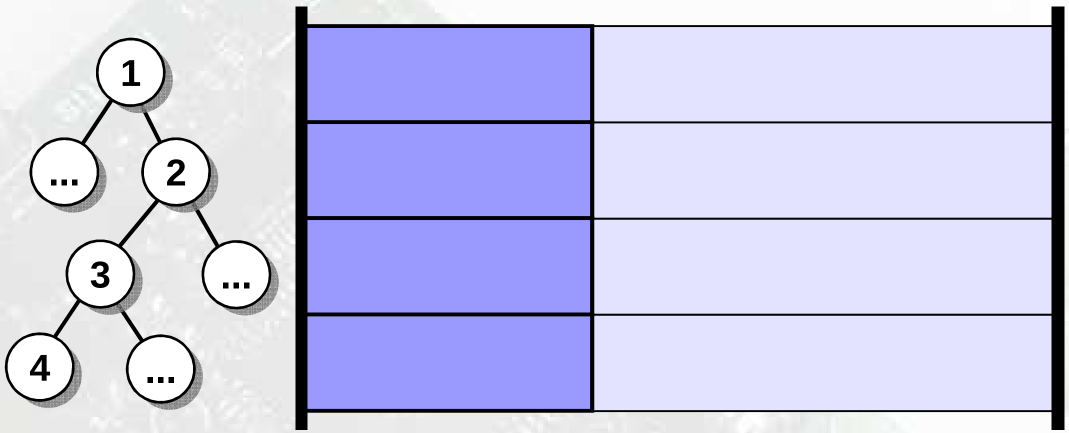


Fully Synchronized Scheme (TinyDB)

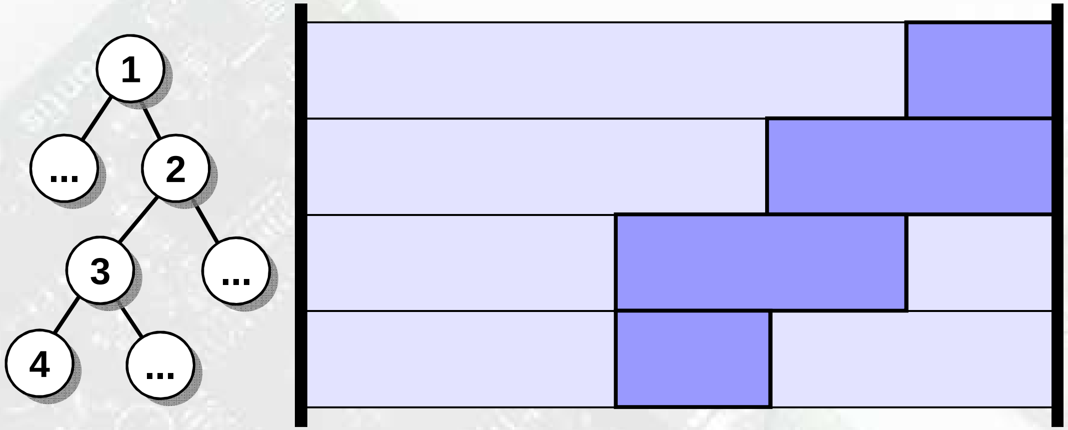


- Pros
  - Simplicity

- Cons
  - Global duty-cycle
    - ⇨ low energy efficiency
  - Static

Sam Madden, Michael J. Franklin, Joseph M. Hellerstein and Wei Hong. **TinyDB: An Acqusitional Query Processing System for Sensor Networks**. ACM TODS, 2005

Fixed Staggered Scheme (TAG, TASK)



- Parent-child talk intervals
  - Adjacent to reduce sleep-awake commutations
  - Pros
    - ⇨ Staggered scheme
    - ⇨ Suitable to data aggregation
  - Cons
    - ⇨ Fixed activity times
    - ⇨ Global parameters

Samuel R. Madden, Michael J. Franklin, Joseph M. Hellerstein, and Wei Hong. **TAG: a Tiny AGgregation Service for Ad-Hoc Sensor Networks**. OSDI, December 2002

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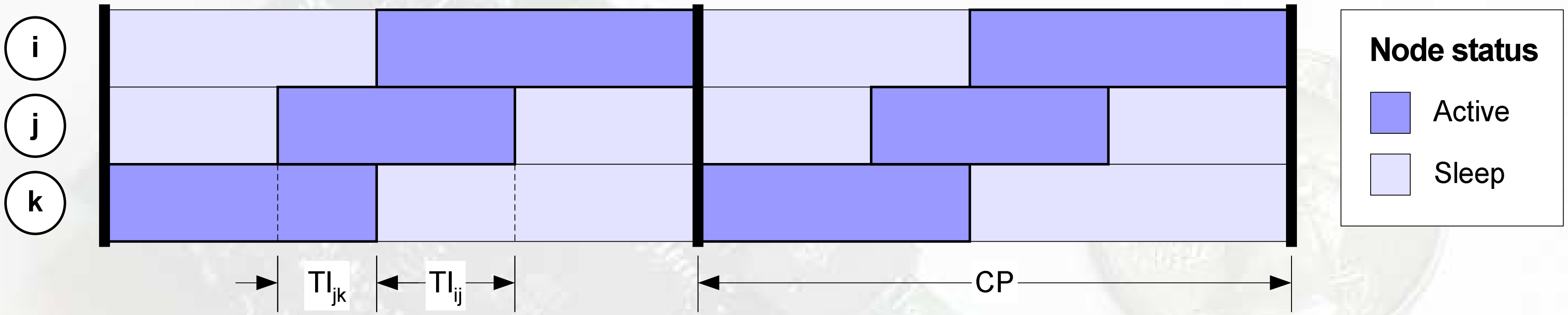
Adaptive Staggered Scheme (ASLEEP)



- **Adaptive talk interval**
  - number of children
  - network traffic
  - channel conditions
  - nodes join/leaves, etc.
- **Components**
  - Talk Interval Prediction
  - Sleep Coordination

G. Anastasi, M. Conti, M. Di Francesco, **Extending the Lifetime of Wireless Sensor Networks through Adaptive Sleep**, *IEEE Transactions on Industrial Informatics*, Vol. 59, N.2, February 2010.

ASLEEP Components

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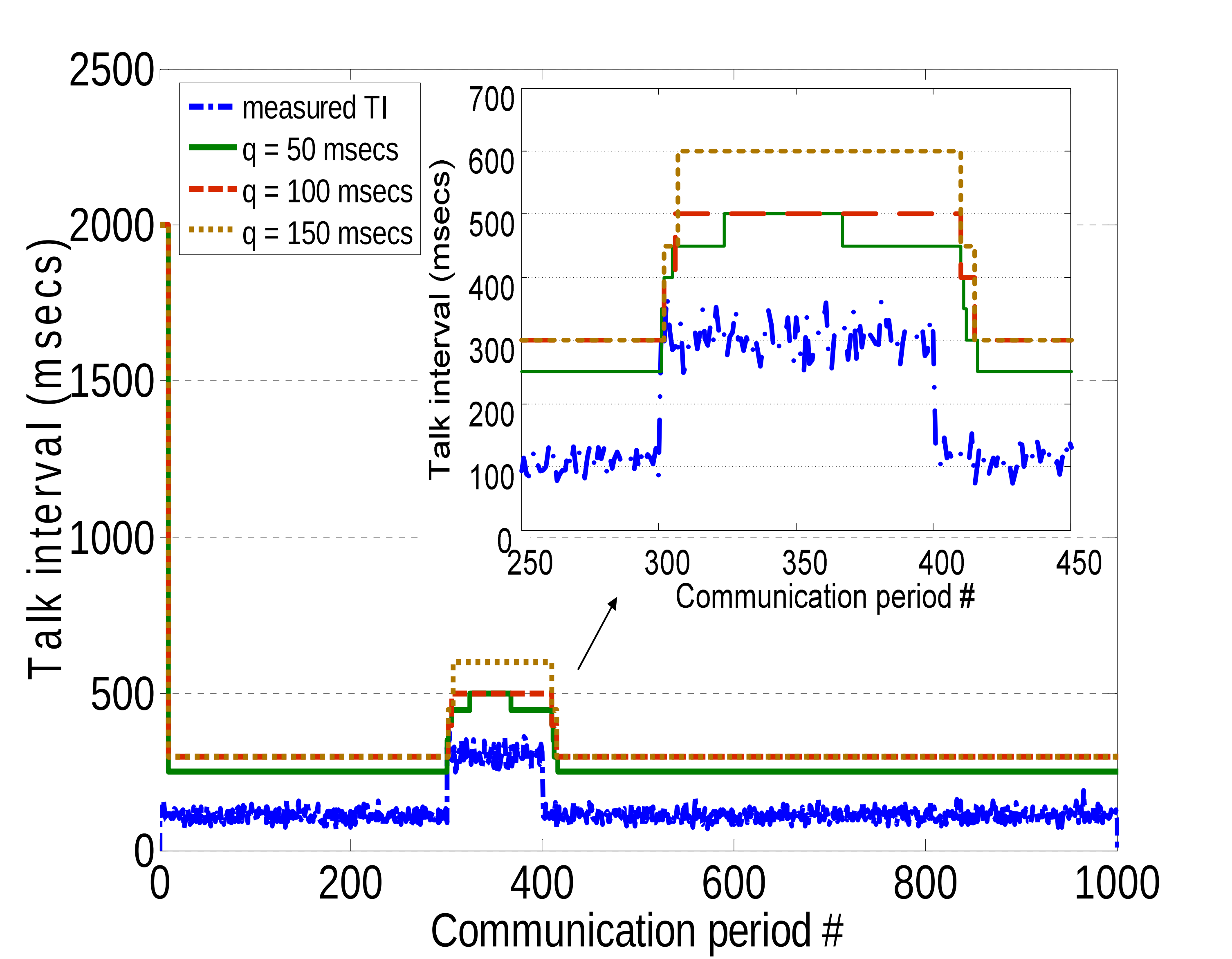
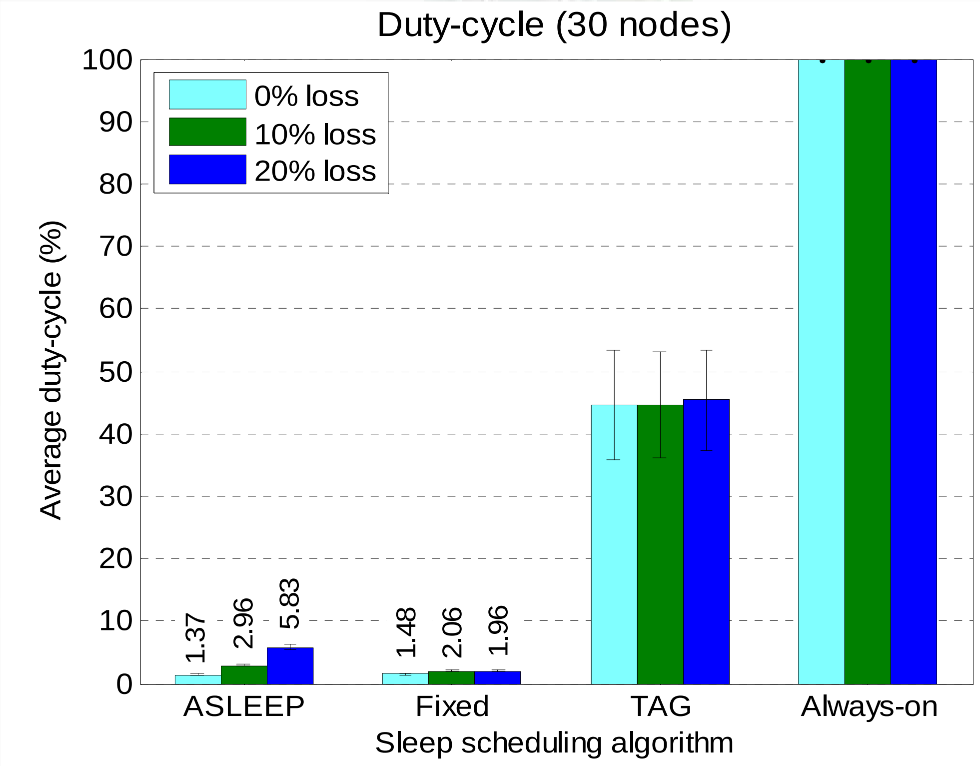
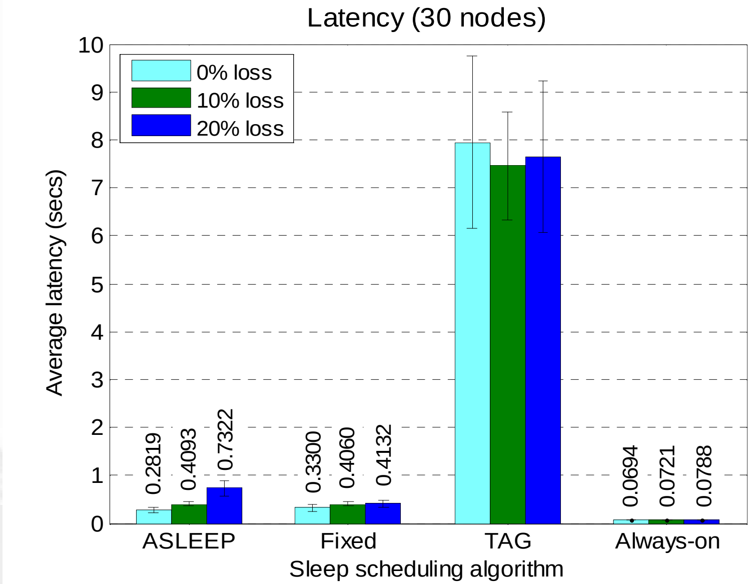
- Talk Interval Prediction Algorithm
- Sleep Coordination Algorithm
  - Direct Beacons
  - Reverse Beacons
- Beacon Protection
- Beacon Loss Compensation

