Self-Organization in Autonomous Sensor/Actuator Networks [SelfOrg]

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Overview

- **Self-Organization**
  Introduction; system management and control; principles and characteristics; natural self-organization; methods and techniques
- **Networking Aspects: Ad Hoc and Sensor Networks**
  Ad hoc and sensor networks; self-organization in sensor networks; evaluation criteria; medium access control; ad hoc routing; data-centric networking; clustering
- **Coordination and Control: Sensor and Actor Networks**
  Sensor and actor networks; communication and coordination; collaboration and task allocation
- **Self-Organization in Sensor and Actor Networks**
  Basic methods of self-organization – revisited; evaluation criteria
- **Bio-inspired Networking**
  Swarm intelligence; artificial immune system; cellular signaling pathways

Basic Methods of Self-Organization – Revisited

- Positive and negative feedback
- Interactions among individuals and with the environment
- Probabilistic techniques

Positive and negative feedback

Networking aspects	
MAC	positive and negative feedback for controlling the used transmission energy, e.g. in PCM; enforcement of synchronization between multiple nodes to a common schedule
Ad hoc routing	positive feedback for route discovery in most table-driven routing protocols; negative feedback for suppression further data messages over erroneous paths, both used e.g. in AODV and DYMO
Data-centric networking	positive feedback in form of interest messages controlling the behavior of sensor nodes, e.g. in directed diffusion; energy levels and timeouts as negative feedback to suppress unnecessary communication, e.g. in rumor routing
Clustering	feedback is provided for example in form of energy levels controlling system-inherent parameters such as the probability to become clusterhead in HEED

Positive and negative feedback

Coordination and control	
Communication and coordination	feedback loops are inherently used by all time synchronization techniques; positive and negative feedback enables adaptive coordination among nodes, e.g. for optimizing the utility by ASCENT or to ensure a latency bound by DEPR
Collaboration and task allocation	positive feedback in the biddings in auction-based task allocation, e.g. in MURDOCH, and negative feedback through re-allocation; feedback based probability adaptation in the case of emergent cooperation

Interactions among individuals and with the environment

Networking aspects	
MAC	intensive protocol inherent interactions between neigh-boring nodes to detect or prevent collisions, e.g. MACA based protocols; synchronization according to local message exchanges; indirect information exchange using signal strength measurements, e.g. in PCM
Ad hoc routing	state and topology maintenance for address-based routing; interactions among neighboring and remote nodes to search shortest path information, e.g. in AODV and DYMO; duplicate address detection based on node interactions, e.g. in PDAD and DAA
Data-centric networking	optimized gossiping strategies exploiting the local topology information; agent based approaches relying on stigmergic information exchange and on local interactions between neighboring nodes, e.g. in rumor routing; adaptation of source-sink relationships according to remote interactions in directed diffusion
Clustering	interaction provides the basis for clustering techniques; transmission power estimation and cluster affiliation using local interactions, e.g. in LEACH and HEED

Interactions among individuals and with the environment

Coordination and control	
Communication and coordination	time synchronization based on exchanged data or specific time protocol messages (used by all the discussed algorithms); topology maintenance and clustering techniques based on local interactions, e.g. in Span, ASCENT, and DEPR
Collaboration and task allocation	intentional coordination based on directed communication to a central decision taker, either for periodic state maintenance, e.g. in OAA, or for auction systems, e.g. in MURDOCH and mediation; local interactions among neighboring agents and stigmergic communication in emergent cooperation

Probabilistic techniques

Networking aspects	
MAC	reduced collision probability through randomized medium access; fairness and mutual exclusion are achieved by using random startup delays for the RTS/CTS handshake, e.g. in all MACA based protocols
Ad hoc routing	gossiping techniques to reduce the flooding overhead in reactive routing approaches, e.g. in optimized AODV; dynamic address allocation based on stateless random address selections in combinations with DAD algorithms, e.g. in PDAD and DAA
Data-centric networking	probabilistic data forwarding in gossiping approaches; agent based techniques relying on random waypoint strategies, e.g. in rumor routing
Clustering	randomized clusterhead selection to maximize the network lifetime and to provide fair distribution of the energy load, e.g. in LEACH and HEED

