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BEIJING UNIVERSITY OF POSTS AND TELECOMMUNICATIONS

Wireless Sensor Networks

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Content

- Introduction to Wireless Sensor networks (WSNs)
- Medium Access Control (MAC)
- Routing Protocols
- Deployment and Management
- In-network processing
- QoS and Security

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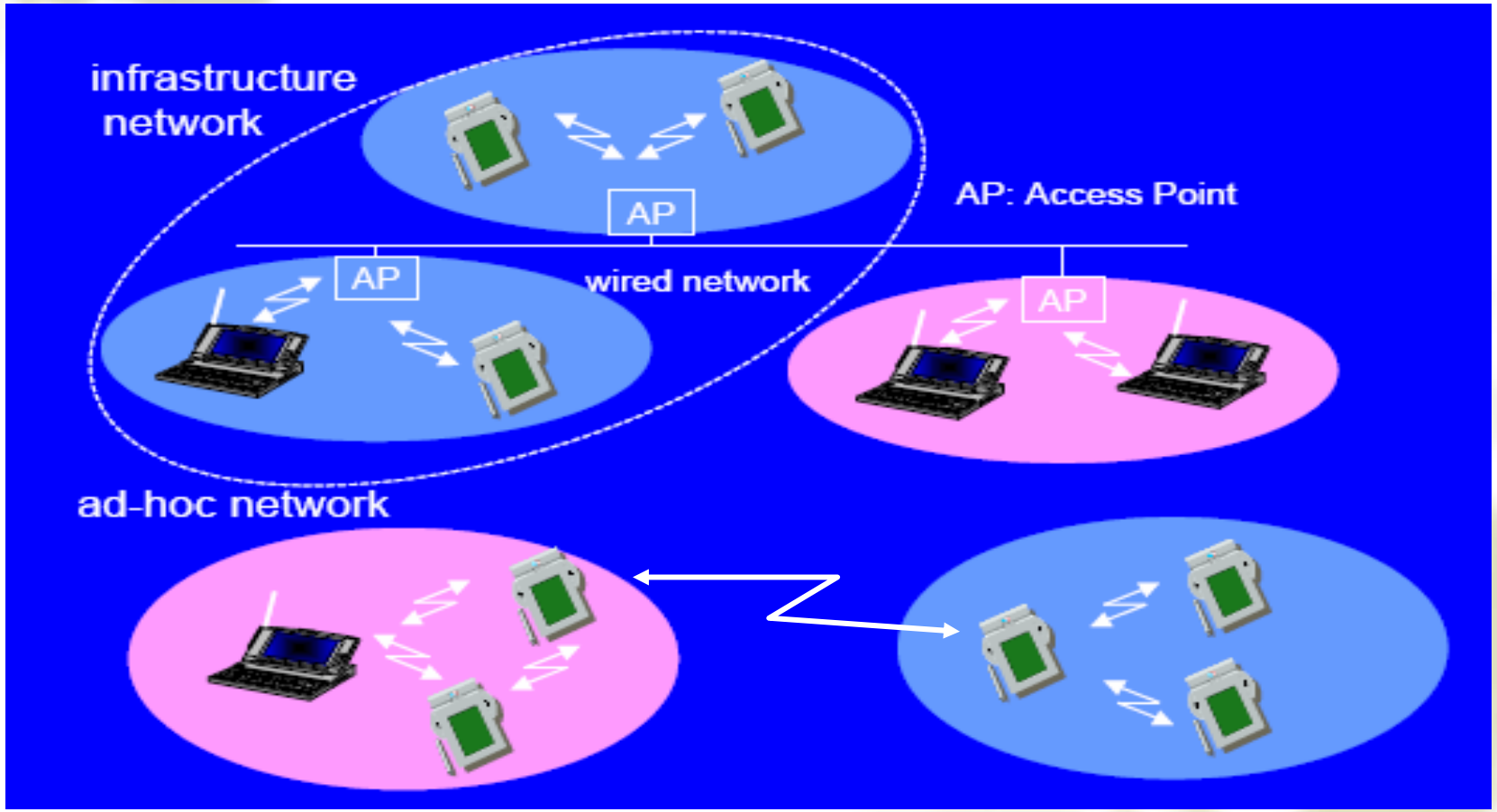
Architecture of wireless networks

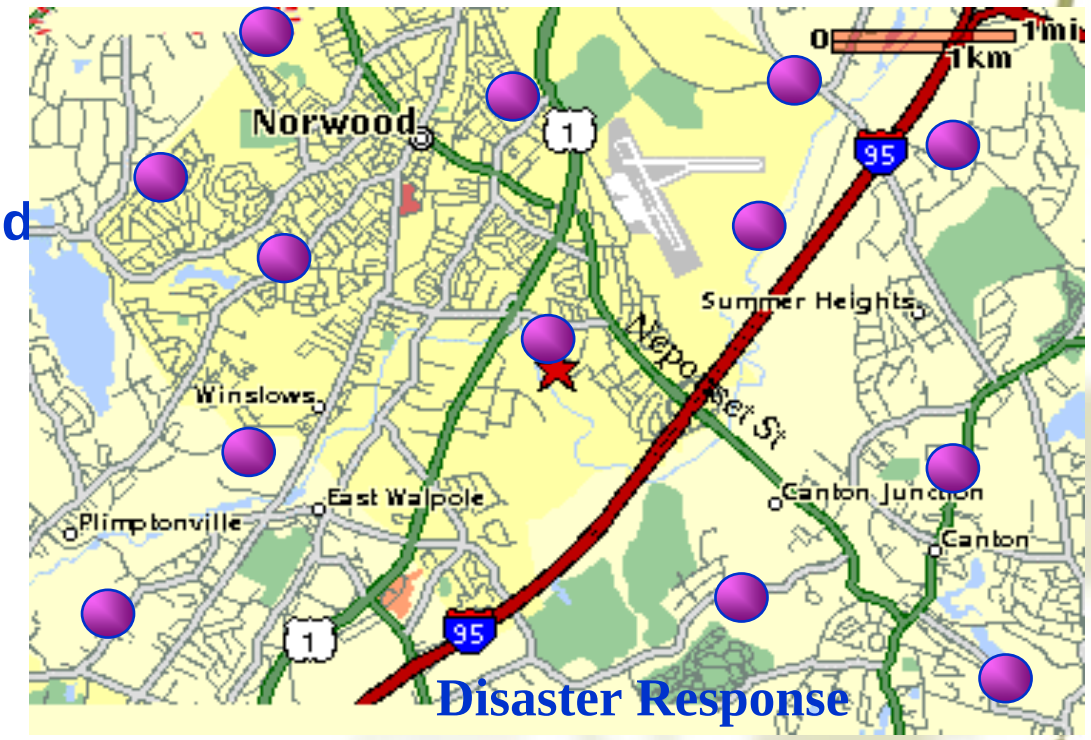
- **Architecture of wireless networks**
  - **infrastructure-based networks;**
  - **non-infrastructure networks**
- **Infrastructure-based networks：**
  - **Cellular mobile communication system (need BSS,MSC etc.)**
  - **WLAN (need AP)。**
- **non-infrastructure networks：**
  - **Ad hoc networks**
    - **Wireless Sensor networks**

The comparison of two types of wireless networks



Overview of WSNs

- WSN is a wireless network of a group of sensor nodes, connected with Ad-Hoc method.
- It is consisted of a large number of nodes, densely deployed within or near the detected region.
- The location of each sensor nodes is uncertainty in advance, usually randomly deployed in harsh and inhospitable physical environments.



