Timely and Energy Efficient Node Discovery in WSNs with Mobile Elements

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Timely and Energy Efficient Node Discovery in WSNs with Mobile Elements

Based on Joint work with

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ART DECO

adaptive infrastructures for decentralised organisations

Overview

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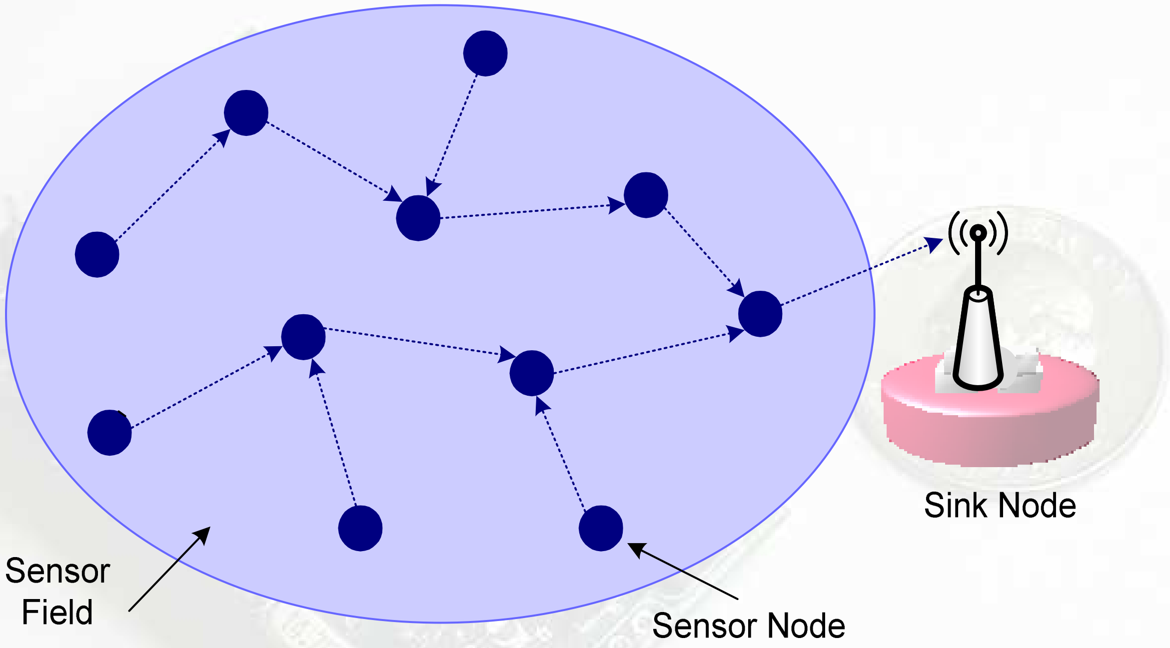
- WSNs with MEs
- ME Discovery
  - Classification of proposed approaches
- Adaptive Discovery Scheme
  - Resource-Aware Data Accumulation (RADA)
- Hierarchical Discovery Scheme
  - Dual Beacon Discovery (2BD)

Static Sensor Networks



All sensor nodes have a fixed location

What about introducing mobility?

WSNs with Mobile Elements

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Advantages

- 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
- Energy Efficiency
  - Mobile nodes can help reducing the *funneling effect*

WSNs with Mobile Elements

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Challenges

- Contact Detection
  - Timely and energy efficient contact detection is required
- Mobility-aware Power Management
  - The mobility pattern should be exploited to optimize energy efficiency
- Reliable Data Transfers
  - Since contacts may be scarce and short, the (reliable) data transfer phase must be very efficient
- Mobility Control
  - If node mobility can be controlled, this should be exploited to optimize the system

Components of a WSN-ME

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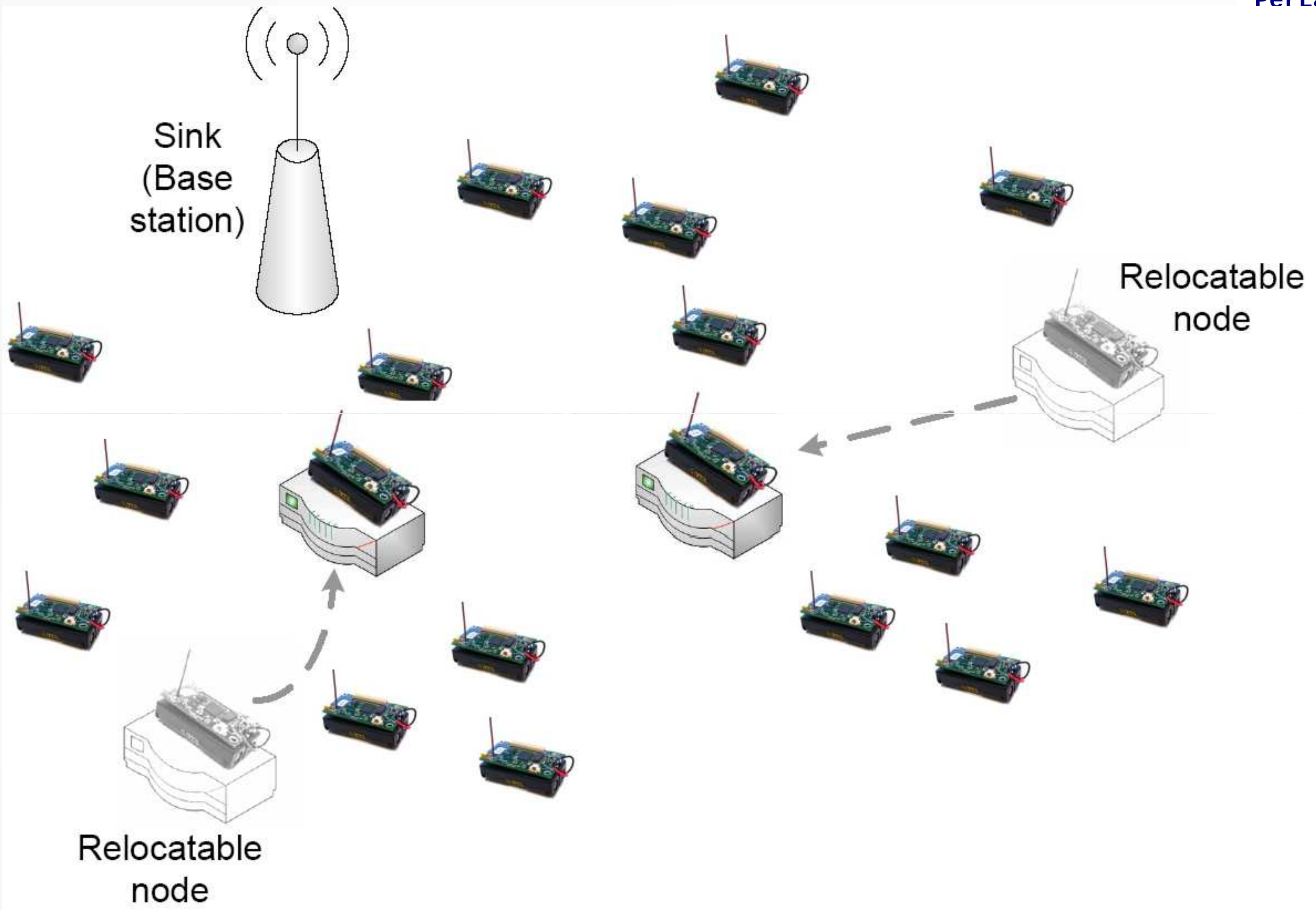
- Regular Sensor Nodes
  - Sensing (source of information)
  - Data Forwarding
  - May be Static or Mobile
- Sink Nodes (Base Stations)
  - Destination of Information
  - Collect information directly o through intermediate nodes
  - May be Static or Mobile
- Special Support Nodes
  - Neither source nor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

