Energy Conservation in Wireless Sensor Networks with Mobile Elements

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Overview

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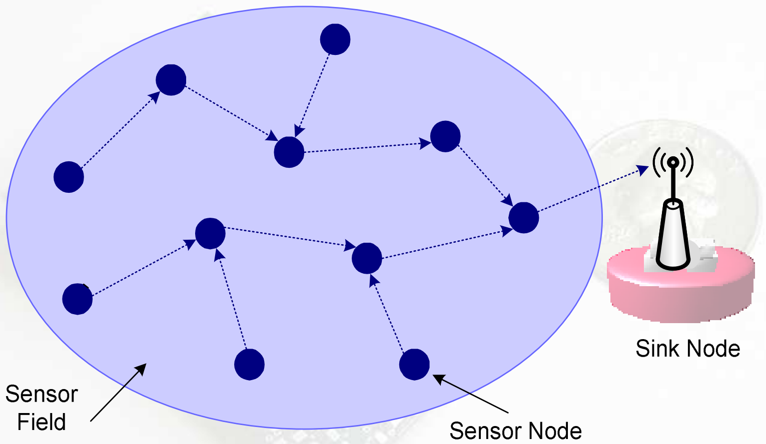
- WSN-MEs
- Power Management & Node Discovery
  - Schedule-based
  - On demand
  - Asynchronous
    - ⇨ Fixed
    - ⇨ Adaptive (Learning-based, Hierarchical)
- Conclusions and Research Questions

Wireless Sensor Networks with Mobile Elements

Static Sensor Networks



Funneling Effect!

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Other advantages of using WSN-MEs

- Connectivity
  - A sparse sensor network may be a feasible solution for a large number of applications
- Cost
  - Reduced number of sensor nodes ➔ reduced costs
- Reliability
  - Single-hop communication instead of multi-hop communication
  - Reduced contentions/collisions and message losses

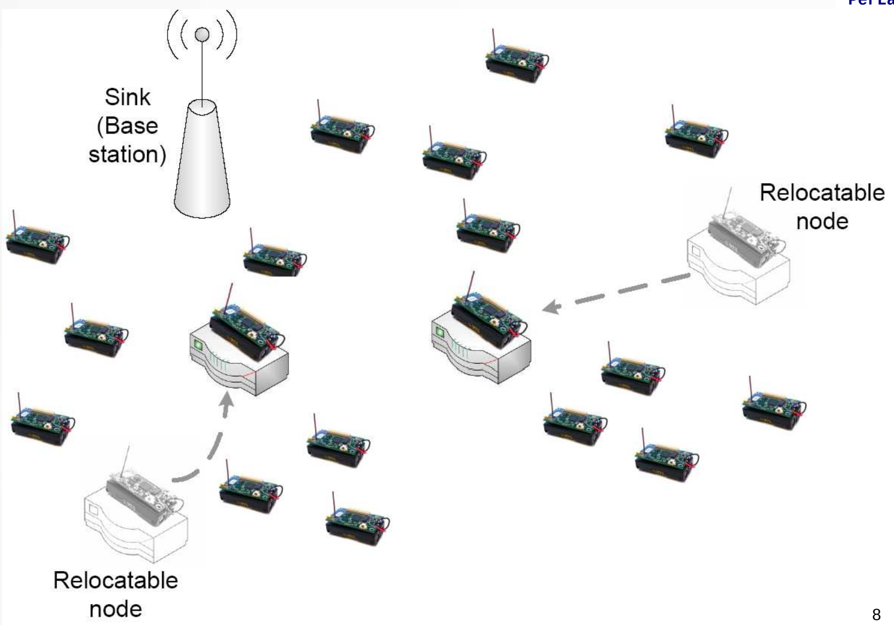
Components of a WSN-ME

- Regular Sensor Nodes
  - Sensing (source of information)
  - Data Forwarding
  - May be Static or Mobile
- Sink Nodes (Base Stations)
  - Destination of Information
  - Collect information directly or through intermediate nodes
  - May be Static or Mobile
- Special Support Nodes
  - Neither source nor destination of information
  - Perform a specific task (e.g., data relaying)
  - Typically mobile

Mobile Elements

- **Relocatable Nodes**
  - **Limited mobility**
  - **Do not carry data while moving**
  - **Typically used in dense networks**
- **Mobile Data Collectors**
  - **Mobile Sinks**
  - **Mobile Relays**
- **Mobile Peers**
  - **Regular mobile nodes**

Relocatable Nodes



Mobile Sinks

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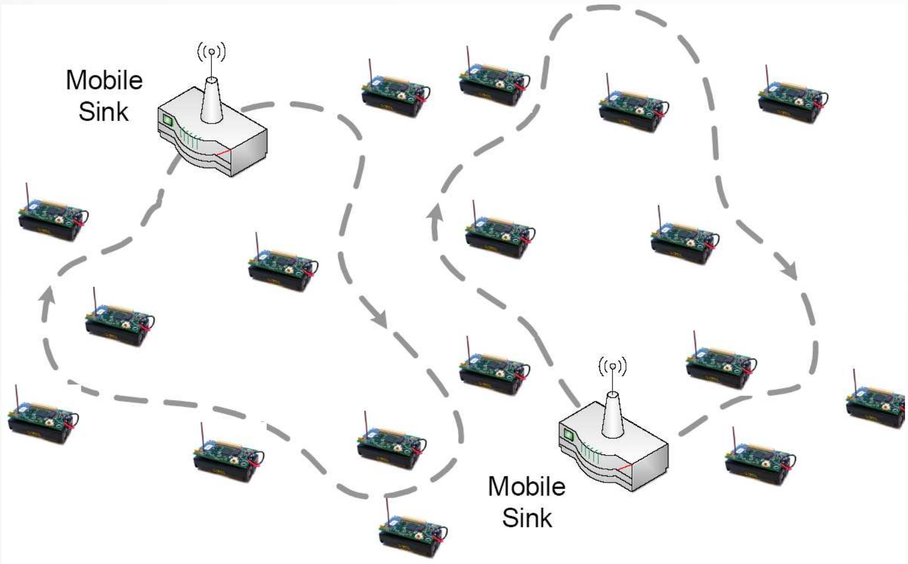

