Green Networking in Wireless Sensor Networks

Based on article:

Giuseppe Anastasi, Marco Conti, Mario Di Francesco, Andrea Passarella. *Energy conservation in wireless sensor networks: A survey*. Ad Hoc Networks Elsevier. 2008

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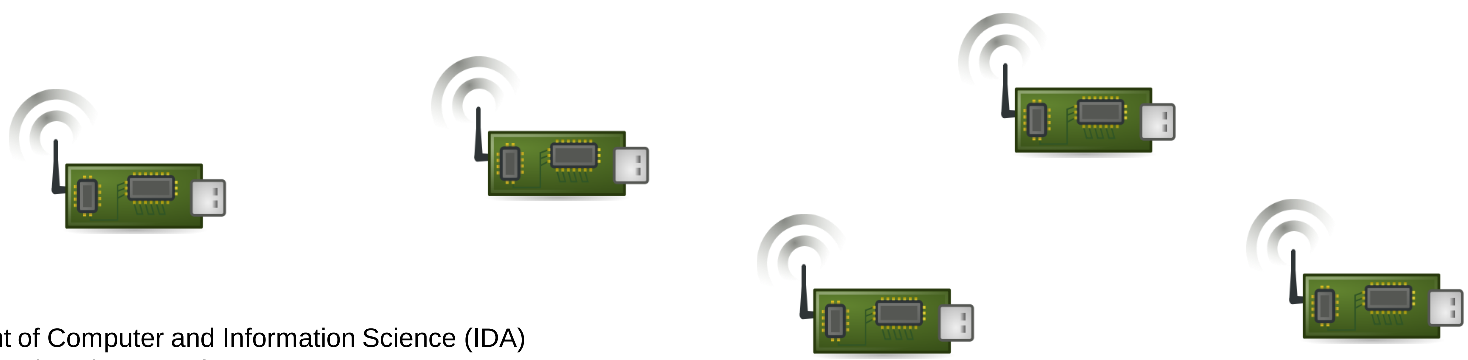
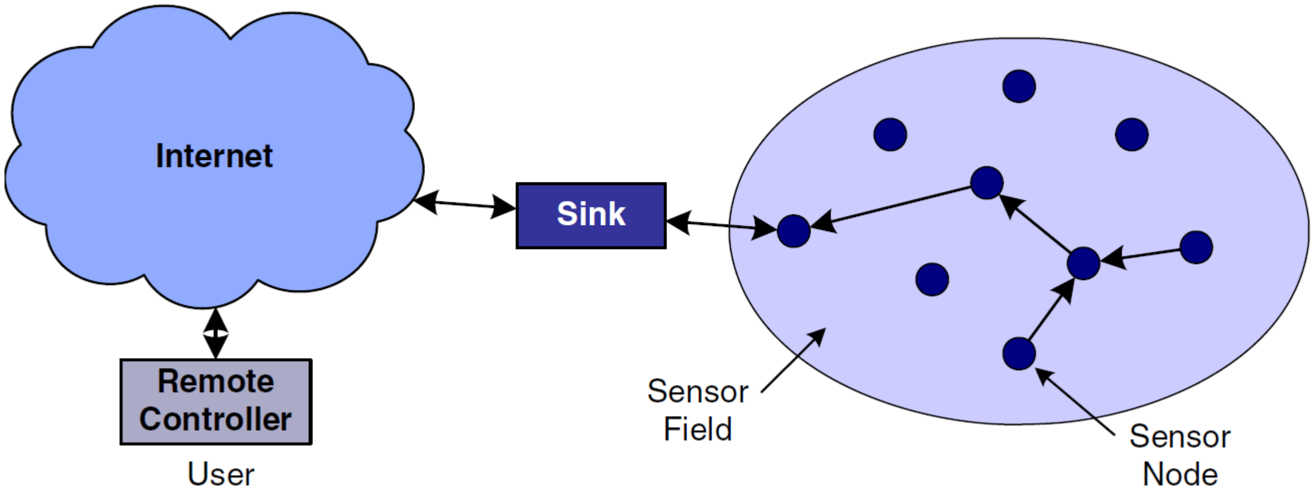
Sensor networks

- Infrastructure to collect data from the environment
  - Data can be used to study many problems
    - Climate change, animal migrations, office energy consumption
  - Composed of wirelessly linked sensor nodes
- Sensor nodes are deployed over a geographical area
  - Monitor physical phenomena
  - Collaborate forwarding the data collected

