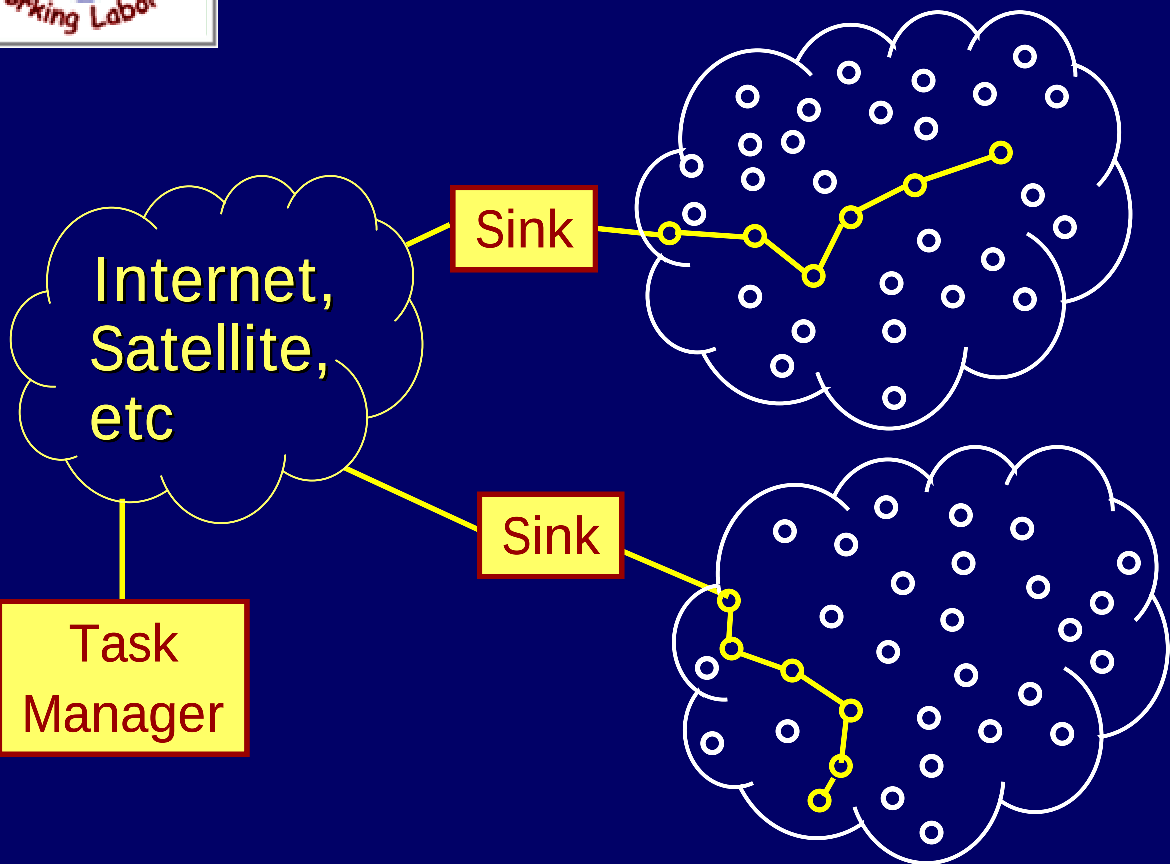
WIRELESS SENSOR AND ACTOR NETWORKS

I. F. Akyildiz

Broadband & Wireless Networking Laboratory
School of Electrical and Computer Engineering
Georgia Institute of Technology
Tel: 404-894-5141; Fax: 404-894-7883
Email: ian@ece.gatech.edu
Web: http://www.ece.gatech.edu/research/labs/bwn