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Mobile Relays

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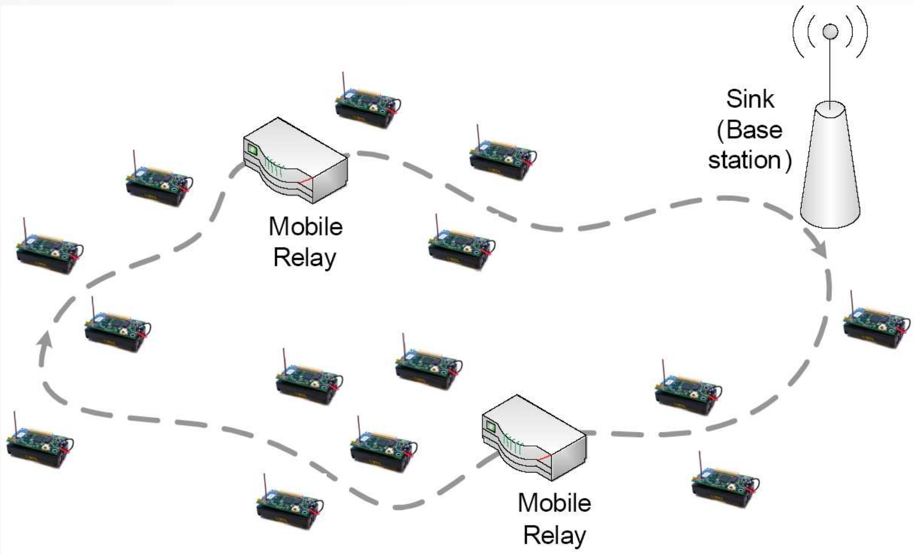

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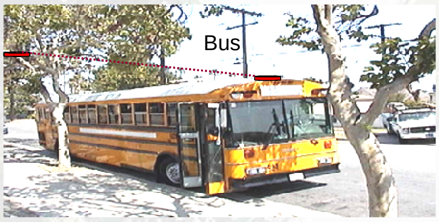
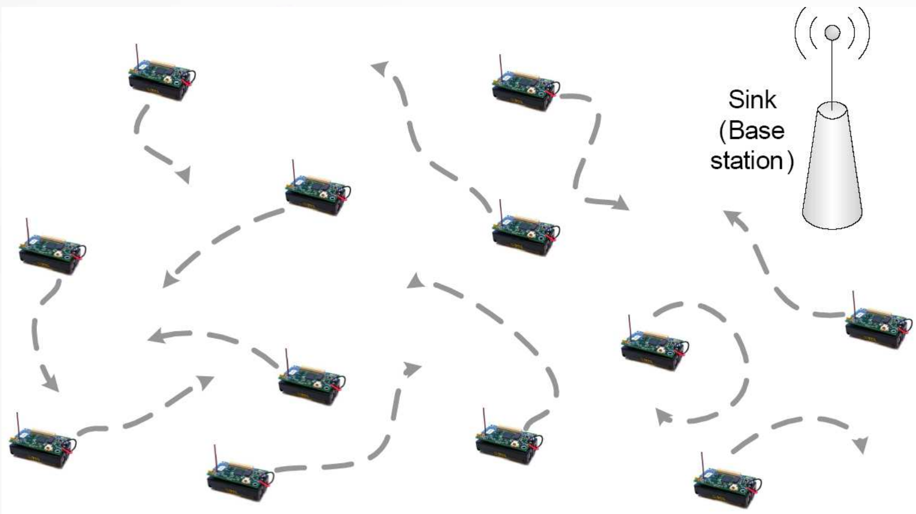
Mobile Sink/Relay: Potential Applications

- Air Quality Monitoring in Urban Areas
  - Sensors in strategic locations along streets.
  - Mobile Nodes are on board of buses
  - Collect data and transport to the sink node



- Urban Sensing Applications
  - Mobile nodes are personal devices
- Sensor-to-vehicle communication
- …

Mobile Peers



Mobile Peers

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N. Lane, E. Miluzzo, H. Lu, D. Peebles, T. Choudhury, A. Campbell, **A Survey of Mobile Phone Sensing**, *IEEE Communication Magazine, Sept. 2010.*

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Mobile Peers: Potential applications

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- Mobile devices equipped with
  - (mobile) sensors
    - ⇨ Camera, audio recorder, accelerometer, …
  - Wireless communication
    - ⇨ 3G, WiFi, Bluetooth, …
- Can be used to implement
  - Personal Sensing applications (e.g., Cence me)
  - Group Sensing applications (e.g., garbage watch)
  - Participatory sensing applications

N. Lane, E. Miluzzo, H. Lu, D. Peebles, T. Choudhury, A. Campbell, **A Survey of Mobile Phone Sensing**, *IEEE Communication Magazine, Sept. 2010.*

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Energy conservation in WSN-MEs

