Energy Management

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Overview

- The Energy Problem
- Energy Harvesting
- Energy conservation
  - Main approaches
- Data-driven approaches
- Topology Management
- Power Management

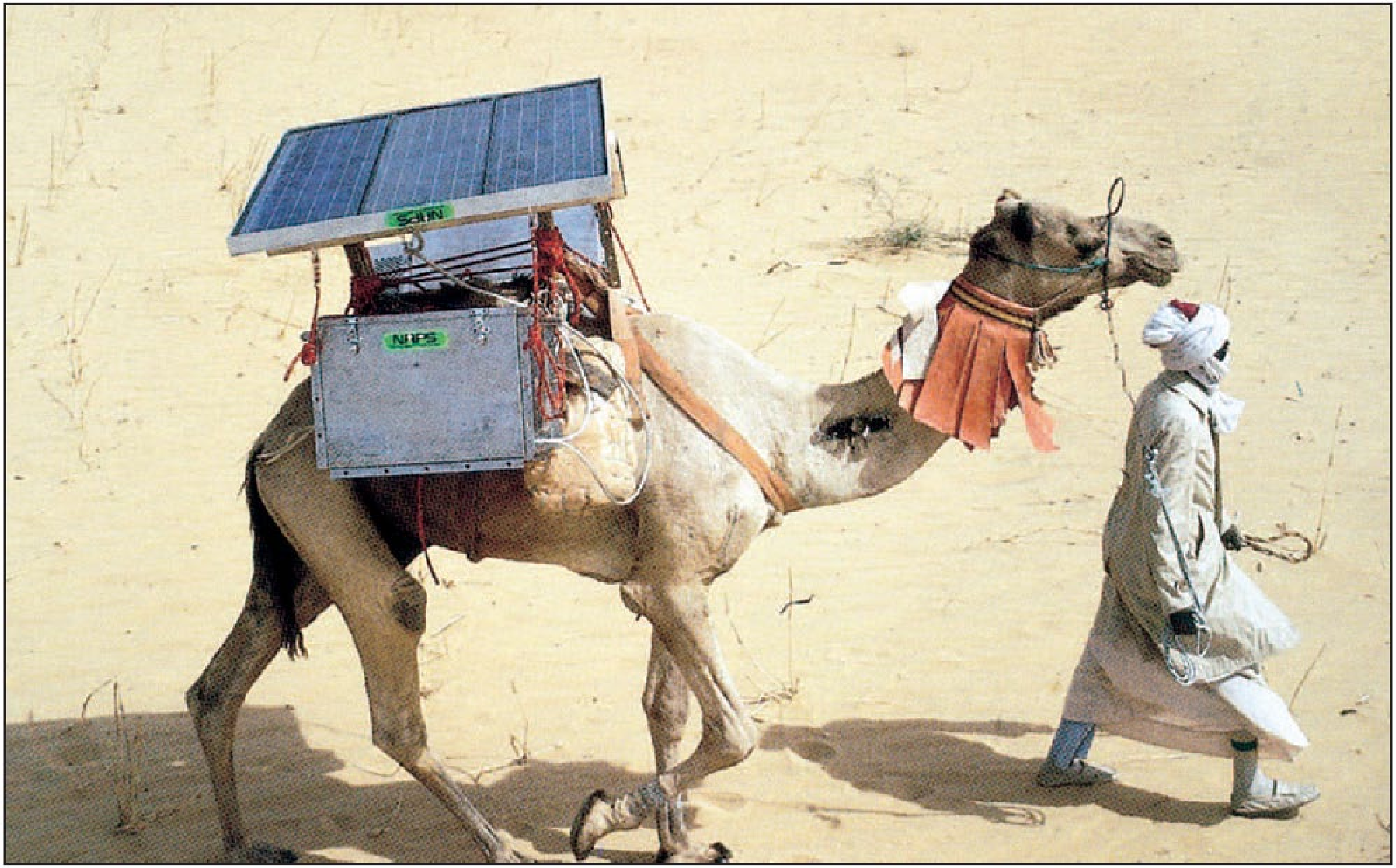
The Energy Problem

The energy problem

- **Energy is the key issue in the LLN design**
  - Applications may require a network lifetime in the order of many months or, even, several years
  - If always active, nodes deplete their energy in less than a week
- **Possible approaches**
  - Low-power devices
  - Energy harvesting
  - Energy conservation
  - Energy efficient protocols/applications
  - Cross-layering
  - …

Energy Harvesting

Energy harvesting is an old problem



The "Camel Fridge." Camels wearing solar-powered refrigeration units helped deliver vaccines to remote African villages in the 1980s. (photo courtesy Naps Systems)

Jan Krikke, **Sunrise for Energy Harvesting Products**, *IEEE Pervasive Computing,* Vol. 4, N. 1, Jan-Mar 2005

Energy harvesting is an old problem

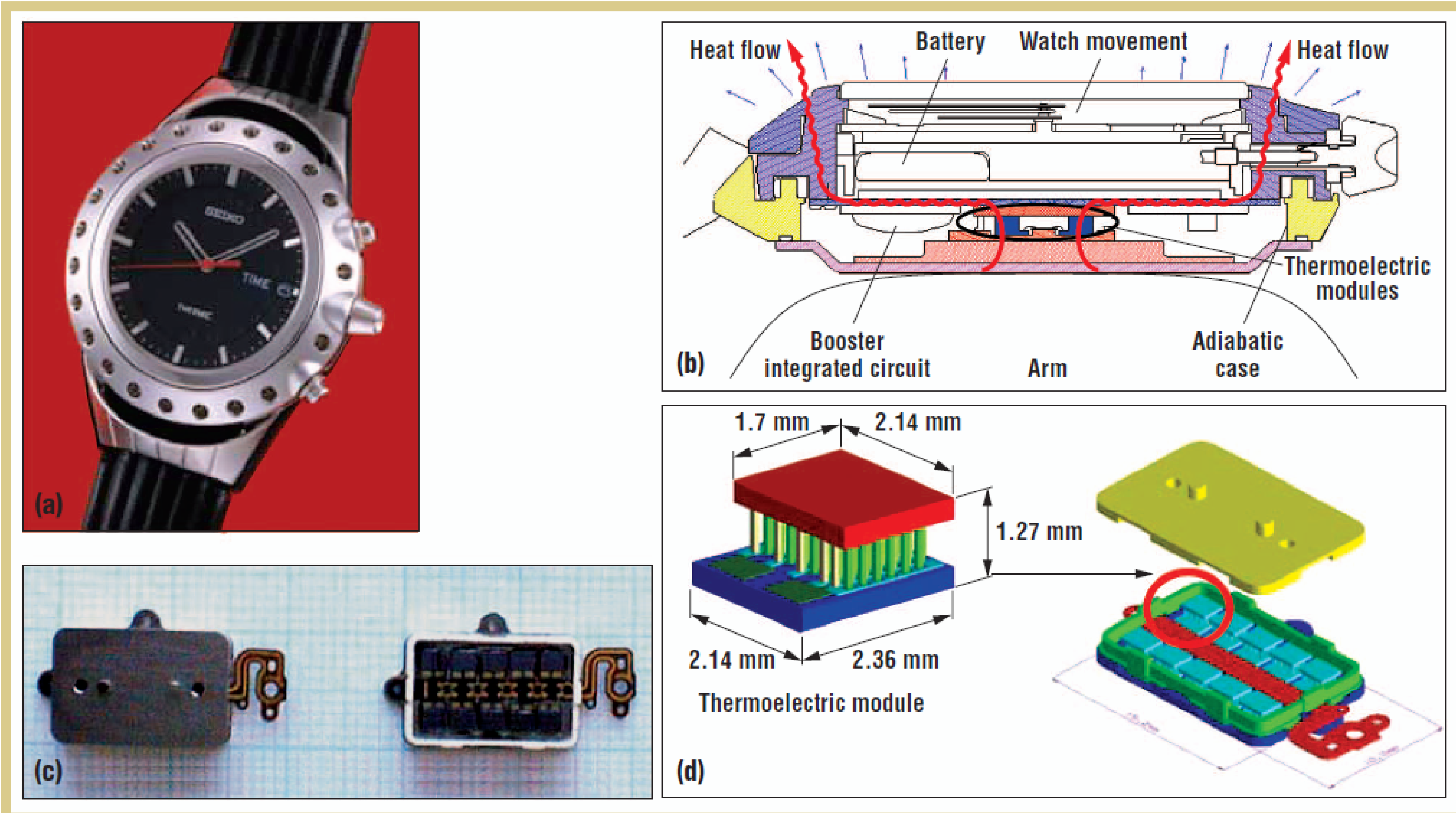


Figure 2. The Seiko Thermic wristwatch: (a) the product; (b) a cross-sectional diagram; (c) thermoelectric modules; (d) a thermopile array. Copyright by Seiko Instruments.

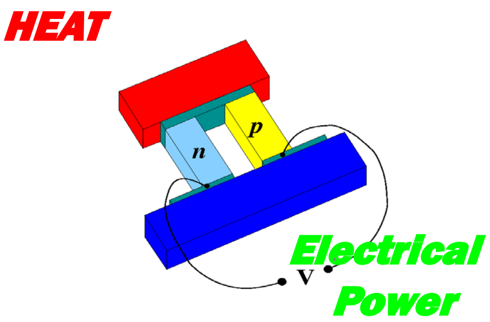
J. Paradiso, T Starner, **Energy Scavenging for Mobile and Wireless Electronics**, *IEEE Pervasive Computing,* Vol. 4, N. 1, Jan-Mar 2005

How to scavenge energy?

- **Thermal gradients**
  - Based on the Carnot cycle
  - The conversion efficiency is the main problem
    - ⇨ especially when the thermal gradient is small.
  - Can be used for wearable sensor nodes
  - Unsuitable for sensor networks deployed in a sensing area

How to scavenge energy?

- **Thermoelectric generators (TGs)**
  - Direct conversion of heat in electrical power
  - Potential applications
    - ⇨ Solar concentration
    - ⇨ Recovery of residual waste heat in industrial processes
    - ⇨ Heat pumps
    - ⇨ Spatial applications (for interplanetary missions)
  - Problems
    - ⇨ Efficiency is limited to few percent (3-4 %), due to the high thermal conductivity of conventional materials

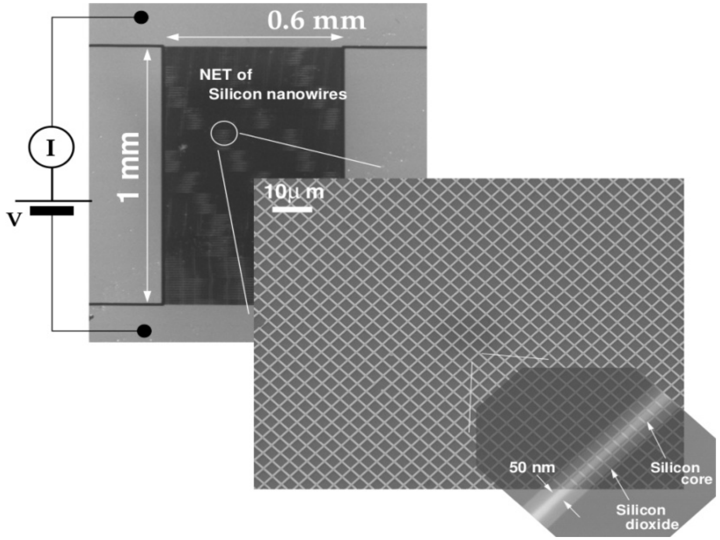


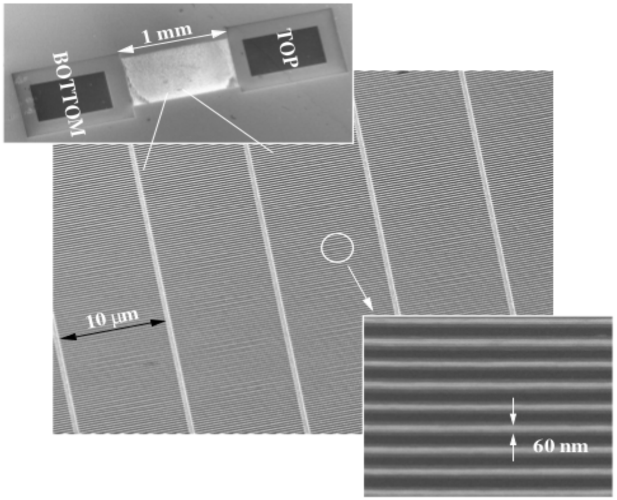
- **Nano-structured Thermoelectric Generators**
  - Reduced Thermal Conductivity
    - ⇨ Bulk silicon: 148 W/mK
    - ⇨ Silicon nanowires: 1 W/mK
  - Expected Efficiency : up to 30 %

How to scavenge energy?

Nanofabrication Lab

- NanoPOL Project
  - Funded by Regione Toscana
  - Nano-structured Thermoelectric Generator for solar energy conversion





  - Exploitation in many potential scenarios, including WSNs

How to scavenge energy?

PerLab

- **Radioactivity**
  - Radioactivity been proposed as a source of energy for small devices.
    - ⇨ The limited size of the radiating material avoids safety and health problems
  - This technology is particularly suitable for devices operating with very limited power (i.e., tens of μW) for very long times

CROSSLAB Innovation for industry 4.0

How to scavenge energy?

- **Kinetic energy**
  - winding wristwatches date back a long ago, as they have been diffused since 1930s.
  - More recently (1997), the same principle has been used to build windup radios to be used when battery availability is an issue
  - Finally, it has also been proposed to harvest energy by heel strikes when people walk.
    - ⇨ It has been proved that this approach can produce an average power in the order of 250-700 mW, thus representing a very promising direction.

Ambulatory Power Generation

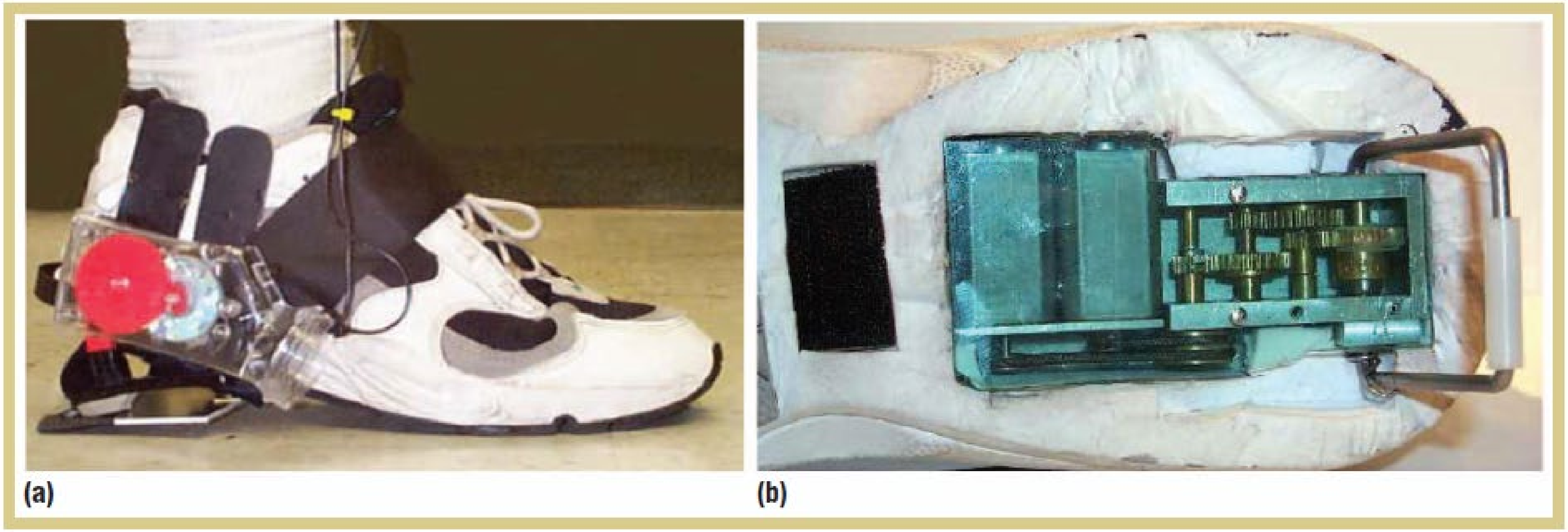


Figure 6. Magnetic generators in shoes at the MIT Media Lab: (a) A strap-on overshoe produced an average of 250 mW during a standard walk, powering a loud radio; (b) an assembly hosting twin motor-generators and step-up gears embedded directly into a sneaker's sole (without springs or flywheels for energy storage) produced 60 mW.

J. Paradiso, T Starner, **Energy Scavenging for Mobile and Wireless Electronics**, *IEEE Pervasive Computing,* Vol. 4, N. 1, Jan-Mar 2005

How to scavenge energy?

- **Radio Frequency (RF) signals**
  - RFID exploit this approach
  - Wireless Energy Transfer used for feeding sensor nodes
    - ⇨ Both one-hop and multi-hop energy transfer
    - ⇨ Very short distance required

Wireless Energy Transfer

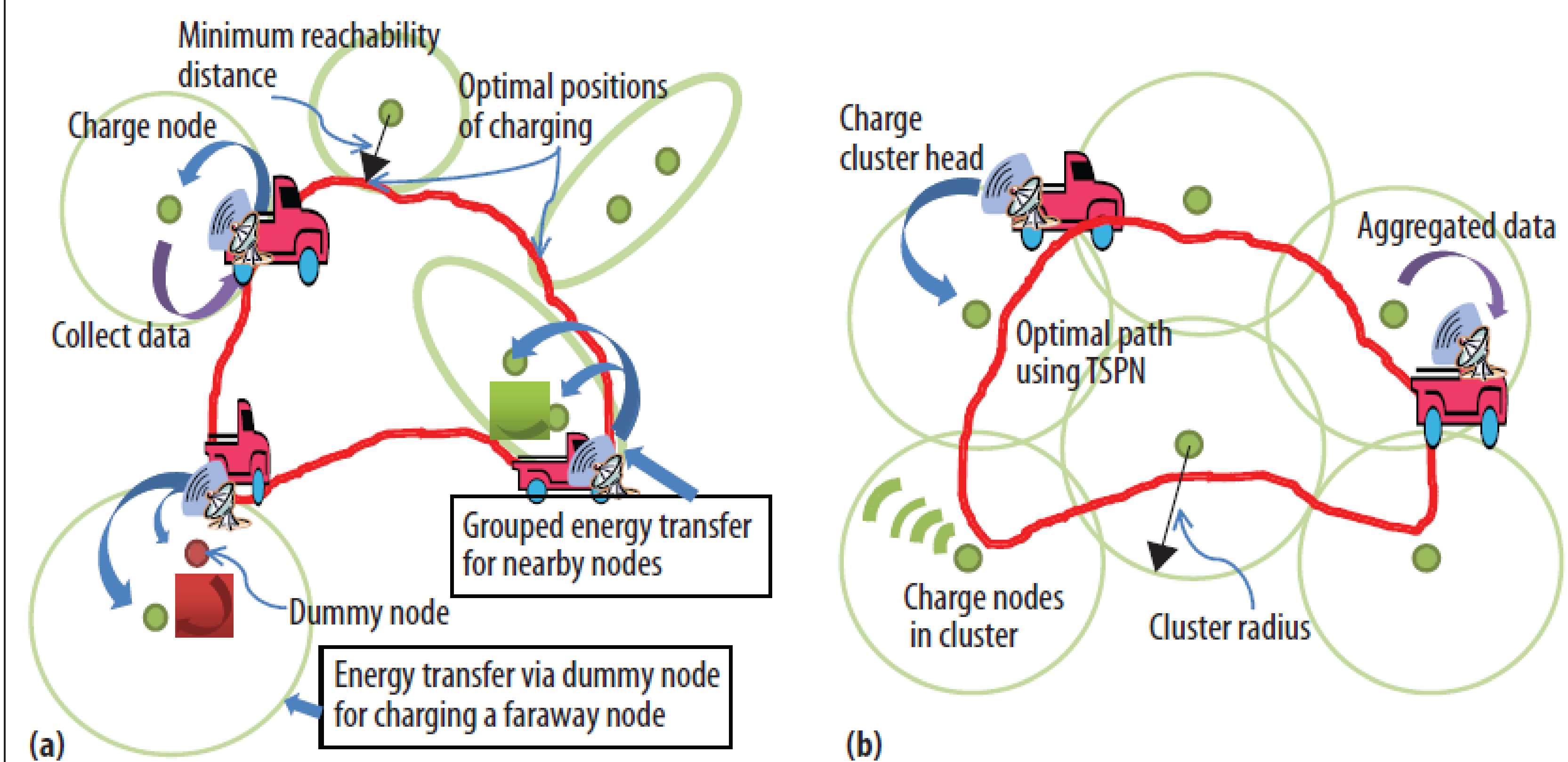


Figure 1. Examples of energy transfer and data collection with integrated data and energy mules (IDEMs) in (a) a flat network topology and (b) a clustered network topology.

S. De, R. Singhal, **Towards Uninterrupted Operation of Wireless Sensor Networks**, *IEEE Computer*, September 2012.

How to scavenge energy?

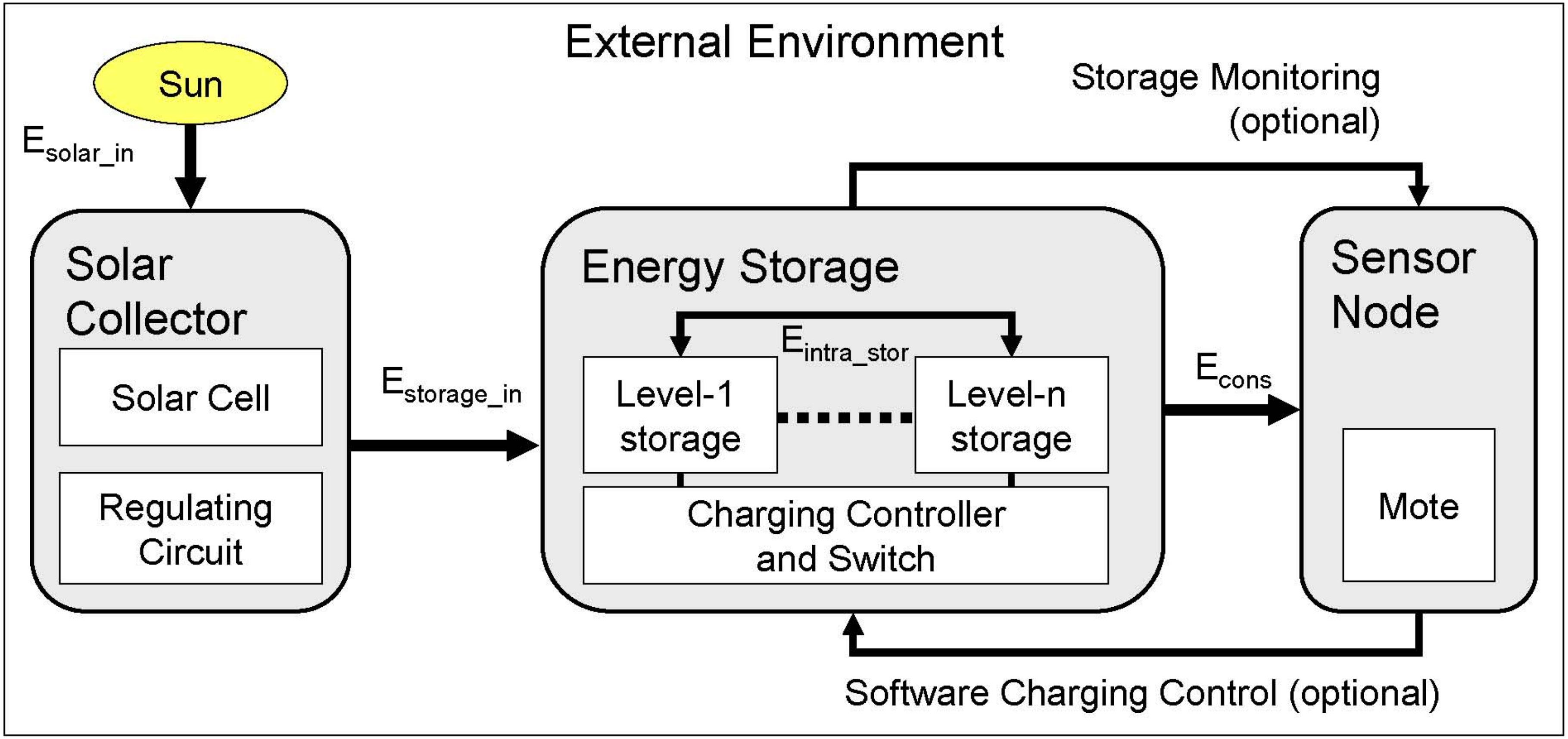
- **Vibration energy**
  - Vibrations can be converted through piezoelectric materials
    - ⇨ Suitable for deployments in bridges, vehicles, …
  - It has been possible to feed an off-the-shelf Mica2Dot Mote
    - ⇨ operating at a 1% duty cycle just by means of such a technique

How to scavenge energy?