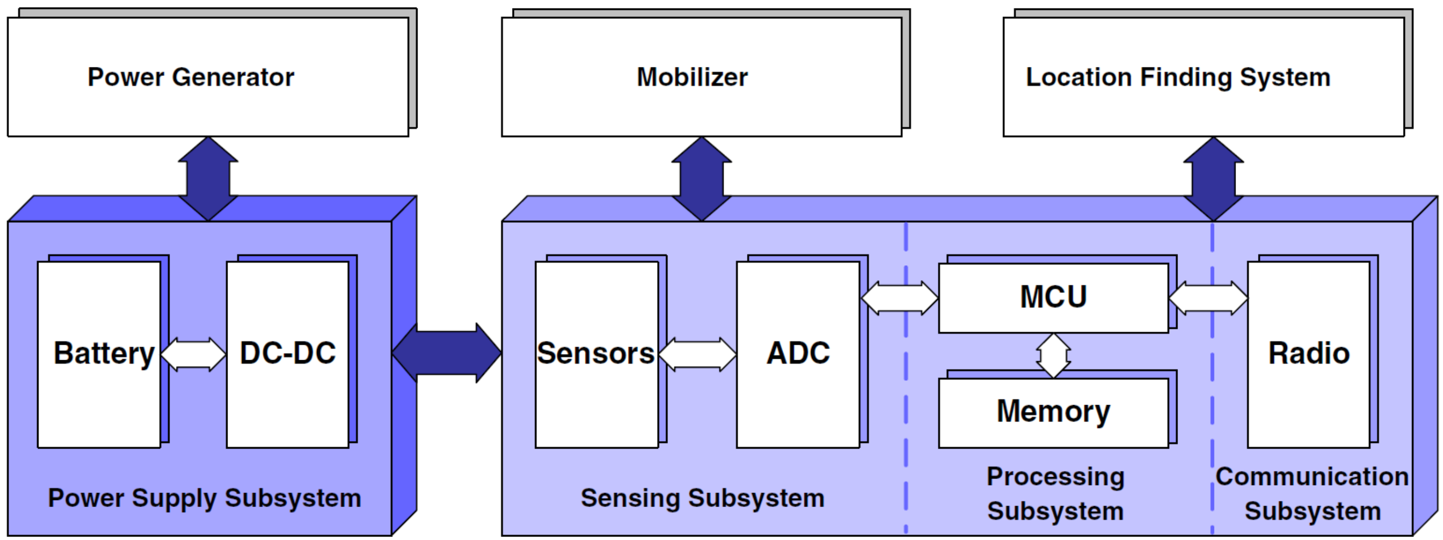


Common sensor network architecture



- Data is sent to a central node called sink
- Sensor nodes collaborate to forward data

Sensor node architecture



Motivation

- Required lifetime in the order of several months or years
  - Energy consumption of the nodes is critical
- Most energy consuming components
  - **Communication subsystem**
  - Sensing subsystem

Energy consumption

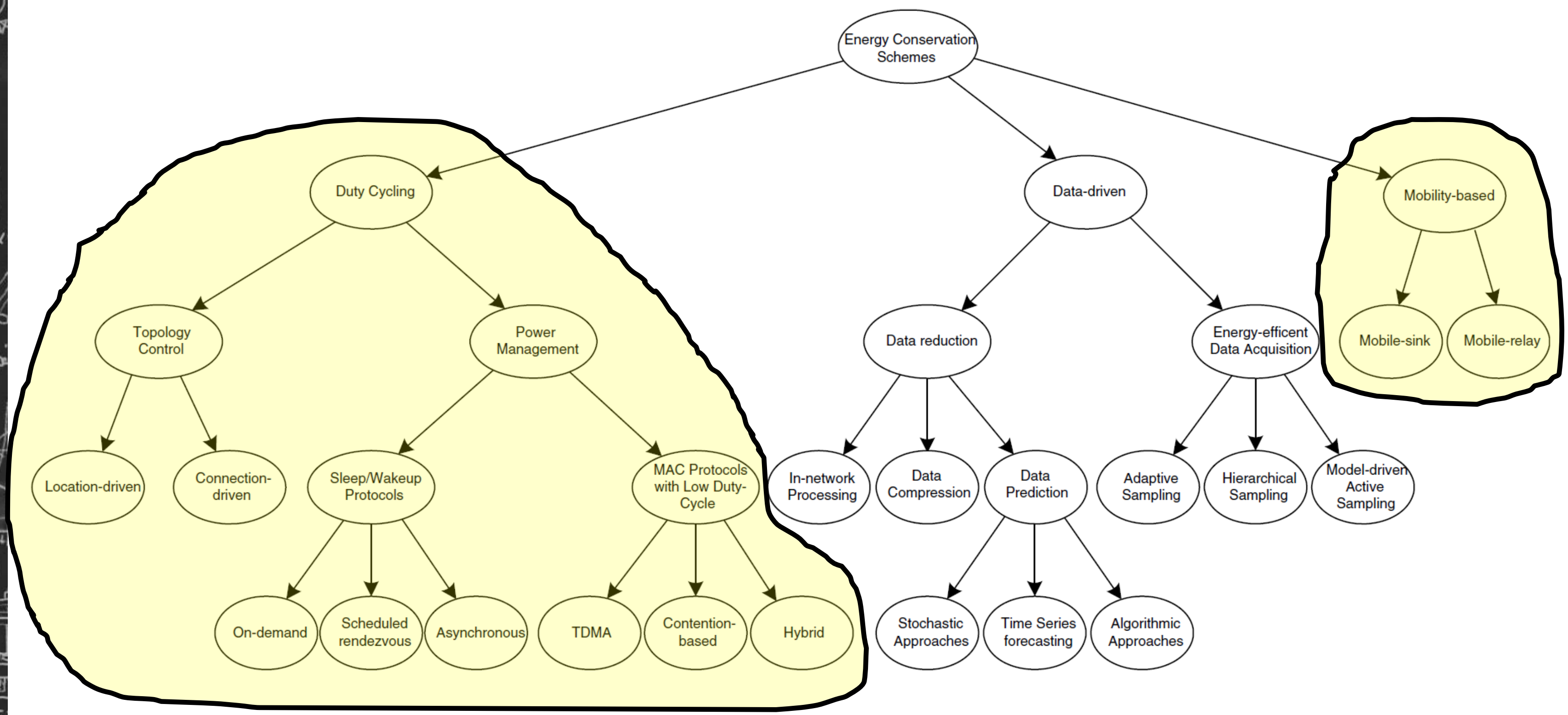
- Power breakdown depends on specific node

- Some general remarks hold for all of them
  - The communication subsystem incurs in much more energy consumption than the computation subsystem
  - Radio reception, transmission and idle states consume energy in the same order of magnitude, while sleep state consumes much less energy
  - Sensing subsystem may consume a significant amount of energy