- **Data-driven approaches**
  - data compression
  - data prediction
  - …
- **Power Management (duty cycling)**
  - The sensor duty cycle should be as low as possible
    - ⇨ to maximize the lifetime
  - Contacts could be missed
  - Efficient ME Discovery
    - ⇨ Maximize the number of detected contacts while minimize energy consumption

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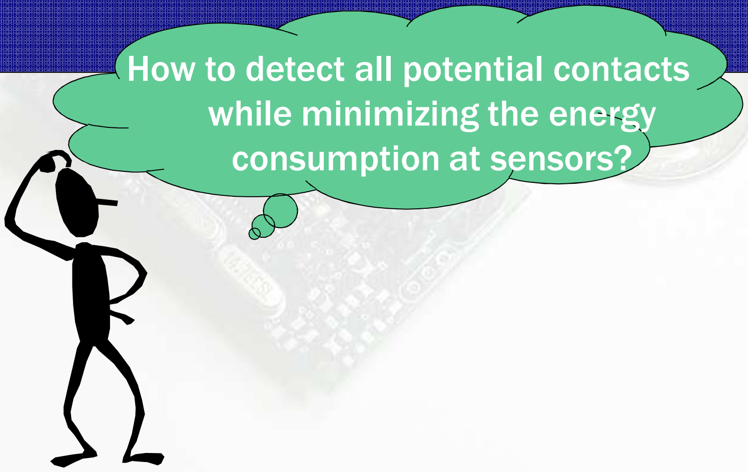
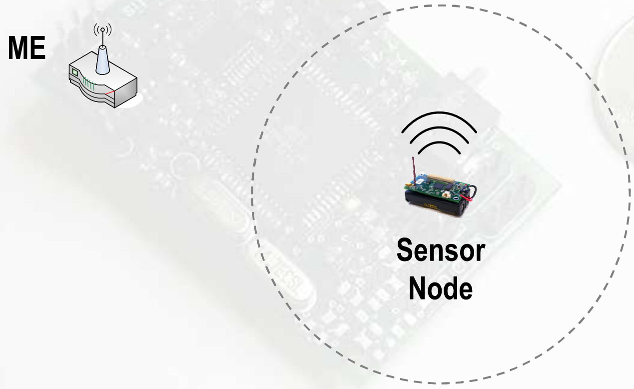
Power Management and Mobile Element Discovery



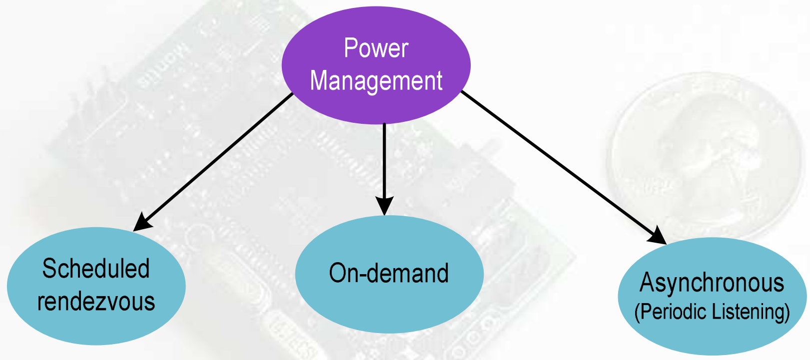
Ideal Scenario



In practice

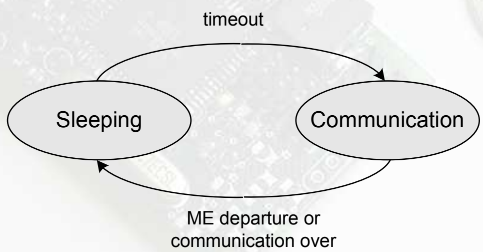
- MDC arrival times are typically not known in advance
- Sensors nodes cannot be always active
  - Low duty cycle δ to save energy
- Discovery Protocol
  - Strictly related with power management

Power Management Schemes



Scheduled Rendez-vous schemes

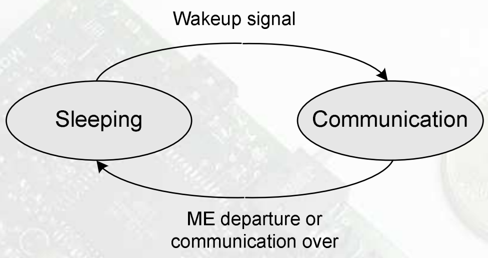
- **Sensor nodes and ME agree on the visit time**
  - **at least with some approximation**
- **Simple to implement and energy Efficient**
- **Synchronization required**
- **Not applicable in some contexts**



Chakrabarti, A., Sabharwal, A., and Aazhang, **Using Predictable Observer Mobility for Power Efficient Design of Sensor Networks**", Proc. International Workshop on Information Processing in Sensor Networks (IPSN 2003), Pages 129-145.