- **Solar cells**
  - current technology allows conversion efficiency just between 10% and 30%
  - In many applications domains can replace batteries
  - Limits
    - ⇨ Sunlight not available everywhere
    - ⇨ Dust over the panel can decrease the conversion efficiency

    …

Solar Power Sensor Nodes



Helio Mote

- **Developed at NESL (UCLA)**
  - the system learn its own energy environment and adapt its power consumption accordingly.
  - not only the energy source varies over time, but also the energy available at different locations
    - ⇨ different nodes of the sensor network differs.
  - Tasks scheduled according to the spatio-temporal characteristics of energy availability.
    - ⇨ How adapt performance to energy availability?

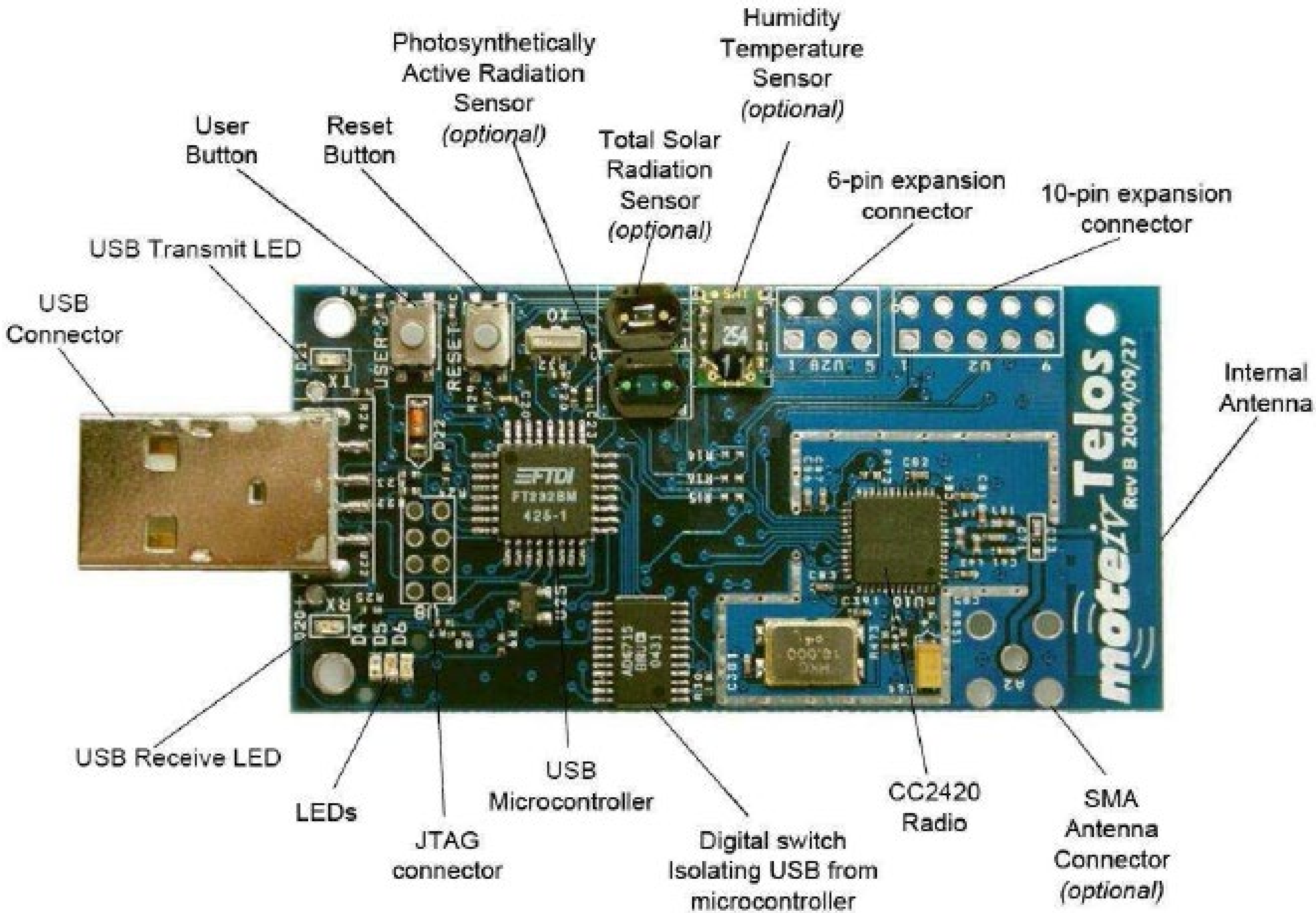
http://nesl.ee.ucla.edu/project/show/24

Concluding remarks

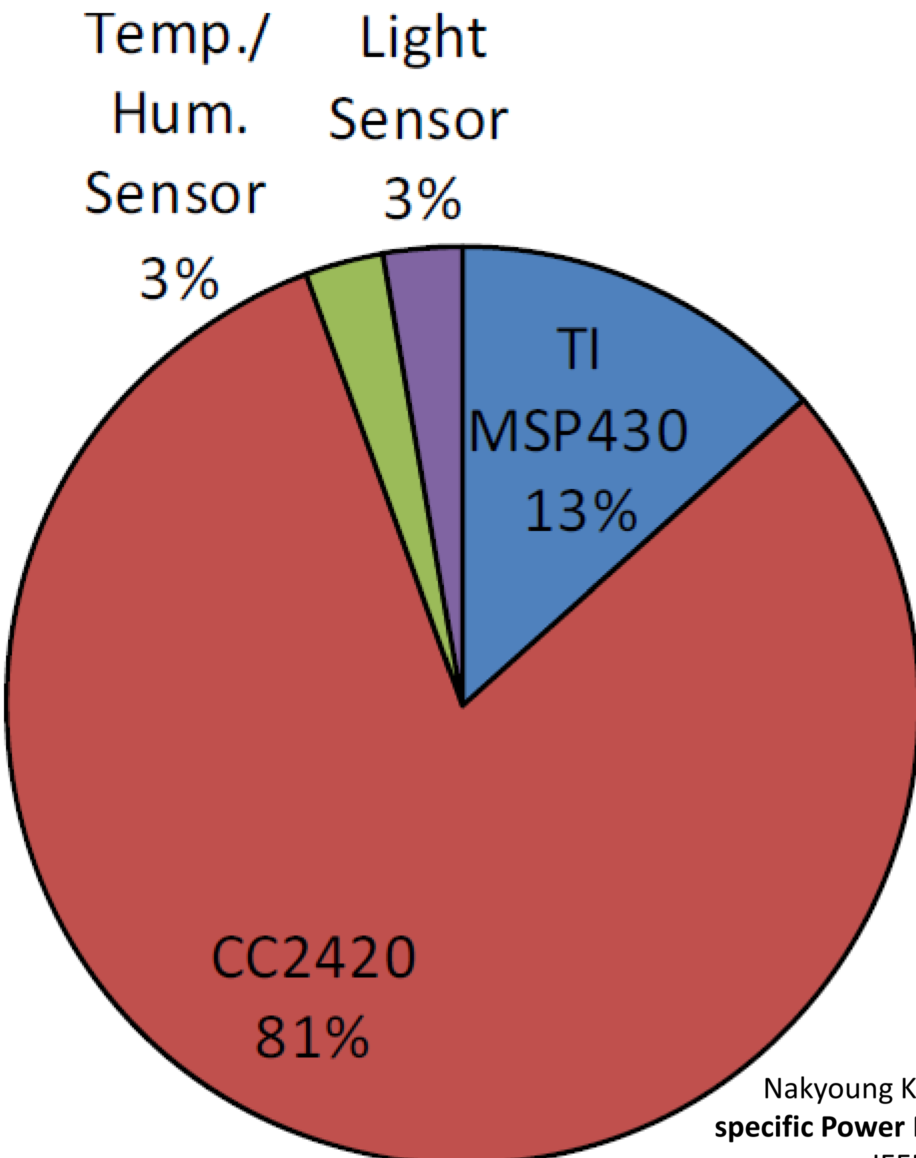
- **Energy harvesting is a very promising approach**
  - But, currently the conversion process is not efficient enough
- **Can be used to power**
  - very simple devices
  - as a complementary power source, e.g., to replenish a battery in the background.
- ***Energy* that can be collected is virtually infinite**
  - However, available power is quite limited
- **Even when using energy scavenging**
  - energetic resources are limited and must be used judiciously
  - Energy harvesting and energy conservation must be used jointly

Energy Conservation

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

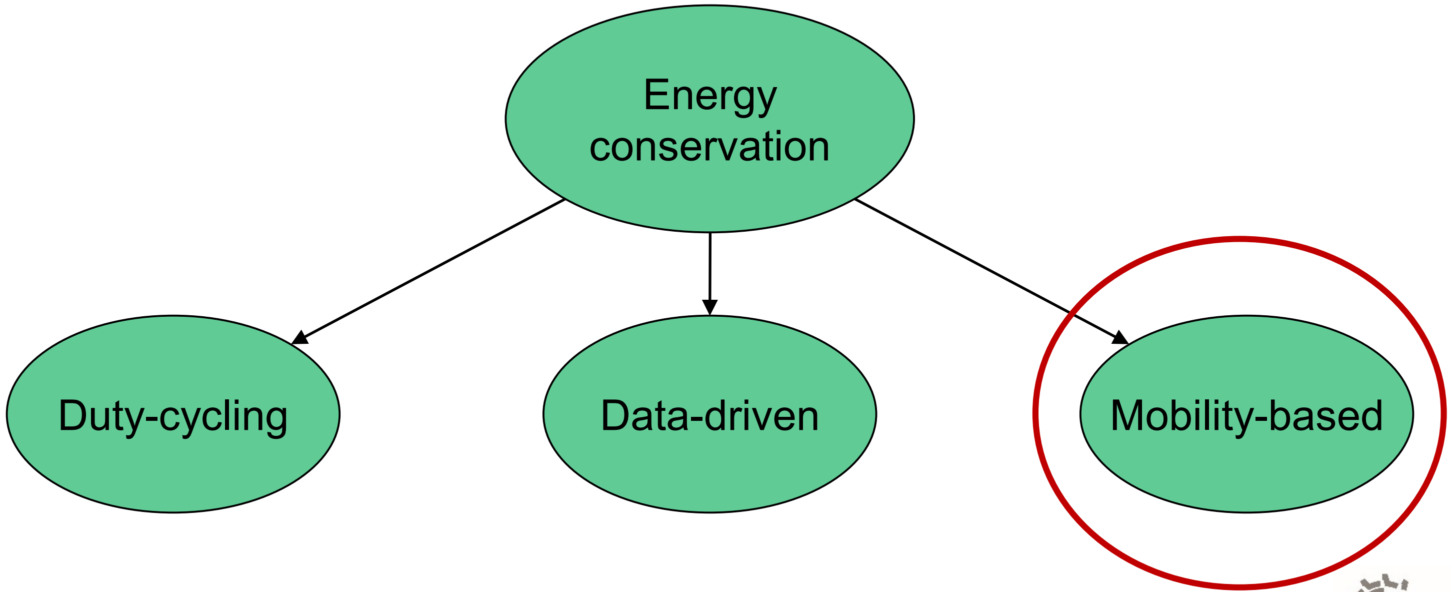
Mode	Current	Power Consumption
Reception	19.7 mA	35.46 mW
Transmission	17.4 mA	31.32 mW
Idle	0.426 mA	0.77 mW
Sleep	20 μA	36 μW

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

- **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.

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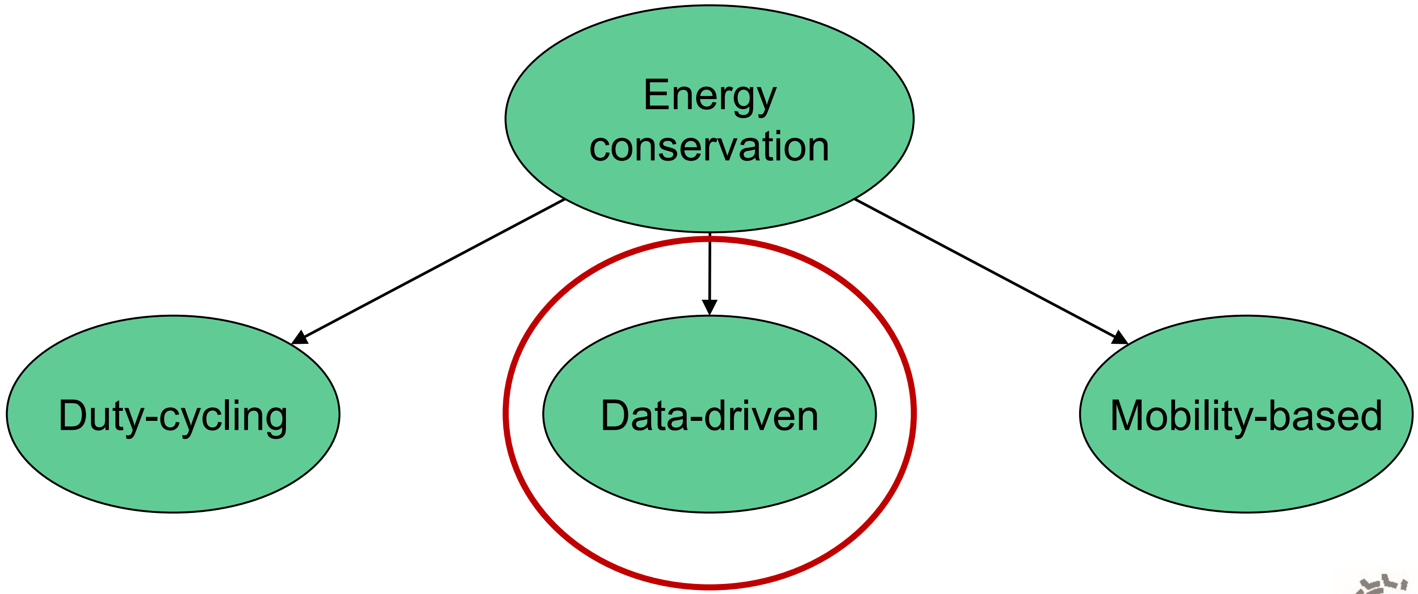
- **Different approaches**



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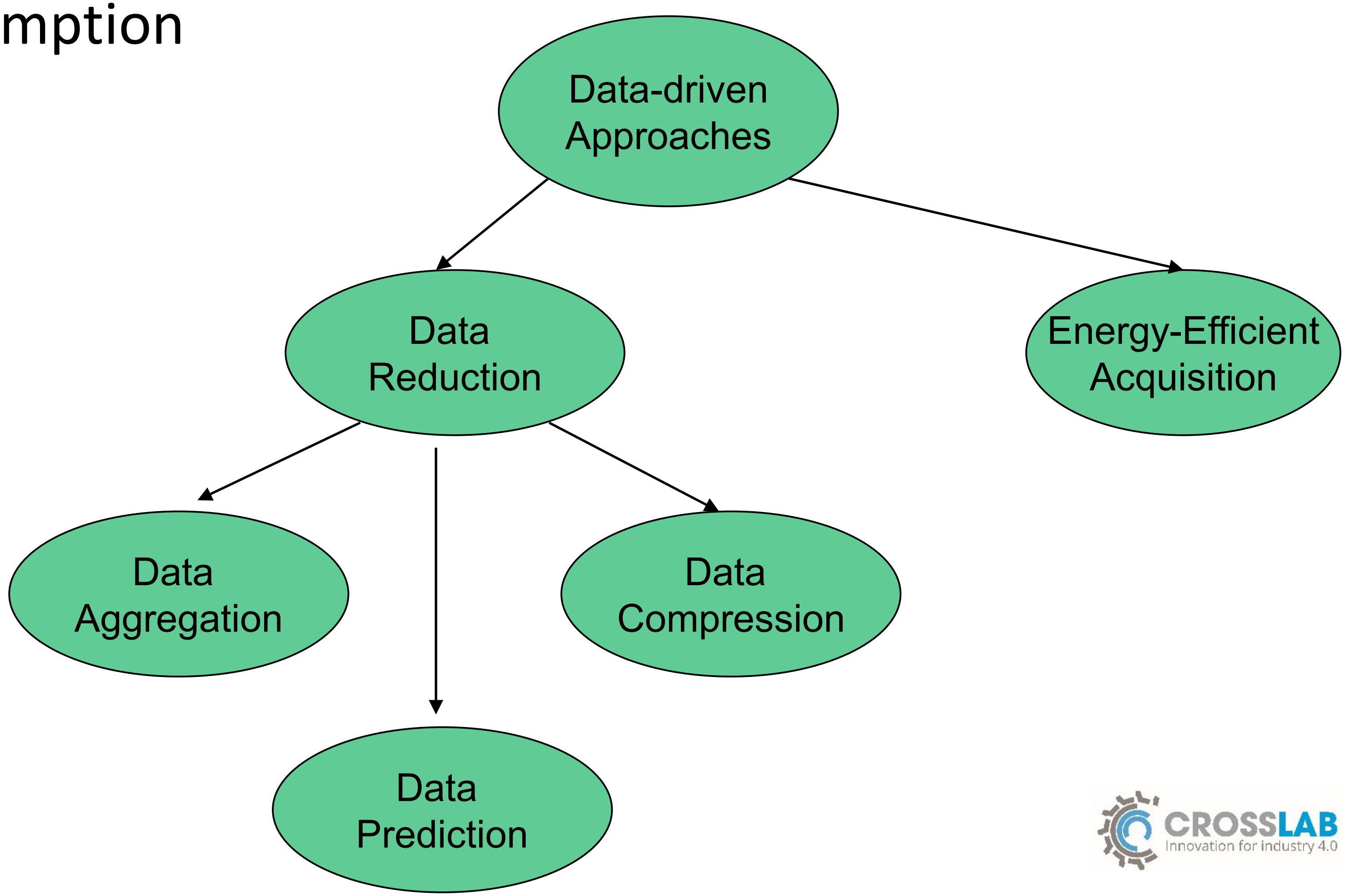
Data Driven Approach

Data-driven approaches

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



Energy efficient acquisition

- **The acquisition rate should be as low as possible**
  - Low sensor activity → low energy consumption
  - Low amount of data generated
  - Low radio activity → low energy consumption
    - ⇨ At source and intermediate nodes
- **The acquisition rate should satisfy application requirements**
  - Timely event detection
  - Accuracy

Energy efficient data acquisition

- **What is the optimal sampling rate?**
  - Application-specific
  - Varies over time
  - In many cases unknown, or difficult to obtain

- **Oversampling is used in many cases**
  - Increases the amount of generated data
  - Increases the energy consumption due to
    - ⇨ Sensor activity
    - ⇨ Radio activity

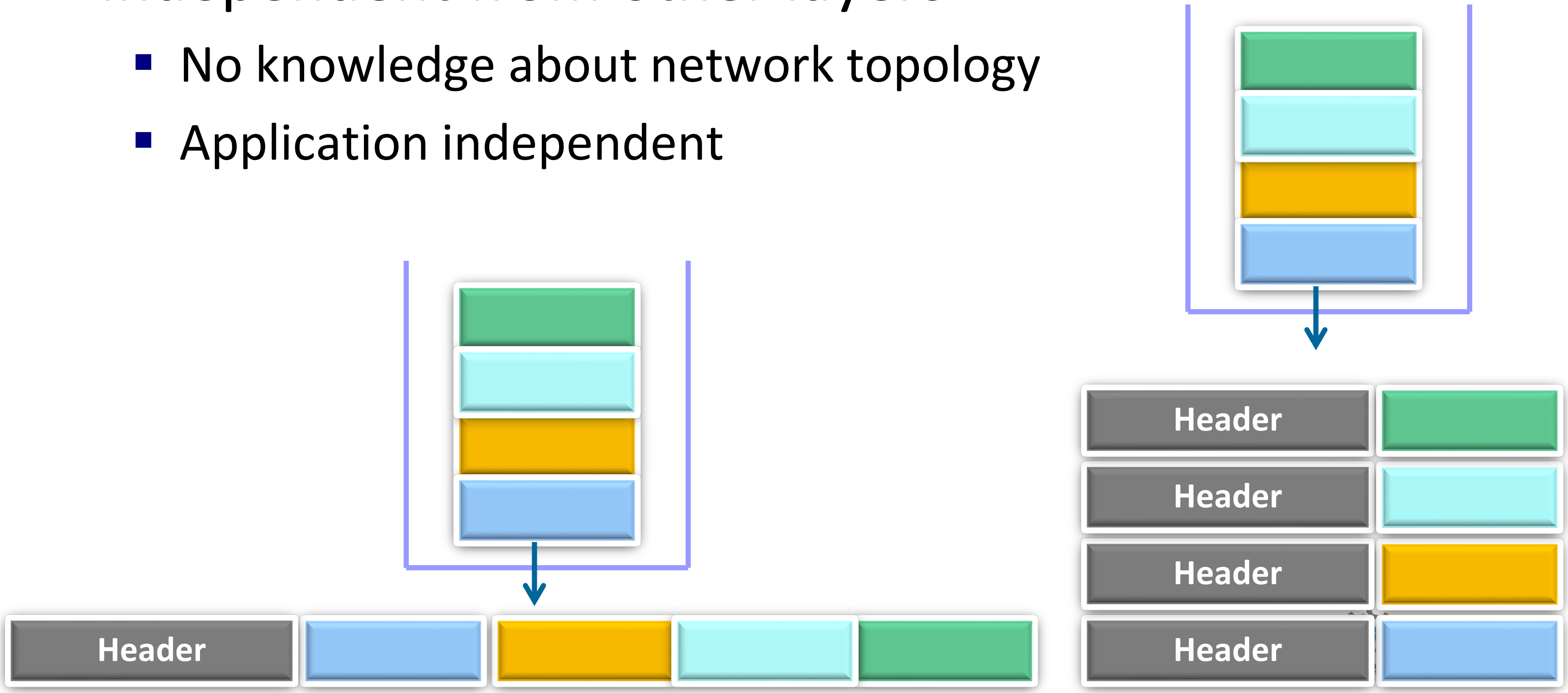
Data Aggregation

Classification

- MAC-Layer Data Aggregation
- Cluster-based Data Aggregation
- Tree-based data Aggregation

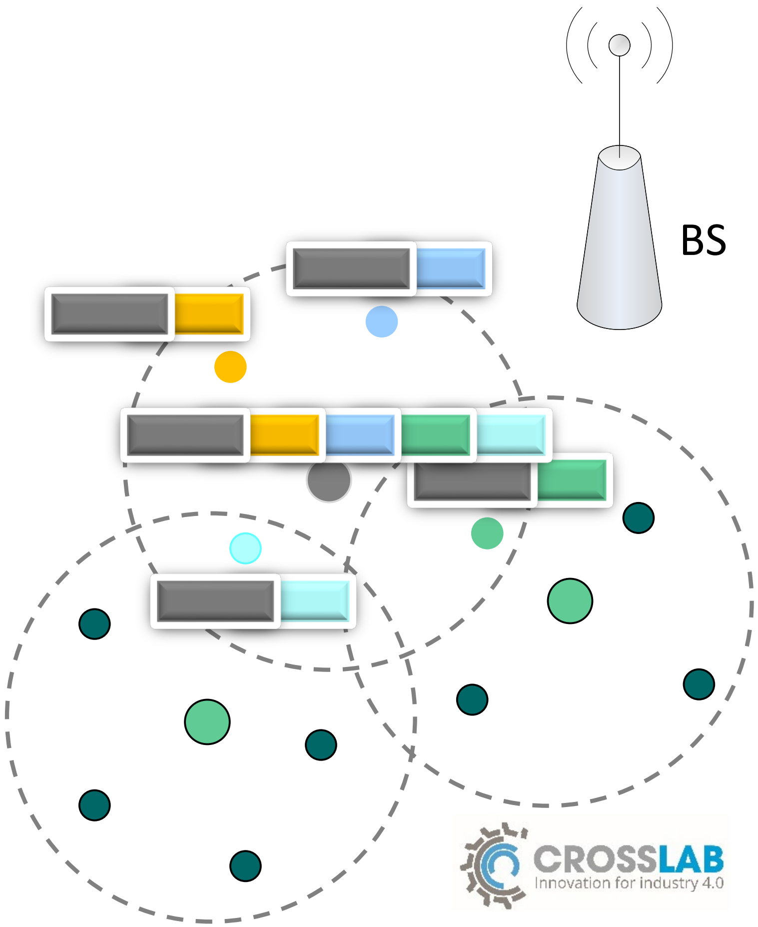
MAC-Layer Data Aggregation

- Combines multiple network packets into a single MAC frame
  - Reduced overhead (header, trailer, RTS, CTS)
- Independent from other layers
  - No knowledge about network topology
  - Application independent