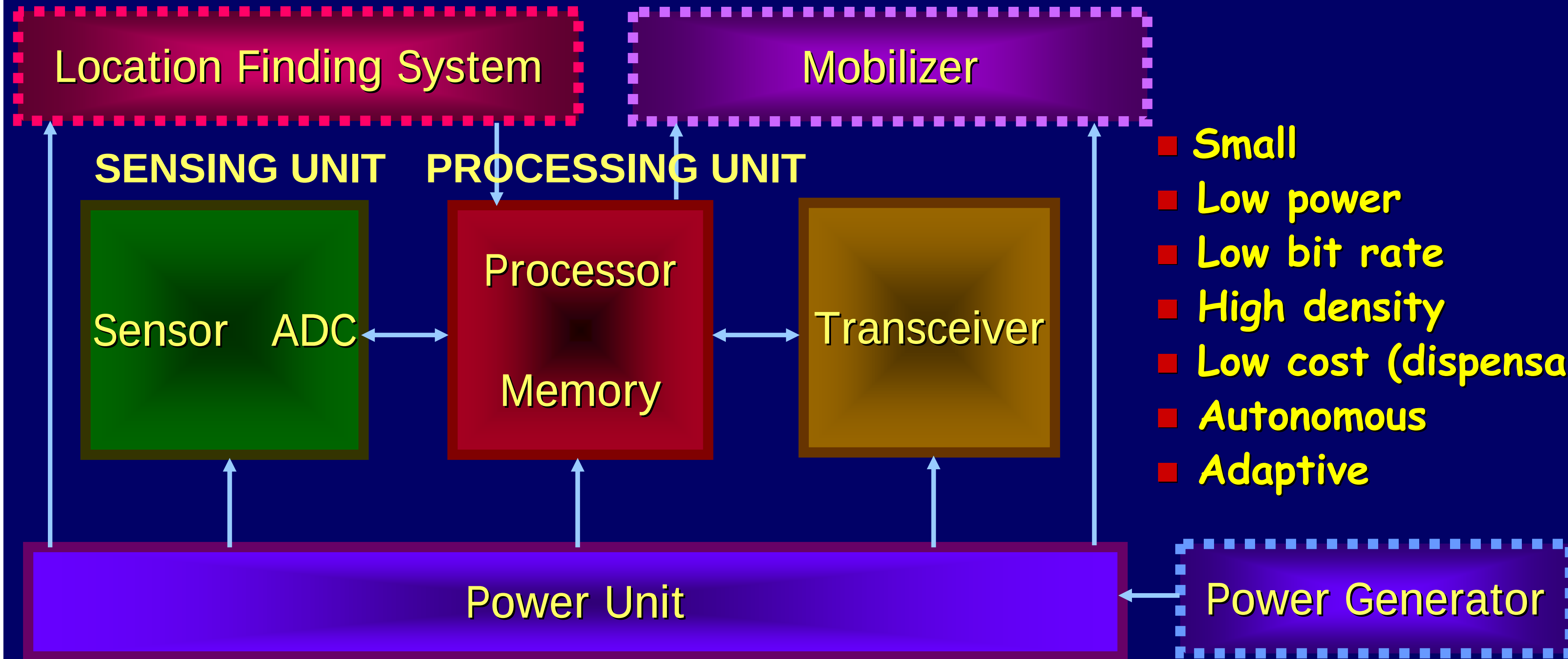
SENSOR NETWORKS ARCHITECTURE



- **Several thousand nodes**
- **Nodes are tens of feet of each other**
- **Densities as high as 20 nodes/m3**

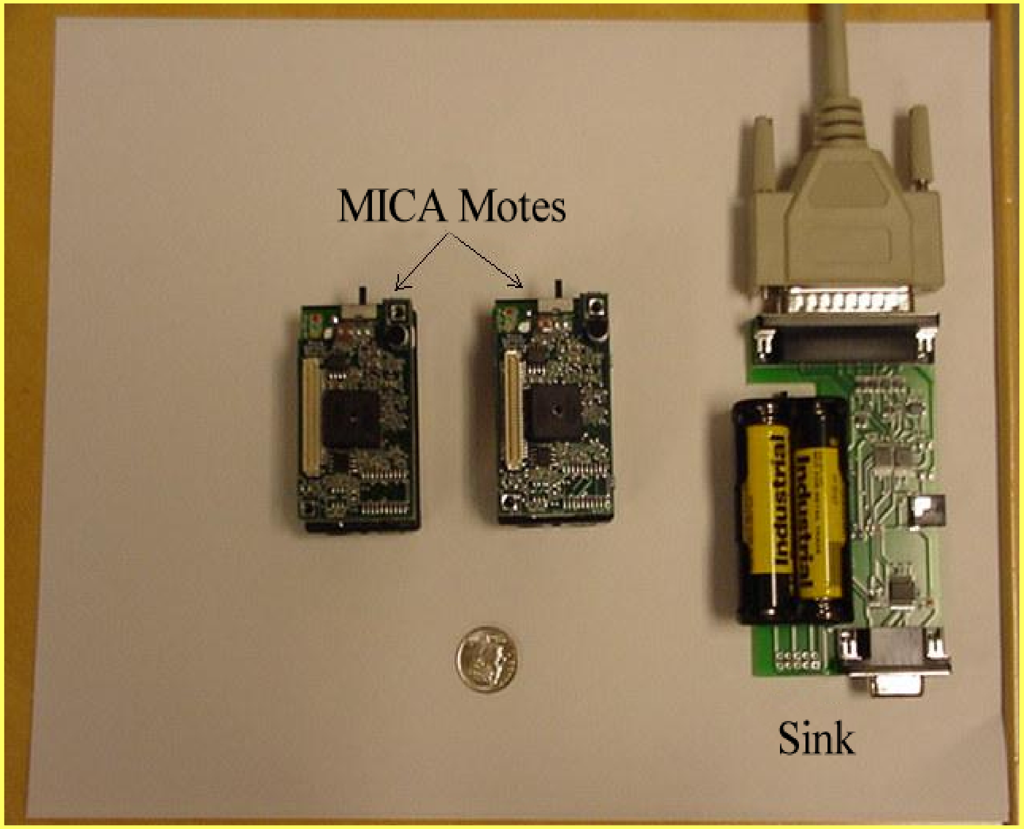
I.F.Akyildiz, W.Su, Y. Sankarasubramaniam, E. Cayirci,
"Wireless Sensor Networks: A Survey", ***Computer Networks (Elsevier) Journal*****, March 2002.**

SENSOR NODE HARDWARE



- Small
- Low power
- Low bit rate
- High density
- Low cost (dispensable)
- Autonomous
- Adaptive

MICA Motes
BWN Lab @ GaTech



Processor/Radio Board	MPR300CB
Speed	4 MHz
Flash	128K bytes
SRAM	4K bytes
EEPROM	4K bytes
Radio Frequency	916MHz or 433MHz (ISM Bands)
Data Rate	40 Kbits/Sec (Max)
Power	0.75 mW
Radio Range	100 feet (prog.)
Power	2 x AA batteries

Processor and Radio platform (MPR300CB) is based on Atmel ATmega 128L low power Microcontroller that runs TinyOs operating system from its internal flash memory.

