

Energy Management

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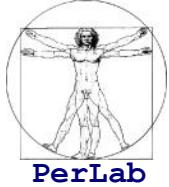


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 CROSSLAB
Innovation for industry 4.0

Overview



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

The Energy Problem

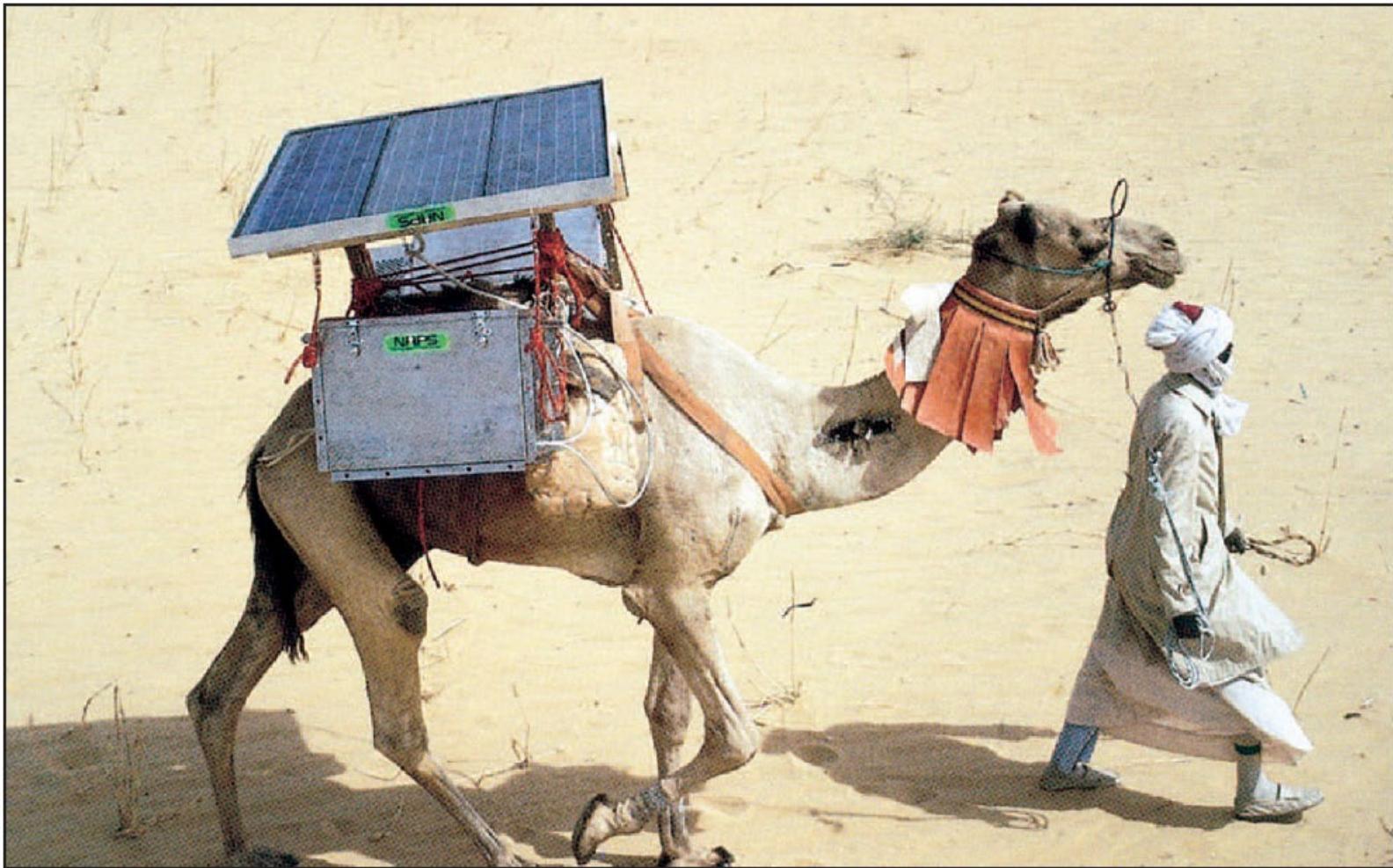
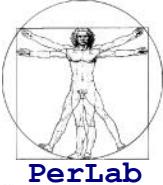
The energy problem



- 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

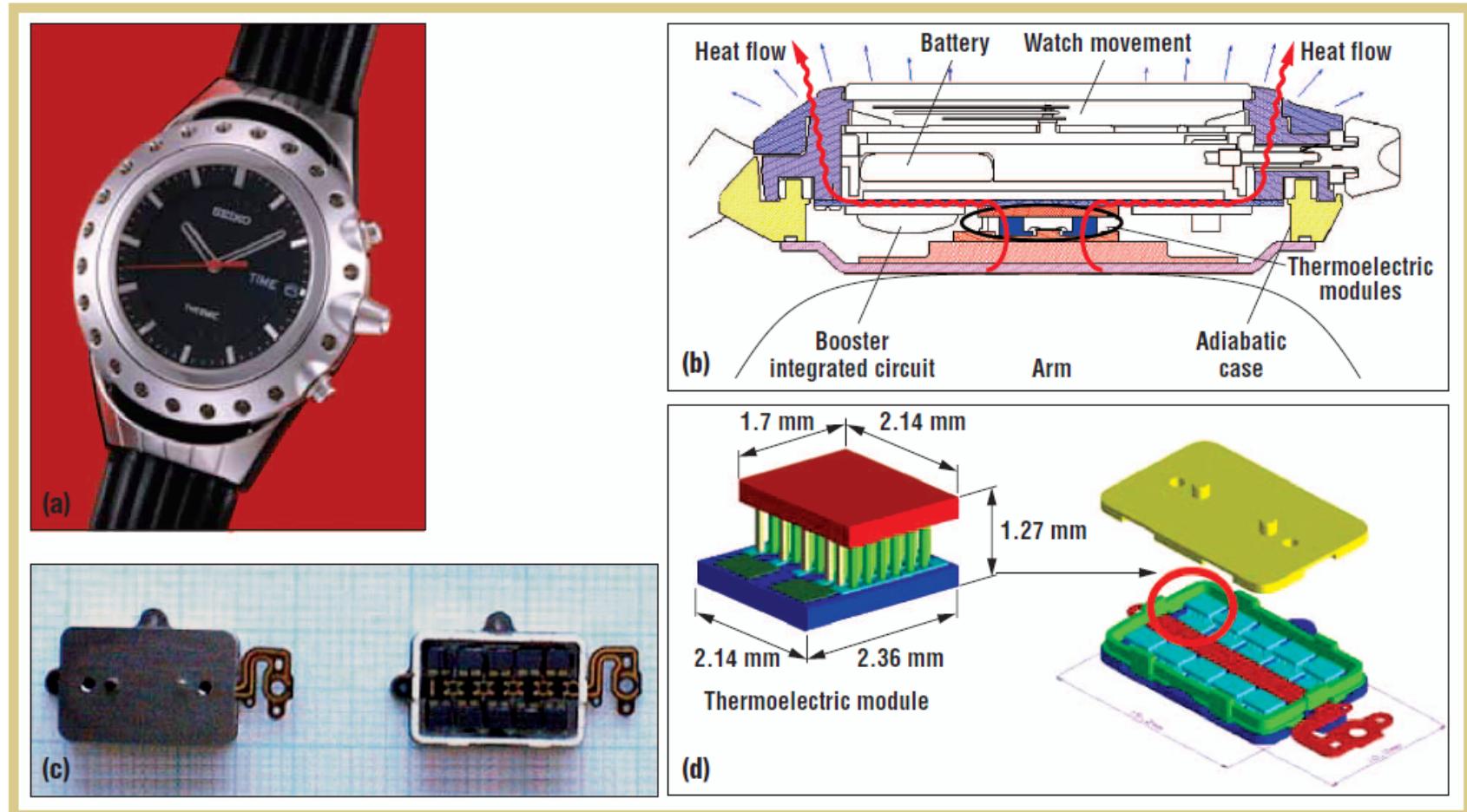
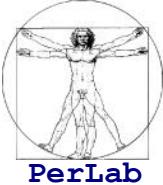


Figure 2. The Seiko Thermic wristwatch: (a) the product; (b) a cross-sectional diagram; (c) thermoelectric modules; (d) a thermopile array. Copyright by Seiko Instruments.

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

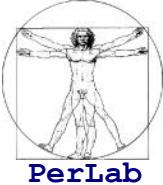
How to scavenge energy?



■ 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

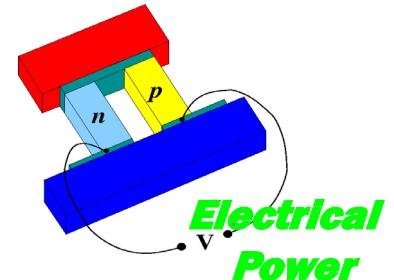
How to scavenge energy?



■ 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

HEAT



■ Nano-structured Thermoelectric Generators

- Reduced Thermal Conductivity
 - ⇒ Bulk silicon: 148 W/mK
 - ⇒ Silicon nanowires: 1 W/mK
- Expected Efficiency : up to 30 %

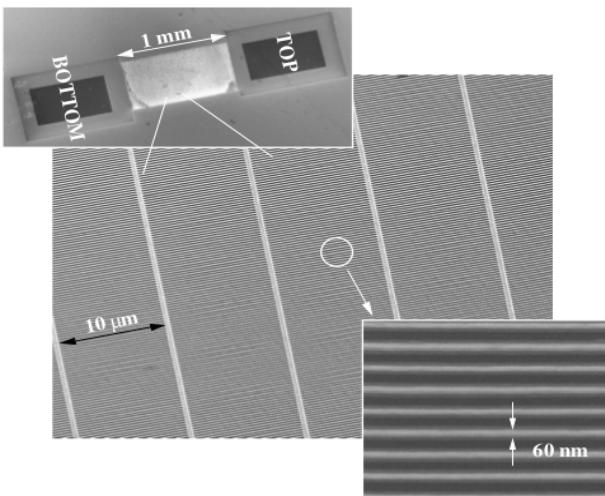
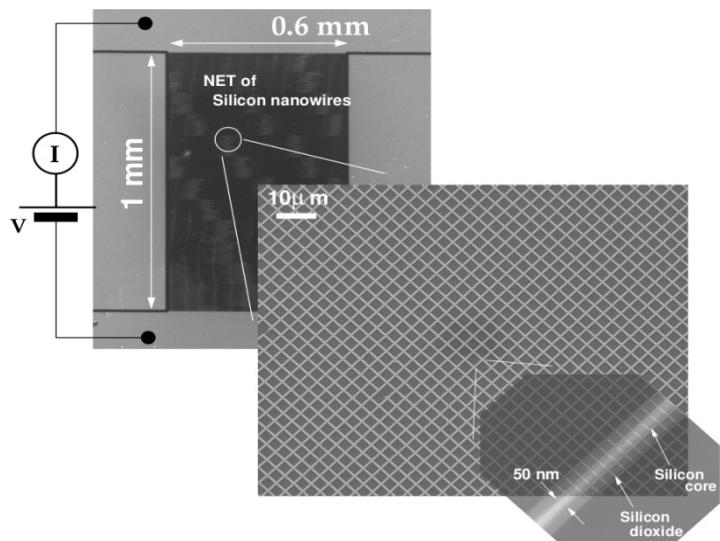
How to scavenge energy?



Nanofabrication Lab

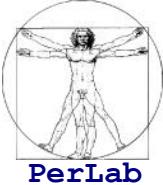
■ NanoPOL Project

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



- Exploitation in many potential scenarios, including WSNs

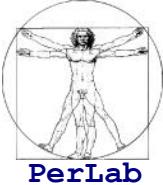
How to scavenge energy?



■ 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

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

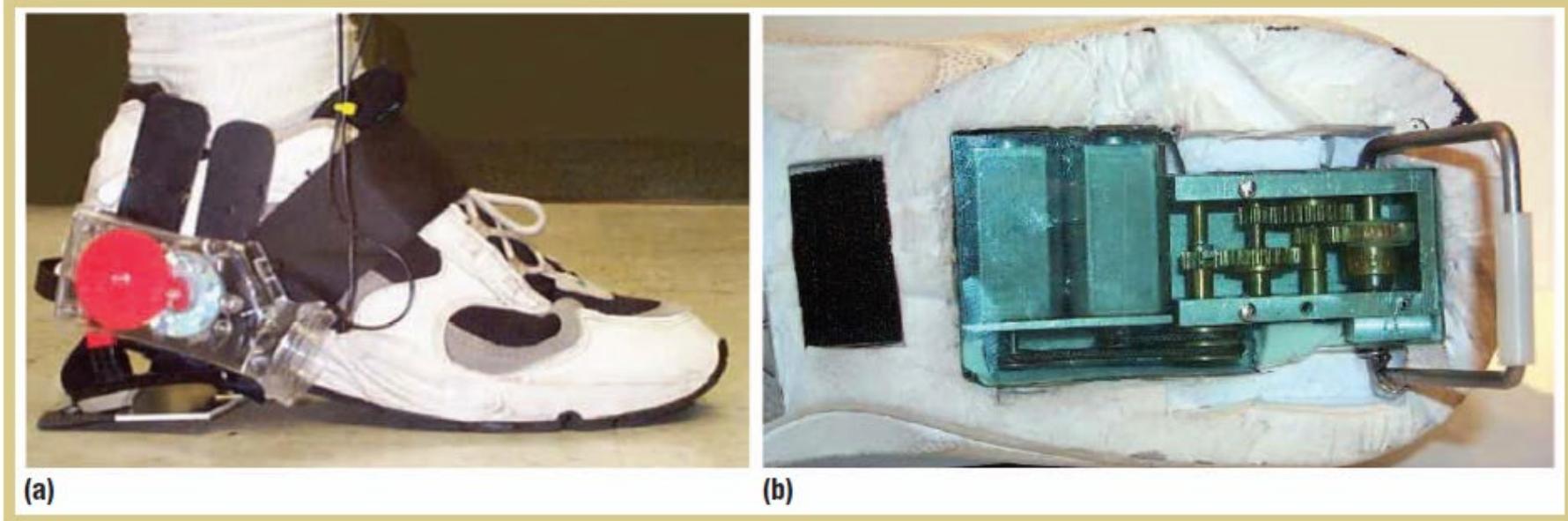


Figure 6. Magnetic generators in shoes at the MIT Media Lab: (a) A strap-on overshoe produced an average of 250 mW during a standard walk, powering a loud radio; (b) an assembly hosting twin motor-generators and step-up gears embedded directly into a sneaker's sole (without springs or flywheels for energy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

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

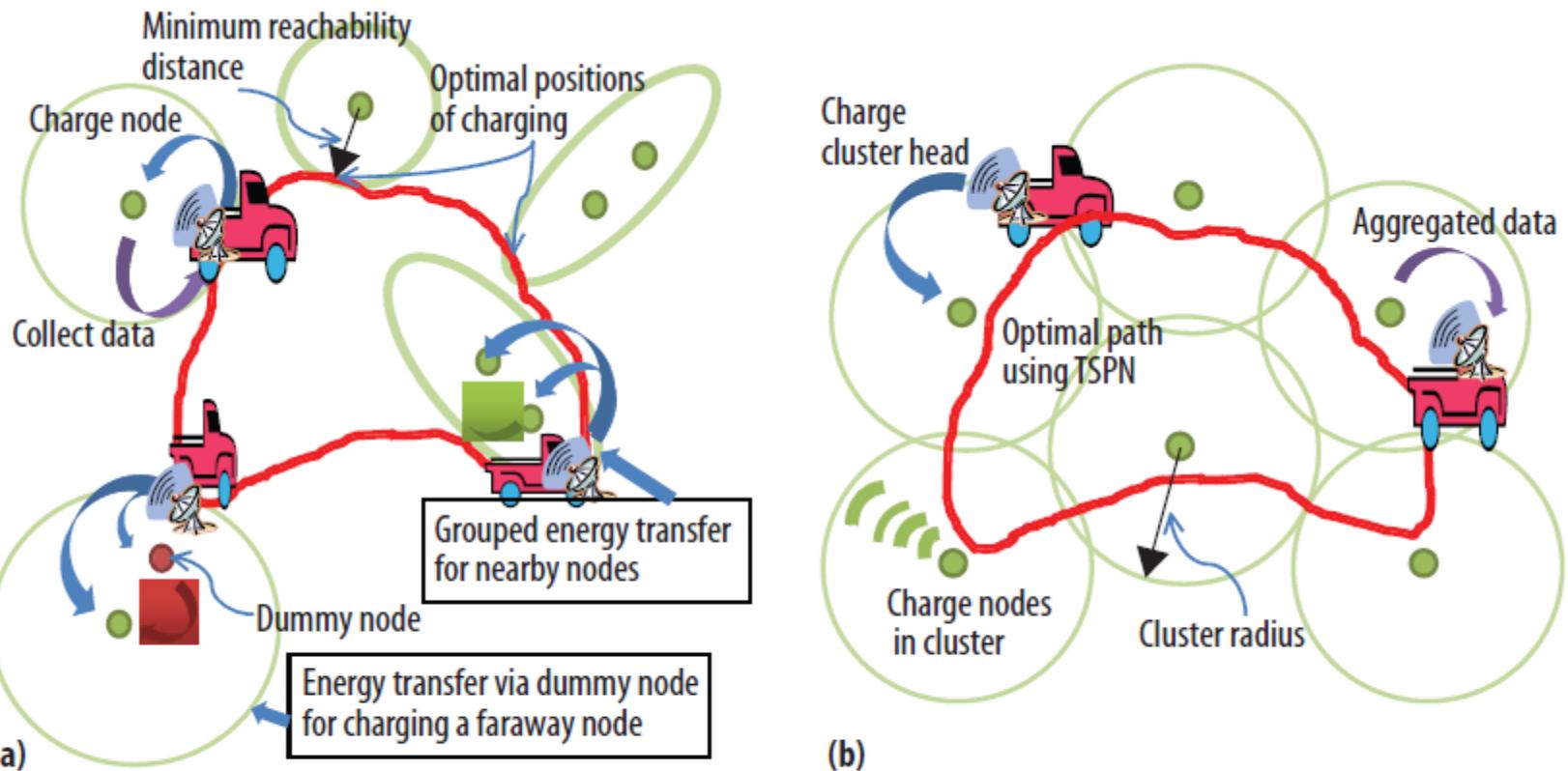


Figure 1. Examples of energy transfer and data collection with integrated data and energy mules (IDEMs) in (a) a flat network topology and (b) a clustered network topology.

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?



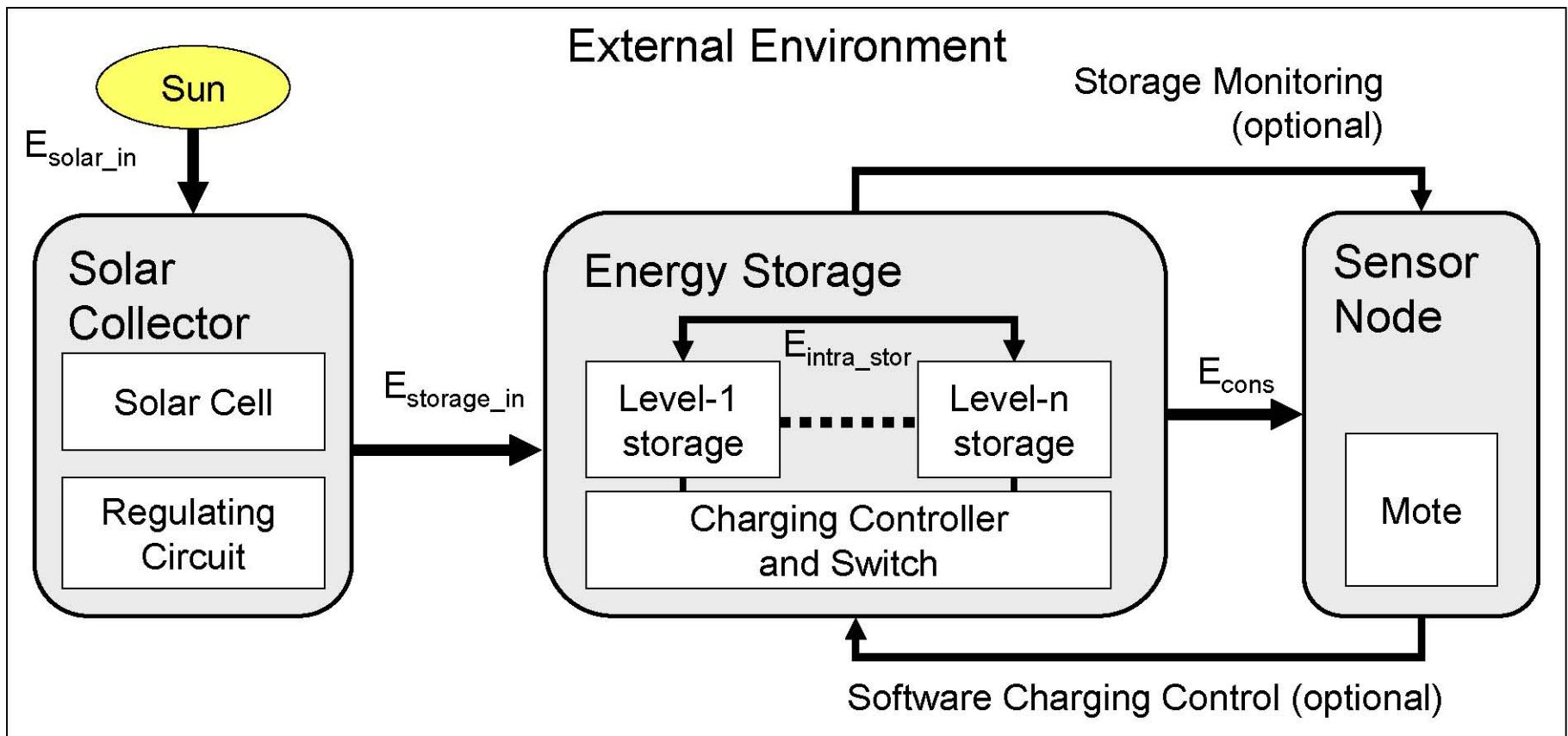
■ Solar cells

- 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

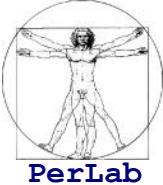


- Developed at NESL (UCLA)
 - the system learn its own energy environment and adapt its power consumption accordingly.
 - not only the energy source varies over time, but also the energy available at different locations
 - ⇒ different nodes of the sensor network differs.
 - Tasks scheduled according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