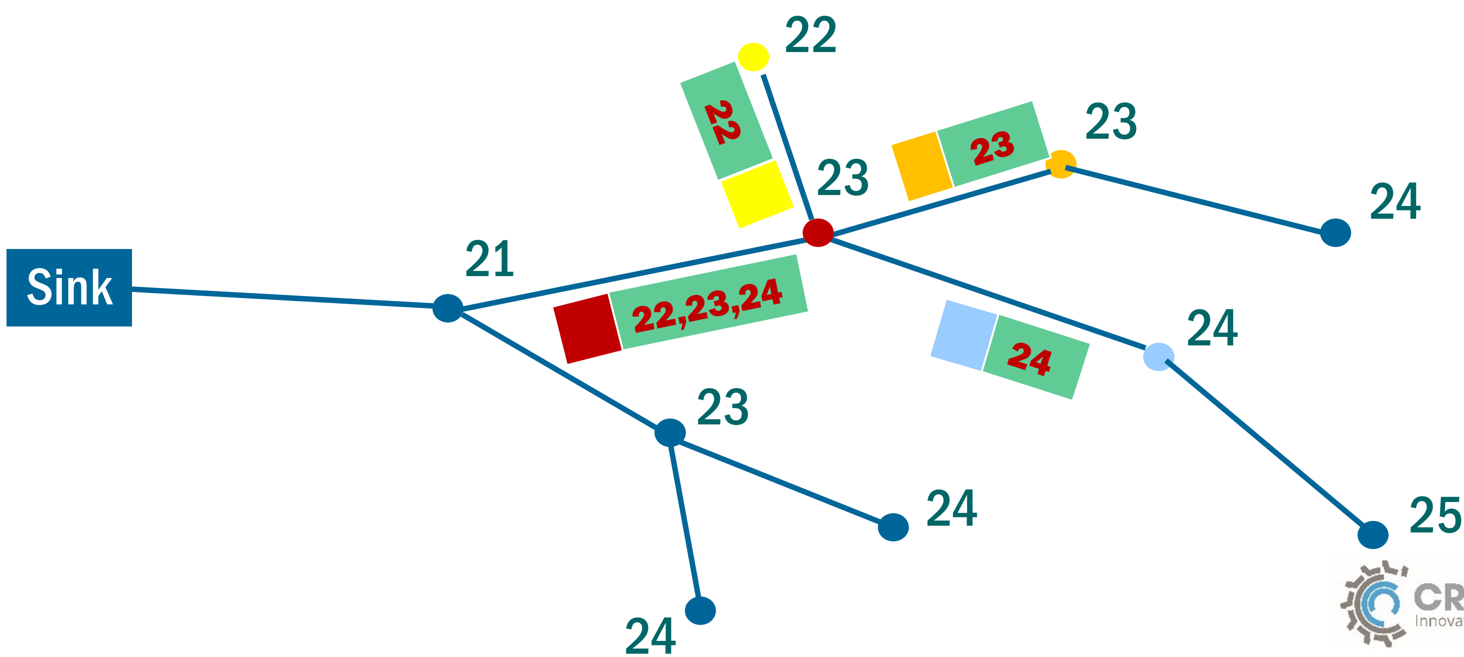
Cluster-based Data Aggregation

- Network Layer Technique
- Assume that sensor nodes are organized in clusters
  - Cluster Head (CH)
    - ⇨ Gathers data from CMs
    - ⇨ Aggregates data
    - ⇨ Forwards aggregate data to BS
  - Cluster members (CM)
    - ⇨ transmit data to CH
- May (or may not) exploit knowledge about the application



Tree-based Data Aggregation

- Network Layer Technique
  - Reduces the communication overhead
  - Reduces the energy consumption
- May (or may not) exploit knowledge about the application



Aggregation Factor

- Ratio between # of bits to be transmitted *with* aggregation and # of bits to be transmitted *without* aggregation

$$\alpha = \frac{D_{agg}}{D_{no-agg}} = \frac{H + N \cdot P}{N(H+P)} = 1 - \frac{H}{H+P} \cdot \frac{N-1}{N}$$

$$h = \frac{H}{H+P}$$

$$\alpha = 1 - h \cdot \frac{N-1}{N}$$

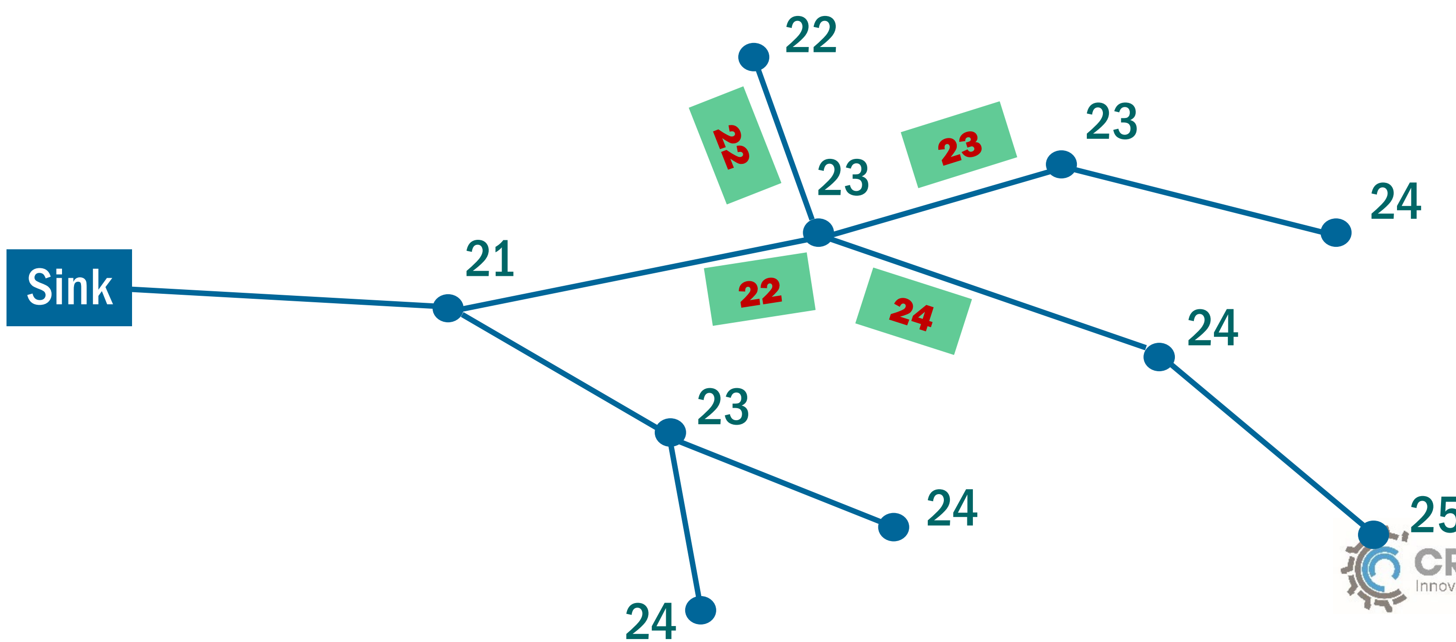
Aggregation Factor

- Assuming H = 9 bytes (IEEE 802.15.4 MAC Frame)

Aggregated packets	Payload Size (bytes)							
	1	**2**	**4**	**8**	**16**	**32**	**64**	**118**
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	0.55	0.59	0.65	0.74	0.82	0.89		
3	0.40	0.45	0.54	0.65	0.76	0.85		
4	0.33	0.39	0.48	0.60	0.73			
5	0.28	0.35	0.45	0.58	0.71			
6	0.25	0.32	0.42	0.56	0.70			
7	0.23	0.30	0.41	0.55				
8	0.21	0.28	0.39	0.54				
9	0.20	0.27	0.38	0.53				
10	0.19	0.26	0.38	0.52				

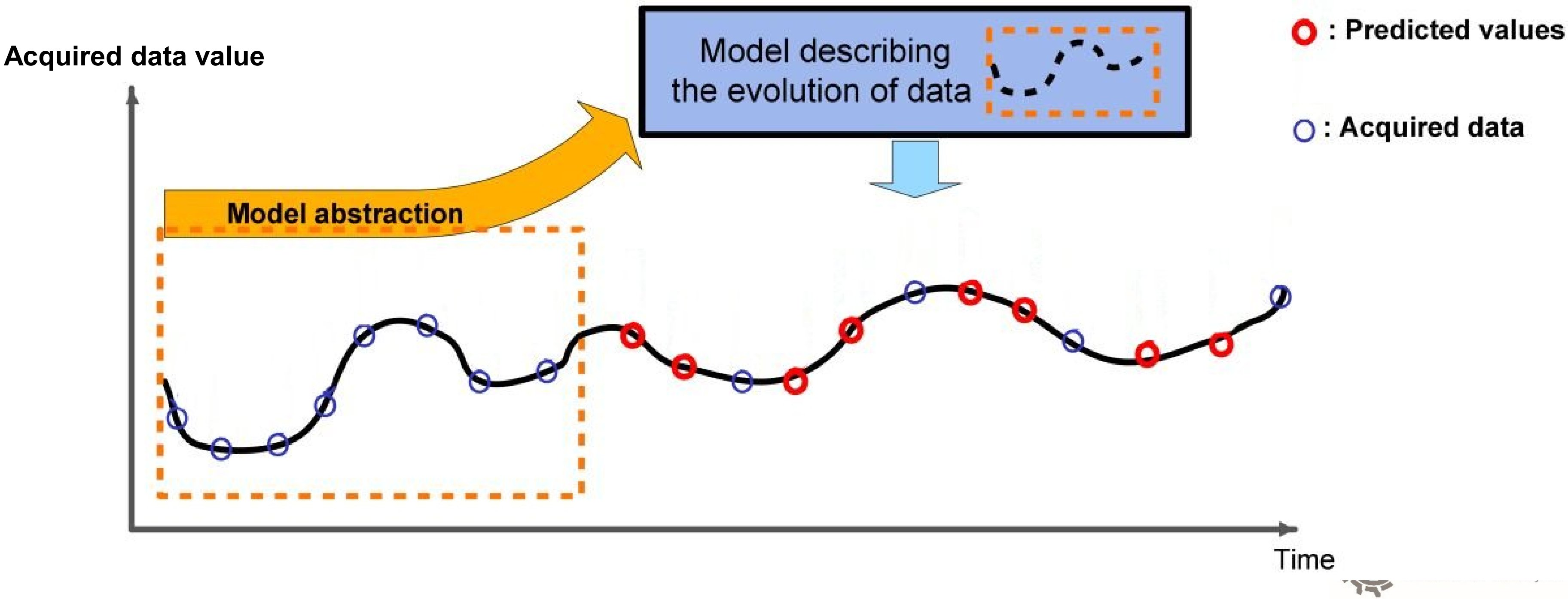
Application-aware Data aggregation

- Information about the application can be exploited in the aggregation strategy
  - Application-specific data aggregation
  - Can be used both in cluster-based and tree-based techniques
- Example: which is the max/min temperature in sensing area?



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

- 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

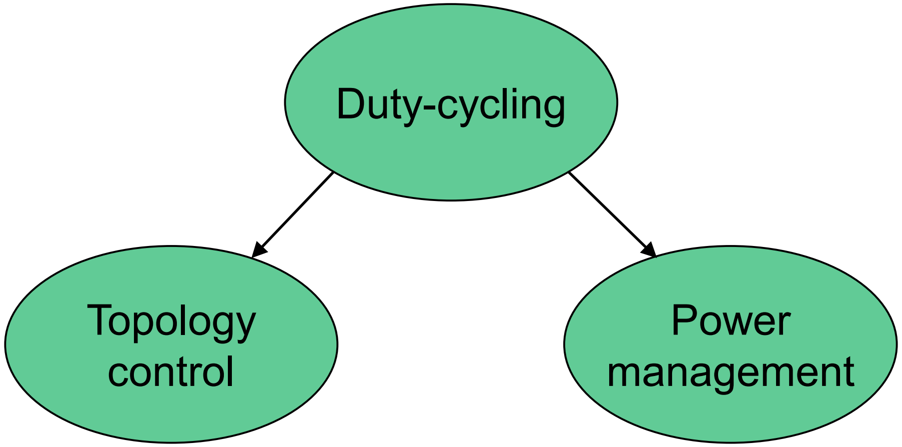
How much energy-consumption reduction in practice?

Limitations of data-driven approaches

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

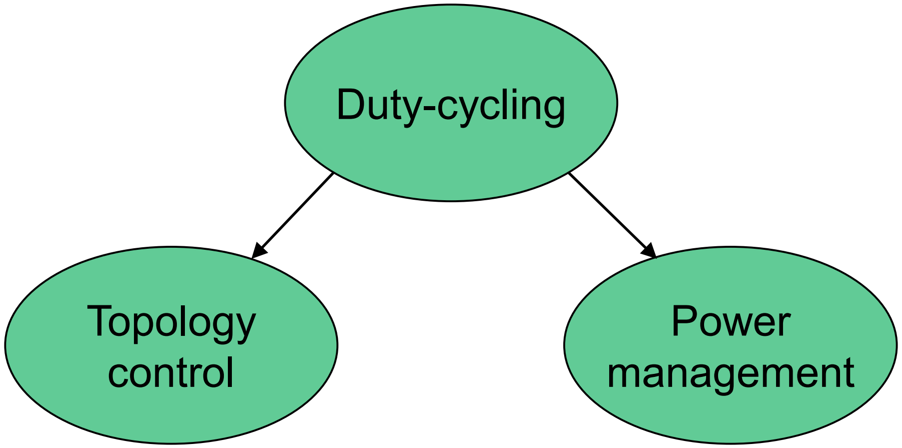
Duty-cycling



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



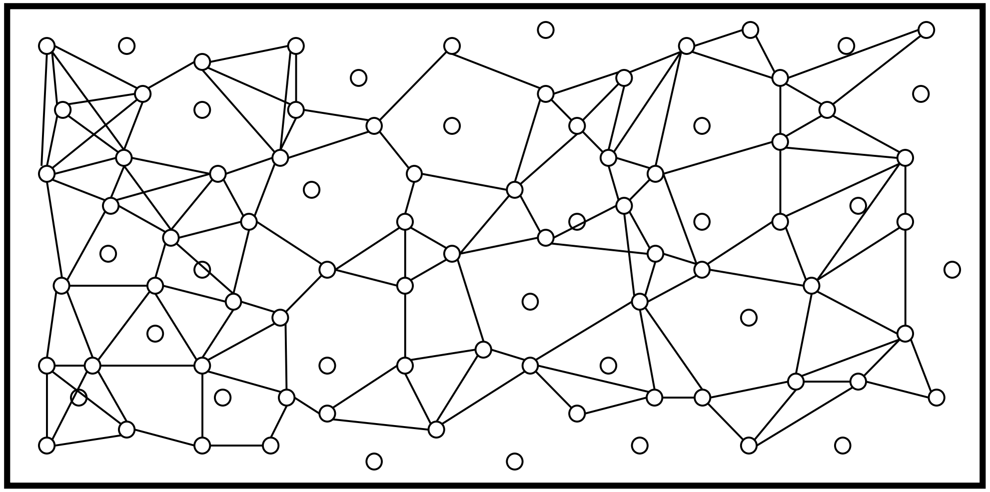
Node's components are switched off when not needed

- **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 -> increased ***packet loss***
    - ⇨ ***higher transmit power*** and ***reduced spatial reuse;***
  - ***Too many*** active nodes:
    - ⇨ At best, ***unnecessary energy consumption;***
    - ⇨ At worst nodes may ***interfere*** with one another, thus ***congesting*** the channel.



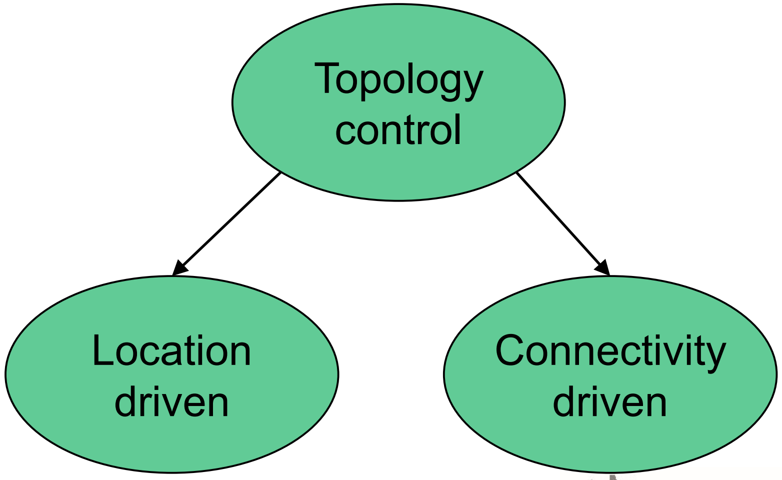
Courtesy of Mani Srivastava, UCLA, USA

Topology control protocols

- **Goal**

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

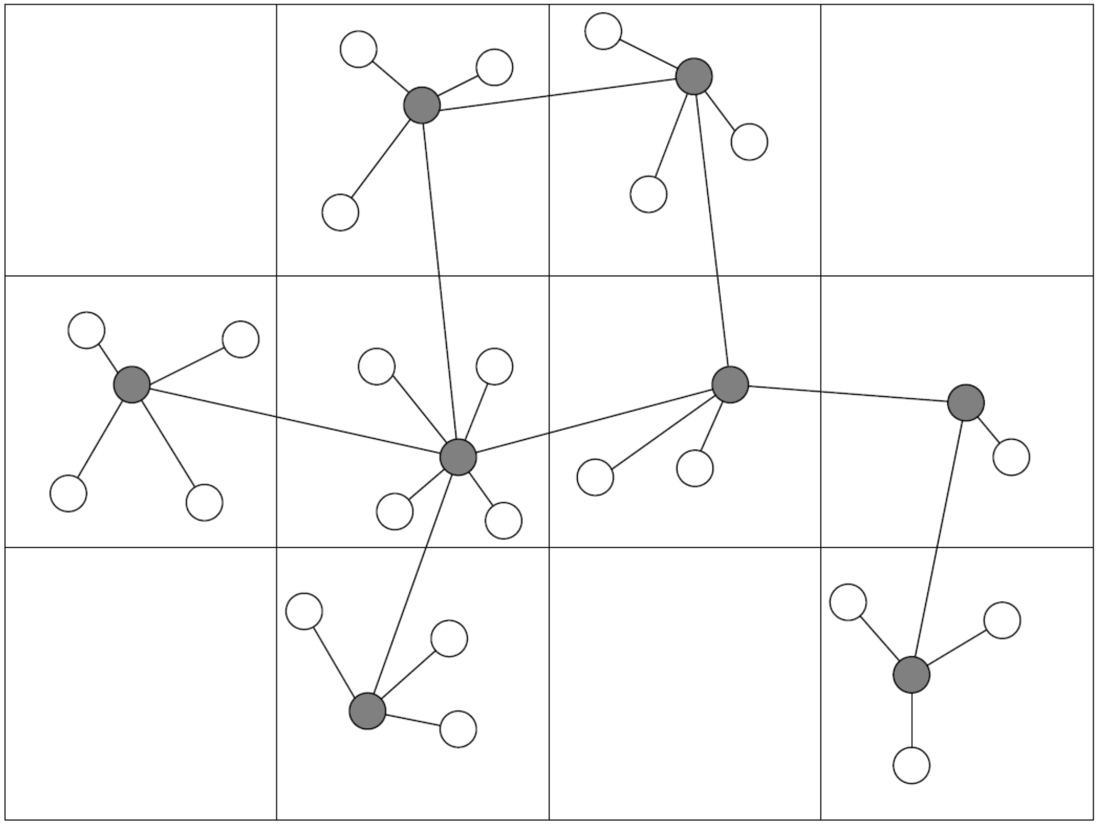
- **Approaches**
  - Location driven
    - ⇨ needs to know the exact location of nodes
    - ⇨ GAF
  - Connectivity driven
    - ⇨ more flexibility
    - ⇨ ASCENT, SPAN



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 (grid leader)

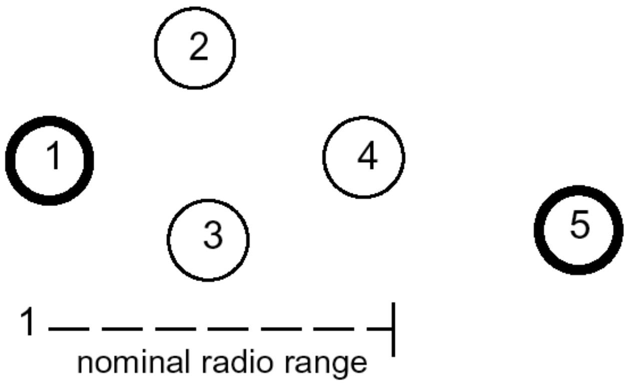
- Nodes alternate between
  - Active state (grid leader)
  - Sleeping (non grid leader)
  - Discovery (leader election)



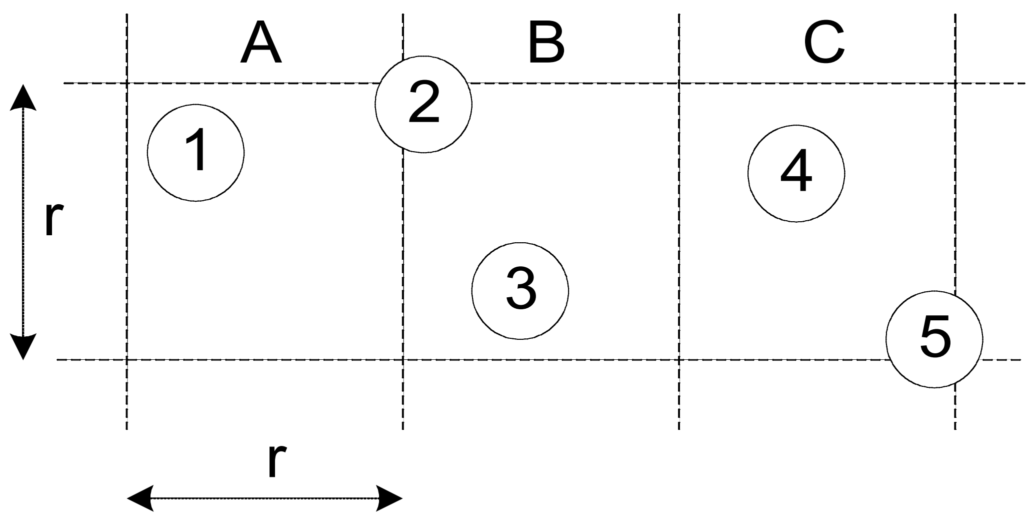
- **Leader Election**
  - Distributed algorithm for leader election in each cell

- **Hierarchical Routing**
  - Sensor nodes to leader
  - Leader to BS

Geographic Adaptive Fidelity (GAF)



- R= nominal radio range
  Assumed equal for all nodes
- r= size of each cell in the grid



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

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

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)

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
- Hierarchical 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)
    - ⇨ AODV
    - ⇨ DSR

ASCENT

Adaptive Self-Configuring sEnsor Networks Topologies

- 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.

