CAS lab
University of Thessaly
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IoT R&D

2. Communications - WSN Industrial IoT

Wireless Sensor Networks (WSN)

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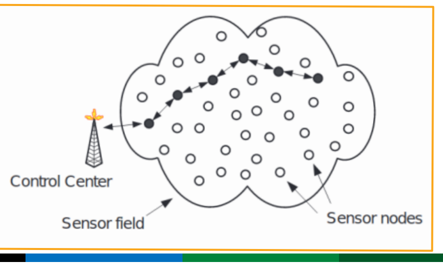
Introduction

Wireless Sensor Networks are networks comprised of spatially dispersed and dedicated sensors that monitor and record the physical conditions of the environment and forward the collected data to a centralized location. They combine sensing, processing and networking over miniaturized embedded devices called sensor nodes.

Key features that differentiate them from conventional data networks:

- Power autonomous (mainly operate on batteries);
- Operate in ad-hoc manner, i.e., do not require fixed infrastructure;
- Cost-effective ⟶ Highly scalable;
- Low data rates (max 1Mbps);
- Easy to deploy;
- Self-organized;



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Introduction

<u>Key characteristic that distinguishes them from remaining networks is the reasoning of existence:</u>

- Collect information from the physical environment – regardless of how accessible that is;
- Couple the end-users directly to the sensor measurements (cyber to physical space);
- Provide information that is precisely localized (in spatio-temporal terms) according to the application demands;
- Establish a bi-directional link with the physical space (remote & adaptable actuation based on the sensing stimulus)

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Network Elements

Node: Autonomous sensor-equipped device

Base station: Data capturer and gateway to external systems

External systems: Data storing and managing centers (servers)

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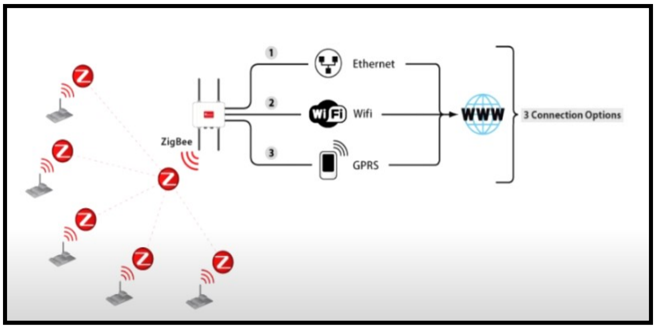
Working Basis

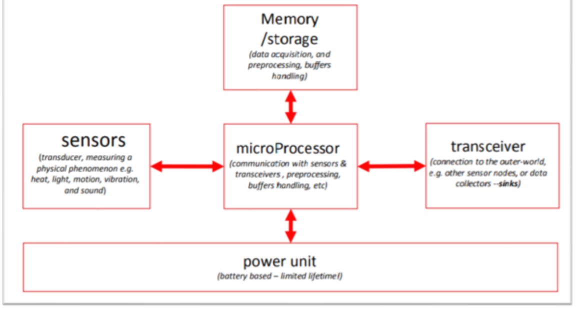
- Nodes collect data from environment.
- Nodes send data to base station via a protocol (etc. ZigBee).
- Base station sends data to external system for storing via various available protocols.



Network Elements - Nodes

Node structure

- Microprocessor
- Sensors
- Battery
- Communication modules
- Memory



Modular structure

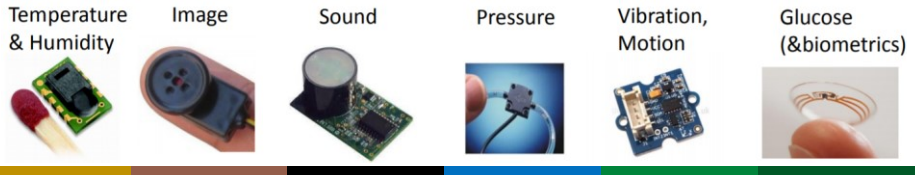
Modules can be switched depending on application goal. Mainly:

- Power source
- Comm modules (ZigBee, BT, WiFi, GPRS)
- Data storing (3KB EEPROM, 2 GB SD)

Network Elements - Nodes

Sensing Elements

- Sensors: capture a signal corresponding to a physical phenomenon (process, system, plant)
- Signal conditioning prepares captured signals for further use (amplification, attenuation, filtering of unwanted frequencies, tec.)
- Analog-to-Digital conversion (ADC) translates analog signals into digital ones.