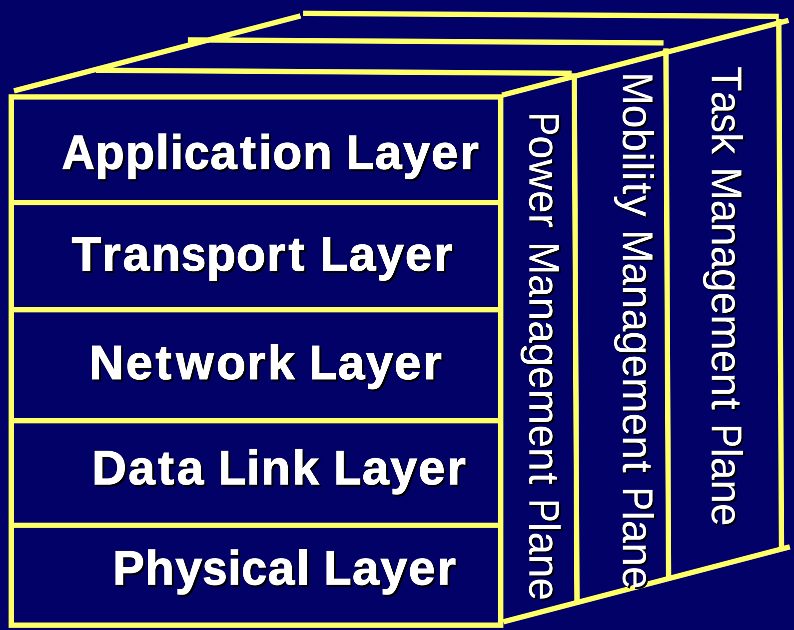
SENSOR NETWORKS FEATURES

- **APPLICATIONS:**
  Military, Environmental, Health, Home, Space Exploration, Chemical Processing, Disaster Relief….

- **SENSOR TYPES:**
  Seismic, Low Sampling Rate Magnetic, Thermal, Visual, Infrared, Acoustic, Radar…

- **SENSOR TASKS:**
  Temperature, Humidity, Vehicular Movement, Lightning Condition, Pressure, Soil Makeup, Noise Levels, Presence or Absence of Certain Types of Objects, Mechanical Stress Levels on Attached Objects, Current Characteristics (Speed, Direction, Size) of an Object ….

Sensor Networks Communication Architecture



- Used by sink and all sensor nodes
- Combines power and routing awareness
- Integrates data with networking protocols
- Communicates power efficiently through wireless medium and
- Promotes cooperative efforts.

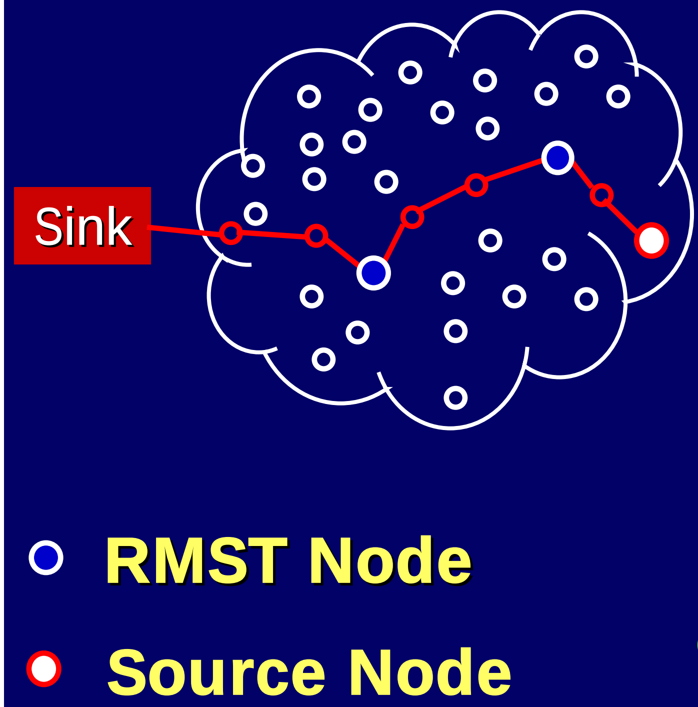
WHY CAN'T AD-HOC NETWORK PROTOCOLS BE USED HERE?