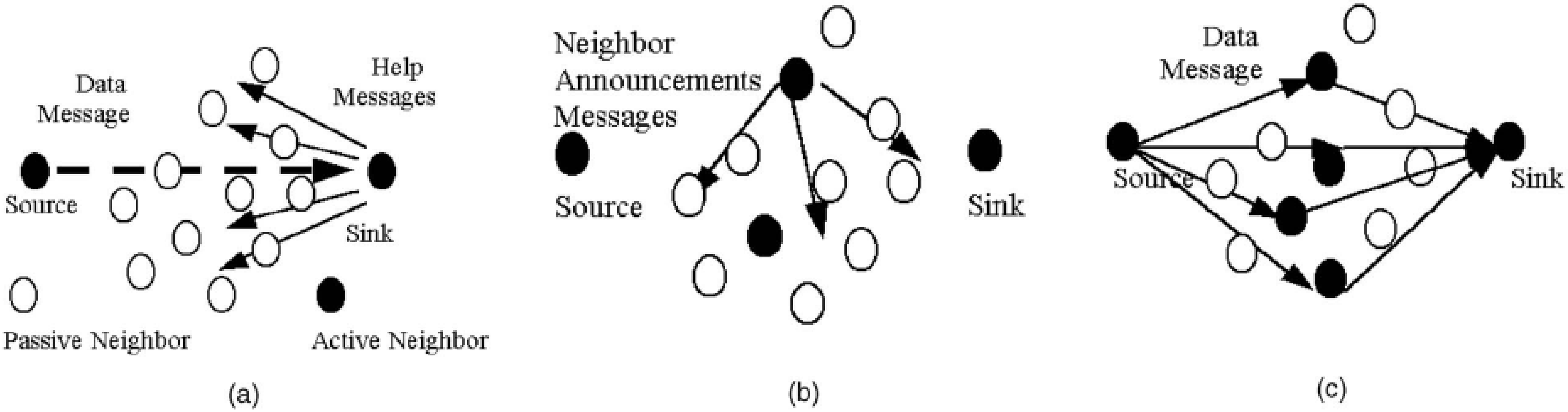
A. Cerpa, D. Estrin, **Ascent: Adaptive Self-Configuring Sensor Network Topologies**, Proc. IEEE INFOCOM 2002.

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.

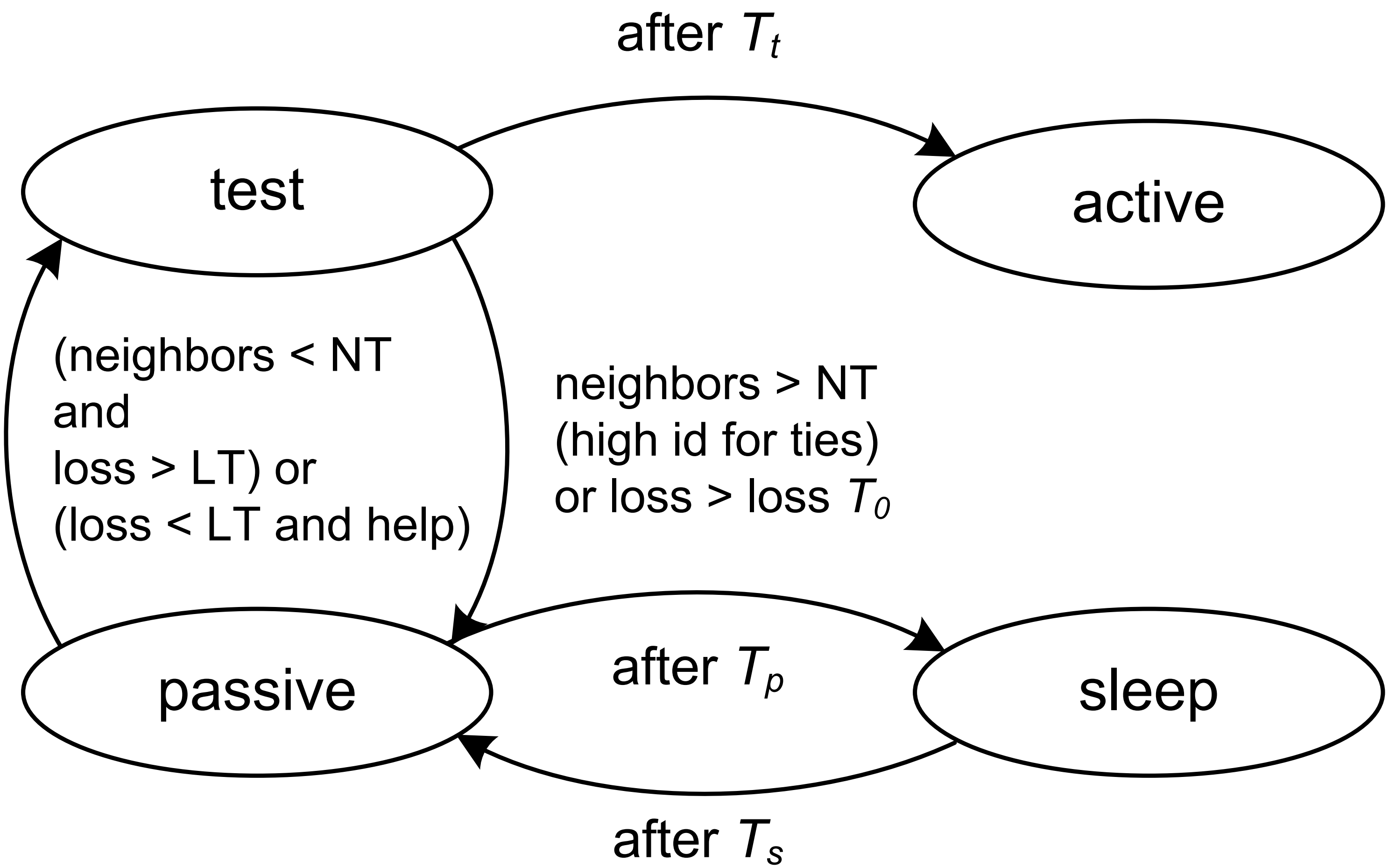
Network Self-Configuration - Example



(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



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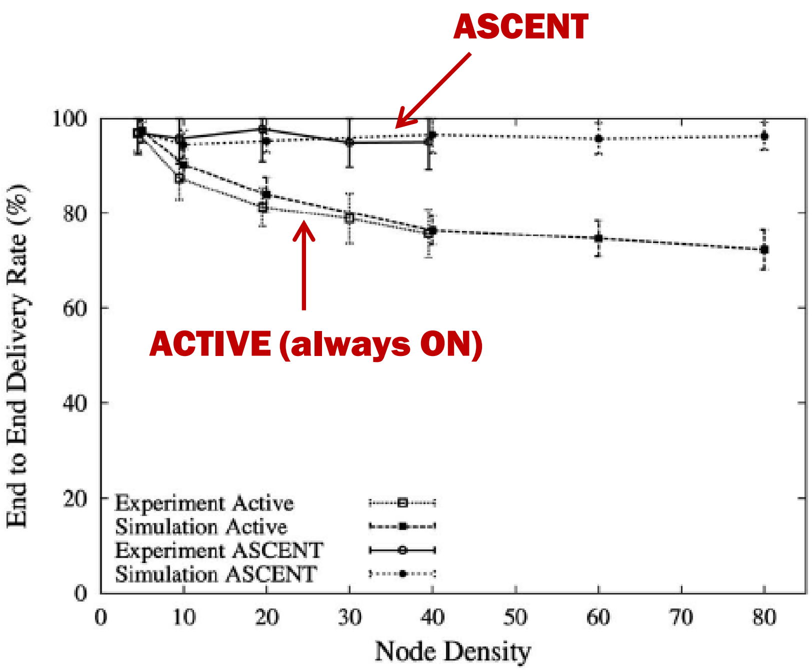
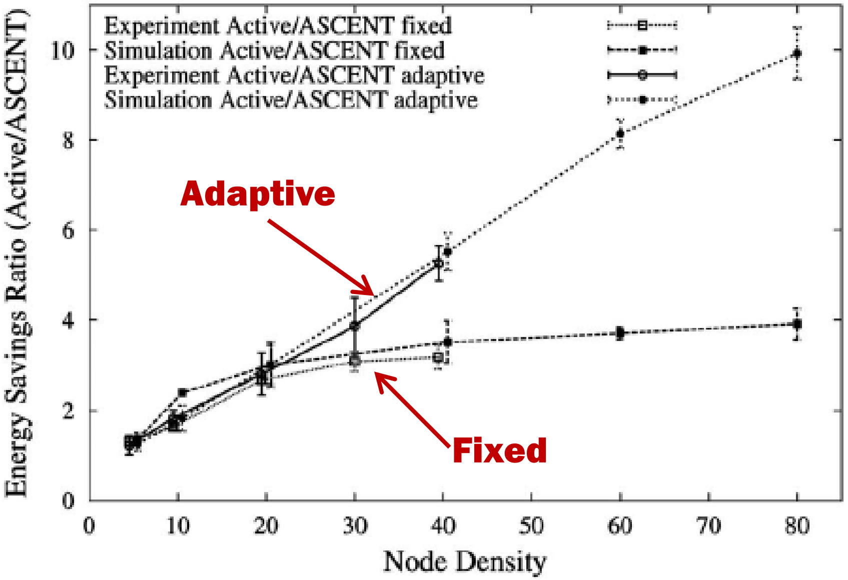
ASCENT Performance

End-2-end Delivery Ratio



Energy Savings



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

Power Management

Motivation for Power Management

- Periodic Reporting
  - 1 packet of size L every T sec

Power Consumption

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
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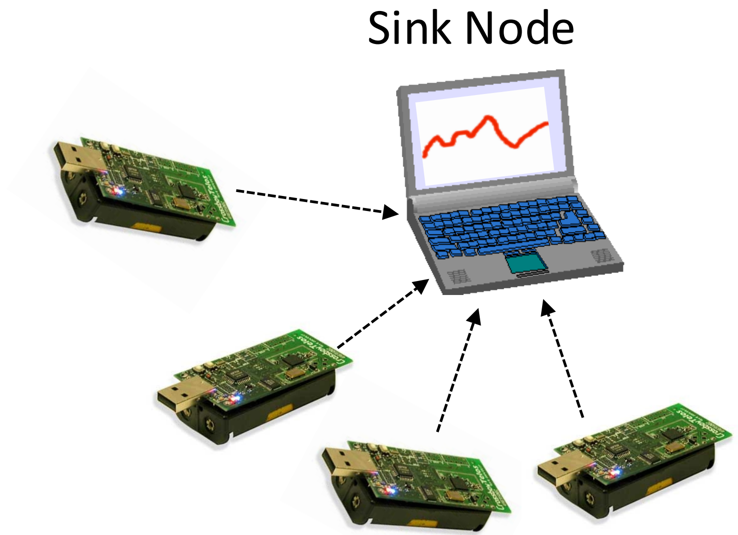
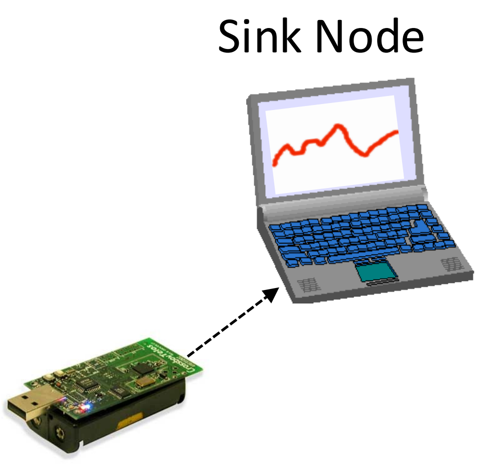


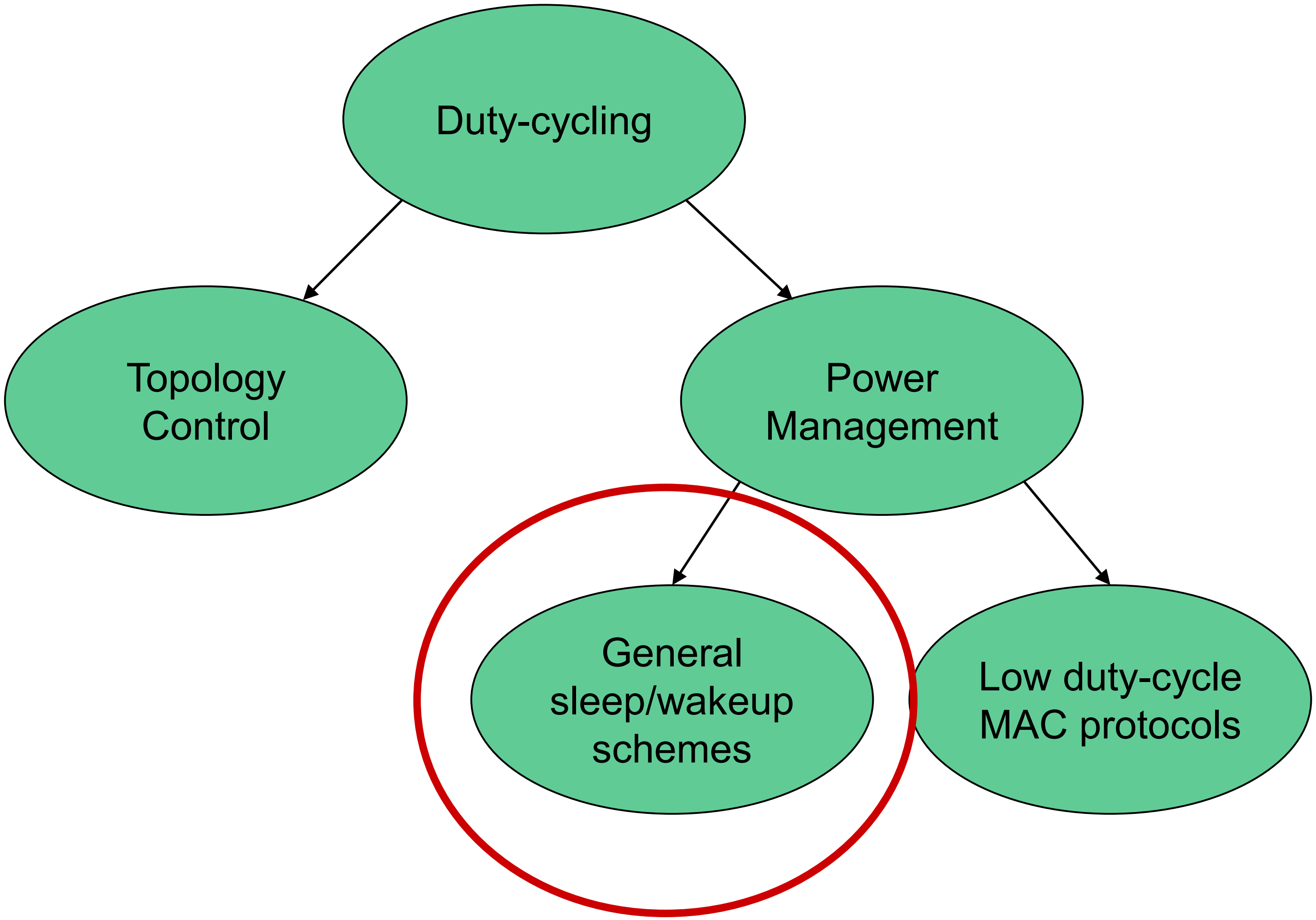
Motivation for Power Management

- Average Power Consumption P
  - Energy E_T consumed during a period T, divided by T
  - T=1 sec
  - L=100 bytes (800 bits)
  - C=250 Kbit/sec
  - alfa=0.01 (aggregation factor)



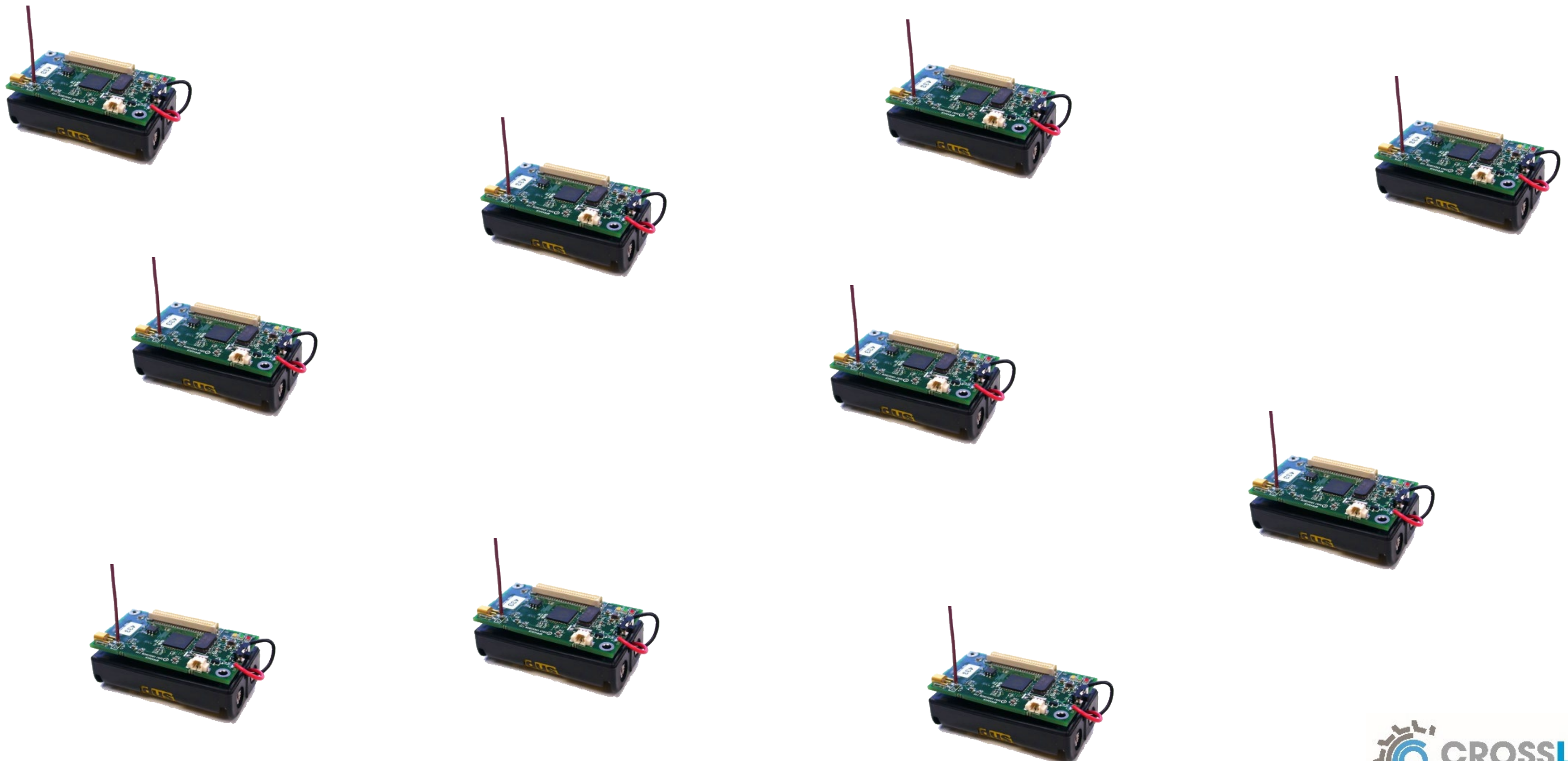
Energy Conservation Strategy	Average Power Consumption		%
Always ON	0,868	mW	100,00%
Aggregation	0,771	mW	88,85%
Power Management	0,136	mW	17,65%
Power Man + Aggregation	0,037	mW	4,26%

Power Management



General sleep/wakeup schemes

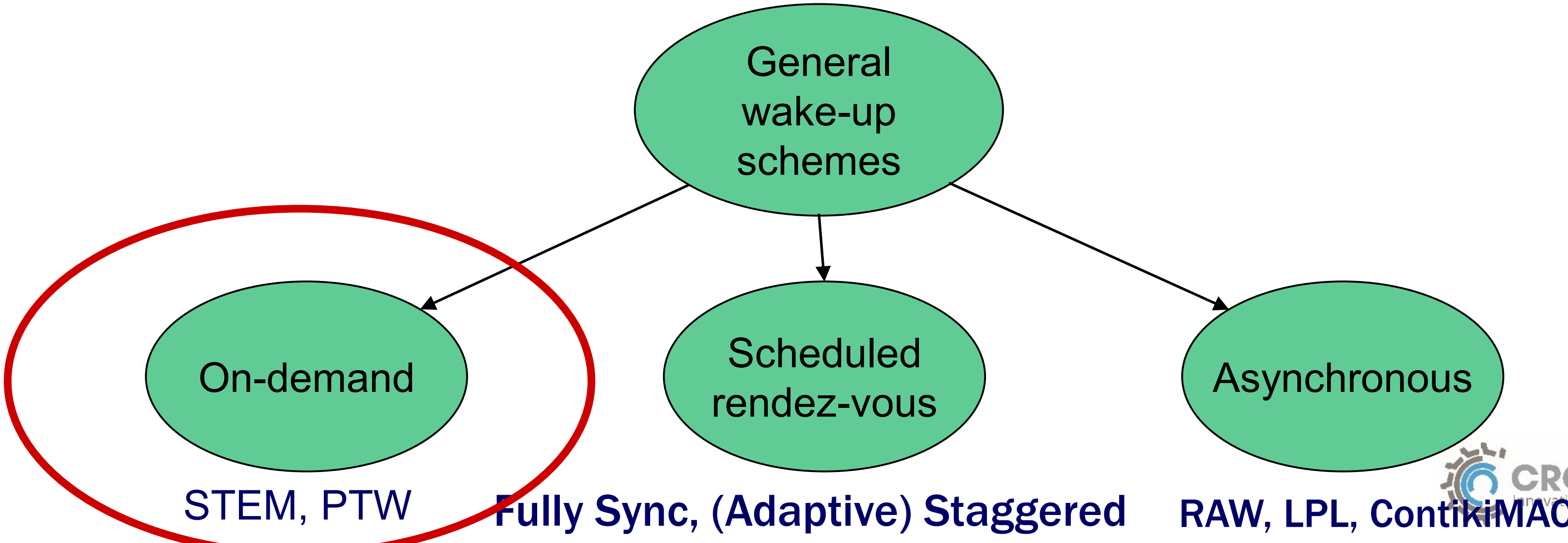
- When should a node wake up for communicating with its neighbors?