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Network Elements - Nodes

Processing Elements

Traditionally: 16-bit archs

- Moving towards higher computational capacity (32 bit – ARM technologies)
- Programming sensor nodes → programming its μProcessor to:
- Access peripheral devices (transceivers, leds, sensors)
- Handle, store, modify the acquired information
- Direct programming on the μProcessor (low level C / Assembly) OR using Real-time Operating Systems

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Network Elements - Nodes

Transceivers

- Conventional: low-level PHY functionalities: frequency and channels, spectrum handling, modulation, bit rate. Advanced network functionalities and processing are implemented on software(microprocessor)
- Current Trend: System-on-Chip → allows implementation of a sophisticated protocol stack on the chip (dedicated microprocessor & memory)
- Either way it is the element with the highest power consumption
- Radio Duty Cycling: putting transceiver to different states:
  - Transmit / Receive
  - Idle: Ready to receive
  - Sleep: significant parts of the chip are switched off

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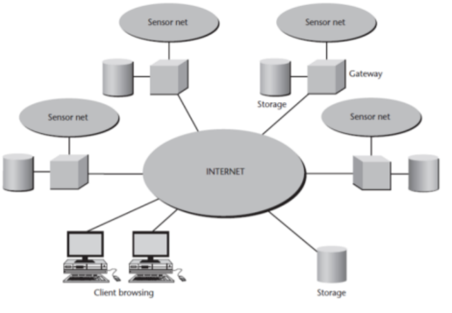
Network Elements – Base station

Base station (Sink node)

A multiprotocol router able to support several interfaces on it. It serves as a gateway that routes user queries or commands to appropriate nodes in a sensor network and sensor data, to users who have requested it or are expected to utilize the information.

- 802.15.4/ZigBee
- WiFi (2.4GHz, 5GHz)
- GPRS
- Bluetooth
- GPS



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Applications

Everywhere there is a need for monitoring a physical space or using sensors for controlling a procedure. For example:

- Industrial Control: Networked Control Systems – closing the industrial loop over WSN;
- Environmental Monitoring & Agriculture: Wild life monitoring, forest fire detection, weather forecast, planetary exploration;
- Health Care: Rehabilitation, prosthetics, chronic conditions management, emergency response;
- Smart Homes – Smart Cities: Energy consumption monitoring and optimization, transportation & traffic management, etc.

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Applications

The Golden Gate Bridge Case Study (Stanford Uni. – 2005)

Objectives:

- Determine the response of the structure to both ambient and extreme conditions;
- Compare actual performance to design predictions;
- Measure ambient structural accelerations from wind load;
- Measure strong shaking from a potential earthquake;
- The installation and the monitoring was conducted without the disruption of the bridge's operation;

WSN:

64 wireless sensor nodes
Synchronous monitoring of ambient vibrations
1 KHz rate, ≤10μs jitter, accuracy=30μg, over a 46-hop network

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Applications

Monitoring Parkinson's Disease (MIT – 2009)

- The aim is to augment or entirely replace a human observer and to help physicians fine-tune medication dosage;
- 12 individuals participated at the study, performing simple tasks;
- More than 80 days of continuous data collection @ 50Hz sampling rate

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Challenges

- **Scalability**
  - Huge number of sensor nodes
  - High densities of nodes
  - Many complex interactions
- **Success rate**: percentage of delivered data
  - How does protocol performance scale with size?
  - Even correctness may be affected by size.

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Challenges

Fault-tolerance

Sensors may :

- fail (temporarily or permanently)
- be blocked/removed
- Cease communication

- due to various reasons:
- Physical damage
- Power exhaustion
- Interference
- Power saving mechanisms

Can the network tolerate failures well?

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Challenges

- Efficiency
  - Energy spent
  - Time (for data propagation)
  - Inherent trade-offs between energy & time

- Competing goals/diverse aspects:
  - Minimizing total energy spent in the network
  - Maximizing the number of “alive” sensors over time
  - Combining energy efficiency and fault-tolerance
  - Balancing the energy dissipation

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Challenges

- Application dependence
- Dynamic changes/heterogeneity
- Variety of protocols needed/hybrid combinations
- Adaptive protocols, locality
- Simplicity, randomization, distributedness

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Data Propagation Protocols

- Directed Diffusion (DD): a tree-structure protocol (for low dynamics)
- LEACH: clustering (for small area networks)
- Local Target Protocol (LTP): local optimization (for dense networks)
- Probabilistic Forwarding Protocol (PFR): redundant optimized transmissions (good efficiency/fault-tolerance trade-offs, best for sparse networks)
- Energy Balanced Protocol (EBP): guaranteeing same per sensor energy (prolong network life-time)

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Directed Diffusion

- Requires some coordination between sensors
- Creates/maintains some global structure (set of paths)
- A paradigm/suite for several protocols
- here: a tree-based version

- Directed Diffusion elements:
- Interest messages (issued by the control center/base station)
- Gradients (toward the control center)
- Data messages (by the relevant sensors)
- Reinforcements of gradients (to select "best" paths)

Directed Diffusion

Interests

- An interest contains the description of a sensing task
- Task descriptions are named e.g., by a list of attribute-value pairs
- The description specifies an interest in data matching the attributes

```
type = wheeled vehicle        // detect vehicle location
interval = 10 ms              // send events every 10 ms
duration = 10 minutes         // for the next 10 minutes
rect = [-100, 100, 200, 400]  // from sensors within rectangle
```