Energy conservation approaches

- Duty-cycle
  - Nodes alternate between active/sleep periods
  - State depends on network activity
- Data-driven approaches
  - Reduction of the data generated and/or transmitted
- Mobility
  - Communication takes place in proximity
  - Directly or short multi-hop traversal

Taxonomy



Energy Conservation Schemes
Duty Cycling
Data-driven
Mobility-based
Topology Control
Power Management
Data reduction
Energy-efficent Data Acquisition
Mobile-sink
Mobile-relay
Location-driven
Connection-driven
Sleep/Wakeup Protocols
MAC Protocols with Low Duty-Cycle
In-network Processing
Data Compression
Data Prediction
Adaptive Sampling
Hierarchical Sampling
Model-driven Active Sampling
On-demand
Scheduled rendezvous
Asynchronous
TDMA
Contention-based
Hybrid
Stochastic Approaches
Time Series forecasting
Algorithmic Approaches

Duty cycling

- Nodes alternate between active/sleep periods
  - State depends on network activity
  - Coordination among nodes is required

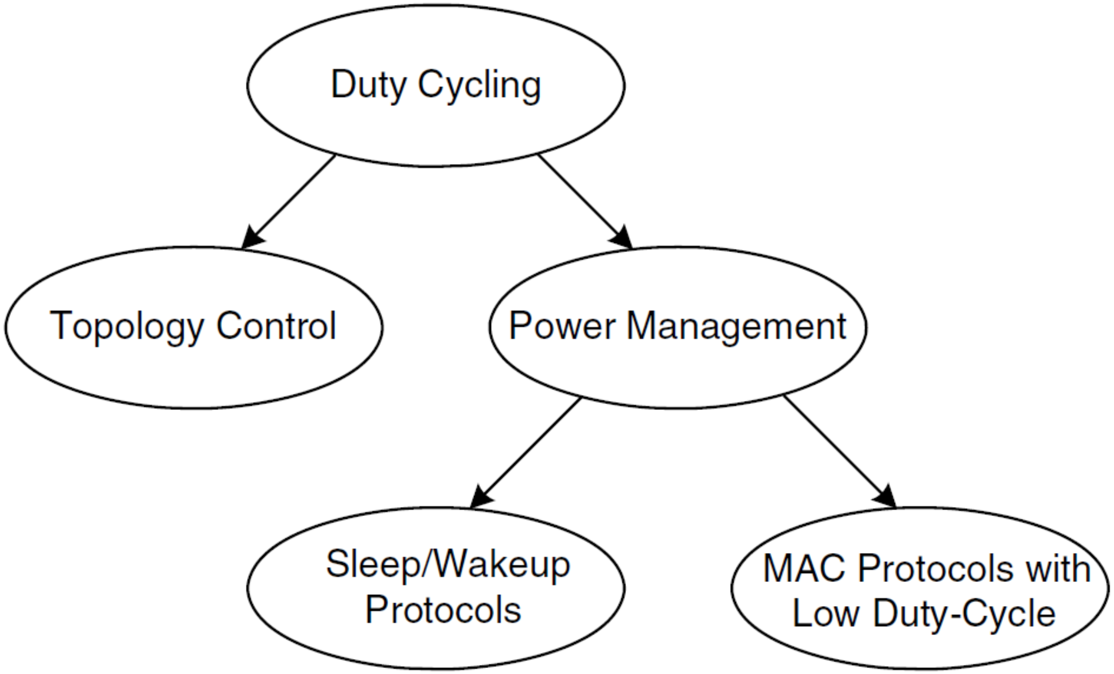
- Sleep/wake-up scheduling algorithm for coordination

- Duty cycle
  - Fraction of time nodes are active during their lifetime

Duty cycling variants

- Topology control
  - Exploits redundancy of nodes
    - Nodes not needed for connectivity go to sleep
    - Search optimal subset of nodes that guarantee connectivity
  - Network topology is dynamically adapted
  - Increased network lifetime around 2-3 times
- Power management
  - Active nodes do not need to keep radio on all the time
  - Switch off radio when there is no network activity
  - Implemented at MAC layer or above it

Duty cycling variants



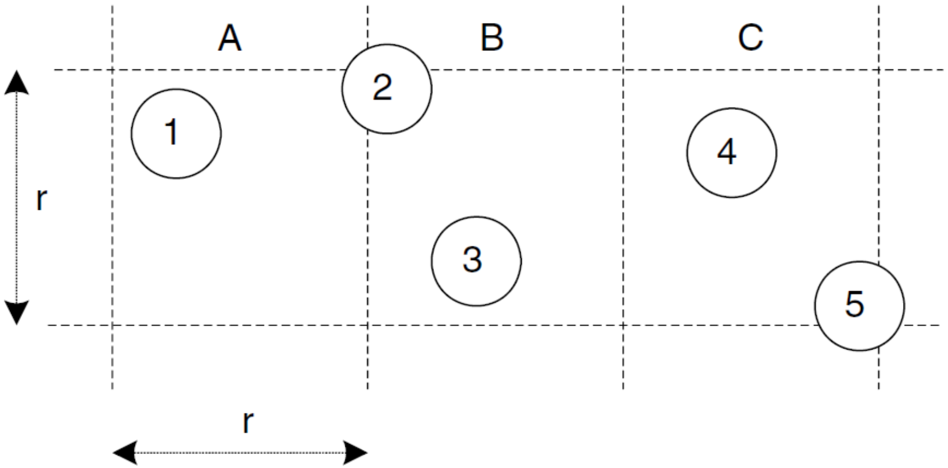
Topology control

- Nodes not needed for connectivity go to sleep

- Several criterions to decide nodes to activate/deactivate
  - Location driven
    - Based on the location of the sensor
    - Location is assumed to be known
    - Examples: GAF, GeRaF
  - Connectivity driven
    - Detection of network connectivity or sensing coverage
    - Examples: Span, ASCENT