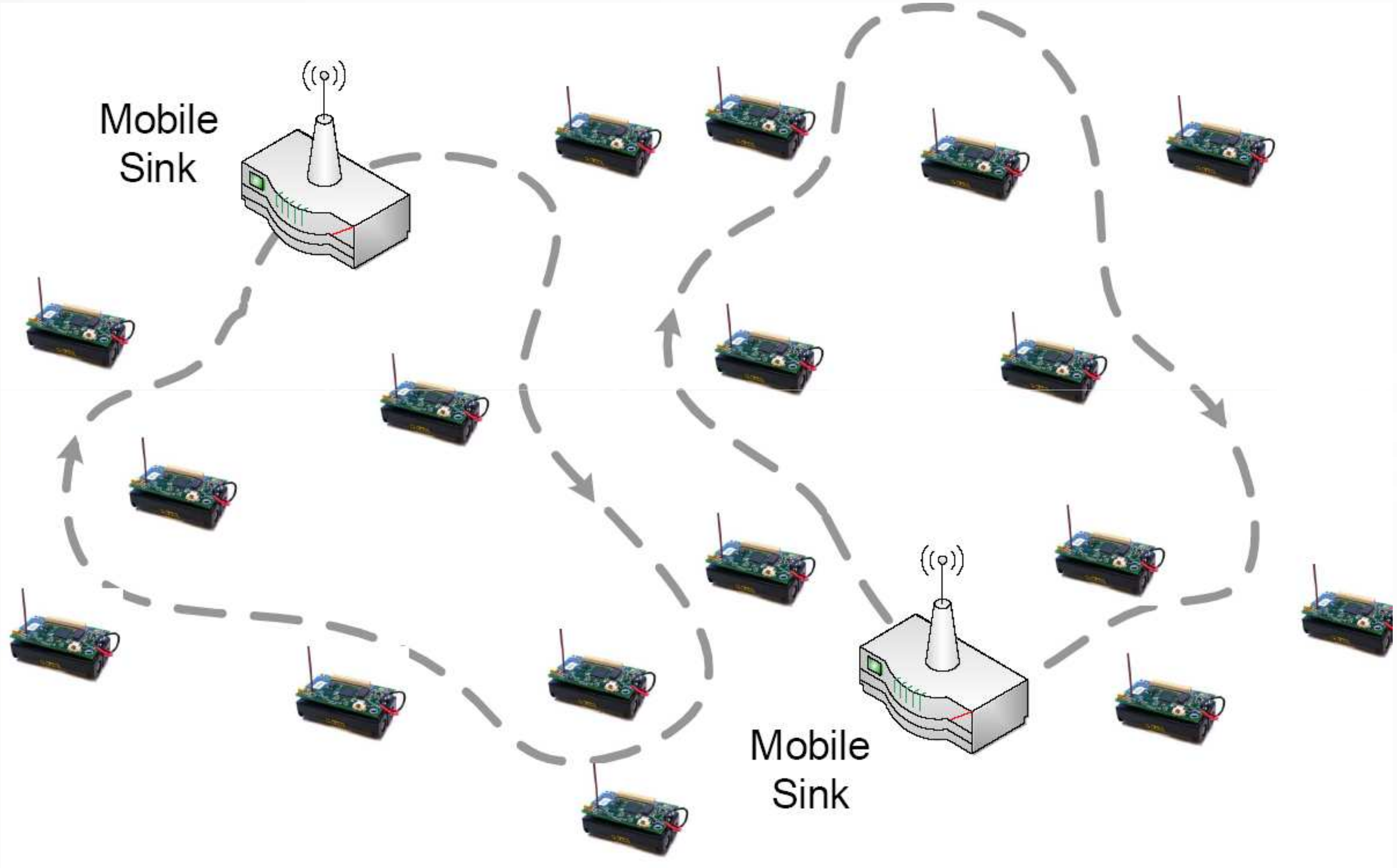
Mobile Elements

- Reloctable 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

Reloctable Nodes



Mobile Sinks



Mobile Relays

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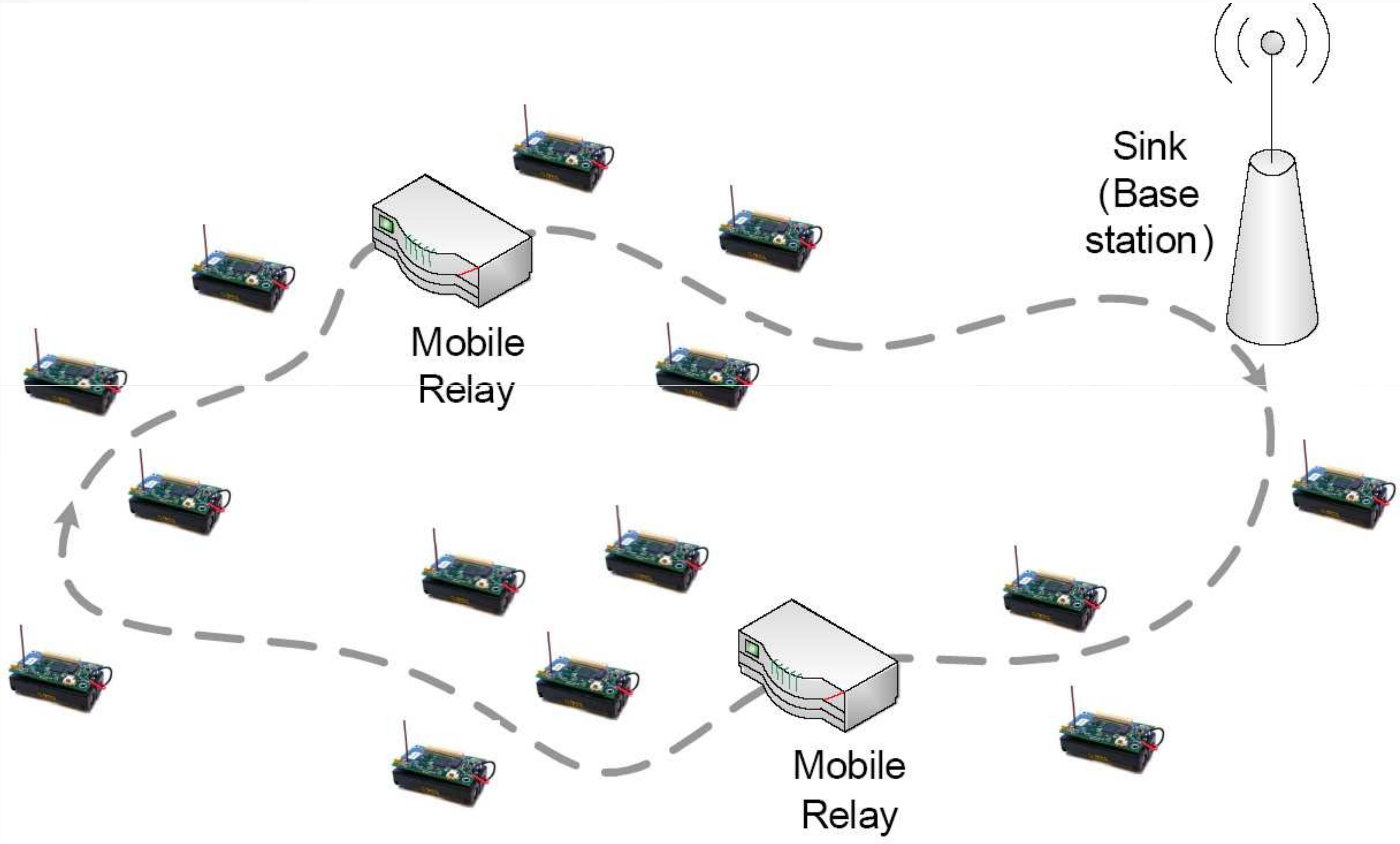