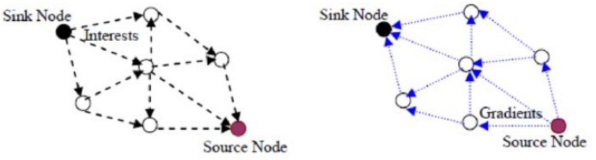
Example of an interest

- Interests are injected into the network at the control center

Directed Diffusion

Gradients

- For each interest message received, a gradient is created
- Gradients are formed by local interaction of neighboring nodes, establishing a gradient towards each other
- Gradients store a value (data rate) and a direction (towards the sink) for "pulling down" data



(a) Interests Propagation (b) Initial Gradients set up

Direct Diffusion

Data Propagation

- A sensor that receives an interest it can serve, begins sensing
- As soon as a matching event is detected, data messages are sent to the relevant neighbors using the gradient established
- A data cache is maintained at each sensor recording recent history

Direct Diffusion

Reinforcement for Path Establishment

- The sink initially repeatedly diffuses an interest for a low-rate event notification, through exploratory messages
- The gradients created by exploratory messages are called exploratory and have low data rate
- As soon as a matching event is detected, exploratory events are generated and routed back to the sink
- After the sink receives those exploratory events, it reinforces one (or more) particular neighbor in order to “draw down” real data
- The gradients that are set up for receiving high data rate information are called data gradients

Direct Diffusion

Path establishment through positive reinforcement

- To reinforce a neighbor, the sink resends the original interest message, with a higher rate
- Upon reception of this message, a node updates the corresponding gradient to match the requested data rate

- The selection of a neighbor for reinforcement is based on local criteria, i.e.:
- The neighbor that reported first a new event is reinforced
- The higher data rate neighbor is reinforced
- More than one neighbors are reinforced

The data cache is used to determine which criteria are fulfilled

Direct Diffusion

Negative Reinforcement

Negative reinforcement is applied when certain criteria are met i.e., a gradient does not deliver any new messages for a given amount of time, or a gradient has a very low data rate, etc.

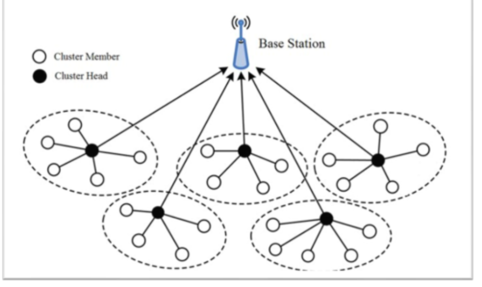
Direct Diffusion

Summary

- Improves over flooding a lot
- Significant energy savings
- Performance drops when network dynamics are high

LEACH

- The network is partitioned in clusters
- Each cluster has one cluster-head
- Each non-cluster-head sends data to the head of the cluster it belongs to
- Cluster-heads gather the sent data, compress it and send it to the sink directly



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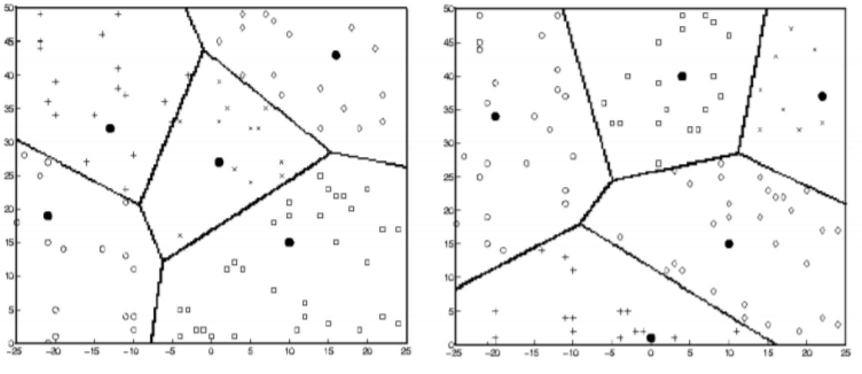
LEACH

Dynamic Clusters



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LEACH

Randomized rotation of cluster-heads

- Node n decides with probability T(n) to elect itself cluster-head
  - P: the desired percentage of cluster heads
  - r: the current round
  - G: the set of nodes that have not been cluster-heads in the last 1/P rounds
- T(n) is chosen to get on the average the same number of cluster-heads in each round

$$T(n) = \begin{cases} \frac{P}{1-P*(r \bmod \frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases}$$

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LEACH

Cluster-head advertisement

- Each cluster-head broadcasts an advertisement message to the rest nodes using a CSMA-MAC protocol
- Non cluster-heads nodes hear the advertisements of all cluster-head nodes
- Each non cluster-head node decides its cluster-head by choosing the one that has the strongest signal

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LEACH

Cluster set-up phase

- Each cluster-head is informed for the members of its cluster
- The cluster-head creates a TDMA schedule
- The cluster-head broadcasts the schedule back to the cluster members

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LEACH

Steady Phase

- Non cluster-heads
  - Sense the environment
  - Send their data to the cluster head during their transmission time
- Cluster-heads
  - Receive data from non cluster-head nodes
  - Compress the data received
  - Send their data directly to the base station

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LEACH

Summary

- Reduces energy dissipation through compression of data at cluster-heads
- In large networks, direct transmissions are very expensive
- Performance drops when the network traffic is high (e.g. many events generated)

References

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