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

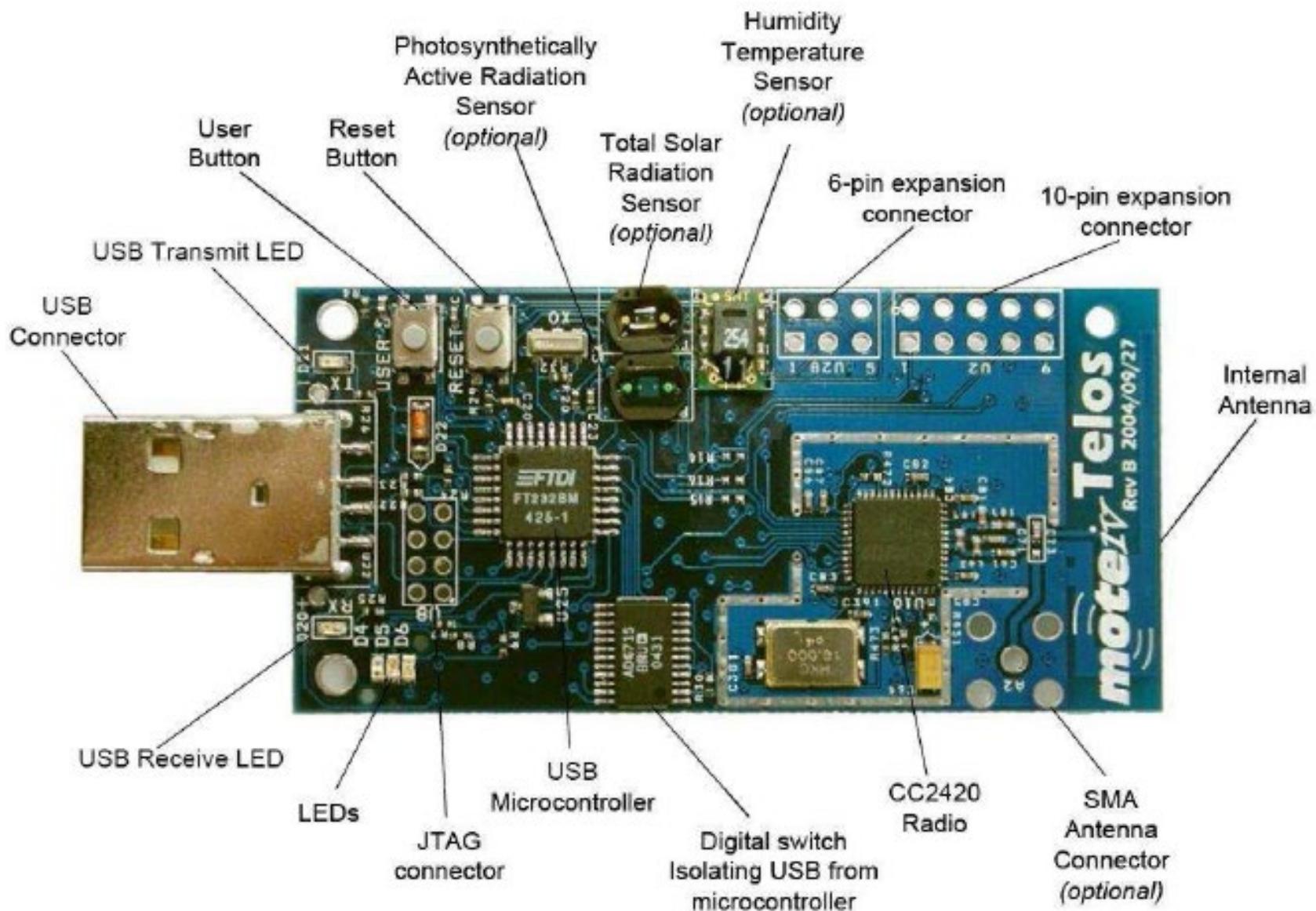
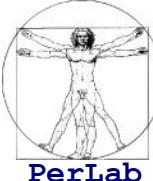
Concluding remarks



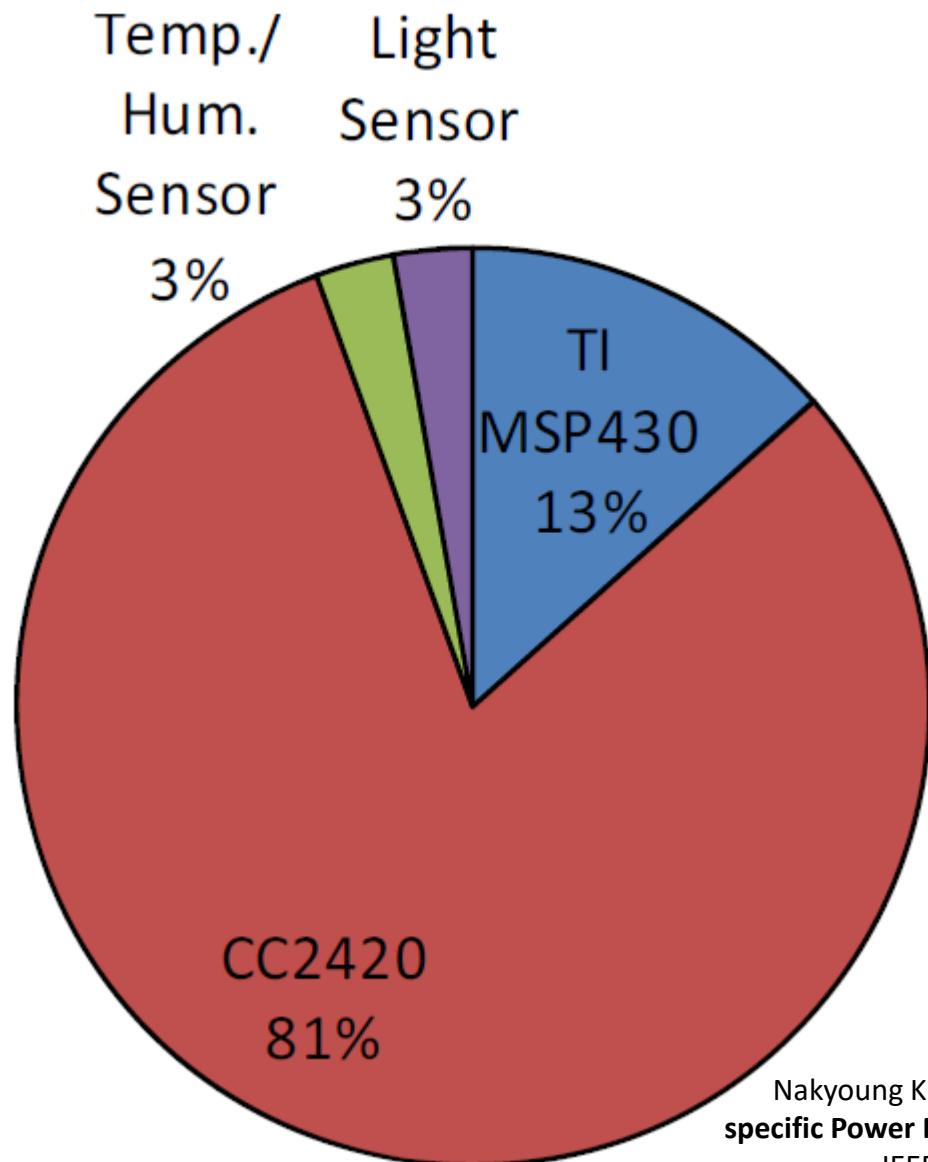
- **Energy harvesting is a very promising approach**
 - But, currently the conversion process is not efficient enough
- **Can be used to power**
 - very simple devices
 - as a complementary power source, e.g., to replenish a battery in the background.
- ***Energy that can be collected is virtually infinite***
 - 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

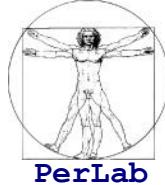


Nakyung Kim, Sukwon Choi, Hojung Cha, **Automated Sensor-specific Power Management for Wireless Sensor Networks**, Proc. IEEE MASS 2008, Atlanta, USA, Sep. 29 – Oct. 2, 2008





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 μ A	36 μ W



Source: **Chipcon CC2420 Data sheet**

2.4 GHz IEEE 802.15.4/ZigBee-ready RF Transceiver

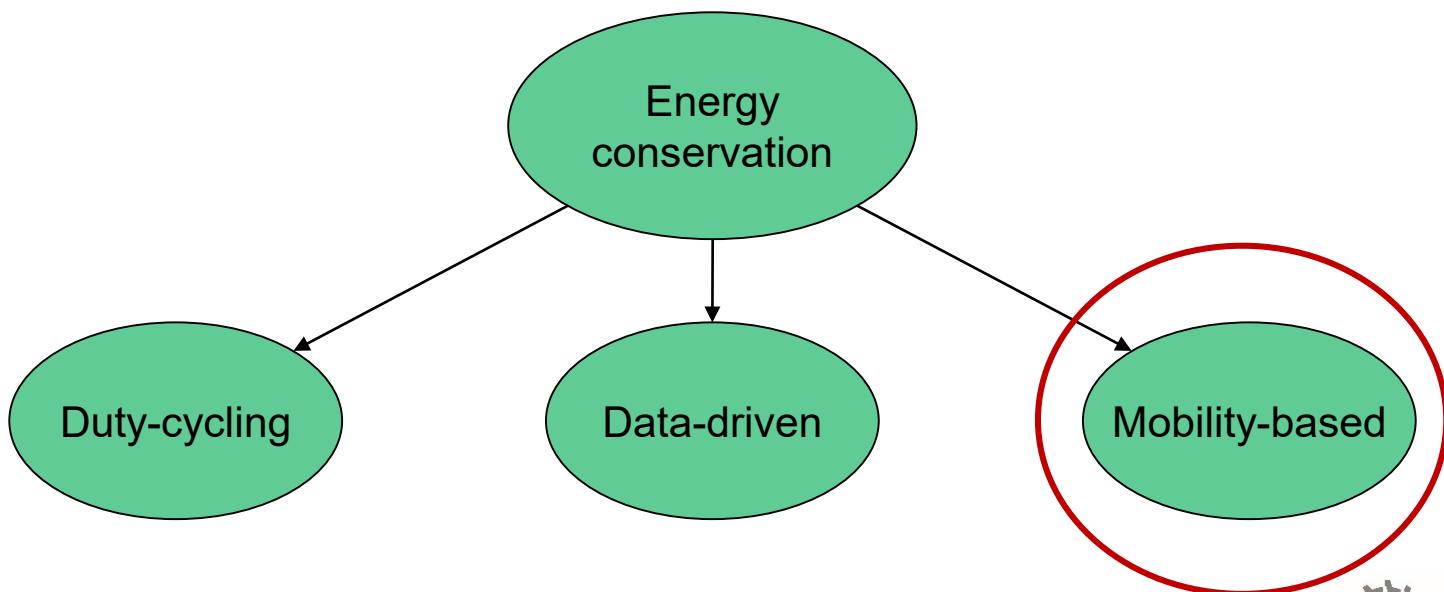
<http://focus.ti.com/docs/prod/folders/print/cc2420.html>

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

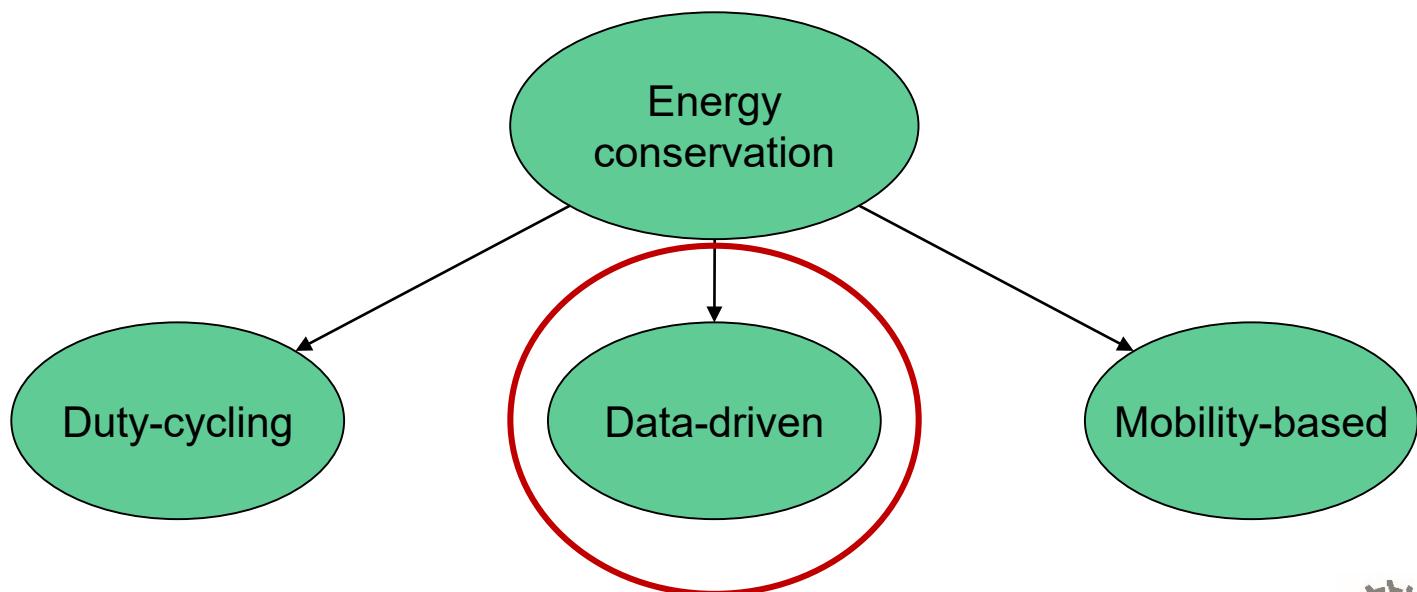


Energy conservation

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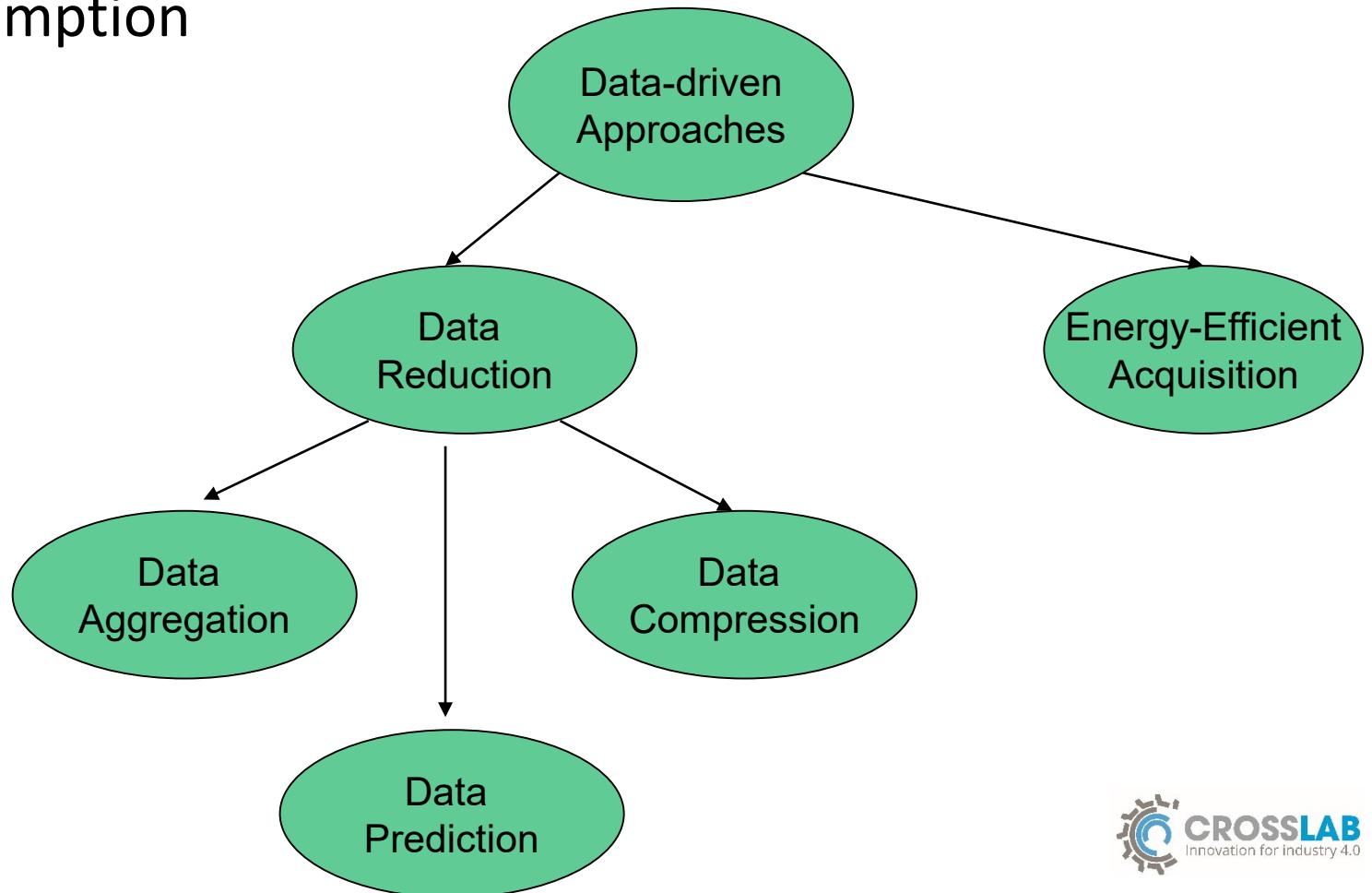
■ Different approaches



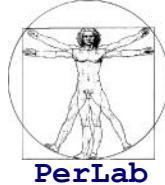
Data Driven Approach

Data-driven approaches

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

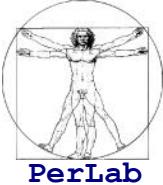


Energy efficient acquisition



- 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

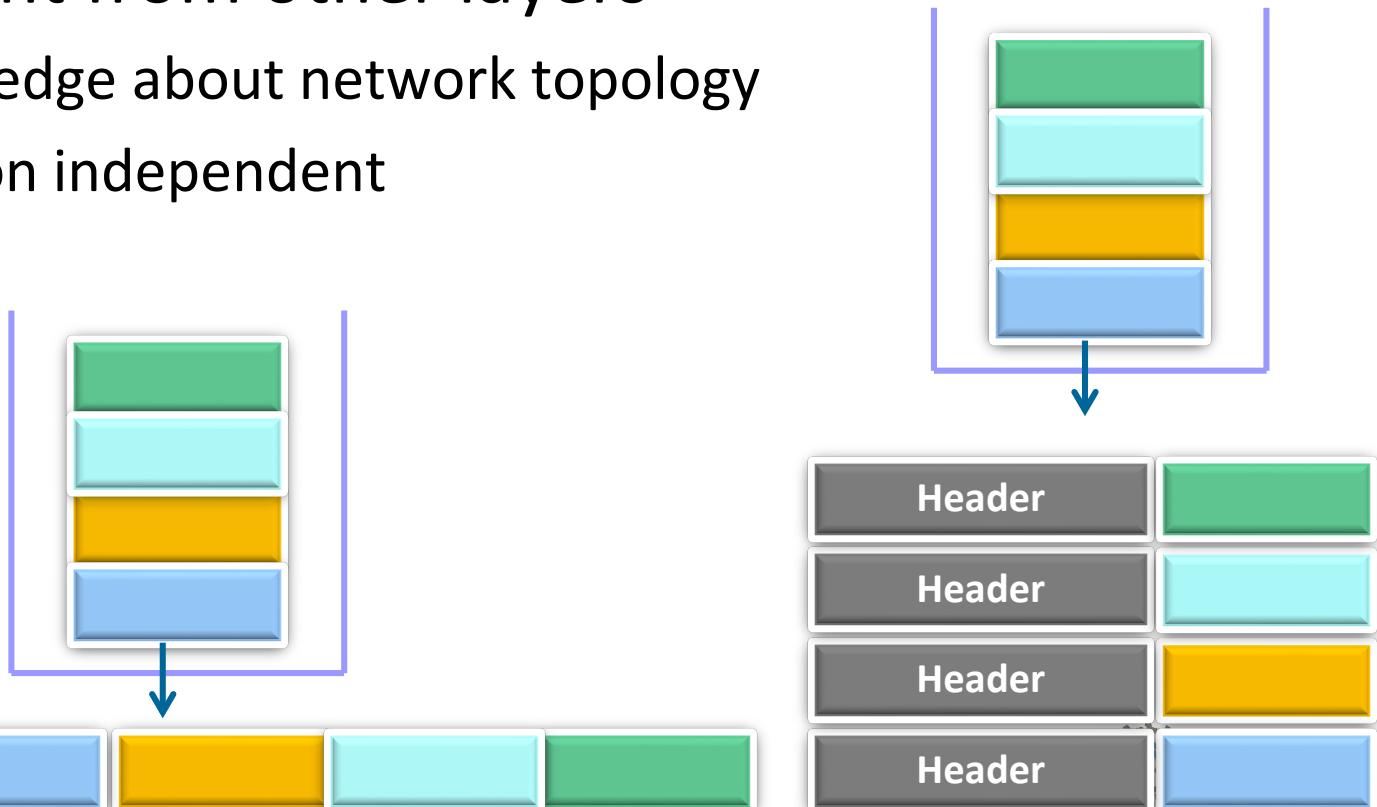
Classification

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

MAC-Layer Data Aggregation

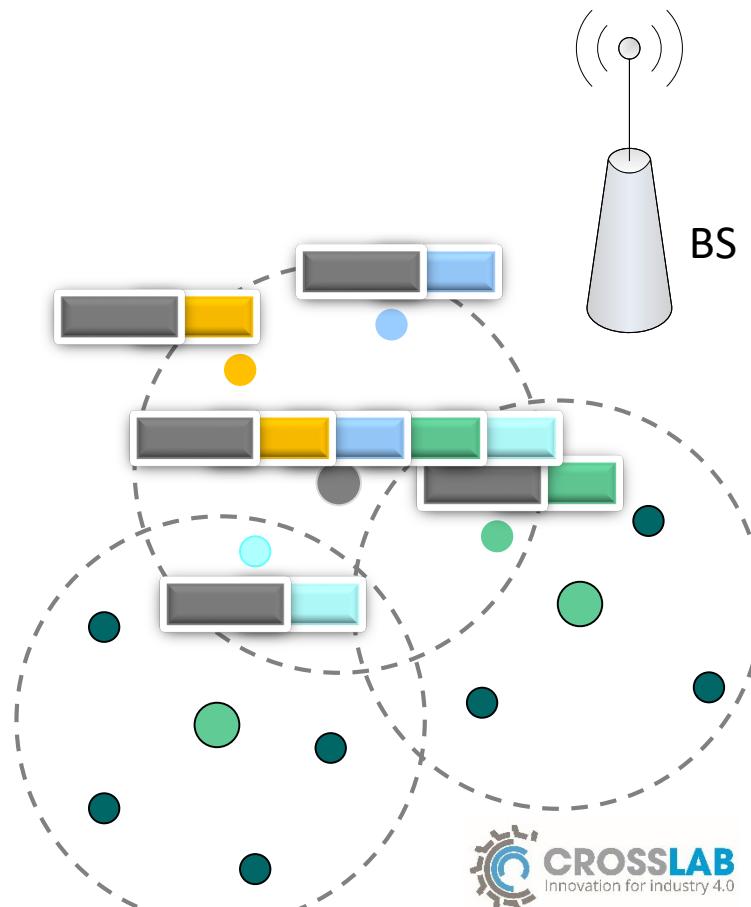


- Combines multiple network packets into a single MAC frame
 - Reduced overhead (header, trailer, RTS, CTS)
- Independent from other layers
 - No knowledge about network topology
 - Application independent