Mobile Peers

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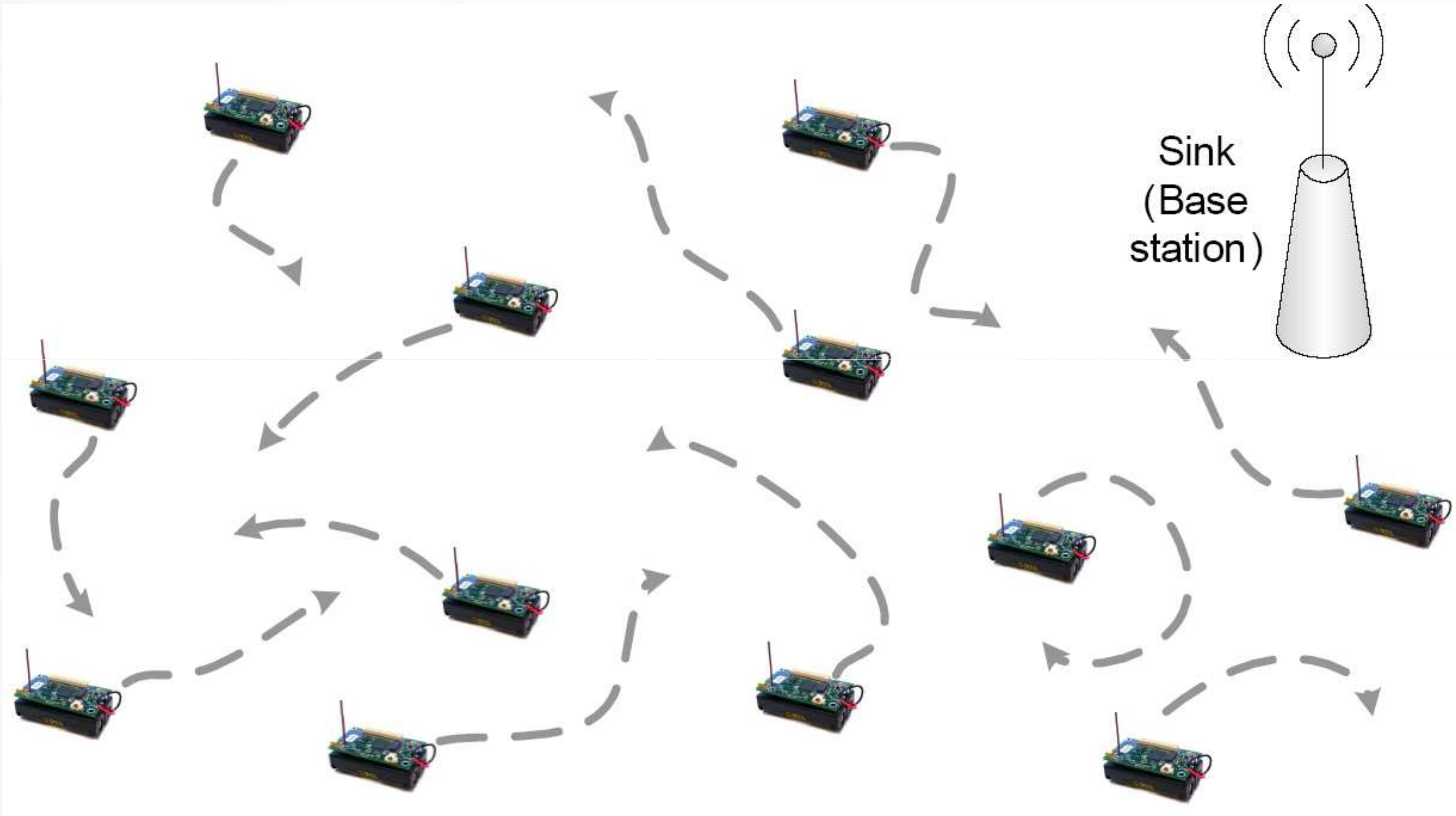
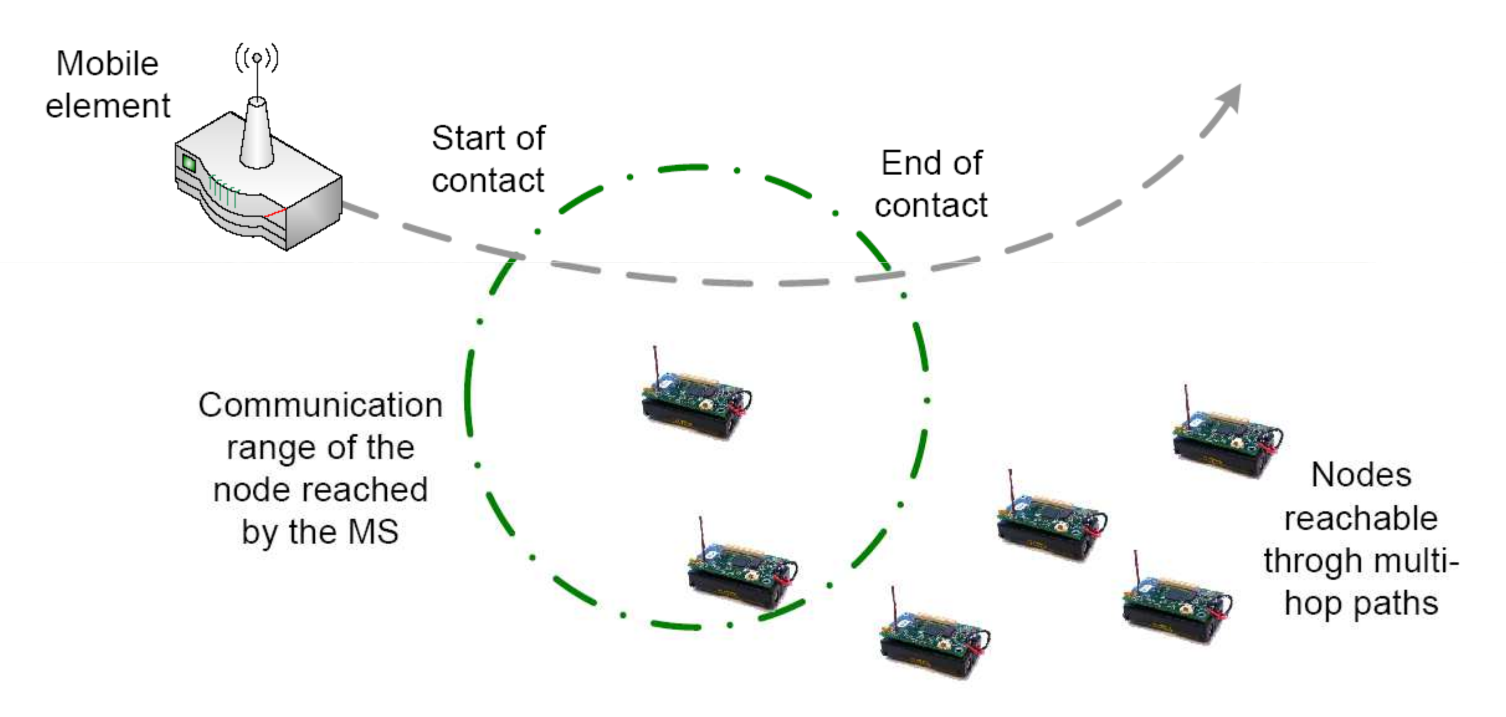


Data Collection in WSN-ME



Terminology

- Contact
  - Happens when two or more nodes are in the mutual communication range
- Discovery
  - The process that allows a node to discover a contact, i.e., the presence of a ME in the communication range
- Data Transfer
  - Message exchange between nodes that are in contact
- Residual Contact Time
  - Amount of time actually available for data transfer

Impact of Node Mobility

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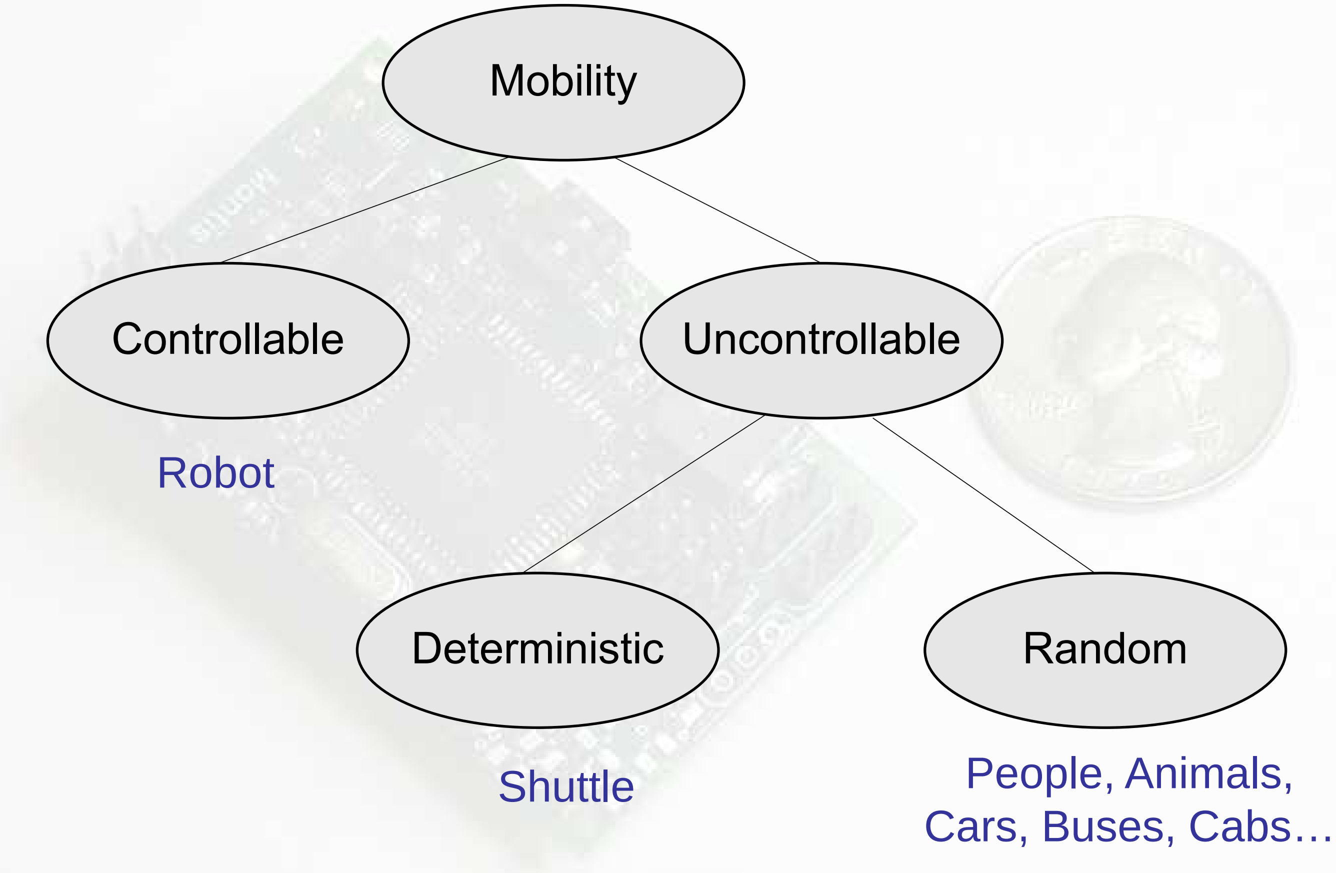

