Chapter 5

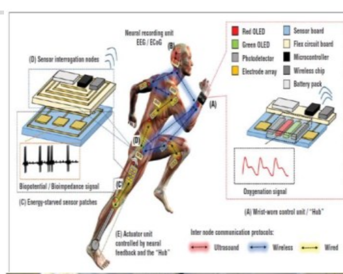
SENSOR
And
WIRELESS SENSOR NETWORK

Introduction

- Wireless Sensor Networks combine sensing, processing and networking over miniaturized embedded devices → **sensor nodes**
- Key Features that differentiate them from conventional data networks
  - Power autonomous (operating mainly on batteries)
  - Highly scalable: distributed in scales of hundreds (or thousands)
  - Operate in a **ad-hoc** manner, i.e., does not require fixed infrastructure (e.g. GSM or WiFi routers)
  - Easy to deploy
  - Cost-effective (cheap hardware)
  - Low data rates (max 1Mbps)

- Key characteristic that distinguishes them from remaining networks is the **reasoning of existence:**
  - Collect information from the physical environment – regardless of how easily 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)

- Application Areas: **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, Vineyards, Forest Fire Detection
  - Structural Health Monitoring
  - Marine monitoring: Ocean life & ecosystem
  - Health Care: rehabilitation, prosthetics, chronic conditions management, emergency response

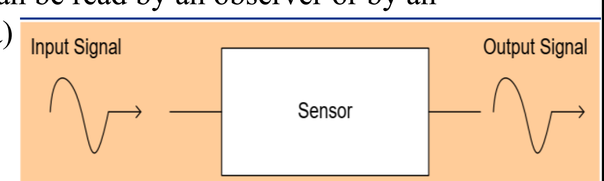


Sensing and Sensors

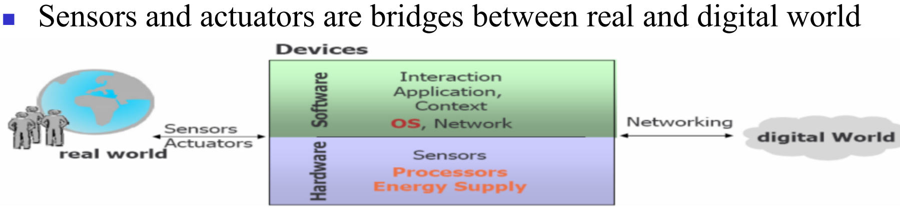
- Sensing: technique to gather information about physical objects or areas
- Sensor (transducer): object performing a sensing task; converting one form of energy in the physical world into electrical energy
- Examples of sensors from biology: the human body
  - eyes: capture optical information (light)
  - ears: capture acoustic information (sound)
  - nose: captures olfactory information (smell)
  - skin: captures tactile information (shape, texture)

Sensor and Actuator

- A **sensor** is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument. (Wikipedia)

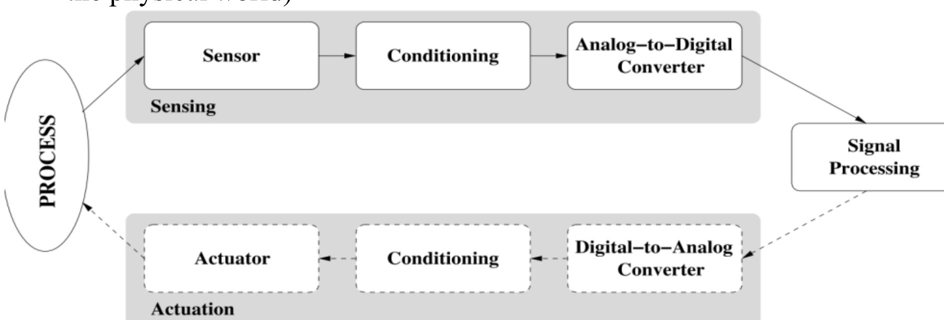


- An **actuator** is a device for moving/controlling a mechanism/system, or generate some output, e.g., motor, LED, buzzer, speaker, etc.
- Sensors and actuators are bridges between real and digital world

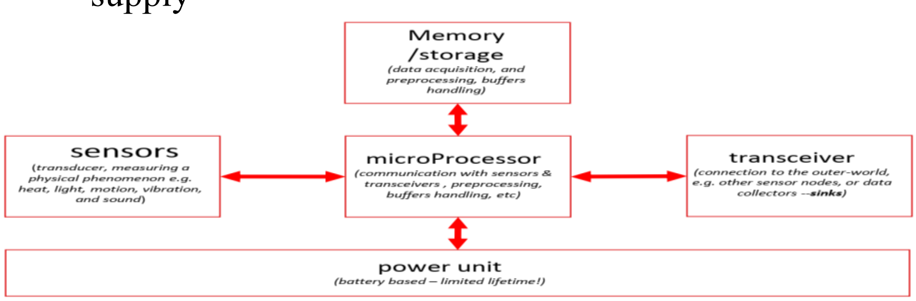


Sensing (Data Acquisition)

- Sensors capture phenomena in the physical world (process, system, plant)
- Signal conditioning prepare captured signals for further use (amplification,attenuation, filtering of unwanted frequencies, etc.)
- Analog-to-digital conversion (ADC) translates analog signal into digital signal
- Digital signal is processed and output is often given (via digital-analog converter and signal conditioner) to an actuator (device able to control the physical world)

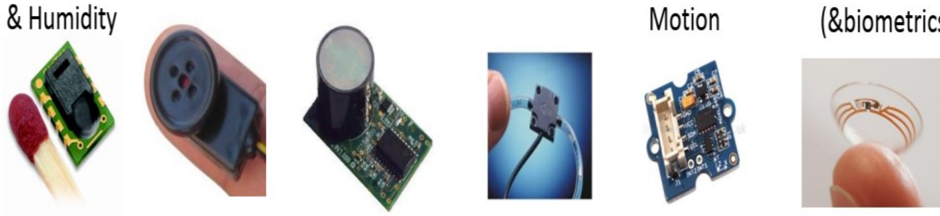


- Sensor Node
  - Basic unit in sensor network
  - Contains on-board sensors, processor, memory, transceiver, and power supply

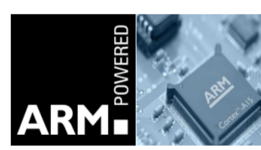


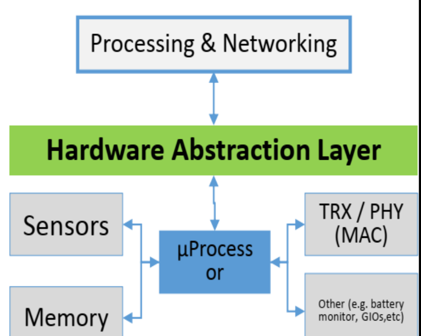
- Sensing Elements
  - Sensors: capture a signal corresponding to a physical phenomenon (process, system, plant)
  - Signal conditioning prepare captured signals for further use (amplification, attenuation, filtering of unwanted frequencies, etc.)
  - Analog-to-digital conversion (ADC) translates analog signal into digital signal
  - **Model to translate raw value to measurable unit**

Temperature & Humidity | Image | Sound | Pressure | Vibration, Motion | Glucose (&biometrics