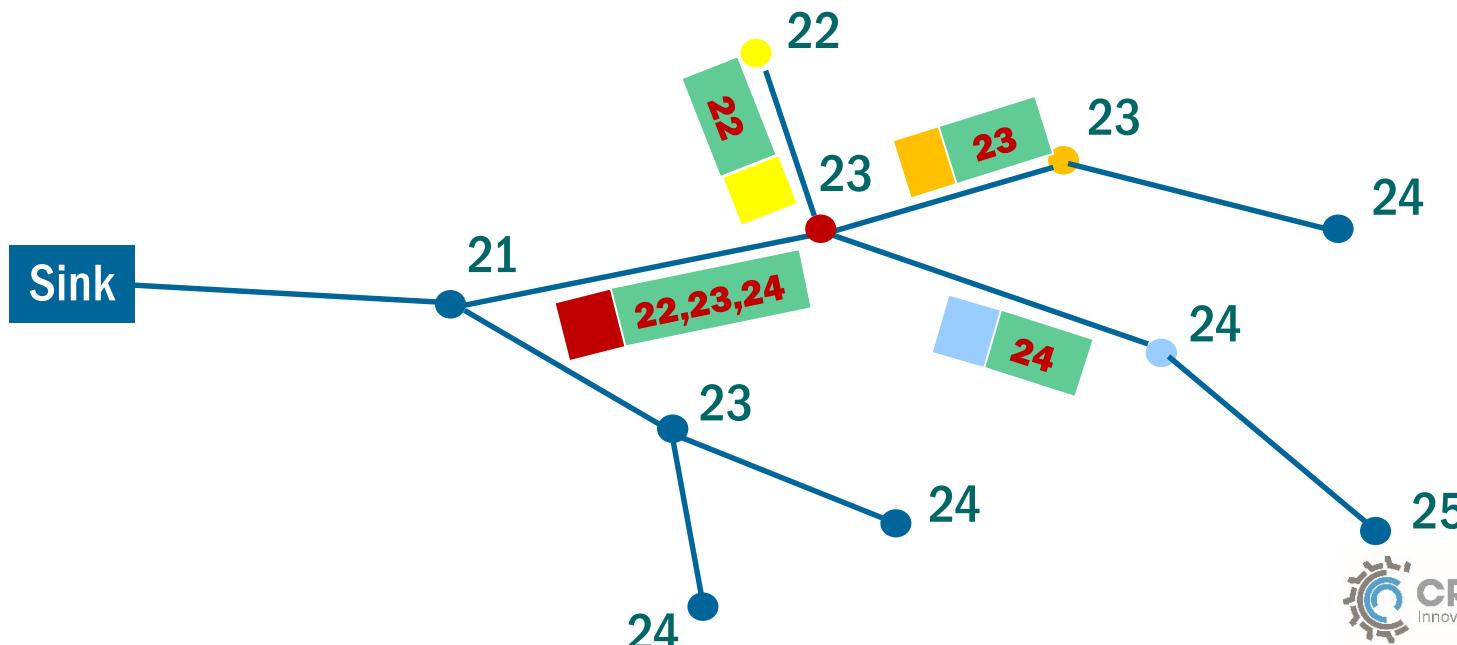
Cluster-based Data Aggregation

- 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

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

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

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

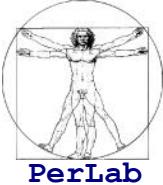
Aggregation Factor



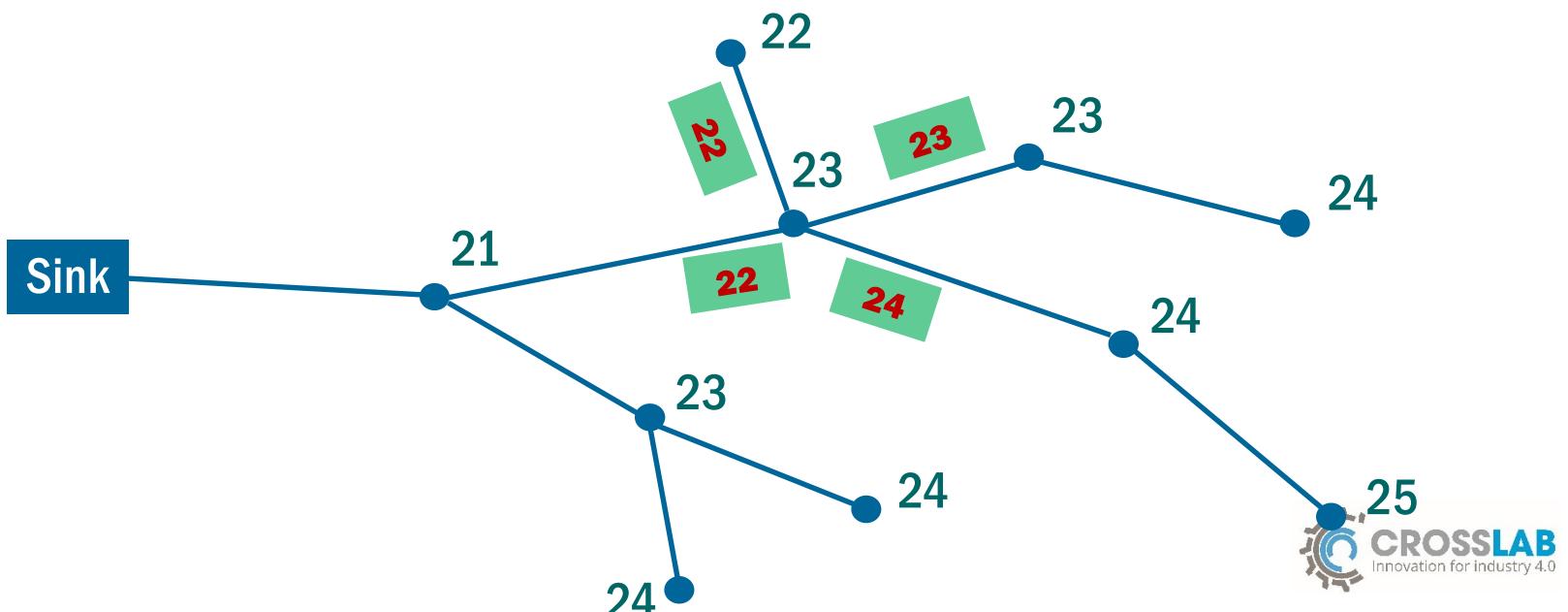
- Assuming H = 9 bytes (IEEE 802.15.4 MAC Frame)

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				

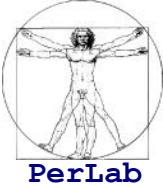
Application-aware Data aggregation



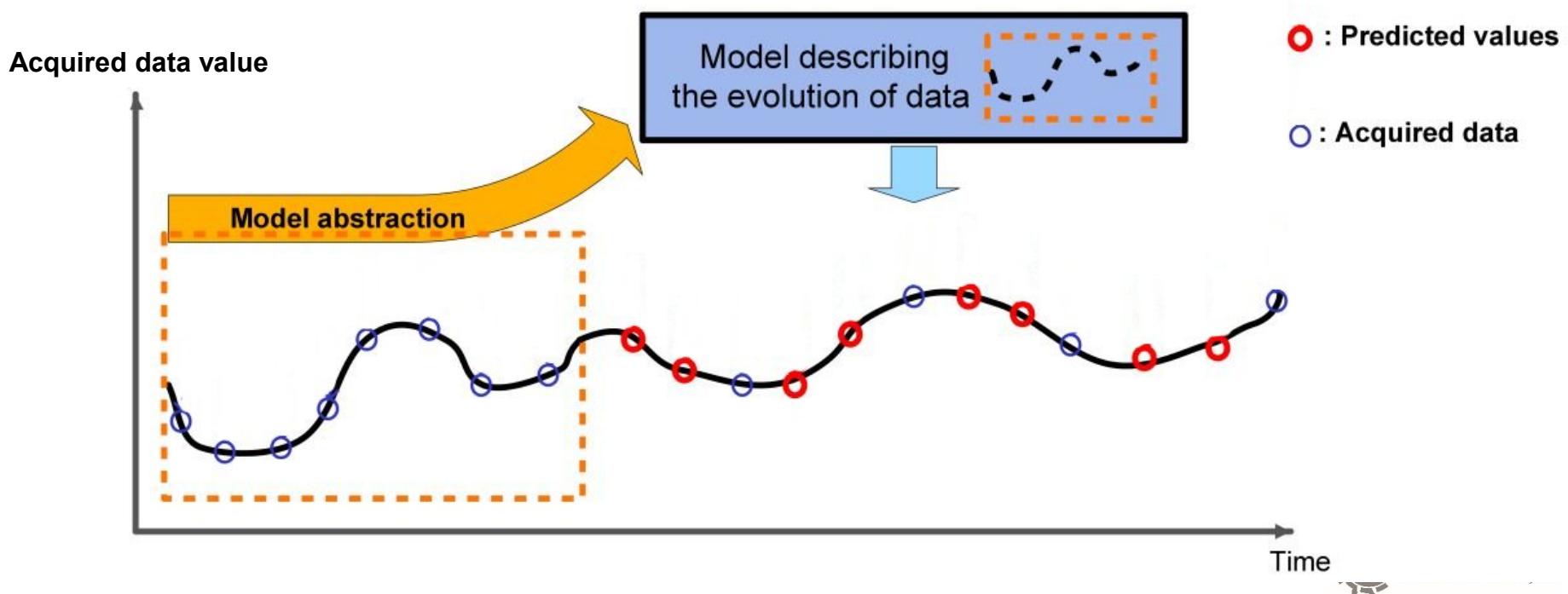
- Information about the application can be exploited in the aggregation strategy
 - Application-specific data aggregation
 - Can be used both in cluster-based and tree-based techniques
- Example: which is the max/min temperature in sensing area?



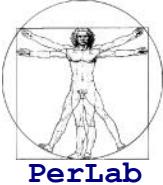
Model-driven Data Prediction



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



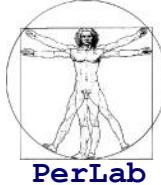
Limitations of Data-driven approaches



- 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?

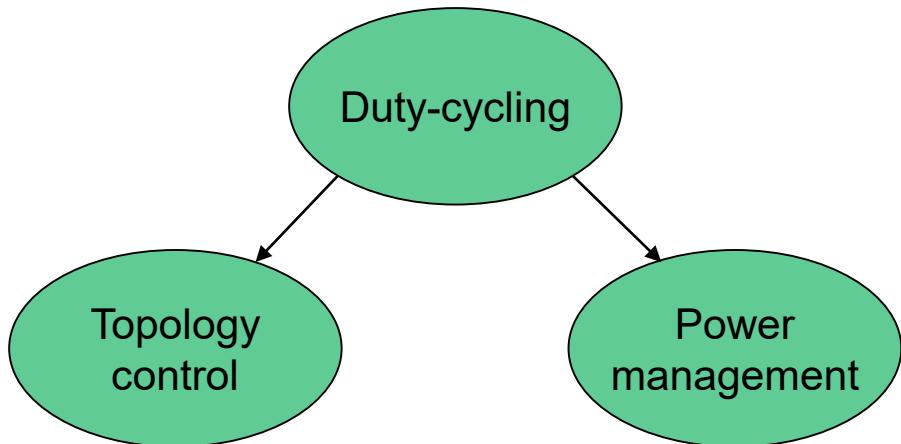
Limitations of data-driven approaches



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

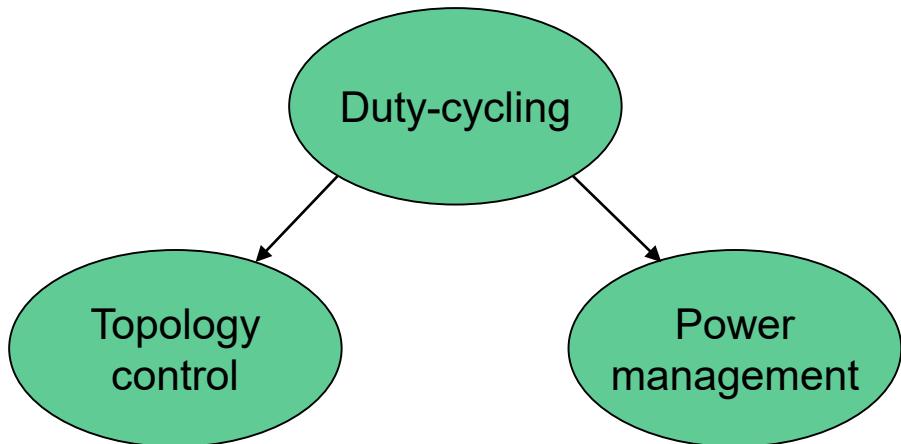


Node's components are switched off when not needed

■ 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

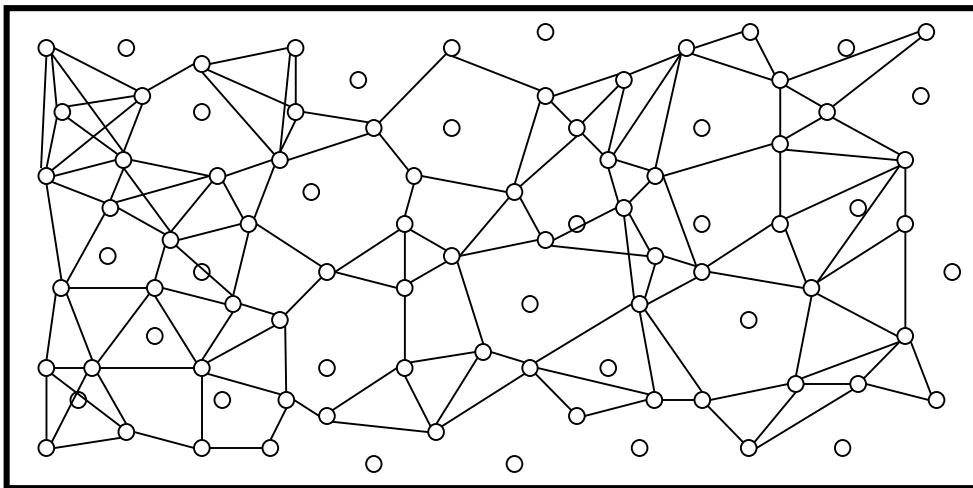
- How many nodes to activate?

- **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.



Topology control protocols

■ Goal

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

■ Approaches

■ Location driven

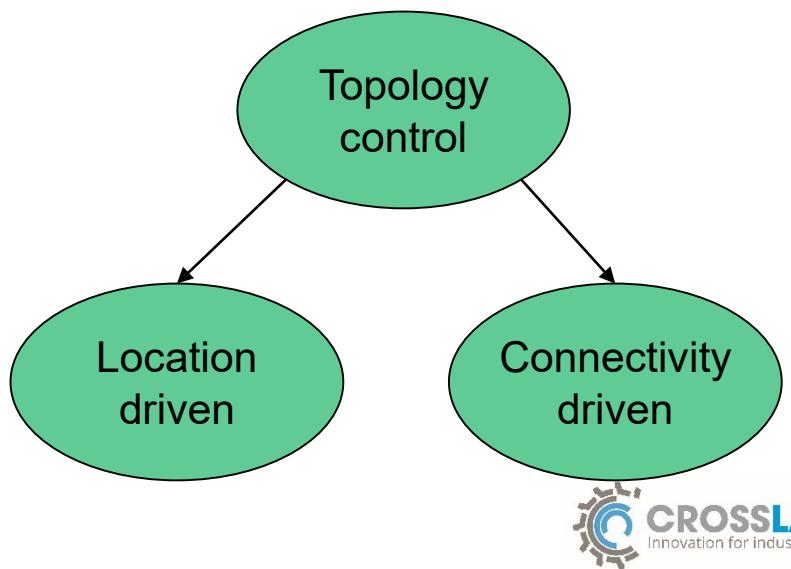
⇒ needs to know the exact location of nodes

⇒ GAF

■ Connectivity driven

⇒ more flexibility

⇒ ASCENT, SPAN



Geographic Adaptive Fidelity (GAF)



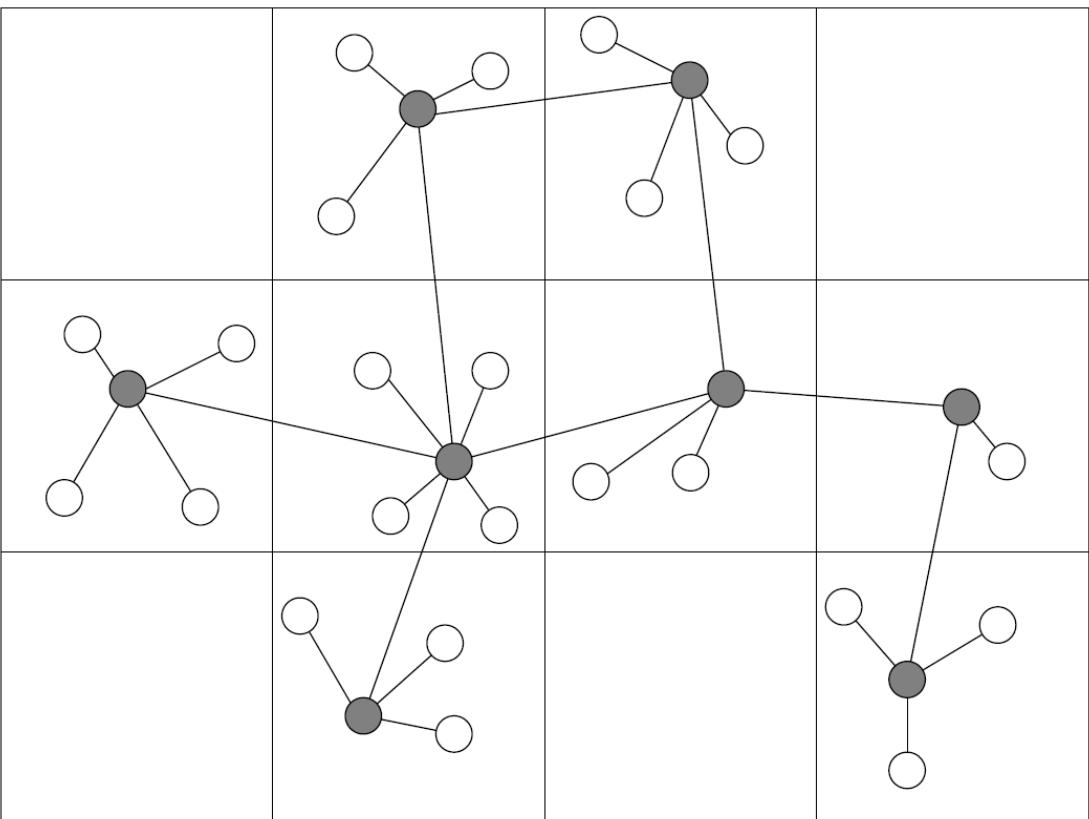
- ❖ Each node knows its location (GPS)
- ❖ A virtual grid of size r is superimposed to nodes
- ❖ Each node in a grid is equivalent from a traffic forwarding perspective
- ❖ Keep **1 node awake in each grid** at each time (grid leader)
- ❖ Nodes alternate between
 - Active state (grid leader)
 - Sleeping (non grid leader)
 - Discovery (leader election)

□ Leader Election

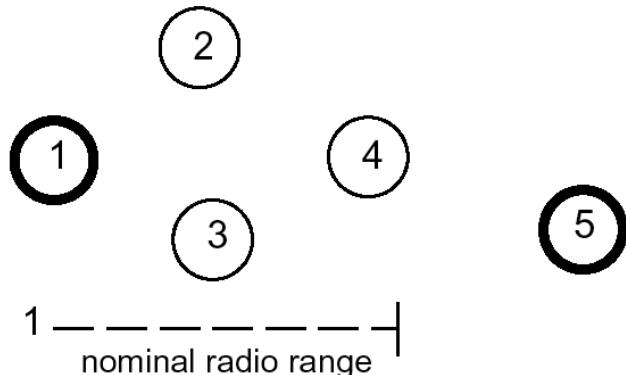
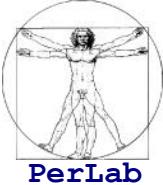
- Distributed algorithm for leader election in each cell

□ Hierarchical Routing

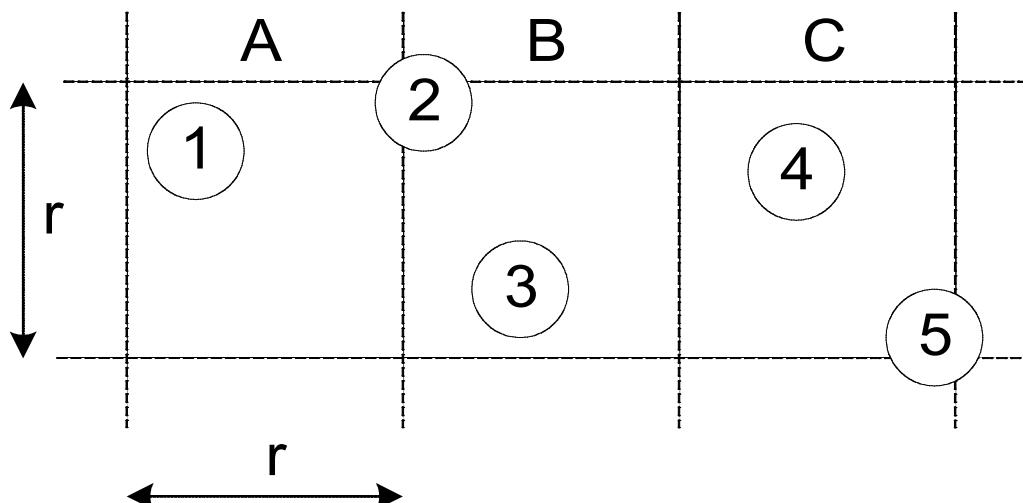
- Sensor nodes to leader
- Leader to BS



Geographic Adaptive Fidelity (GAF)



- $R = \text{nominal radio range}$
Assumed equal for all nodes
- $r = \text{size of each cell in the grid}$



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

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

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

Topology Management + Routing

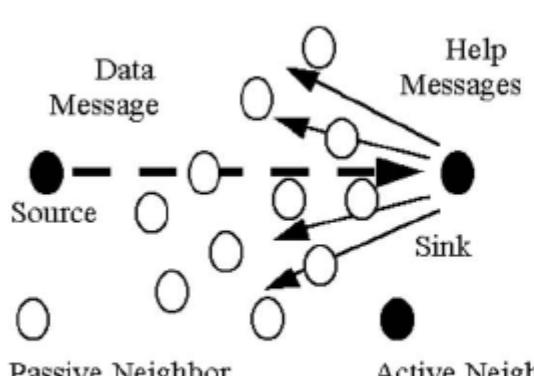
- Clustering
 - Cluster-head election
 - Cluster-head rotation for uniform energy consumption
 - All nodes inside a cluster, but the cluster-head, are sleeping
- Hierarchical Routing
 - As soon as the cluster-head detects an event, it wakes up all the other nodes in the cluster
 - The cluster-head receives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

Adaptive Self-Configuring sEnsor Networks Topologies

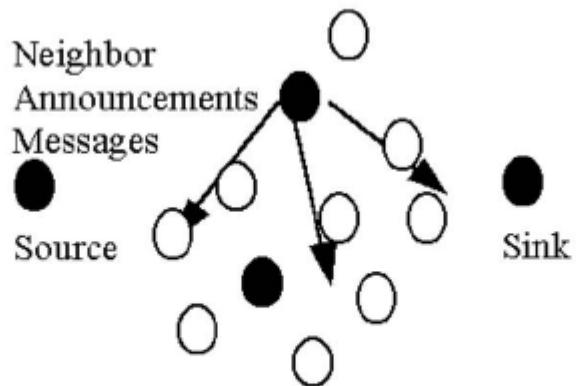
- Does not depend on the routing protocol
- Decision about joining the network based on *local measurements*
 - Each node measures the number of neighbors and packet loss *locally*.
 - Each node then makes an informed decision to *join* the network topology or to *sleep* by turning its radio off.

