Collaborative transmission in wireless sensor networks

Wireless sensor networks

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Motivation

A scenario of distributed adaptive Beamforming

Possibilities of integrating sensor nodes into an environment

Adding [. . .] sensors to everyday objects will create an Internet of Things, and lay the foundations of a new age of machine perception.
(K. Ashton, co-founder and executive director of the Massachussets Institute of Technology's Auto-ID Center in a presentation in spring 1998)

Overview and Structure

- Introduction to context aware computing
- Wireless sensor networks
- Wireless communications
- Basics of probability theory
- Randomised search approaches
- Cooperative transmission schemes
- Distributed adaptive beamforming
  - Feedback based approaches
  - Asymptotic bounds on the synchronisation time
  - Alternative algorithmic approaches
  - Alternative Optimisation environments

Overview and Structure

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- **Wireless sensor networks**
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Outline

Wireless sensor networks

Introduction
Wireless sensor networks

Wireless sensor network

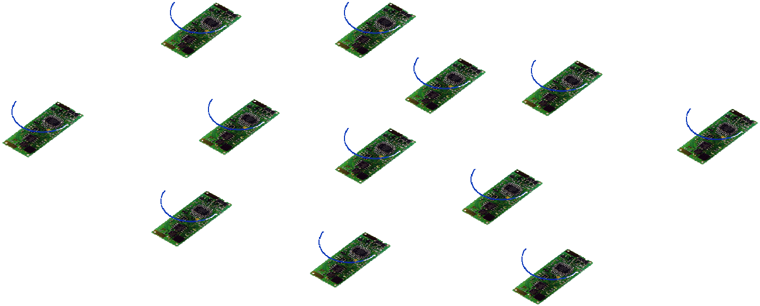
- network of distributed devices
- sensing and communication entities
- collaboration to achieve a common objective
- Typically one or more sinks to collect and forward data from all sensing devices

Introduction
Wireless sensor networks

- Benefits
  - monitor environmental stimuli
  - provide feedback on a monitored area
  - implemented in areas that are seldom or even hard to access
    - monitoring of underwater scenarios
    - animal monitoring
    - Emergency situation (Avalance, earthquake)

Introduction
Wireless sensor networks

- Desired features
  - Easy to deploy
  - Cheap
  - Low maintenance



Introduction

Wireless sensor networks

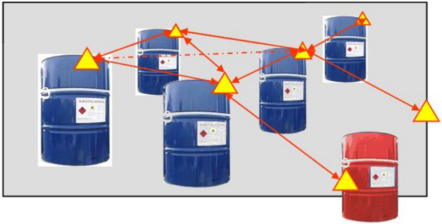
- Applications[1]
  - Monitor and control manufacturing
  - Bio sensors for health monitoring
  - Weather monitoring
  - Habitant monitoring (elderly)
  - Smart environments for home entertainment

[1] Li, Y., Thai, M., Wu, W.: Wireless sensor networks and applications. Signals and Communication Technology. Springer (2008)

Introduction

Wireless sensor networks

- Application: CoBIs – Continuous monitoring of goods
  - Restrictions on storage conditions
    - Neighbouring goods
    - Temperature
    - duration
  - Dangerous combination of materials
  - Correct storage place
  - Integrated into SAP/ERP/EHS over XML-based web services



Introduction

Wireless sensor networks

- Application: LoCostix
  - Polymertransponder
    - Offset-printable electronics
    - Cheap and fast production
    - One transponder per item
  - Problem: High count of items

Introduction
Wireless sensor networks

- Application: LoCostix – Tracking of goods
  - Solution: New communication protocols
    - Collaborative data transfer
    - Estimation sufficient
    - Integration with SAP/AutoID

	Different products on shelf	*Items on shelf*	*Time to check shelf*	*Check time Per item*
Whole food products	241	3000	6h	7 sec
Pharmacological products	487	4000	16h	14 sec