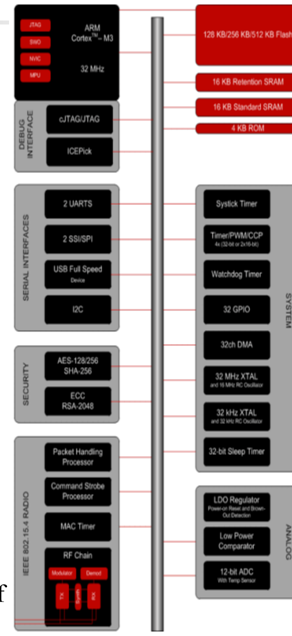


- Processing Elements
- Traditionally: 16-bit archs
  - Moving towards higher computational capacity (32 bit – ARM technologies)
  - When programming a sensor node → programming its μProcessor to:
  - access the peripheral devices (transceiver, leds, sensors etc)
  - handle, store, modify the acquired information
  - Direct programming on the microprocessor (low level C / Assembly) OR using **Real-time Operating Systems**

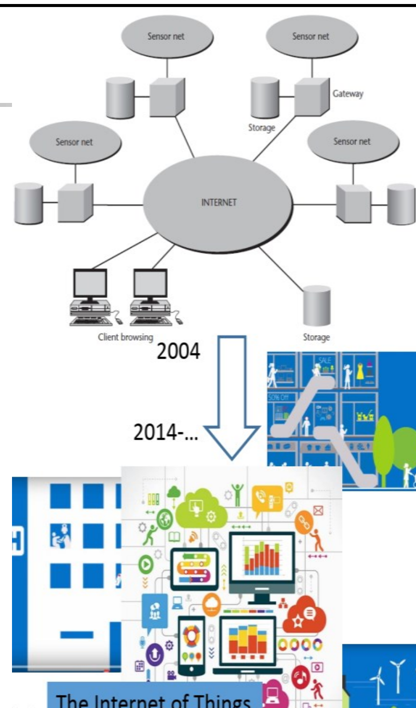




- Transceivers
  - Conventional: low-level PHY functionalities: frequency and channels, spectrum handling, modulation, bit rate. Advanced network functionalities and processing are implemented on software (i.e. microprocessor)
  - Current Trend: System-on-Chip -> allows implementation of a sophisticated 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

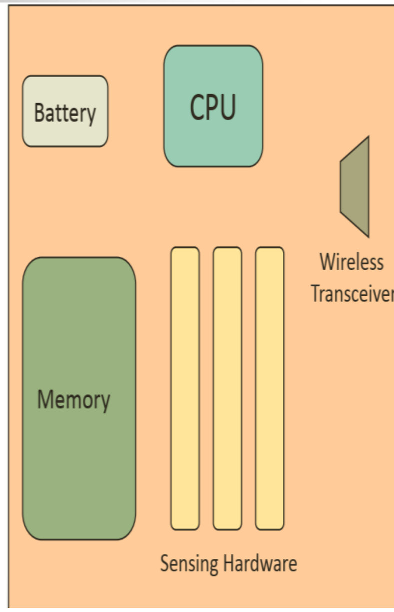


- Interaction with the outer world
  - Gateway: routes user queries or commands to appropriate nodes in a sensor network and sensor data, at times aggregated and summarized, to users who have requested it or are expected to utilize the information.
  - Data repository/storage service:persistent data storage.
  - *Data analytics & Provision of services*



Sensors

- Enabled by recent advances in MEMS technology
- Integrated Wireless Transceiver
  - Limited in
  - Energy
  - Computation
  - Storage
  - Transmission range
  - Bandwidth



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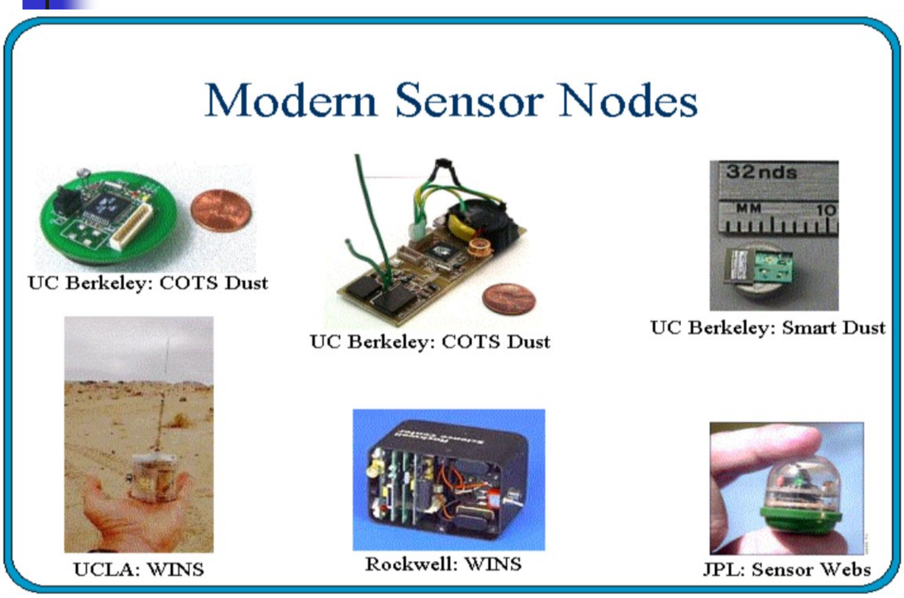
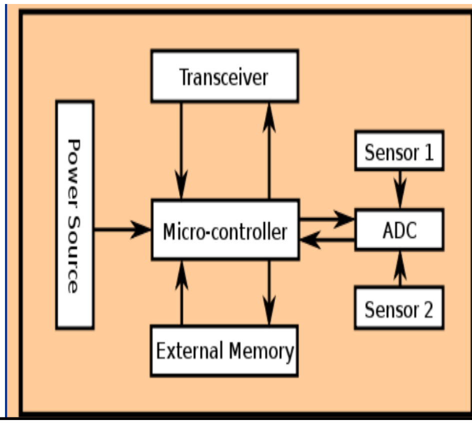


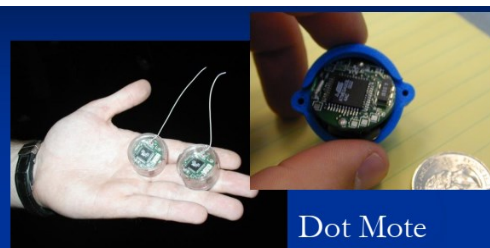
Sensor Nodes

- A sensor node, also called a mote in North America, is a WSN node that is capable of performing some processing, gathering sensory information and communicating with other connected nodes in the WSN



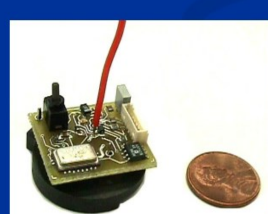
Examples for Wireless Sensor Nodes

Rene Mote

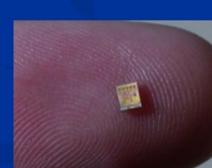


Dot Mote

MICA Mote



weC Mote



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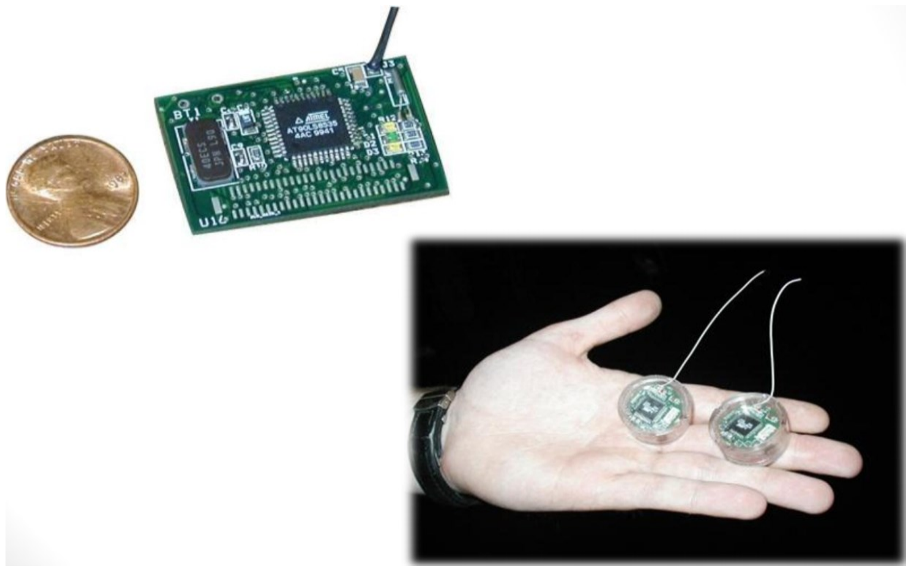