Probabilistic techniques

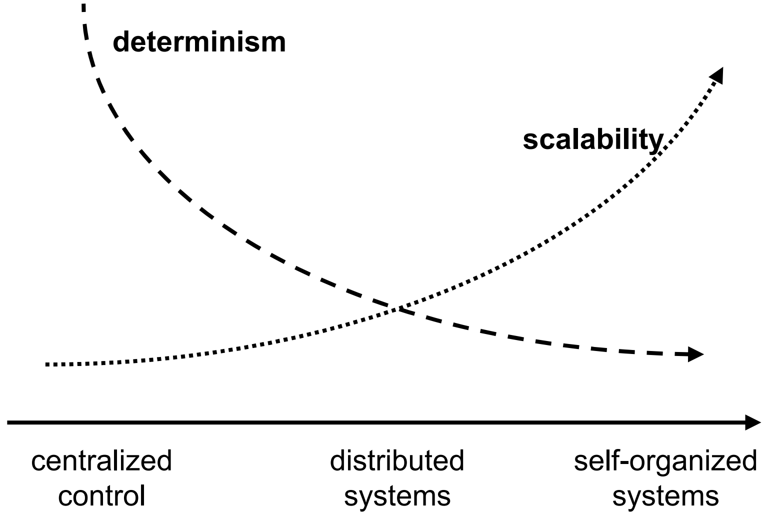
Coordination and control	
Communication and coordination	randomization through variation of network latencies; randomly distributed back-off delay, e.g. in Span; probabilistic state transitions, e.g. in DEPR
Collaboration and task allocation	probabilistic decision processes and task allocation according to estimations for winning the contest for a new task or the nest leaving probability

Evaluation Criteria

- Scalability
- Energy considerations
- Network lifetime

Scalability

- Protocol overhead
  - Number and size of state information that must be stored and maintained at each node in the network
  - Direct communication overhead – goodput vs. network load
- Capacity of wireless networks
  - Bounded capacity of wireless networks according to Gupta & Kumar
- Reduced determinism
  - Scalability vs. predictability

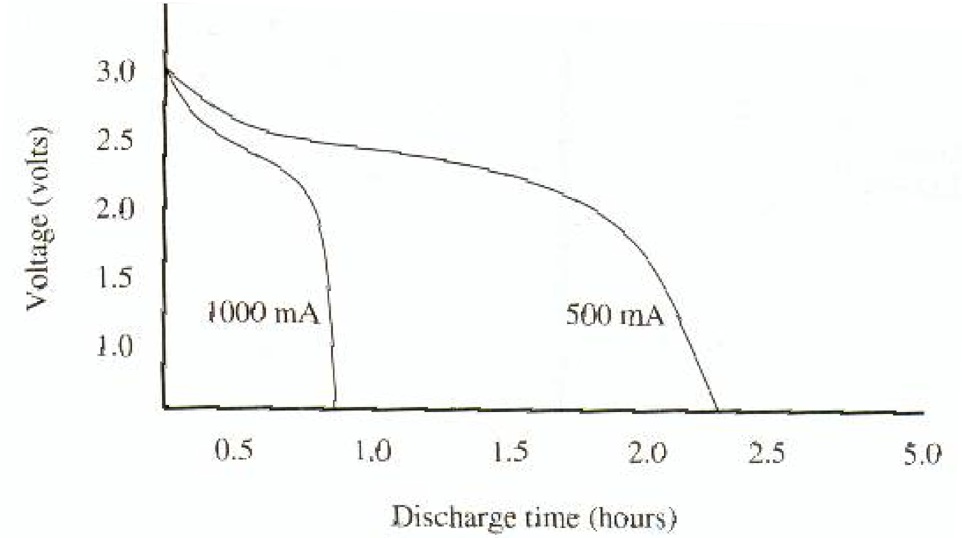


Energy considerations

- Constraints on the battery source
  - Battery size is direct proportional to its capacity
- Selection of optimal transmission power
  - Energy consumption increases with an increase in the transmission power (which is also a function of the distance between communicating nodes)
  - Optimal transmission power decreases the interference among nodes, which, in turn, increases the number of simultaneous transmissions
- Channel utilization
  - As seen before, a reduction of the transmission power increases frequency reuse → better channel utilization
  - Power control becomes especially important in CDMA-based systems