Outline

Wireless sensor networks

1. Introduction

2. The sensor node
   - Power unit
   - Sensing unit
   - Processing unit
   - Communication unit

3. Wireless sensor networks
   - Quality metrics
   - MAC protocols for wireless sensor networks

The sensor node

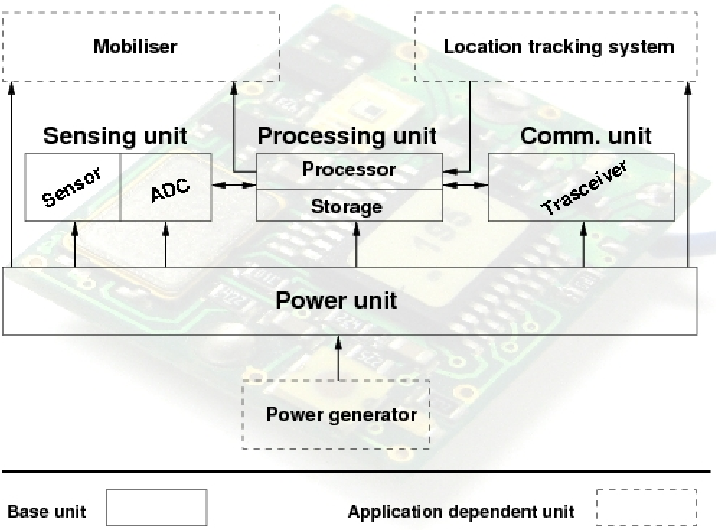
Typical components of a sensor node

- Sensor nodes are deployed either inside or very close a phenomenon to be observed
- Typically unattended operation (low to zero maintenance)
- Due to advances in integrated cirquit design the size, weight and cost of nodes is constantly decreasing while accuracy and resolution are improved [2]
- Nodes typically consist of components for
  - Sensing
  - Data processing
  - Storage
  - Communication
- Additional application dependent components possible
  - Mobiliser (spatial movement)
  - Location tracking (GPS, ultrasound)
  - Power Generator (Solar cells)

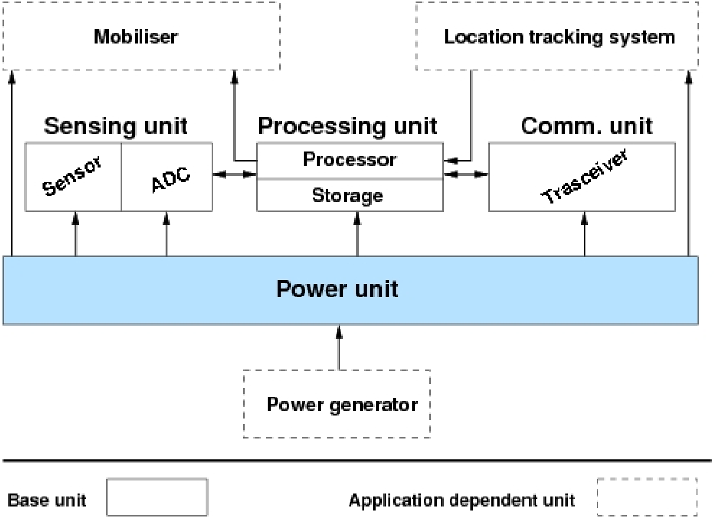
[2] Li, Y., Thai, M., Wu, W.: Wireless sensor networks and applications. Signals and Communication Technology. Springer (2008)

The sensor node

Typical components of a sensor node

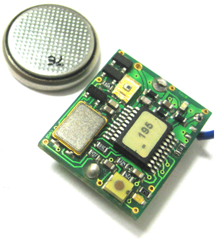


The sensor node
Power unit



The sensor node
Power unit

- Typical design aspect for sensor networks:
  - operate unattended over long time spans
  - disconnected from an external power source
- Energy consumption and capacity of the power unit is a critical aspect



The sensor node
Power unit

- Restrictions:
  - sensor node is a microelectronic device
  - Can only be equipped with very limited power source
    - e.g. $< 0.5Ah, 1.2V$
- In multihop ad-hoc sensor network, each node is data originator and data router
- Malfunctioning of nodes can cause significant topological changes and might require rerouting of packets and reorganisation of the network
- Therefore, power conservation and power management are of additional importance.