- 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.

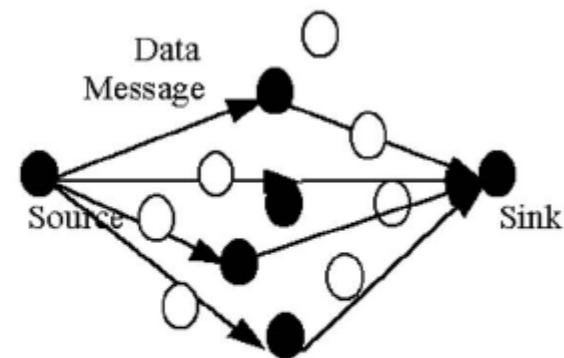
Network Self-Configuration - Example



(a)

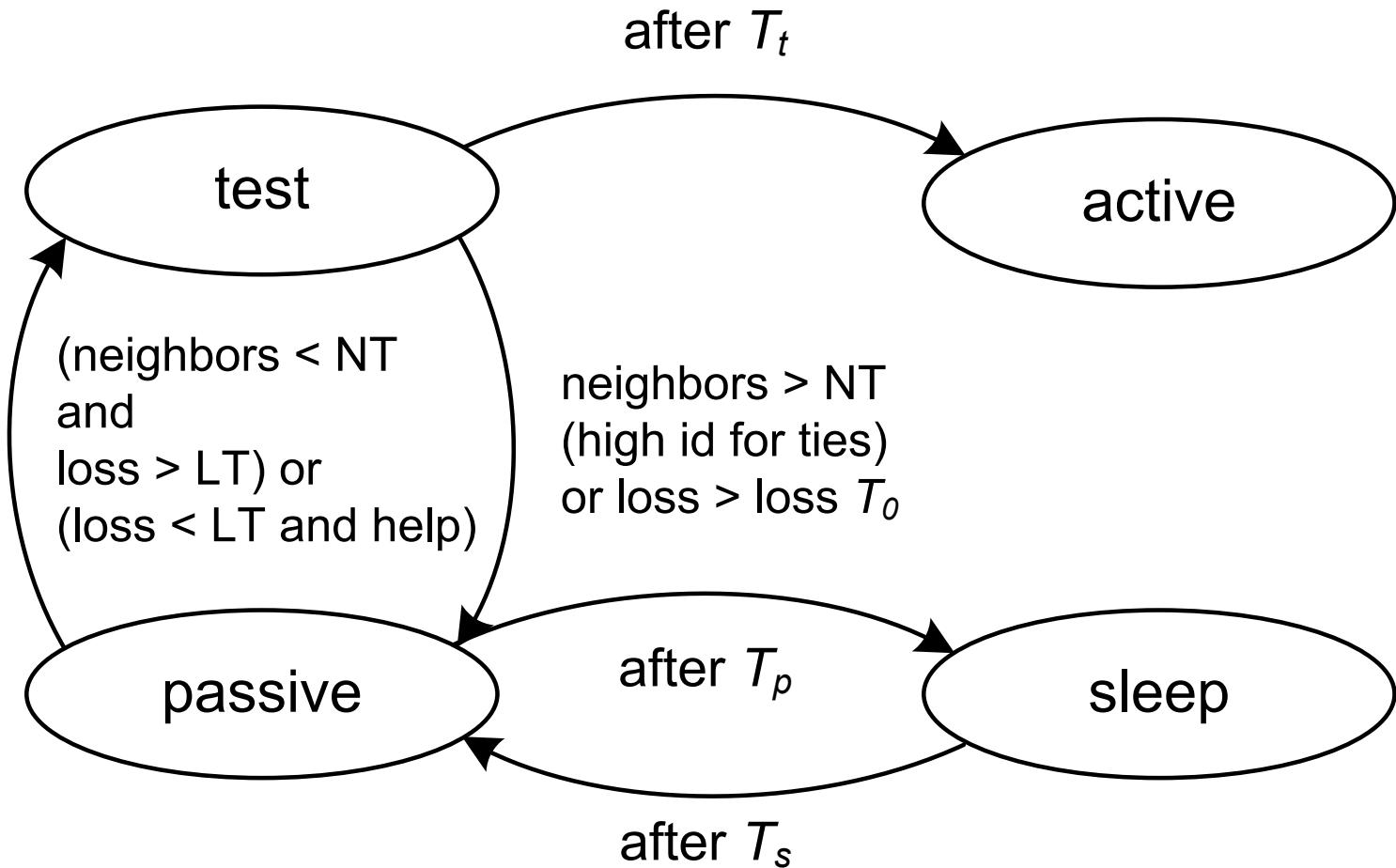


(b)



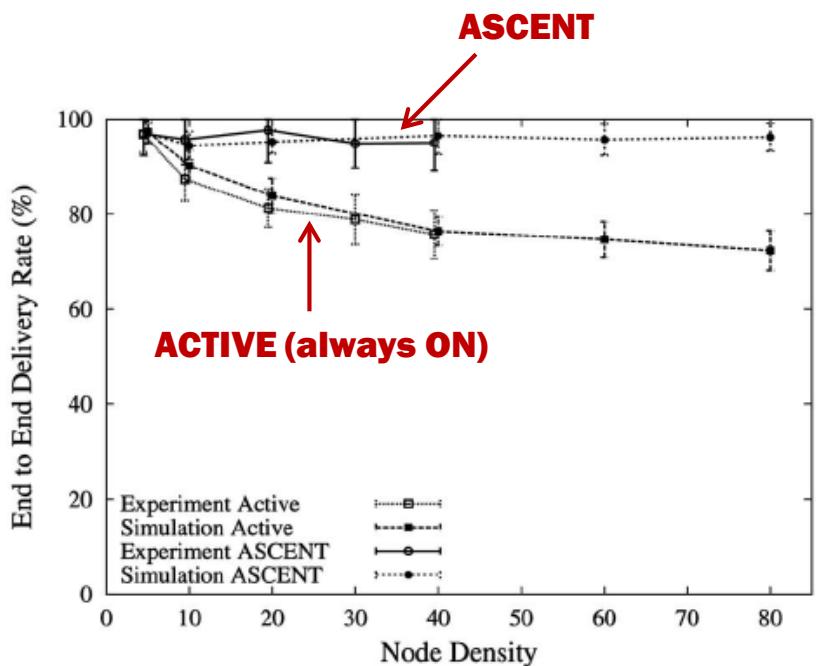
(c)

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

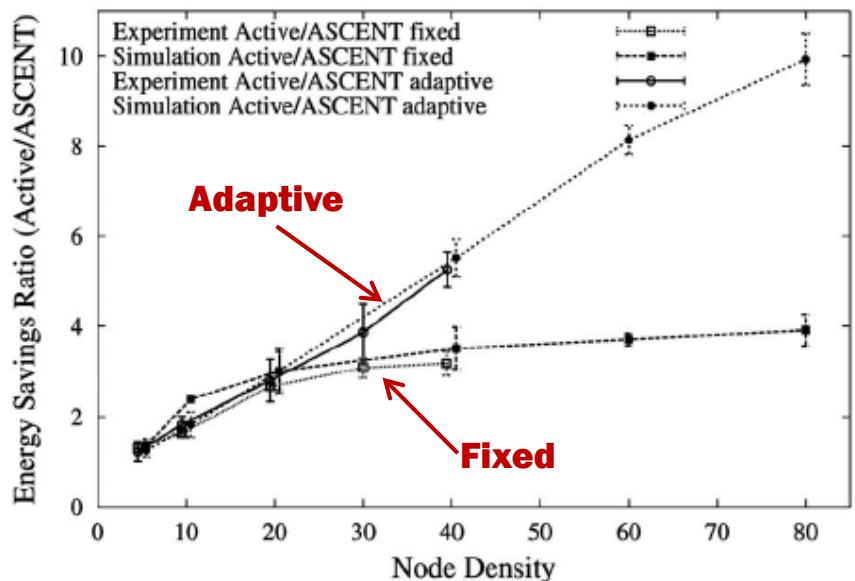


ASCENT Performance

End-2-end Delivery Ratio



Energy Savings



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

Power Management

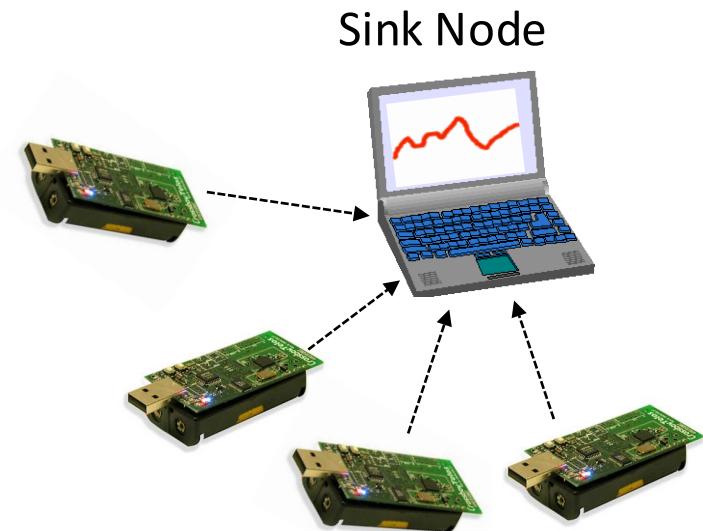
Motivation for Power Management

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

Power Consumption

Supply Voltage: 1.8 V

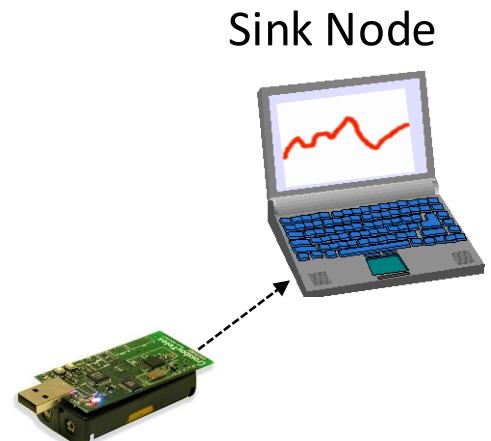
Mode	Current	Power Consumption
Reception	19.7 mA	35.46 mW
Transmission	17.4 mA	31.32 mW
Idle	0.426 mA	0.77 mW
Sleep	20 μ A	36 μ W



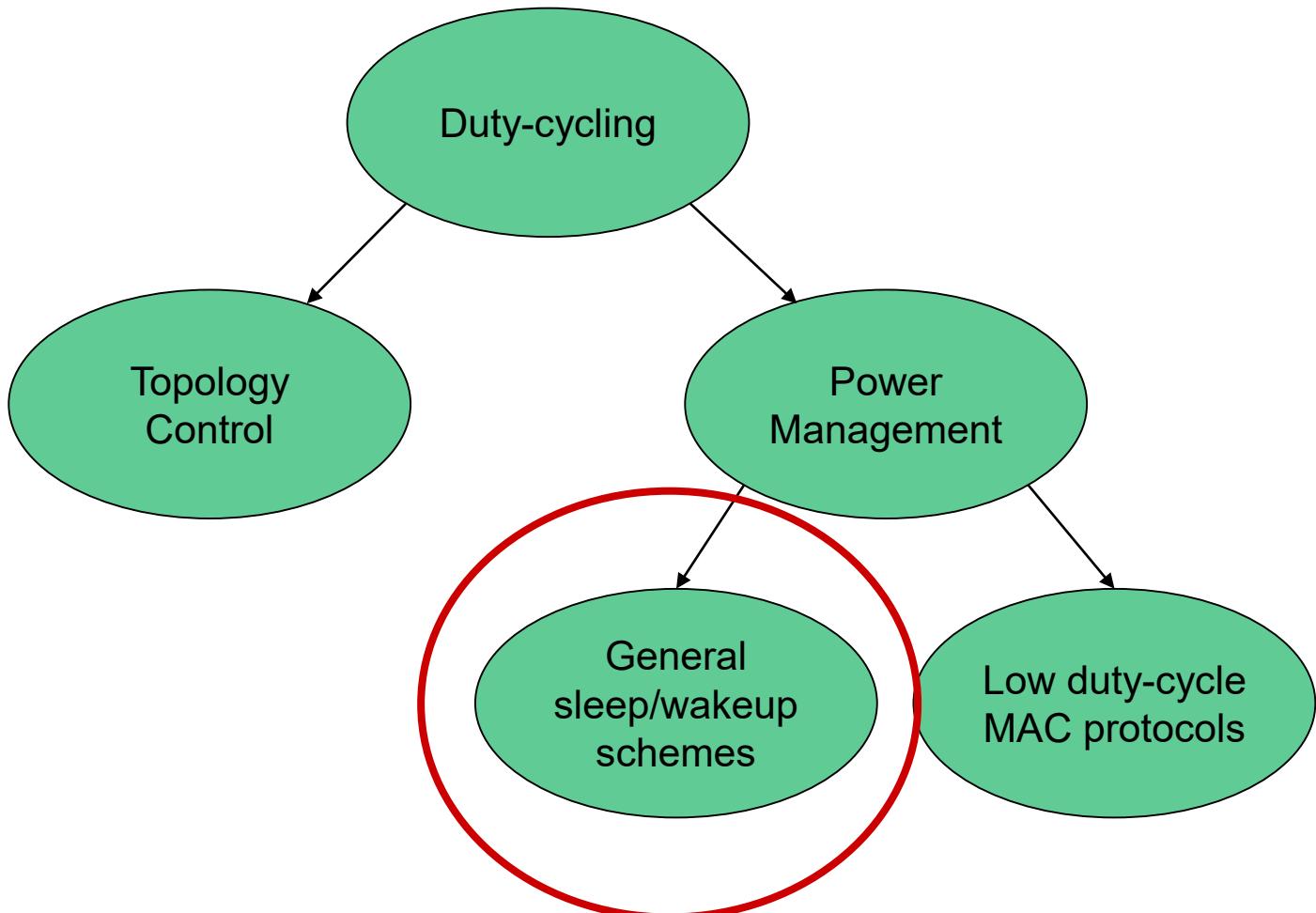
Motivation for Power Management

- 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%



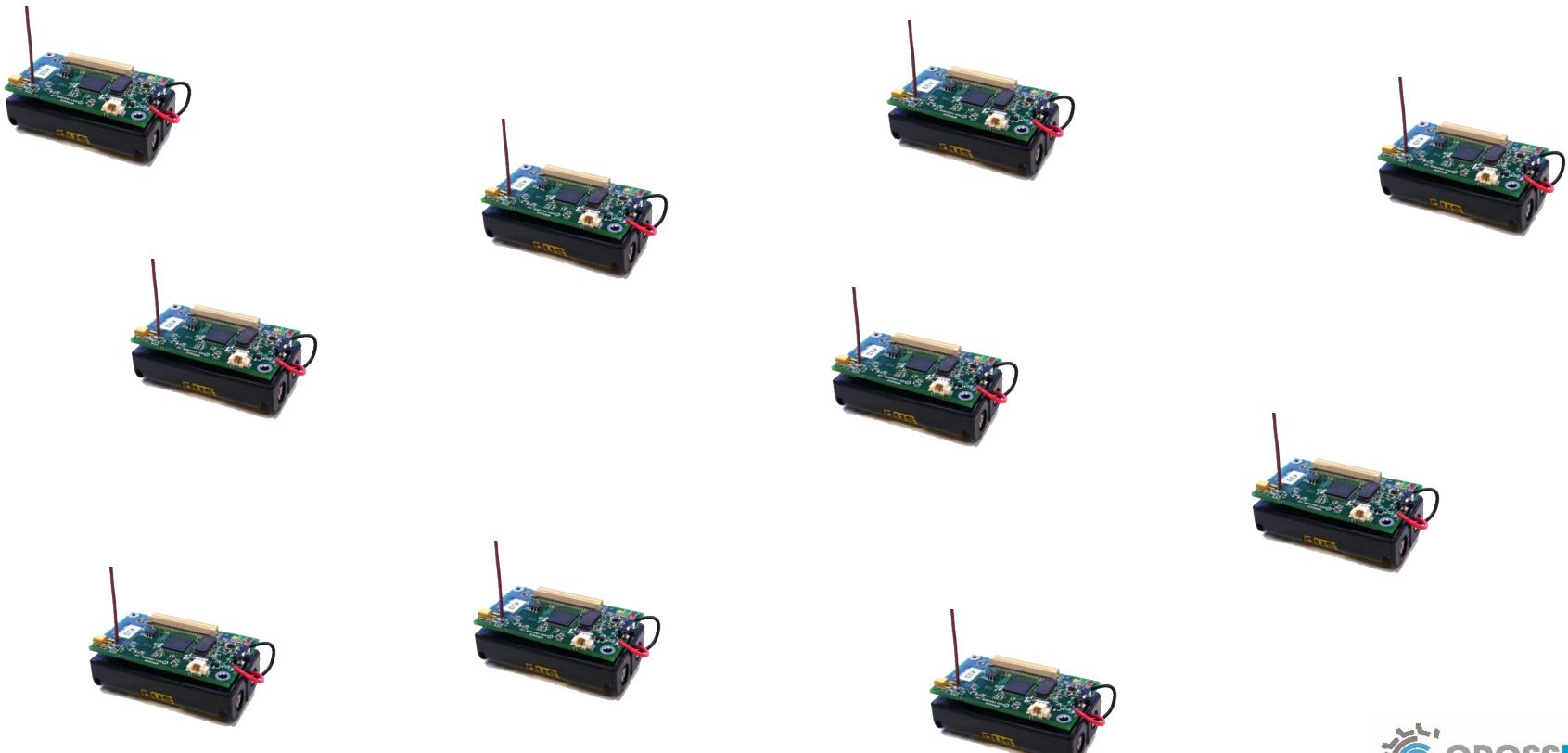
Power Management



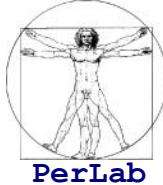
General sleep/wakeup schemes



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

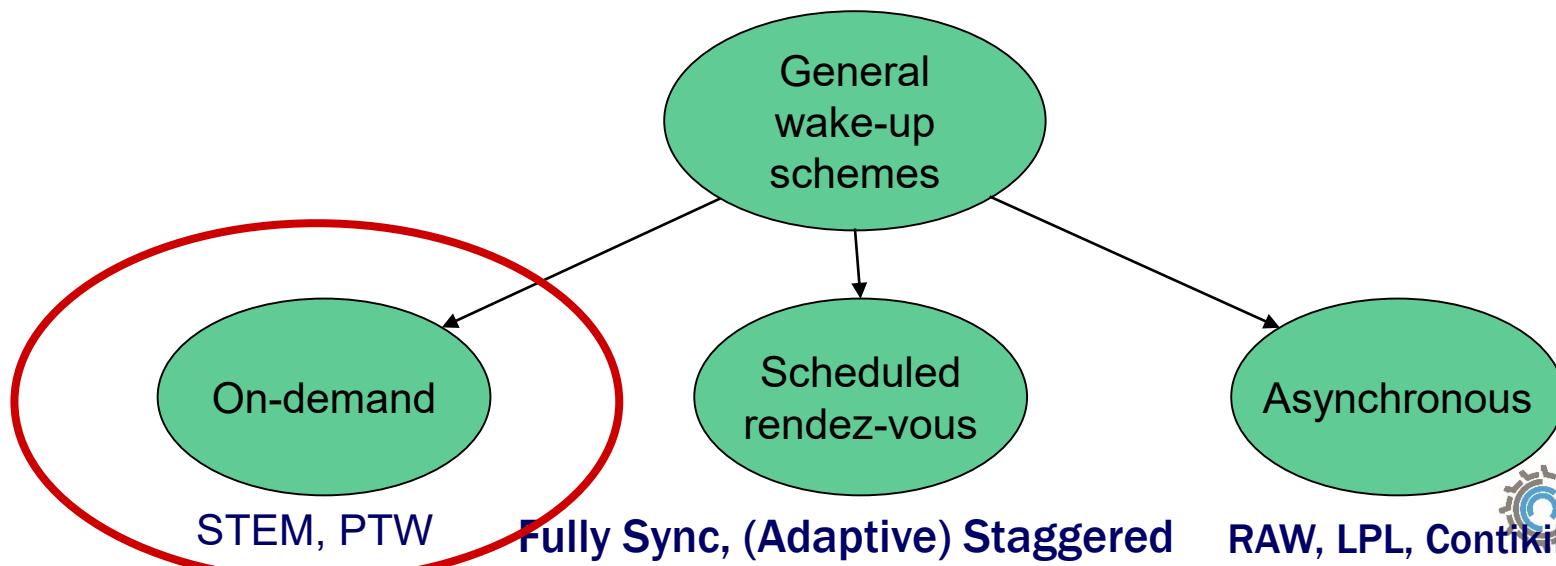


General sleep/wakeup schemes

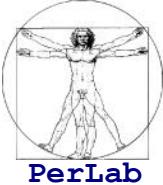


When should a node wake up for communicating with its neighbors?