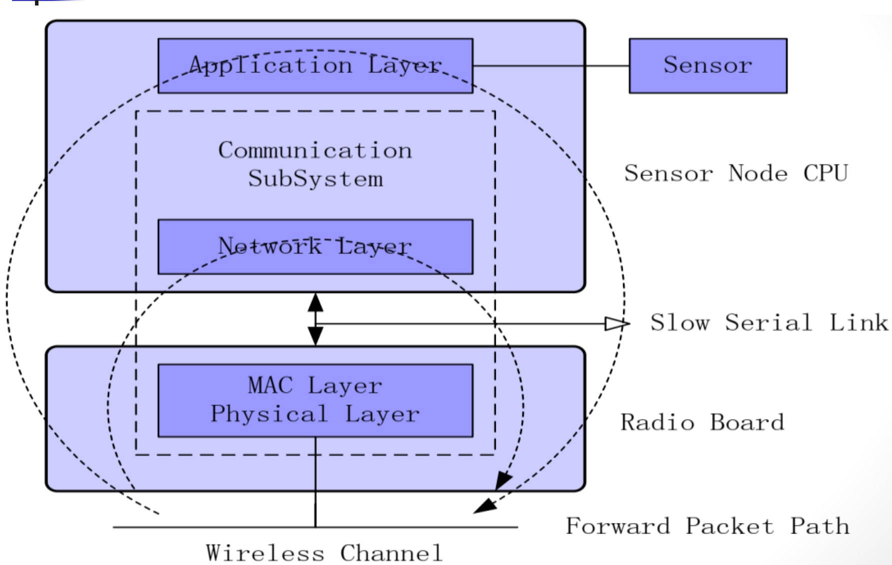
General Features of Sensor Node

- Small Size : few mm to a few inches
- Limited processing and communication
  - MHz clock, MB flash, KB RAM, 100's Kbps (wireless) bandwidth
- Limited power (MICA: 7-10 days at full blast)
- Failure prone nodes and links (due to deployment, fab,wireless medium, etc.)
- But easy to manufacture and deploy in large numbers
- *Need to offset this with scalable and fault-tolerant OS's and protocols*

Sensors (contd.)

- The overall architecture of a sensor node consists of:
  - The sensor node processing subsystem running on sensor node main CPU
  - The sensor subsystem and
  - The communication subsystem
- The processor and radio board includes:
  - TI MSP430 microcontroller with 10kB RAM
  - 16-bit RISC with 48K Program Flash
  - IEEE 802.15.4 compliant radio at 250 Mbps
  - 1MB external data flash
  - Runs TinyOS 1.1.10 or higher
  - Two AA batteries or USB
  - 1.8 mA (active); 5.1uA (sleep)

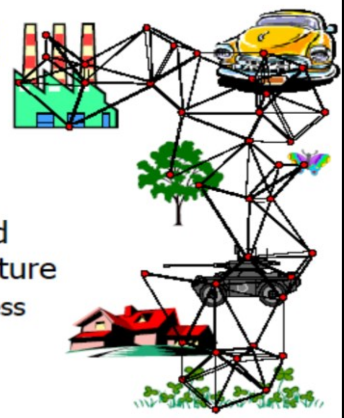
Overall Architecture of a Sensor Node



Sensor Networks

- A **sensor network** (**SN**) is consisted of multiple interconnected sensors.
- A **wireless sensor network** (**WSN**) consists of spatially distributed autonomous sensors (called sensor nodes) to cooperatively monitor physical or environmental conditions → Sensors + Wireless Networks

- Embed numerous distributed devices to monitor the physical world
- Network these devices so that they can coordinate to perform higher-level tasks
- Combine sensing, communication and computation into a complete architecture
  - possible by advances in low power wireless communication technology
  - MEMS bringing rich array of cheap, tiny sensors



Wireless Sensor Networks

- A distributed connection of nodes that coordinate to perform a common task.
- In many applications, the nodes are battery powered and it is often very difficult to recharge or change the batteries.
- Prolonging network lifetime is a critical issue.
- Sensors often have long period between transmissions (e.g., in seconds).
- Thus, a good WSN MAC protocol needs to be energy efficient.

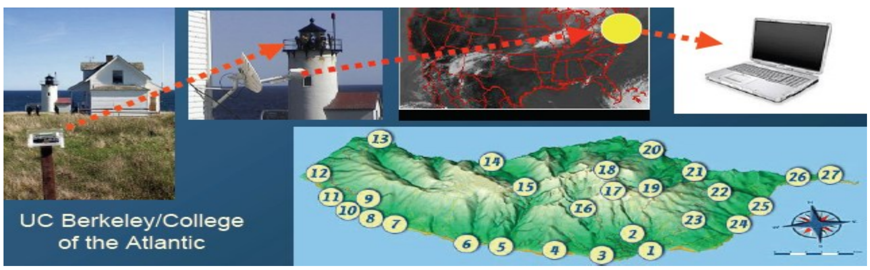
WSN Applications

- Environmental/ Habitat Monitoring
  - Scientific, ecological applications
    - Non-intrusiveness
    - Real-time, high spatial-temporal resolution
    - Remote, hard-to-access areas
  - Acoustic detection
  - Seismic detection
- Surveillance and Tracking
  - Military and disaster applications
  - Reconnaissance and Perimeter control
  - Structural monitoring (e.g., bridges)

- "Smart" Environments
  - Precision Agriculture
  - Manufacturing/Industrial processes
    - Inventory (RFID)
    - Process Control
  - Smart Grid
- Medical Applications
  - Hospital/Clinic settings
  - Retirement/Assisted Living settings

Environment Monitoring

- Great Duck Island
- 150 sensing nodes deployed throughout the island relay data temperature, pressure, and humidity to a central device.
- Data was made available on the Internet through a satellite link.



Wireless Sensor Networks

- Another attribute is scalability and adaptability to change in network size, node density and topology.
  - In general, nodes can die, join later or be mobile.
- Often high bandwidth is not important.
- Nodes can take advantage of short-range, multi-hop communication to conserve energy.