- **Number of sensor nodes can be several *orders of magnitude higher***
- **Sensor nodes are *densely deployed* and are *prone to failures***
- **The topology of a sensor network changes very frequently due to *node mobility and node failure***
- **Sensor nodes are limited in *power, computational capacities, and memory***
- **May not have global ID like IP address.**
- **Need tight integration with sensing tasks.**

TRANSPORT LAYER

Reliable Multi-Segment Transport (RMST)

F. Stann and J. Heidemann, "RMST: Reliable Data Transport in Sensor Networks," *In Proc. IEEE SNPA'03, May 2003, Anchorage, Alaska, USA*



- End-to-end data-packet transfer reliability
- Each RMST node caches the packets
- When a packet is not received before the so-called WATCHDOG timer expires, a NAK is sent backward
- The first RMST node that has the required packet along the path retransmits the packet

- In-network caching brings significant overhead in terms of power and processing.
- Relies on Directed Diffusion Scheme

Transport Layer

PSFQ - Pump Slowly Fetch Quickly

Y. Wan, A. T. Campbell and L. Krishnamurthy, "PSFQ: A Reliable Transport Protocol for Wireless Sensor Networks,"
In Proc. ACM WSNA'02, September 2002, Atlanta, GA

- Packets are injected slowly into the network
- Aggressive hop-by-hop recovery in case of packet losses
- "PUMP" performs controlled flooding and requires each intermediate node to create and maintain a data cache to be used for local loss recovery and in-sequence data delivery.
- Applicable only to strict sensor-sensor guaranteed delivery
- Does not address congestion control

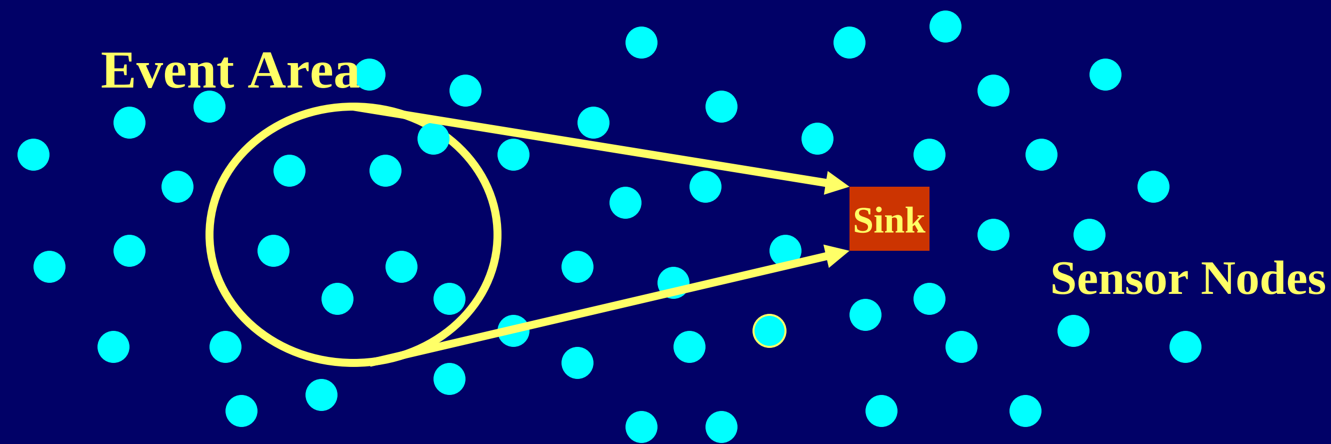
Related Work-Bottomline

- **Wireless TCP variants are NOT suitable for sensor networks**
  - **Different notion of end-to-end reliability**
  - **Huge buffering requirements**
  - **ACKing is energy draining**
- **BOTTOMLINE: Traditional end-to-end guaranteed reliability (TCP solutions) cannot be applied here.**

→ New Reliability Notion is required!!!

Event-to-Sink Reliability

Y.Sankarasubramaniam, O. B. Akan, I. F. Akyildiz,
Proc. of ACM MobiHoc'03, Annapolis, Maryland, June 2003.
Also in IEEE Transactions on Networking, 2004



- Sensor networks are *event-driven*
- Multiple correlated data flows from event to sink
- GOAL: To reliably detect/estimate event features based on the collective reports of several sensor nodes observing the event.
- → *Event-to-sink collective reliability notion*
- → EXPLORE SPATIAL CORRELATION !!!!

Event-to-Sink Reliability

- **Sink decides about event features every τ time units (decision intervals)**

- ***DEFINITION 1: Observed Event Reliability***

  r_i is the number of data packets received in decision interval i at sink

- ***DEFINITION 2: Desired Event Reliability***

  R is the number of packets required for reliable event detection (application specific and is known a-priori at the sink)

  (If $r_i > R$, *then the event is reliably detected.*
  Else, appropriate actions must be taken to achieve R.)