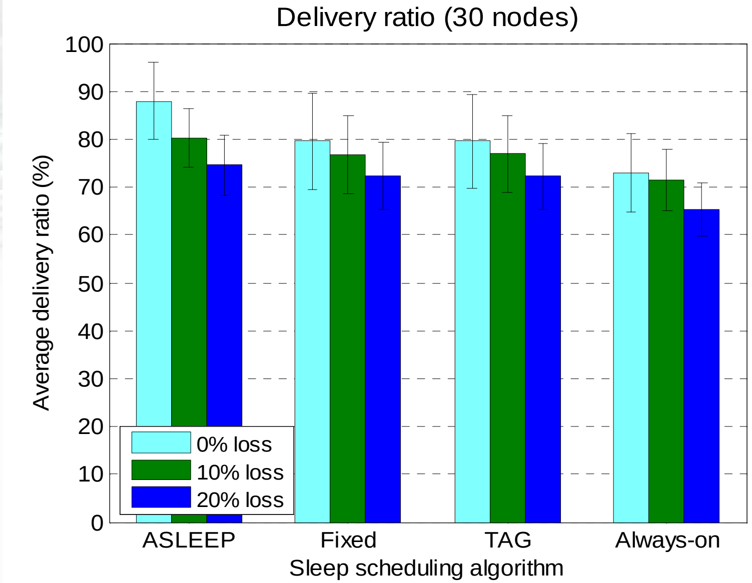
ASLEEP: Analysis in Dynamic Conditions



Performance Comparison







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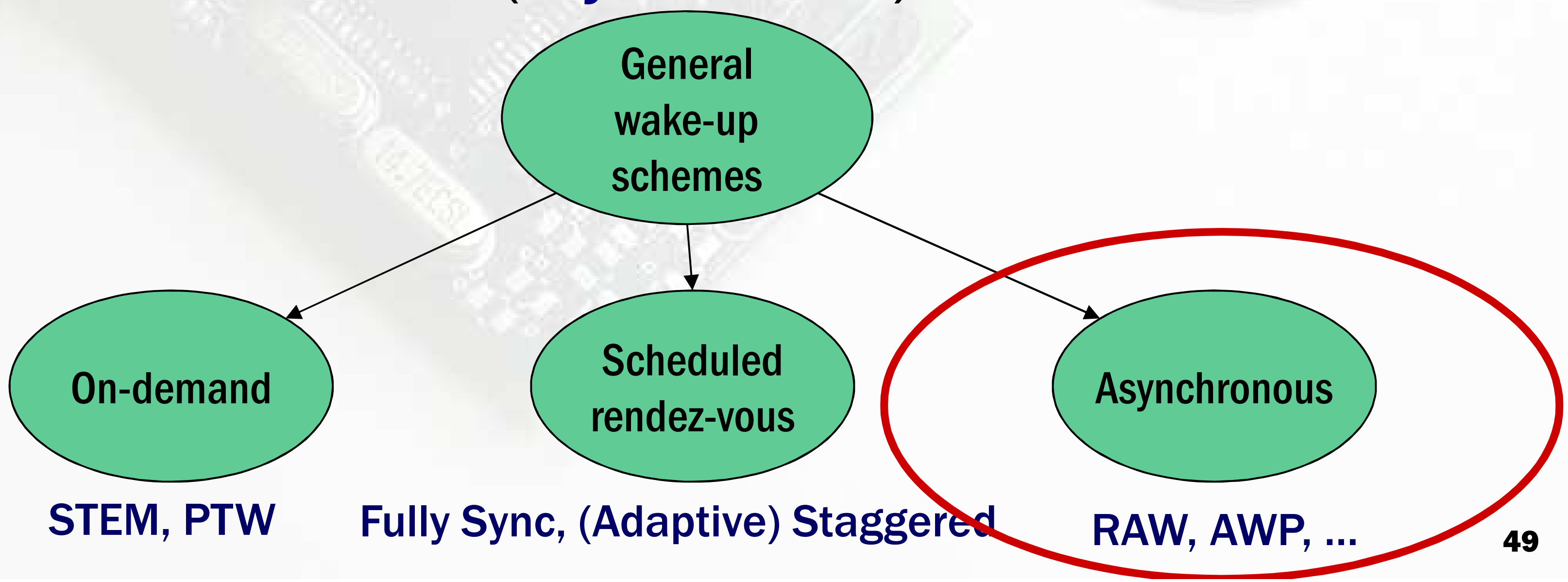

Random Asynchronous Wakeup (RAW)

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Routing Protocol + Random Wakeup Scheme

- Several Paths towards the destination
  - Especially if the network is dense

- *Forwarding Candidate Set* (FCS)

  set of active neighbors that are closest to the destination
  - In terms of number of hops (h-FCS)
  - In terms of distance (d-FCS)

V. Paruchuri, S. Basavaraju, R. Kannan, S. Iyengar, **Random Asynchronous Wakeup Protocol for Sensor Networks**, *Proc. IEEE Int'l Conf. On Broadband Networks (BROADNETS 2004)*, 2004.

Random Asynchronous Wakeup (RAW)

Algorithm

- Each node wakes up randomly once in every time interval of fixed duration *T*
- Remains active for a predefined time *Ta* (*Ta* ≤ *T*), and then sleeps again.
- Once awake, a node looks for possible active neighbors by running a neighbor discovery procedure.

If *S* has to transmit a packet to *D* and in the FCS of *S* there are *m* neighbors, then the probability that at least one of these neighbors is awake along with S is given by

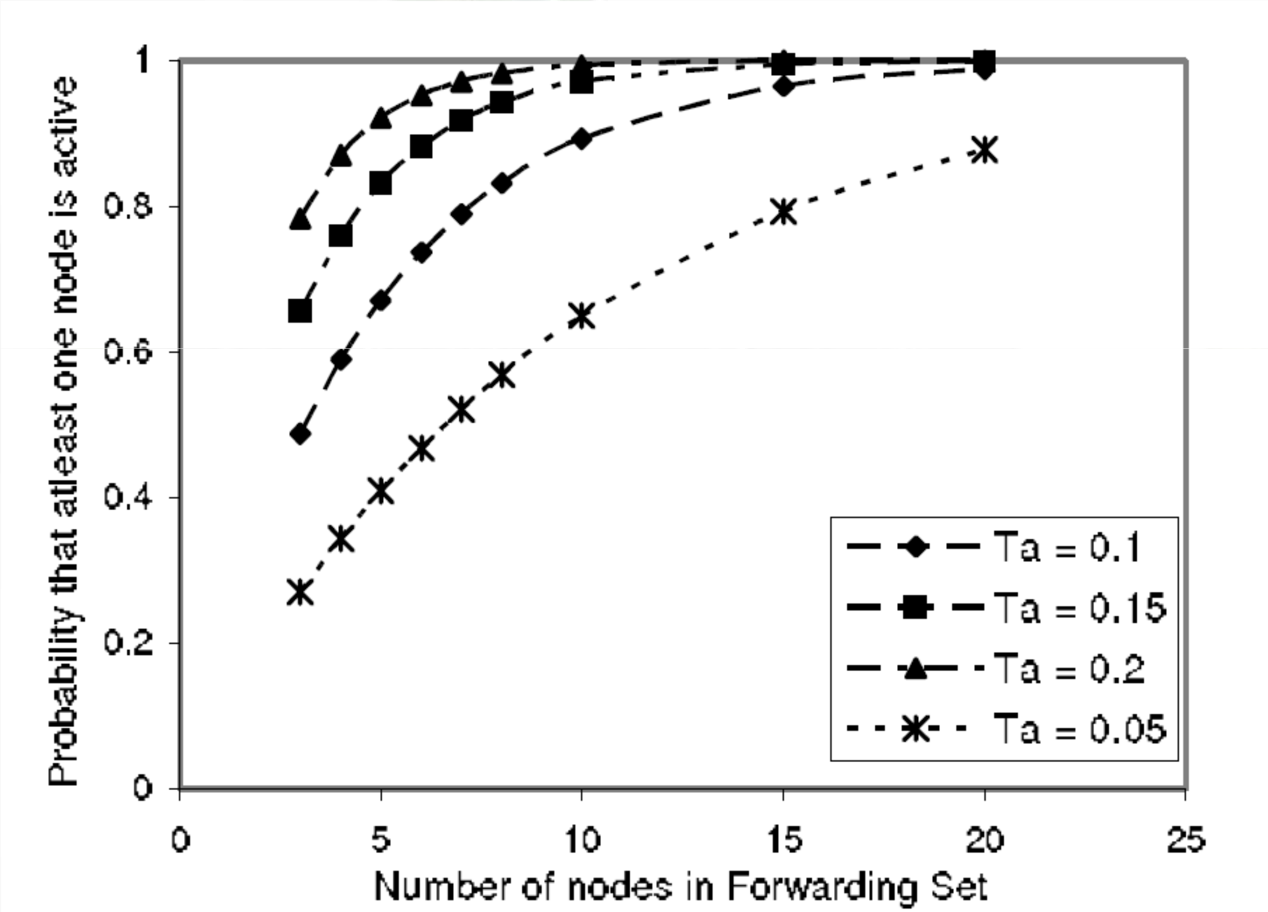
$$P = 1 - \left(1 - \frac{2 \cdot T_a}{T}\right)^m$$

V. Paruchuri, S. Basavaraju, R. Kannan, S. Iyengar, **Random Asynchronous Wakeup Protocol for Sensor Networks**, *Proc. IEEE Int'l Conf. On Broadband Networks (BROADNETS 2004)*, 2004.