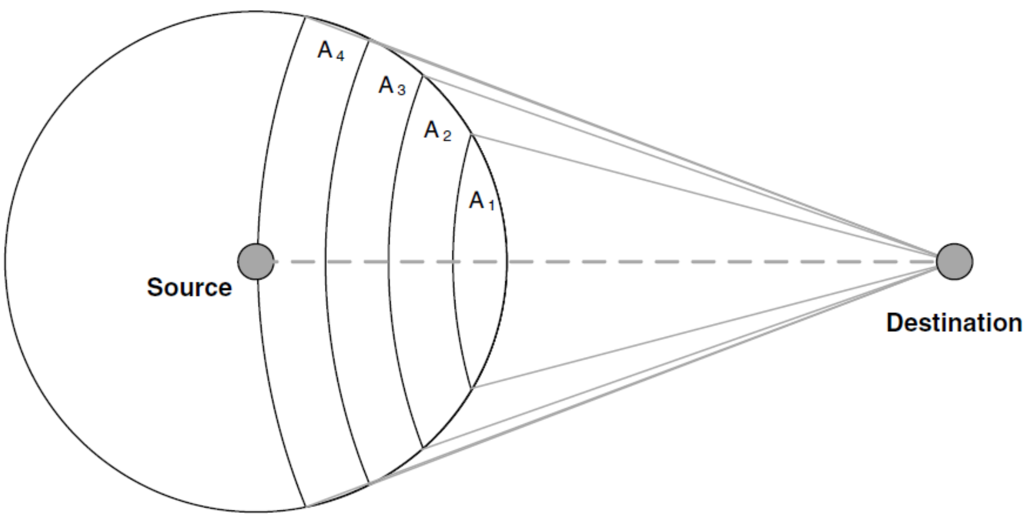
Geographical Adaptive Fidelity (GAF)

- Type: Location-driven Topology Control
- Description:
  - Divides area in small virtual grids with one or more nodes
  - Each node can communicate with nodes of adjacent grids
  - One (periodically) elected node in each grid is active



Geographic Random Forwarding (GeRaF)

- Type: Location-driven Topology Control
- Description:
  - Nodes periodically wake up for possible forwarding
  - Transmission requests include source and target location
  - Nodes closer to the destination request the source to forward the packet to them



Span

- Type: Connectivity-driven Topology Control
- Description:
  - Adaptively elects coordinators that stay awake continously
    - If two nodes of a non-coordinator cannot reach each other, this node should become coordinator
    - Nodes sleep and periodically check for becoming coordinator
  - Rules
    - Nodes with higher lifetime expectancy should be more likely to become coordinators
    - The number of coordinators should be the minimum possible
  - Neighbour and connectivity information required for selection
    - Integrated with routing protocol

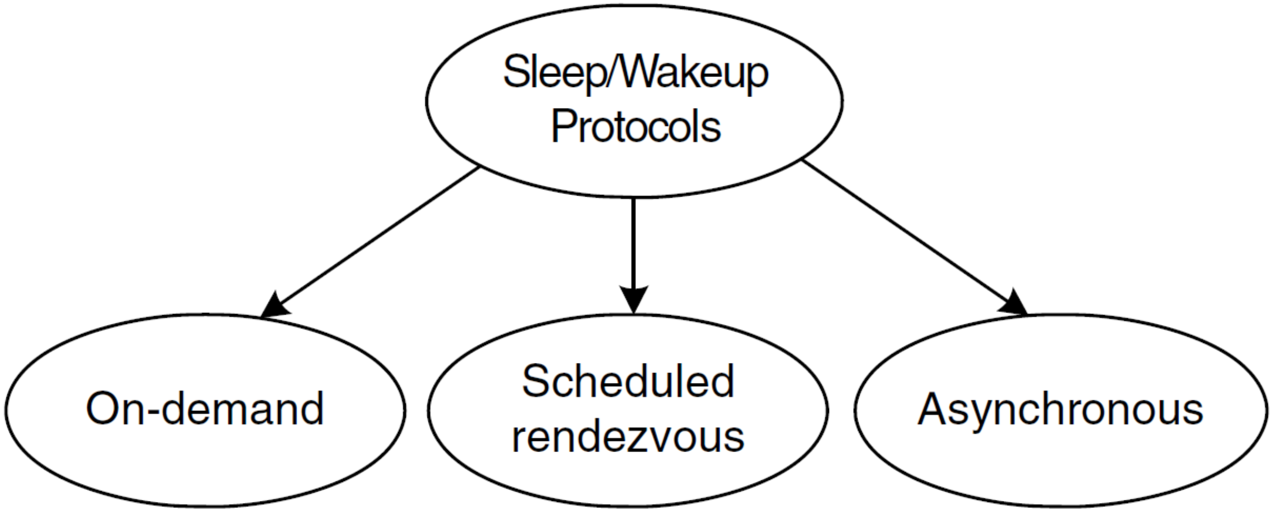
Adaptive Self-Configuring sEnsor Networks Topologies (ASCENT)

- Type: Connectivity-driven Topology Control
- Description:
  - Decision to become active and join the network based on local measurements of connectivity and packet loss
    - No dependency on external routing information
  - Some nodes are active and the rest are passive
    - Passive nodes have their radio on and listen
    - The sink and nodes can request to activate more nodes