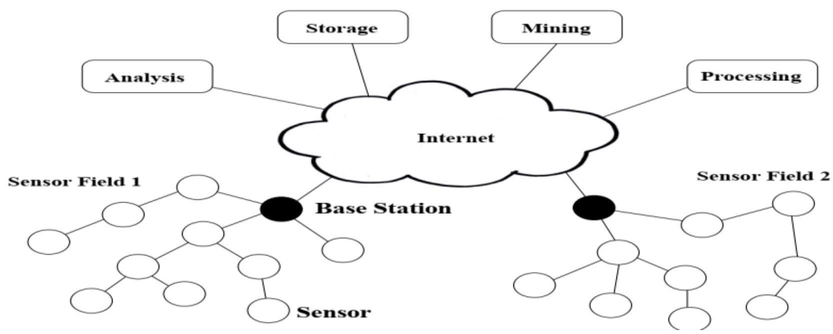
- Sources of energy waste:
  - Idle listening, collisions, overhearing and control overhead and overmitting.
  - Idle listening dominates (measurements show idle listening consumes between 50-100% of the energy required for receiving.)
- Idle listening:: listen to receive possible traffic that is not sent.
- Overmitting:: transmission of message when receiver is not ready.

WSN Communication Patterns

- Broadcast:: e.g., Base station transmits to all sensor nodes in WSN.
- Multicast:: sensor transmit to a subset of sensors (e.g. cluster head to cluster nodes)
- Convergecast:: when a group of sensors communicate to one sensor (BS, cluster head, or data fusion center).
- Local Gossip:: sensor sends message to neighbor sensors.

Wireless Sensor Network (WSN)

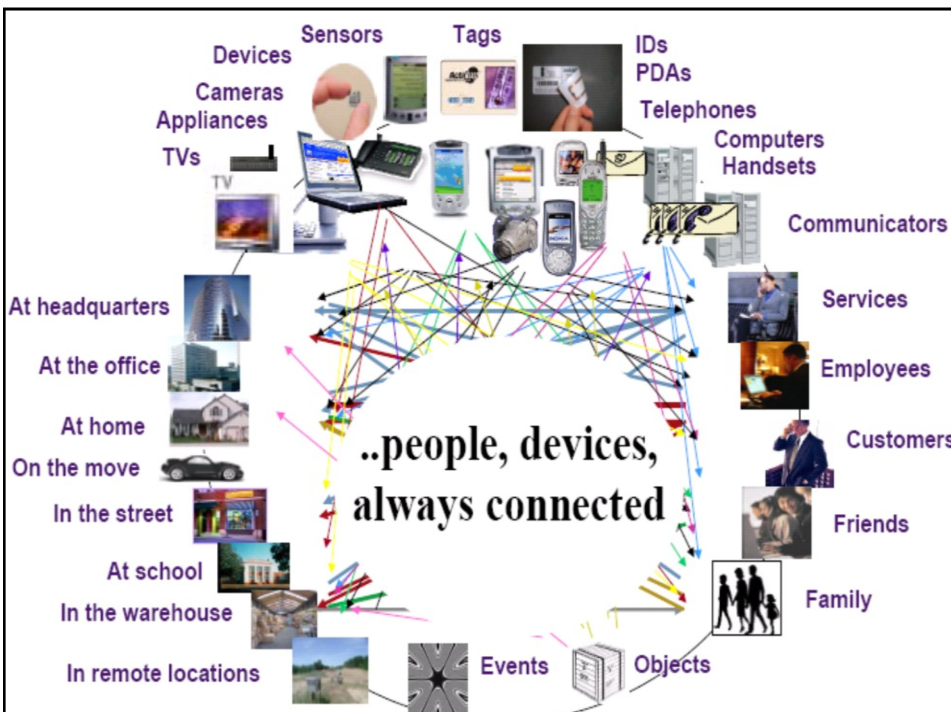
- Multiple sensors (often hundreds or thousands) form a network to cooperatively monitor large or complex physical environments
- Acquired information is wirelessly communicated to a base station (BS), which propagates the information to remote devices for
storage, analysis, and processing

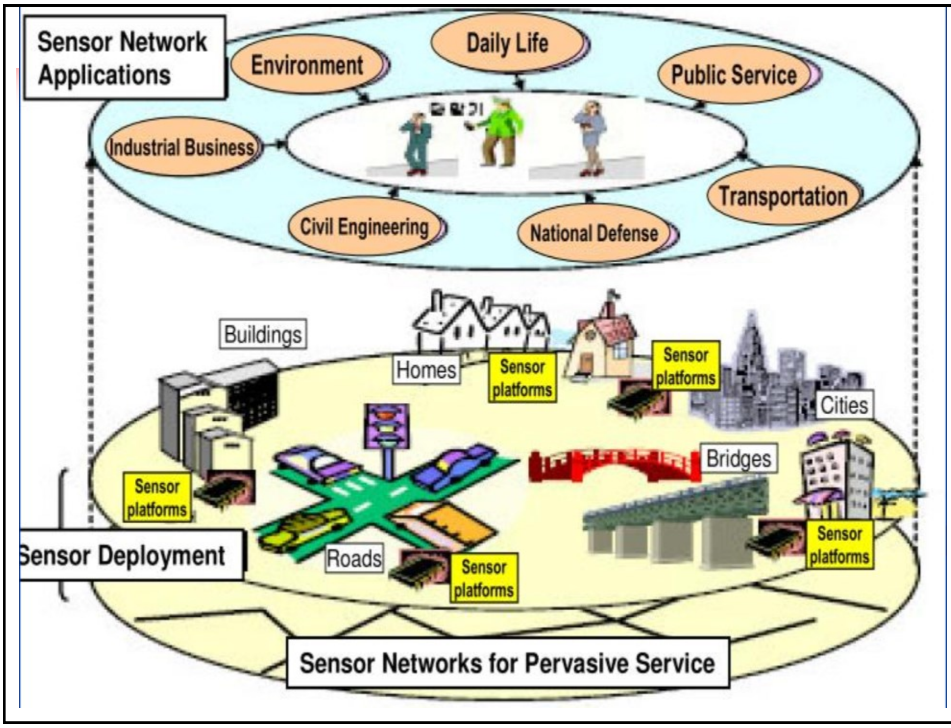


Networked vs. Individual Sensors

- Extended range of sensing:
  - Cover a wider area of operation
- Redundancy:
  - Multiple nodes close to each other increase fault tolerance
- Improved accuracy:
  - Sensor nodes collaborate and combine their data to increase the accuracy of sensed data
- Extended functionality:
  - Sensor nodes can not only perform sensing functionality, but also provide forwarding service.

- Wireless sensor networks (WSN) are nowadays being deployed in a large number of application domains
  - military environments and perimeter sensing weather and ambient control
  - industrial applications
  - power grids
  - health care
  - Security – Harvesting – Cognitive Network



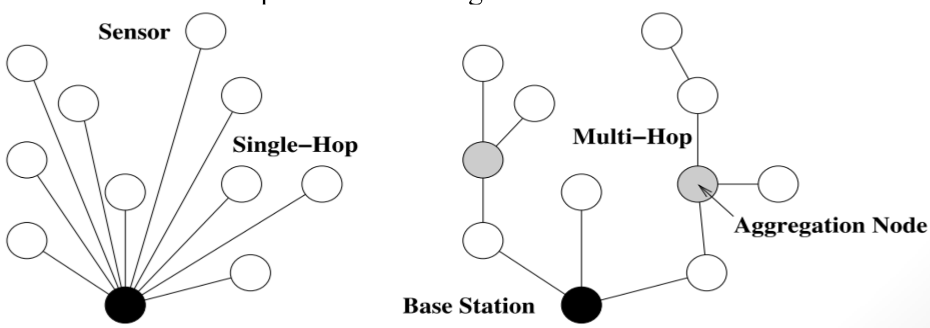


WSN Communication

- Characteristics of typical WSN:
  - Low data rates (comparable to dial-up modems)
  - Energy-constrained sensors
- IEEE 802.11 family of standards
  - Most widely used WLAN protocols for wireless communications in general
  - Can be found in early sensor networks or sensors networks without stringent energy constraints
- IEEE 802.15.4 is an example for a protocol that has been designed specifically for short-range communications in WSNs
  - Low data rates
  - Low power consumption
  - Widely used in academic and commercial WSN solutions