Approaches to Data Collection

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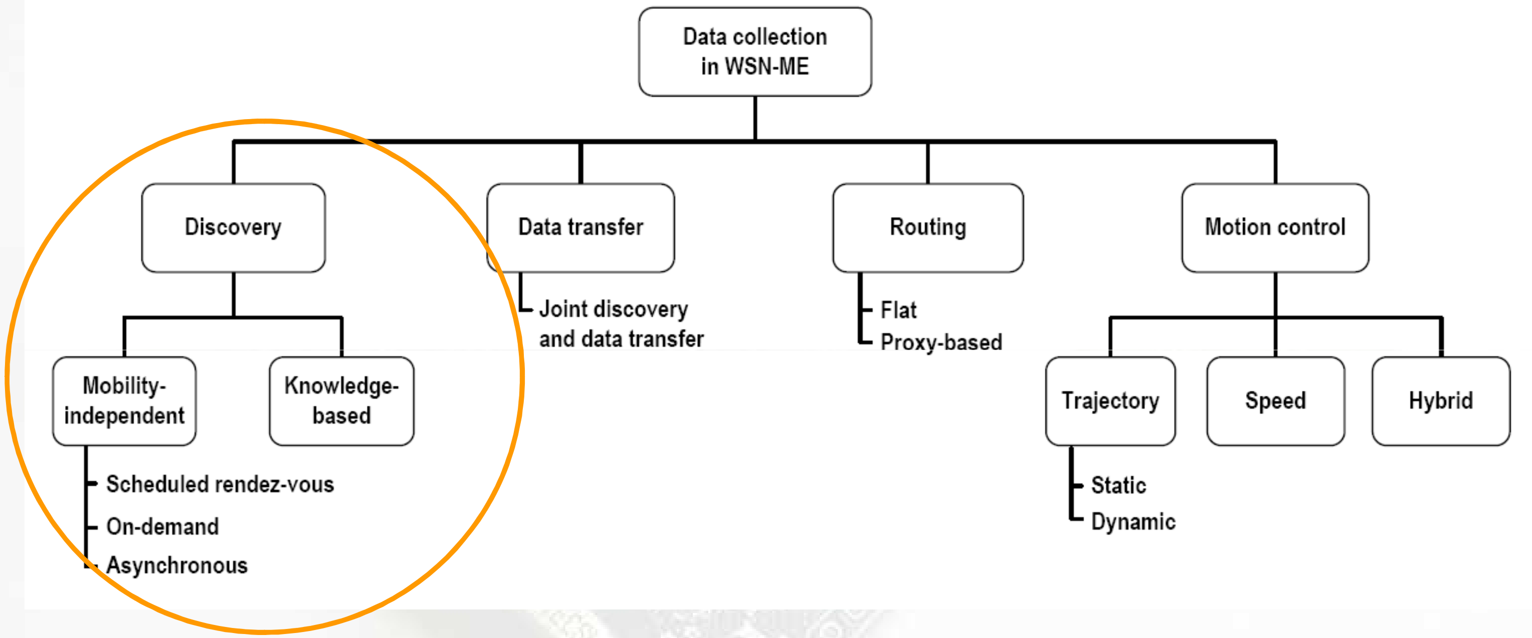
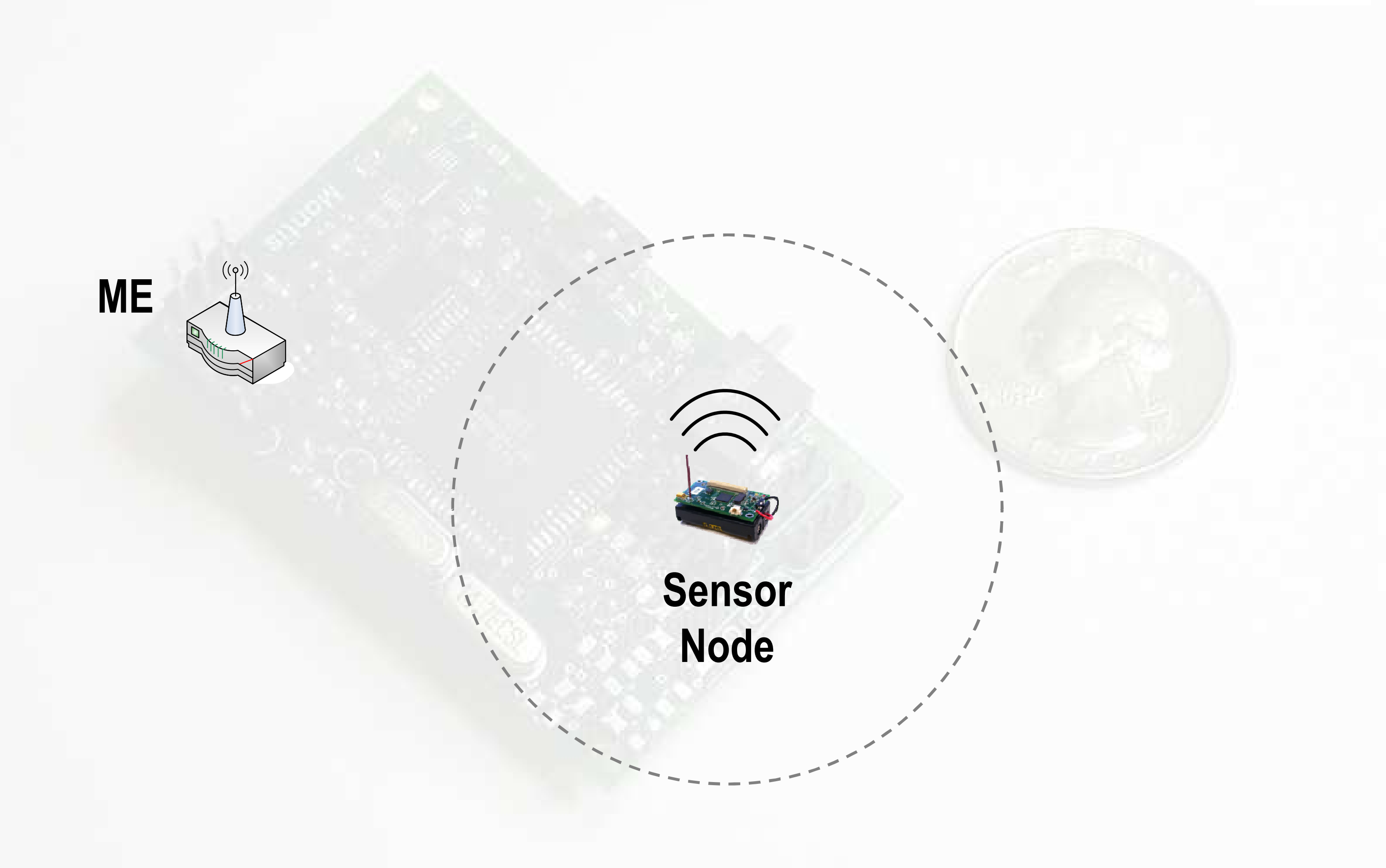


M. Di Francesco, S. Das, G. Anastasi, **Data Collection in Wireless Sensor Networks with Mobile Elements: A Survey**, *ACM Transactions on Sensor Networks*, to appear (2012), Available at http://info.iet.unipi.it/~anastasi/pubblications.html

Mobile Element Discovery

How to miss the minimum number contacts while consuming the minimum amount of energy?

Ideal Scenario



In practice

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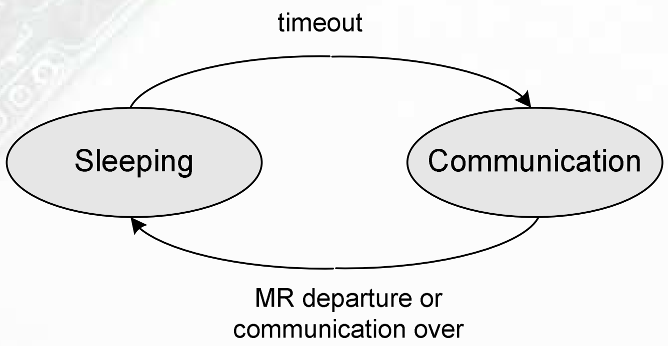
- ME arrival times are typically not known in advance
- Sensors nodes cannot be always active
  - Low duty cycle δ to save energy
- Discovery Protocol
  - Strictly related with power management