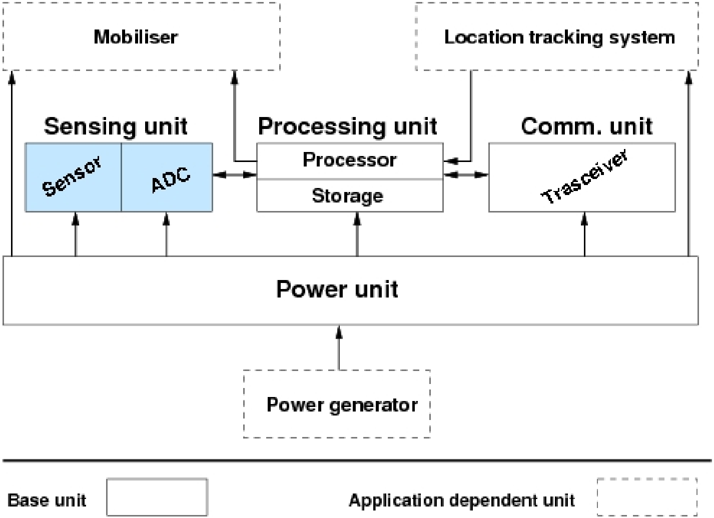
The sensor node

Power unit

- Power consumption in a sensor network is divided into
  - Sensing
  - Communication
  - Data processing
- Communication most energy consuming (receiving and transmission of data)
- Can also be accompanied by power harvesting units such as e.g. solar cells.

The sensor node

Sensing unit

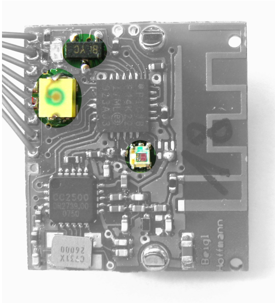


The sensor node
Sensing unit

- Sensing units are usually composed of two sub-units
  - Sensors
    - Transforms physical parameters into analog electrical signals
    - Temperature, pressure, light intensity, ...
  - AD-Converters
    - Transform analog signals procured by sensors to digital signals for further processing
    - Digital signal is a binary voltage signal (either on or off)

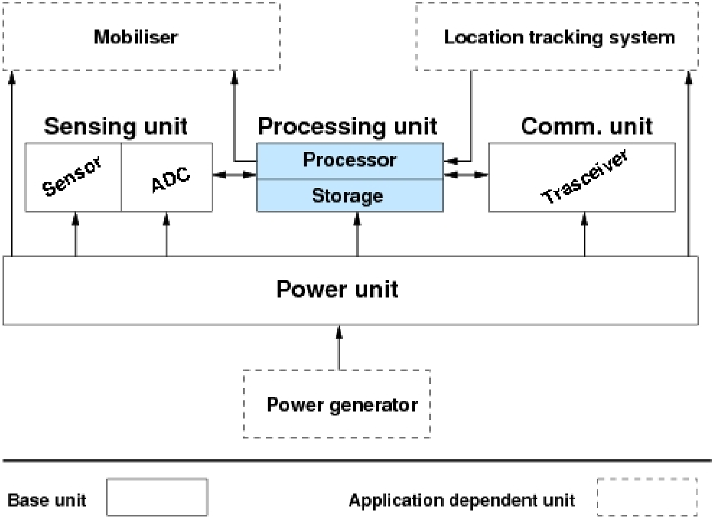
The sensor node
Sensing unit

- Digital signals might control components or parameters of the sensor nodes via actuators
- Actuator:
  - electromechanical device that can control other parts of an electromechanical system
    - e.g. relay
- Typical sensors
  - Audio
  - Light or humidity
  - Ball switch
  - Acceleration