Random Asynchronous Wakeup (RAW)

Performance

$$P = 1 - \left(1 - \frac{2 \cdot T_a}{T}\right)^m$$



V. Paruchuri, S. Basavaraju, R. Kannan, S. Iyengar, **Random Asynchronous Wakeup Protocol for Sensor Networks**, *Proc. IEEE Int'l Conf. On Broadband Networks (BROADNETS 2004)*, 2004.

Asynchronous Wakeup Protocol (AWP)

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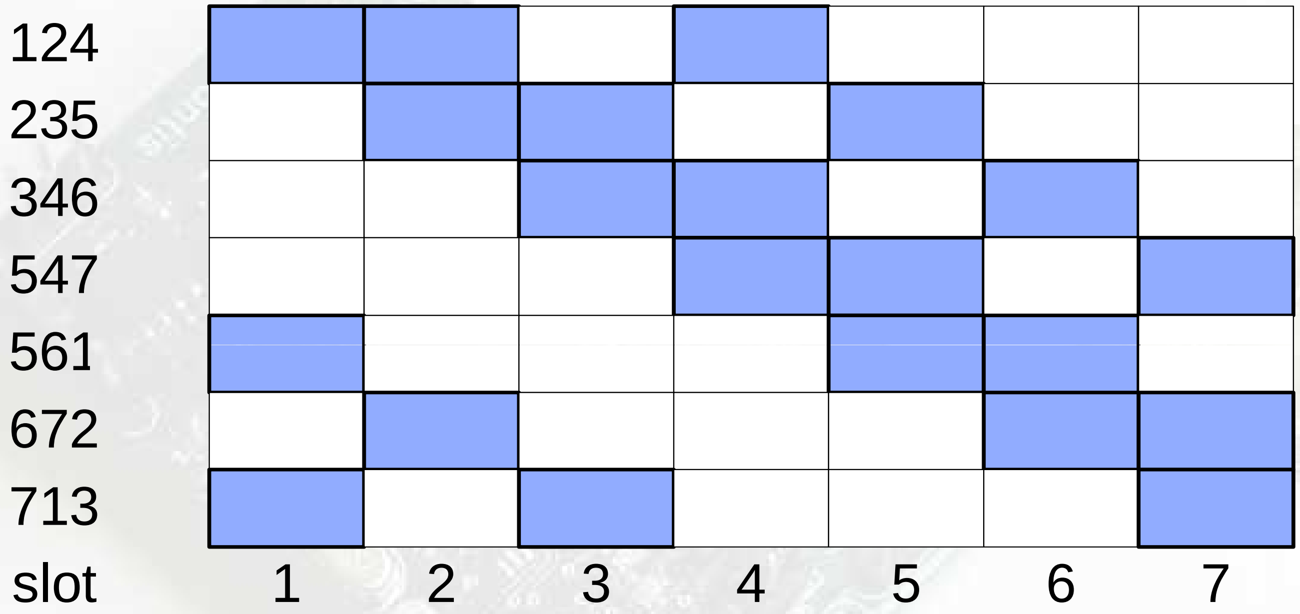
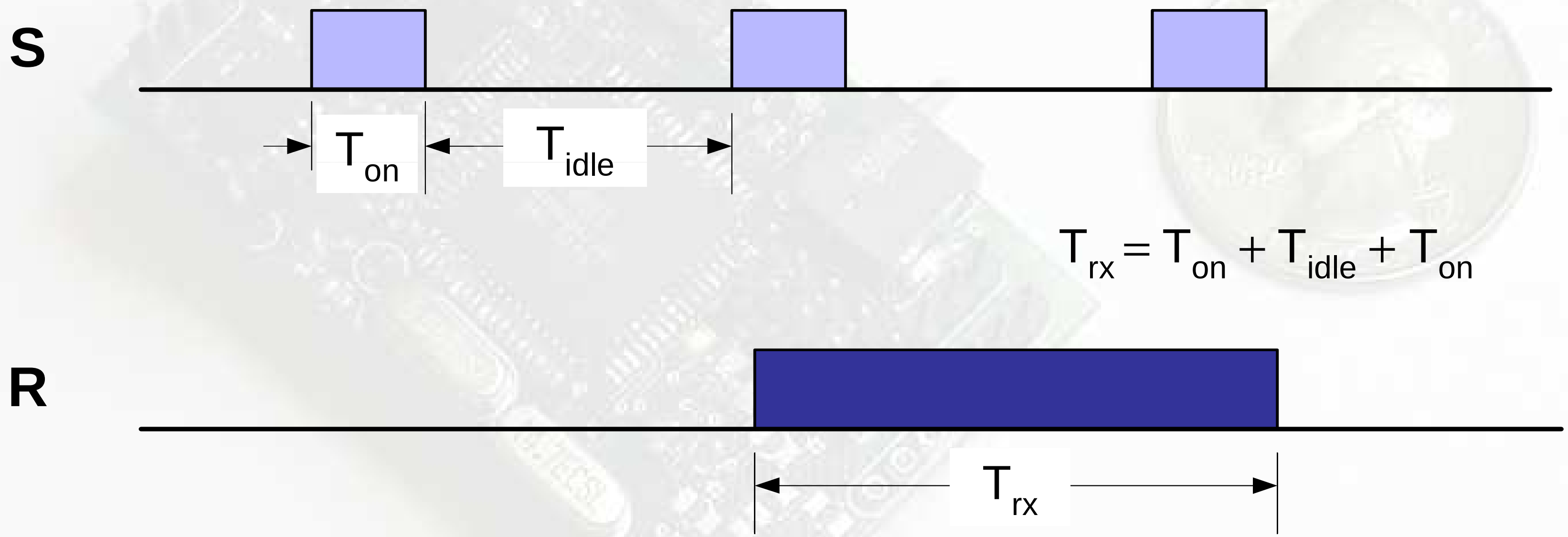


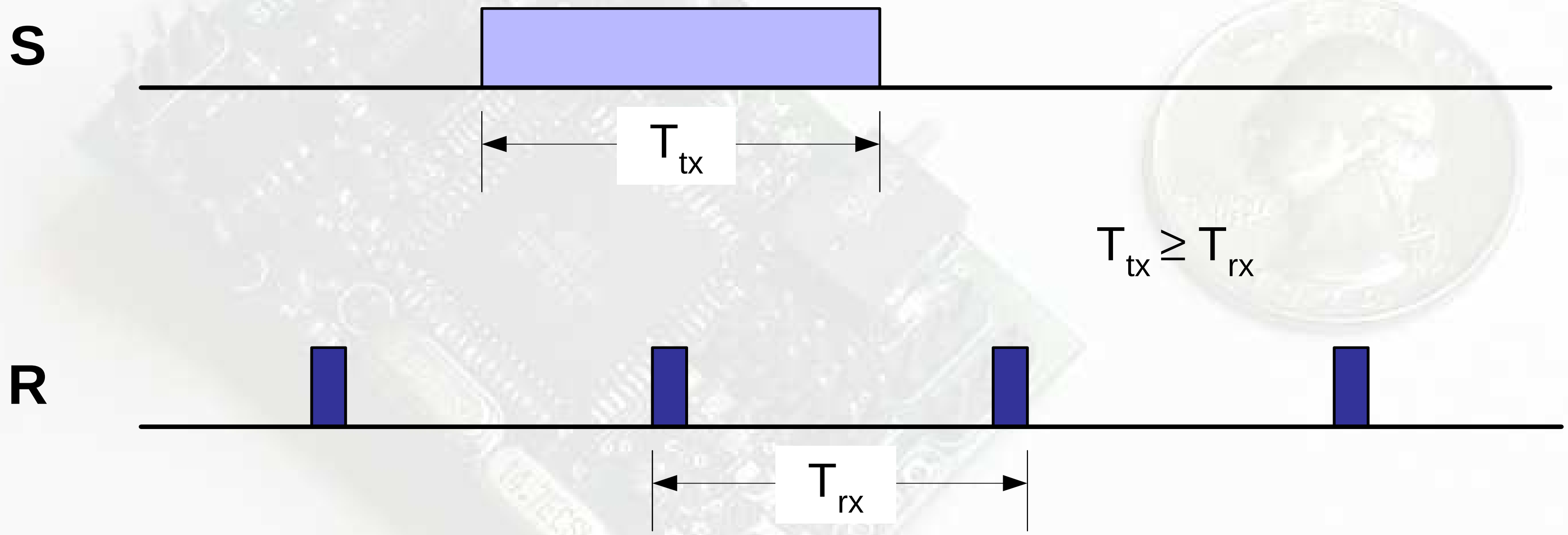
An example of asynchronous schedule based on a symmetric (7,3,1)-design of the wakeup schedule function.

R. Zheng, J. Hou, L. Sha, **Asynchronous Wakeup for Ad Hoc Networks**, Proc. *ACM MobiHoc 2003*, pp 35-45, Annapolis (USA), June 1-3, 2003.