Disaster Response

- Sensor node
  - Sensor
  - Processor
  - Communicator

Architecture of Sensor Node

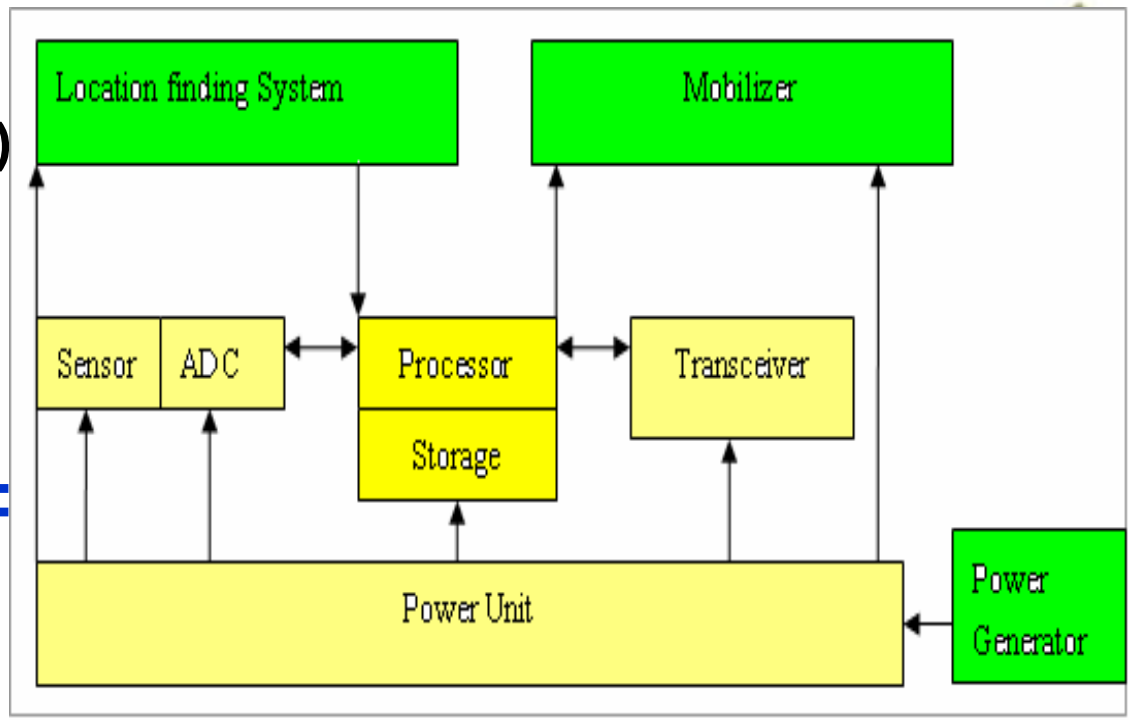
Low cost, low-power, multi-functional device

Data collection module:
(Sensors and A/D Convertor)

Data processing and Control module:
(CPU 、 Memory and embedded OS)

Communication module:
(Wireless Communication System)

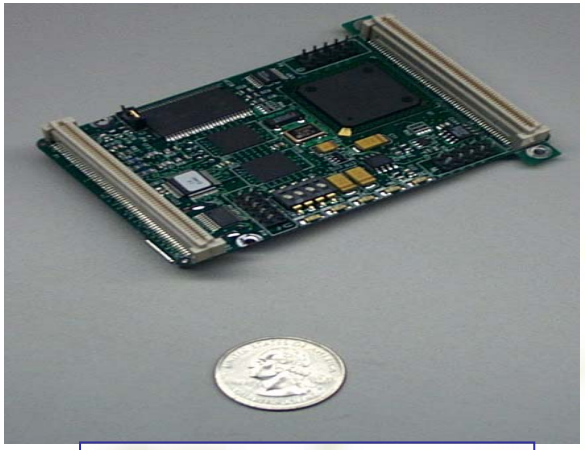
Power supply module:
(Power Unit)



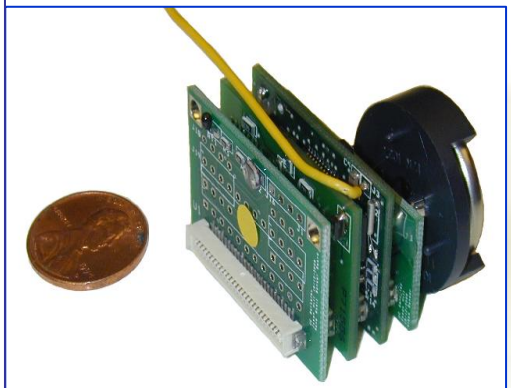
Location Finding System、Mobilizer、 Power Generator;

Examples

LWIM III
UCLA, 1996
Geophone, RFM radio, PIC, star network

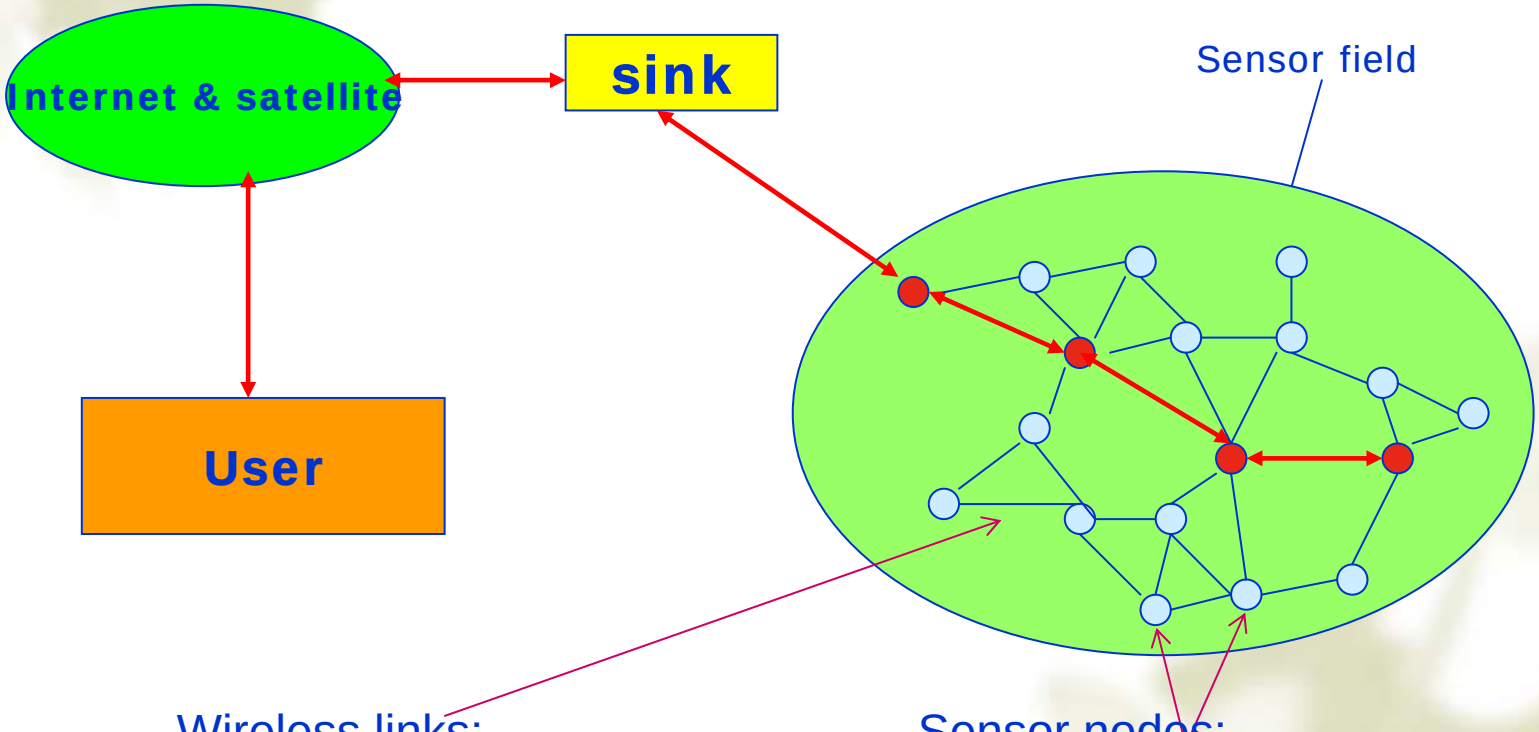


UCB Mote, 2000
4 Mhz, 4K Ram
512K EEProm,
128K code,
CSMA
half-duplex RFM radio



WINS NG 2.0
Sensoria, 2001
Node development platform; multi-sensor, dual radio, Linux on SH4,