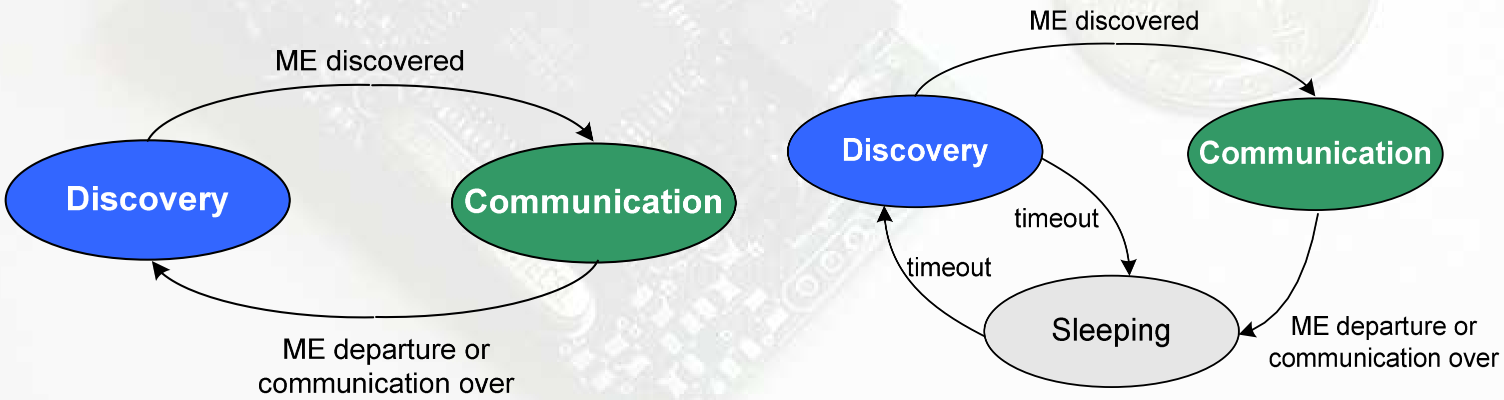
Approaches to ME Discovery

- Schedule Rendez-vous
  - Sensor node 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
- On demand
  - The ME wakes up the static node when it is nearby
    - ⇨ Radio triggered activation
    - ⇨ Dual Radio
  - Special hardware required

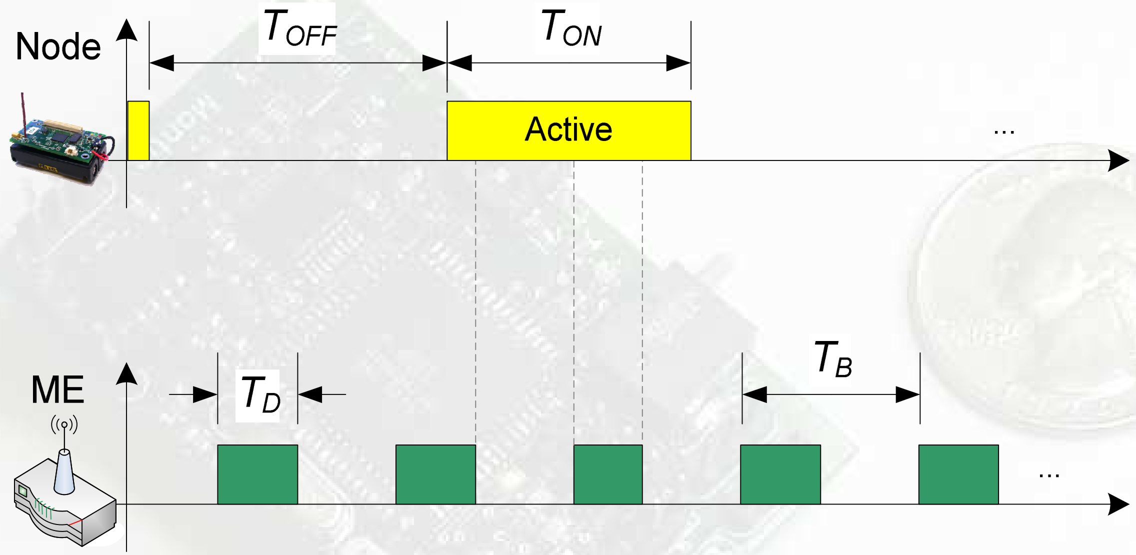


Approaches to ME Disciovery

- Asynchronous
  - Periodic listening



Periodic Listening



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

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

Classification of Periodic Listening Schemes

- **Fixed Schemes**
  - Both the beacon period and the sensor node's duty cycle are fixed over time
- **Adaptive Schemes**
  - The beacon time and/or sensor node's duty cycle are dynamically adapted
- **Hierarchical Schemes**
  - Two different operation modes for sensor nodes
    - ⇨ Low-power mode (most of the time)
    - ⇨ High-power mode (when the ME is nearby)
  - Typically require two different communication channels

Fixed Schemes

- **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 [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.

Adaptive Beacon Rate

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- Reference Scenario
  - All sensor nodes are mobile
  - Can be easily adapted to a scenario where sensor nodes are static and data collection is though MEs
- 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 accordingly
  - Based on reinforcement learning

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

Adaptive Data Collection (RADA)

- Reference Scenario
  - Static Sensor Nodes (with energy limitations)
  - MEs are resource-rich devices
- Basic ideas
  - Fixed (Periodic) Beacon Emission by ME
  - Sensor's wake-up period (duty cycle) is dynamically adjusted
  - Based on DIRL framework
- DIRL framework
  - Based on Q-learning
  - Autonomous and adaptive resource management
    - ⇨ suitable to sparse WSNs

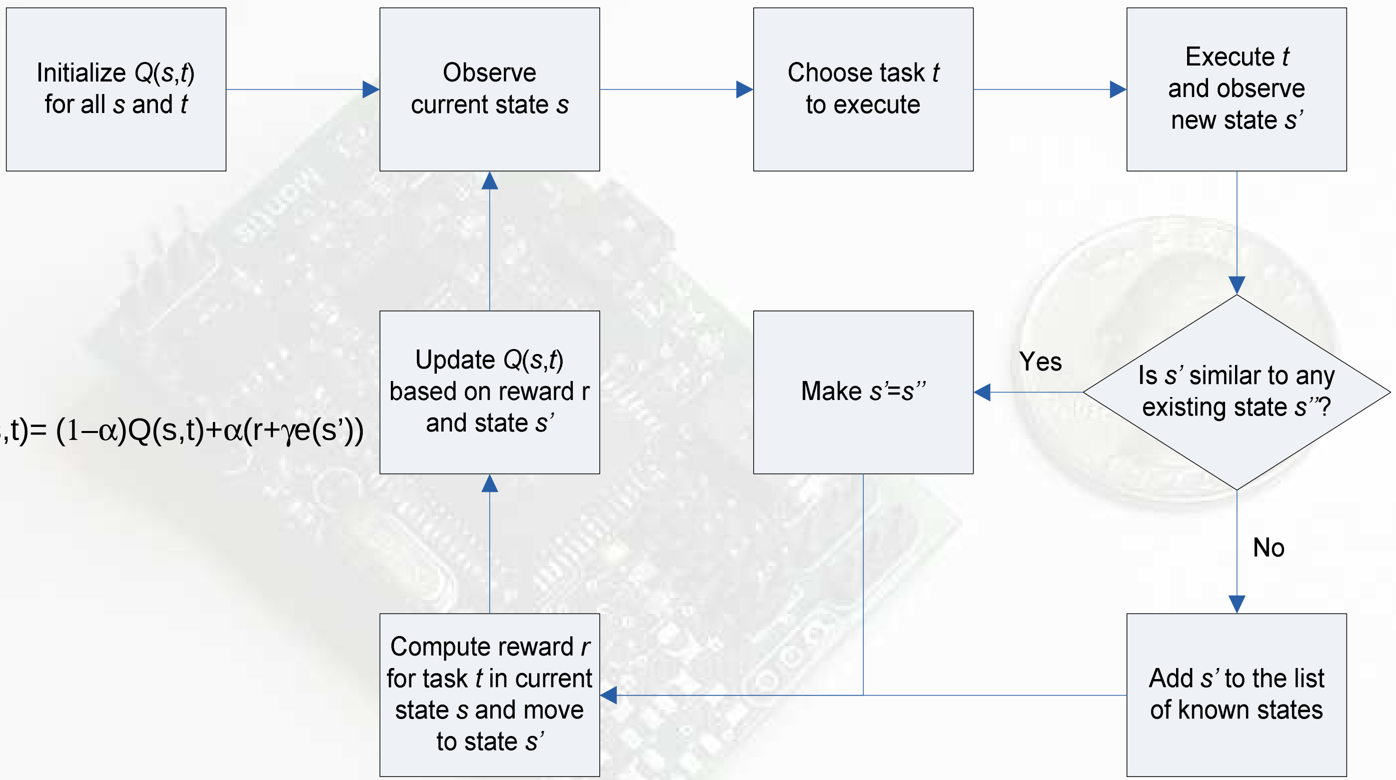
M. Di Francesco, K. Shah, M. Kumar, G. Anastasi, An Adaptive Strategy for Energy Efficient Data Collection in Sparse Wireless Sensor Networks, *Proc. European Conference on Wireless Sensor Systems (EWSN 2010)*, Coimbra, Portugal, February 17-19, 2010.