Single-Hop vs. Multi-Hop

- Star topology
  - Every sensor communicates directly (single-hop) with the base station
  - May require large transmit powers and may be infeasible in large geographic areas
- Mesh topology
  - Sensors serve as relays (forwarders) for other sensor nodes (multihop)
  - May reduce power consumption and allows for larger coverage
  - Introduces the problem of routing



Challenges in WSNs: Energy

- Sensors typically powered through batteries
  - replace battery when depleted
  - recharge battery, e.g., using solar power
  - discard sensor node when battery depleted
- For batteries that cannot be recharged, sensor node should be able to operate during its entire mission time or until battery can be replaced
- Energy efficiency is affected by various aspects of sensor node/network design
- Physical layer:
  - switching and leakage energy of CMOS-based processors

$$E_{CPU} = E_{switch} + E_{leakage} = C_{total} * V_{dd}^{2} + V_{dd} * I_{leak} * \Delta t$$

Challenges in WSNs: Energy

- Medium access control layer:
  - contention-based strategies lead to energy-costly collisions
  - problem of idle listening
- Network layer:
  - responsible for finding energy-efficient routes
- Operating system:
  - small memory footprint and efficient task switching
- Security:
  - fast and simple algorithms for encryption, authentication, etc.
- Middleware:
  - in-network processing of sensor data can eliminate redundant data or aggregate sensor readings

Challenges in WSNs: Self-Management

- Ad-hoc deployment
  - many sensor networks are deployed “without design”
    - sensors dropped from airplanes (battlefield assessment)
    - sensors placed wherever currently needed (tracking patients in disaster zone)
    - moving sensors (robot teams exploring unknown terrain)
  - sensor node must have some or all of the following abilities
    - determine its location
    - determine identity of neighboring nodes
    - configure node parameters
    - discover route(s) to base station
    - initiate sensing responsibility

Challenges in WSNs: Self-Management

- Unattended operation
  - Once deployed, WSN must operate without human intervention
  - Device adapts to changes in topology, density, and traffic load
  - Device adapts in response to failures
- Other terminology
  - Self-organization is the ability to adapt configuration parameters based on system and environmental state
  - Self-optimization is the ability to monitor and optimize the use of the limited system resources
  - Self-protection is the ability recognize and protect from intrusions and attacks
  - Self-healing is the ability to discover, identify, and react to network disruptions

Challenges in WSNs: Wireless Networks

- Wireless communication faces a variety of challenges
- Attenuation:
  - limits radio range

$$P_r \propto \frac{P_t}{d^2}$$

- Multi-hop communication:
  - increased latency
  - increased failure/error probability
  - complicated by use of duty cycles

Challenges in WSNs: Decentralization

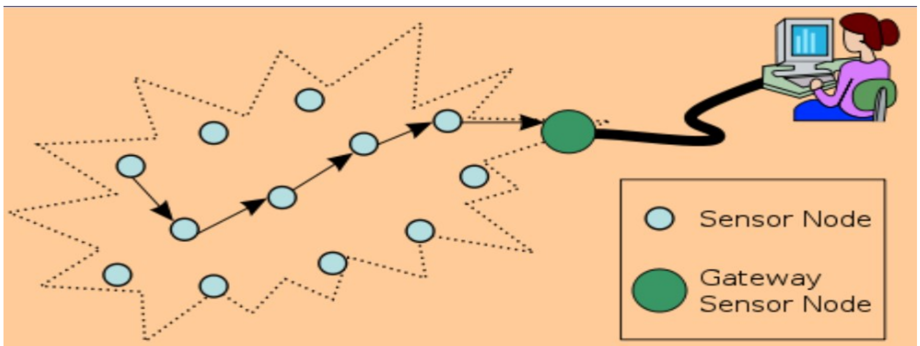
- Centralized management (e.g., at the base station) of the network often not feasible to due large scale of network and energy constraints
- Therefore, decentralized (or distributed) solutions often preferred, though they may perform worse than their centralized counterparts
- Example: routing
- Centralized:
  - BS collects information from all sensor nodes
  - BS establishes "optimal" routes (e.g., in terms of energy)
  - BS informs all sensor nodes of routes
  - Can be expensive, especially when the topology changes frequently
- Decentralized:
  - Each sensors makes routing decisions based on limited local information
  - Routes may be nonoptimal, but route establishment/management can be much cheaper

WSN Characteristics

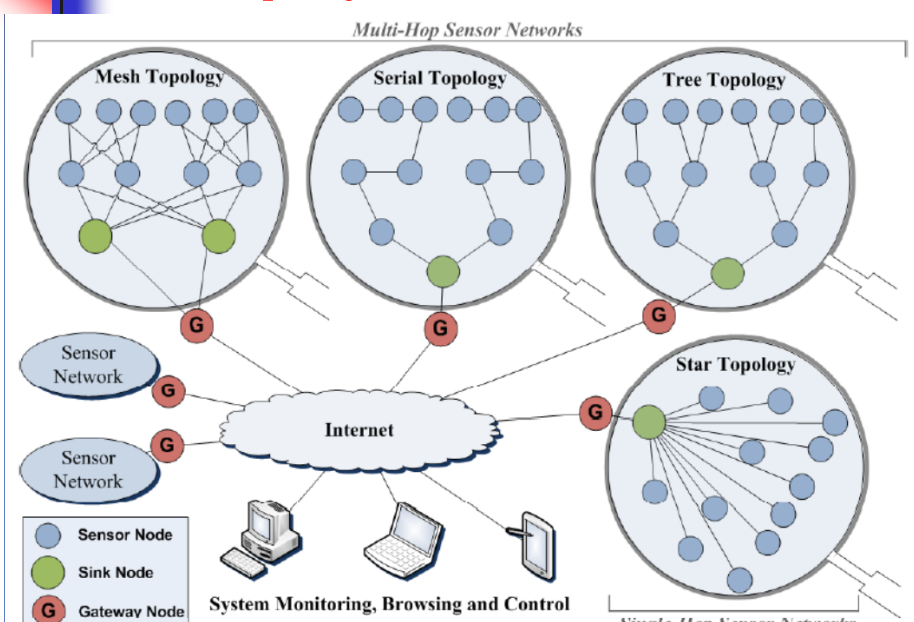
- Limited power they can harvest or store
- Ability to withstand harsh environmental conditions
- Ability to cope with node failures
- Mobility of nodes
- Dynamic network topology
- Communication failures
- Heterogeneity of nodes
- Large scale of deployment
- Unattended operation
- Nodes are scalable, only limited by bandwidth of gateway node