On-demand schemes

- The ME wakes up the static node when it is nearby



- **Passive wakeup** radio
  - ⇨ Use energy harvested by the wakeup radio (e.g., RFID)
- **Active wakeup** radio
  - ⇨ Low-power radio + high-power radio

Passive Wakeup radio

- Use the energy *passively* received through the wakeup radio to activate the data radio
- Very limited distance
  - ⇨ Few meters (suitable only for robotic networks)
  - ⇨ The distance can be increased at the cost of
    - Increased complexity on the wakeup radio (increased cost)
    - Increased wakeup time
- Additional hardware required

H. Ba, I. Demirkol, W. Heinzelman, **Feasibility and Benefits of Passive RFID Wakeup Radios for Wireless Sensor Networks**, *Proc. IEEE Globecom 2010*, Miami, Florida, USA, Dec. 6-10, 2010

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

Passive Wakeup Radio

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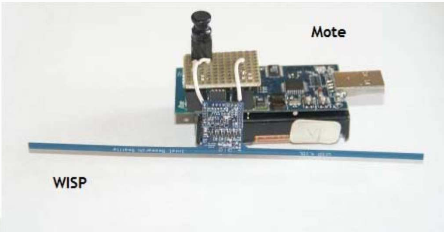
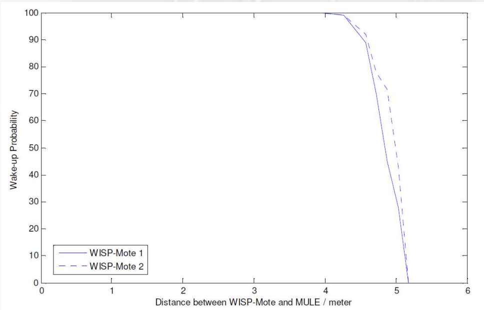
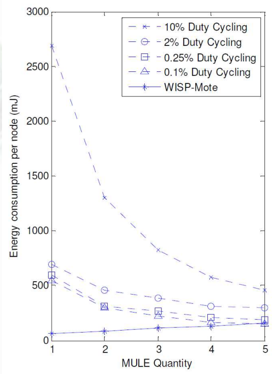
WISP

- Wireless Identification and Sensing Platform
- Integration of Tmote Sky mote with a passive RFID tag
- RFID reader on the ME
- Maximum distance: few meters







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Active Wakeup Radio

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Radio Hierarchy

- **Scenario**
  - Mobile opportunistic network of handheld devices
- **Multiple-radio strategy**
  - Higher-level radio for data exchange, lower-level radio for discovery
    - ⇨ Bluetooth and WiFi, Mote and WiFi
  - The lower-level radio is used to discover, configure and activate the higher-level radio
    - ⇨ Bluetooth used to discover a nearby WiFi Access Point or node and configure the WiFi interface

T. Pering, V. Raghunathan, R. Want, **Exploiting Radio Hierarchies for Power-Efficient Wireless Device Discovery and Connection Setup**, Proc. *International Conference on VLSI Design*, 2005

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Active Wakeup Radio

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Hierarchical Power Management

- Scenario
  - Opportunistic networks of handheld devices
  - WSNs with all mobile nodes
- Multiple radio's strategy
  - Low- power radio for discovery
  - High-power radio for both discovery and data exchange
  - High-power radio is awakened by the low-power radio
    - ⇨ E.g., mote radio and WiFi

[Jun09] H. Jun, M. Ammar, M. Corner, E. Zegura, **Hierarchical Power Management in Disruption Tolerant Networks with Traffic-aware Optimization**, *Computer Communications*, Vol. 32 (2009), pp. 1710-1723

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Active Wakeup Radio

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Network Interrupts

- Scenario
  - Sensor Networks (with MEs)
- Two different radios
  - A primary high-power radio usually in sleep mode
    - ⇨ Used for data communication
  - Control Low-power radio always powered on
    - ⇨ Used for control messages
- A node can activate the high-power radio of a nearby node by sending it a beacon through the low-power radio

J. Brown, J. Finney, C. Efstratiou, B. Green,N. Davies, M. Lowton, G. Kortuem, **Network Interrupts: Supporting Delay Sensitive Applications in Low Power Wireless Control Networks**, Proc. *ACM Workshop on Challenged Networks (CHANTS 2007)*, Montreal, Canada, 2007

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Limits of On-demand schemes

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- On-demand schemes require multiple radios
  - which may not available in current sensor platforms
- The range of the wakeup radio is typically limited
  - Few meters for passive radios
- Active radios have a longer range, but they consume energy
  - The energy consumption should be below 50 μW
  - And the wakeup range should be as long as the communication range

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Power Management Schemes

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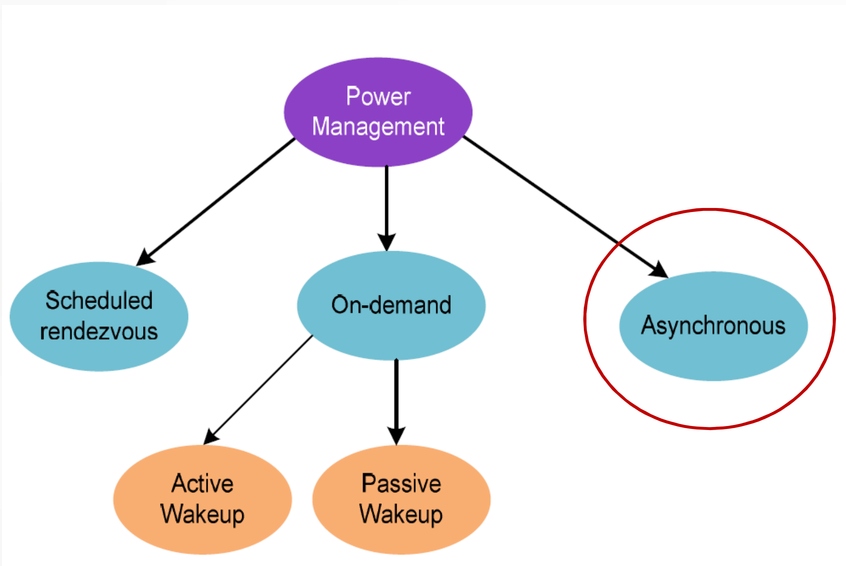