Power Management

- Switch off radio when there is no network activity
- Depending on the layer of implementation
  - Sleep/Wakeup protocols
    - Routing/Application layer
  - MAC protocols with low duty cycle
    - MAC layer

Sleep/Wakeup Protocols



Sleep/Wakeup Protocols

- On-demand schemes
  - Nodes only wake up when others want to communicate
  - How to inform the sleeping node? Use of multiple radios
  - Examples: STEM, PTW
- Scheduled rendezvous
  - Each node wakes up at the same time that its neighbours
  - Wake up schedule and short active time intervals
  - Examples: FSP, SWP
- Asynchronous
  - Nodes wake up whenever they want and still communicate
  - Examples: AWP, RAW

Sparse Topology and Energy Management (STEM)

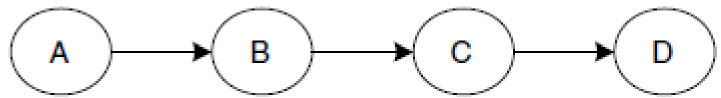
- Type: On-demand schemes
- Description:
  - Each node has two radios
    - Wake up and data transmission radios
    - When node wants to transmit requests wake up of other nodes
  - Wake up radio uses an asynchronous duty cycle scheme
    - Each node turns radio on for T_{active} every T duration
    - Nodes request wake up sending beacons' stream during T_{wakeup}
    - Waken up nodes send acknowledgement after T_{wack}
  - STEM trades energy saving for path setup latency:

$$T_{active} \geq 2T_{wakeup} + T_{wack}$$

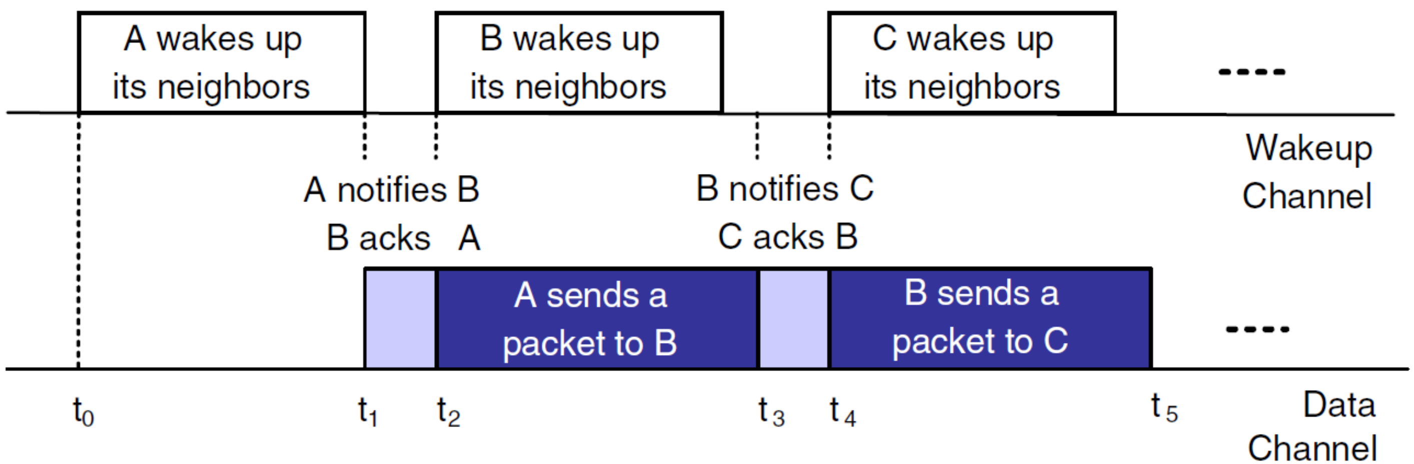
Pipelined Tone Wakeup (PTW)

- Type: On-demand schemes
- Description:
  - Also relies on two different radios
    - Wake up signaled by tone that awakes **all the nodes** around
    - Nodes periodically turn on their radio to listen
      - Long enough tone to be heard by them
  - Wake up procedure is pipelined with packet transmission
    - Latency is reduced

Pipelined Tone Wakeup (PTW)



Network topology



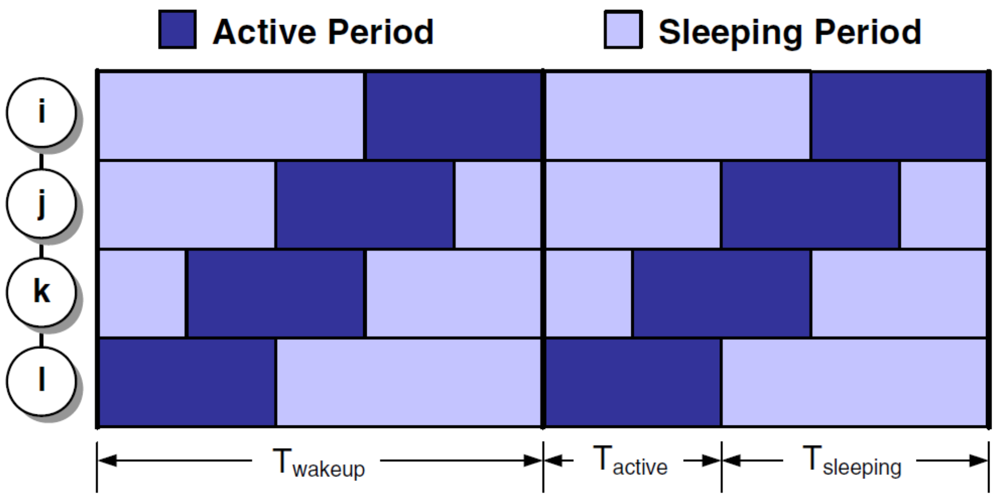
Fully Synchronized Pattern (FSP)

