Design Trade-offs in Wireless Sensor Network System Development

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Overview

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- Introduction
- System Design Constraints
- Sensor Node Architecture
- Protocol Design Issues
- Summary

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Building Automation

- HVAC Control
- Lighting Control
- Access Control
- Refrigeration Control

Industrial Automation

- Temperature Sensing and Control
- Pressure Sensing
- Level Sensing
- Machinery Monitoring

Power and Utility Automation

- Remote reading of Residential Meters
- Power Distribution Diagnostics

Environmental Monitoring

- Air quality, water quality, and seismic activity
- Helps maintaining the integrity and safety of buildings, industrial facilities, roadways, water supplies, utilities, and other public infrastructure.

Tele-Health Monitoring and Diagnostics

- Significantly reduce overall medical costs by enabling home-based proactive monitoring and medical care
- Create personalized patient-based monitoring techniques (heart rate, respiration etc)

Why is Bosch interested?

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Several wire-based sensor/actuator network products in

- Building automation
- Industrial automation
- Security systems
- Automotive

All share the disadvantages to be

- Expensive to install
- Inflexible once installed
- Limited in size, complexity, and functionality
- Obtrusive in existing infrastructure

BUT a wireless channel clearly creates challenges in terms of

- Reliability
- Security
- Bandwidth

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What factors outweigh these challenges..

New functions

- Wireless data collection
- Collective operation of simple sensors for complex tasks

Scalability

Multi-hop networks

10 -1000s of devices

Robustness

Ad hoc Network

Self Reconfiguration

Distributed Intelligence

Profitability

- Low installation cost
- Flexibility

New market opportunities

Building Control Networks
- Tens to thousands of nodes
- Many device types (sensors, actuators)
- Low effective data rate
- Regular low-priority data

Thermo technology
- Climate control systems
- Tens to hundreds of nodes
- Frequent communication of non-critical data

Security Systems
- Tens up to several thousand nodes
- Asynchronous high-priority data
- Periodic low-priority data
- Safety-critical products

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Nodes

- Application specific sensors
- Few tens to thousands, small, low cost, “smart”
- Low power: 2x AA
- Static nodes

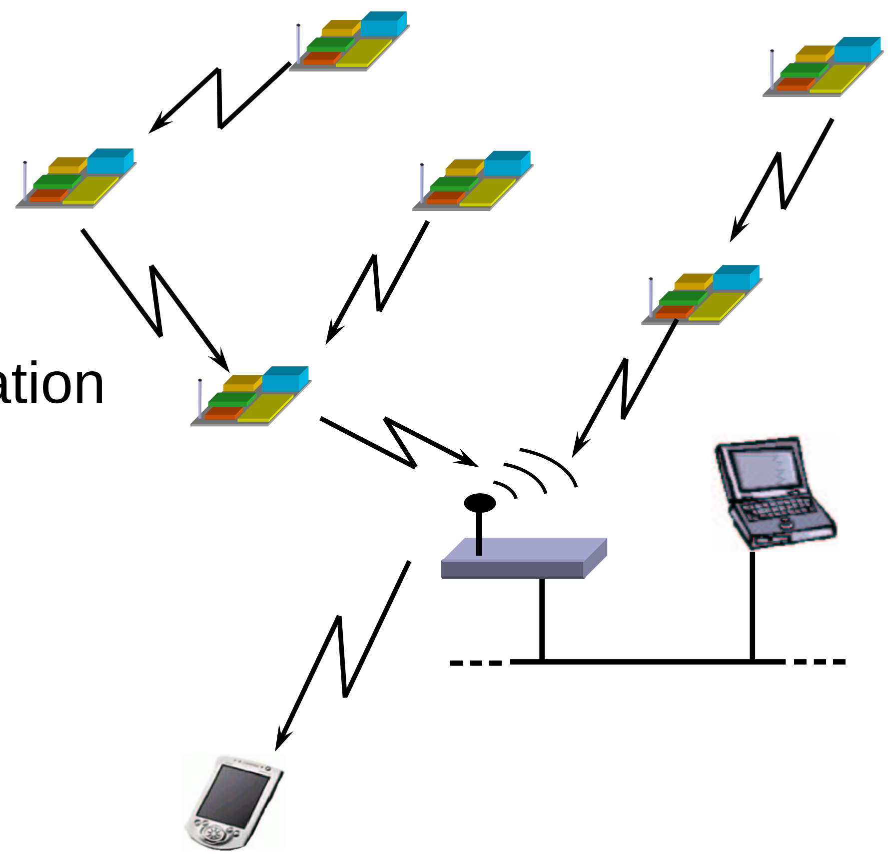
Base station

- Control of network
- Data aggregation and interpretation

Network protocol

- Ad hoc, multi hop operation
- Self organizing, self healing
- Scalable network

Interfaces to other networks



System Design Constraints (1)