Asynchronous Sender and Periodic Listening

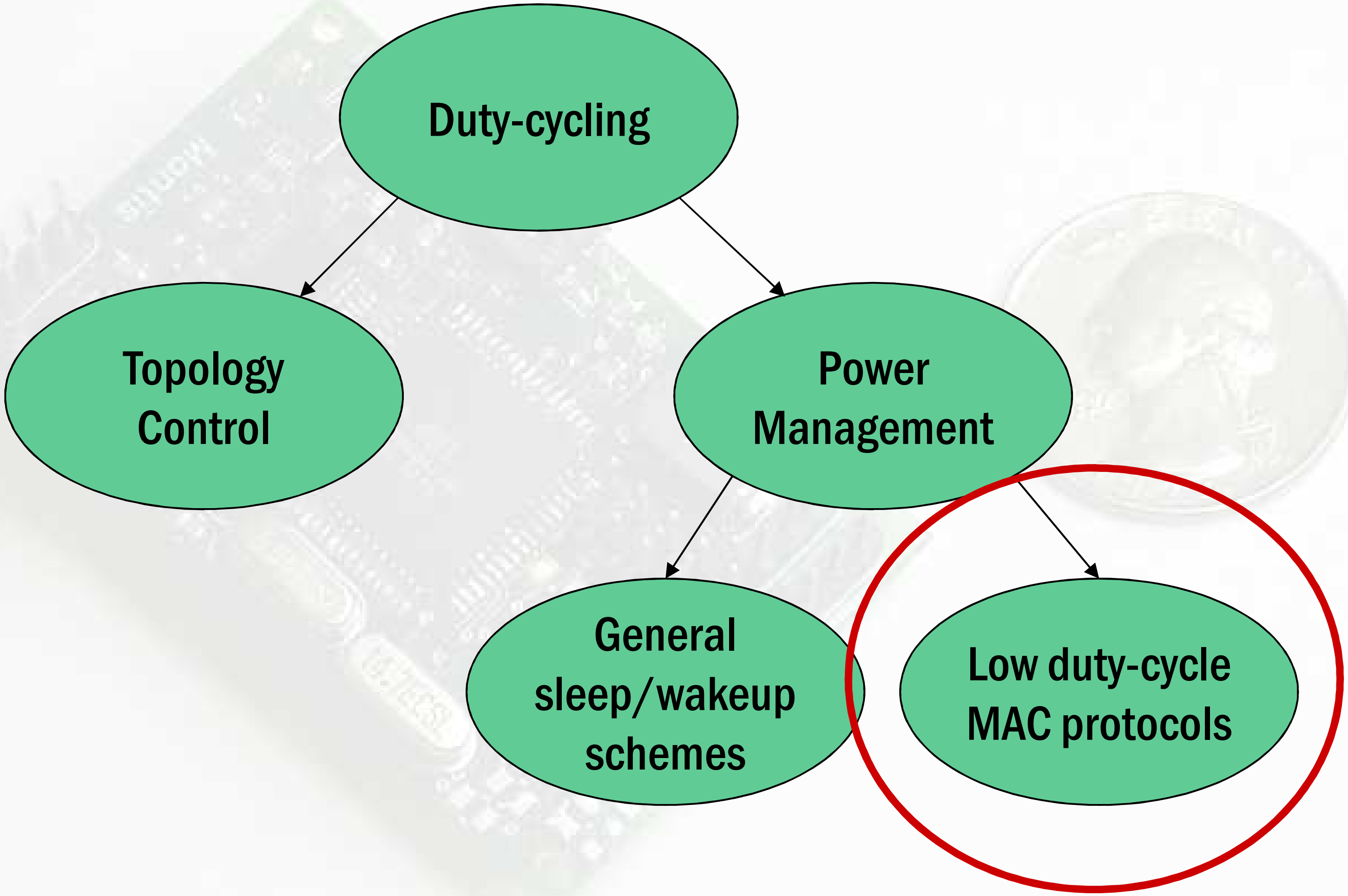


Asynchronous Sender and Periodic Listening



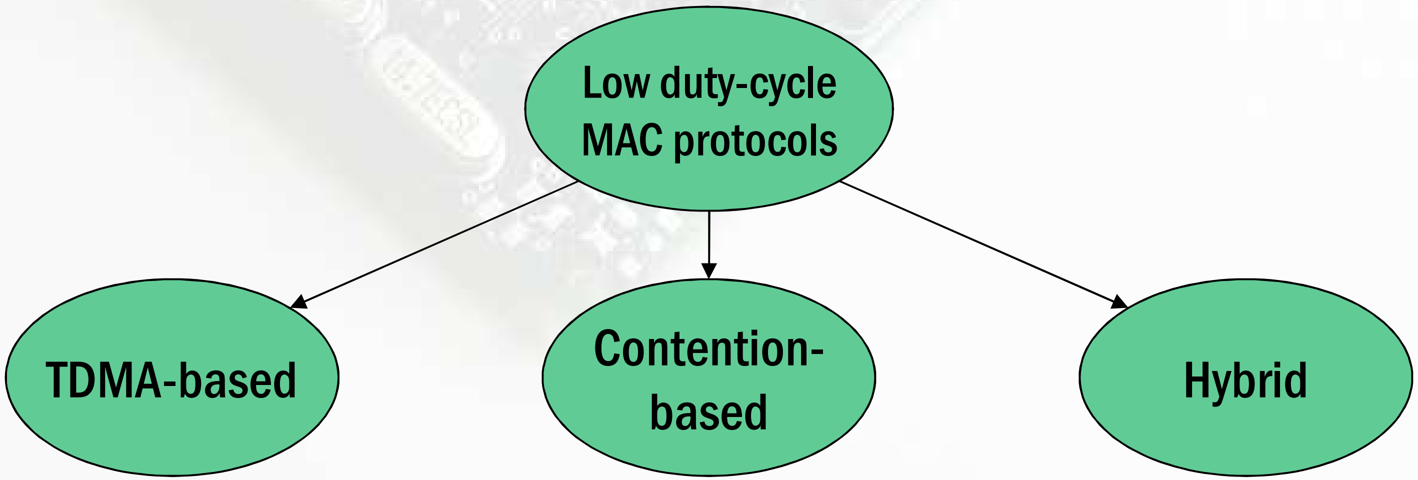
Power Management
Low-duty Cycle MAC Protocols

Power Management



Low duty-cycle MAC protocols

- Embed a duty-cycle within channel access
- TDMA-based (Bluetooth, LEACH, TRAMA)
  - ✓ effective reduction of power consumption
  - ✗ need precise synchronization, lack flexibility
- Contention-based ([B,S,T,D]-MAC, IEEE 802.15.4)
  - ✓ good robustness and scalability
  - ✗ high energy expenditure (collisions, multiple access)
- Hybrid schemes (Z-MAC)
  - switch between TDMA and CSMA based on contention



TDMA-based MAC Protocols

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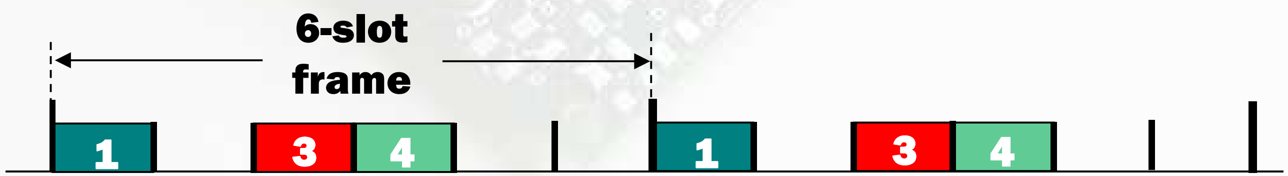
TDMA: Time Division Multiple Access

- access to channel in "rounds"
- each station gets fixed length slot (length = pkt trans time) in each round - Guaranteed Bandwidth
- each station is active only during its own slot, and can sleep during the other slots
- unused slots go idle
- example: 6-station WSN, 1,3,4 have pkt, slots 2,5,6 idle



LEACH

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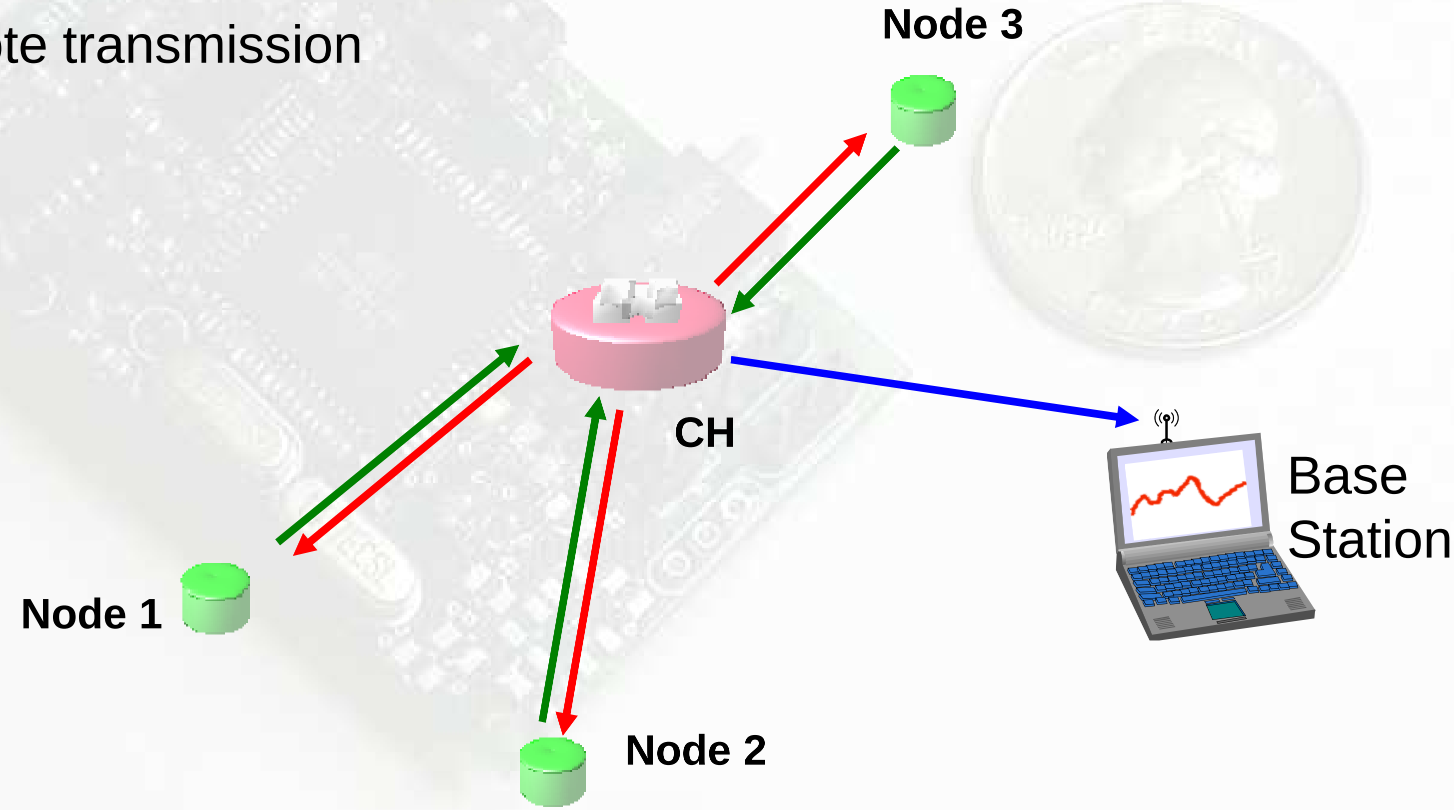
Low Energy Adaptive Clustering Hierarchy

- Nodes are organized in clusters
- A Cluster-Head (CH) for each cluster
  - Coordinates all the activities within the cluster
- Nodes report data to their CH through TDMA
  - Each nodes has a predefined slot
  - Nodes wakeup only during their sleep
- The CH has the highest energy consumption

W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, **Energy-Efficient Communication Protocol for Wireless Microsensor Networks**, Proc. Hawaii International Conference on System Sciences, January, 2000.