DIRL framework

- Set of tasks to be executed
  - Applicability predicates
  - Task priority
- Set of states
  - State representation includes system and application variables
- 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

DIRL Algorithm



$$Q(s,t) = (1-\alpha)Q(s,t)+\alpha(r+\gamma e(s'))$$

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

Resource-Aware Data Accumulation (RADA)

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- **Discovery tasks**
  - High duty-cycle (HDC): $\delta=\delta_{max}$ (δ=5%)
  - Low duty-cycle (LDC): $\delta= 0.5\ \delta_{max}$ (δ=2.5%)
  - Very low duty-cycle (VLDC): $\delta= 0.1\ \delta_{max}$ (δ=0.5%)
- **Reward Function**
  - For any task t
    - r=expected_price–energy_spent — if contact is detected
    - r=–energy_spent — if contact is not detected
- **Time Domains (TDs)**
  - Time is split in a number of time intervals (Time Domains)
  - Each task is executed for a TD
  - TDs are part of the state characterization

M. Di Francesco, K. Shah, M. Kumar, G. Anastasi, An Adaptive Strategy for Energy Efficient Data Collection in Sparse Wireless Sensor Networks, *Proc. European Conference on Wireless Sensor Systems (EWSN 2010)*, Coimbra, Portugal, February 17-19, 2010.

ADC Strategy

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- Mobility-aware exploration policy
  - $\varepsilon = \varepsilon_{min} + \max(0, k(c_{max} - c)/c_{max})$
  - c_{max}= maximum number detected contacts
  - c= current number detected contacts
  - k= descending rate

  - In our experiments:
    - ⇨ $\varepsilon_{max} = 0.3$
    - ⇨ $\varepsilon_{min} = 0.1$

Simulation Parameter Values

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Parameter	Value	Parameter	Value
Min Exploration Probability (ε_{min})	0.1	Beacon Duration	10 ms
Max Exploration Probability (ε_{max})	0.3	Window Size (Comm. Protocol)	16
Descending Rate (k)	0.2	Lost Contact Threshold (N_{ack})	5
Max Number of Contacts (c_{max})	10	Message Payload Size	24 bytes
Time Domain duration	100 s	Frame Size	36 bytes
Message Generation Interval	10 s	Radio Transmit Power (0 dBm)	49.5 mW
Expected Price Multiplier	10	Radio Receive/Idle Power	28.8 mW
Beacon Emission Period	100 ms	Radio Sleep Power	0.6 μW

Other Discovery Strategies

- Random
  - At each step the sensor node executes a random task
- SORA (Self-Organizing Resource Allocation)
  - SORA-based adaptive discovery
    - ⇨ Heuristic strategy based on reinforcement learning
    - ⇨ Does not consider any state-based learning
- Oracle
  - Assumes a complete knowledge of MDC mobility

Analysis in Stationary Conditions

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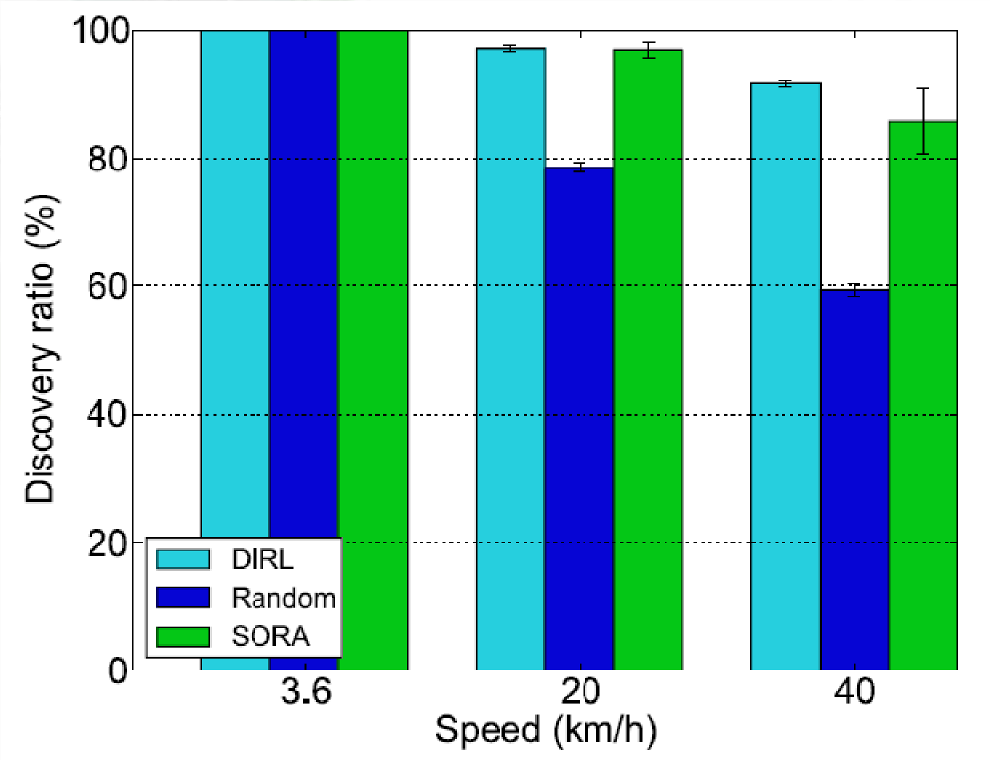
- Discovery Ratio
  - % of Detected Contacts



Analysis in Stationary Conditions

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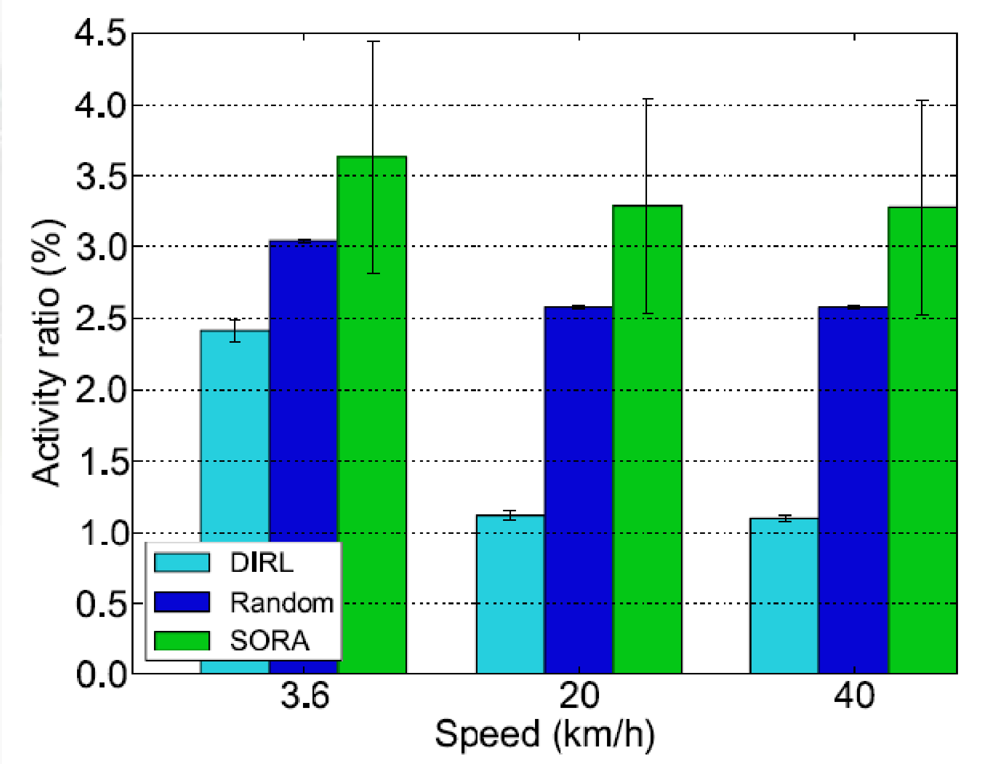
- Activity Ratio
  - Average Duty Cycle in Discovery State



Limits of Adaptive Schemes

- The duty cycle id adjusted at the beginning of each time slots
  - Based on the estimated contact probability or long-term reward
- If the time slot is large the sensor node may remain at a high duty cycle for a long time
  - This results in energy wastage

Hierarchical Discovery

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- Radio Hierarchy [Per05]
  - **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 and configure the WiFi interface

This proposal refers to opportunistic networks of handeld devices

And requires multiple radios

[Per05] 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

Hierarchical Discovery

- Hierarchical Power Management [Jun09]
  - Scenario : Opportunistic networks of handheld devices
  - 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

This proposal refers to opportunistic networks of handeld devices

And requires multiple radios

[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

Hierarchical Discovery

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- Network Interrupts [Bro07]
  - Scenario : Sensor Networks (with MEs)
  - Based on two different radio channels
    - ⇨ 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,

This approach requires multiple radios, which may not be available in some sensor platforms