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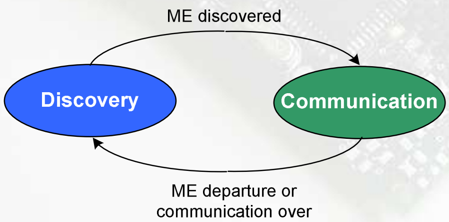
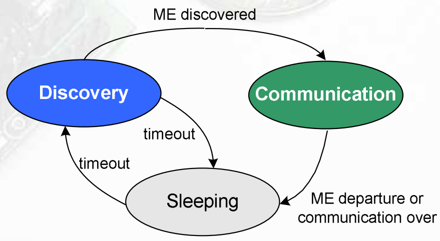
Asynchronous schemes

- **ME emits periodic beacons to announce its presence**
- **SN wakes up periodically (*period listening*), and for short periods**
  - **Very low duty cycle for saving energy**





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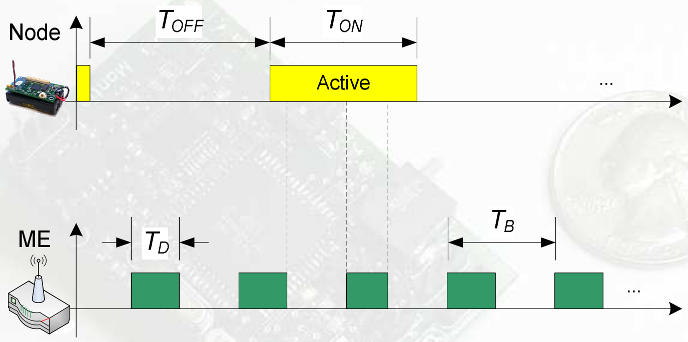
Asynchronous (Periodic Listening)



$$T_{ON} = T_B + T_D$$

$$\delta = T_{ON}/(T_{ON} + T_{OFF})$$

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Classification of Periodic Listening Schemes

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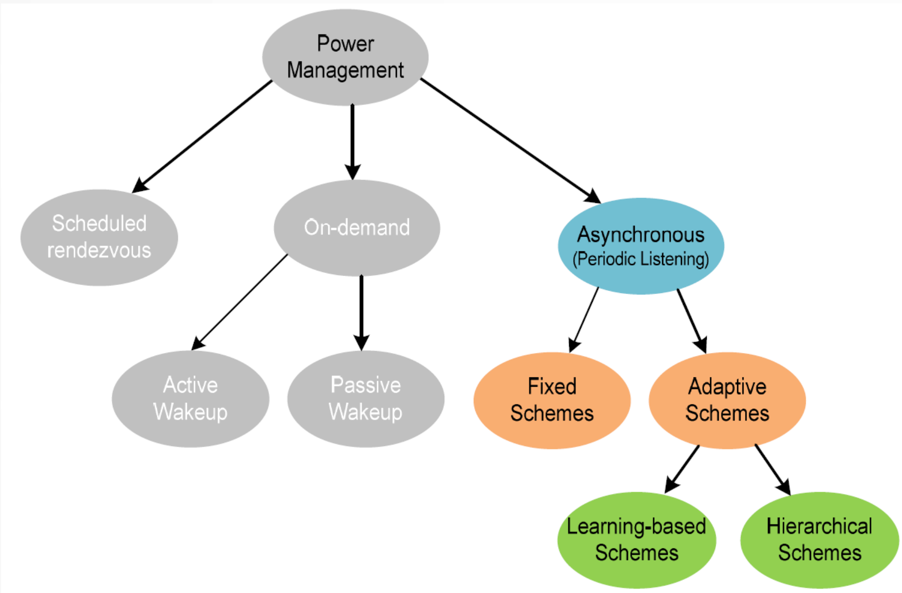

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Classification of PeriodicListening Schemes

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- **Fixed Schemes**
  - **Both the beacon period and the sensor node's duty cycle are fixed over time**
- **Adaptive Schemes**
  - **Learning-based schemes**
    - ⇨ **The arrival time of the ME is predicted based on the past history, and the duty cycle is adjusted accordingly**
  - **Hierarchical schemes**
    - ⇨ **Two different operation modes for sensor nodes**
      - – **Low-power mode (most of the time)**
      - – **High-power mode (when the ME is nearby)**

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Fixed Schemes

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- **Fixed Beacon Period**
- **Fixed Sensor's Duty Cycle (δ)**
  - **A low duty cycle saves energy, but contacts may be missed**
  - **A high duty cycle increases the % of detected contacts, but decreases the sensor's lifetime**
- **Key Question**
  - **Which is the optimal duty cycle that allows to detect *all contacts* with the *minimum energy* expenditure?**
  - **The optimal duty cycle depends on a number of factors that are difficult (if not impossible) to know in advance.**

G. Anastasi, M. Conti, M. Di Francesco, **Reliable and Energy-efficient Data Collection in Sparse Sensor Networks with Mobile Elements**, *Performance Evaluation*, Vol. 66, N. 12, December 2009.

Fixed Schemes

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- **Fixed approach**
  - **Fixed Beacon Period**
  - **Fixed Sensor's Duty Cycle (δ) [Mat05] [Jai06]**
    - ⇨ **A low duty cycle saves energy, but contacts may be missed**
    - ⇨ **A high duty cycle increases the % of detected contacts, but decreases the sensor's lifetime**

This approach is quite inefficient, especially when sensor nodes spend a long time in the discovery phase

[Mat05] R. Mathew, M. Younis, S. Elsharkawy **Energy-Efficient Bootstrapping Protocol for Wireless Sensor Network**, *Innovations in Systems and Software Engineering*, Vol. 1, No 2, Sept. 2005

[Jai06] S. Jain, R. Shah, W. Brunette, G. Borriello, and S. Roy, **Exploiting Mobility for Energy Efficient Data Collection in Wireless Sensor Networks**, *Mobile Networks and Applications*, Vol. 11, No. 3, June 2006.