Event-to-Sink Reliability

- ***DEFINITION 3: Reporting Rate***

  f **is the frequency of packet transmissions at a sensor node**

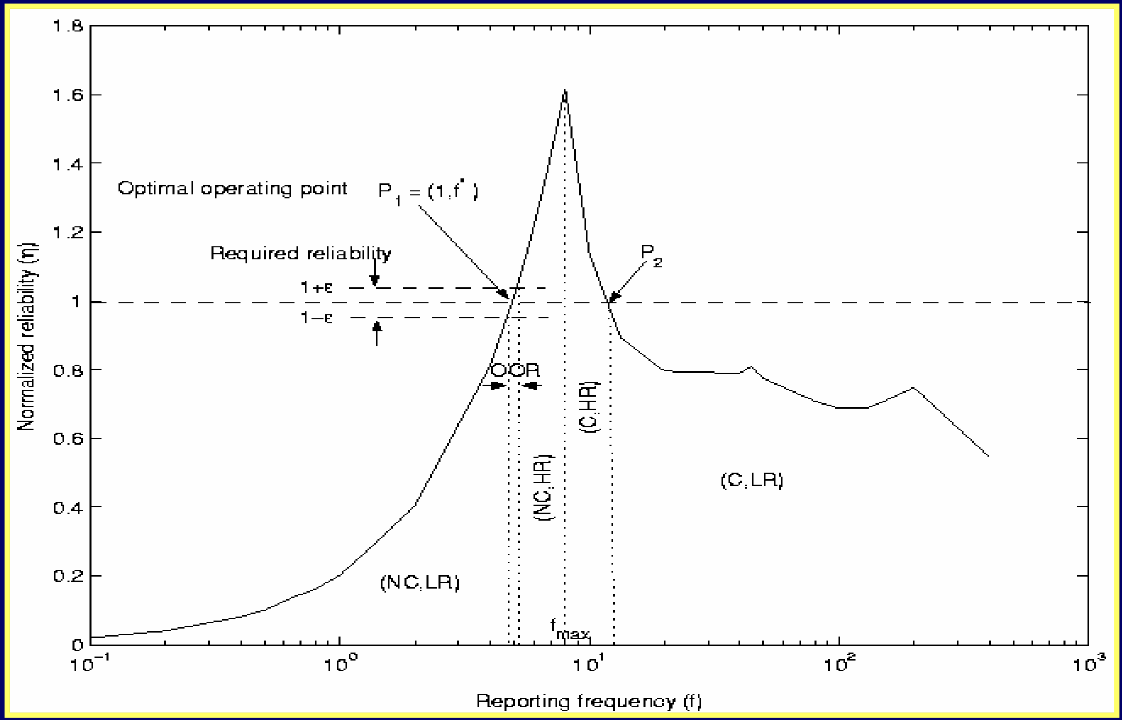
TRANSPORT PROBLEM IN SENSOR NETWORKS:

To configure the reporting rate, f, of sensor nodes so as to achieve the required event detection reliability, R, at the sink with minimum resource utilization.

ESRT: Protocol Overview

- Determine reporting frequency *f* to achieve desired reliability *R* with minimum resource utilization
- Source (Sensor Nodes):
  - Send data with reporting frequency *f*
  - Monitor buffer level and notify congestion to the sink
- Sink:
  - Measures the *observed event reliability* r_i at the end of decision interval *i*
  - *Normalized Reliability* → $\eta_i = r_i / R$
  - Performs congestion decision based on the feedback from the sensor nodes (to determine $f \lessgtr f_{max}$).
  - Updates *f* based on η_i and $f \lessgtr f_{max}$ (congestion) to achieve *desired event reliability R*
  - *Broadcasts the new reporting rate to all sensor nodes*

Network States



State	Description	Condition
(NC,LR)	**(No Congestion, Low reliability)**	$f < f_{max}$ and $\eta < 1 - \varepsilon$
(NC,HR)	**(No Congestion, High reliability)**	$f \leq f_{max}$ and $\eta > 1 + \varepsilon$
(C,HR)	**(Congestion, High reliability)**	$f > f_{max}$ and $\eta > 1$
(C,LR)	**(Congestion, Low reliability)**	$f > f_{max}$ and $\eta \leq 1$
OOR	**Optimal Operating Region**	$f < f_{max}$ and $\eta \in [1-\varepsilon, 1+\varepsilon]$

ESRT: Congestion Detection Mechanism

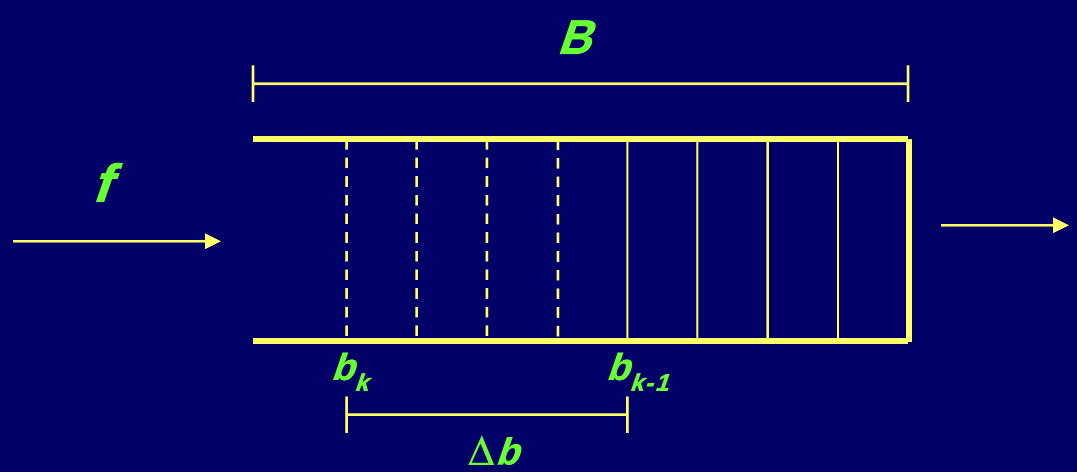
- ACK / NACK not suitable
- We use local buffer level monitoring in sensor nodes