Battery Management

- Battery lifetime estimation
  - Manufacturer-specified rated capacity, discharge plot of the battery
  - Discharge current ratio can be computed
  - Efficiency is calculated by the interpolation of point in the discharge plot

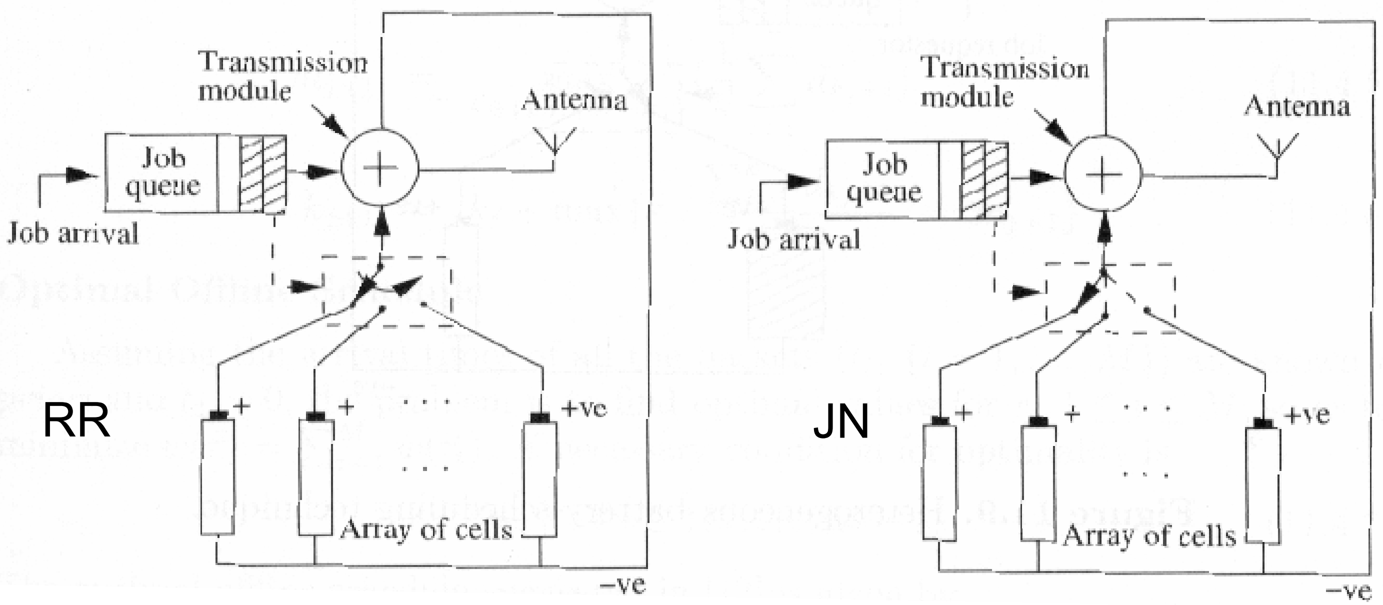


- Recovery capacity effect
  - In idle conditions, the charge of the cell recovers → by increasing the idle time the theoretical capacity of the cell may be used

    → Battery scheduling

Battery-Scheduling Techniques

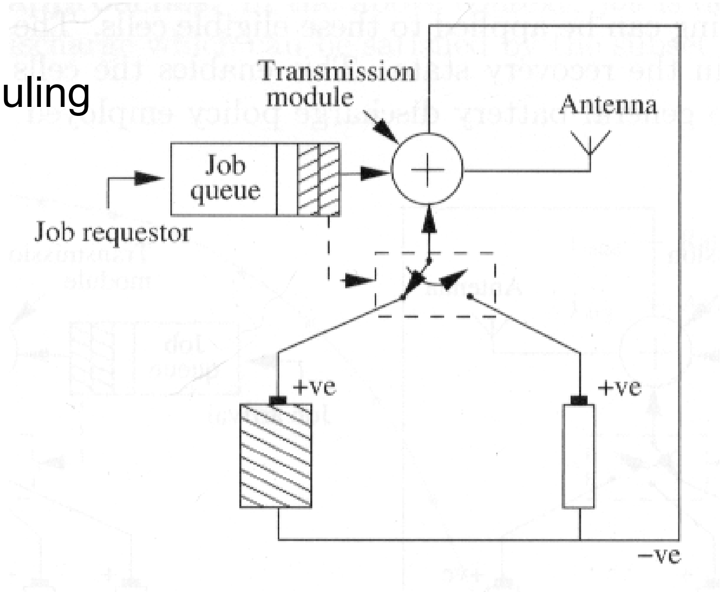
- Delay-free approaches
  - As soon as a job arrives, the battery charge for processing the job will be provided from the cells without any delay
    - Joint technique (JN) - the same amount of current is drawn equally from all the cells, i.e. each cell is discharged by 1/L of the current required
    - Round robin technique (RR) - batteries are selected in round robin fashion, the current job gets the required energy from the selected cell
    - Random technique (RN) - similar to RR but the cells are selected randomly