- Type: Scheduled rendezvous
- Description:
  - Nodes wake up at the same time according to periodic pattern
    - Wake up every T_{wakeup} and remain active for T_{active}
  - Very simple approach used in many implementations
  - The protocol suffers from a large number of collisions
    - Because all nodes become active at the same time

Staggered Wakeup Pattern (SWP)

- Type: Scheduled rendezvous
- Description:
  - Nodes at different levels of data-gathering tree wake up at different times
  - Portion of active period used to receive packets from a children is adjacent to portion required to send to its parent

Staggered Wakeup Pattern (SWP)

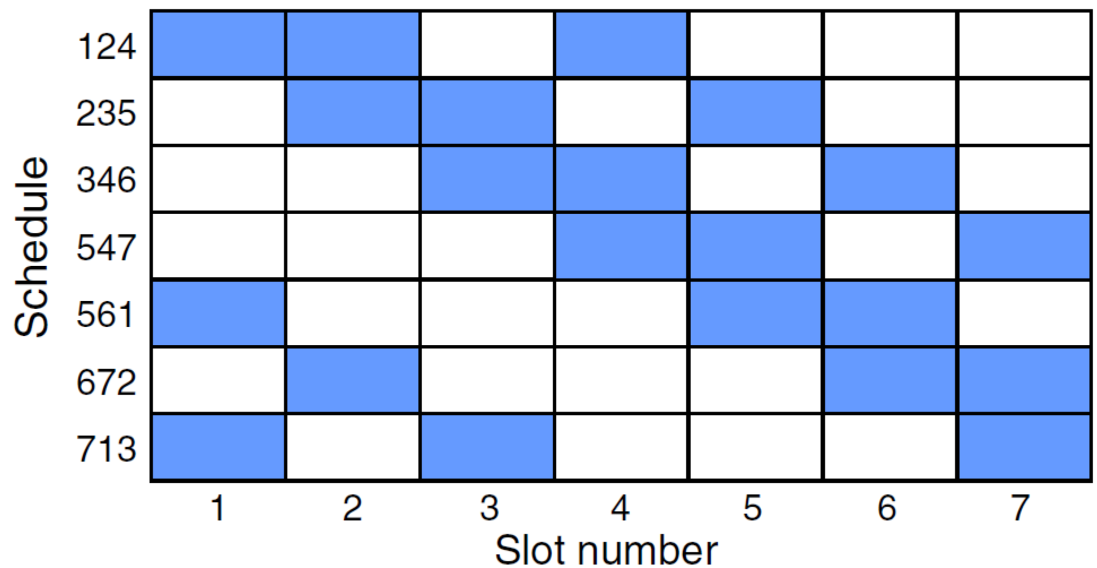


- Advantages
  - Only a small subset of nodes is active
  - Active period of each node can be shortened

Asynchronous Wakeup Protocol (AWP)

- Type: Asynchronous
- Description:
  - Detect neighbour nodes in a finite time without slot alignment
  - Each node has associated a Wakeup Schedule Function
    - Used to generate the wake up schedule
    - See example of symmetric (7,3,1) function
  - The schedule guarantees communication with all the nodes
    - Latency may be long
    - Broadcast is not possible

Asynchronous Wakeup Protocol (AWP)



Symmetric (7, 3, 1) design

7 – Each schedule repeats every seven slots

3 – Every schedule has three active slots

1 – Every two schedules overlaps with at most one slot

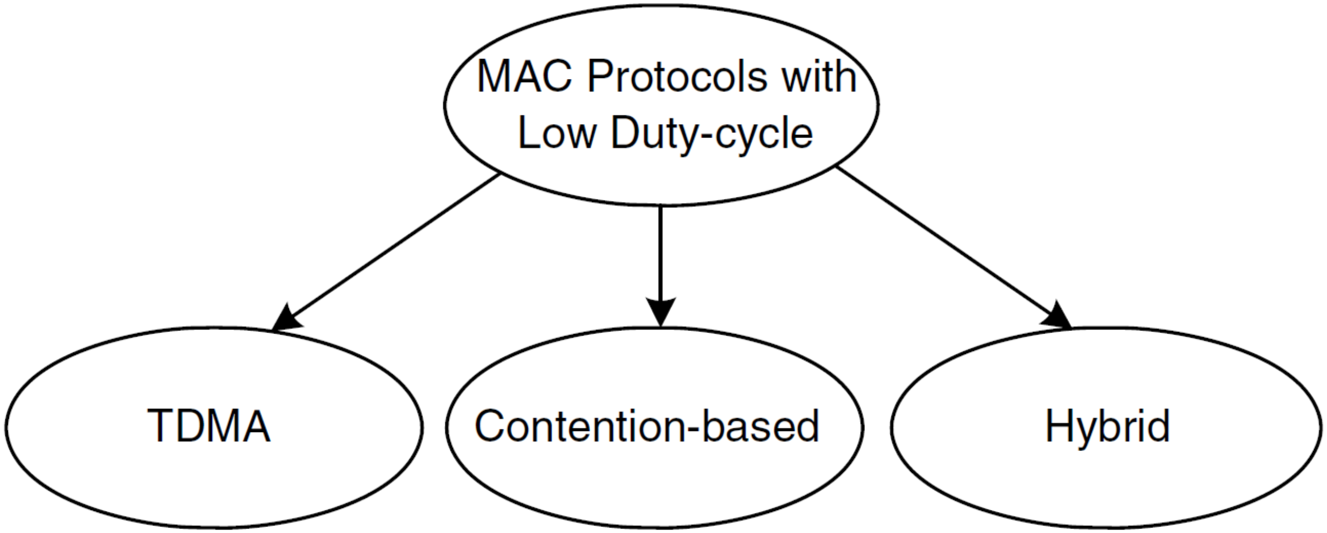
Active slot

Inactive slot

Random Asynchronous Wakeup (RAW)