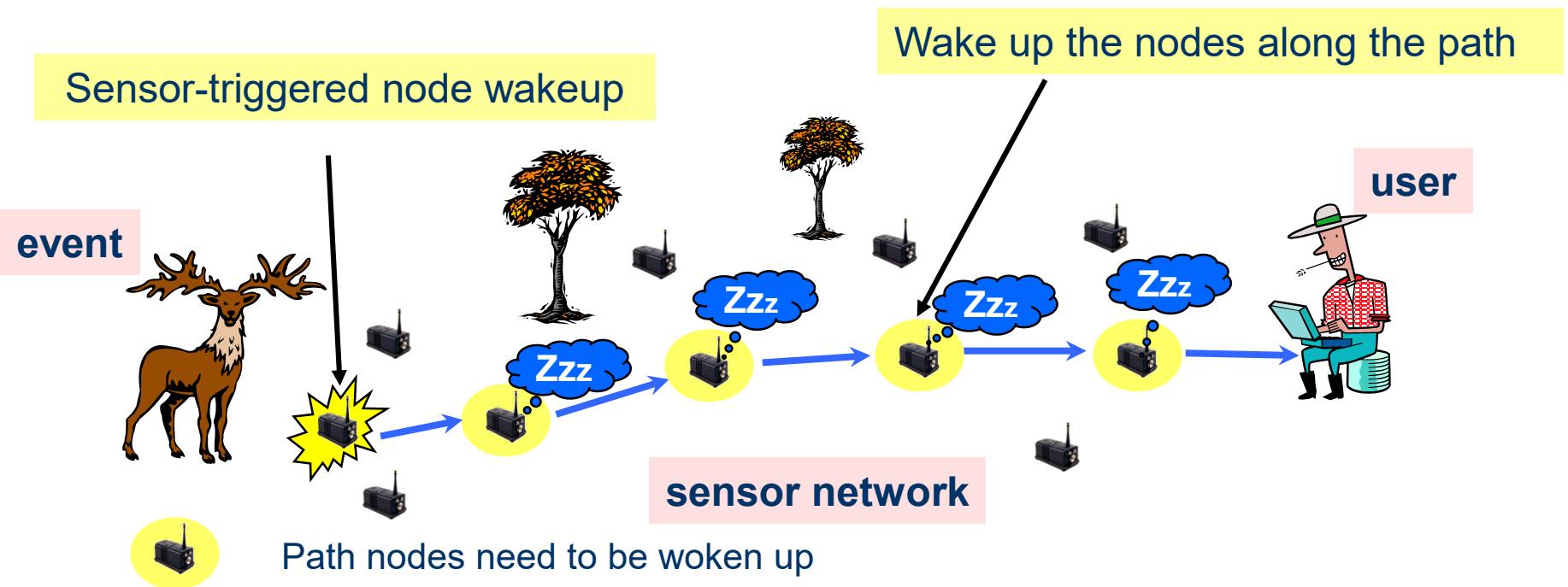
- When another node wants to communicate with it (*on demand*)
- At the same time as its neighbors (*scheduled rendez-vous*)
 - ⇒ Clock synchronization required
- Whenever it wants (*Asynchronous*)



On-demand Schemes



Sparse Topology and Energy Management (STEM)



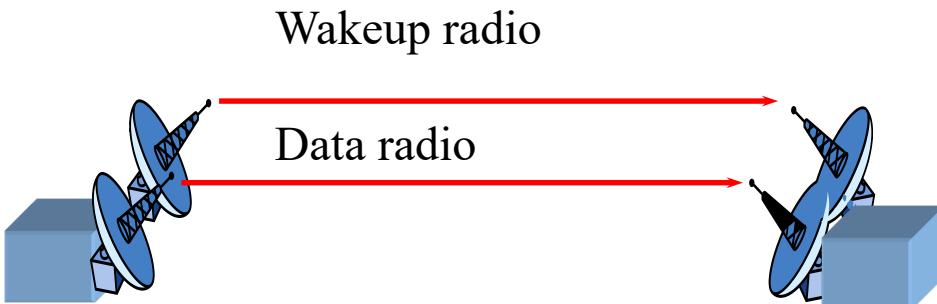
C. Schurgers, V. Tsiatsis, M. B. Srivastava, **STEM: Topology Management for Energy Efficient Sensor Networks**, *IEEE Aerospace Conference 2002*, Big Sky, MT, March 10-15, 2002.

ROSS LAB
solution for Industry 4.0

On-demand Schemes

Sparse Topology and Energy Management (STEM)

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



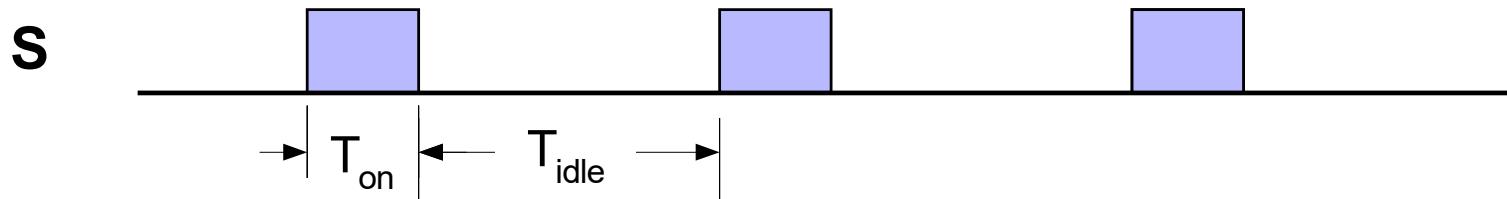
C. Schurgers, V. Tsiatsis, M. B. Srivastava, **STEM: Topology Management for Energy Efficient Sensor Networks**, *IEEE Aerospace Conference 2002*, Big Sky, MT, March 10-15, 2002.

Sparse Topology and Energy Management (STEM)

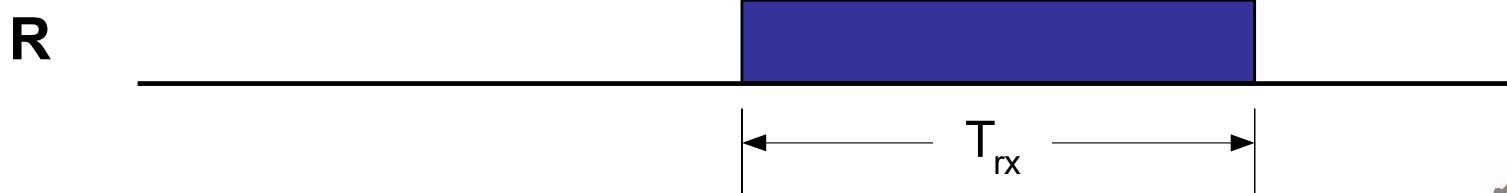
- Wakeup Radio
 - Ideally, a low-power radio should be used
 - ⇒ It would result in a wakeup range shorter than the data transmission range
 - In practice, two similar radios are used for data and wakeup
 - ⇒ Similar power consumption, similar transmission range
 - Duty cycle on the wakeup radio, using 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)

Power Management on Wakeup Radio

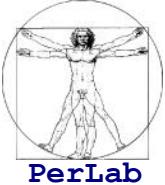
- Asynchronous Initiator
 - Periodic beacon transmission
 - Busy tone
- Potential Target Nodes periodically listening



$$T_{rx} = T_{on} + T_{idle} + T_{on}$$

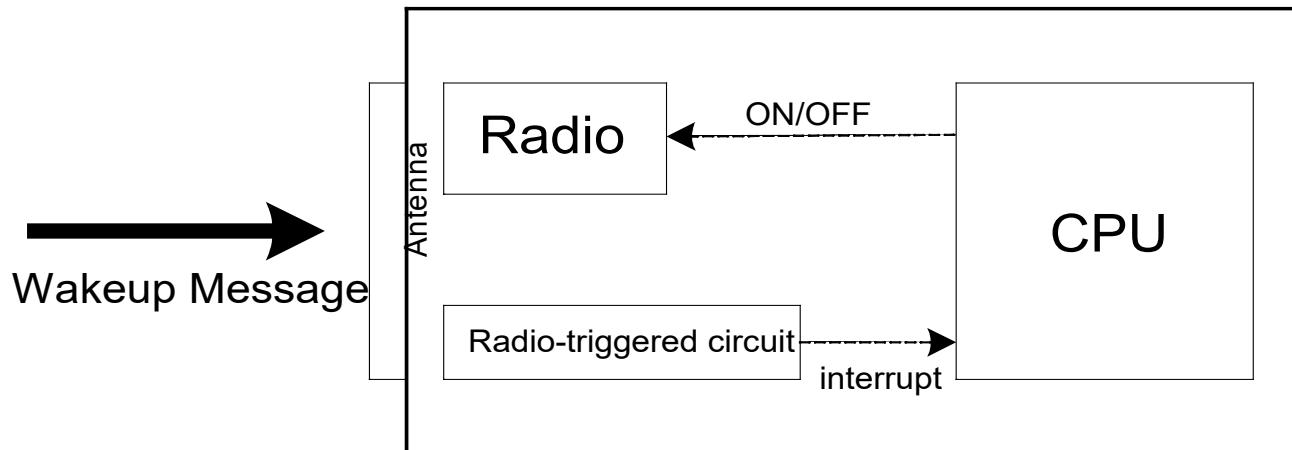


STEM: performance



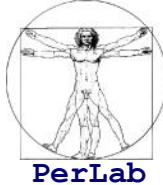
- Can be used in combination with topology control
 - GAF + STEM can provide a duty cycle of about 1%
- STEM trades energy saving for path setup latency
 - May not be suitable when latency is an issue

Radio-triggered Power Management



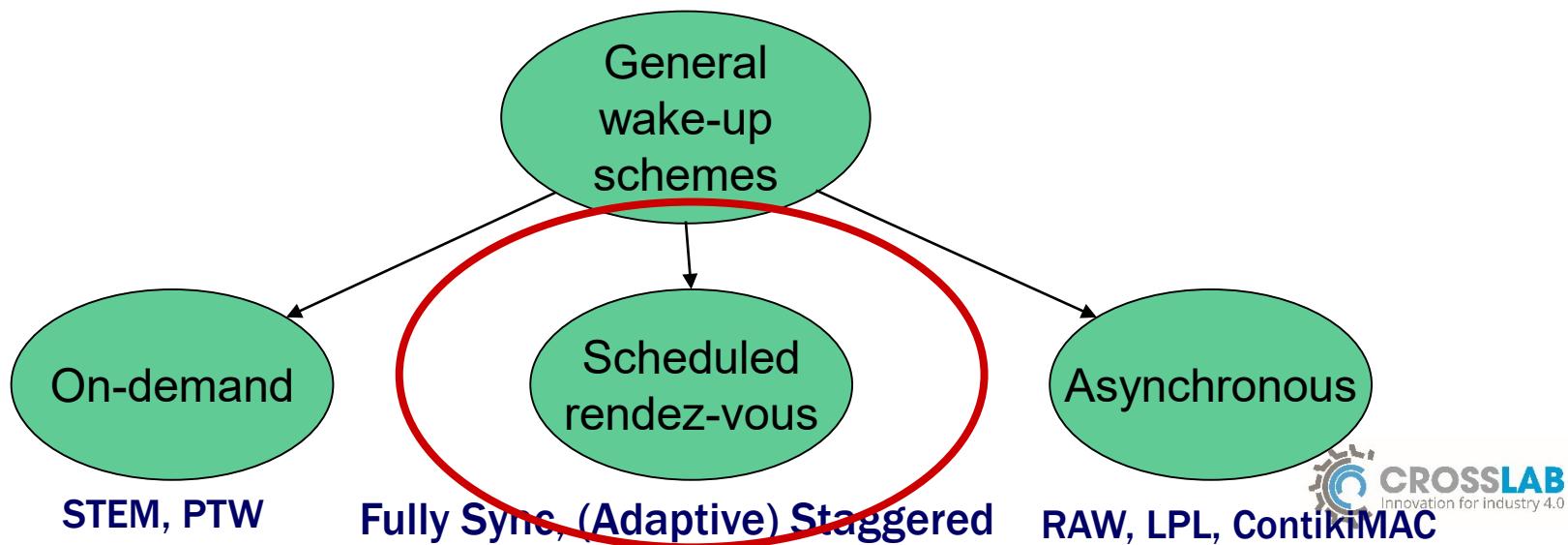
L. Gu, J. Stankovic, **Radio-Triggered Wake-up for Wireless Sensor Networks**, *Real-Time Systems Journal*, Vol. 29, pp. 157-182, 2005.

General sleep/wakeup schemes

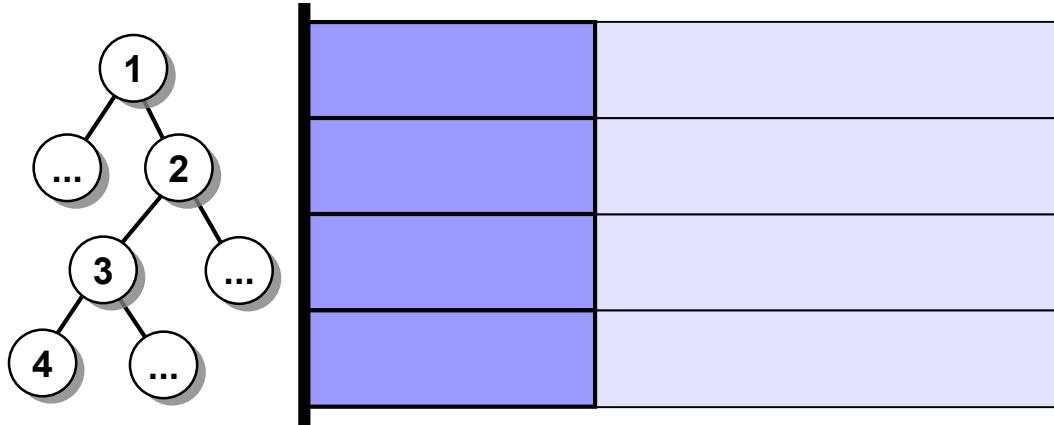


When should a node wake up for communicating with its neighbors?

- 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*)



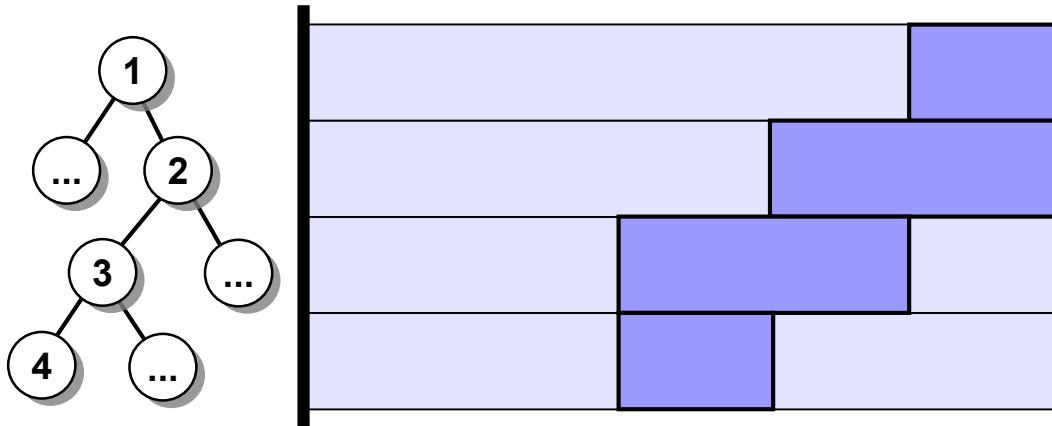
Fully Synchronized Scheme (TinyDB)



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

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

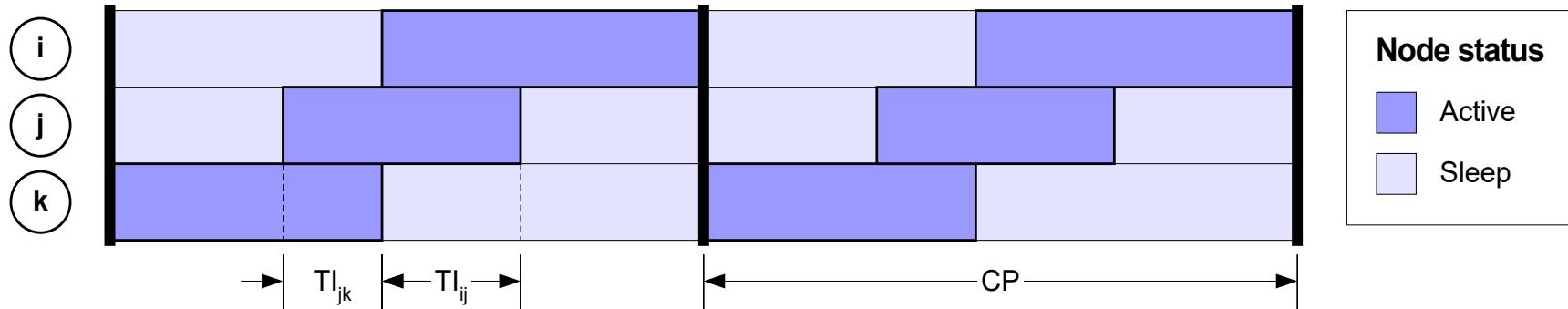
Fixed Staggered Scheme (TAG, TASK)



- 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

Adaptive Staggered Scheme (ASLEEP)



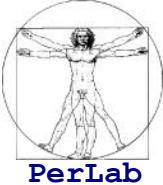
■ Adaptive talk interval

- number of children
- network traffic
- channel conditions
- nodes join/leaves, etc.

■ Components

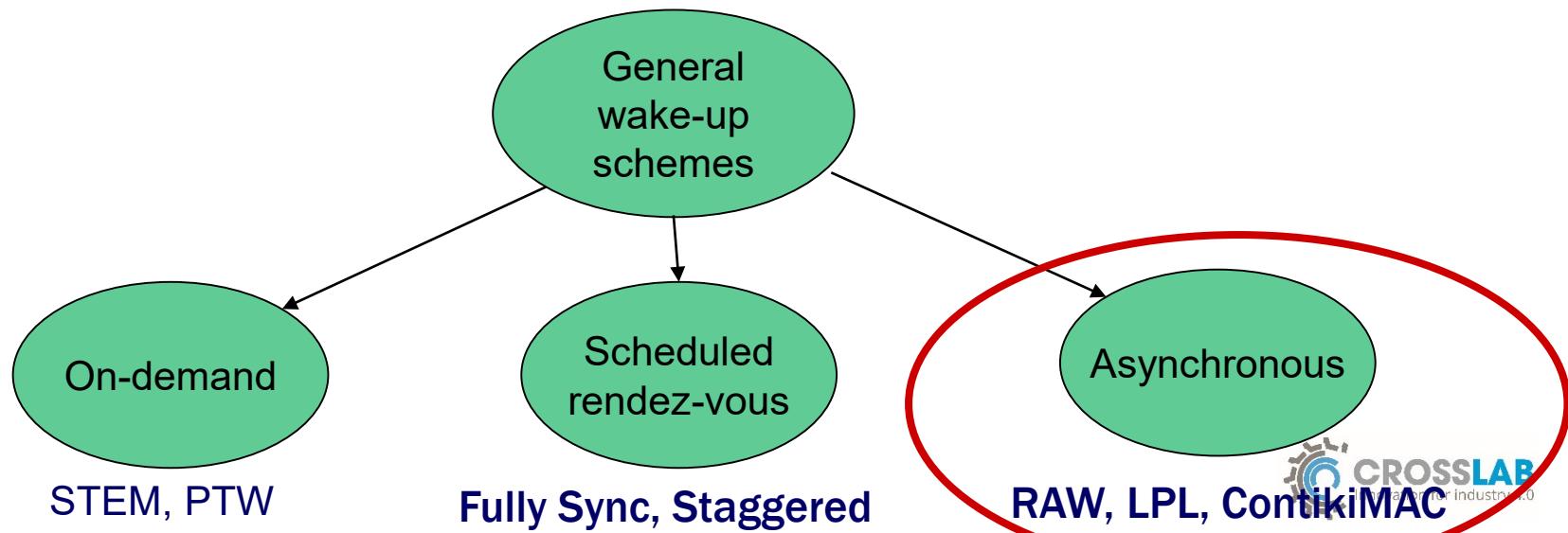
- Talk Interval Prediction
- Sleep Coordination

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*)



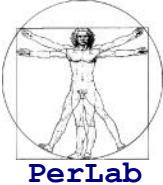
Random Asynchronous Wakeup (RAW)



Routing Protocol + Random Wakeup Scheme

- Several Paths towards the destination
 - Especially if the network is dense
- *Neighbor Forwarding Candidate Set* (FCS)
set of neighbors that are closest to the destination
 - In terms of number of hops (h-FCS)
 - In terms of distance (d-FCS)

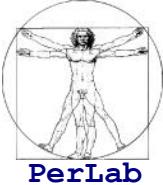
Random Asynchronous Wakeup (RAW)



Algorithm

- Each node wakes up randomly
 - once in every time interval of fixed duration T
- Remains active for a predefined time T_a
 - $T_a < T$ (*duty cycle*: T_a/T)
 - and then sleeps again
- Once awake, a node looks for possible active neighbors
 - running a neighbor discovery procedure

Random Asynchronous Wakeup (RAW)

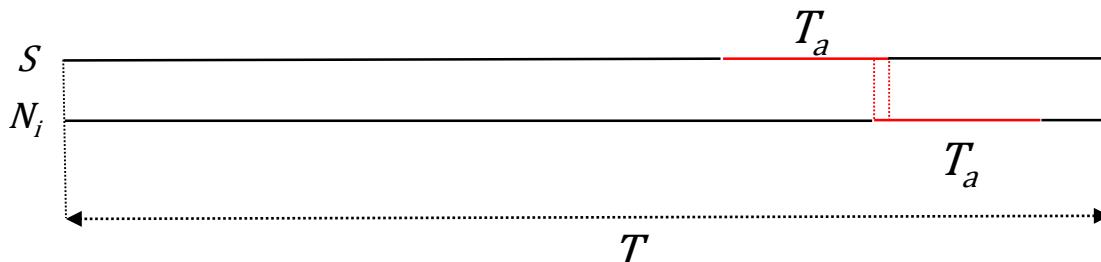


Forwarding Probability

- S has a packet destined to D
- The FCS of source node S include m neighbors $N_i (i=1, 2, \dots, m)$

Discovery probability

Probability to discover any neighbor $N_i : 2 T_a / T$



Forwarding probability

- Probability to discover, at least, one active neighbor (out of m)
- The packet can be transferred