Battery-Scheduling Techniques

- No delay-free approaches
  - The batteries coordinate among themselves based on their remaining charge
  - E.g. by defining a threshold for the remaining charge → all the cells which have their remaining charge greater than the threshold value become eligible for providing energy
  - Delay-free approaches can be applied to the eligible cells
  - Non-eligible cells stay in recovery state to maximize their capacity

- Further enhancements
  - Heterogeneous battery-scheduling technique



Energy Consumption

- A "back of the envelope" estimation

- Number of instructions
  - Energy per instruction: 1 nJ
  - Small battery ("smart dust"): 1 J = 1 Ws
  - Corresponds: 10^9 instructions!

- Lifetime
  - Or: Require a single day operational lifetime = 24x60x60 = 86400 s
  - 1 Ws / 86400 s ≅ ***11.5 μW*** as max. sustained power consumption!

→ Not feasible!

Multiple Power Consumption Modes

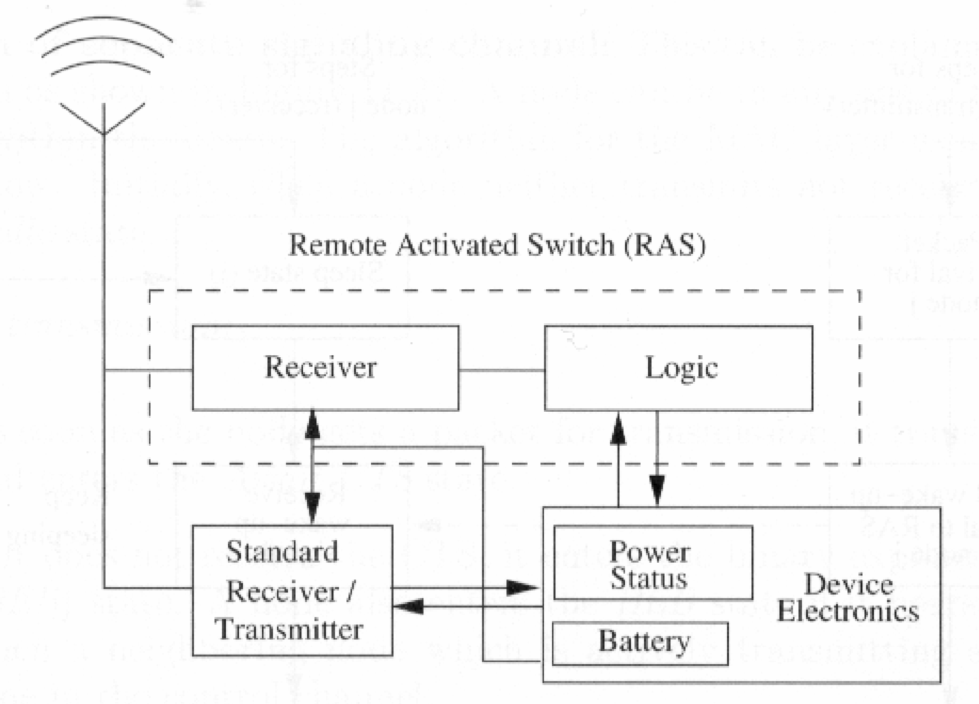
- Way out: Do not run sensor node at full operation all the time
  - If nothing to do, switch to ***power safe mode***
  - Question: When to throttle down? How to wake up again?