- Type: Asynchronous
- Description:
  - Random wakeup scheme combined with routing protocol
    - **Assumes a high density of nodes**
  - Each node wakes up randomly once in a time interval T
    - The node remains active a predefined time T_a ($T_a \leq T$)
  - Once awake a node looks for active neighbours
    - A candidate is selected to forward the packet
  - Extremely simple and good for changing topologies
    - But does not guarantee packet forwarding within a given time frame

MAC protocols with low duty cycle



MAC protocols with low duty cycle

- Time Division Multiple Access (TDMA)
  - Time divided in frames that consist of a number of time slots
  - Every node has one or more time slots assigned per frame
  - Examples: TRAMA
- Contention-based
  - Channel access functionalities with sleep/wakeup schemes
  - Examples: B-MAC
- Hybrid
  - Adapt protocol behaviour to the network level of contention
  - Examples: Z-MAC

TRAMA

- Type: Time Division Multiple Access
- Description:
  - Divides time in two portions
    - Random-access period devoted to slot reservation
      - Contention-based access
    - Scheduled-access period devoted to data transmission
      - Number of slots assigned to each node
  - Algorithm to create schedule
    1. Nodes derive two-hop neighbourhood information
    2. Election procedure to assign a slot to each node
    3. Transmission of list with schedule to all the nodes

B-MAC

- Type: Contention-based
- Description:
  - Low complexity and low power MAC protocol
    - Implemented in the TinyOS operating system
  - Asynchronous sleep/wake up scheme
    - Based on periodic listening and called Low Power Listening
  - Parameters
    - *Check interval* is the period between consecutive wakeups
    - *Wakeup time* is the time nodes remain active after wake up
  - Packet structure
    - Long preamble of at least *check interval* length
    - Payload to transmit

Z-MAC

- Type: Hybrid
- Description:
  - Setup similar to TRAMA algorithm
    - A list of two-hop neighbours is created
    - Slot assigned to each node of the list to avoid collision
  - No global time synchronisation
    - Each node keeps its own local time frame
    - Local slot assignment and time frame forwarded to neighbours