Typical Multiple WSN Architecture

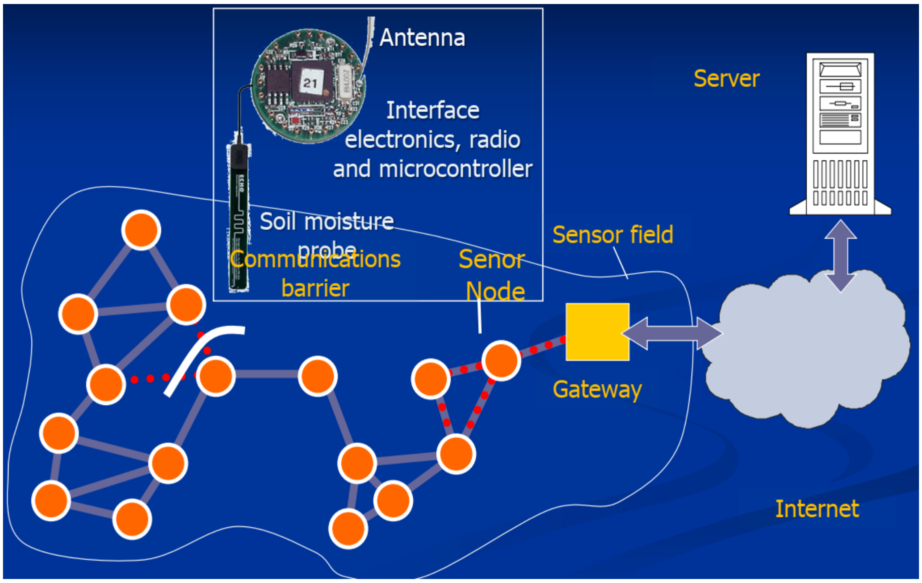
- A sensor network normally constitutes a wireless ad-hoc network, and each sensor supports a multi-hop routing algorithm where nodes function as forwarders, relaying data packets to a base station.



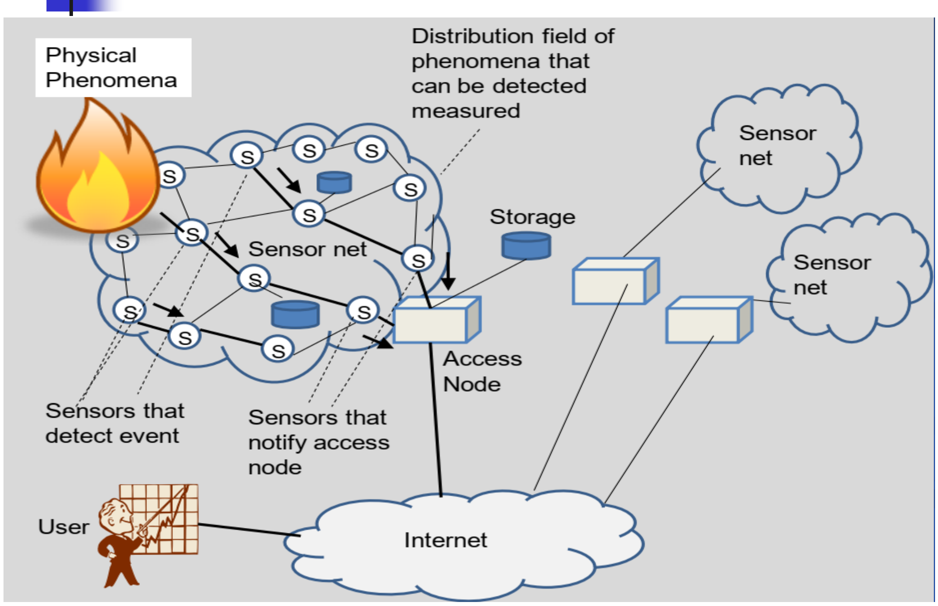
WSN Topologies



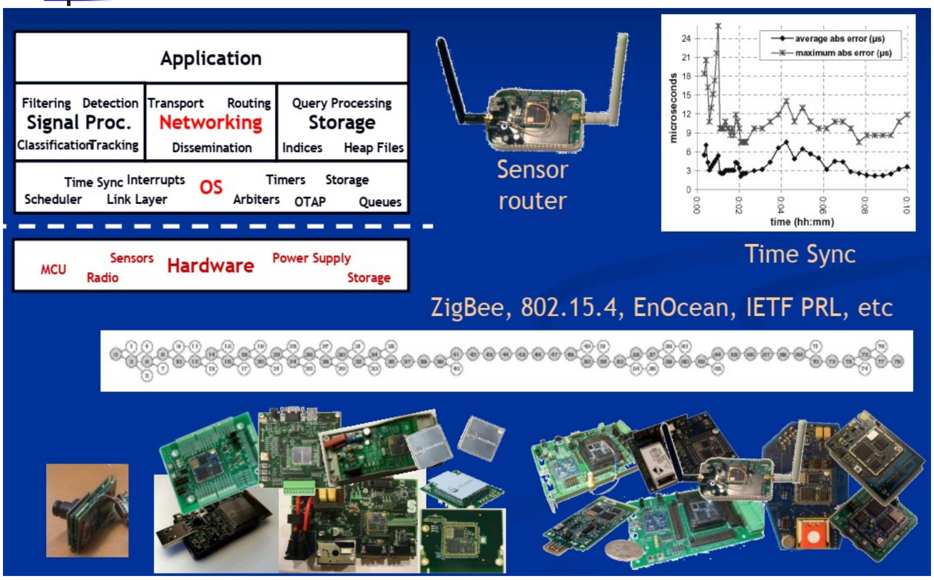
Sensor Network System



Multiple Sensor Networks System



WSN System Platforms



Wireless Sensor Network Standards IEEE 802.15.4 & ZigBee

Application	Customer
API	ZigBee Alliance
Security 32- / 64- / 128-bit encryption	ZigBee Alliance
Network Star / Mesh / Cluster-Tree	ZigBee Alliance
MAC	IEEE 802.15.4
PHY 868MHz / 915MHz / 2.4GHz	IEEE 802.15.4

ZigBee Alliance

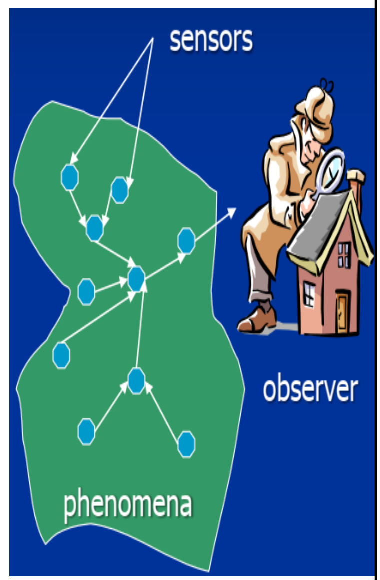
- "the software"
- Network, Security & Application layers
- Brand management

IEEE 802.15.4

- "the hardware"
- Physical & Media Access Control layers

Sensor Data Management

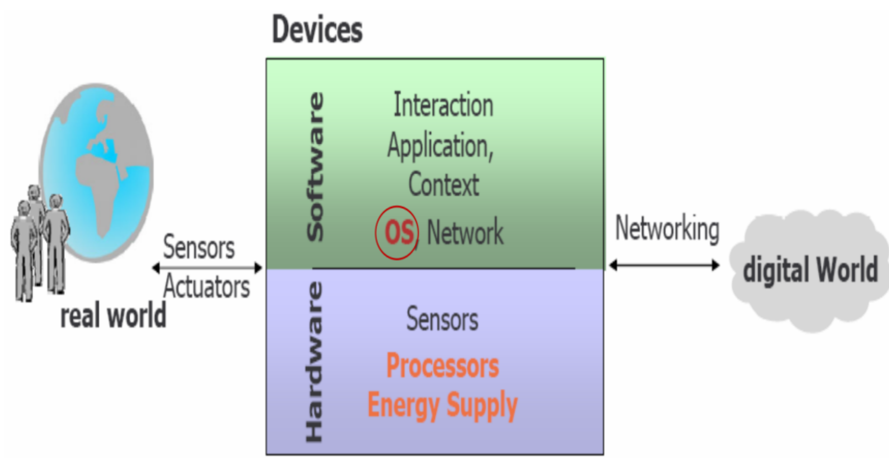
- Observer interested in phenomena with certain tolerance
  - Accuracy, freshness, delay
- Sensors sample the phenomena
- Sensor Data Management
  - Determining spatio-temporal sampling schedule
  - Difficult to determine locally
- Data aggregation
  - Interaction with routing
- Network/Resource limitations
  - Congestion management
  - Load balancing
  - QoS/Realtime scheduling