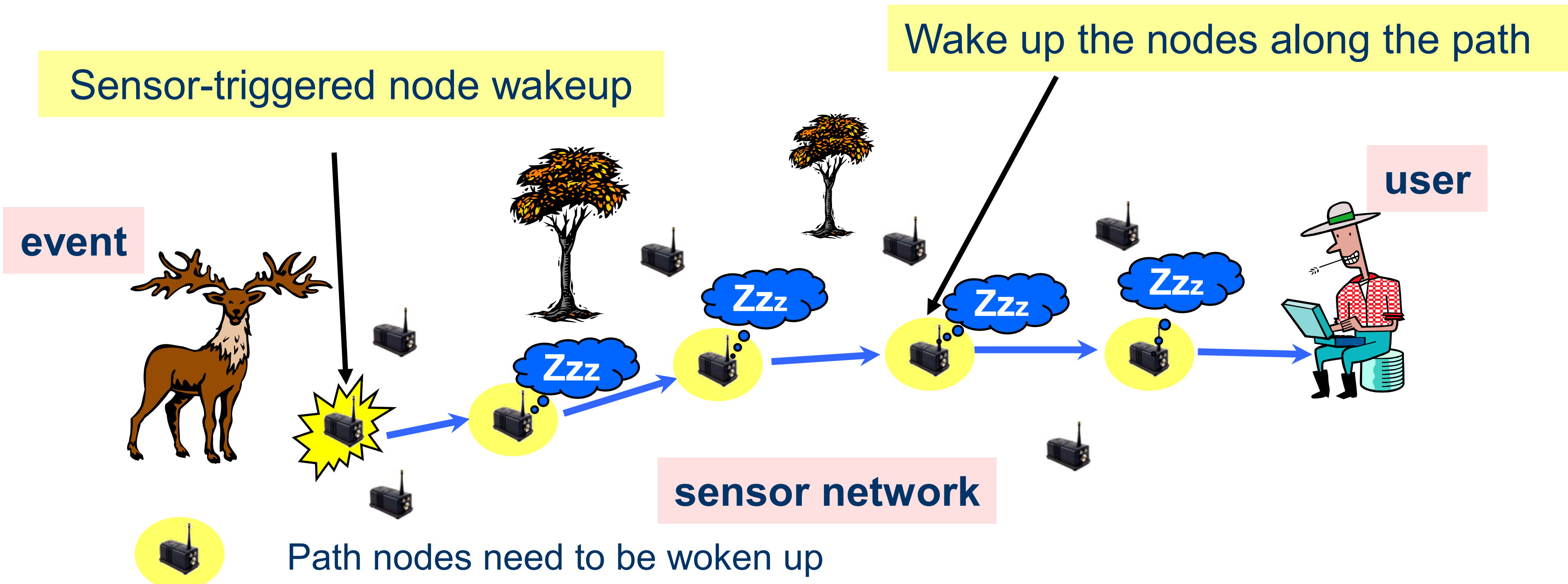
General sleep/wakeup schemes

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

- When another node wants to communicate with it (*on demand*)
- At the same time as its neighbors (*scheduled rendez-vous*)
  - ⇨ Clock synchronization required
- Whenever it wants (*Asynchronous*)



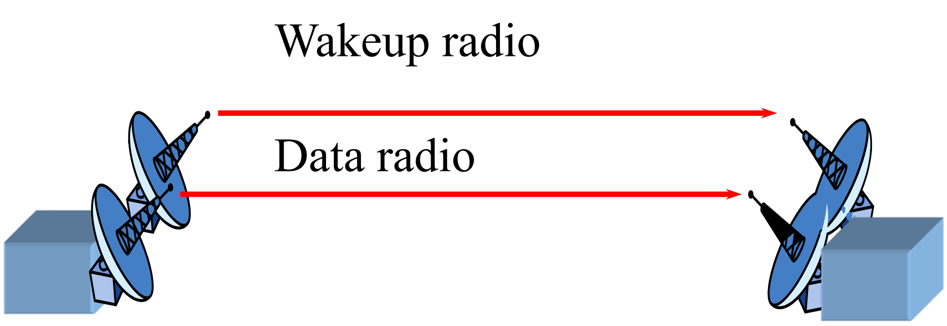
On-demand Schemes



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

On-demand Schemes

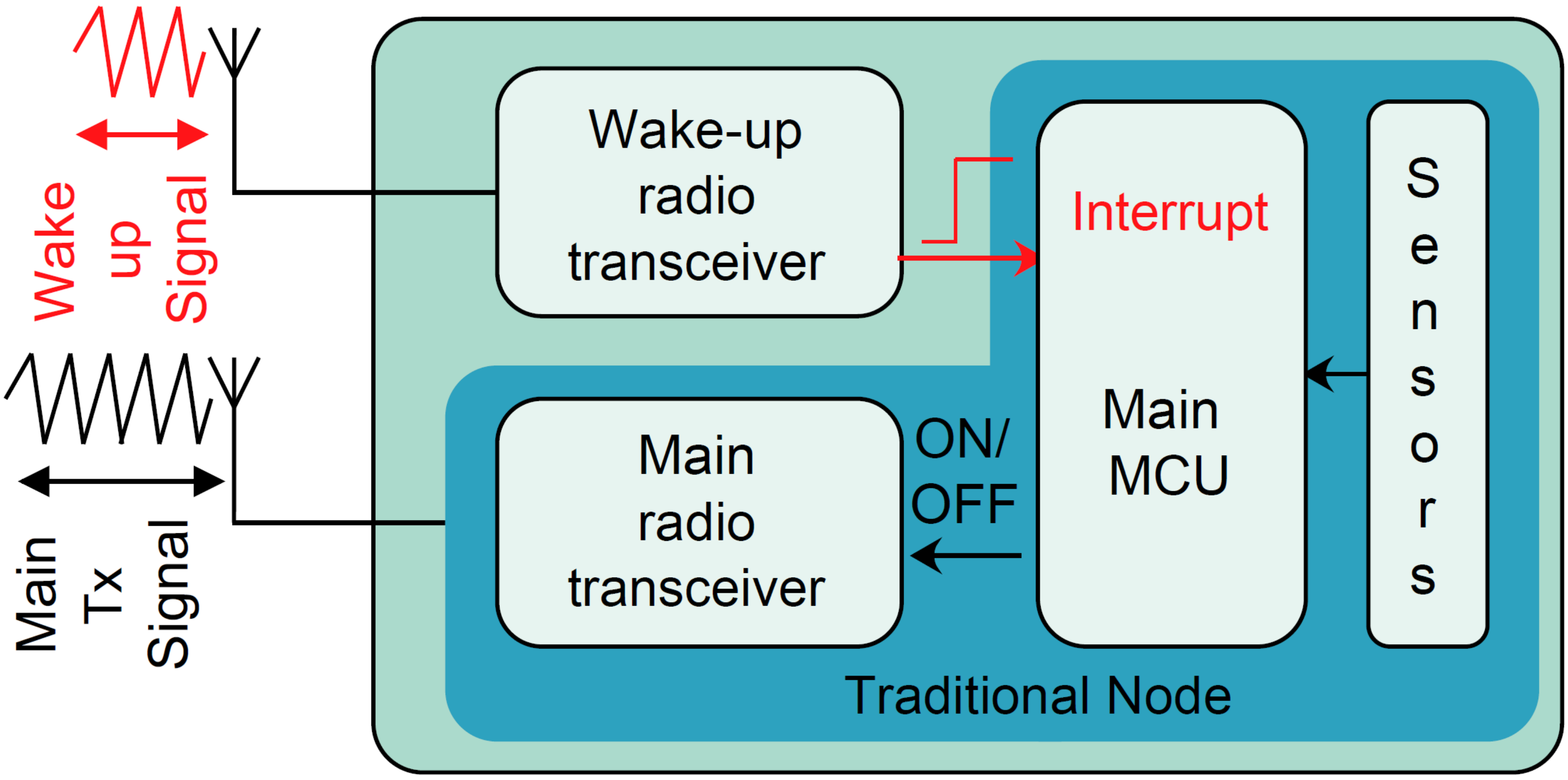
- Two different radios
  - Data Radio (data transmissions)
  - Wakeup Radio
- Possible variant
  - Single radio with two different frequencies for data and wakeups



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

On-demand Schemes

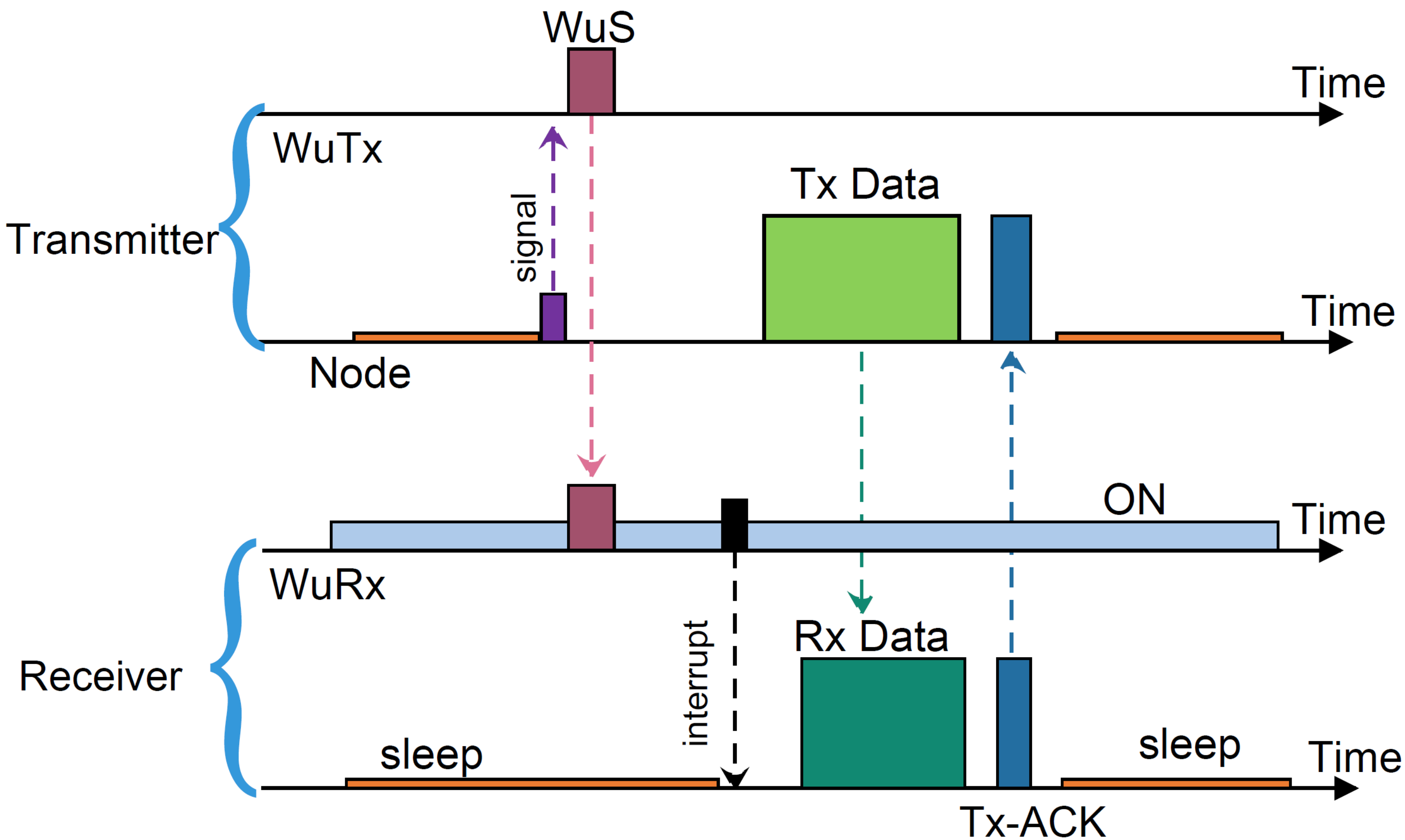
Wake-up Radio



Rajeev Piyare Amy L. Murphy Csaba Kiraly, Pietro Tosato, Davide Brunelli, **Ultra Low Power Wake-Up Radios: A Hardware and Networking Survey**, *IEEE Communications Surveys & Tutorials,* Vol. 19, N. 4, 2017.

On-demand Schemes

- **Wake-up Radio**



Rajeev Piyare Amy L. Murphy Csaba Kiraly, Pietro Tosato, Davide Brunelli, **Ultra Low Power Wake-Up Radios: A Hardware and Networking Survey**, *IEEE Communications Surveys & Tutorials,* Vol. 19, N. 4, 2017.

On-demand Schemes

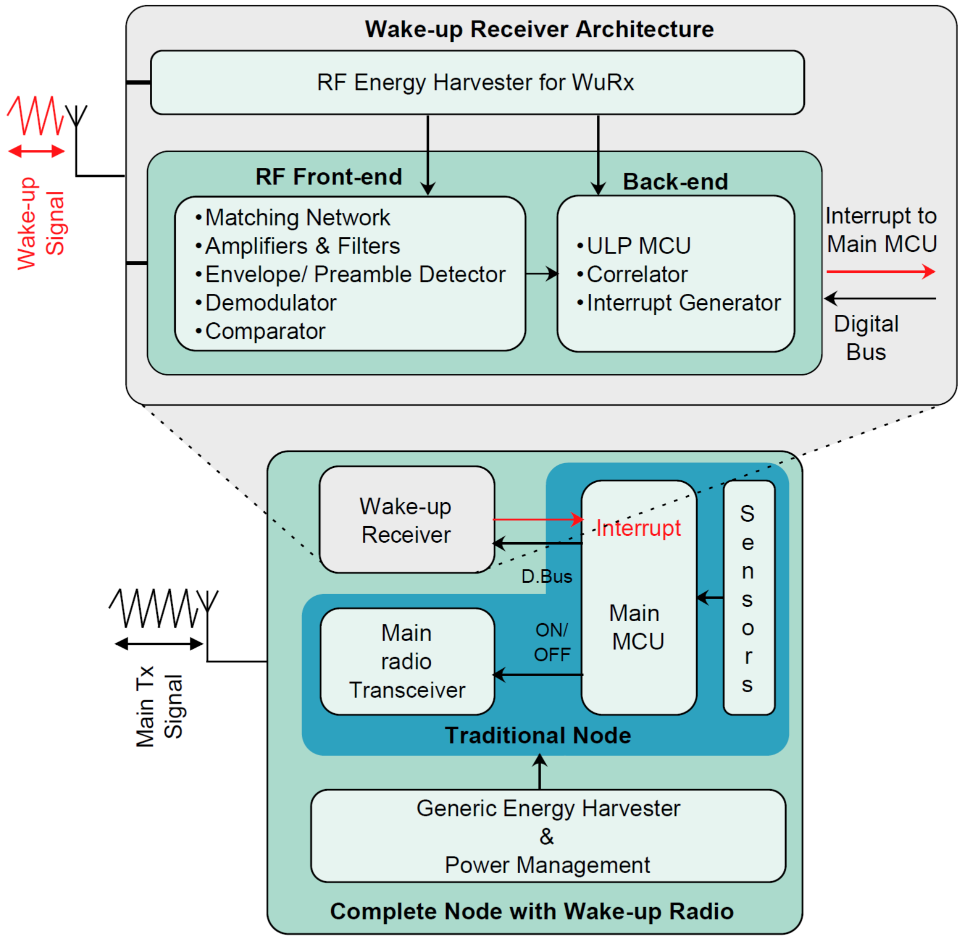
- Power Consumption
  - No more than tens of micro-watts
- Time to wake-up
  - The WuR must wake-up with minimum latency upon reception of WuS
    - ⇨ To avoid latency incurred from multi-hops toward the sink
    - ⇨ to increase the overall responsiveness of a purely asynchronous network
- False wake-ups and interference
  - when WuTx tries to wake-up a node, it will trigger all the nodes in the neighborhood causing significant energy waste
    - ⇨ node addressing to trigger only the intended node
    - ⇨ interference and noise that can result in erroneous wake-ups must be filtered

On-demand Schemes

- Sensitivity and range
  - WuR ideally should have the same range of the data radio
    - ⇨ Most WuR designs target tens of meters of communication range (30 m)
    - ⇨ Could be improved through antenna diversity and directional antennas
- Data rate
  - High data rate ➔ faster wakeup
  - Low data rate ➔ longer range and better communication reliability
  - A high data rate is not strictly required by the WuR
    - ⇨ only a few bytes of data are required
- Cost and size
  - the cost of this additional hardware should be 5-10% of the overall cost

On demand Schemes

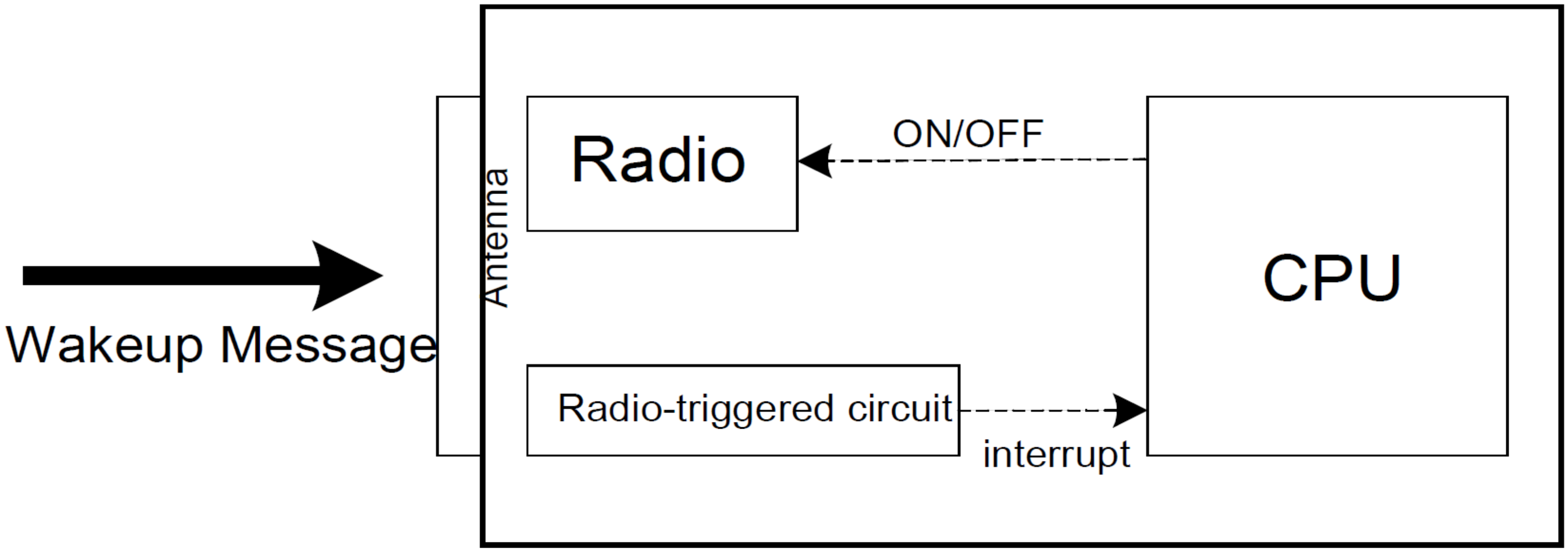
- **Wakeup Radio with Energy Harvesting**



Rajeev Piyare Amy L. Murphy Csaba Kiraly, Pietro Tosato, Davide Brunelli, **Ultra Low Power Wake-Up Radios: A Hardware and Networking Survey**, *IEEE Communications Surveys & Tutorials*, Vol. 19, N. 4, 2017.

On demand Schemes

- Passive Wakeup Radio



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

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

- When another node wants to communicate with it (*on demand*)
- At the same time as its neighbors (*scheduled rendez-vous*)
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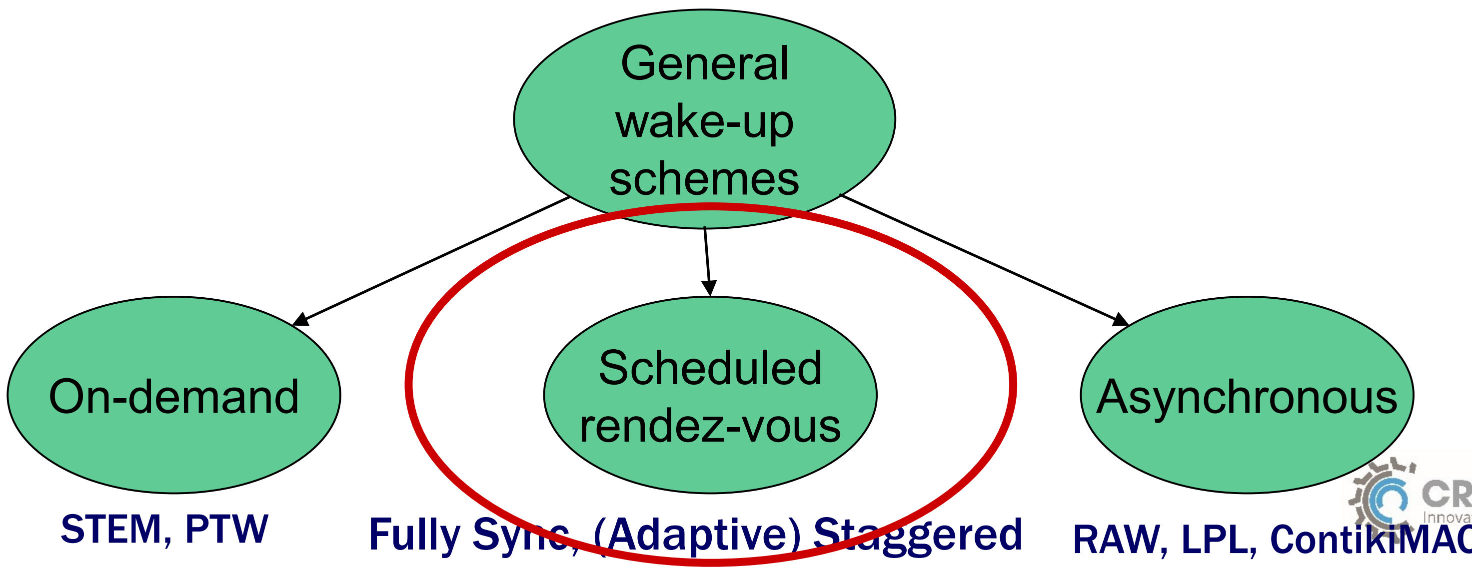
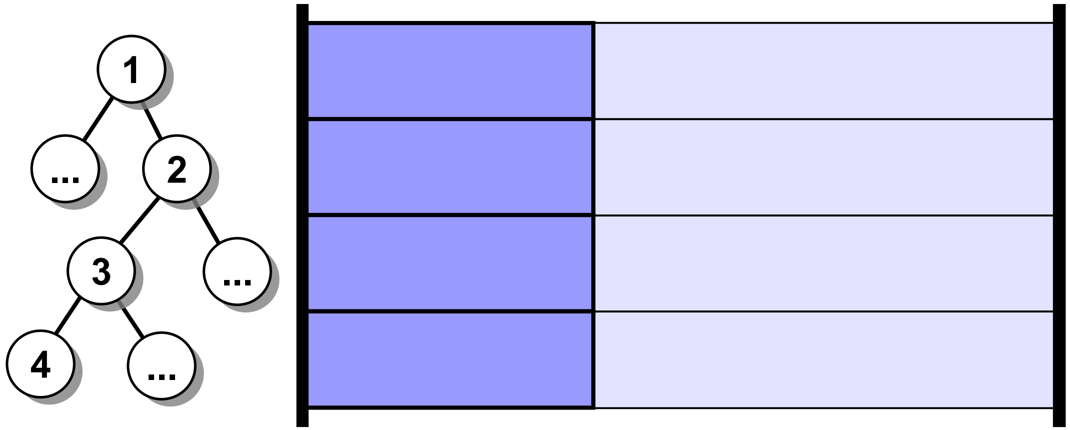


Fully Synchronized Scheme (TinyDB)

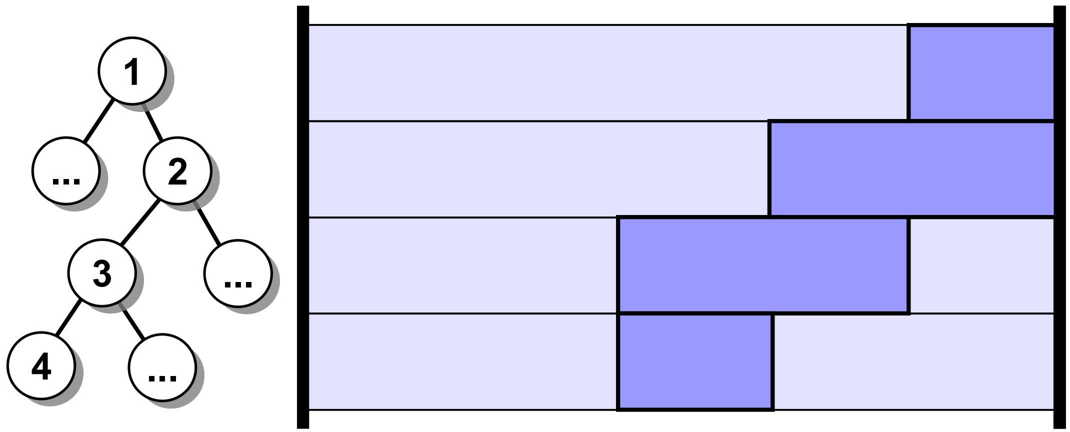


- Pros
  - Simplicity
- Cons
  - Global duty-cycle
    - ⇨ low energy efficiency
  - Static

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

Scheduled Rendez-Vous

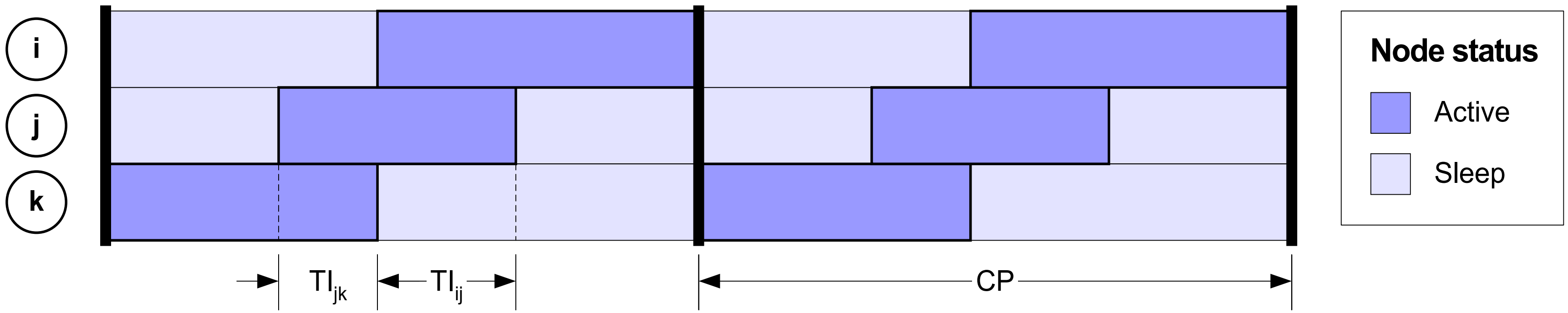
Fixed Staggered Scheme (TAG, TASK)



- 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

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.