Architecture of WSNs

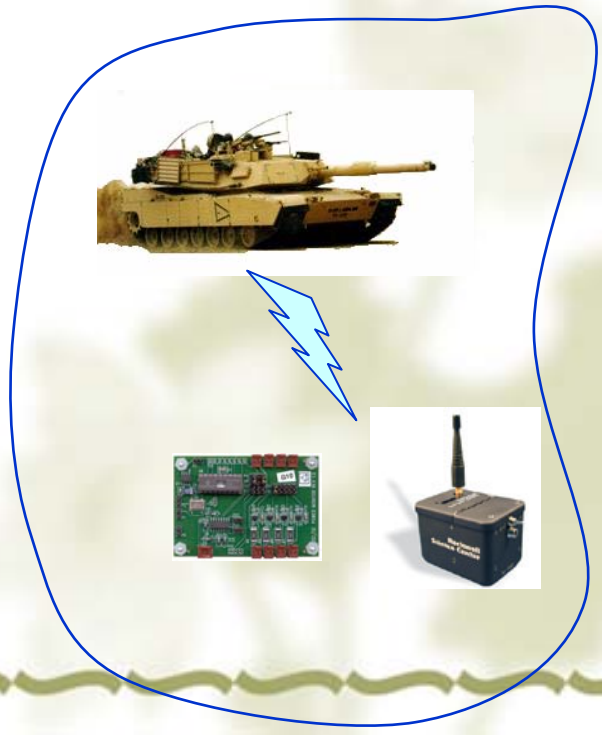


Wireless links:
distance limited
Multi-hop communication
Self organization

Sensor nodes:
Battery, power limited
Active and sleep modes
Can route adjacent sensor's data

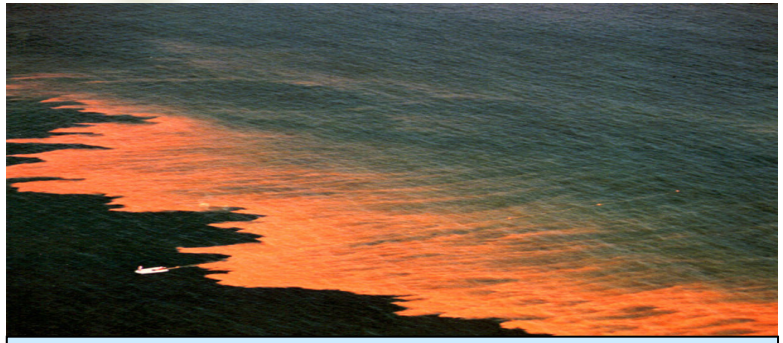
WSN Applications (1)

- **Military**
  - Characteristics of WSNs:
    - rapid deployment, self-organization, fault tolerance
  - Battlefield command system
    - Intruder detection,
    - Battlefield Surveillance
    - Target (enemy) tracking,
    - Equipments safeguarding,
    - Forces monitoring



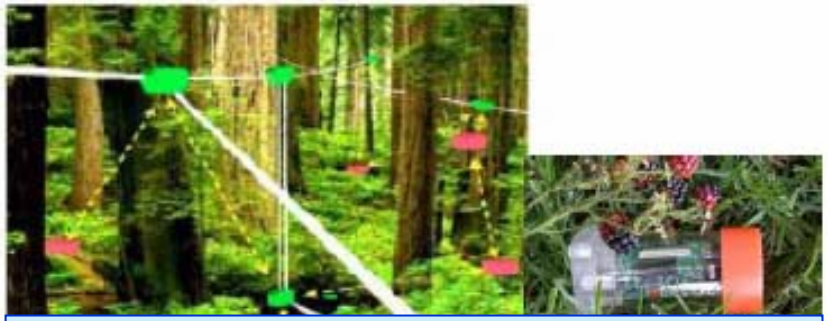
WSN Applications (2)

- **Environmental monitoring**



Flood detection

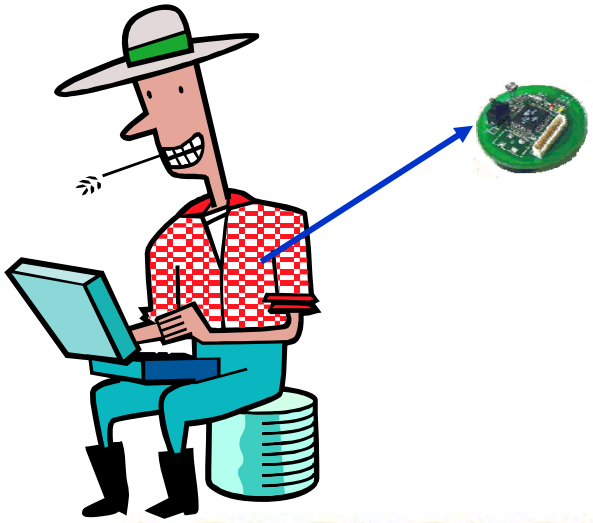
Forest fire detection



Ecosystems mapping

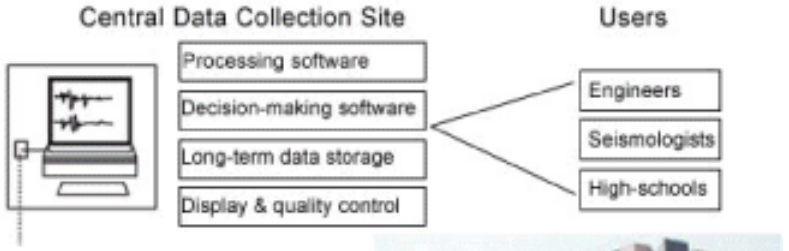
WSN Applications (3)

- **Health Care**
  - Detect abnormity (behavior of patients: fall)
  - Identify potential health risks (heart rate, blood pressure)
  - Automatically remind doctors and assistants
  - Monitor health trends (long term and short term)



WSN Applications (4)

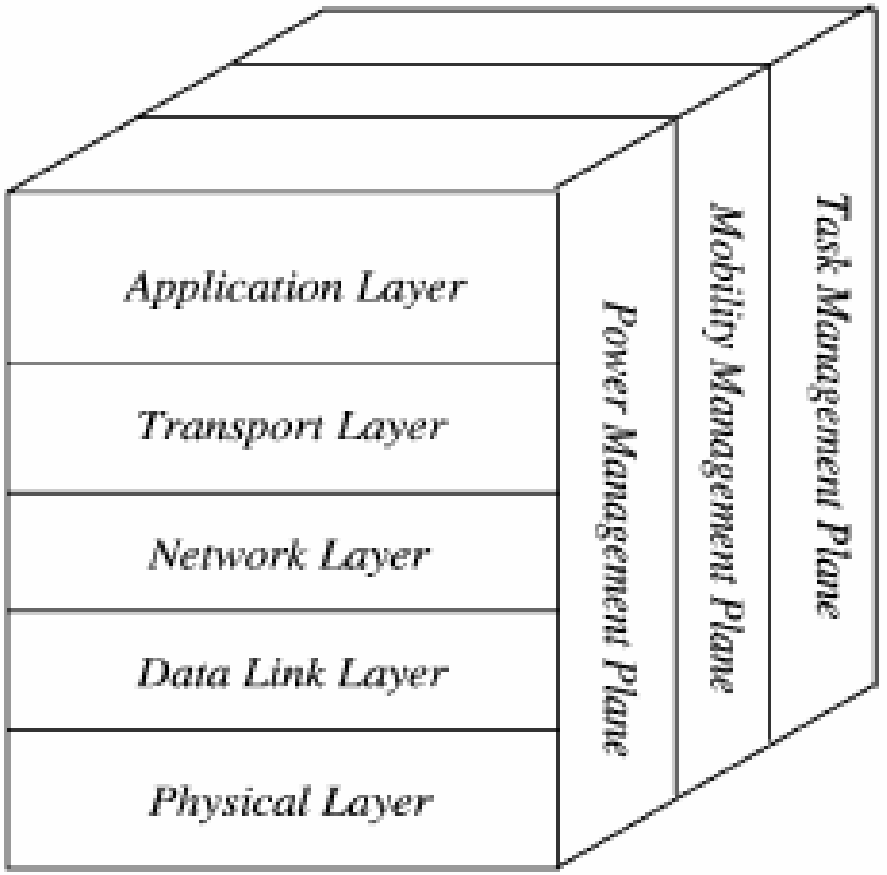
- **Civilian construction**
  - SHM
  - Environmental control