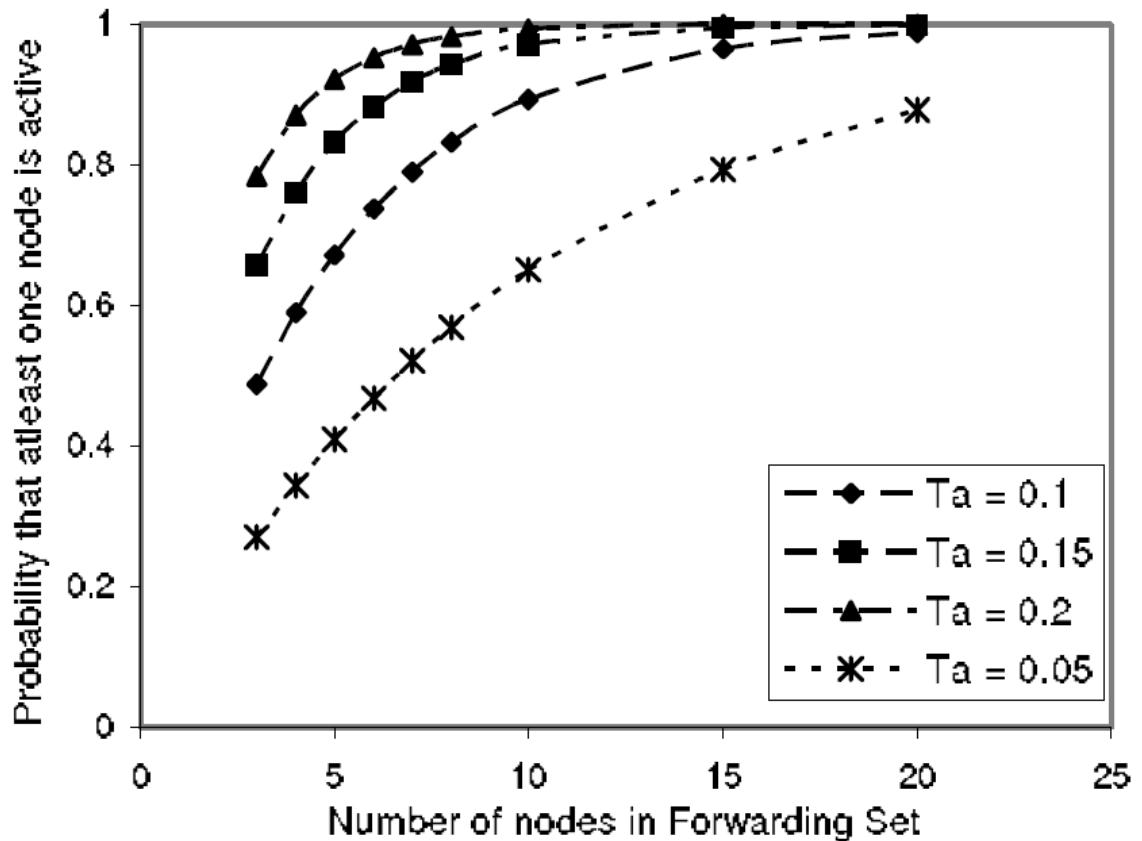
$$P = 1 - \left(1 - \frac{2 \cdot T_a}{T}\right)^m$$

Random Asynchronous Wakeup (RAW)



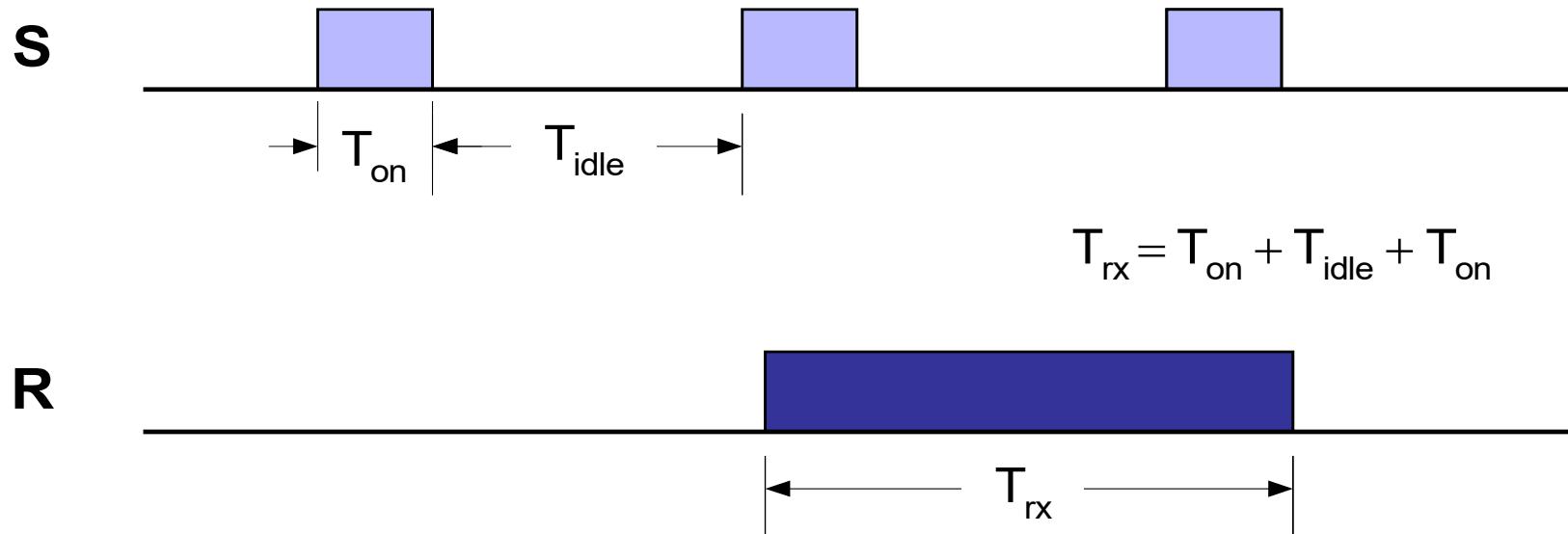
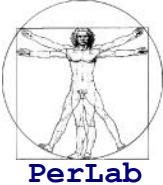
Performance

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

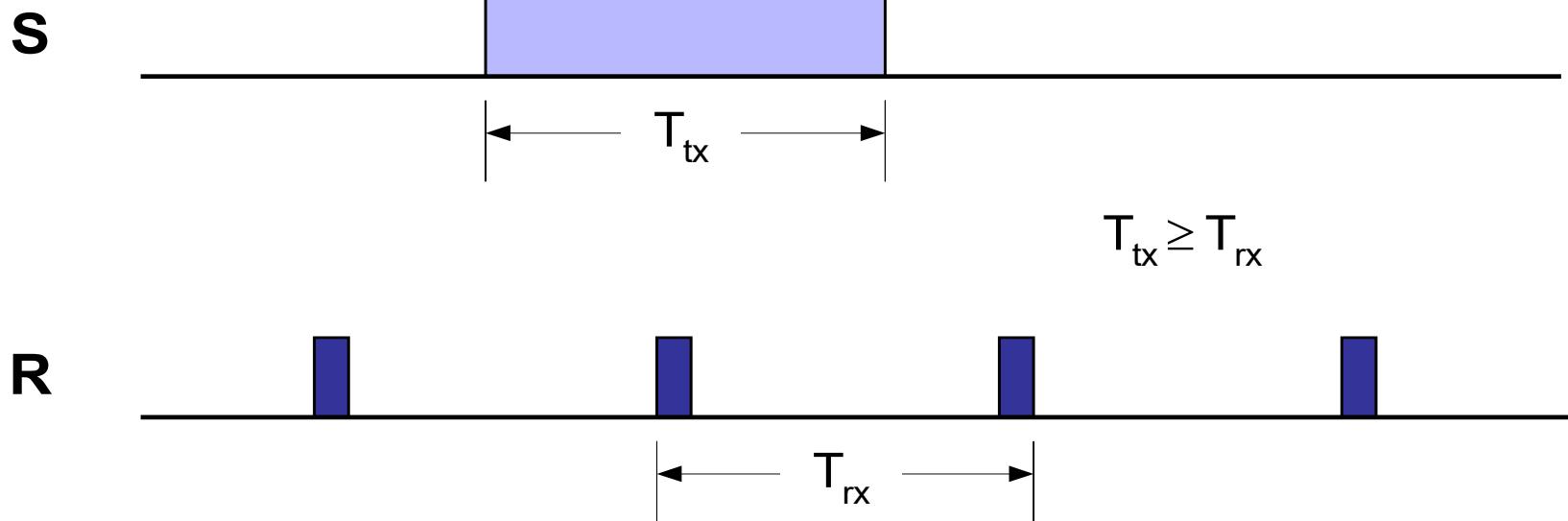
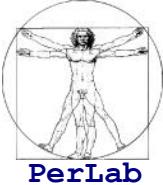


V. Paruchuri, S. Basavaraju, R. Kannan, S. Iyengar, **Random Asynchronous Wakeup Protocol for Sensor Networks**, Proc. IEEE Int'l Conf. On Broadband Networks (BROADNETS 2004), 2004.

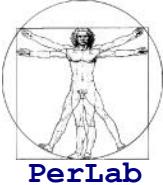
Asynchronous Sender and Periodic Listening



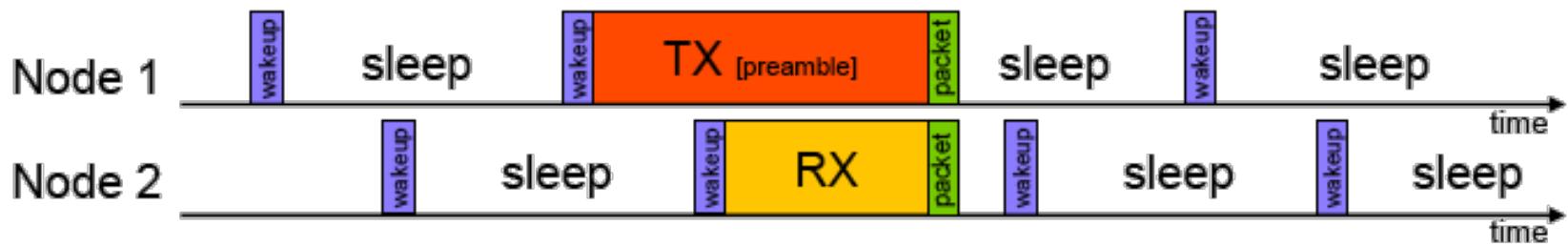
Asynchronous Sender and Periodic Listening



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: $\text{check interval} \leq \text{preamble duration}$

- 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

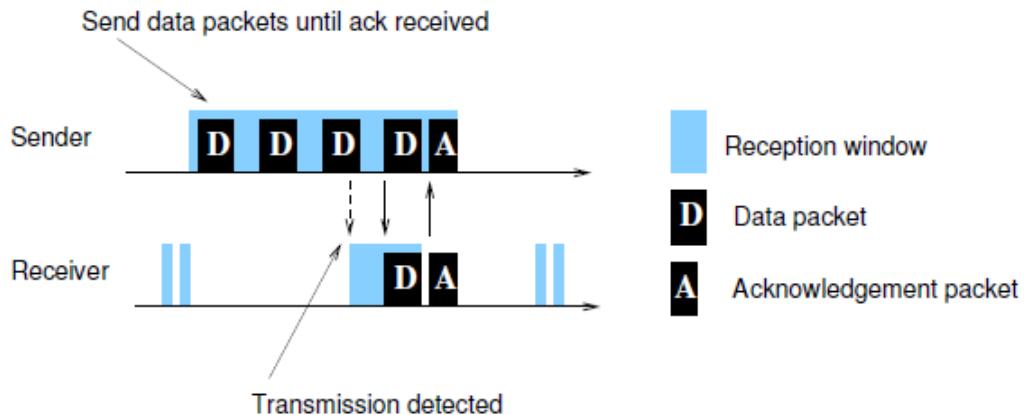
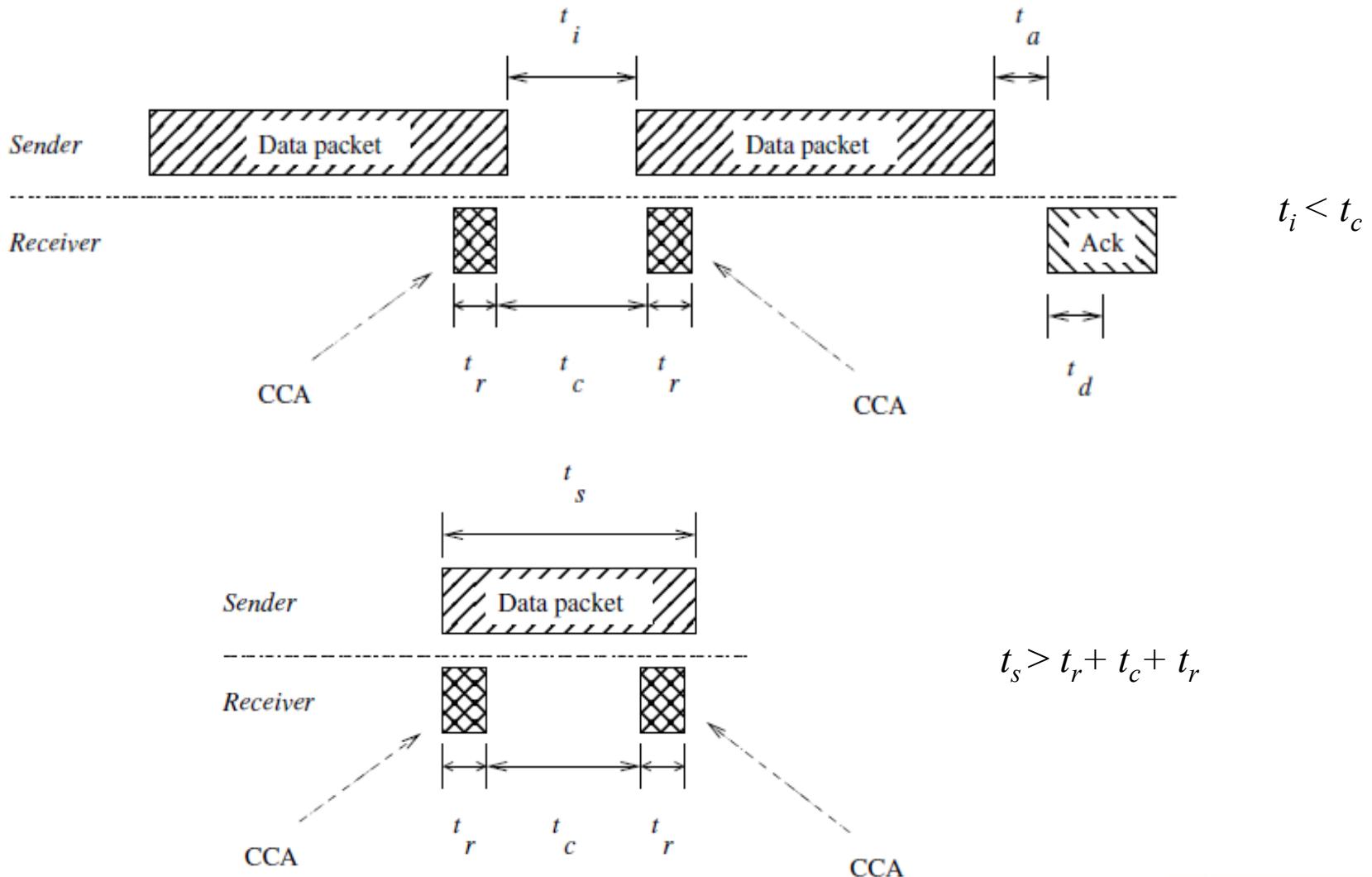


Figure 1: ContikiMAC: nodes sleep most of the time and periodically wake up to check for radio activity. If a packet transmission is detected, the receiver stays awake to receive the next packet and sends a link layer acknowledgment. To send a packet, the sender repeatedly sends the same packet until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

ContikiMAC Timing



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

ContikiMAC Sleep Optimization

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

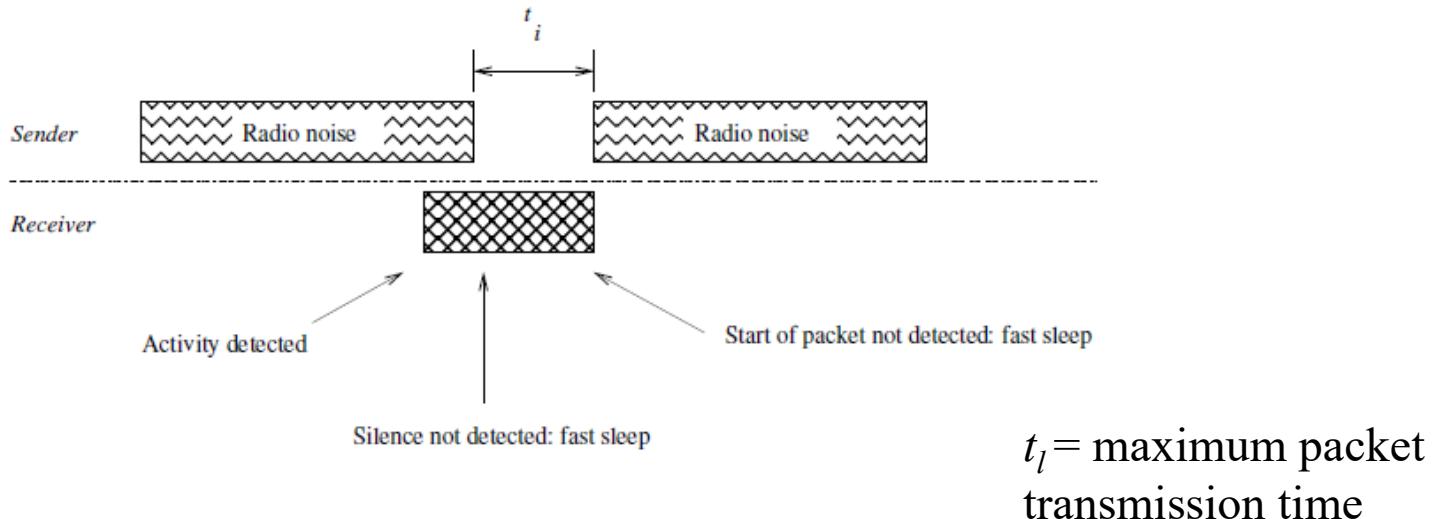


Figure 5: The ContikiMAC fast sleep optimization: if a silence period is not detected before t_l , the receiver goes back to sleep. If the silence period is longer than t_i , the receiver goes back to sleep. If no packet is received after the silence period, even if radio activity is detected, the receiver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

ContikiMAC Transmission Phase Lock

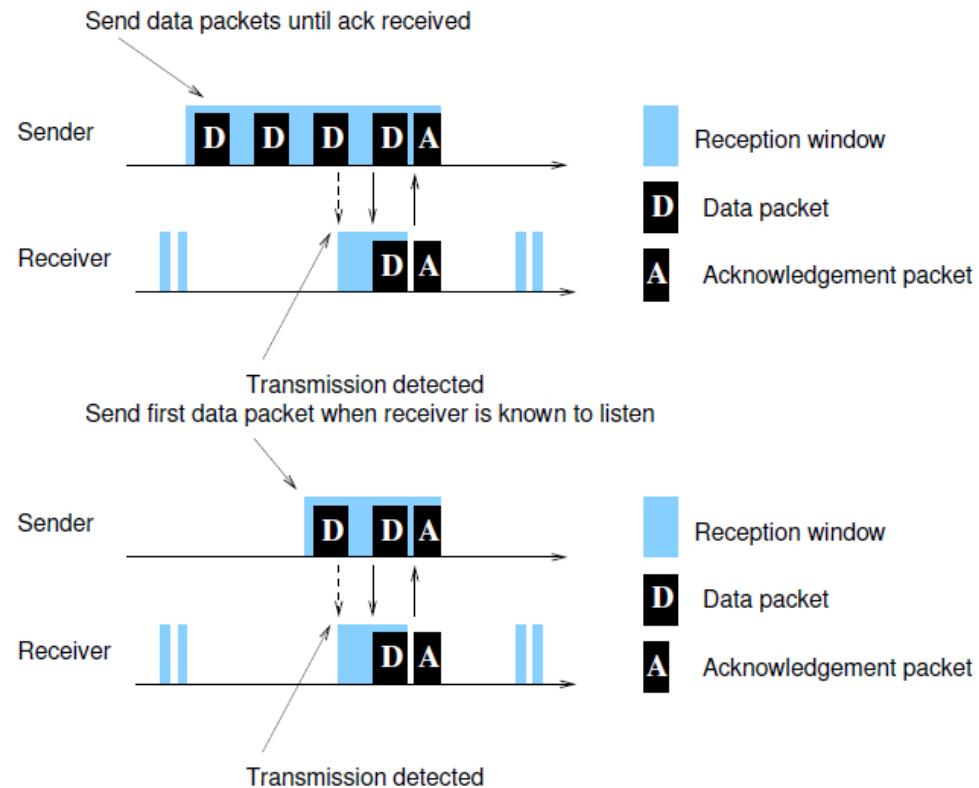
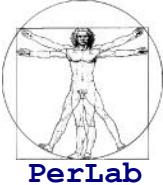
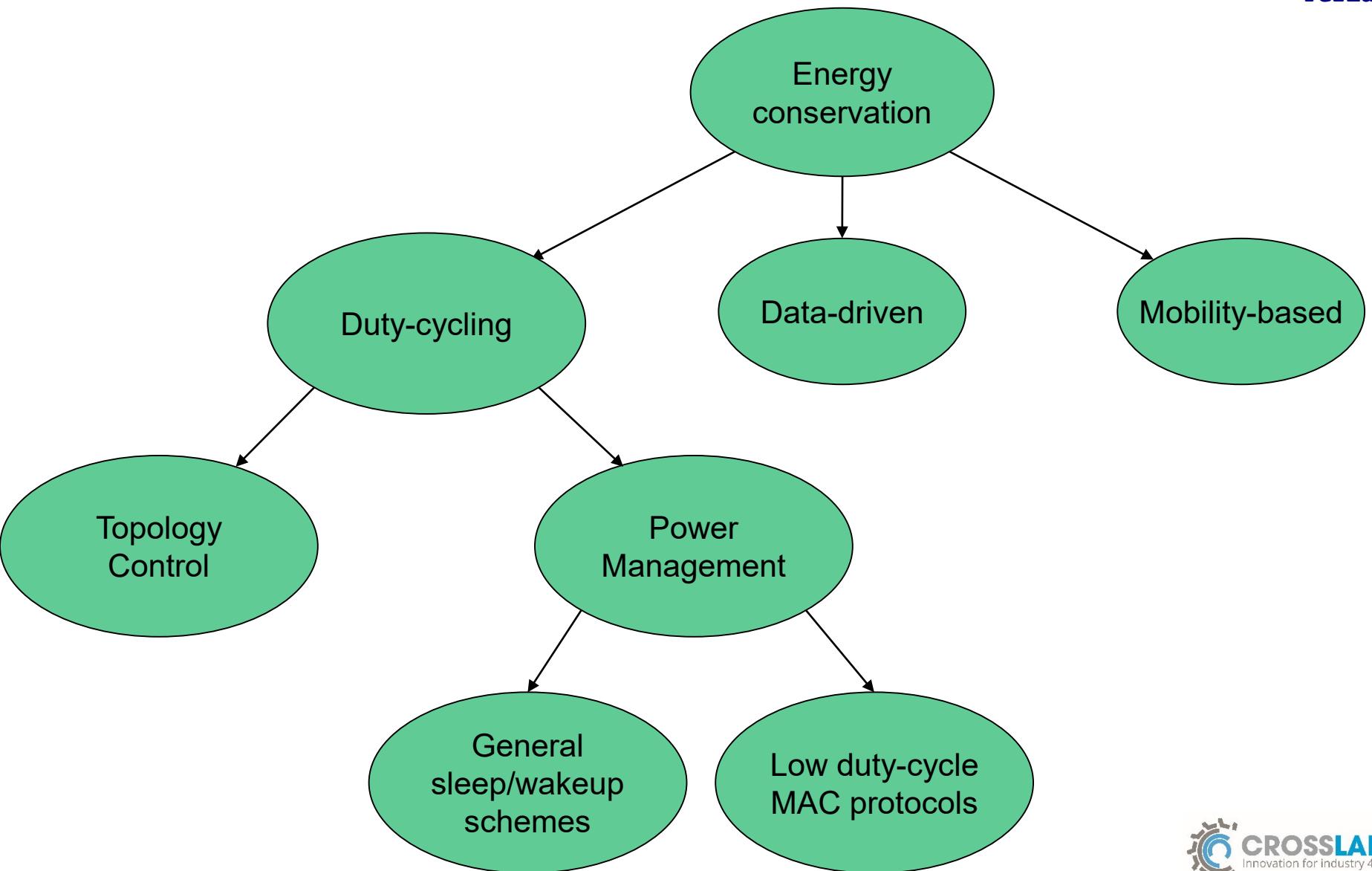


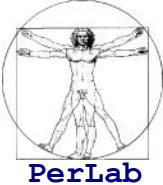
Figure 6: Transmission phase-lock: after a successful transmission, the sender has learned the wake-up phase of the receiver and subsequently needs to send fewer transmissions.