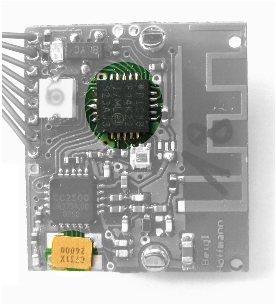
The sensor node

ProcessingUnit



The sensor node
ProcessingUnit

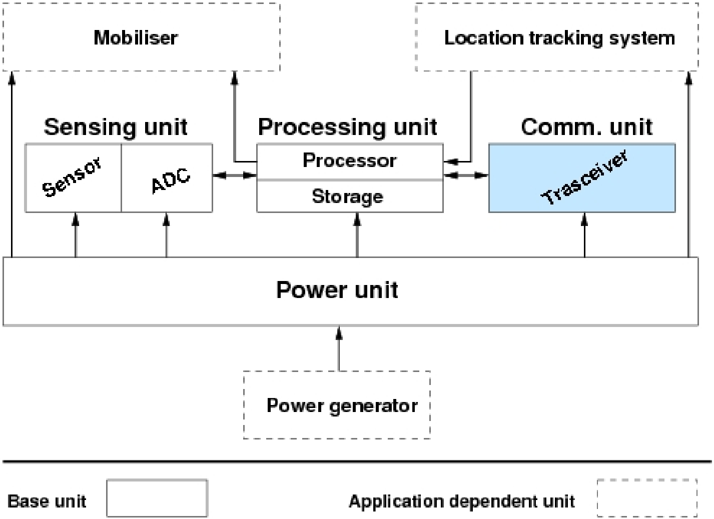
- Processing unit consists of
  - Processor
  - Typically small storage
- Pre-processing of sensed information
- Communication related logic
  - TCP
  - Network layer (routing)



The sensor node
ProcessingUnit

- Before transmission: Node converts raw data to common representation
- Possibly: Discard data to save energy for communication
    - redundant
    - error prone
- Processor decides when and which data to transmit
- Typically microprocessors are utilised for their low power consumption

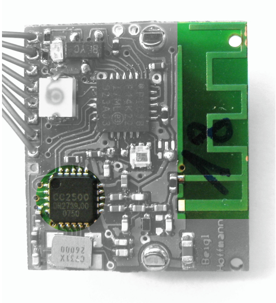
The sensor node
Communication unit



The sensor node

ProcessingUnit

- Communication unit consists of a transceiver
  - connect node to sensor network
  - Combines transmitter and receiver
- Communication technologies
  - Radio frequency (typical)
  - Infrared
  - Optical



The sensor node

Communication unit

- Problems with RF-communication for low-lying antennas[3] [4]
  - RF signal propagation influenced by
    - surface roughness
    - reflecting objects
    - obstructing objects
    - antenna elevation
  - Signal intensity drops as the fourth power of distance
    - due to partial cancellation by ground-reflected ray

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[3] Rappaport, T.: Wireless Communications: Principles and Practice. Prentice Hall (2002)

[4] Sohrabi, K., Manriquez, B., Pottie, G.: Near-ground wideband channel measurements. In: Proceedings of the 49th vehicular technology conference. (1999) 571–574

The sensor node
Communication unit

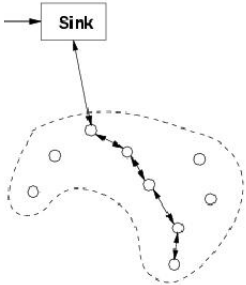
- Exemplary path loss measurements[5]

Location	Mean Path loss exponent	Shadowing variance σ^2 (dB)
Apartment Hallway	2.0	8.0
Parking structure	3.0	7.9
One-sided corridor	1.9	8.0
One-sided patio	3.2	3.7
Concrete Canyon	2.7	10.2
Plant fence	4.9	9.4
Small boulders	3.5	12.8
Sandy flat beach	4.2	4.0
Dense bamboo	5.0	11.6
Dry tall underbrush	3.6	8.4

[5] Sohrabi, K., Manriquez, B., Pottie, G.: Near-ground wideband channel measurements. In: Proceedings of the 49th vehicular technology conference. (1999) 571–574

The sensor node
Communication unit

- Signal strength quickly diminishes with increasing transmission range
- Therefore:
  - multi-hop topology with short hops more energy efficient

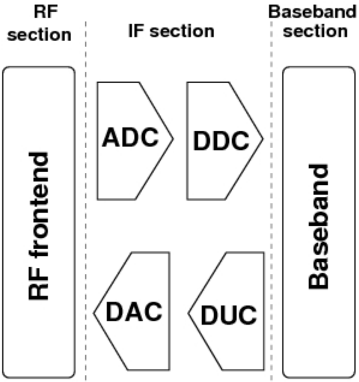


The sensor node
Communication unit

- Infrared communication
  - License free
  - Robust to interference from electrical devices
    - One mayor concern in RF-based devices
  - But: Only feasible in direct line of sight
- Also: Wired communication is possible and, in fact often implemented