WSNs Protocol Stack

Application Layer
Transport Layer
Network layer
Data Link Layer
Physical Layer

Power Management Plane
Mobility Management Plane
Task Management Plane



WSNs vs. Other networks

- Target
  - WSN is data-centric, not communication-oriented.
- Communication pattern
  - Traditional networks put all the processing functions into terminals, the Intermediate nodes are just in charge of relaying data packages; while for the WSNs, all sensor nodes have to sense events; transmit, receive and relay information; and process information.
- Diversity of applications
  - No “one fits all” solution in WSNs
- Energy
  - Impossible to change battery (lifetime is critical)
- Reliability
  - WSN nodes are more prone to failure

Performance

- **Energy efficiency**
  - Network lifetime
  - Tradeoff for energy, coverage, delay, accuracy.
- **Robustness**
  - Vulnerability to node failure and environmental dynamics
- **Reliability**
  - Measurement accuracy, transmission reliability
- **Scalability**
  - Centralized vs. Distributed
- **QoS**
  - Response time, probability of event detection , security

——The first objective is Energy Conservation

Key Technologies

- Energy aware and application aware algorithms and protocols
- Data aggregation (fusion) for accuracy & redundancy control
- Dynamic topology management and localization
- Dynamic routing discovery and maintenance
- Gathering, processing and analyzing massive sensory data in real time for prompt event detection and response
- Reliability and fault tolerance in data transmission
- Security, privacy, trust

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Medium Access Control Strategy

- **Techniques**
  - Schedule-based TDMA access strategy
  - Contention-based CSMA access strategy
  - FDMA/CDMA-based access strategy
- **Design Considerations**
  - Energy conservation:
    - First Objective
  - Scalability:
    - Adaptive to the change of network size, node density and topology
  - Network utility:
    - Throughput, fairness, latency and bandwidth utilization

Schedule-based (TDMA)

Allocate a time slot for each node to send and receive data, and node sleeps when not in an active period

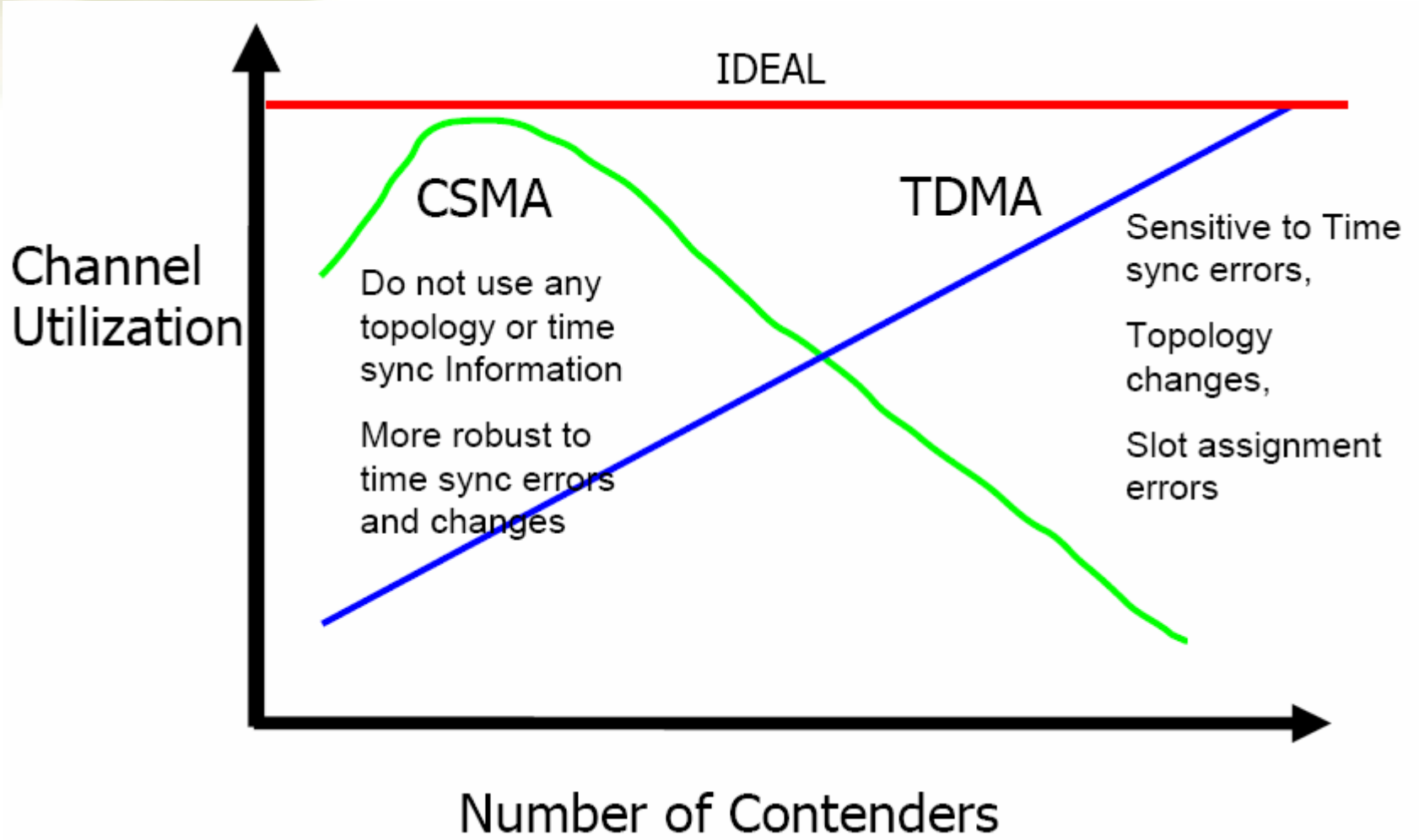
- **Features**
  - Collision free
  - Low idle listening and overhearing overheads
  - Heavily dependent on time sync and not robust to topology changes
  - Low throughput and high latency even during low contention
- **Typical Algorithm--Bluetooth IEEE 802.15.1**

Contention-based (CSMA)

When a node needs to send data，it uses wireless channel through competition. If collision happens, nodes retransmit data by some algorithm till sending data successfully or giving up sending.

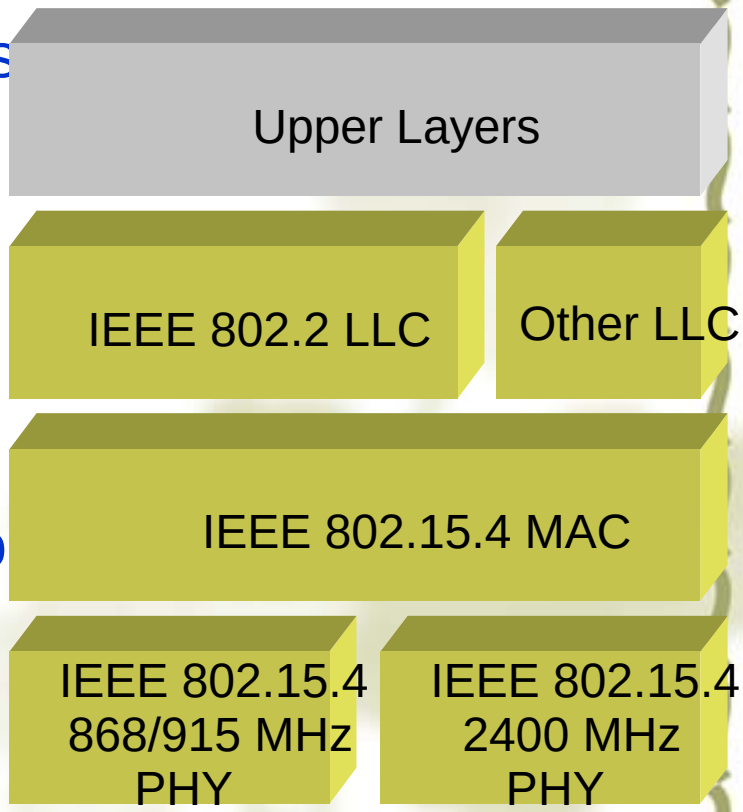
- **Features**
  - Algorithms to avoid collisions or reduce probability
  - Random back-off and carrier-sensing
  - High idle listening and overhearing overheads
  - High control overhead
- **Typical Algorithm: IEEE 802.11**
  - CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance)