b_k : Buffer fullness level at the end of reporting interval k

Δb : Buffer length increment

B : Buffer size

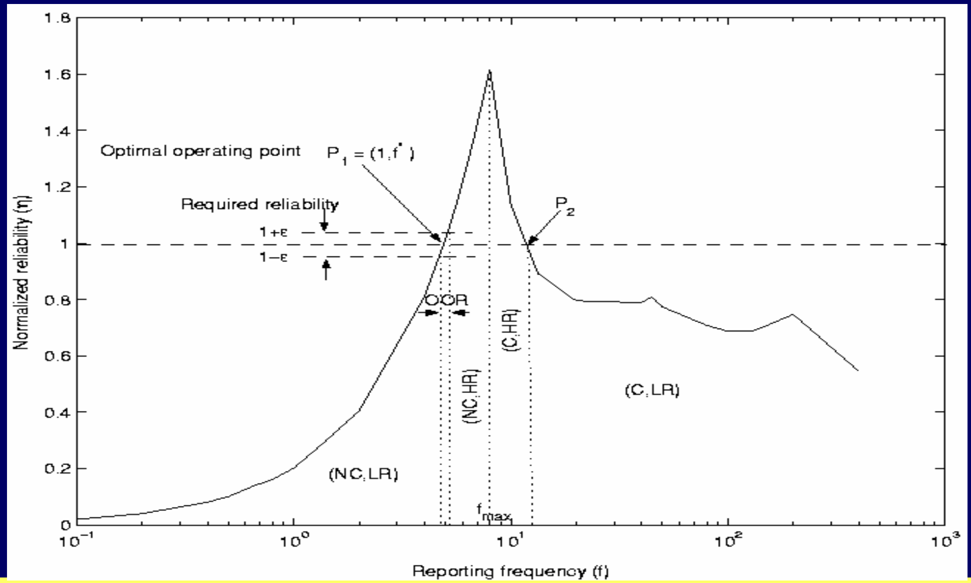
f : reporting frequency



- Mark Congestion Notification (*CN*) field in packet if congested, i.e., $b_k + \Delta b > B$ (*the node infers that it will experience congestion in the next reporting interval*)

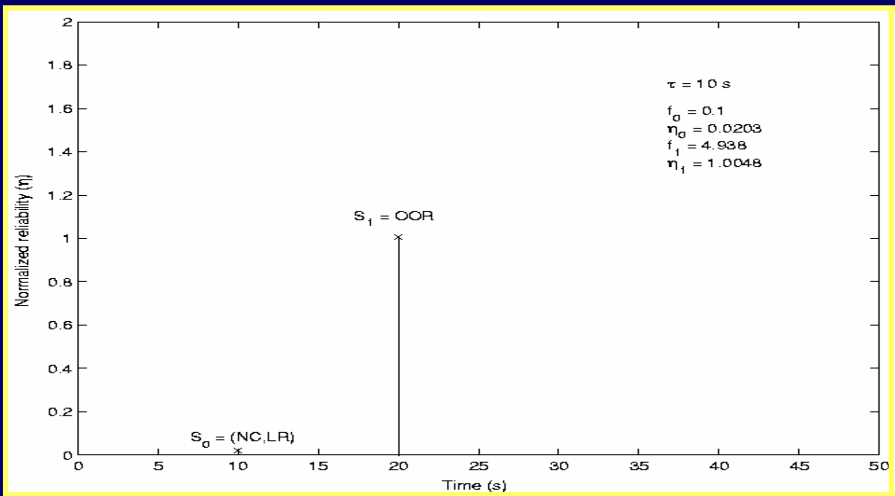
Event ID	CN (1 bit)	Destination	Time Stamp	Payload	FEC