General sleep/wakeup schemes

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

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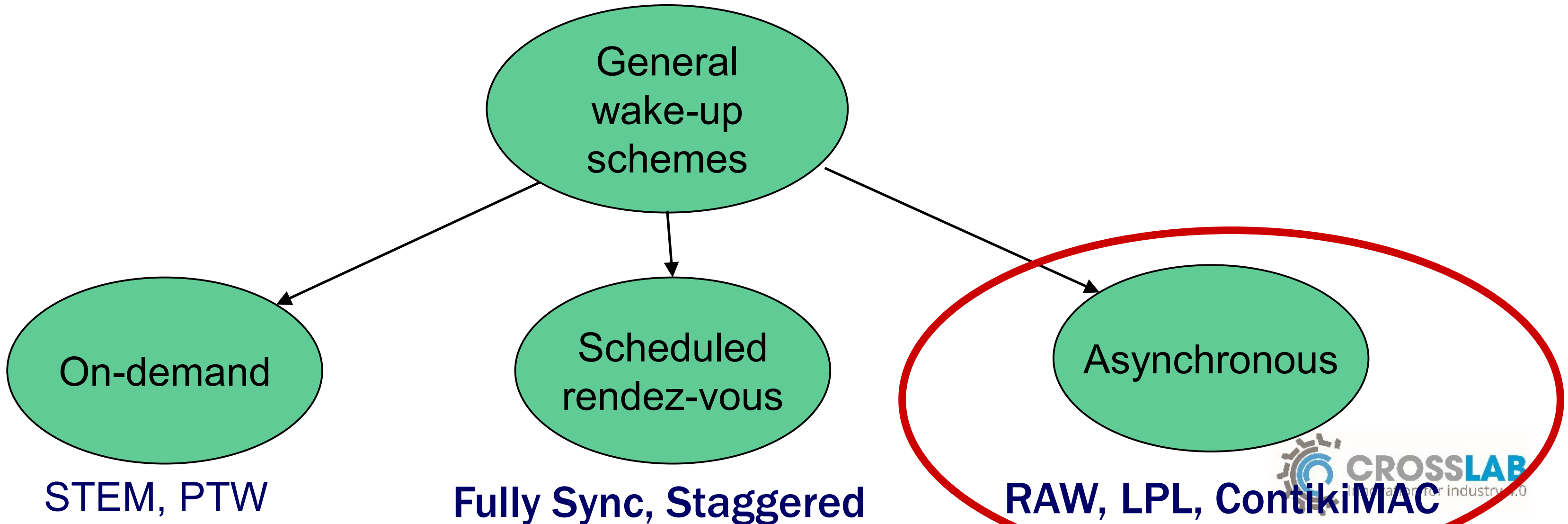
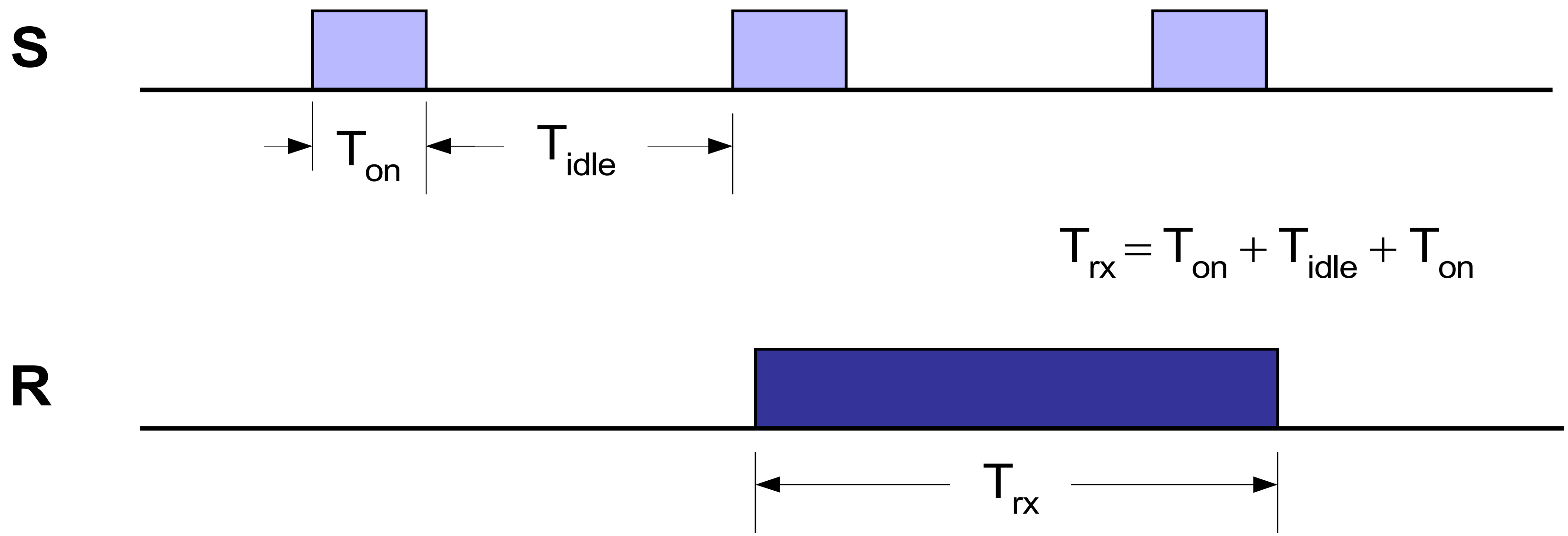
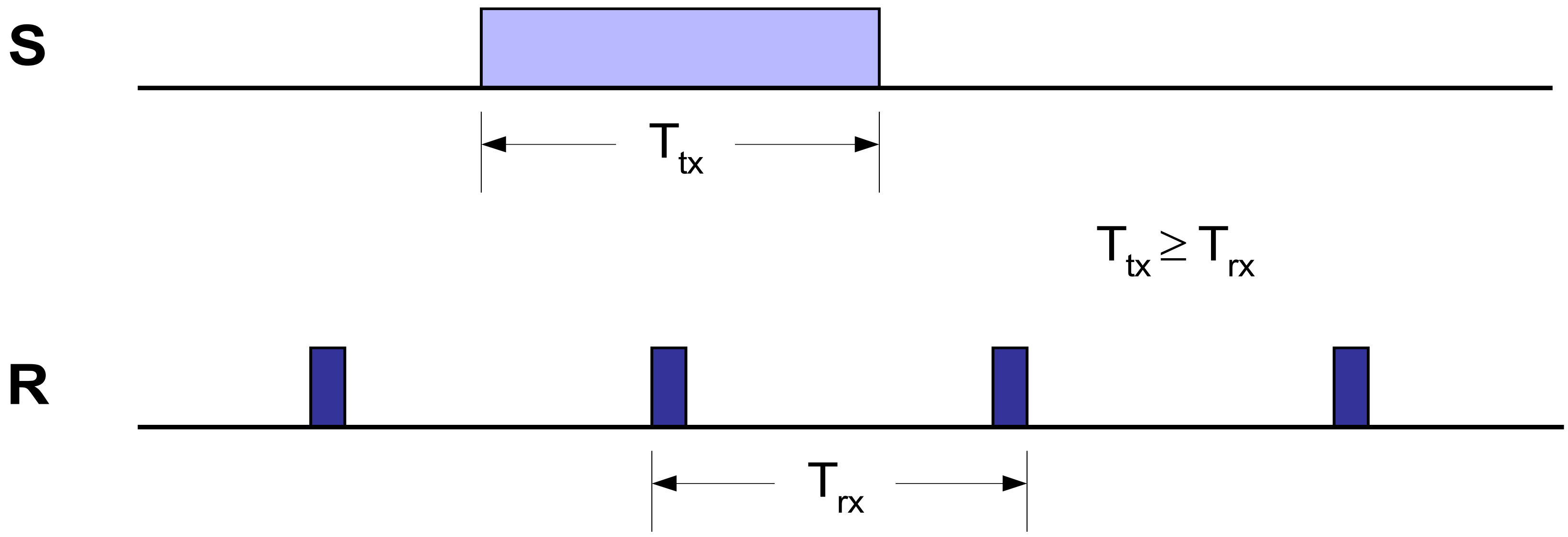


Asynchronous Sender and Periodic Listening

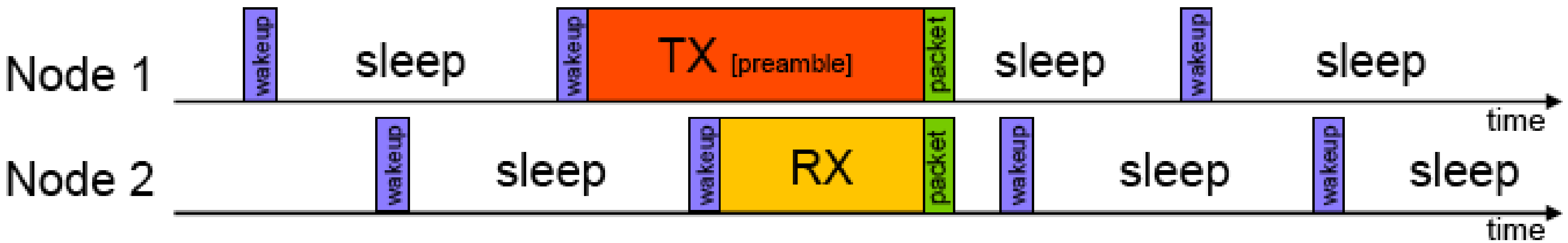


Asynchronous Sender and Periodic Listening



Low Power Listening (LPL)

- Nodes periodically sleep and perform LPL
- Nodes do not synchronize 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!

ContikiMAC Duty Cycling

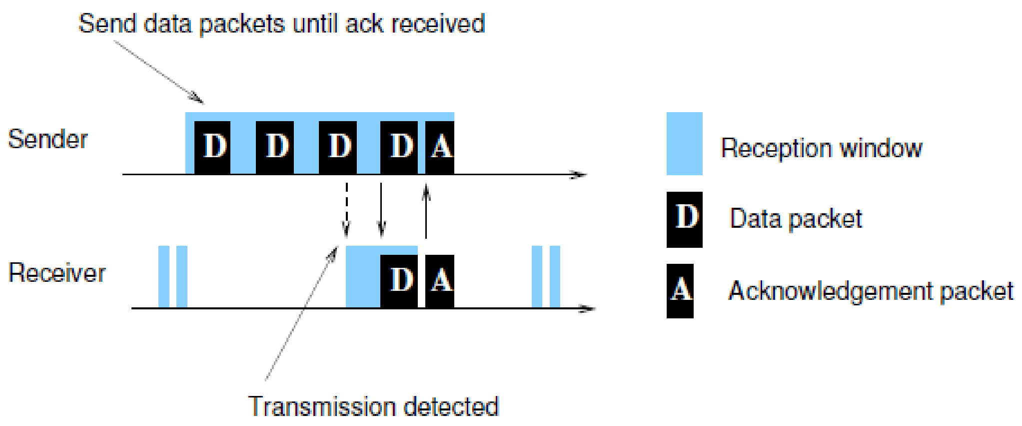
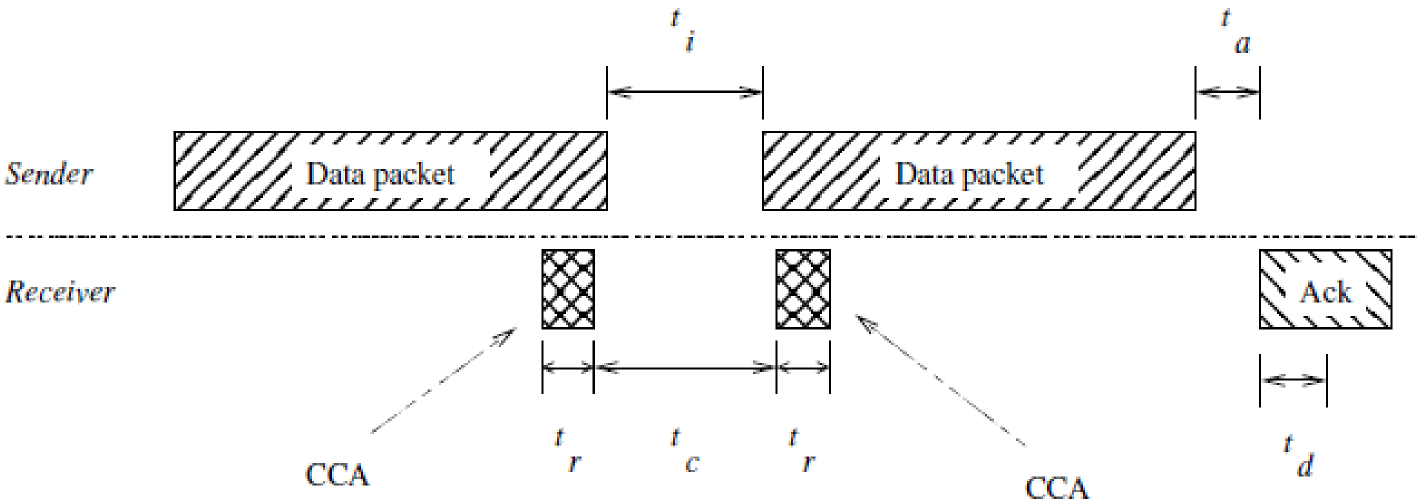


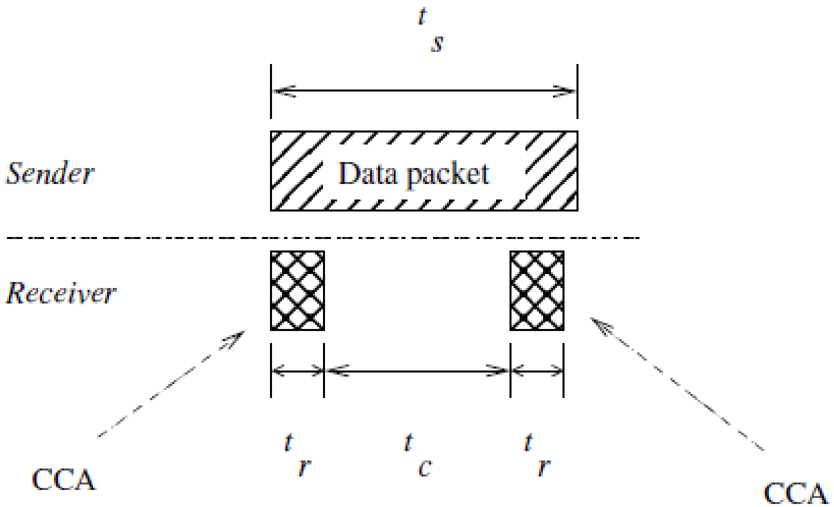
Figure 1: ContikiMAC: nodes sleep most of the time and periodically wake up to check for radio activity. If a packet transmission is detected, the receiver stays awake to receive the next packet and sends a link layer acknowledgment. To send a packet, the sender repeatedly sends the same packet until a link layer acknowledgment is received.

Adam Dunkels, The Contiki Radio Duty Cycling Protocol, SICS Technical Report T2011:13, December 2011.

ContikiMAC Timing



$t_i < t_c$



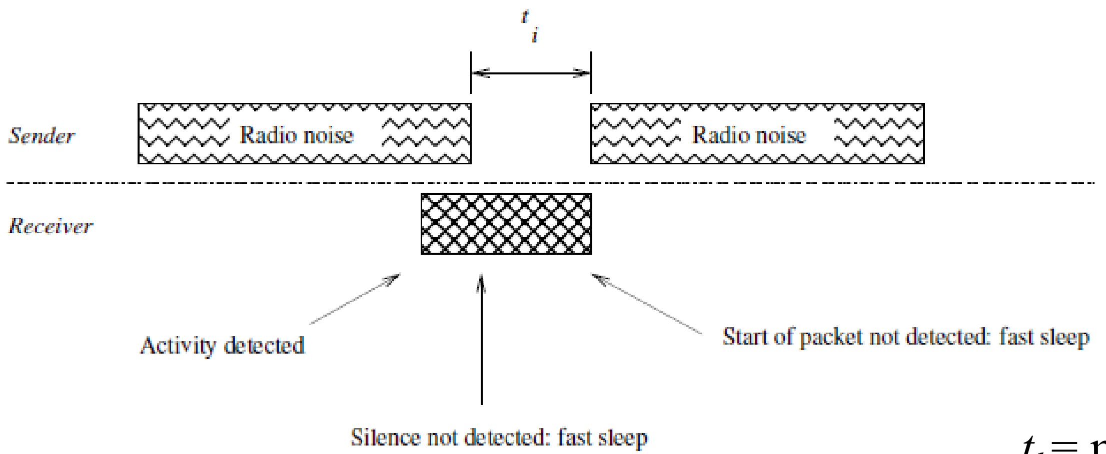
$t_s > t_r + t_c + t_r$

Adam Dunkels, **The Contiki Radio Duty Cycling Protocol**, SICS Technical Report T2011:13, December 2013.

ContikiMAC Sleep Optimization

PerLab

Allows potential receivers go to sleep quickly if the CCA woke up due to spurious radio



t_l = maximum packet transmission time

Figure 5: The ContikiMAC fast sleep optimization: if a silence period is not detected before t_l, the receiver goes back to sleep. If the silence period is longer than t_i, the receiver goes back to sleep. If no packet is received after the silence period, even if radio activity is detected, the receiver goes back to sleep.

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Adam Dunkels, The Contiki Radio Duty Cycling Protocol, SICS Technical Report T2011:13, December 2011.

ContikiMAC Transmission Phase Lock

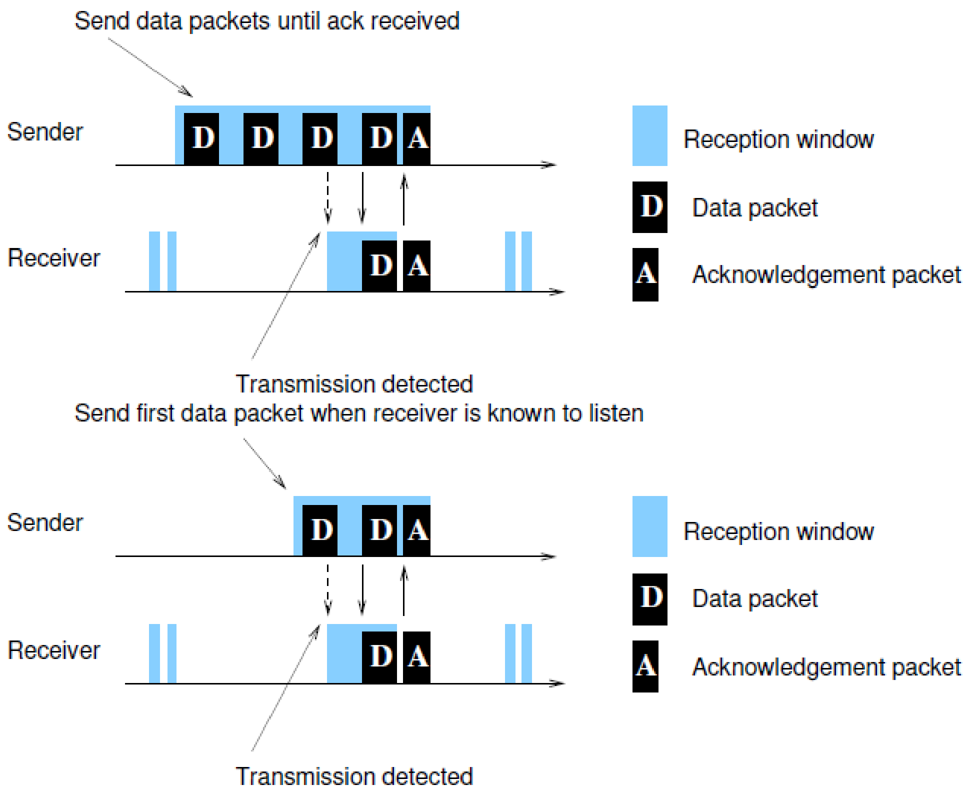
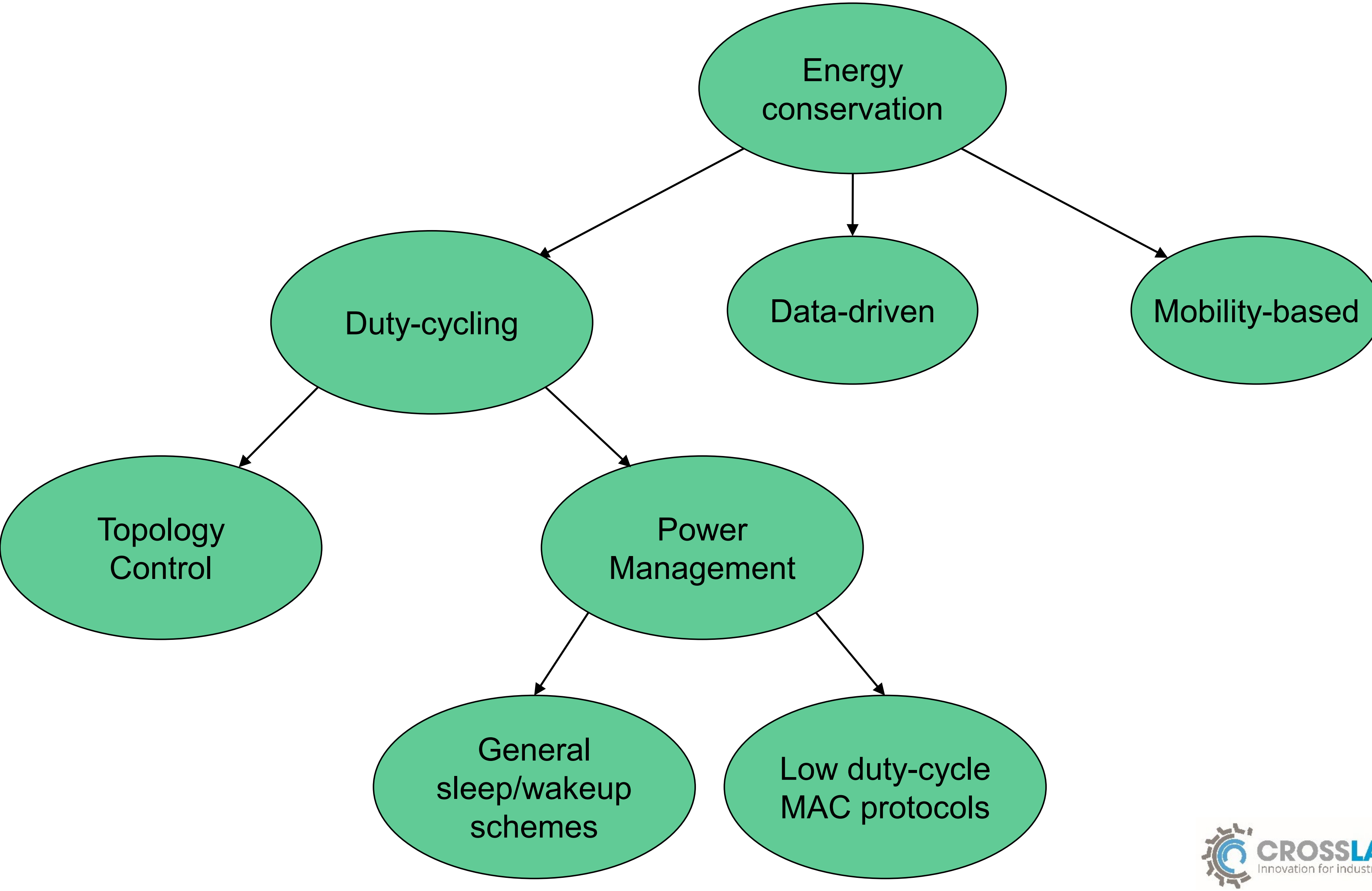


Figure 6: Transmission phase-lock: after a successful transmission, the sender has learned the wake-up phase of the receiver and subsequently needs to send fewer transmissions.

Adam Dunkels, The Contiki Radio Duty Cycling Protocol, SICS Technical Report T2011:13, December 2011.

Summary


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

Summary

- 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?

Summary

- 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)
- Power Management removes 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

Readings

- G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, **Energy Conservation in Wireless Sensor Networks**, *Ad Hoc Networks*, Vol. 7, N. 3, pp. 537-568, May 2009. Elsevier .