CSMA / TDMA Comparison



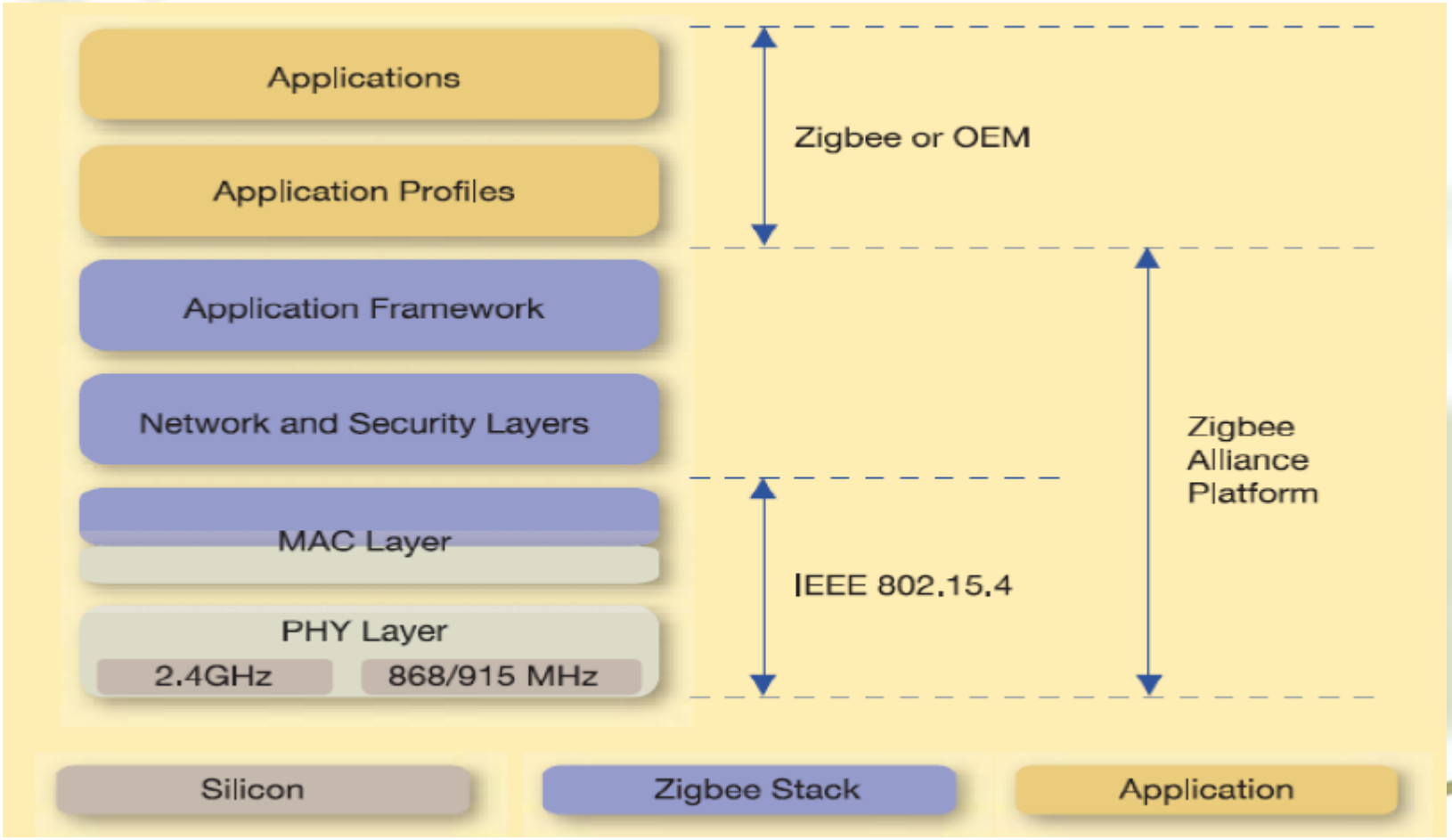
IEEE 802.15.4

- **Personal wireless network**
  LR-WPAN standard
  - Provide connection among low-power, low-rate, low-cost devices in short distance
  - Can be used in wireless sensor networks.
- **Features**
  - Speed: 250, 40, and 20 kb/s
  - network topology: star or point-to-point.
  - CSMA / CA access
  - low-power, low latency devices



ZigBee Union

Based on an open global standard, make the stable, low-cost, low-power, wireless networking systems or products possible



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Routing Protocols in WSNs

- **Features**
  - Energy priority
  - Depending on local information of topology
  - Data-centric

The Classification of Routing Protocols

- **Data-centric**
  - Determine routes according to the data content
  - Data transmission process goes with data aggregation
  - SPIN、Directed Diffusion
- **Location-based**
  - Determine routes according to node location, do not use flood method
  - GPSR、GEAR
- **Hierarchical**
  - Applied to the large networks
  - Use data aggregation to reduce redundant data in transmission
  - LEACH、TTDD、TEEN、PEGASIS

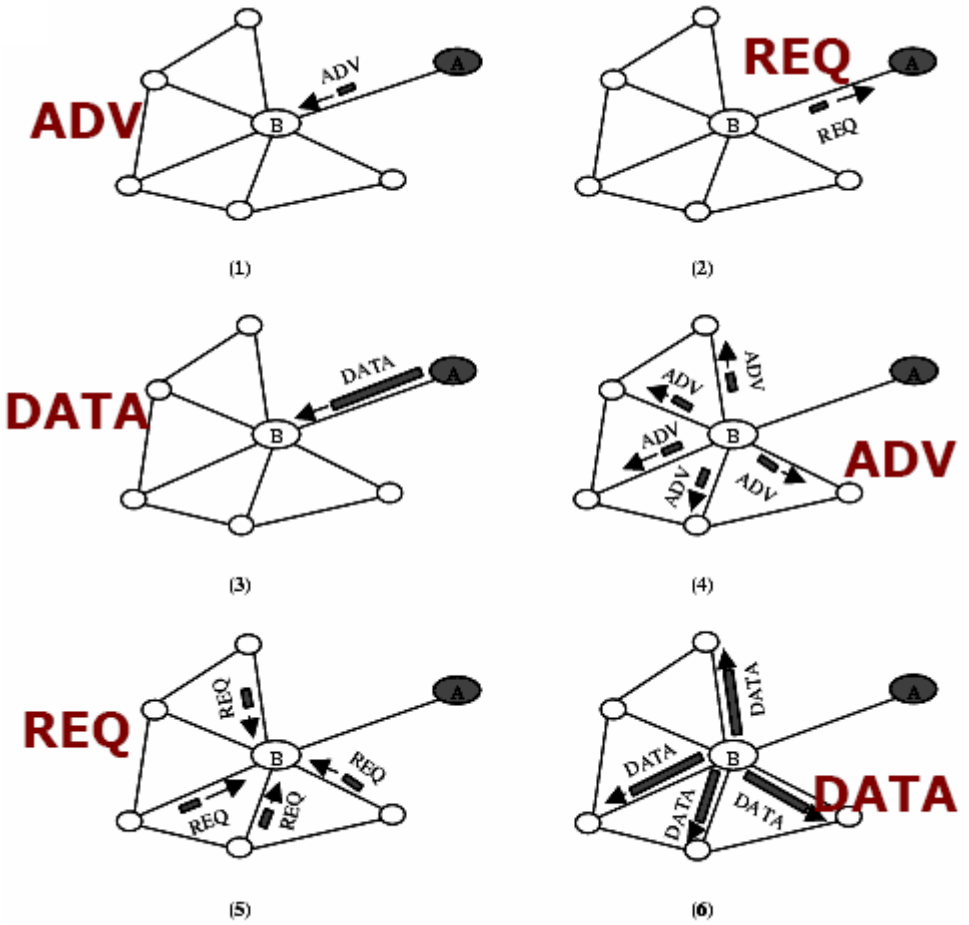
Negotiation-based Routing——SPIN

Sensor Protocol for Information via Negotiation

- **Applied to active data dissemination system**
- **Using metadata for negotiation before data transmission**
- **Metadata**
  - Data description of data
  - Shorter than raw data
  - Avoid redundant data transmission