Learning-based approaches

Adaptive Beacon Rate

- Reference Scenario
  - All sensor nodes are mobile
  - Fixed sink with limited energy budget
  - Energy harvesting
- Basic idea
  - Adaptive beacon emission rate
    - ⇨ Time is divided in slots (1-hour duration)
    - ⇨ For each time slot the expected contact probability is derived and updated dynamically based on the past history
    - ⇨ The beacon emission rate is varied according to the estimated probability and the available energy
  - Based on reinforcement learning

V. Dyo, C. Mascolo, **Efficient Node Discovery in Mobile Wireless Sensor Networks**, *Proc. DCOSS 2008, LNCS, vol. 5067*. Springer, Heidelberg (2008)

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Learning-based approaches

Resource-Aware Data Accumulation (RADA)

- Reference Scenario
  - Static Sensor Nodes (with energy limitations)
  - MEs are resource-rich devices
- Basic idea
  - Fixed (Periodic) Beacon Emission by ME
  - The wake-up period (i.e., duty cycle) of the sensor node is adjusted dynamically, depending on the past history
  - Based on DIRL framework
- DIRL framework
  - Based on Q-learning
  - Autonomous and adaptive resource management
    - ⇨ suitable to sparse WSNs

K. Shah, M. Di Francesco, G. Anastasi, M. Kumar, **A Framework for Resource-Aware Data Accumulation in Sparse Wireless Sensor Networks** *Computer Communications*, Vol. 34, N. 17, November 2011.

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DIRL framework

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- Set of tasks to be executed
  - Task priority
  - Applicability predicate
- Set of states
  - State representation includes system and application variables
  - Hamming distance used for deriving distance between states and aggregate similar states
- Utility Lookup Table: *Q(s, t)*
  - *Q(s,t)* gives the long-term utility of executing task *t* in state *s*
- Exploration/Exploitation strategy
  - Exploration with probability ε
    - ⇨ A random task is executed
  - Exploitation with probability $1-\varepsilon$
    - ⇨ The best task, according to Q-values, is selected

K. Shah, M. Kumar, **Distributed Independent Reinforcement Learning (DIRL) Approach to Resource Management in Wireless Sensor Networks**, *Proc. IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS07)*, Pisa, Italy, October 2007

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DIRL Algorithm

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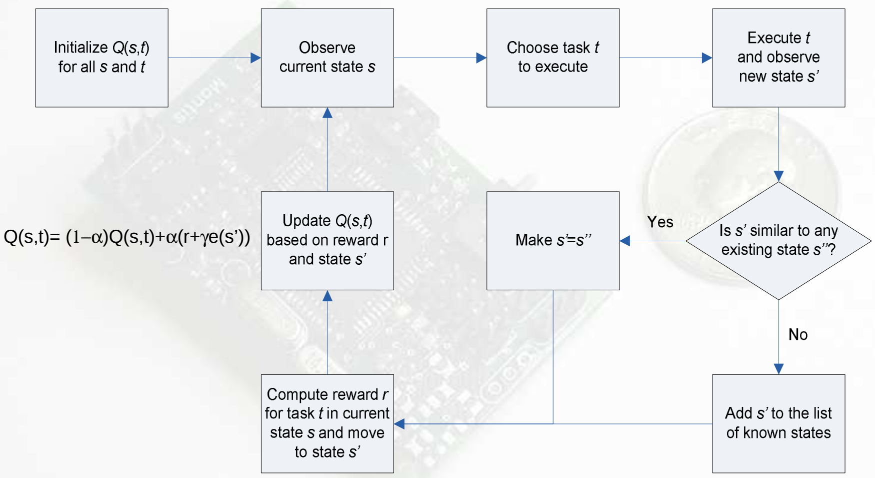

K. Shah, M. Kumar, **Distributed Independent Reinforcement Learning (DIRL) Approach to Resource Management in Wireless Sensor Networks**, *Proc. IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS07)*, Pisa, Italy, October 2007

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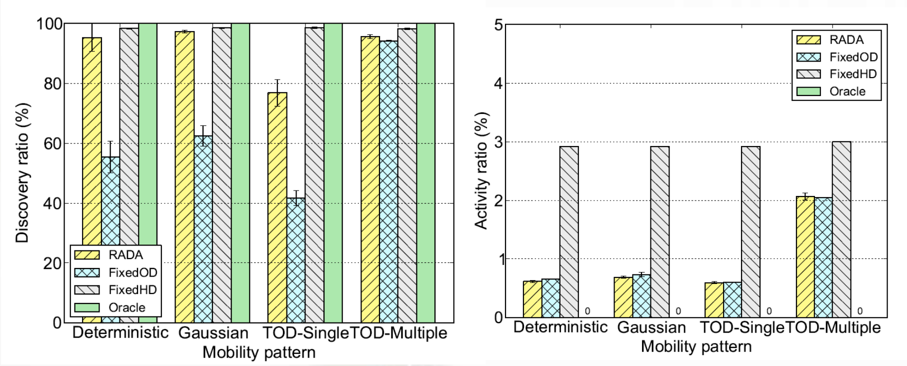
Simulation Results

Sparse Scenario



K. Shah, M. Di Francesco, G. Anastasi, M. Kumar, **A Framework for Resource-Aware Data Accumulation in Sparse Wireless Sensor Networks** *Computer Communications*, Vol. 34, N. 17, November 2011.