The sensor node
Communication unit – Transceiver design

- Transceiver design



The sensor node
Communication unit – Transceiver design

- Typical transceiver consists of
    - RF-frontend
    - Baseband processor

The sensor node

Communication unit – Transceiver design

- RF-frontend
  - Processes analog signal as transmitted or received over wireless channel
  - Typically, high frequencies (e.g. 2.4 GHz) utilised
  - Industrial, Scientific and Medical (ISM) band

The sensor node

Communication unit – Transceiver design

- Baseband processor
  - Processing at high frequencies would surcharge processing capabilities
  - RF-signals transformed to intermediate frequency to digital signals
  - Analog signals converted by AD-converters
  - Downconverted by digital downconverters (DDC)
  - Result: Frequency of several kHz
  - This are the baseband signals processed by processor

The sensor node

Communication unit – Transceiver states

- Normally, a transceiver is in one of four states:
  - Transmit
  - Receive
  - Idle
  - Sleep

The sensor node

Communication unit – Transceiver states

- Transmit and receive states
  - transceiver transmits or receives RF signals
  - typically most energy consuming tasks of a sensor node
  - time in which the transceiver is in transmit or receive states should be minimised to reduce the energy consumption

The sensor node

Communication unit – Transceiver states

- Idle state
  - transceiver not receiving or transmitting
  - but: ready to receive an RF signal
  - some parts of the receive circuitry are switched off to reduce energy consumption.

The sensor node

Communication unit – Transceiver states

- Sleep state
  - major parts of transceiver switched off
  - Often several sleep states depending on the amount of parts switched off
  - recovery times and energy required to wake up differ for these sleep states

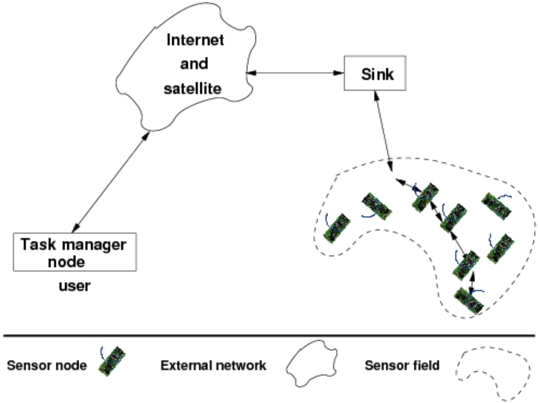
Outline

Wireless sensor networks

Wireless sensor networks

Introduction

- Schematic illustration of a sensor network implementation[6]



[6] Laneman, J., Wornell, G., Tse, D.: An efficient protocol for realising cooperative diversity in wireless networks. In: Proceedings of the IEEE International Symposium on Information Theory. (2001) 294

Wireless sensor networks
Introduction

Sensor networks

- sets of sensor nodes
- accomplish one or more tasks collaboratively
- Desired: self-organising capabilities

- Applications
  - Health care
  - Military
  - Desaster monitoring
  - Home appliance
  - . . .

Wireless sensor networks

Introduction

Source nodes

- addressor node of transmitted information

Sink nodes

- Recipient of transmitted information
- May communicate over external network with task manager node

All nodes

- Data collection
- Routing of data from source to sink
- Single hop communication or multi-hop protocol

Wireless sensor networks

Introduction

- To achieve this, WSNs require ad-hoc networking
- Common ad-hoc networking protocols usually not suited

Differences between WSNs and ad-hoc networks

- Count of nodes in WSN higher than in ad-hoc networks
- Sensor nodes are densely deployed
- Sensor nodes are prone to failures
- Topology of WSN changes (node failure, environment)
- Sensor nodes mainly use broadcast communication paradigm
- Most ad-hoc networks are point-to-point communications
- Sensor nodes limited in power, processing and memory
- Typically no global ID in WSN (overhead, node count)

Wireless sensor networks

Introduction

Observation

- transmission range is restricted due to signal decay
- maximum distance for a single hop is restricted

Classical approach to reach a distant receiver

- Multi-hop transmission
- Intermediate nodes are utilised as relay nodes that forward received packages along the network

Wireless sensor networks

Introduction

- It is sometimes claimed that ...