SPIN——3-stage handshake

- Data source A sends ADV（Meta data）
- B sends REQ for data
- A sends DATA
- B could aggregate AB data, relay/ transmits ADV (Meta data of A/AB)
- Other nodes request data
- B directly responses the request of A data



Request-based Routing —— Directed Diffusion

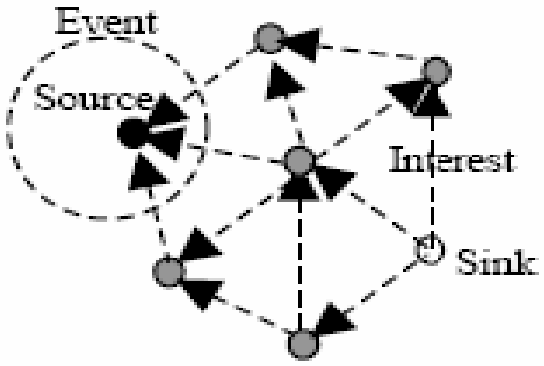
Applied to system where sink sends interests for request

```
type = four-legged animal // detect animal location
interval = 20 ms // send back events every 20 ms
duration = 10 seconds // .. for the next 10 seconds
rect = [-100, i00, 200, 400] // from sensors within rectangle
```

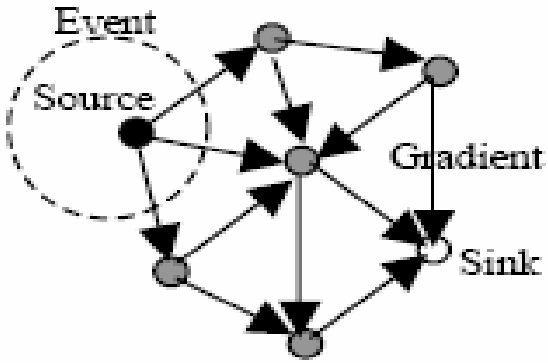
- **Data generated by sensor nodes is named by attribute-value pairs**
- **Sink publishes interests message**
- **Nodes satisfied interest send data back**

Directed Diffusion

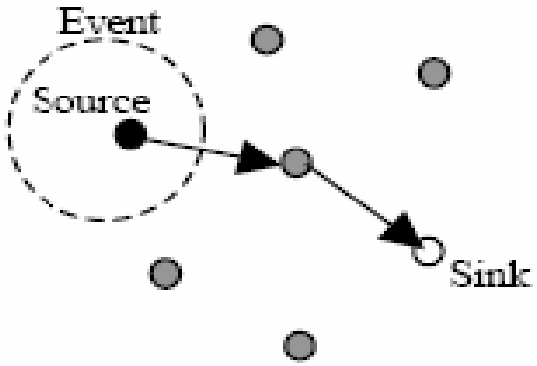
- Sink sends interests message in flooding way
- Build initiate gradients when sending request message
- Source nodes transmit data back to the sink along with the gradients.
- During data sending back，data with same interest can be aggregated



(a) Interest propagation



(b) Initial gradients setup

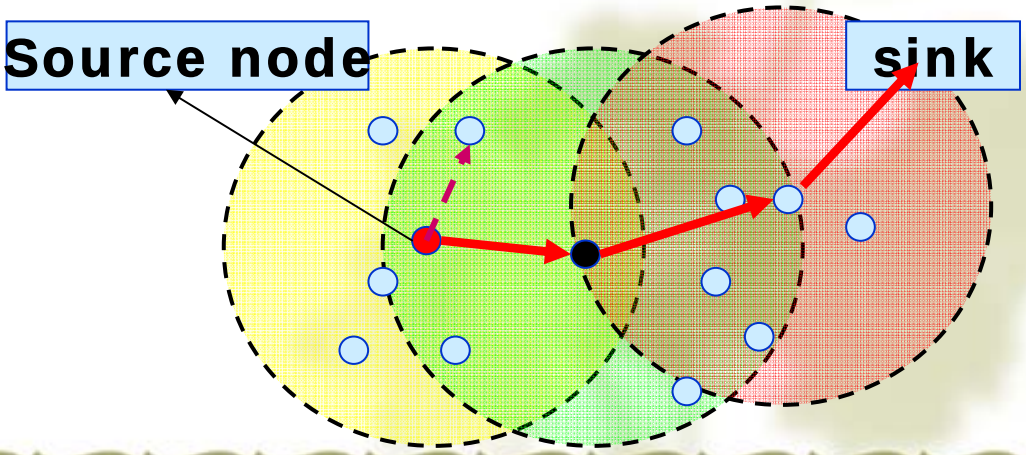


(c) Data delivery along reinforced

Location-based Routing——GPSR

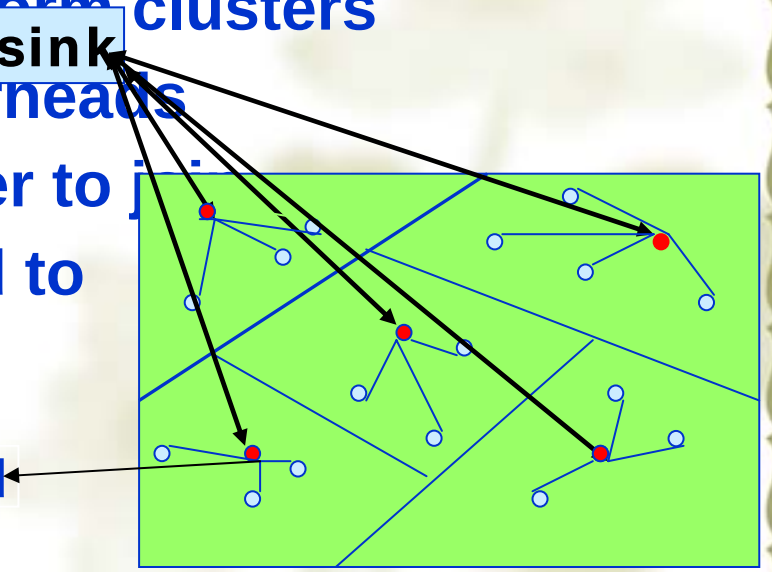
Applied to networks with constantly changing topology

- **Exchange location info and remaining energy info through "Hello" message**
- **Greedy forwarding: taking the neighbor nearest to the sink as the next hop**



Cluster-based routing ——LEACH

- Low Energy Adaptive Clustering Hierarchy protocol
- Divide sensor nodes into clusters，every node sends data to its cluster-head，the cluster-head sends data to the sink after data aggregation.
- Adjacent nodes automatically form clusters
  - Some nodes become clusterheads
  - Other nodes choose a cluster to join
- Randomization election is used to balance energy load



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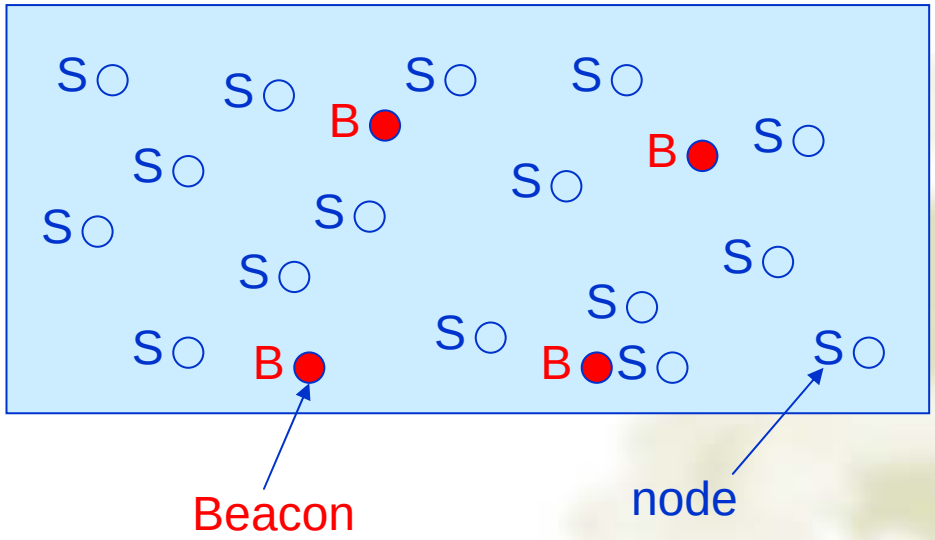
- **Medium Access Control (MAC)**
- **Routing Protocols**
- **Deployment and Management**
  - localization
  - topology control
  - coverage
  - Synchronization
- **In-network processing**
- **QoS and Security**