LEACH Phases

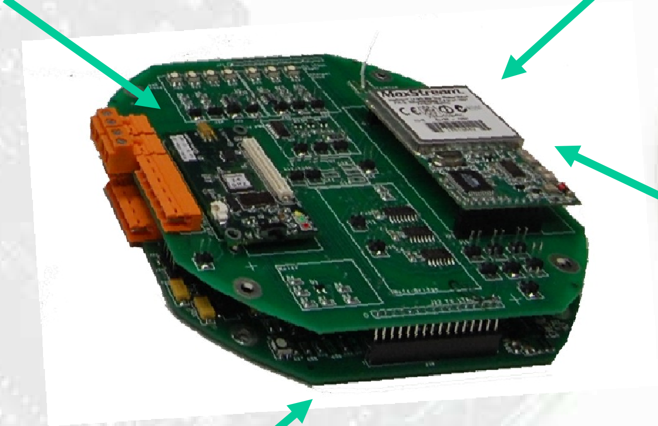
1. Subscription (Cluster Formation)
2. Synchronization
3. TDMA Table update notification
4. Data communication
5. Remote transmission



LEACH-PoliMI

Remote Communication Radio Link

Node-to-node transmission unit



Sensorial control

Energy harvesting board

C. Alippi, R. Camplani, G. Boracchi, M. Roveri, **Wireless Sensor Networks for Monitoring Vineyard, Chapter** in “Methodologies and Technologies for Networked Enterprises” (G. Anastasi, E. Bellini, E. Di Nitto, C. Ghezzi, L. Tanca, E. Zimeo Editors), in preparation.

Hierarchical LEACH

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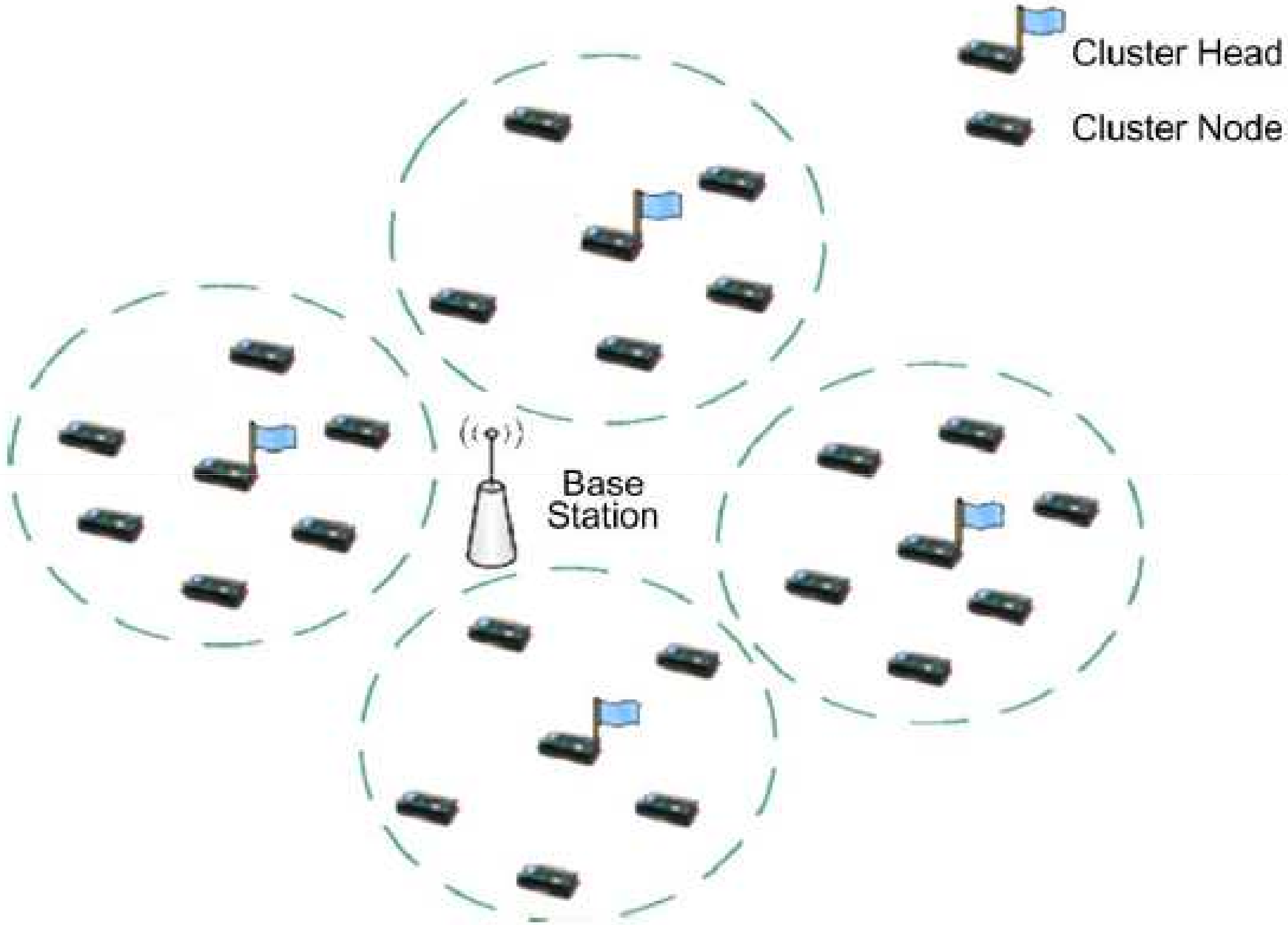

Cluster Heads also use a TDMA approach for sending data received from Cluster Nodes to the Base Station

TDMA-based MAC Protocols: Summary

- High energy efficiency
  - Nodes are active only during their slots
  - Minimum energy consumption without extra overhead
- Limited Flexibility
  - A topology change may require a different slot allocation pattern
- Limited Scalability
  - Finding a scalable slot allocation function is not trivial, especially in multi-hop (i.e., hierarchical) networks
- Interference prone
  - Finding an interference-free schedule may be hard
  - The interference range is larger than the transmission range
- Tight Synchronization Required
  - Clock synch introduces overhead

CSMA-based MAC Protocols

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- No synchronization required
  - Robustness
  - Synch may be needed for power management
- Large Flexibility
  - A topology change do not require any re-configuration or schedule update notification
- Limited Scalability
  - A large number of nodes can cause a large number of collisions and retransmissions
- Low Energy Efficiency
  - Nodes may conflict
  - Energy consumed for overhearing

IEEE 802.15.4/ZigBee standard

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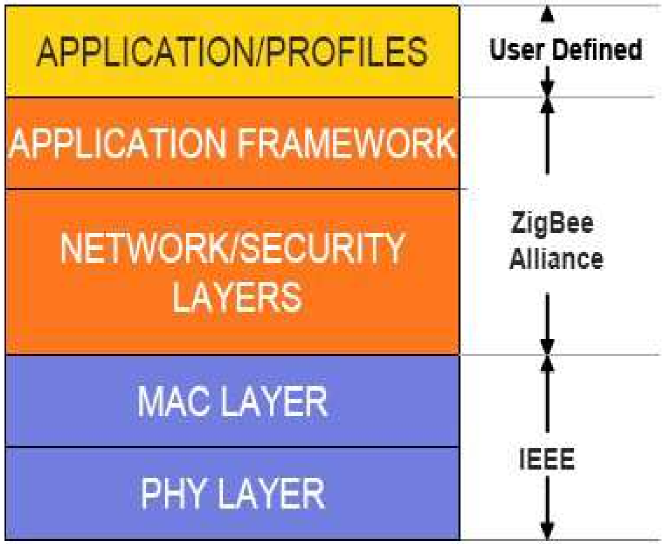
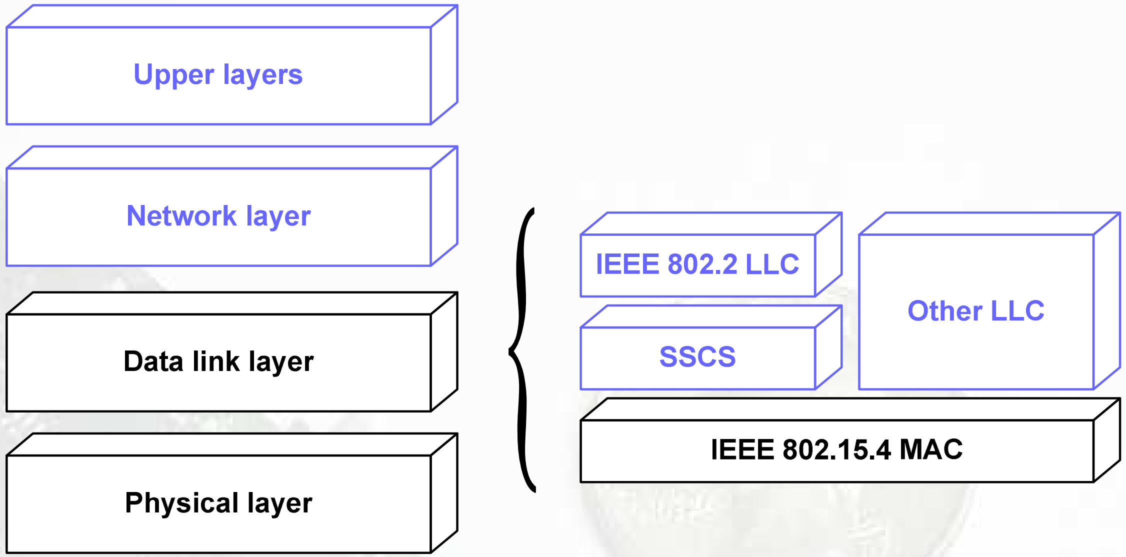
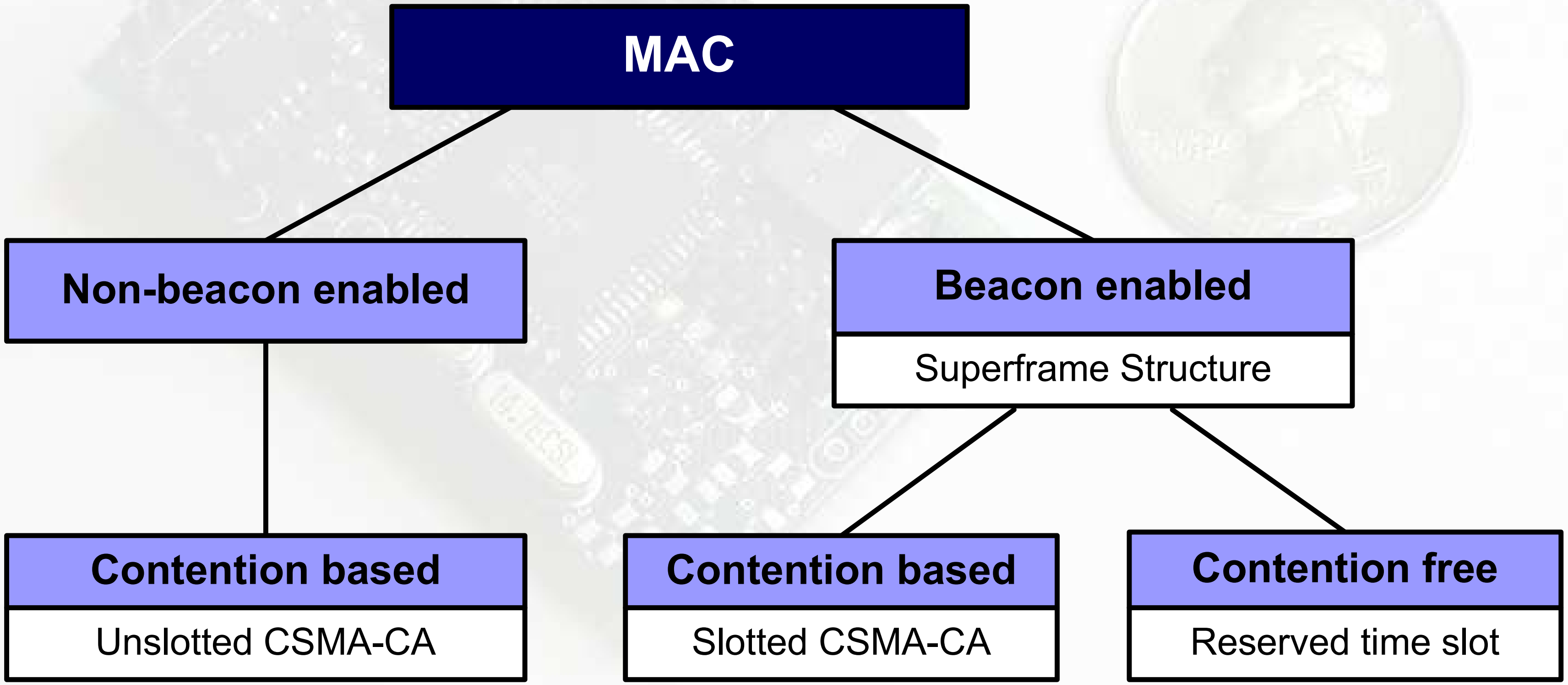