[Bro07] 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

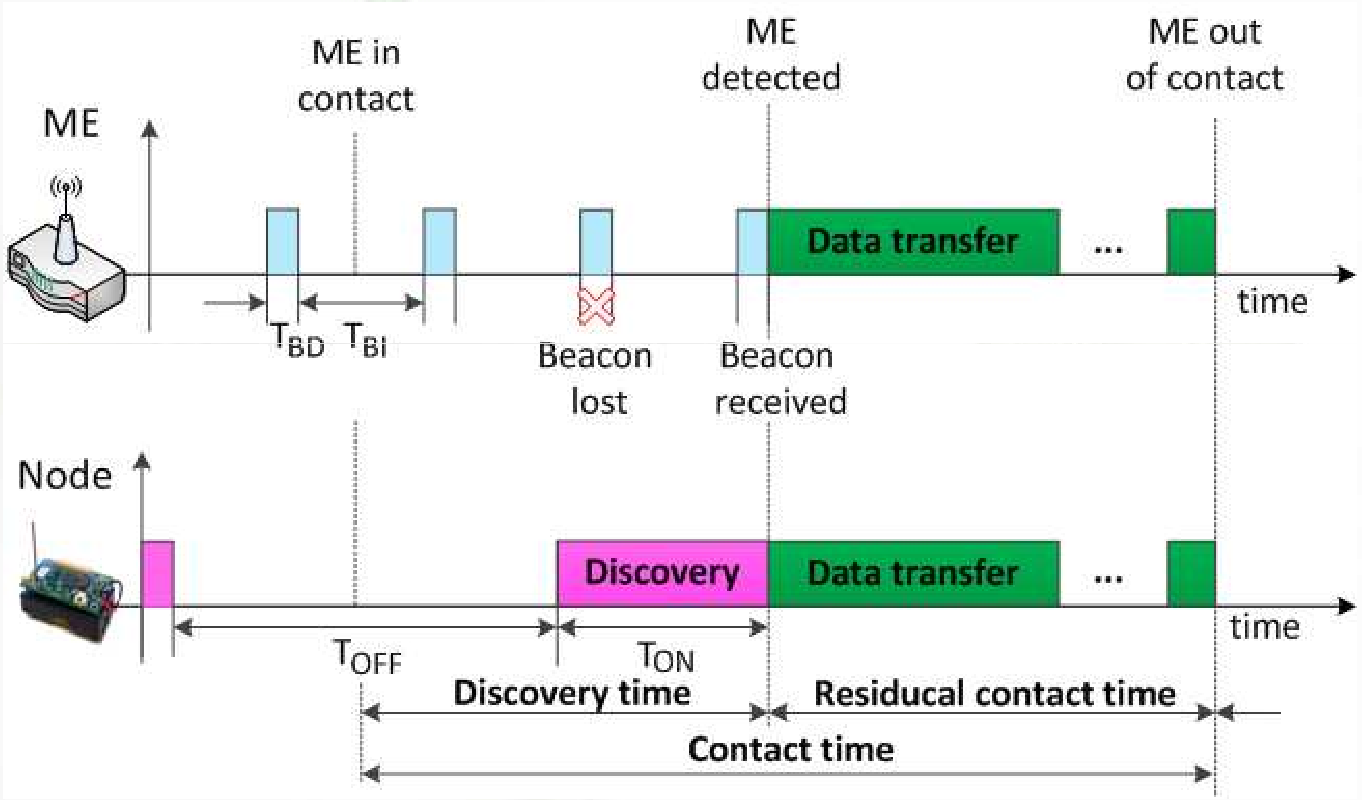
Hierarchical Discovery

- Dual Beacon Discovery
  - Scenario : Sensor Networks with MEs
  - Sensor nodes alternate bewee two duty cycles
    - ⇨ Low duty cycle when the ME is far
    - ⇨ High cycle when the ME is nearby
  - Based on two different Beacon messages
    - ⇨ Long-Range Beacons
    - ⇨ Short-Range Beacons

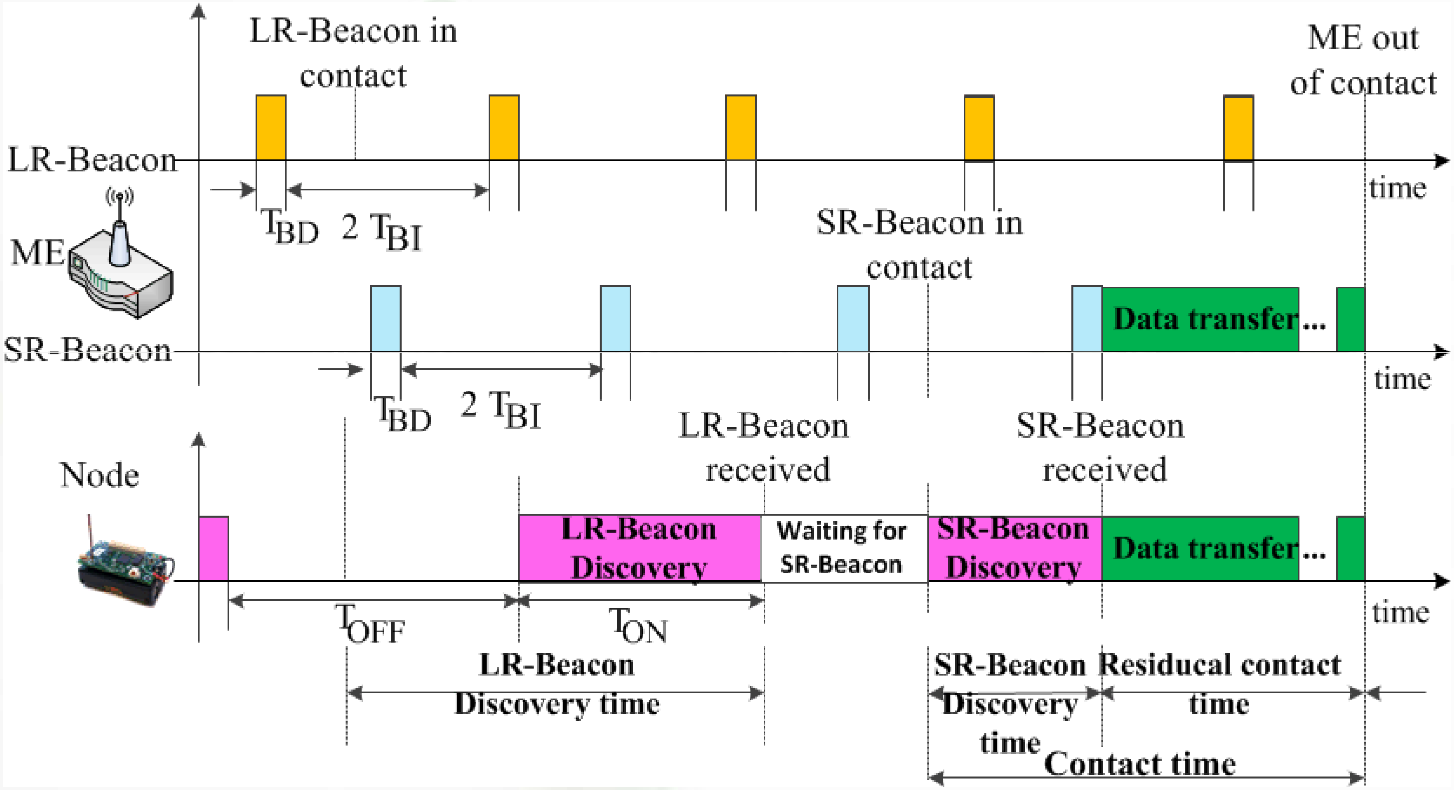
This approach do NOT requires multiple radios, and can thus be implmeneted on all sensor platforms

[Kon11] K. Kondepu, G. Anastasi, M. Conti, **Dual-Beacon Mobile-Node Discovery in Sparse Wireless Sensor Networks**, Proceedings of the *IEEE International Symposium on Computers and Communications (ISCC 2011)*, Corfu, Greece, June 28 – July 1, 2011.

Single Beacon Scheme



2BD Protocol



Simulation Setup

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- Event-driven simulator implemented for sparse wireless sensor networks
- Single Sensor Node, Single ME Scenario
- Adopted the disc model for packet loss

Performance Metrics

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- Contact Miss Ratio
  - The fraction of potential contacts that are not detected by the sensor node
- Residual Contact Ratio
  - The ratio between the average residual contact time and the nominal contact time
- Energy Consumption
  - The average energy consumed by the sensor node per detected contact

Simulation Parameter Values

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Parameter	Value
Beacon period (T_{BI})	100 ms
Beacon duration (T_{BD})	10 ms
ME Speed	40 Km/h
Distance from the sensor node	15 m
Discovery range (R)	{100m, 200m}
Communication range (r)	50 m
Nominal contact time	8.6 s
High duty cycle δ_H	3%
Transmission power (P_{tx}) at 0 dBm	52.2 mW
Reception power (P_{rx})	56.4 mW