Localization

- **Importance**:
  - locating the monitored events in target tracking
  - Foundation of location-based routing
  - Network management, use location information to construct network topology
- **Traditional localization**
  - Global Positioning System **GPS**
    - High precision, strong anti-interference capability
    - Suitable for outdoor environment,
    - high energy consumption

Localization

- **Localize each node with the beacon location**
  - Range-based: using ranging techniques for distance estimate or angle estimate in location calculation
  - Range-free: depending only on the received message content



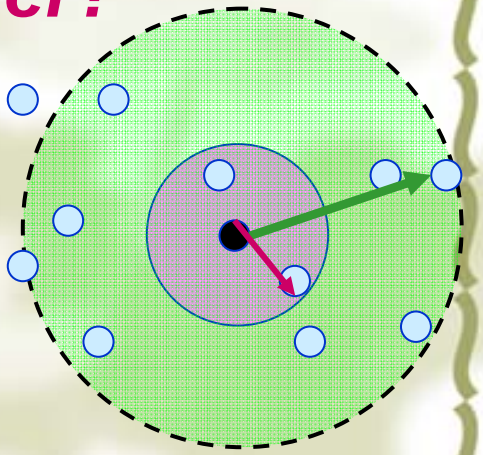
- **Challenge: *precision of estimated location***

Topology Control

- **Targets:**
  - Minimize the energy consumption of each sensor node while ensuring network connectivity
  - Restrict the neighbor set of a given node to reduce the channel interference
- **Methods:**
  - **Node power control:**
    - adjust transmission power
    - sleep/wake-up mechanism
  - **Hierarchical topology:**
    - clustering mechanism
    - coordination mechanism

Power Control

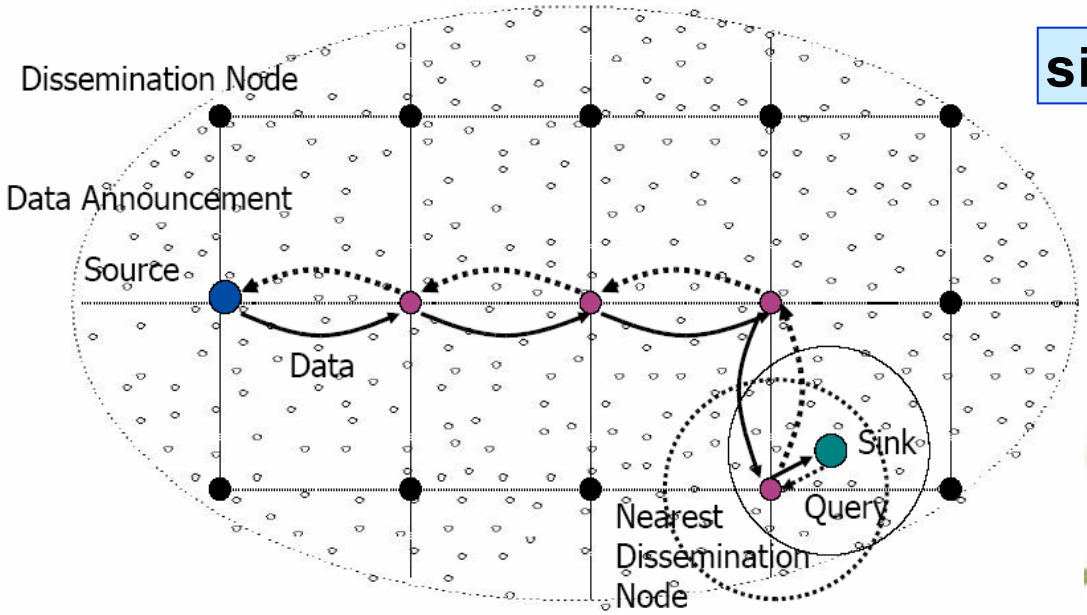
- **Each node in the network uses the best transmission power**
  - depending on the node degree algorithm
  - All the nodes in the network use the same transmission power
- **Challenge: *how to get the best power?***

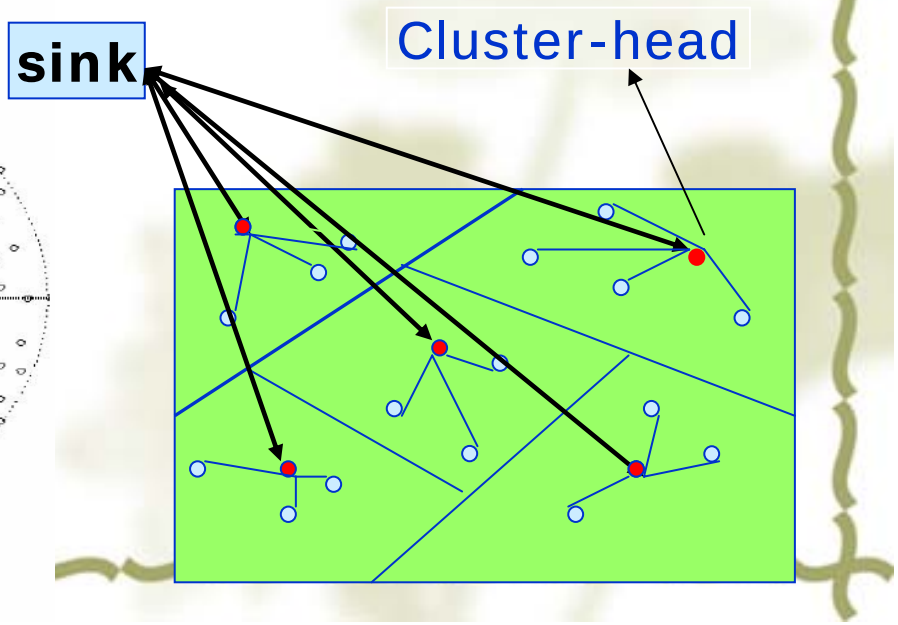


Hierarchical topology

Nodes are divided into backbone nodes and ordinary nodes. Backbone nodes construct a connected network responsible for routing of data.

- Two-tier topology TTDD
- Cluster topology LEACH → Multi-layer cluster topology





Coverage and Sensing Model

Ensure that any point or any sub-region in the network can be monitored by sensors.