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Limits of Adaptive Schemes

- **Learning-based schemes perform well when the ME has a regular mobility pattern**
  - **The regularity can be learned and exploited for predicting next arrivals**
- **Performance degrades significantly as the randomness in the mobility pattern increases**

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Hierarchical Discovery schemes

- Basic idea
  - The duty cycle is adjusted dynamically (as in learning-based approaches)
    - Low duty cycle when the ME is far
    - High duty cycle when the ME is about to arrive
  - Information about the ME location are provided by the ME itself
- Dual Radio
  - Low-power radio for discovery and a high-power radio for data communication
  - Already considered as on-demand schemes
- Dual Beacon
  - Long-range beacons for announcing the presence of the ME in the area
  - Short-range beacons for informing that communication can take place

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Dual Beacon Discovery (2BD)

- ME uses two different beacon messages
  - Long-range beacons (LRB) for announcing the presence of the ME in the area
  - Short-range beacons for informing that communication can take place
- Sensor nodes alternate between two duty cycles
  - Typically in Low duty cycle
  - Switch to High duty cycle upon receiving a LRB
  - Enter the communication phase upon receiving a SRB
  - Switch back to Low duty cycle at the end of the communication phase

F. Restuccia, G. Anastasi, M. Conti, and S. Das, **Performance Analysis of a Hierarchical Discovery Protocol for WSNs with Mobile Elements**, Proc. *IEEE International Symposium on a World of Wireless, Mobile, and Multimedia Networks (WoWMoM 2012)*, San Francisco, CA, USA, June 25-28, 2012.

K. Kondepu, G. Anastasi, M. Conti, **Dual-Beacon Mobile-Node Discovery in Sparse Wireless Sensor Networks**, Proc. *IEEE International Symposium on Computers and Communications (ISCC 2011),* Corfu, Greece, June 28 – July 1, 2011.

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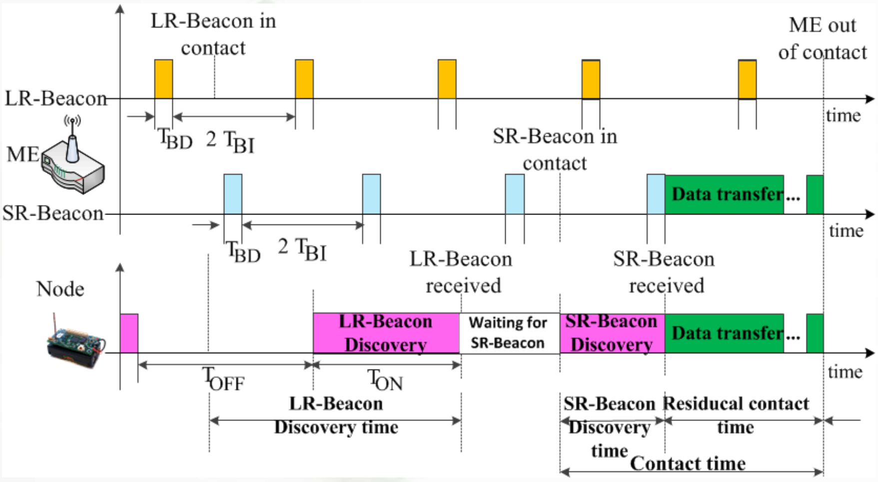
2BD Protocol



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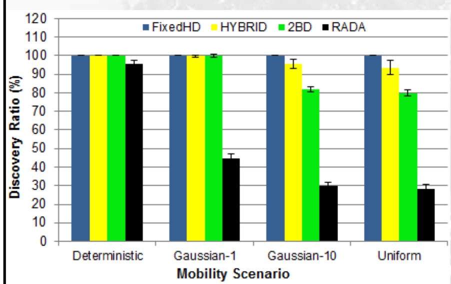
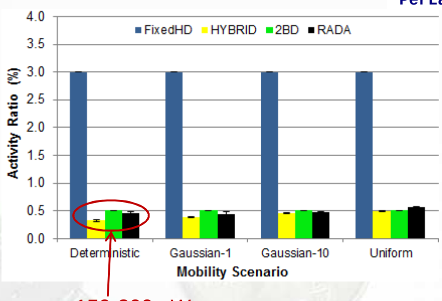
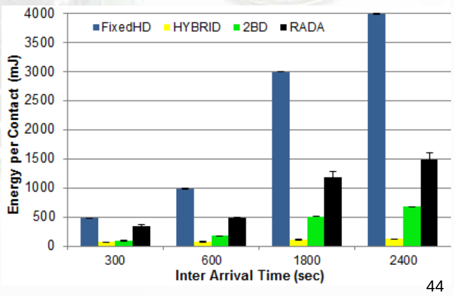
Simulation Results