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

Summary



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

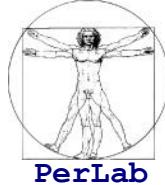
- **Topology Management** exploits node redundancy
 - The increase in the network lifetime depends on the actual redundancy, and is limited in practice (some %)
 - It allows a longer lifetime at the cost of increased redundancy (i.e., larger economic costs)
- **Power Management** removes idle times
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

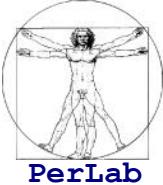
Sensor Energy Management

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

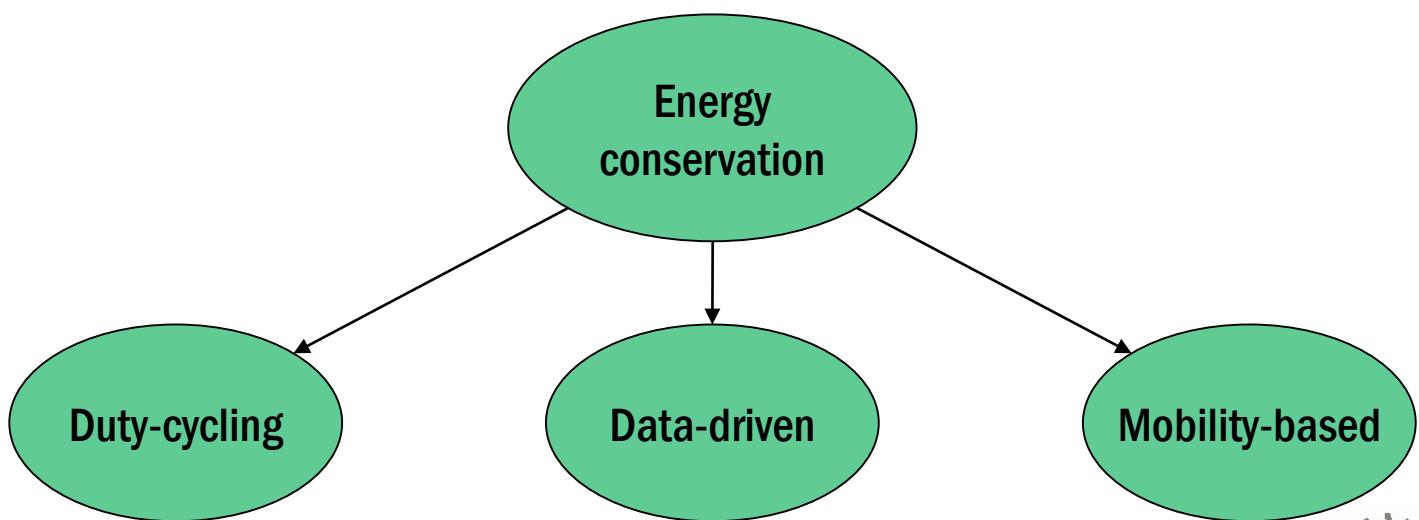
Critical Applications: Characteristics



- 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
- ...

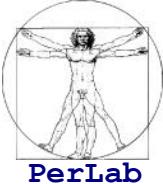
Energy conservation

- 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)





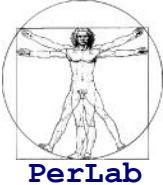
Power Consumption of Common Radios



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

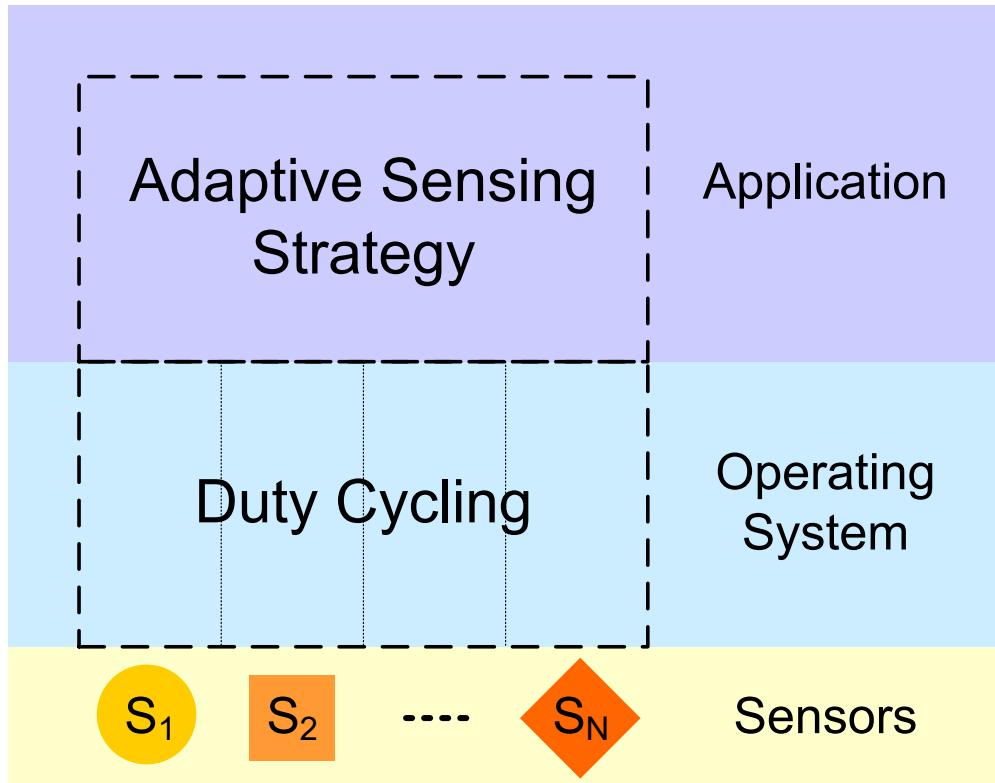
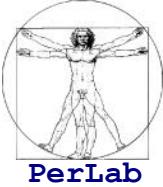


Power Consumption of Some Sensors



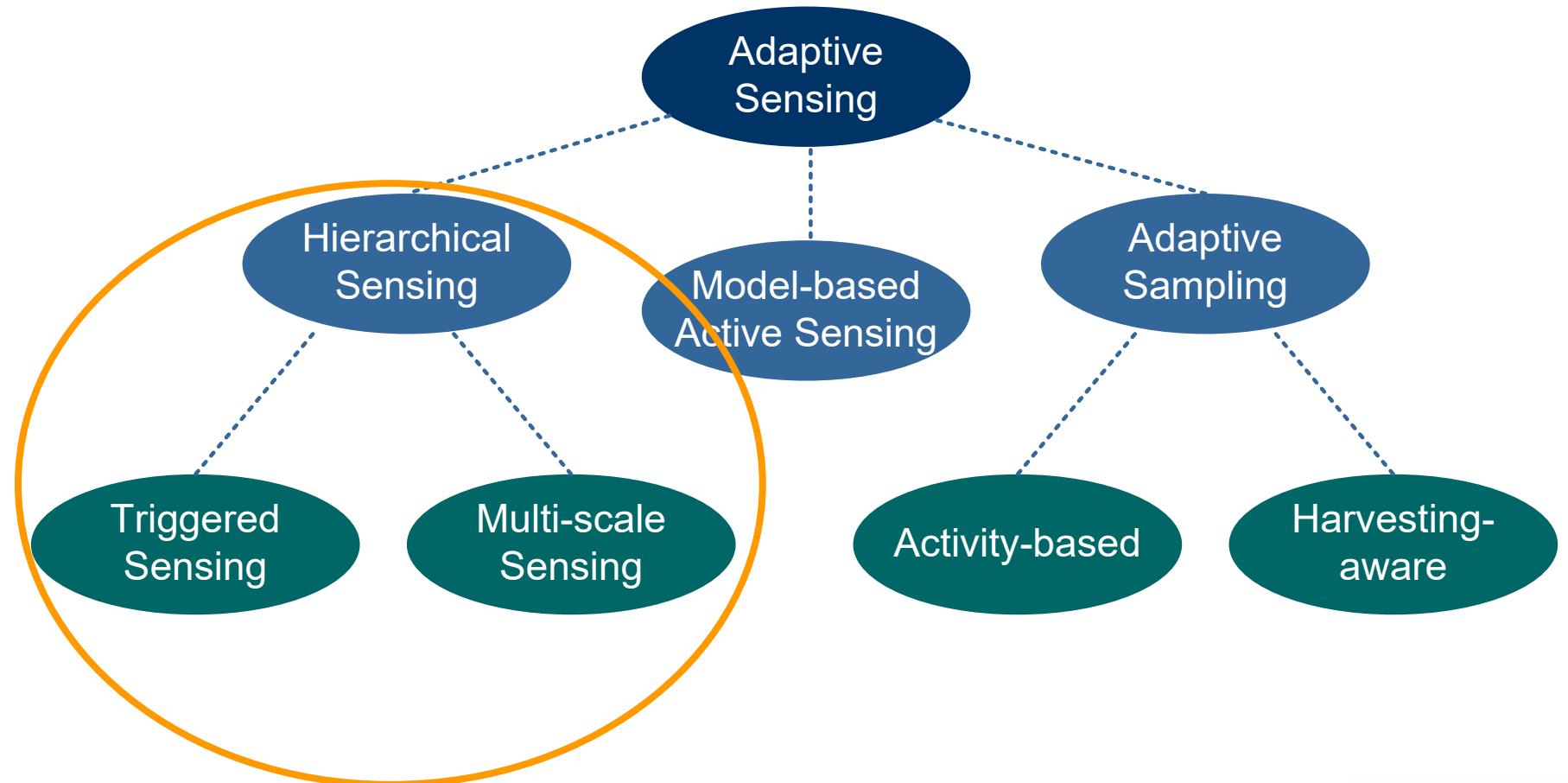
Sensor	Producer	Sensing	Power Consumption
STCN75	STM	Temperature	0.4 mW
QST108KT6	STM	Touch	7 mW
iMEMS	ADI	Accelerometer (3 axis)	30 mW
2200 Series, 2600 Series	GEMS	Pressure	50 mW
T150	GEFRAN	Humidity	90 mW
LUC-M10	PEPPERL+FUCHS	Level Sensor	300 mW
CP18, VL18, GM60, GLV30	VISOLUX	Proximity	350 mW
TDA0161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

Sensor Energy Management



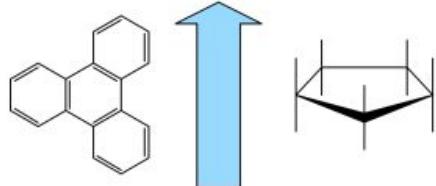
C. Alippi, G. Anastasi, M. Di Francesco, M. Roveri, **Energy Management in Sensor Networks with Energy-hungry Sensors**, *IEEE Instrumentation and Measurement Magazine*, Vol. 12, N. 2, April 2009

Adaptive Sensing Strategies



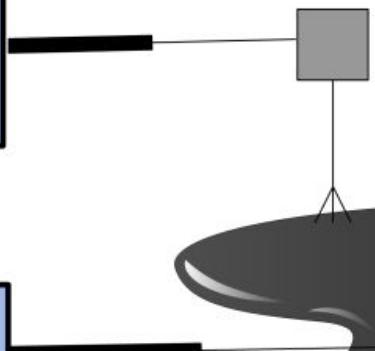
Hierarchical Sensing

Alarm

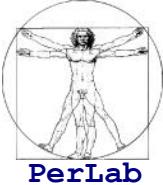


High Level Analysis
(Structure identification)

Low Level Analysis
(Element detection)



Hierarchical Sensing



■ Basic idea

- ⇒ Using different sensors with different power consumption and resolution properties
- ⇒ Accuracy/energy consumption trade-off

■ Triggered sensing

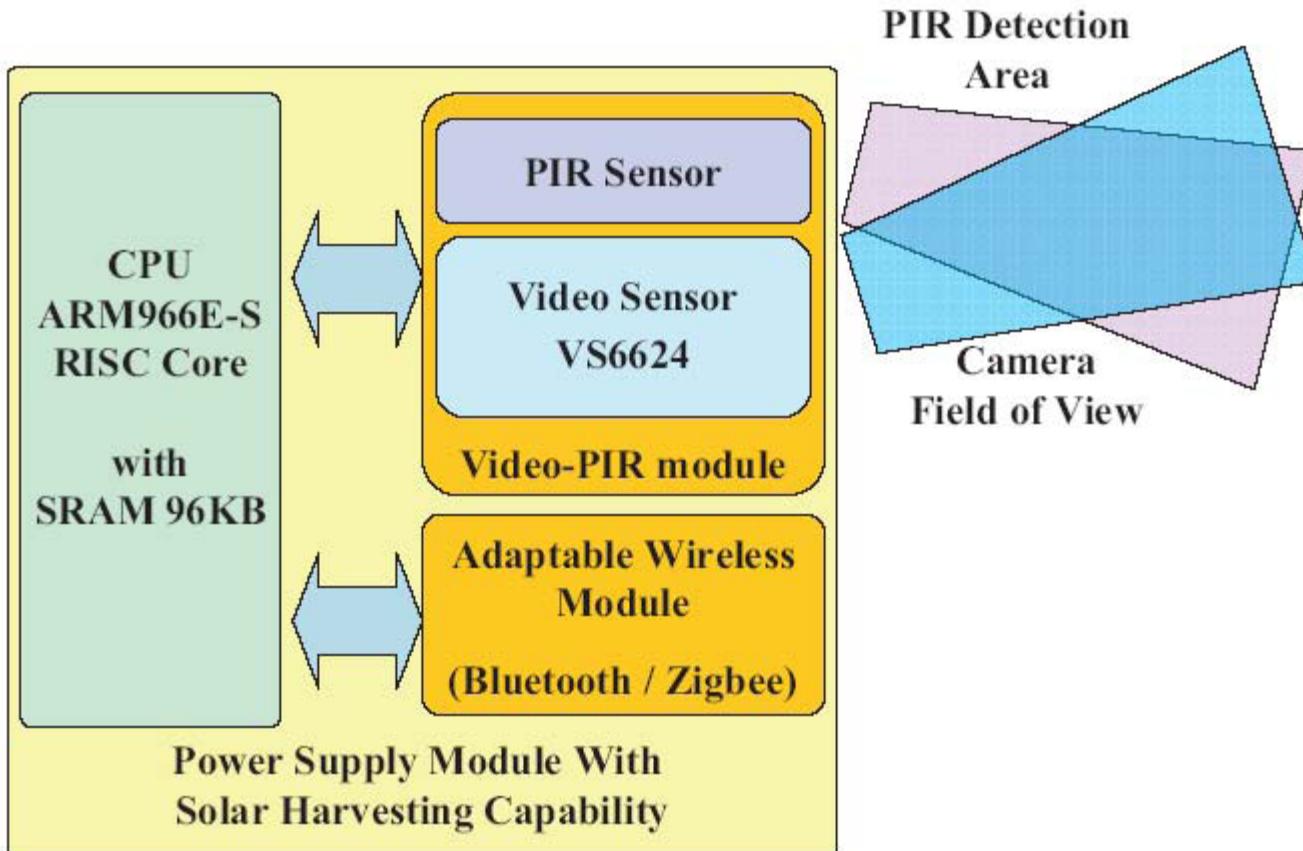
- ⇒ Low-power low resolution sensors **trigger** high-power high-accuracy sensors

■ 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)

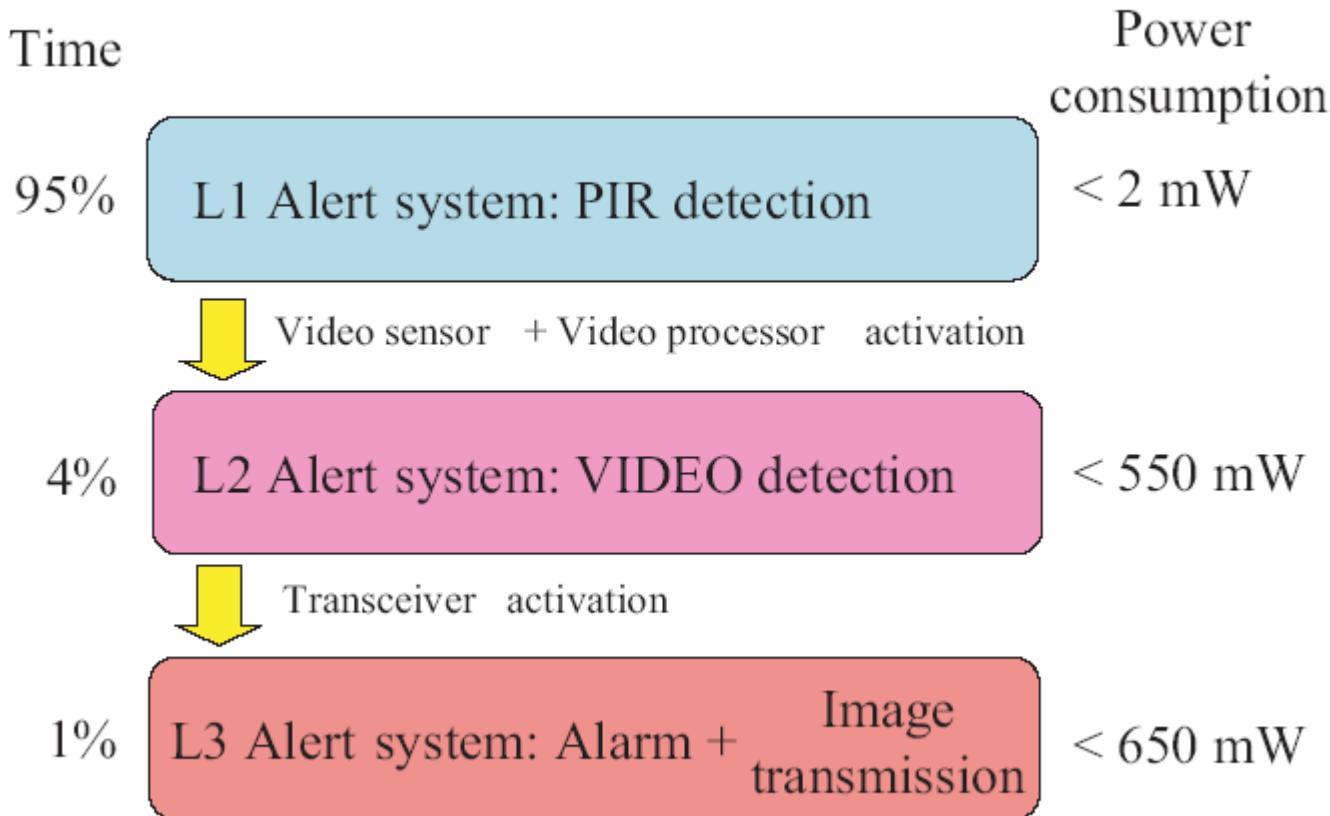


M. Magno, D. Brunelli, P. Zappi, L. Benini, **A Solar-powered Video Sensor Node for Energy Efficient Multimodal Surveillance**, Proc. EUROMICRO Conference on Digital System Design (DSD 2008), Parma, Italy, 2008.