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System Cost

- No redundant nodes
- Low cost microcontroller, low available memory
- Expensive labor: Infrequent maintenance requirements
- Limited technical expertise of installers, no configuration tools.

Marketing Issues

- Ease of use: user friendly functioning
- Low latency for control commands from user
- System for global market
- Secure communication
- Network life longevity
- Additional appealing features

System Design Constraints (2)

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Application specific requirements

- ➔ Latency requirements for high priority data
- ➔ Periodic monitoring of nodes
- ➔ Detection of channel jamming

Government regulations on frequency usage

- ➔ Limited output power
  - Depending on frequency band, limitations on output power
  - Transmitter field strength is restricted to –1dBm when spread spectrum is not used (FCC 15.249).
- ➔ Duty cycle restrictions
- ➔ Limited channel width
- ➔ Few available channels

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Latency vs Low Power

- Power limitation → Sleep as much as possible
- Low latency requirements → Wakeup frequently

Frequent low priority data vs Low Power

- Frequent low priority data → Communication overhead
- Power limitation → Low communication overhead

Ad hoc, reconfigurable vs Low Power, memory

- Ad hoc, reconfigurable → Complex algorithms,high communication overhead
- Power limitation → Low communication overhead

Overview

Architecture Goals

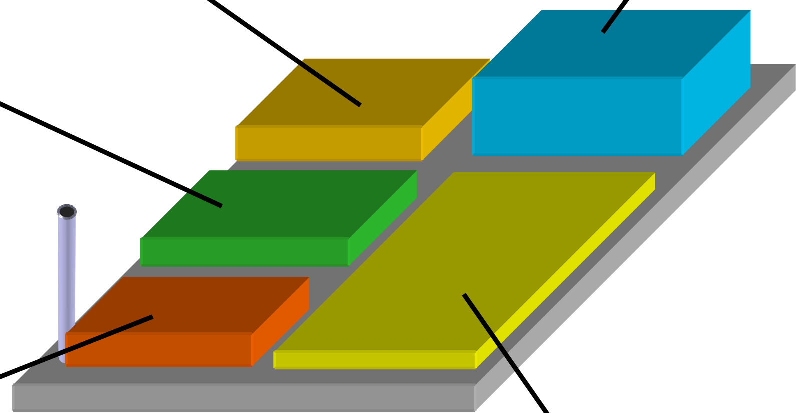
- Low power consumption
- Low cost nodes that use cheap and commonly available batteries
- Small physical size to facilitate deployment
- Compliance to standards and regulations
- Single design for international markets
- Ability to maintain time synchronization with other nodes
- Operate over wide temperature ranges

Architecture of a Sensor Node

Energy Storage:
- Battery
- Fuel cell

Sensor:
- Application specific.

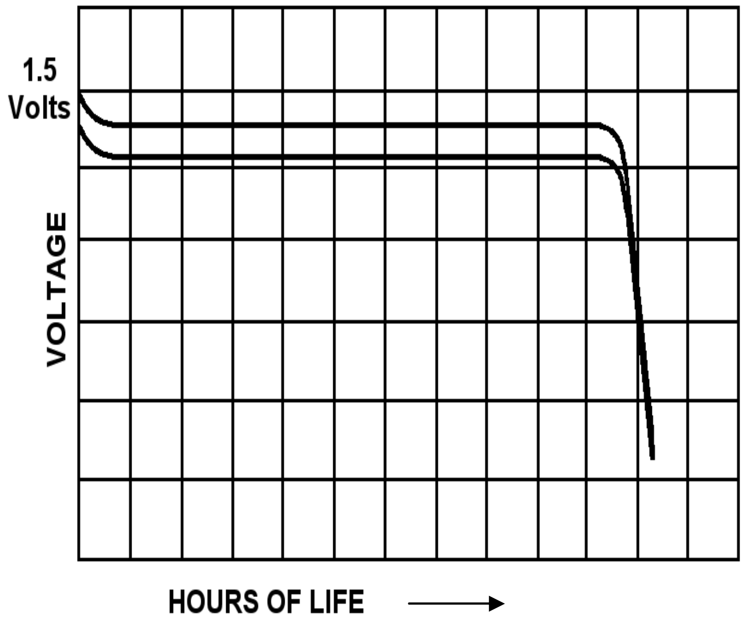
Microcontroller:
- OS, networking.
- Signal processing.
- Power management.