- IEEE 802.15.4
  - Standard for low-rate and low-power PANs
  - PHY and MAC layers
    - ⇨ transceiver management, channel access, PAN management
- ZigBee Specifications
  - Network/security layer
  - Application framework

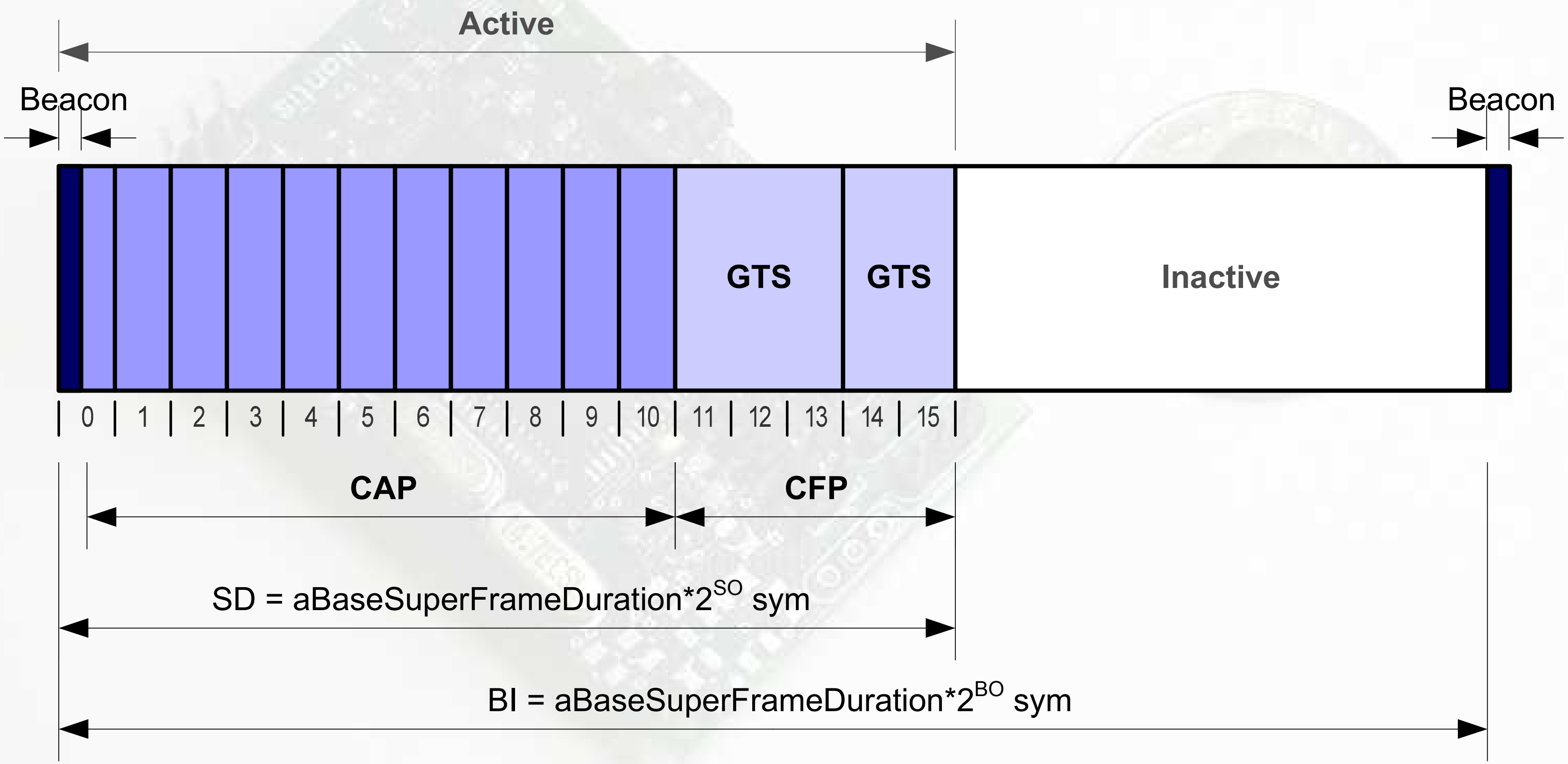
IEEE 802.15.4: MAC protocol

- Two different channel access methods
  - Beacon-Enabled duty-cycled mode
  - Non-Beacon Enabled mode (aka Beacon Disabled mode)

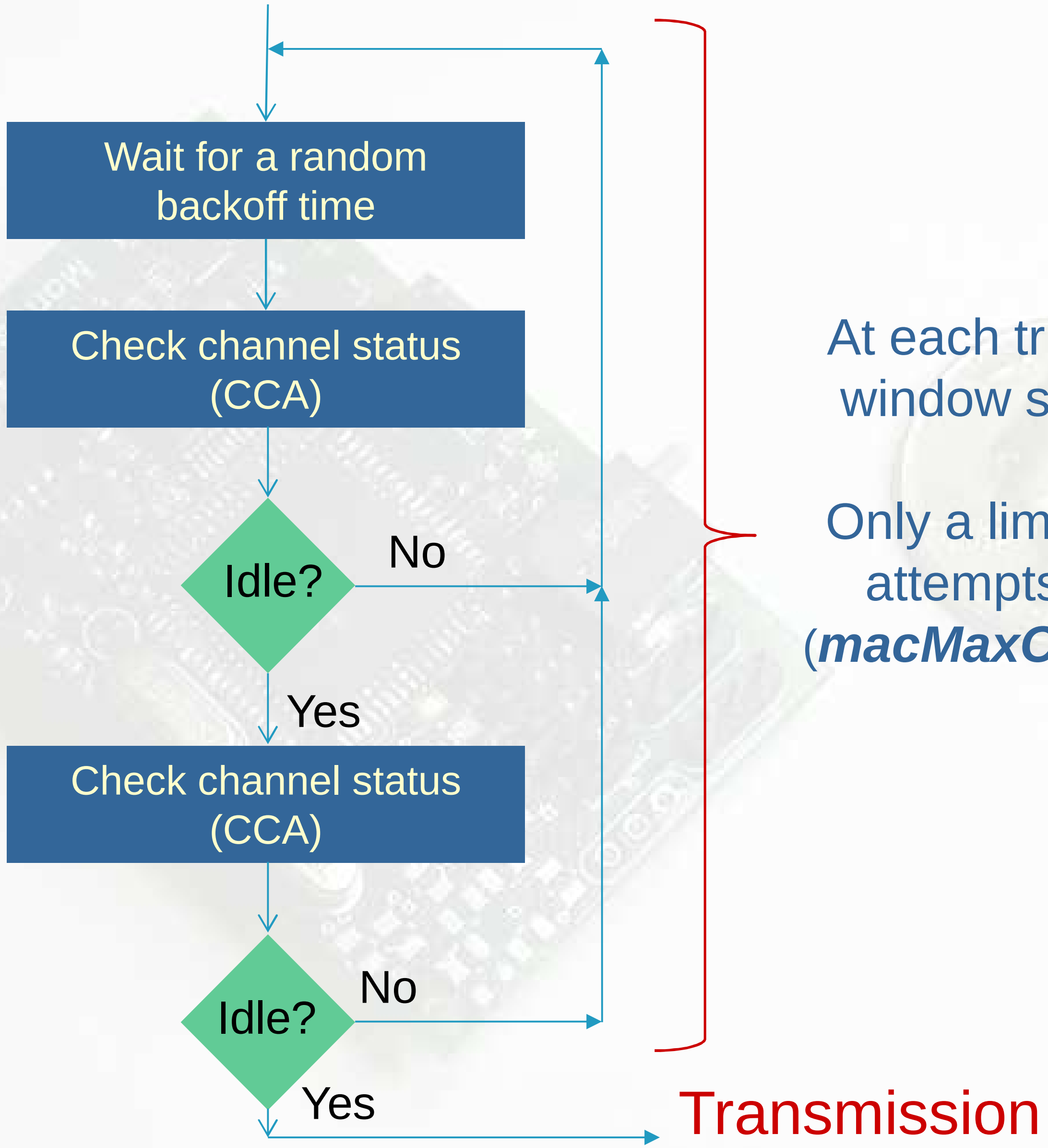


IEEE 802.15.4: Beacon Enabled mode

PerLab



CSMA/CA: Beacon-enabled mode



At each trial the 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 backoff window size is re-initialized
  - Only a maximum number of retransmissions allowed (*macMaxFrameRetries*)