Assertion

- Multi-hop transmission schemes more energy efficient than direct transmission schemes
- Radiated energy for a direct connection higher than sum of radiated energy of relay nodes along the transmission path
- Intuition behind this assumption:
  - decay in signal strength is more than linear with increasing transmission distance
  - (we will discuss this in the communication part of the lecture)

Wireless sensor networks
Introduction

This assertion is wrong!

- Reduce the distance between relay nodes to a small ε
- Nodes are then placed next to each other
- Overall energy consumed extra nodes much higher than the gain in transmission energy.

[7]

[7] Kahn, J.M., Katz, R.H., Pister, K.S.J.: Next century challenges: Mobile networking for smart dust. In: Proceedings of the ACM MobiCom. (1999) 271-278

Wireless sensor networks
Introduction

- Multi-hop transmission feasible only when chain of intermediate nodes exists so that for each two neighbouring nodes in this chain the distance is smaller than transmission range.
- We will consider alternative, cooperative transmission schemes later in this lecture

Wireless sensor networks

Quality metrics

What is the purpose of quality metrics for WSNs?

Distinct WSNs are utilised for distinct applications. Each application has other requirements on a WSN. Quality metrics are utilised to derive a measure how well a WSN is suited for a given application

Wireless sensor networks
Quality metrics – Fault tolerance

- Nodes of a sensor network are cheap and low power devices
  - nodes might fail in the course of operation (power shortage, physical damage, environmental interference)
- Network is required to provide some means of fault tolerance
  - Ability to sustain network functionality with node failures
- Reliability $R_k(t)$ or fault tolerance of sensor nodes modelled by Poisson distribution.
- Probability of not having a failure in time interval $(0, t)$ is [8]
  - $R_k(t) = e^{-\lambda_k t}$
  - λ_k: Failure rate of node k
  - t: time period

[8] Hoblos, G., Staroswiecki, M., Aitouche, A.: Optimal design of fault tolerant sensor networks. In: Proceedings of the IEEE International Conference on Control Applications. (2000) 467-472

Wireless sensor networks

Quality metrics – Scalability

- Another relevant aspect for WSNs: scalability of the network
  - Sensor networks consist of densely deployed nodes
  - Number of nodes in a network may easily reach extreme values (e.g. hundreds of nodes on no more than 10 m^2
  - To be able to support these huge networks, new protocols are developed
- Density of a sensor network is calculated as $\mu(R) = \frac{N \cdot \pi R^2}{A}$ [9]
  - N: Number of nodes
  - A: Region
  - R: Transmission range.

[9] Bulusu, N., Estrin, D., Girod, L., Heidemann, J.: Scalable coordination for wireless sensor networks: Self-configuring localisation systems. In: Proceedings of the 6th IEEE International Symposium on Communication Theory and Application. (2001)

Wireless sensor networks

MAC protocols

- MAC protocols
  - First protocol layer above the physical layer
    - Heavily impacted by physical layer properties
  - Coordination of the communication among nodes
  - When do nodes access the shared medium?
  - Communication energy consuming
    - Reduction of energy consumption important task
    - Possible: Switch transceiver into sleep mode

Wireless sensor networks

MAC protocols

Requirements and design constraints

- High throughput
- stability
- Fairness
- Low access delay (Packet arrival and first transmission attempt)
- Low transmission delay (Delay between reception and forwarding)
- High robustness against bit errors
- Low Energy consumption
- Low overhead

Wireless sensor networks

MAC protocols

- Reasons for overhead
  - Collisions
  - Exchange of extra control packets
  - Protocol overhead

Wireless sensor networks
MAC protocols

- Energy problems result from
  - Collisions
  - Overhearing
  - Idle listening

Wireless sensor networks

MAC protocols

Collisions

- Collision means that energy spent for all packages wasted
- Can be avoided by design
  - Fixed assignment schemes (TDMA)
  - Demand assignment protocols
- Naturally:
  - Reduction of load leads to fewer collisions
  - With low load collision avoidance schemes may be omitted

Wireless sensor networks

MAC protocols

Overhearing

- Wireless channel is a broadcast channel
  - All neighbouring nodes receive transmitted packet
  - non-addressees discard the received packet
  - Energy for reception wasted
- Especially in dense networks
  - Schemes to reduce overhearing
  - Energy efficiency drastically improved
- But:
  - Overhearing sometimes desired
  - Multi-hop transmission requires overhearing