Definition: Autonomous Systems

- An Autonomous System (AS) is a collection of routers whose prefixes and routing policies are under common administrative control. This could be a network service provider, a large company, a university, a division of a company, or a group of companies

- Sensors and actuators are Bridges Between Real and Digital Worlds



Sensor networks

- A sensor network (SN) consists of multiple interconnected sensors or *motes*
- Combine sensing, communication and computation into a complete architecture
  - Possible by advances in low power wireless communication technology
  - MEMS brings a rich array of cheap, tiny sensors
-

Sensor nodes

- Processor in various modes (sleep, idle, active)
- Power source (AA or Coin batteries, Solar Panels)
- Memory used for the program code and for inmemory buffering
- Radio used for transmitting the acquired data to some storage site
- Sensors for temperature, humidity, light, etc

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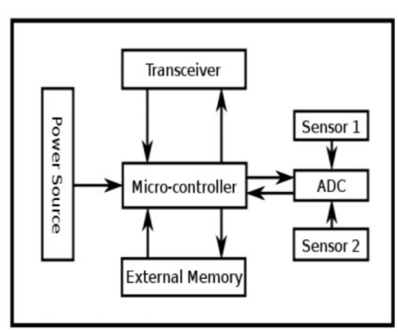


Wireless sensor networks

- A self-configuring network of small sensor nodes communicating among themselves using radio signals, and deployed in quantity to sense, monitor and understand the physical world.
  - Coordinate to perform a common task.
- Prolonging network lifetime is a critical issue.
- Sensors often have long period between transmissions (e.g., in seconds).

Wireless communication

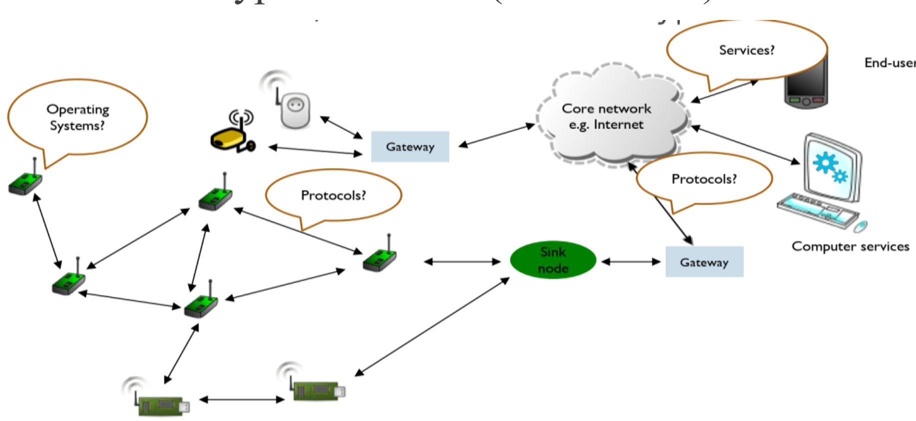
- The two wireless standards used by WSN are *802.15.4* and *Zigbee*
  - They are low-power protocols
  - Performance is an issue
  - Max distance is around 100 m

Wireless sensor networks

- Another attribute is scalability and adaptability to change in network size, node density and topology.
- In general, nodes can die, join later or be mobile.
- Often high bandwidth is not important.
- Nodes can take advantage of short-range, multi-hop communication to conserve energy

Wireless sensor (and actuator) Networks

- The networks typically run *Low Power Devices*
- Consist of one or more sensors, could be different type of sensors (or actuators)



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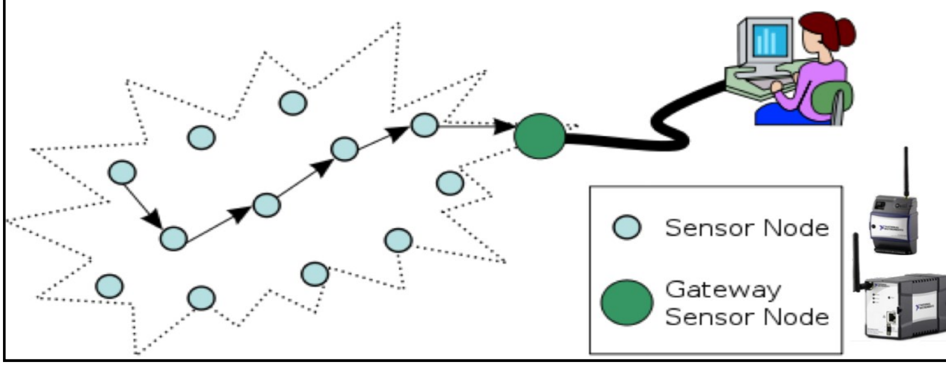
- Large scale of deployment
- Unattended operation
- Nodes are scalable, only limited by bandwidth of gateway node

Typical WSN Architecture

- A sensor network normally constitutes a wireless ad-hoc network, and each sensor supports a multi-hop routing algorithm where nodes function as forwarders, relaying data packets to a base station



WSN Communication Patterns

- Broadcast
  - Base station transmits to all sensor nodes in WSN.
- Multicast
  - Sensor transmit to a subset of sensors (e.g. cluster head to cluster nodes)
- ConvergeCast
  - Data is collected from outlying nodes through a direct spanning tree to the root (BS, cluster head, or data fusion center).
- Local Gossip
  - Sensor sends message to neighbor sensors.

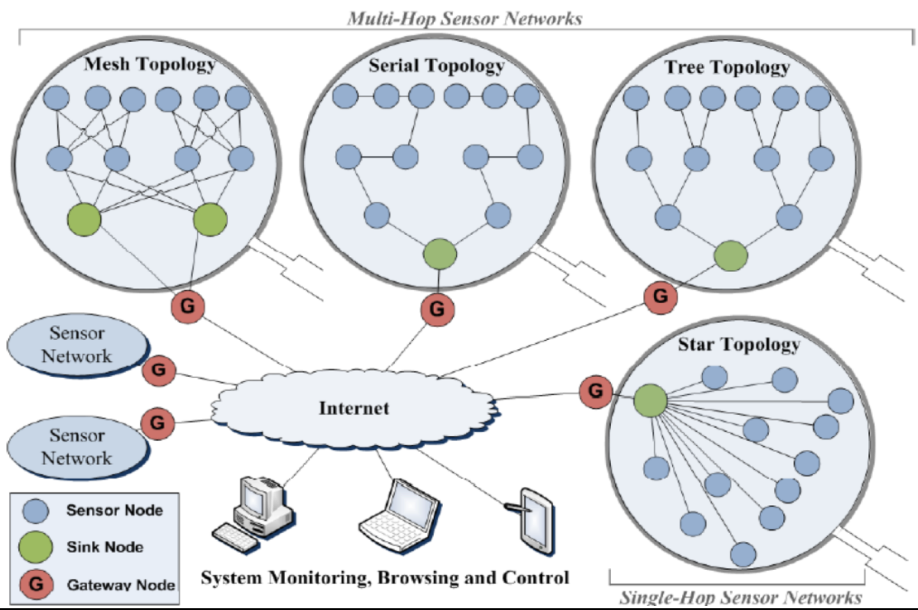
Wireless sensor networks

- Central approach:
  - Lower the duty cycle by turning the radio off part of the time.
  - Duty cycle is the ratio between listen time and the full listen sleep cycle
- Three techniques to reduce the duty cycle:
  - TDMA
  - Scheduled contention periods
  - LPL (Low Power Listening)

Techniques to Reduce Idle Listening

- TDMA requires cluster-based or centralized control.
- Scheduling – ensures short listen period when transmitters and listeners can rendezvous and other periods where nodes sleep (turn off their radios).
- LPL – nodes wake up briefly to check for channel activity without receiving data.
  - If channel is idle, node goes back to sleep.
  - If channel is busy, node stays awake to receive data.
  - A long preamble (longer than poll period) is used to assure than preamble intersects with polls.