Transceiver
- ISM Band
  (433/900 MHz, 2.4 GHz)

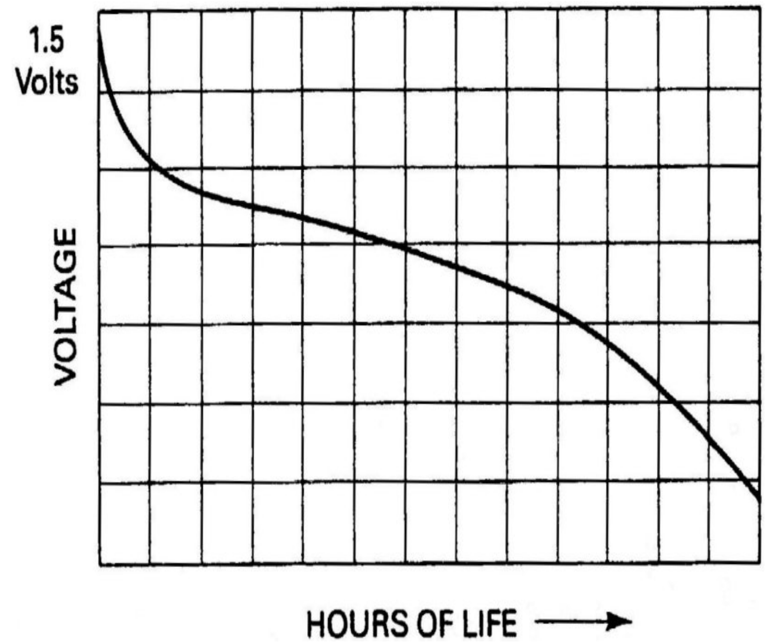
Autonomous Power Supply:
- Solar power.
- Temperature differences.
- Vibration.
- …

- Lithium-Ion



- Constant voltage over life.
- Works at lower temperatures than alkaline batteries.
- More expensive.
- Hard to determine remaining capacity.

- Alkaline



- Cheap, commonly available.
- Discharge curve helps determine remaining capacity.
- Requires nodes to operate over wide voltage range.

Energy Scavenging: http://bwrc.eecs.berkeley.edu/People/Faculty/jan/

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Power consumption

- Active Mode Current : varies from 150uA to 2.5mA.
- Sleep Mode Current : varies from 1uA – 50uA.
- Sleep mode is critical since it accounts for about 99% of life time.

Wakeup Time

- Fast transition from active to power down modes and vice-versa.
- Helps sleep during intermittent periods of inactivity.

Speed

- Typical applications run on low clock rates (1MHz– 8MHz).
- Determined by real-time activities plus time required to execute security algorithms.

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Memory

- Program memory size and types (Flash/ROM).
- Data memory size (RAM).

Peripherals

- I/O ports to interface to radio, sensors and any other device.
- Timers to support timed events.
- Counter sizes (8bit/ 16 bit): counter overflow determines frequency of wakeups.

Supply Voltage Range

- Low voltage operation increases longevity of alkaline battery powered nodes.

Architectural Issues: Transceiver (1)

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Power consumption

- For low power operation, receive and transmit energy is comparable.

Data rate

- Increased data rates $\Rightarrow$ Less transmission times

Wakeup time

- Most frequently performed act in order to check for signal in air.

Modulation Techniques

- Amplitude Modulation (AM): Simple to design, lesser bandwidth usage.
- Frequency Shift Keying (FSK): Better noise immunity.
- Gaussian FSK (GFSK): Desirable for systems with limited bandwidth

Operation in desired Frequencies

- Operable in different frequency bands
- Multi-channel operation needed for channel hopping.

Range

- Desired communication range of 30-50 meters indoor.
- Desirable to have adjustable power levels for transmission.

Supply Voltage Range

- Low voltage operation increases longevity of alkaline battery powered nodes.