ESRT: Frequency Update

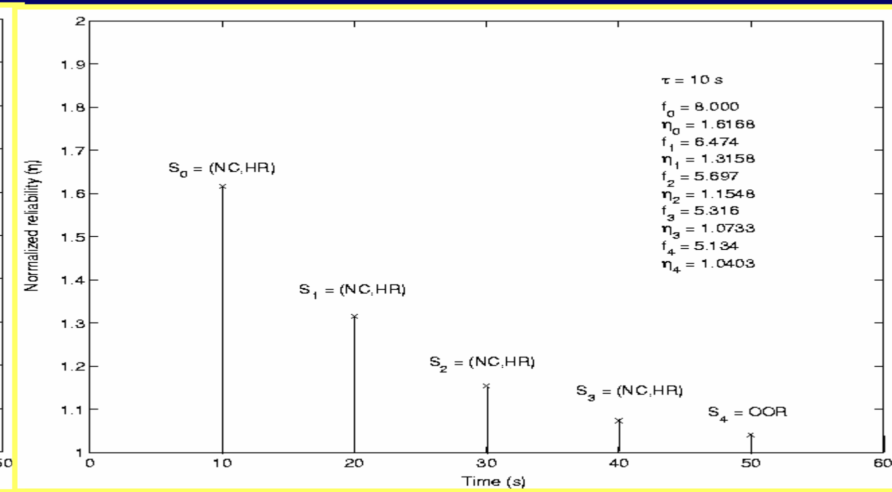


State	Frequency Update	Comments
(NC,LR)	$f_{i+1} = f_i / \eta_i$	Multiplicative increase, achieve desired reliability asap
(NC,HR)	$f_{i+1} = f_i (\eta_i + 1) / 2\eta_i$	Conservative decrease, no compromise on reliability
(C,HR)	$f_{i+1} = f_i / \eta_i$	Aggressive decrease to state (NC,HR)
(C,LR)	$f_{i+1} = f_i^{\eta_i}$	Exponential decrease, relieve congestion asap
OOR	$f_{i+1} = f_i$	Unchanged

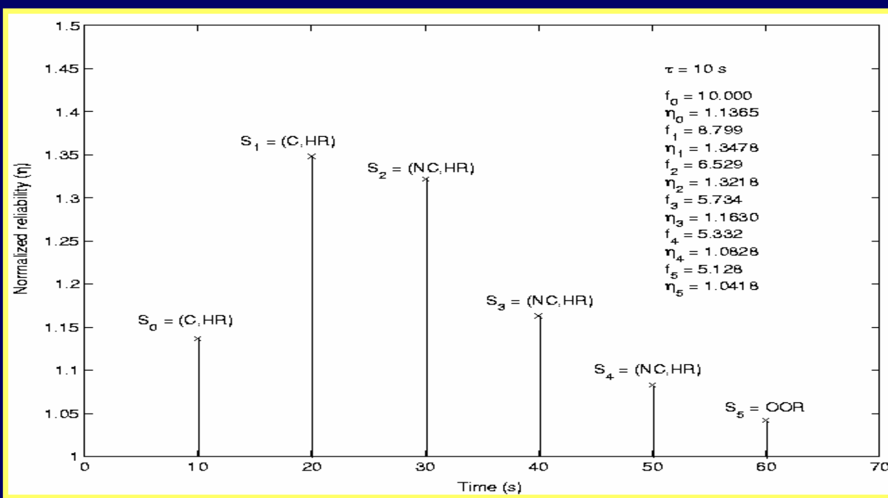
ESRT Performance



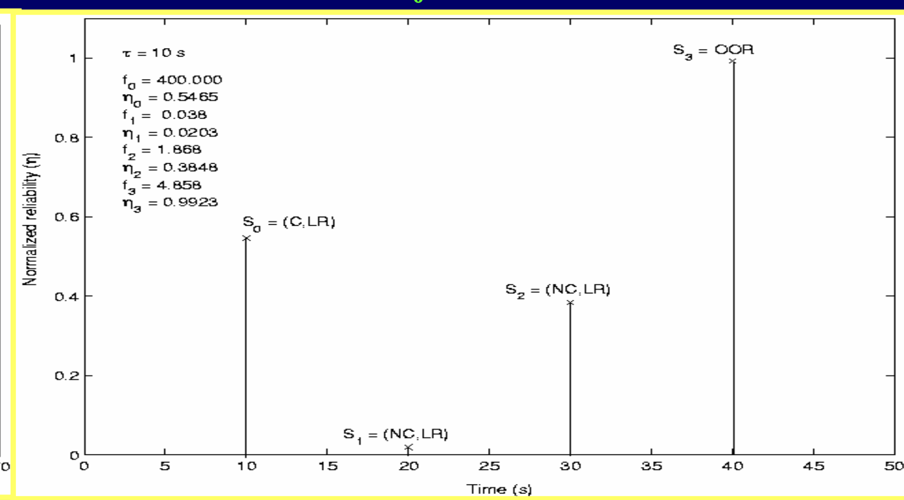
S_0 = (NC,LR)



S_0 = (NC,HR)



S_0 = (C,HR)



S_0 = (C,LR)

Medium Access Control (MAC) in WSN

- IEEE 802.11 [1]
  - Originally developed for WLANs
  - Per-node fairness
  - High energy consumption due to *idle listening*
- S-MAC [2]
  - Aims to decrease energy consumption by sleep schedules with virtual clustering
  - Redundant data are still sent with increased latency due to sleep schedules

[1] IEEE 802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," 1999

[2] W. Ye, J. Heidemann and D. Estrin, "An Energy Efficient MAC Protocol for Wireless Sensor Networks," *In Proc. ACM MOBICOM '01,* pp.221 –235, Rome, Italy 2001

Related Work

- **TRAMA[3]**
  - Based on time-slotted structure
  - Information about every two-hop neighbor is used for slot selection
  - High signaling overhead for high density networks
  - High latency due to time-slotted structure

[3] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks," in *Proc. ACM SenSys 2003*, Los Angeles, California, November 2003.