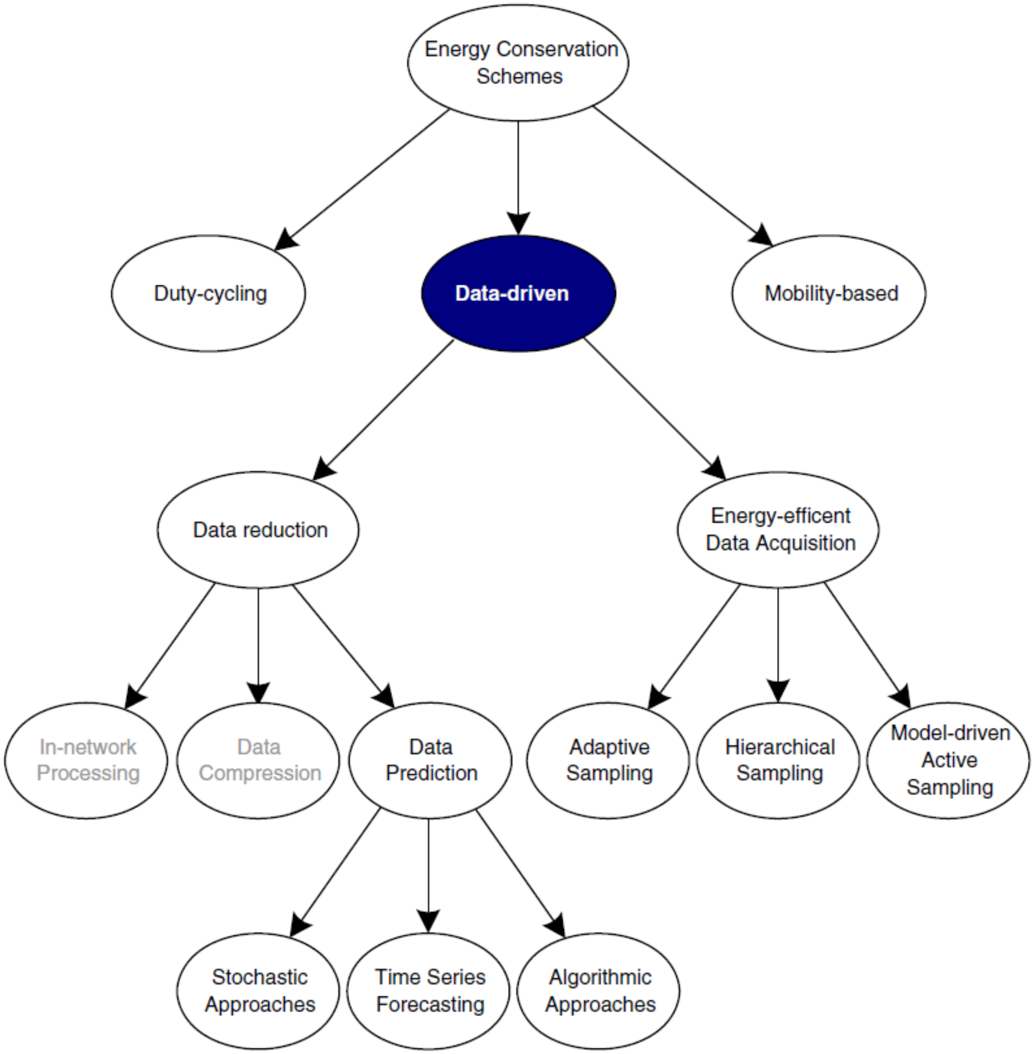
Z-MAC

- Two modes of operation
  - Low Contention Level (LCL)
    - All nodes can compete for the channel
    - This is the default mode
  - High Contention Level (HCL)
    - Only owners of slot and one hop-neighbours compete for the channel
- Selection of operation mode
  - Default mode is LCL
  - Node changes to HCL after receiving explicit request for it
    - ECN message sent with high contention is experienced

Data-driven

- Reduction of the data generated and/or transmitted
- Different types of solutions according to the problem
  - Data-reduction schemes
  - Energy-efficient data acquisition

Data-driven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Mobility-based

- Most of literature assumes static Wireless Sensor Networks
  - Recently mobility is considered as alternative solution for energy-efficient data collection
- Different mobility alternatives
  - Sensors equipped with mobilisers
  - Mobility limited to special nodes
  - Sensors placed in mobile elements
- Connectivity advantages of mobility
  - A sparse architecture can be considered as an option
  - Network reorganisation for fault tolerance is possible

Mobility-based

- Energy advantages of mobility
  - Prevent fast depletion of nodes around the sink
  - Communication with data collector takes place in proximity

- Two main approaches
  - Mobile-sink-based
    - The sink moves close to many sensor locations
    - Linear Programming formulation common to optimise parameters
  - Mobile-relay-based
    - A node moves through the sensors to collect data
    - The node laterly delivers the data to the sink

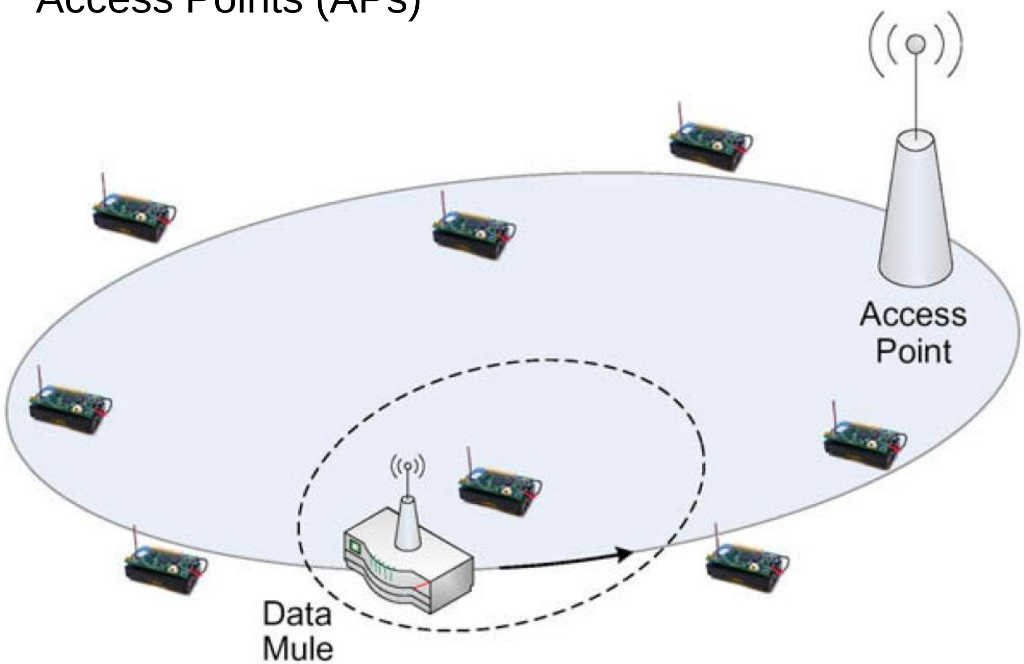
Mobile-sink-based example

- Wang et al. proposes the following approach
  - Mobile sink visits a given sensor and communicate with it
  - The sink spends a certain time in each place
    - Authors derive Linear Programming formulation to calculate the optimal stay time at each site
    - The solution maximises the network lifetime
    - Costs of sink relocation are not considered
  - Nodes outside the sink area can still send messages with multi-hop routing

Z.M.Wang, S.Basagni, E.Melachrinoudis, C. Petrioli, Exploiting sink mobility for maximizing sensor networks lifetime, in: Proc. 38 Annual Hawaii Interantional Conference on System Sciences (HICSS'05), Hawaii, January 03-06, 2005

Mobile-relay

- data-Mule system
  - Three-tier architecture
    - Sensor nodes
    - Mobile Ubiquitous LAN Extensions (MULE)
    - Access Points (APs)



Mobile-relay

- MULEs characteristics
  - Move independently from each other and from sensor positions
  - Follow unpredictable routes
- Procedure
  - Sensor nodes wait for a MULE to pass
    - Short-range radio signals are used to transmit the data
  - The MULE eventually passes close to an AP
    - The data collected is transmitted to it
- Energy savings are due to large number of nodes visited by the MULE
  - Latency for data arrival at the sink can be high
  - Sensors have to listen for the MULE arrival and cannot sleep

Conclusions

- Many approaches help to save up energy on WSNs
  - Duty cycle, data driven, mobility-based
- Some approaches can be combined, others not
- Most of them are based on the same principles of energy conservation in other types of networks