Crystal Inaccuracy Issues

- Precise reference needed for frequency synthesizer
- Inaccurate crystals cause drift in reference frequency
- Drifts due to temperature changes, aging
- Accurate crystal $\Rightarrow$ Higher cost

Challenges

- Long periods of silence, drastic temperature changes could result in frequency mismatch of transmitter and receiver

Solution

- Temperature compensation based on manufacturer inputs
- Periodic adjustment of frequencies based on measured drifts

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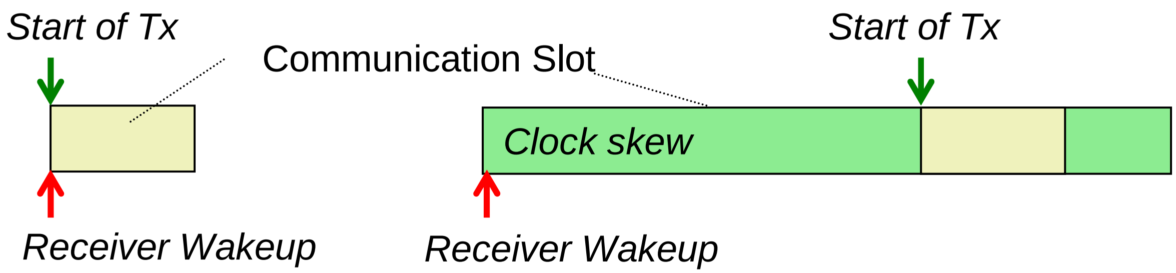
Serious problem : Clocks drift due to crystal inaccuracies.

- Periodic synchronization needed.
- Increased crystal accuracy ⇒ increased cost.
- Less accurate crystal ⇒ more drift.

Solutions:

- More frequent synchronization messages.
- Longer time slots ("receiver waits for sender").



Example:

- Communication of 20 bytes requires 4.17ms @ 76.8kbps.
- For a 20ppm crystal, in half hour, clock drifts 36ms max.
- Worst case drift between 2 nodes is 72ms.
- Required slot length is 77ms approximately!!!

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Channel access mechanisms

- Most common MAC protocols are TDMA or contention based.
- Contention based schemes are inherently less energy efficient.
- Time synchronization required for minimal energy consumption.
- For static network TDMA based scheduling favorable.

Routing mechanisms

- Data Gathering, Data-centric storage in Sensor Networks
- Directed diffusion
- Geographical and Energy Aware Routing
- Negotiation-based Protocols for Disseminating Information

Mesh Networks or Tree

- Choice based on application requirements.
- Tree topologies help in optimal data aggregation.
- Hierarchical clustering is beneficial for scalable networks

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Advantages

- Less information exchange $\Rightarrow$ Low communication overhead
- No overhead in gathering data at a central location
- Faster network formation
- Beneficial for dynamic networks

Disadvantages

- Less efficient topologies based on local information
- Reconfiguration could be complex for TDMA based networks.
- Higher algorithmic complexity at node
- Possibly higher memory requirements at the node

Centralized network control

Advantages

- Complete Network Information available
- Very efficient topologies, efficient load balancing
- Determine optimal communication schedules
- Optimal reconfiguration based on link qualities and current network dynamics
- Optimizations in data aggregation
- Base station could execute very complex algorithms to determine optimal topologies
- Base station has capability to store large amounts of data

Disadvantages

- Overhead in gathering data at a central location
- Increased Network formation time.
- Increased overhead in frequently changing networks.

Static networks could benefit from a centralized control.

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→ **Most challenging and critical phase of the system!**

Challenges

→ Efficient network discovery process.
  - Discover valid network nodes.
  - Reject nodes not belonging to the system.

→ Neighbor discovery and link assessment process.

→ Aggregation of link statistics information

→ Algorithms to compute energy efficient topologies

→ Dissemination of configuration information to the nodes.