Results

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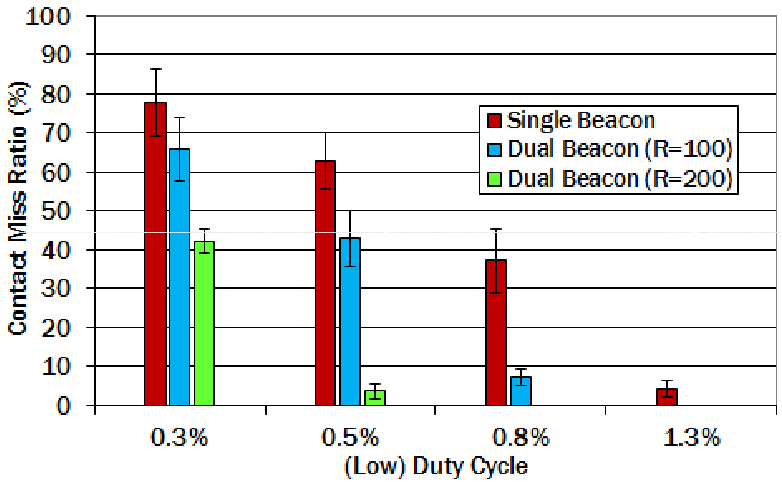
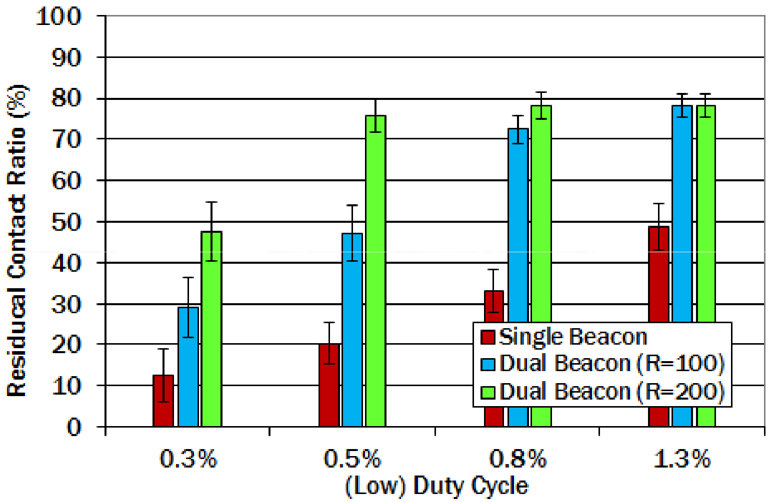
- **Contact Miss Ratio, Residual Contact Ratio (r=50m)**





Results

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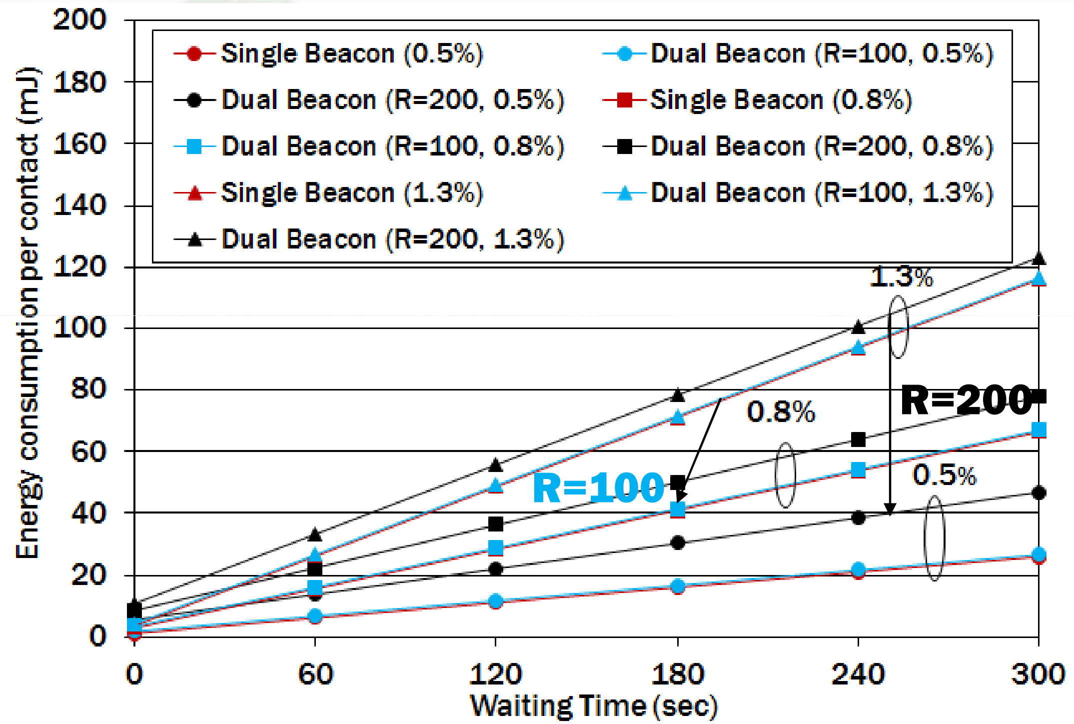
- Energy consumption

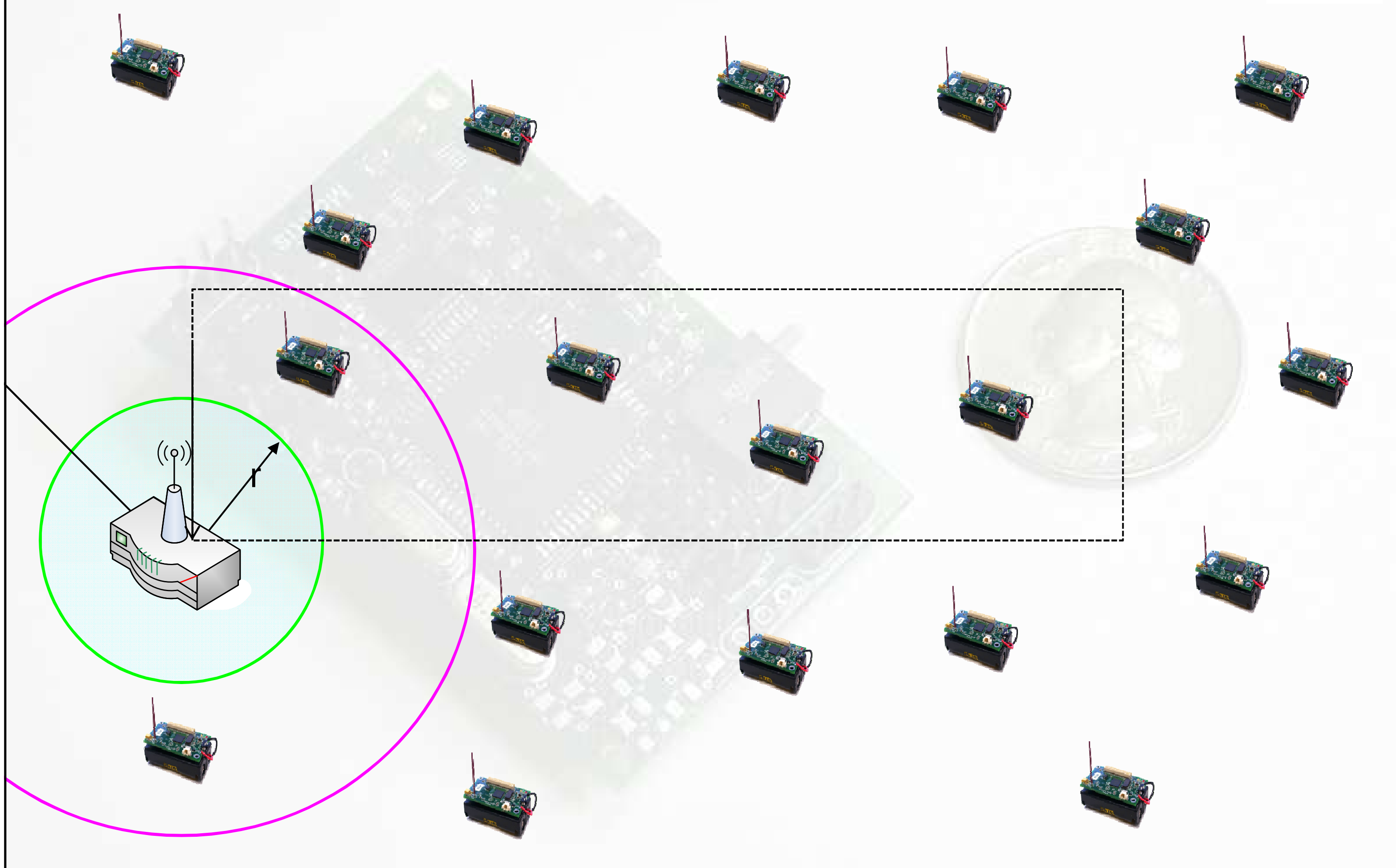


Results

- **ENERGY SAVINGS WITH DUAL BEACON (r=50m)**

Waiting Time (s)	R=100 δ_L =0.8%	R=200 δ_L =0.5%
15	22.2%	22.2%
30	33.3%	33.3%
60	38.5%	46.2%
120	40.8%	55.1%
180	42.2%	57.7%
240	42.6%	58.5%
300	43.1%	59.5%

2BD in Dense Network Scenario



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- K. Shah, M. Di Francesco, G. Anastasi, M. Kumar, "A Framework for Resource Aware Data Accumulation in Sparse Wireless Sensor Networks", submitted to *Computer Communications.*

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Conclusions

- Mobile Node Discovery in WSN-Mes
- Classification of Discovery Schemes
- Adaptive Discovery Scheme (RADA)
  - Based on DIRL (Q-learning)
- Hierarchical Discovery Scheme (2BD)
  - Based on two different Beacon messages

Thank you!