Wireless sensor networks

MAC protocols

Idle listening

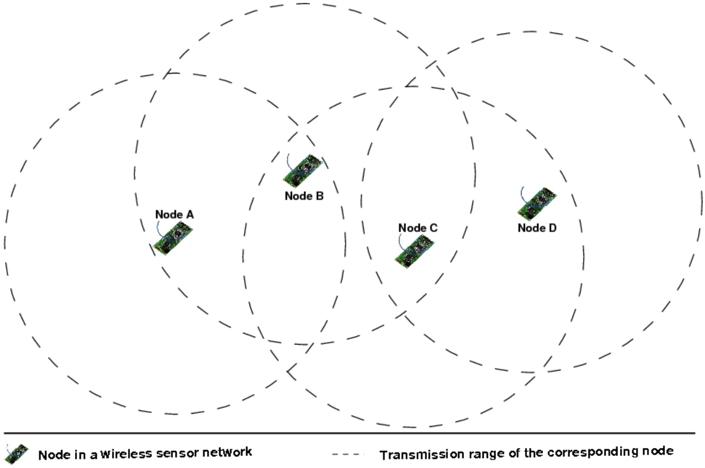
- Node in idle state requires still sufficient amount of energy
- Desired to reduce the idle time of nodes
- Switch to sleep state more frequently
  - Node is then 'deaf'
  - Tradeoff: Transition between states also consumes energy

Wireless sensor networks
MAC protocols

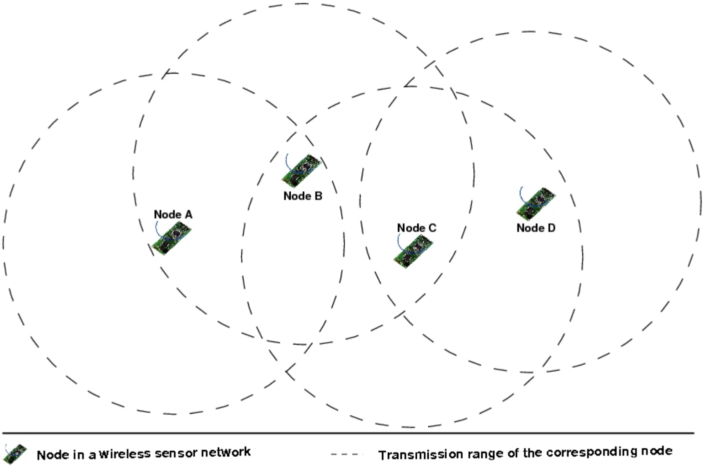
- Prominent problems in wireless sensor networks:
    - Hidden node problem
    - Exposed node scenario

Wireless sensor networks
MAC protocols

- The hidden node problem
  - Problem: Collision



- The exposed node scenario
  - Problem: Unnecessary delay



Wireless sensor networks

MAC protocols

- Many protocols exist already for wireless communication
  - Bluetooth
  - IEEE 802.11
- Are there any arguments for not applying these protocols also in wireless sensor networks?

Wireless sensor networks

MAC protocols

Bluetooth

- Designed as Wireless Personal Area Network (WPAN)
  - Major application: Connect wireless device to PC
  - Frequency hopping at 1.6 kHz
  - Allocation of hopping sequences
  - Nodes organised in piconets
    - One Master
    - Up to seven active slaves
    - 254 nodes overall (address assigned but inactive)
    - Master polls active slaves continuously

- Drawbacks
  - Master spends much energy on node polling
  - Limited number of nodes in a piconet
  - Not compatible with dense, energy restricted WSNs

Wireless sensor networks

MAC protocols

IEEE 802.11

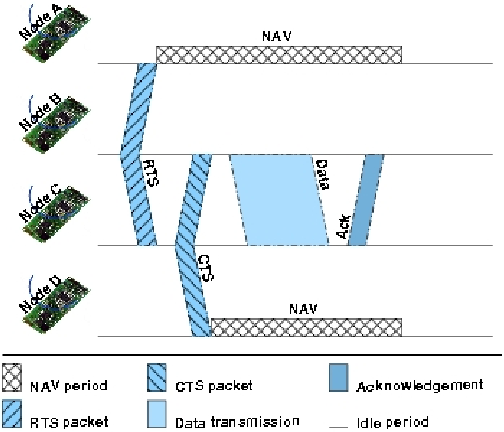
- Several physical layers specified
- Share single MAC protocol
- In the basic version, every node constantly listens on the channel
- System targeted towards high bit rates