Sensor Energy Management

Critical Applications

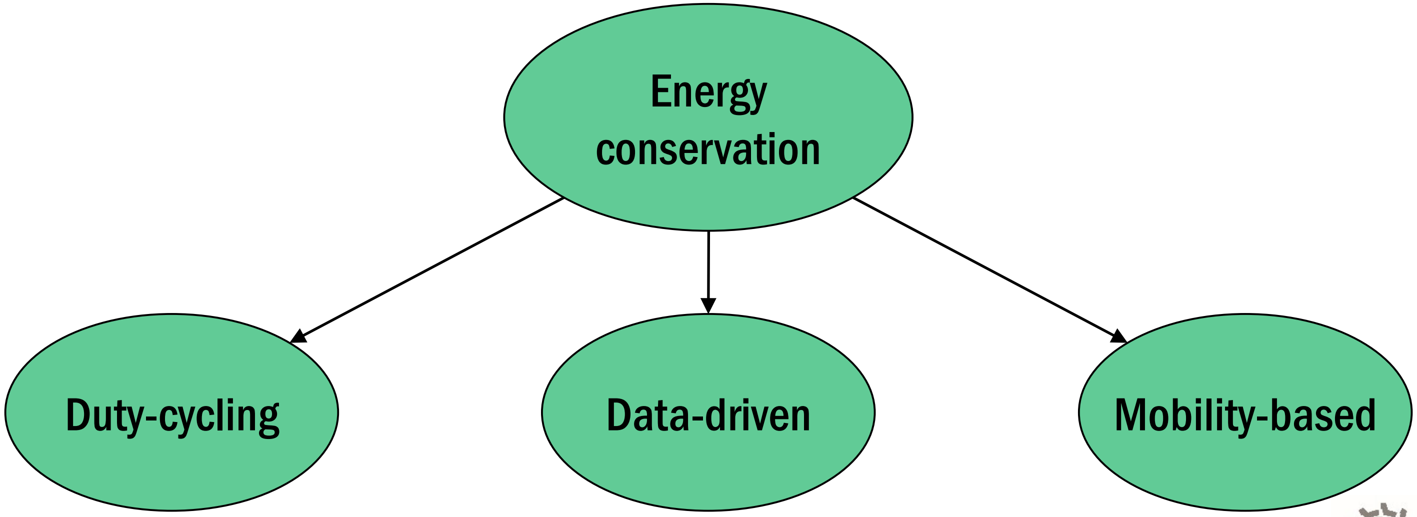
- Monitoring of complex phenomena
  - Structural Health Monitoring
  - Seismic events
  - Avalanche prevention (snow sensors)
  - …
- Monitoring of hazardous environments
  - Detection of hazardous conditions
  - Detection of liquid/gas leakage
  - Remote monitoring of contaminated areas
- Application with special requirements
  - Smart Cities
  - Smart Buildings
  - Industrial Applications

Critical Applications: Characteristics

- Pre-arranged topologies
  - Random topologies never occur in certain applications
  - Star topologies are often used
- Complex Sensing Units
  - The energy consumption for sensing cannot be neglected wrt communication
- Large Data Volumes
  - Cameras, complex sensors
  - Need to build an accurate model
- …

Energy conservation

- Goal
  - Use the available energy very efficiently so as to extend the network lifetime to meet the application requirements
- Different approaches
  - Mainly targeted to the radio subsystem (typically, the most energy consuming component)



Power Consumption of Common Radios

PerLab

Radio	Producer	Power Consumption	
		Transmission	Reception
JN-DS- JN513x (Jennic)	Jennic	111 mW (1 dBm)	111 mW
CC2420 (Telos)	Texas Instruments	35 mW (0 dBm)	38 mW
CC1000 (Mica2/Mica2dot)	Texas Instruments	42 mW (0 dBm)	29 mW
TR1000 (Mica)	RF Monolithics	36 mW (0 dBm)	9 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*

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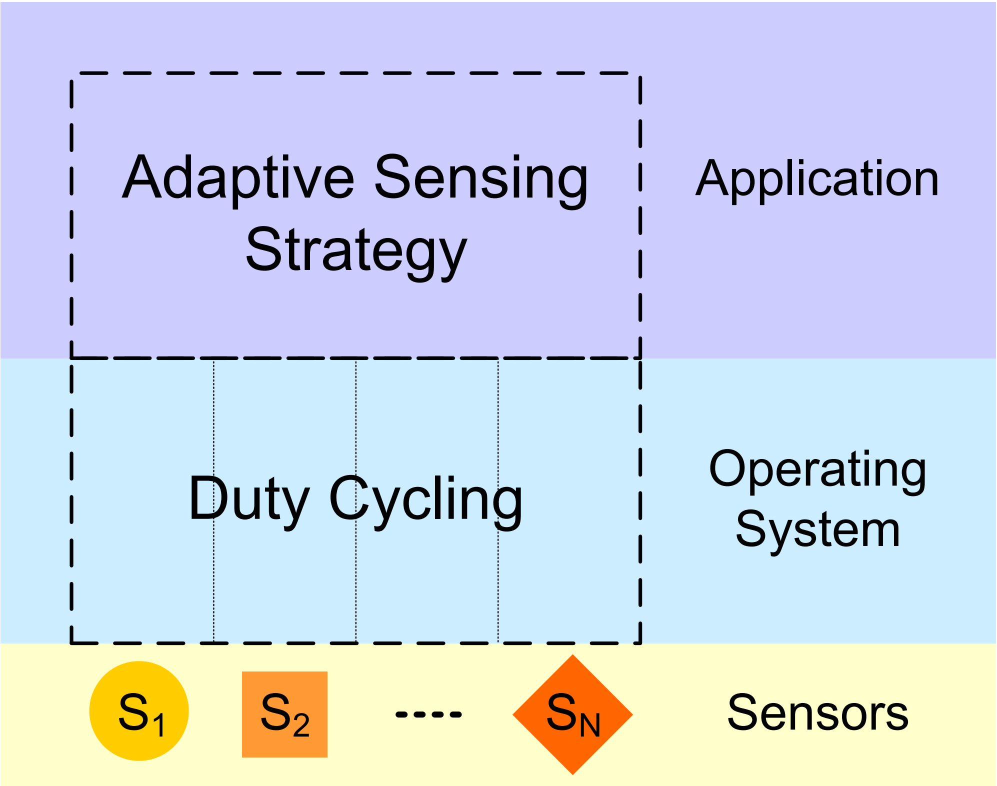
Power Consumption of Some Sensors

Sensor	Producer	Sensing	Power Consumption
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*

Sensor Energy Management



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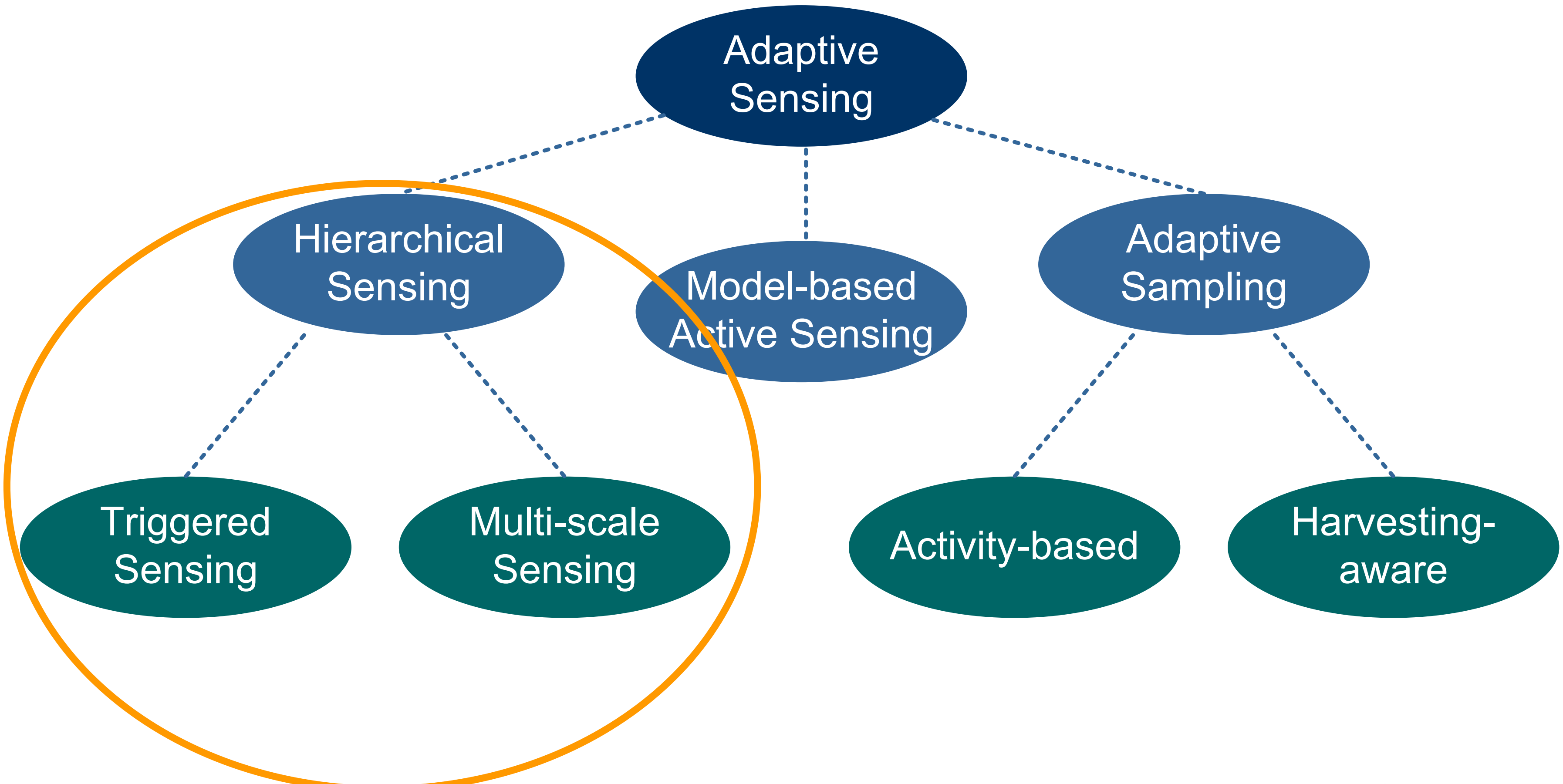
Adaptive Sensing Strategies



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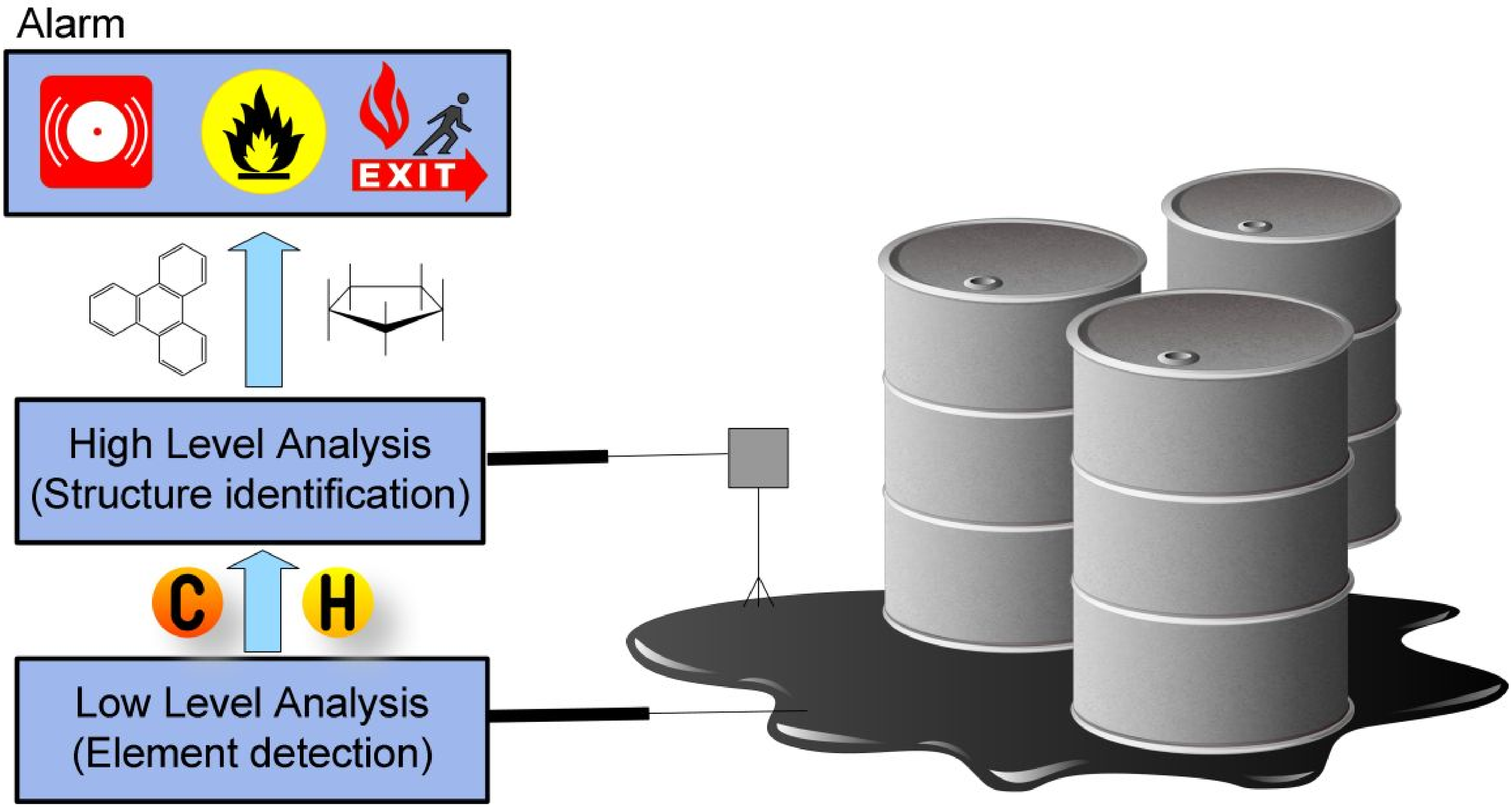
Hierarchical Sensing

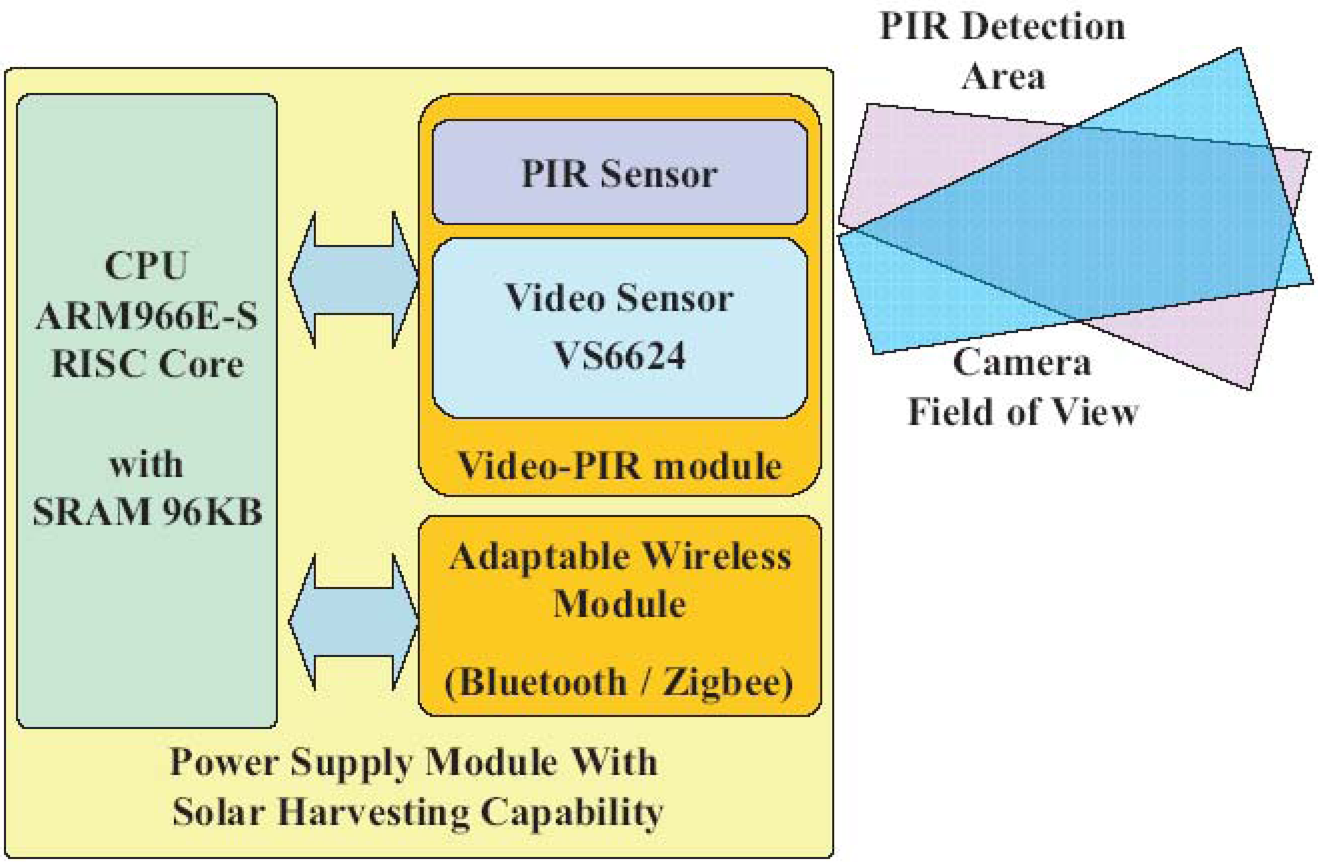


Hierarchical Sensing

- Basic idea
  - ⇨ Using different sensors with different power consumption and resolution properties
  - ⇨ Accuracy/energy consumption trade-off
- Triggered sensing
  - ⇨ Low-power low resolution sensors trigger high-power high-accuracy sensors
- Multi-scale sensing
  - ⇨ Low-resolution wide area sensors are used to identify areas of interests
  - ⇨ High resolution sensors are, then, switched on for more accurate measurements

Triggered Sensing

- **Low-power Low-cost Video sensor**



M. Magno, D. Brunelli, P. Zappi, L. Benini, **A Solar-powered Video Sensor Node for Energy Efficient Multimodal Surveillance**, Proc. *EUROMICRO Conference on Digital System Design (DSD 2008),* Parma, Italy, 2008.

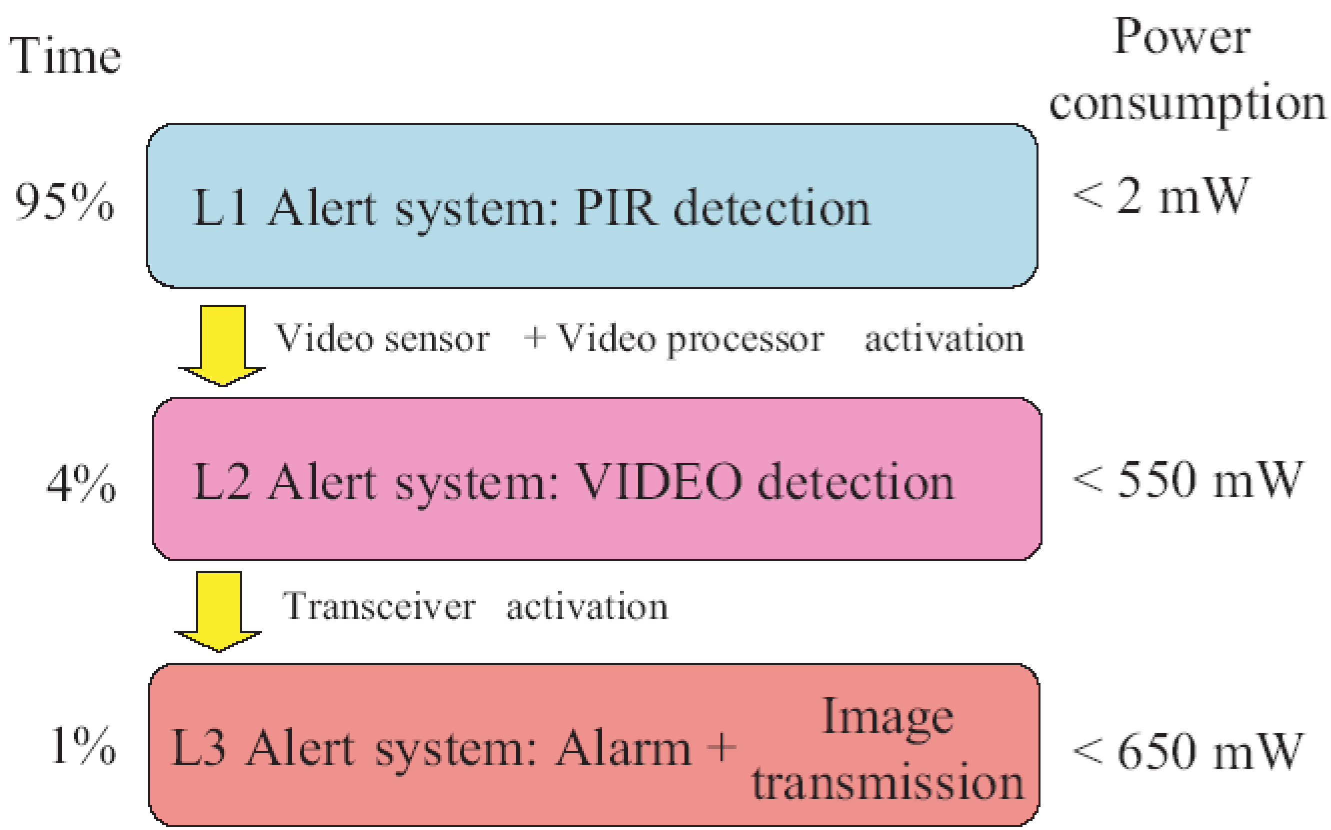
Triggered Sensing

- **Low-power Low-cost Video sensor**
  - Video surveillance, traffic control, intrusion detection, …
  - CMOS video camera (550 mW)
  - Pyroelectric InfraRed (PIR) sensor (2 mW)
  - Bluetooth/ZigBee module (100 mW)
  - Energy harvesting system (solar cells)

M. Magno, D. Brunelli, P. Zappi, L. Benini, **A Solar-powered Video Sensor Node for Energy Efficient Multimodal Surveillance**, Proc. *EUROMICRO Conference on Digital System Design (DSD 2008),* Parma, Italy, 2008.