Sparse Scenario





150-200 µW



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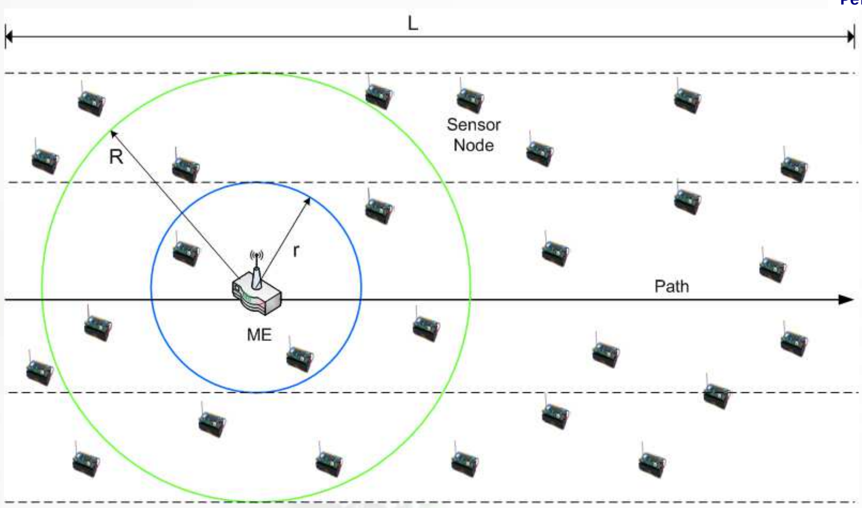
False Activations



$$E_{FA} = \left(\frac{R}{r} - 1\right) \cdot T_{out} \cdot [\delta_H \cdot P_{RX} + (1 - \delta_H) \cdot P_{SL}]$$

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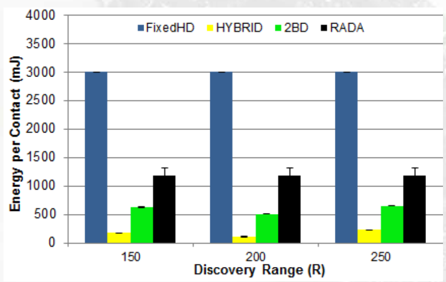
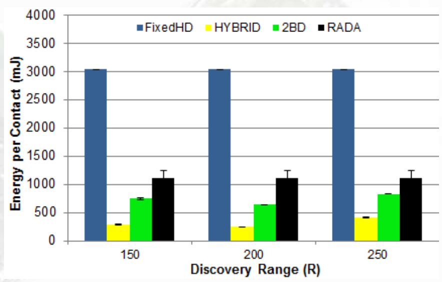
Simulation Results

Sparse Scenario
(false activations never occur)



Dense Scenario
(false activations may occur)



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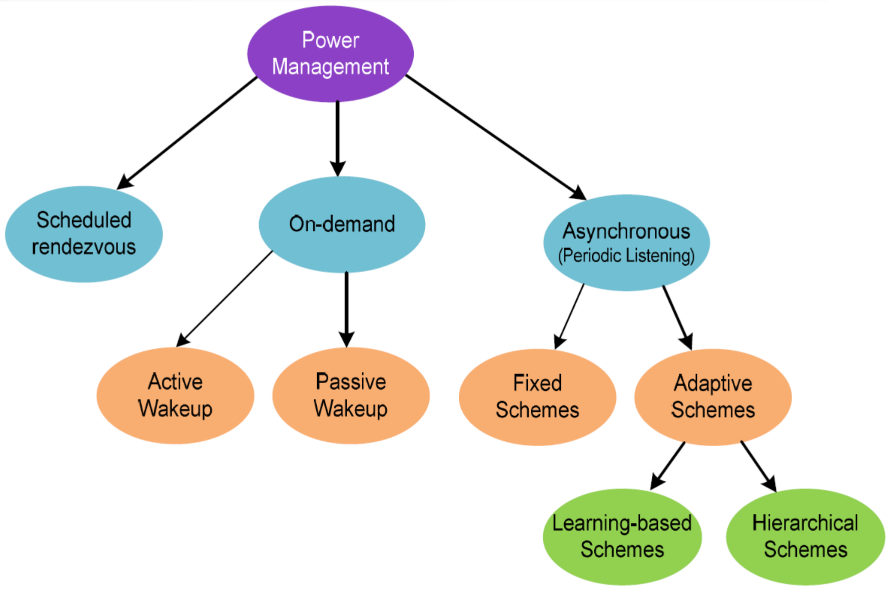
Conclusions & Key Research Questions

Summary



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Summary

- Schedule-based power management can be used only in some special cases
- On-demand wakeup is pretty interesting! However …
  - Active wakeup radio consume energy
    - ⇨ Low power consumption * long time = large energy consumption
  - Passive wakeup radios do not consume additional energy, but they have very very short ranges (few meters)
  - In both cases, special hardware is required

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Summary

- Periodic Listening can be always used
  - As it does not require special hardware
  - Finding the appropriate parameters may not be so easy
  - Using fixed parameters may result in inefficient solutions
- Periodic Listening with adaptive parameters is more efficient
  - Learning-based schemes are suitable for scenarios where ME moves with a regular pattern
  - Hierarchical schemes (based on dual beaconing) are more flexible
    - ⇨ False activations may occur in dense scenarios

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Key Research Question

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Is there any room for new research activities?

- Adaptive strategies
  - More complex (and efficient) adaptive strategies can be investigated
  - Adaptive strategies for
    - Energy conservation + energy harvesting = unbounded lifetime
  - Optimization over multiple parameters
    - Data generation process
    - ME arrival pattern (next arrival)
    - Available space in the local buffer
    - Available energy (energy harvesting)

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Key Research Question

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Is there any room for new research activities?

- WSN with *all* mobile nodes (opportunistic networks)
- In opportunistic networks a lot of work has been done for data dissemination
- Less attention has been devoted to node discovery (related with power management)
  - Although nodes spend most of time for discovery (rather than for data dissemination).

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Reference

- M. Di Francesco, S. Das, G. Anastasi, **Data Collection in Wireless Sensor Networks with Mobile Elements: A Survey**, *ACM Transactions on Sensor Networks,* Vol. 8, N.1, August 2011.

  Available at

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

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