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Study of channel behavior*

- Link quality study is crucial for node survivability
- Determine metrics and ways to grade channel
- Helps determining appropriate channel coding schemes

Energy Efficient Link Assessment*

- Neighbor discovery and measurement of link quality (SNR, PSR)
- Nodes are assigned codes (constant weight codes)
- Time slotted communication of nodes to determine link qualities
- Reception and Transmission pattern for each node based on assigned codes
- Link quality information calculated based on packets received from neighbors
- Base station aggregates this information

Papers available on http://www.stanford.edu/~abtink/

**Work in collaboration with Prof Balaji and his students, Stanford University*

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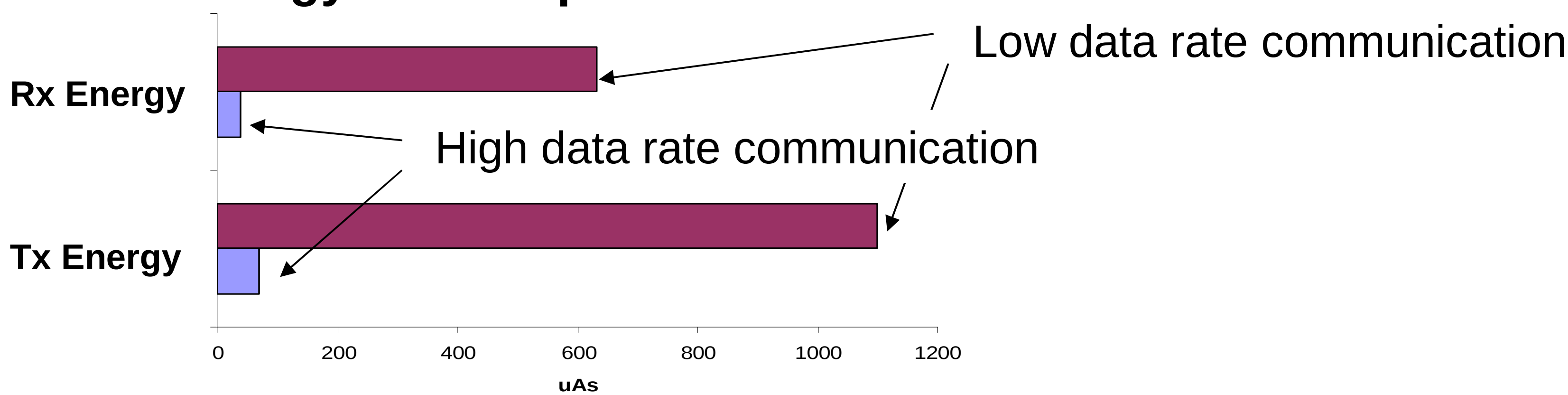
Example: Impact of data rate on energy budget:

- Pay load: 20 bytes, (Manchester encoding: 40 bytes)

- Transmit and receive times @ 76.8 kbps : 4.17ms.
- Transmit energy @ 76.8 kbps 4.17ms * 16.5mA = **68.8uAs**.

- Transmit and receive times @ 4.8 kbps: 66.67 ms.
- Transmit energy @ 4.8 kbps: 66.67ms * 16.5mA = **1100.1uAs**.

Energy consumption for different data rates



uAs = micro Ampere seconds.

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Example data rate on protocol design:

- Number of Nodes: 100
- Pay load: 20 bytes

System using 76.8 kbps

- At **76.8kbps**, approximately 10 milliseconds slot required.
- Every node gets to communicate **once in 1 second.**

System using 4.8 kbps

- At **4.8 kbps**, approximately 70 milliseconds slot required
- Every node gets to communicate **once in 7 seconds.**

1	2	3	.....	1	2	3	......	1	2	3	....	1	2	3	...	1	2	3	...	1	2	3	...	1	2	3	...

1	2	3	………	100

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Requirements

- Confidentiality: Efficient encryption schemes
- Authentication of unicast, broadcast and multicast messages
- Replay prevention
- Message Integrity
- In-Network Processing
- Secure bootstrapping of Keys

Challenges

- Very low available memory
- Low computational capabilities
- Scarce power

Additional Issues

Periodic Communication

- Periodic monitoring of every node and link
- Periodicity as frequent as every 2-3 minutes
- Energy overhead due to periodic communication
- Collision free communication of several nodes in a small time
- Lower data rates also pose a big challenge here.

Network Auto configuration

- Possibility to add new nodes during network operation
- Reconfiguration of network in case of link/node failures

- Introduction
- Regulatory Issues
- Architectural Issues
- Protocol Design Issues
- **Summary**

Summary

- Most industry applications need static sensor networks.
- Redundant nodes $\Rightarrow$ Redundant cost.
- System design driven by:
  - Application requirements
  - Cost
  - Regulatory constraints and
  - Market factors

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Your questions, please.