- Typical modes
  - Controller: Active, idle, sleep
  - Radio mode: Turn on/off transmitter/receiver, both

- Multiple modes possible, “deeper” sleep modes
  - Strongly depends on hardware
  - TI MSP 430 (@ 1 MHz, 3V):
    - Fully operation 1.2 mW
    - Deepest sleep mode 0.3 μW – only woken up by external interrupts (not even timer is running any more)
  - Atmel ATMega
    - Operational mode: 15 mW active, 6 mW idle
    - Sleep mode: 75 μW

Processor Power Management Schemes

- Power-saving modes
  - Key idea: remain in sleep mode as long as possible
  - Example: RAS – remote activated switch
    - Receiver and control logic can be turned off until a packet is received
    - Caution: the preamble must be long enough for turning on and initializing the receiver



Transmitter Power/Energy Consumption for n Bits

- Amplifier power: $P_{amp} = \alpha_{amp} + \beta_{amp} P_{tx}$
  - P_{tx} ***radiated power***
  - α_{amp}, β_{amp} constants depending on model
  - Highest efficiency ($\eta = P_{tx} / P_{amp}$) at maximum output power
  - In addition: transmitter electronics needs power P_{txElec}
- Time to transmit n bits: $n / (R \times R_{code})$
  - R nomial data rate, R_{code} coding rate
- To leave sleep mode
  - Time T_{start}, average power P_{start}

$$\rightarrow E_{tx} = T_{start} P_{start} + n / (R \times R_{code}) (P_{txElec} + \alpha_{amp} + \beta_{amp} P_{tx})$$

- Simplification: Modulation not considered

Computation vs. Communication Energy Cost

- Tradeoff?
  - Directly comparing computation/communication energy cost not possible
  - But: put them into perspective!
  - Energy ratio of “sending one bit” vs. “computing one instruction”:
    → anything between 220 and 2900 in the literature
  - Transmitting (send & receive) one kilobyte ≈ computing three million instructions!

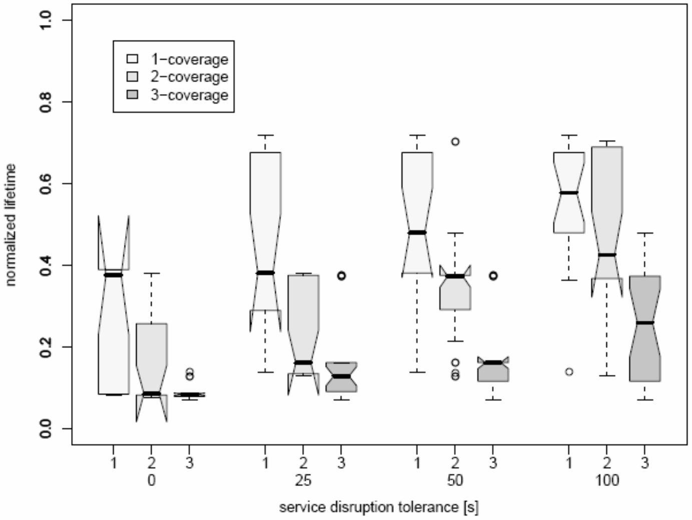
- Hence: try to compute instead of communicate whenever possible

- Key technique in WSN – ***in-network processing!***
  - Exploit compression schemes, intelligent coding schemes, …

Network lifetime

- Considered as a comprehensive evaluation metric for sensor networks

- Individual parameters $\zeta_{**}(t)$
  - Active nodes, alive nodes, availability / service disruption tolerance
  - Area coverage, target coverage, k-coverage
  - Latency, loss, connectivity
  - Connected coverage



- Liveliness
  - $\zeta(t)$: if all $\zeta_{**}(t)$ are provided

- Lifetime measures
  - Accumulated network lifetime Z_a is the sum of all times the network is alive
  - Total network lifetime Z_t is the time at which the liveliness criterion is lost for a time period longer than the service disruption tolerance

Summary (what do I need to know)

- ***Self-organization techniques***
  - Basic methods (positive and negative feedback, interactions among individuals and with the environment, probabilistic techniques)
  - Applicability in sensor and actor networks

- ***Evaluation criteria***
  - Scalability – limiting factors
  - Energy considerations (limitations, battery management)
  - Network lifetime

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