IEEE 802.15.4: MAC protocol

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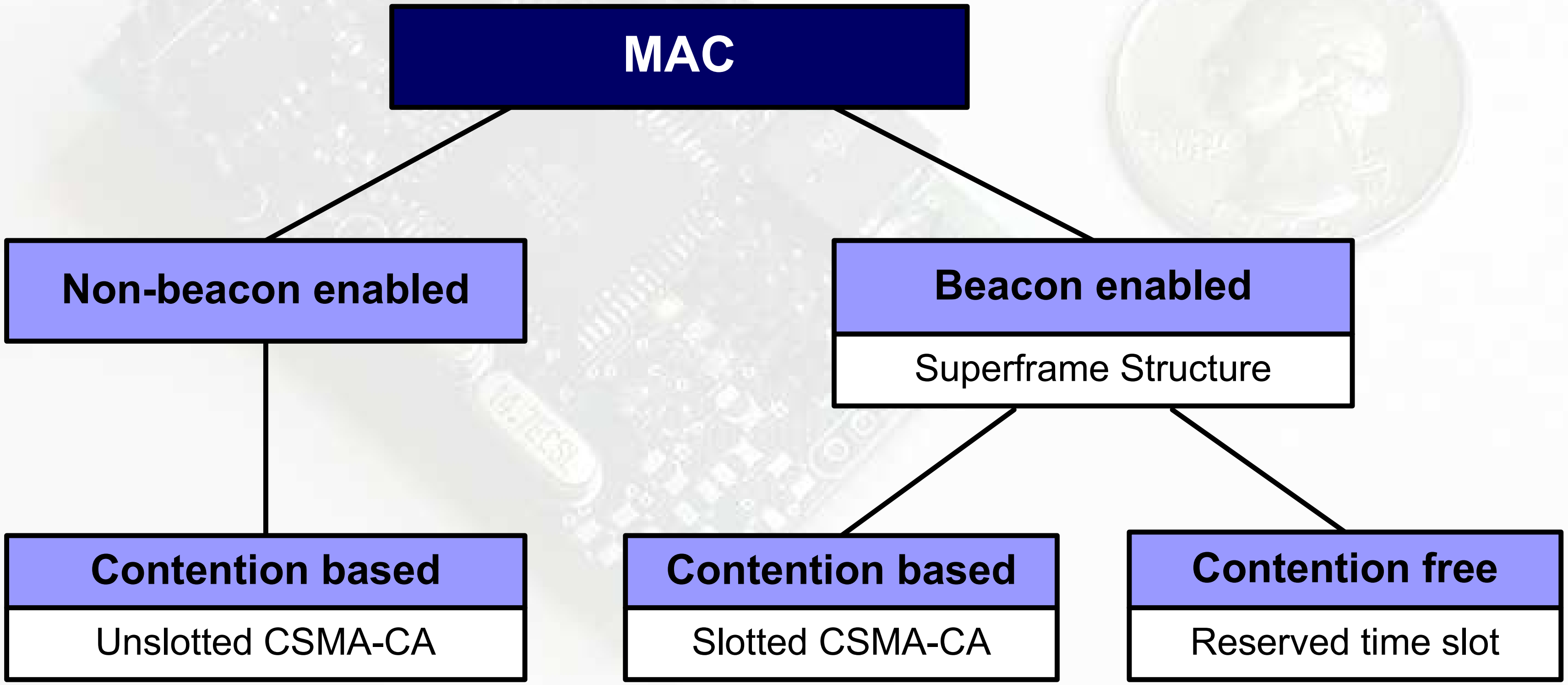
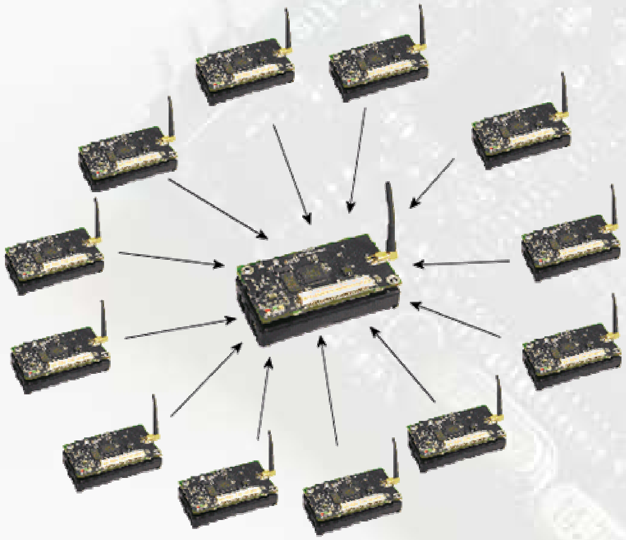
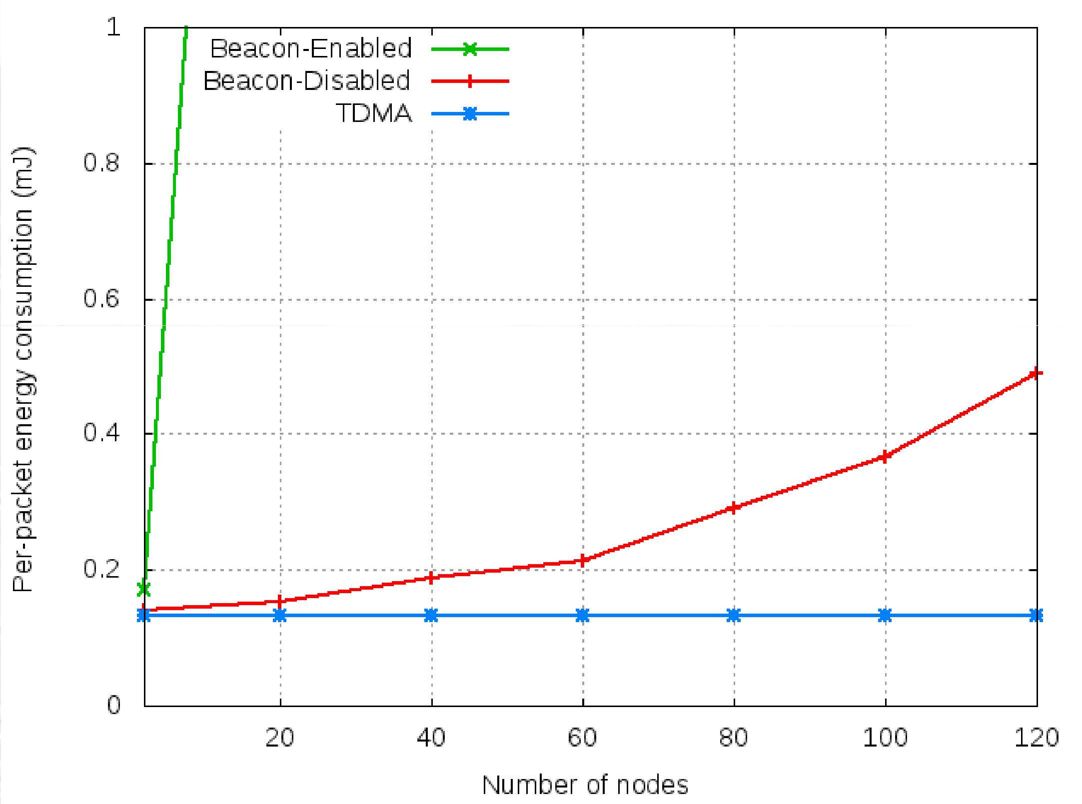
- Two different channel access methods
  - Beacon-Enabled duty-cycled mode
  - Non-Beacon Enabled mode (aka Beacon Disabled mode)

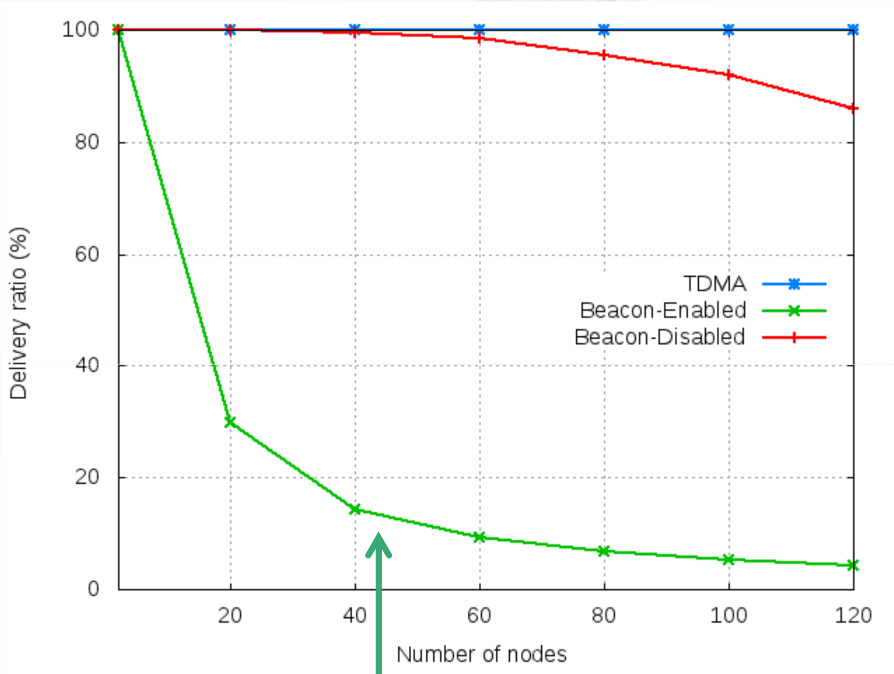


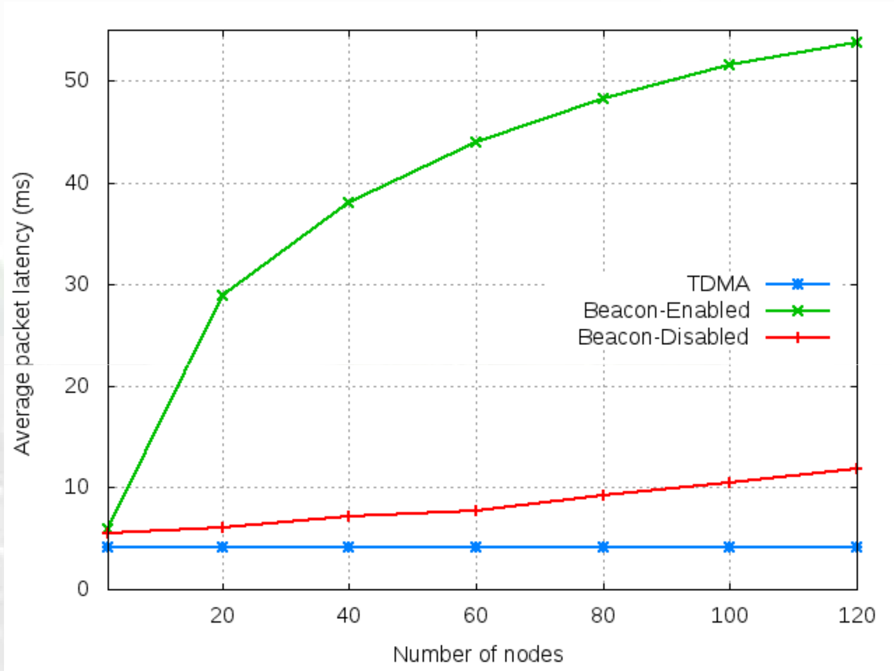
Comparison between BE and BD





Comparison between BE and BD





MAC Unreliability Problem in IEEE 802.15.4 Beacon-Enabled MAC Protocol

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.