- **K-coverage**
  - Each location is at least covered (monitoring) by k nodes, so as to guarantee the reliability of sensing.
- **Boolean sensing model**
  - Events within sensing range are detected reliably and events outsides cannot be detected at all
- **General sensing model**
  - Sensing capability degrades as distance increases

Time Synchronization

- **Importance**
  - Ensure the cooperative work between nodes
  - Complete TDMA schedule mechanism
  - Complete the data aggregation of multiple sensors
  - Assist localization process
- **Synchronization technology**
  - In-network exchange and adjustment
    - RBS (Reference Broadcast Synchronization)
  - hierarchical synchronization structure
    - TPSN (Timing-sync Protocol for Sensor Networks)

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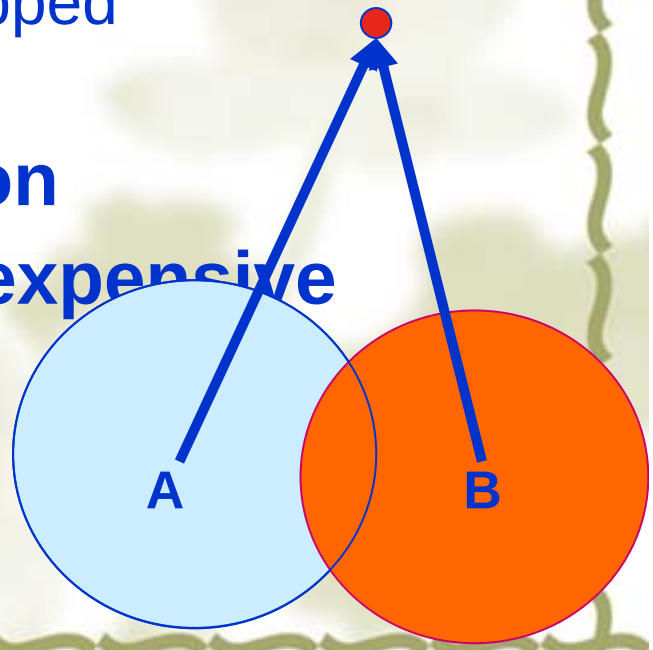
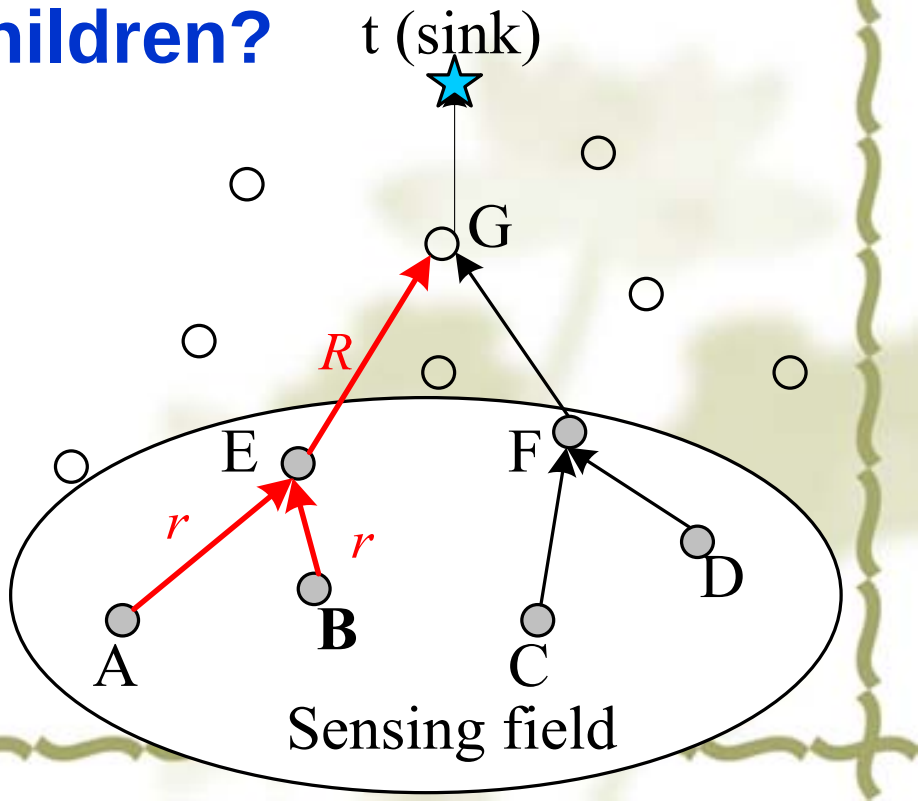
Need for Data Fusion/Aggregation

- **Data-centric**
- **Individual sensor readings are of little use**
- **The collection of readings from different sensors produce the big picture**
  - Coverage of sensor nodes is overlapped
  - Sensory data is highly correlated
- **Common data analysis operation**
- **Forwarding raw information is expensive**
  - Scarce energy and bandwidth
- **In-network processing**
  - Data fusion/aggregation



Data aggregation routing structure

- How can the aggregation tree be formed?
- Where should aggregation point be placed?
- How long should a node wait for data from its children?



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- **QoS and Security**
  - Reliability
  - Real-time
  - Security
  - Fault-tolerance

Reliability

- **Reliability**

  Sink to source nodes:

  - query, task planning, and other command.
  - need 100% reliable data transmission.

  Source nodes to the sink:

  - Sensory data.
  - reliable collection of information --- data from nearby nodes are highly relevant, instead of guaranteeing single sensed data, network should provide effective information that users care.

- **Reliability technology**

  - Single data -- reliable routing mechanism
  - Collection of information -- redundant transmission

Reliable Routing Protocol

Multi-path routing technique

- **Main/backup multi-path**
  - First, build a main path from source node to the sink, then build multiple backup paths.
  - The main path transmits data, backup paths transmit maintenance data.
  - If the main path fails, choose a new one from backup paths.
- **Simultaneous multi-path**
  - Build paths from source to sink according to some metric
  - Send data on all paths simultaneously
- *Challenge: How many paths are needed?*
  - ReInForM

Real-time in WSNs

- Real-time applications
  - Intrusion monitoring
  - disaster alarm,….
- Delay in WSNs
  - CSMA-based MAC will bring random delay, TDMA-based MAC has constant delay.
  - Active/sleep mode can save energy, but bring in delay of monitoring and transmission
  - During data aggregation, aggregating node needs to wait for the data from children to complete the aggregation, further intensifies the delay.

Real-time in WSNs

Consider real-time in each layer

- **MAC layer：**
  - Choose suitable MAC mechanism, reduce retransmission.
  - flexible wakeup mechanism, reduce waiting time
- **Network layer：**
  - Choose small delay links to construct routes
  - Proactive routing vs. reactive routing——reactive routing needs time to build routes.
- **Transmission layer：**
  - Multi-path vs. retransmission mechanism
  - multi-path routing: switch between main/backup multi-path vs. simultaneous multi-path
- **Application layer：** Aggregation? No aggregation?

Security Goals in WSNs

- **Confidentiality (privacy)**
  - ——accessible to only authorized parties
- **Integrity**
  - ——only authorized parties can modify the data
- **Availability**
  - ——reliable delivery of data against denial of service
- **Authentication**
  - ——data is really sent by the claimed sender
- **Freshness**
  - ——data is current and fresh (not replayed by adversary)
- **Security management**
  - ——key distribution and management mechanism

Security Challenges in WSNs

- **Limited storage capability and computing capability**
  - Impractical to use public key cryptosystems
- **Limited bandwidth and communication capability**
  - Need light-weight and distributed security protocols
- **No centralized control**
  - Over-reliance on base station → the problem of single point failure
- **Physical security of the region can not be guaranteed**
  - Compromised nodes may lead to high security risks
- **In-network processing**
  - integrity and confidentiality

Fault Tolerance

- **Causes of errors**
  - Measurement errors of sensor
  - Transmission errors
  - Loss of information since lossy compression
  - Interference brought in by compromised nodes
  - Attacks

Fault Tolerance

- **Fault-tolerant request**
  - Network can identify, filter the wrong message
  - Ensure the end-user to make the correct decision
- **Fault-tolerant strategy**
  - For data errors at nodes——Improving the accuracy of measurement, dense deployment, data aggregation
  - For transmission problems——reliable transmission
  - Against various attacks ——establishing a security framework to resist all kinds of attacks

Summary

- Wireless sensor network is a brand new kind of network, the demand for the applications accelerates its research.
- Researchers have done a lot of studies in deployment, networking, data querying, and routing. Many experimental systems have been applied now.
- There are still many challenges in WSNs, such as power supplies, security, fault-tolerance, cross layer design, and standardization. Breakthrough of these issues can significantly promote the practicability of WSNs.

References

- M. Ilyas and I. Mahgoub, “Handbook of Sensor Networks: Compact of wireless and wired sensing systems”, CCR Press LLC, 2005.

- **Main related work teams:**
  - **IPSN (information processing in sensor networks);**
  - **SenSys;**
  - **EWSN (European workshop on wireless sensor networks);**
  - **SNPA (sensor network protocols and applications);**
  - **WSNA (wireless sensor networks and applications)**
- **Related international conferences: ICC, Globecom, INFOCOM, MobiCom, MobiHoc**

Thank you!

Q&A