WSN Topologies



General Features of Sensor Node

- Small Size
  - From few mms to few inches
- Limited processing and communication
  - Mhz clock, MB flash, KB RAM, 100's Kbps bandwidth (wireless)
- Limited power
  - MICA: 7-10 days at full blast
- Failure prone nodes and links
  - Due to deployment, fabrication, wireless medium, …
- Easy to manufacture
- Needs to offset this with scalable and fault-tolerant OS'es and protocols

Power aware MAC Protocols

- Three approaches to saving power:
  - TDMA: TRAMA, EMACs, L-MAC
  - Schedule: PAMAS, S-MAC, T-MAC, D-MAC, PMAC, SCP MAC, Crankshaft, AS-MAC
  - Low Power Listening: LPL, B-MAC, WiseMAC, X-MAC
    - Newest approaches include
  - Receiver Initiated: RI-MAC, A-MAC, LPP

Sensor-MAC (S-MAC)

- All nodes periodically listen, sleep and wakeup. Nodes listen and send during the active period and turn off their radios during the sleep period.
- The beginning of the active period is a SYNC period used to accomplish periodic synchronization and remedy clock drift {nodes broadcast SYNC frames}.
- Following the SYNC period, data may be transferred for the remainder of the fixed-length active period using RTS/CTS for unicast transmissions.

Sensor MAC (S-MAC)

- Long frames are fragmented and transmitted as a burst.
- SMAC controls the duty cycle by trading off energy for delay.
- However, as density of WSN grows, SMAC incurs additional overhead in maintaining neighbors' schedules
-

Required Mechanism

- Multi-hop wireless communications
  - Communication over long distances can require intermediary nodes as relay (instead of using high transmission power for long range communications).
- Energy-efficient operation
  - To support long lifetime
  - Energy efficient communication/dissemination of information
  - Energy efficient determination of a requested information
- Auto-configuration
  - Self-xxx functionalities
  - Tolerating node failures
  - Integrating new nodes

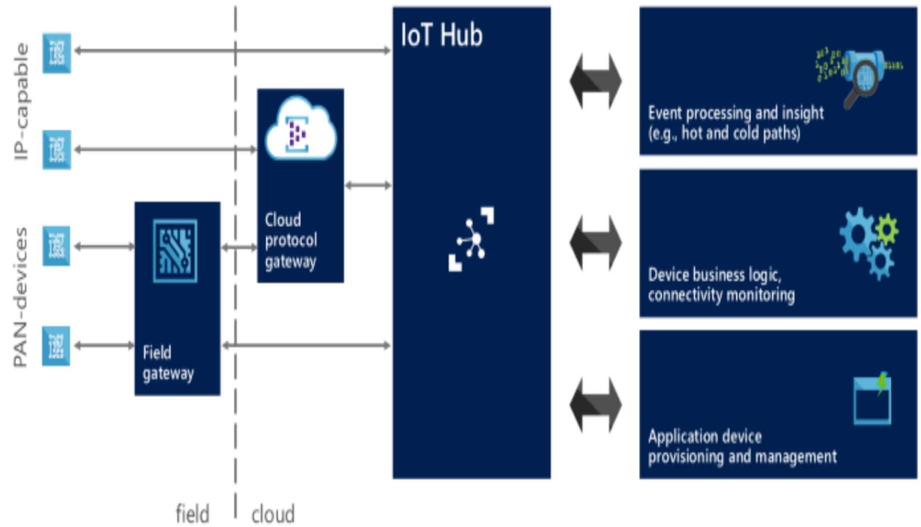
Required Mechanisms

- Collaboration and in-network processing
  - In some applications a single sensor node is not able to handle the given task or provide the requested information.
  - Instead of sending the information form various source to an external network/node, the information can be processed in the network itself.
  - e.g. data aggregation, summarisation and then propagating the processed data with reduced size (hence improving energy efficiency by reducing the amount of data to be transmitted).
- Data-centric
  - Conventional networks often focus on sending data between two specific nodes each equipped with an address.
  - Here what is important is data and the observations and measurements not the node that provides it

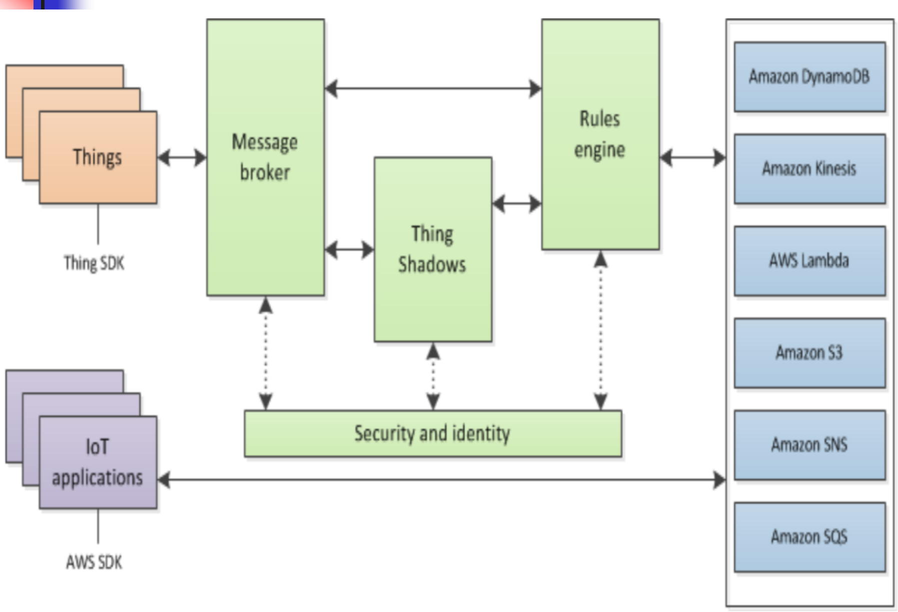
IoT Cloud Solutions

- IoT Hub from Microsoft
- AWS IoT
- PubNub
- Initial State
- SmartThings, Thingsee

IoT Hub



AWS IoT Data Services



WSN Applications

- Environmental/ Habitat Monitoring
  - Scientific, ecological applications
    - Non-intrusiveness
    - Real-time, high spatial-temporal resolution
    - Remote, hard-to-access areas
  - Acoustic detection
  - Seismic detection
- Surveillance and Tracking
  - Military and disaster applications
  - Reconnaissance and Perimeter control
  - Structural monitoring (e.g., bridges)

- "Smart" Environments
  - Precision Agriculture
  - Manufacturing/Industrial processes
    - Inventory (RFID)
    - Process Control
  - Smart Grid
- Medical Applications
  - Hospital/Clinic settings
  - Retirement/Assisted Living settings