MAC with asynchronous PM

- 802.15.4 Non-Beacon Enabled
  - Asynchronous: nodes can wake up and transmit at any time
    - ⇨ Possible conflicts are regulated by CSMA/CA
  - It assumes that the destination is always ON
    - ⇨ The destination may be either the sink or a ZigBee router
  - This is a strong limitation

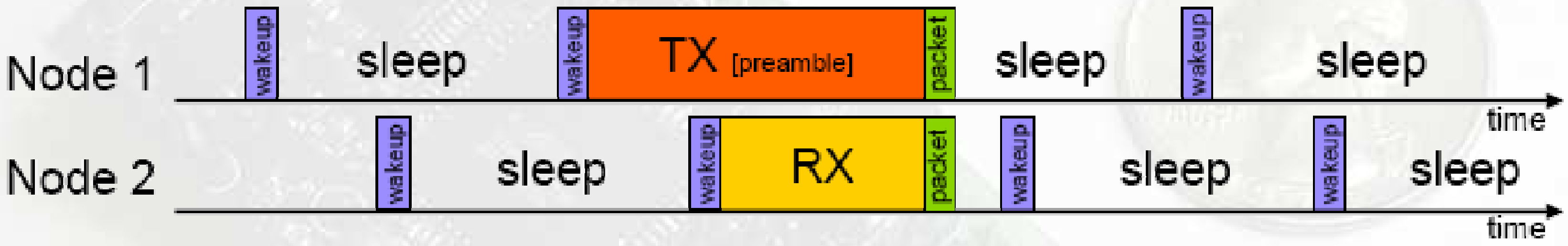
B-MAC with Low-power Listening

PerLab

- Availability
  - Designed before IEEE 802.15 MAC (at UCB)
  - Shipped with the TinyOS operating system
- B-MAC design considerations
  - simplicity
  - configurable options
  - minimize idle listening (to save energy)
- B-MAC components
  - CSMA (without RTS/CTS)
  - optional low-power listening (LPL)
  - optional acknowledgements

B-MAC Low-power Listening mode

- Nodes periodically sleep and perform LPL
- Nodes do not synchronized on listen time
- Sender uses a long preamble before each packet to wake up the receiver

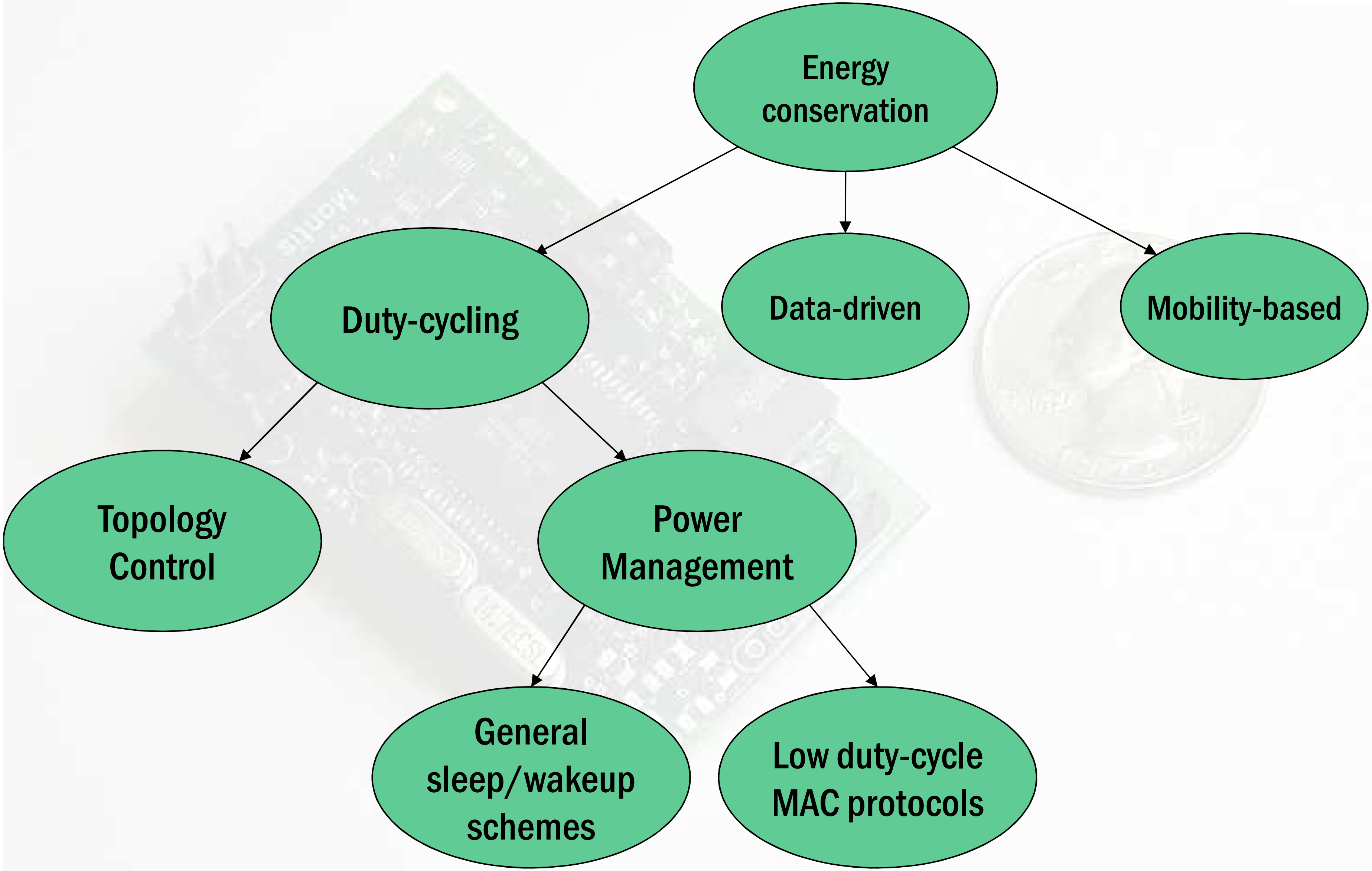


Constraint: check interval ≤ preamble duration

- Shift most burden to the sender
- Every transmission wakes up all neighbors
  - presence of chatty neighbor leads to energy drain in dense networks
- Preambles can be really long!

Conclusions
&
Research Key Questions

Summary



Energy conservation
Duty-cycling
Data-driven
Mobility-based
Topology Control
Power Management
General sleep/wakeup schemes
Low duty-cycle MAC protocols

Key Research Questions

PerLab

- Data-driven approaches can significantly reduce the amount of data to be transmitted
  - Up to 99% and beyond
- However, this does not necessarily result in energy consumption reduction, due to
  - Energy costs introduced by transmission overhead, network management
  - Additional costs due to communication reliability

Are they really useful in practice?

Key Research Questions

- Topology Management exploits node redundancy
  - The increase in the network lifetime depends on the actual redundancy, and is limited in practice (some %)
  - It allows a longer lifetime at the cost of increased redundancy (i.e., larger economic costs)

Key Research Questions

- Power Management eliminates idle times
  - May provide very large energy reductions, with limited costs (in terms of additional complexity)
  - Energy Efficiency vs. Robustness
    - ⇨ Simple approaches → high robustness/limited energy efficiency
    - ⇨ Complex approaches → higher energy efficiency but less robustness
    - ⇨ Very complex solutions cannot work in practice

Key Research Questions

PerLab

- General (i.e., application-layer) sleep/wakeup schemes or MAC-layer schemes?
- And which MAC protocol?
  - TDMA or contention-based (802.15.4, B-MAC)?
  - IEEE 802.15.4: BE or BD?
  - ...

Key Research Questions

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- Is the radio the most consuming component?

Radio	Producer	Power Consumption	
		Transm.	Reception
JN-DS-JN513x (Jennic)	Jennic	111 mW (1 dBm)	111 mW
CC2420 (Telos)	Texas Instruments	31 mW (0 dBm)	35 mW
CC1000 (Mica2/Mica2 dot)	Texas Instruments	42 mW (0 dBm)	29 mW
TR1000 (Mica)	RF Monolithics	36 mW (0 dBm)	9 mW

Sensor	Producer	Sensing	Power Cons.
STCN75	STM	Temperature	0.4 mW
QST108KT6	STM	Touch	7 mW
iMEMS	ADI	Accelerometer (3 axis)	30 mW
2200 Series, 2600 Series	GEMS	Pressure	50 mW
T150	GEFRAN	Humidity	90 mW
LUC-M10	PEPPERL+FUCHS	Level Sensor	300 mW
CP18, VL18, GM60, GLV30	VISOLUX	Proximity	350 mW
TDA0161	STM	Proximity	420 mW
FCS-GL1/2A4-AP8X-H1141	TURCK	Flow Control	1250 mW

C. Alippi, G. Anastasi, M. Di Francesco, M. Roveri, **Energy Management in Sensor Networks with Energy-hungry Sensors**, *IEEE Instrumentation and Measurement Magazine, Vol. 12, N. 2, April 2009*

Key Research Questions

PerLab

- Power Management or Energy Harvesting?
  - Power management reduces energy consumption, while energy harvesting captures energy

Are they really alternative approaches?

Key Research Questions

- When using energy harvesting the WSN protocols and applications can take advantage of the available energy

How to maximize the WSN performance while guaranteeing perpetual operations (i.e., infinite lifetime)?

References

- G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, **Energy Conservation in Wireless Sensor Networks: a Survey**, *Ad Hoc Networks*, Vol. 7, N. 3, pp. 537-568, May 2009. Elsevier.
- C. Alippi, G. Anastasi, M. Di Francesco, M. Roveri, **Energy Management in Sensor Networks with Energy-hungry Sensors**, *IEEE Instrumentation and Measurement Magazine*, Vol. 12, N. 2, pp. 16-23, April 2009.
- M. Di Francesco, S. Das, G. Anastasi, **Data Collection in Wireless Sensor Networks with Mobile Elements: A Survey**, *ACM Transactions on Sensor Networks,* Vol. 8, N.1, August 2011.

Available at

http://www.iet.unipi.it/~anastasi/

Comments or Questions?