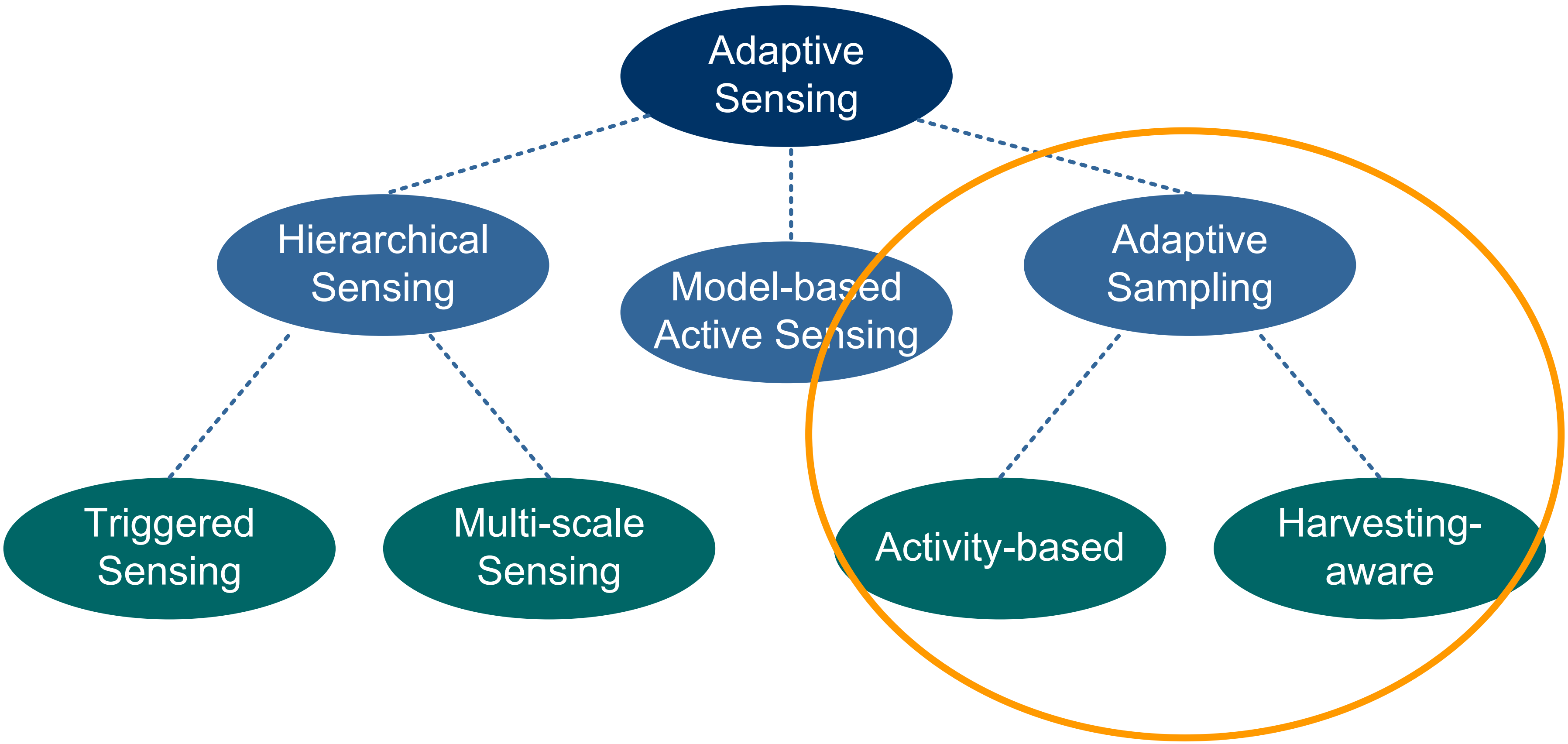
Triggered Sensing

- **Low-power Low-cost Video sensor**
  - A typical scenario

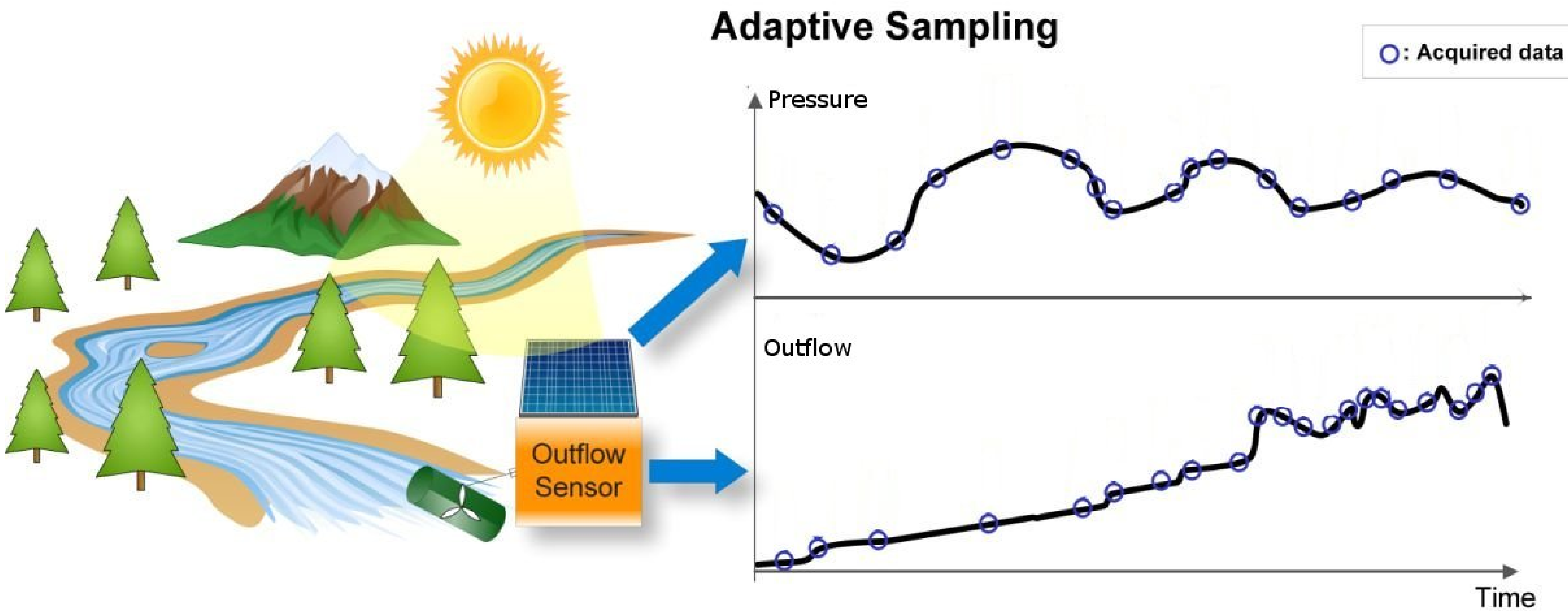


Courtesy of M. Magno, University of Bologna

Adaptive Sensing Strategies



Adaptive Sampling



Activity-based Adaptive Sampling

PerLab

- Adapts the sampling rate to the dynamics of the phenomenon under monitoring
- Exploits
  - Temporal Correlation
  - Spatial Correlation
- Traditionally used for optimizing the communication process
  - Lower number of sensor nodes to activate
  - Lower amount of data to transmit
- Recently proposed also for sensor’s energy management

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Activity-based Adaptive Sampling

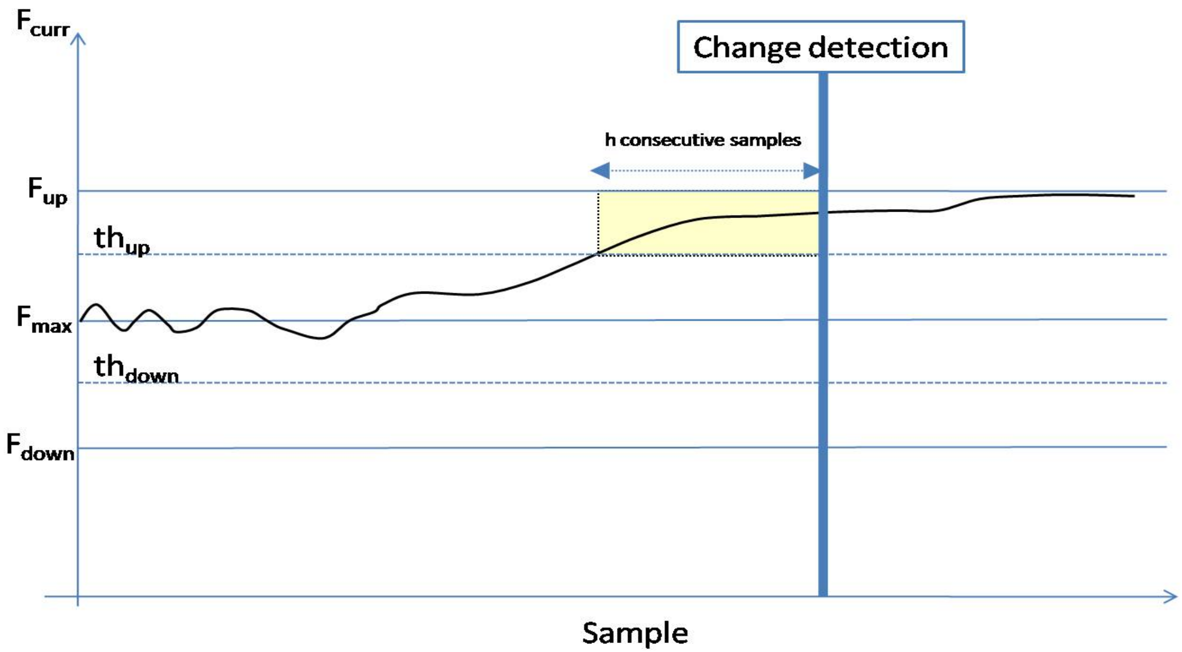
Key Questions

- When to change?
- How to change?

Adaptive Sampling Algorithm (ASA)

PerLab

- Based on the Nyquist Theorem
- Dynamic computation of maximum frequency
- Dynamic adaptation of the sampling rate based on the signal's dynamics



C. Alippi, G. Anastasi, M. Di Francesco, M. Roveri, **Adaptive Sampling for Effective Energy Management in Sensor Networks with Energy-hungry Sensors**, *IEEE Transactions on Instrumentation and Measurement,* Vol. 59, N. 2, February 2010.

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The frequency change detection

- Modified CUSUM → basic idea:
  1. Estimate the maximum frequency $\overline{F}_{\max}$ of the signal by using a training sequence (*W* samples)
  2. Define two alternative hypothesis F_{up}, F_{down} for the maximum frequency of the signal during the operational life
  3. If the current maximum frequency F_{curr} of the signal (*W* samples) during the operational life is closer to F_{up} or F_{down} than $\overline{F}_{\max}$ for *h* consecutive samples, a change is detected in the maximum frequency of the signal
  4. A new sampling frequency is defined

The ASA Algorithm

Algorithm 1: ASA (c, δ, h)

1. Store the W initial samples that come from the process in the *Dataset;*
2. Estimate $\overline{F}_{\max}$ on the *Dataset* and set $F_c = c\overline{F}_{\max}$;
3. Define $F_{up} = \min\{(1+\delta) \cdot \overline{F}_{\max}, F_c/2\}$; $F_{down} = (1-\delta) \cdot \overline{F}_{\max}$;
4. $h_1 = 0$, and $h_2 = 0$; $i = W + 1$;

The ASA Algorithm

5\. **while** (1){

6\. Acquire the ith sample and add it to the *Dataset*;

7\. Estimate the current maximum frequency F_{curr} on the sequence *Dataset* $(\mathrm{i} - W + 1, \mathrm{i})$;

8\. **if** $(|F_{curr} - F_{up}| < |F_{curr} - \overline{F}_{\max}|)$

9\. $h_1 = h_1 + 1;\ h_2 = 0;$

10\. **else if** $(|F_{curr} - F_{down}| < |F_{curr} - \overline{F}_{\max}|)$
$h_2 = h_2 + 1;\ h_1 = 0;$

11\. **else** $h_1 = 0;\ h_2 = 0;$

12\. **if** $(h_1 > h) \| (h_2 > h)$ {

13\. $F_c = cF_{curr};$

14\. $F_{up} = \min\{(1 + \delta) \cdot \overline{F}_{\max}, F_c/2\};$

15\. $F_{down} = (1 - \delta) \cdot \overline{F}_{\max};$

16\. $\overline{F}_{\max} = F_{curr};$

17\. }

18\. }

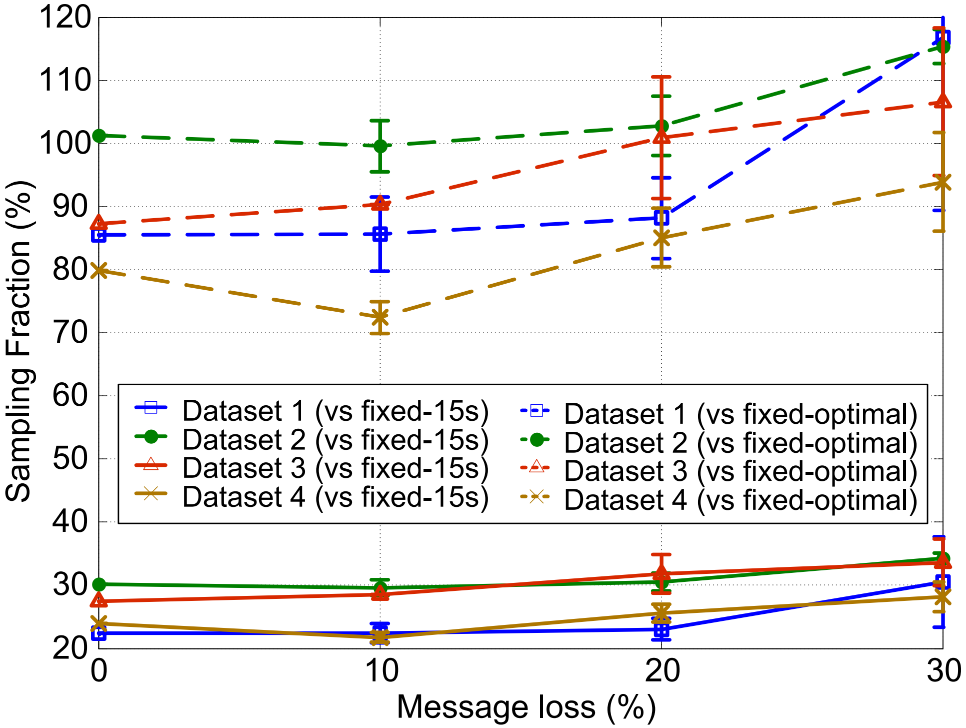
Parameter selection: c, *h* and *W*

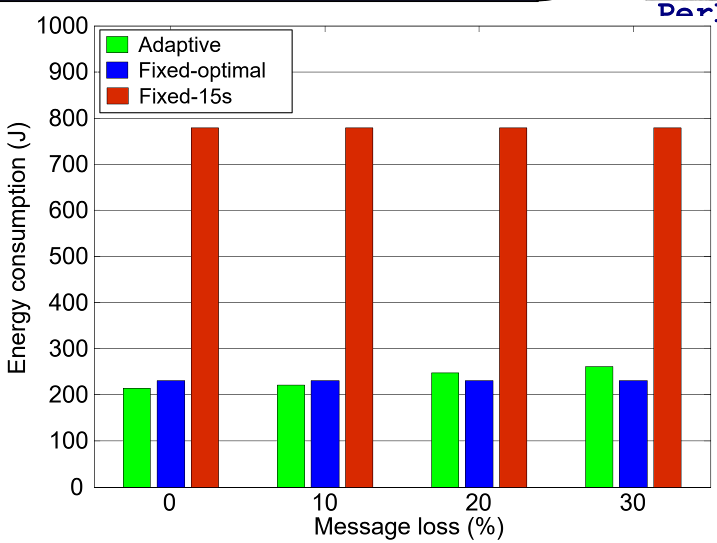
- Parameter *c*
  - *confidence* parameter for the maximum frequency detection ($c > 2$, Nyquist)
- Parameter *h*
  - critical to the *robustness* of the algorithm
    - ⇨ low values (e.g., 1 or 2): quick detection but possible false positives
    - ⇨ high values (e.g., 1000): few false positives but less promptness in detecting the changes
- Parameter *W*
  - critical to the *accuracy* of the algorithm
    - ⇨ low values: not accurate estimation but low energy consumption
    - ⇨ high values: accurate estimation of F_c but energy consumption

A-priori information about the process could provide the designer with a suitable parameter

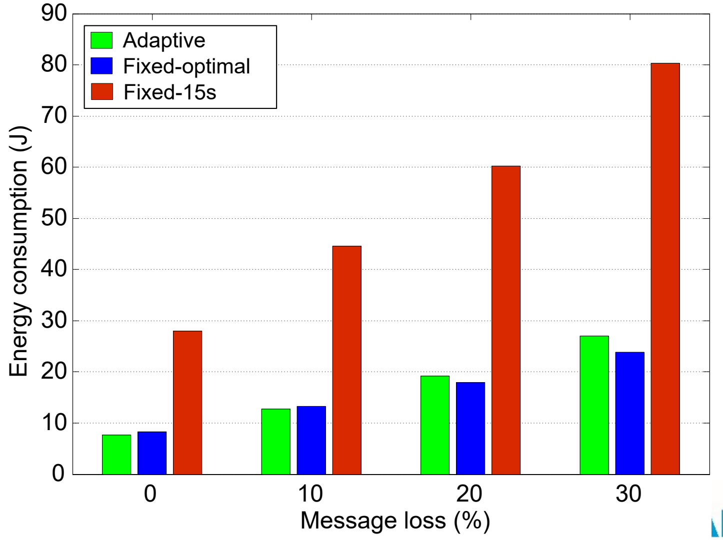
Adaptive Sampling Algorithm (ASA)

$$\text{Sampling Fraction} = \frac{\text{Number of Samples with } \textit{Adaptive} \text{ Sampling}}{\text{Number of Samples with } \textit{Fixed} \text{ Sampling}}$$





Sensor Energy Consumption



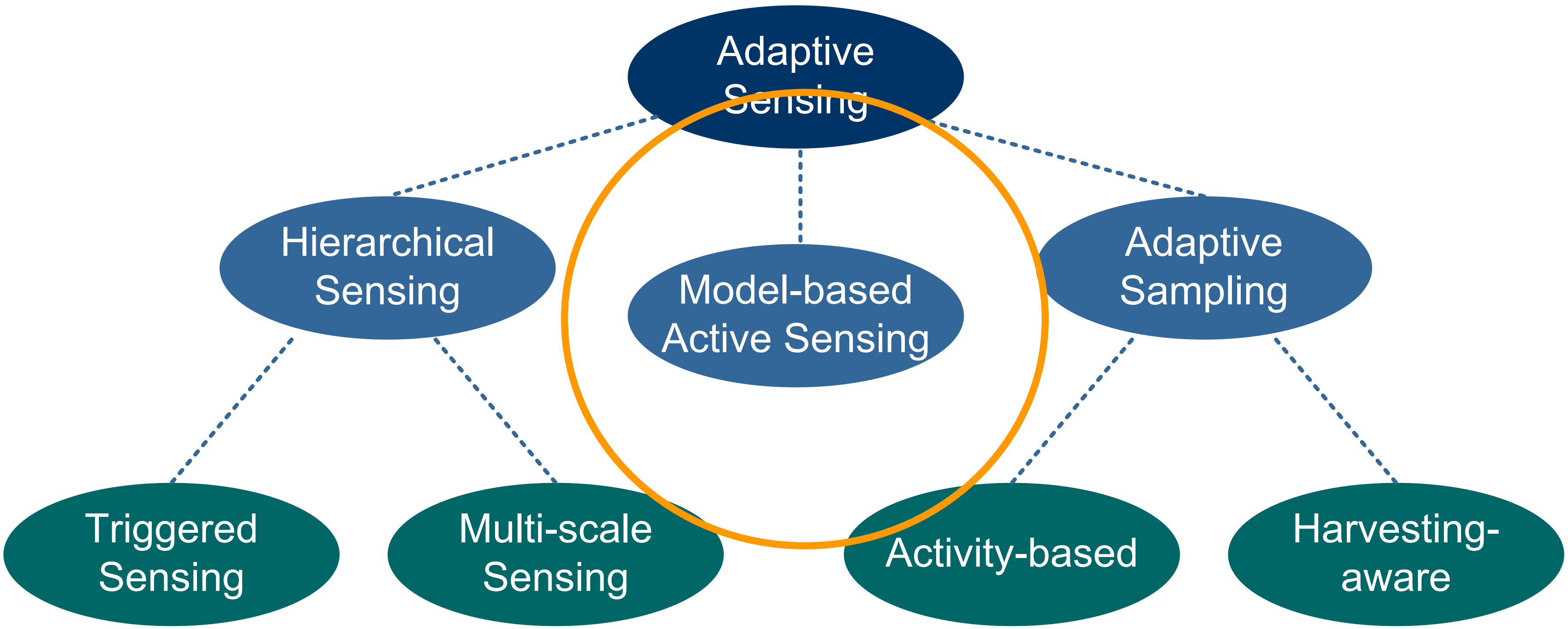
Radio Energy Consumption

Harvesting-aware

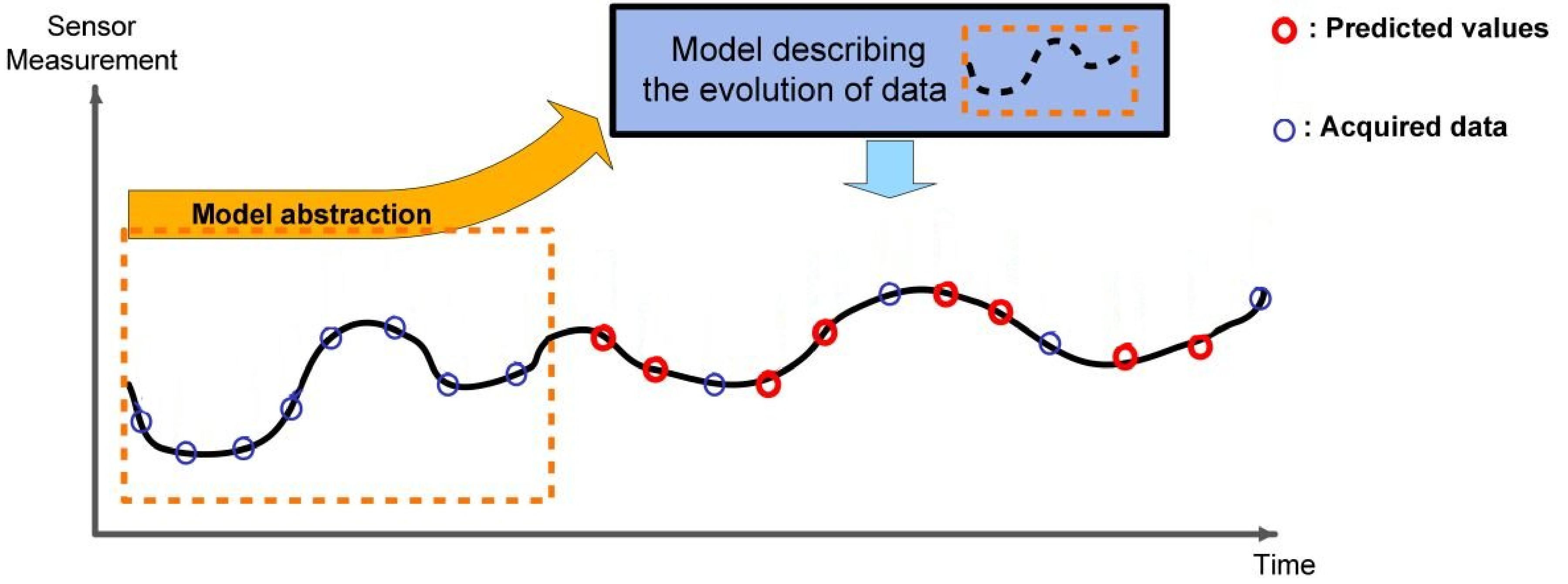
- Decentralized Adaptive Sampling
  - Sampling rate adapted on the basis of the available energy
    - ⇨ Nodes are powered by solar cells
  - Goal: minimize the total uncertainty error, given that the sensor can take a maximum number of samples on that day

J. Kho, A. Rogers, N. R. Jennings, **Decentralised Adaptive Sampling of Wireless Sensor Networks**, Proc. International Workshop on Agent Technology for Sensor Networks (ATSN 2007), Honolulu, Hawaii, USA, May 14, 2007.

Adaptive Sensing Strategies



Model-based Active Sensing



Model-based Active Sensing

- Basic idea
  - Learn the spatio-temporal relationship among measurements
  - and use this knowledge to make the sensing process energy efficient
  - A model of the phenomenon to be monitored is built
    - ⇨ And updated dynamically, based on measurements from sensor nodes
  - The sensor node decides whether
    - ⇨ To acquire a new sample through a measurement
    - ⇨ To estimate this new sample, with the desired accuracy, through the model

- Different kind of models
  - Probabilistic models, Regressive models, …
  - The most appropriate model depends on the specific application

Model-based Active Sensing (cont'd)

- Barbie-Q (BBQ) Query System
  - Probabilistic model
    - ⇨ based on time-varying multivariate Gaussians
  - Query planner
    - ⇨ Executed at the base station
  - The model is built and updated dynamically based on sensor readings
  - The system decides the most efficient way to answer a query with the required confidence level
    - ⇨ Some values are acquired from sensors, some others are derived from the model

A. Deshpande, C. Guestrin, S. Madden, J. M. Hellerstein, W. Hong, **Model-Driven Data Acquisition in Sensor Networks**, Proc. International Conference on Very Large Data Bases (VLDB 2004), Toronto, Canada, 29 August - 3 September, 2004.

Model-based Active Sensing (cont'd)

- Utility-based Sensing and Comm. (USAC)
  - Glacial environment monitoring
  - Linear regression model (sensor node)
    - ⇨ data are expected to be piecewise linear functions of time
  - If the next observed data is within the CI the sampling rate is reduced for energy efficiency
  - Otherwise, the sampling rate is set to the maximum to incorporate the change in the model

P. Padhy, R. K. Dash, K. Martinez, N. R. Jennings, **A Utility-Based Sensing and Communication Model for a Glacial Sensor Network**, Proc. International Joint Conference on Autonomous Agents and Multi-agent Systems (AAMAS 2006), Hakodate, Japan, May 08-12, 2006

Readings

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

Questions