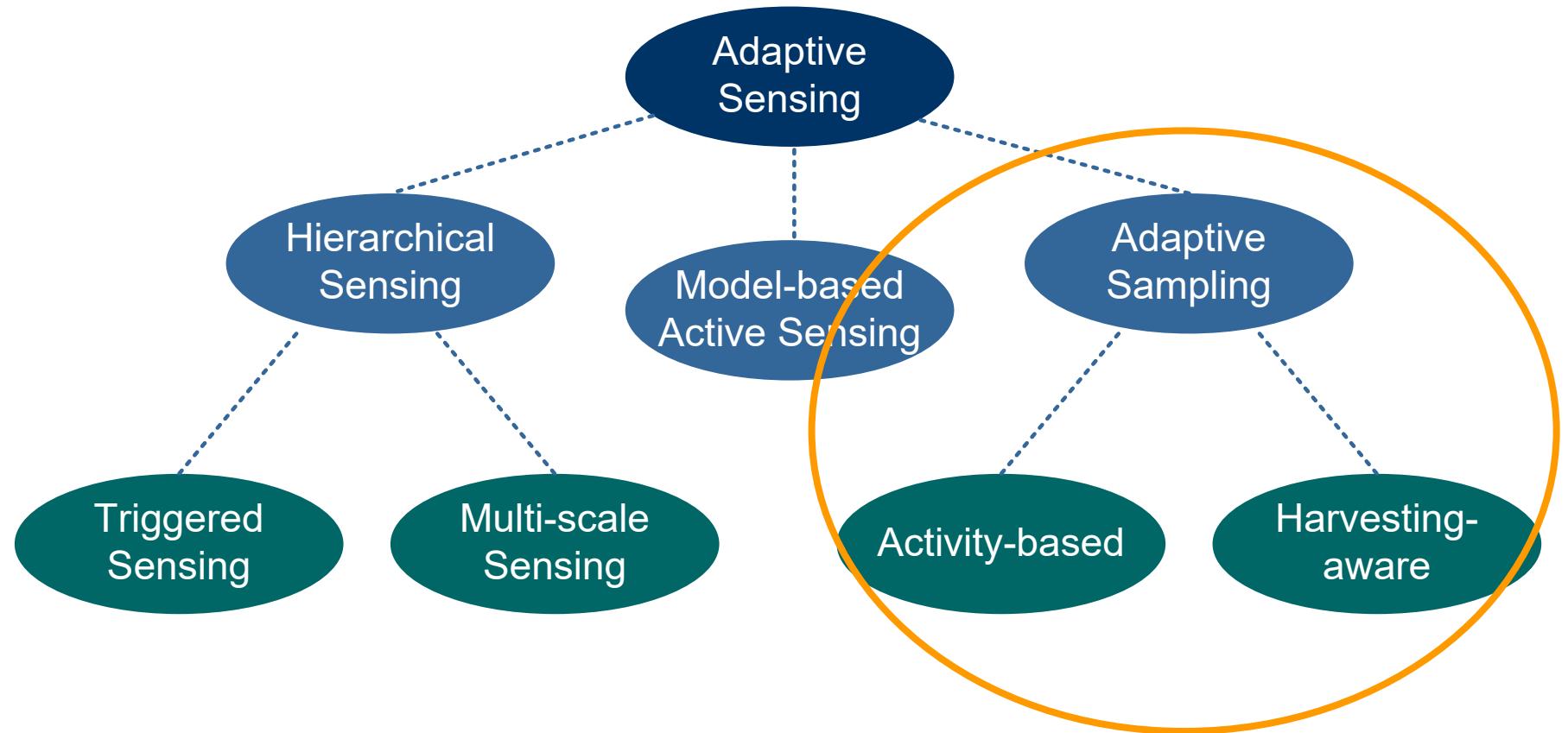
Triggered Sensing

- Low-power Low-cost Video sensor

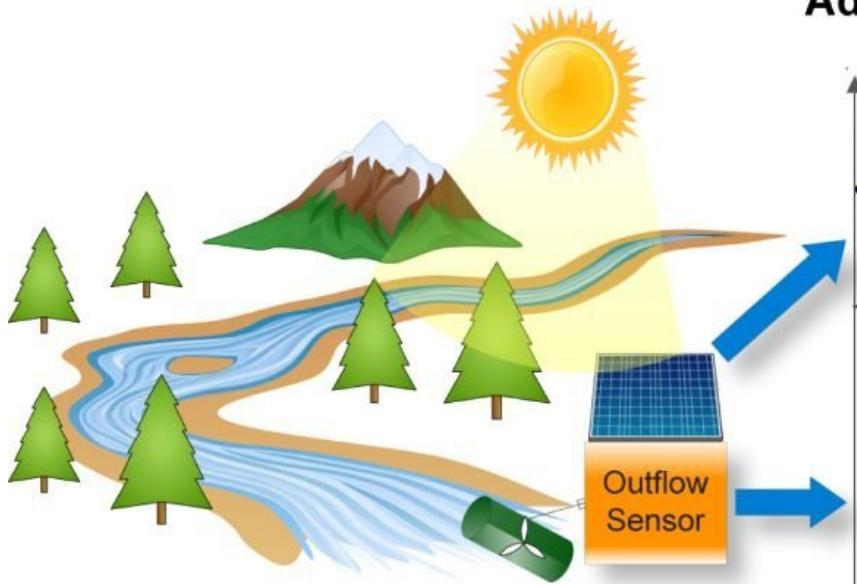
- A typical scenario



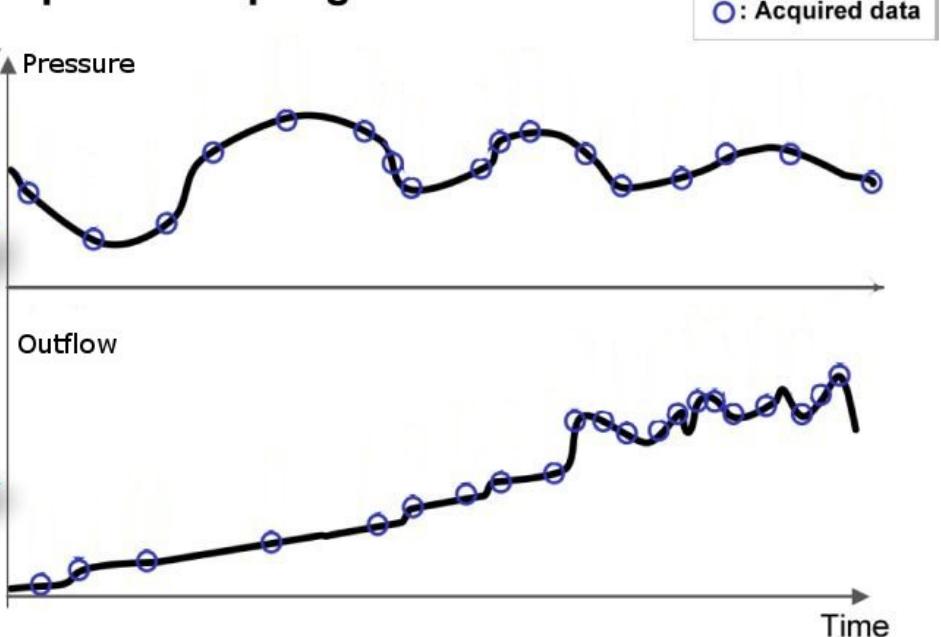
Adaptive Sensing Strategies



Adaptive Sampling



Adaptive Sampling



Activity-based Adaptive Sampling



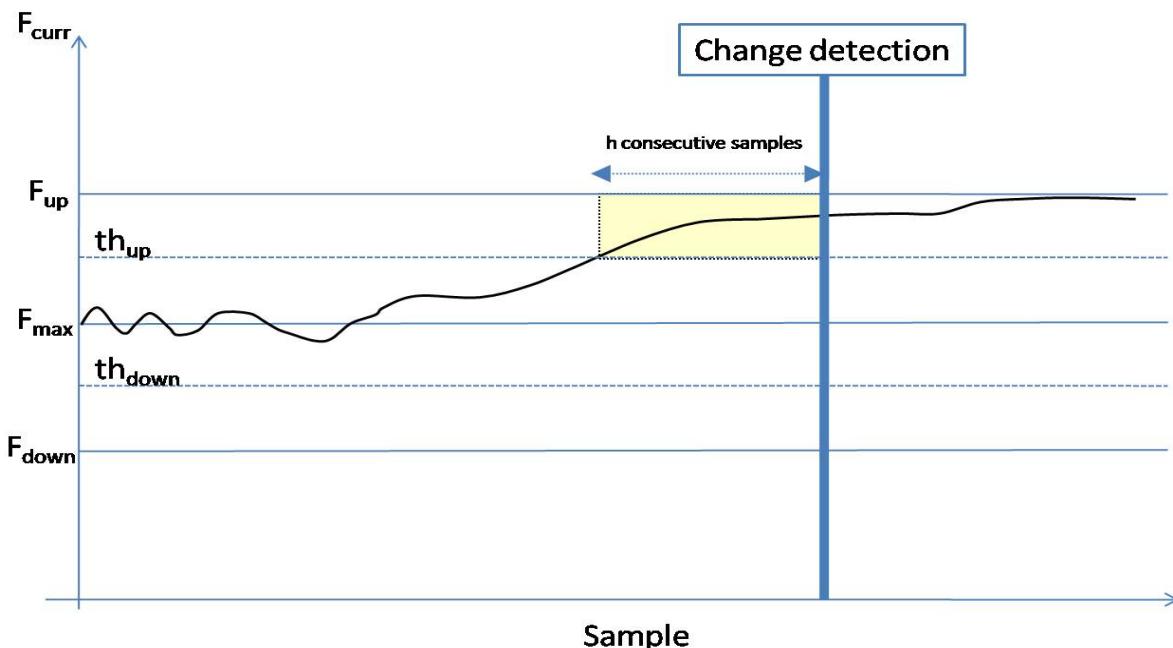
- Adapts the sampling rate to the dynamics of the phenomenon under monitoring
- Exploits
 - Temporal Correlation
 - Spatial Correlation
- Traditionally used for optimizing the communication process
 - Lower number of sensor nodes to activate
 - Lower amount of data to transmit
- Recently proposed also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

Key Questions

- When to change?
- How to change?

Adaptive Sampling Algorithm (ASA)

- 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.

The frequency change detection

- Modified CUSUM → basic idea:
 1. Estimate the maximum frequency \bar{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 \bar{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)

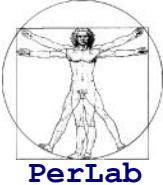
1. Store the W initial samples that come from the process in the *Dataset*;
2. Estimate \overline{F}_{\max} on the *Dataset* and set $F_c = c\overline{F}_{\max}$;
3. Define $F_{up} = \min\{(1 + \delta) \cdot \overline{F}_{\max}, F_c/2\}$; $F_{down} = (1 - \delta) \cdot \overline{F}_{\max}$;
4. $h_1 =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

The ASA Algorithm



5. **while** (1){
6. Acquire the i th sample and add it to the *Dataset*;
7. Estimate the current maximum frequency F_{curr} on the sequence *Dataset* ($i - W + 1, i$);
8. **if** ($|F_{curr} - F_{up}| < |F_{curr} - \bar{F}_{max}|$)
9. $h_1 = h_1 + 1; h_2 = 0;$
10. **else if** ($|F_{curr} - F_{down}| < |F_{curr} - \bar{F}_{max}|$)
11. $h_2 = h_2 + 1; h_1 = 0;$
12. **else** $h_1 = 0; h_2 = 0;$
13. **if** ($h_1 > h) \parallel (h_2 > h)$ {
14. $F_c = cF_{curr};$
15. $F_{up} = \min\{(1 + \delta) \cdot \bar{F}_{max}, F_c/2\};$
16. $F_{down} = (1 - \delta) \cdot \bar{F}_{max};$
17. $\bar{F}_{max} = F_{curr};$
18. }

Parameter selection: c , h and W

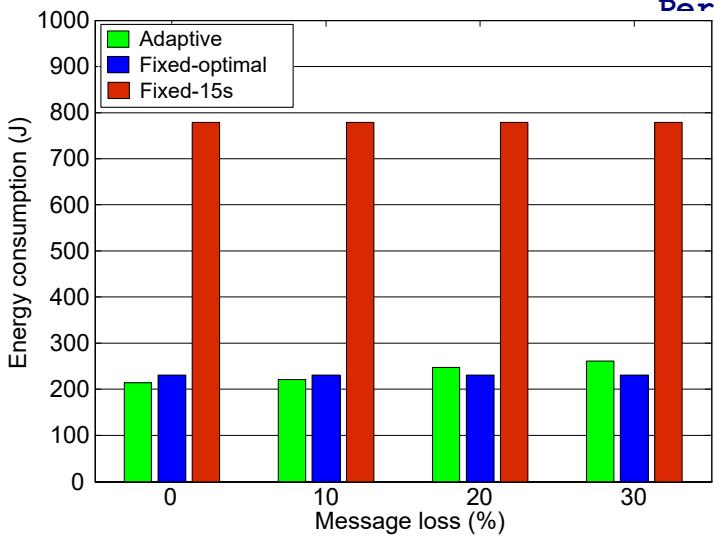
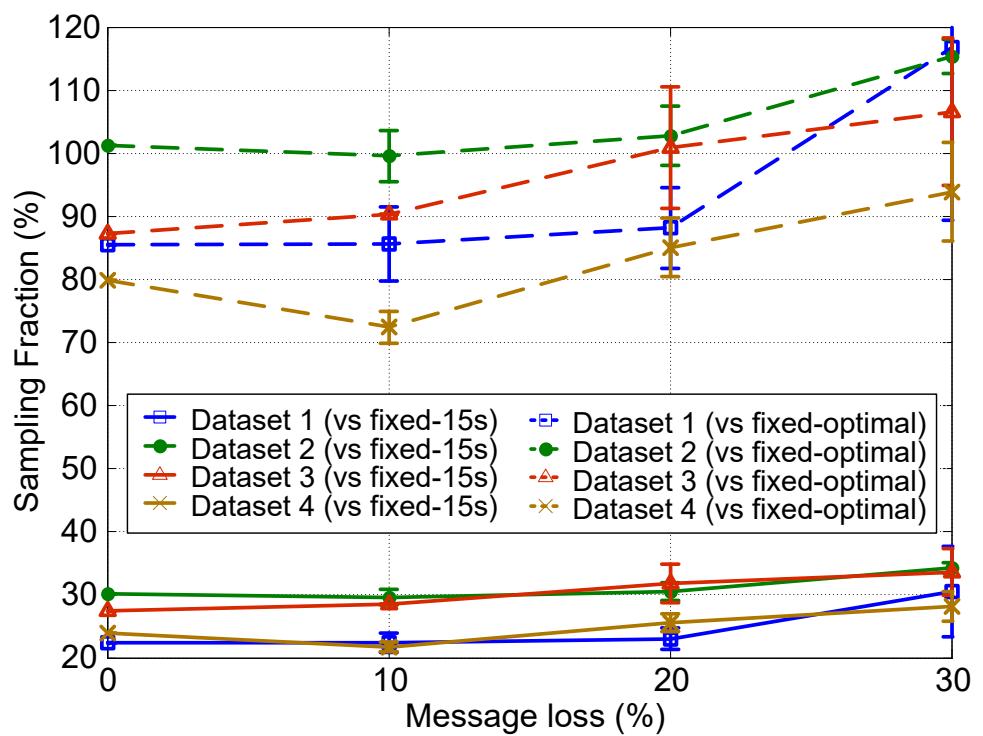


- Parameter c
 - *confidence* parameter for the maximum frequency detection ($c > 2$, Nyquist)
- Parameter h
 - critical to the *robustness* of the algorithm
 - ⇒ low values (e.g., 1 or 2): quick detection but possible false positives
 - ⇒ high values (e.g., 1000): few false positives but less promptness 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

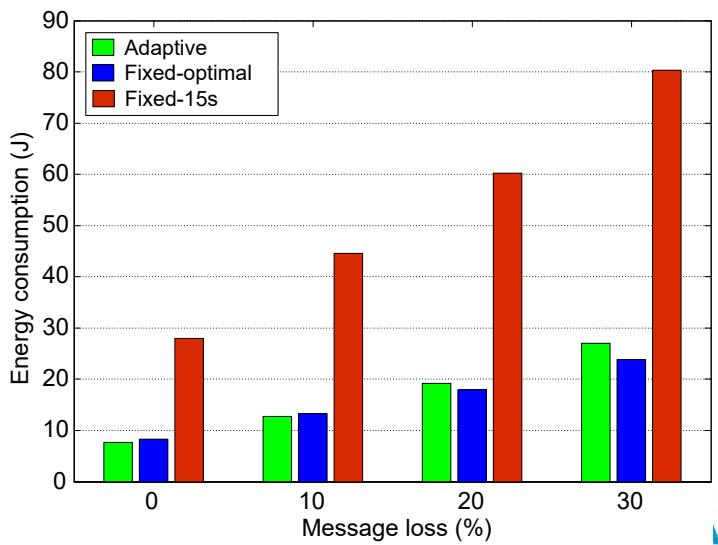
A-priori information about the process could provide the designer with a suitable parameter

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



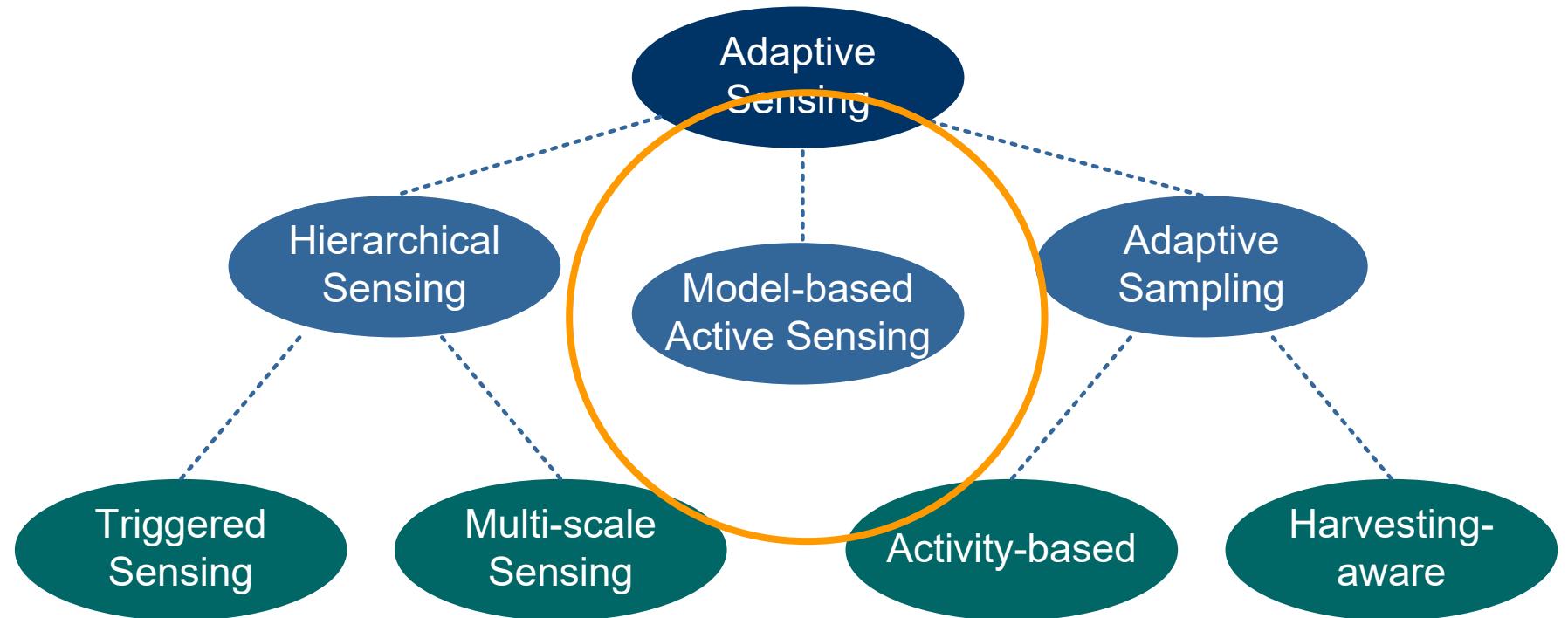
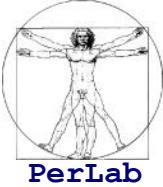
Radio Energy Consumption

Harvesting-aware

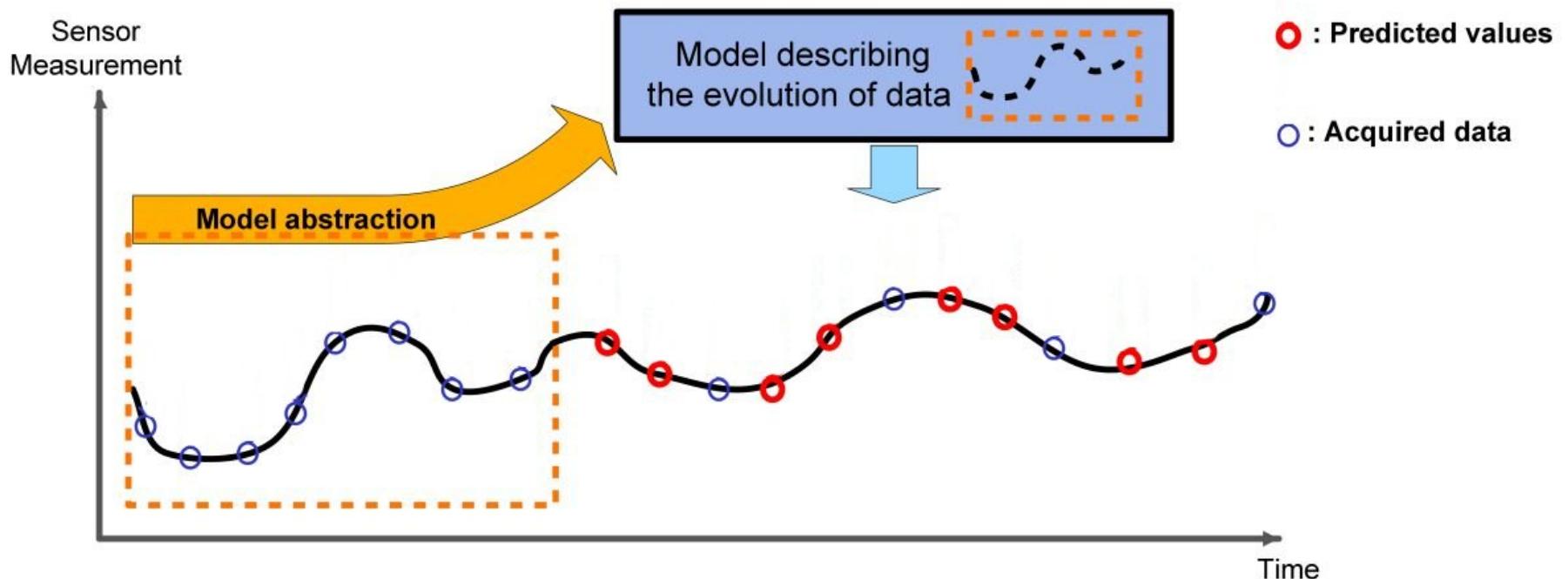


- Decentralized Adaptive Sampling
 - Sampling rate adapted on the basis of the available energy
 - ⇒ Nodes are powered by solar cells
 - Goal: minimize the total uncertainty error, given that the sensor can take a maximum number of samples on that day

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

■ 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

Model-based Active Sensing (cont'd)

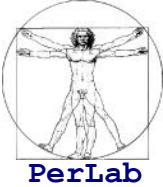


- Utility-based Sensing and Comm. (USAC)
 - Glacial environment monitoring
 - Linear regression model (sensor node)
 - ⇒ data are expected to be piecewise linear functions of time
 - If the next observed data is within the CI the sampling rate is reduced for energy efficiency
 - Otherwise, the sampling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