- Drawbacks
  - single-hop protocol
  - High energy consumption since nodes constantly listen on the channel

Wireless sensor networks

MAC protocols

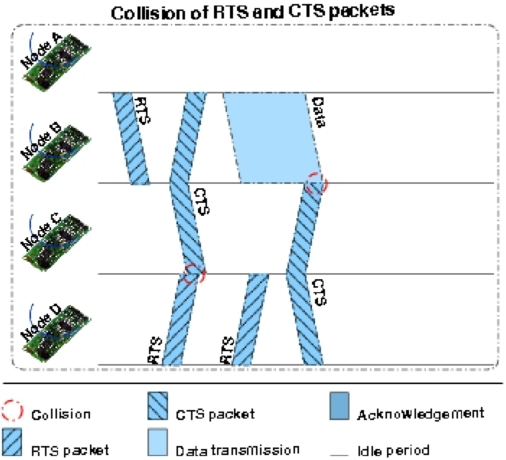
- IEEE 802.11
- RTS/CTS handshake



Wireless sensor networks

MAC protocols

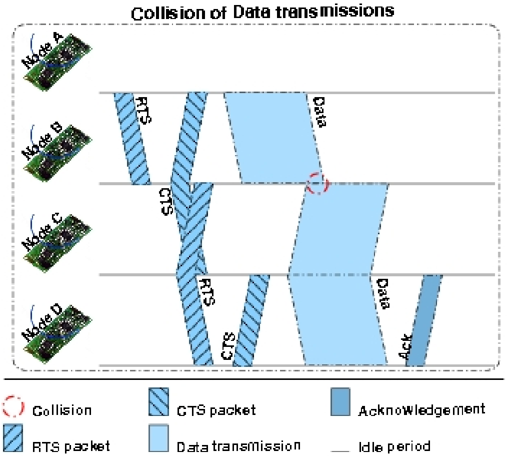
- Problems with RTS/CTS handshake



Wireless sensor networks

MAC protocols

- Problems with RTS/CTS handshake



Wireless sensor networks

MAC protocols

- Problems with RTS/CTS handshake
  - Higher energy consumption
  - Retransmission of packets
  - Much control overhead for small data packets
  - Long data packets increase the probability of bit errors
  - In Wireless sensor networks, long data packets typically fragmented into smaller packets

Wireless sensor networks

MAC protocols

- Wake up radio
  - Transmission and receive most energy consuming
  - Idle phase also waste of energy resources
  - Optimum:
    - Wake up node when required to listen on channel
    - Utilise a very low power receiver
    - This receiver triggers regular transceiver
  - Such a radio has not yet been designed
  - However, several projects work on this topic

Wireless sensor networks

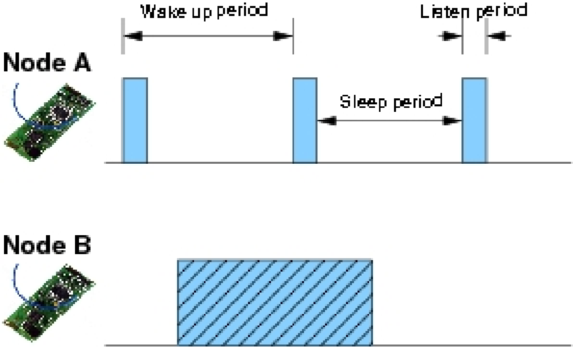
MAC protocols

- Wake up radio
  - Intermediate solution:
    - Switch on radio periodically
    - Node listens on the channel
    - If no attention required: Again sleep mode
  - Tradeoff:
    - Change of modes also requires energy

Wireless sensor networks

MAC protocols

- Generic wake up radio scheme
  - S-MAC (one channel)
  - STEM (separate channels)



Wireless sensor networks

MAC protocols

- Mediation device protocol
  - Mediation device as intermediate node
  - coordinates communication
  - All but mediation node in sleep mode
  - Mediation node never in sleep mode

Wireless sensor networks

MAC protocols

- Mediation device protocol