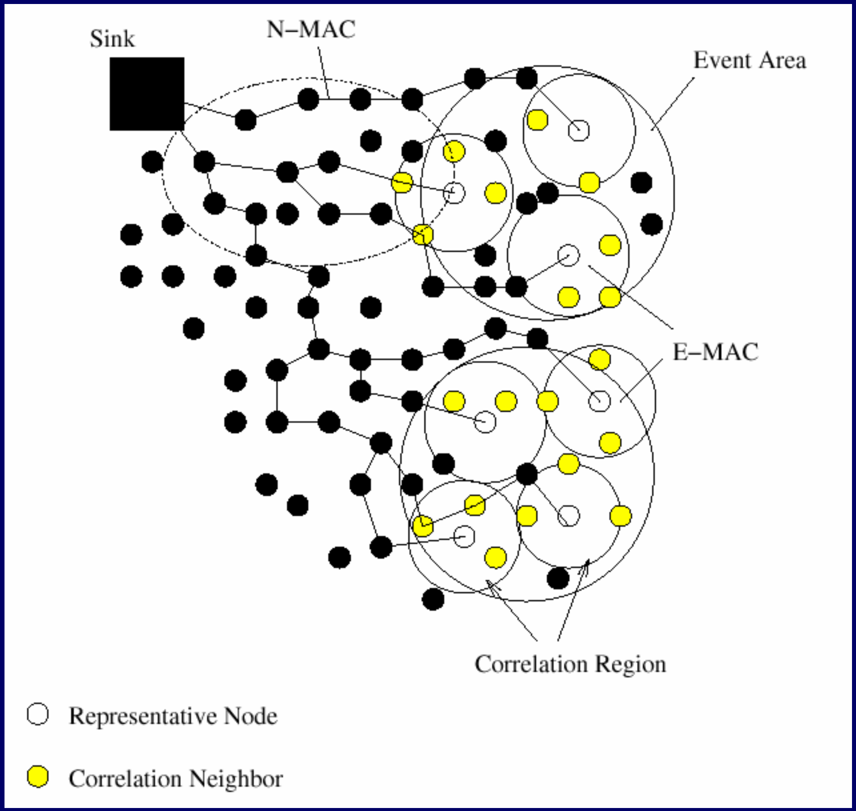
MAC for Sensor Networks

- **MAC Layer Challenges**
  - Limited power resources
  - Need for a self-configurable, distributed protocol
  - Data centric approach rather than per-node fairness

Exploit SPATIAL CORRELATION to reduce transmissions in MAC layer !

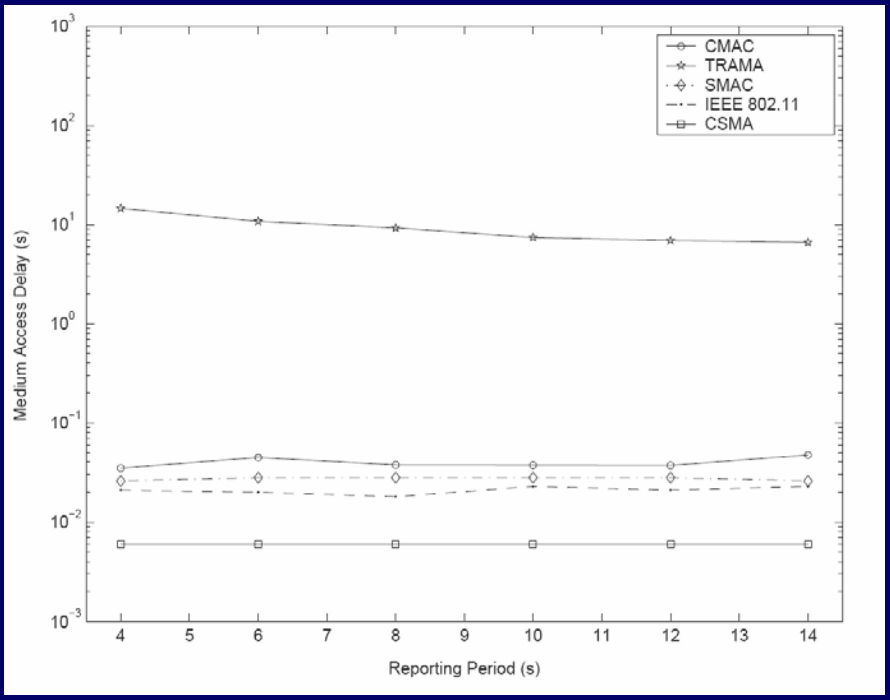
Collaborative MAC (CMAC) Protocol

M.C. Vuran, and I. F. Akyildiz, "Spatial Correlation-based Collaborative Medium Access Control in Wireless Sensor Networks," ***Submitted for publication***, **2004.**

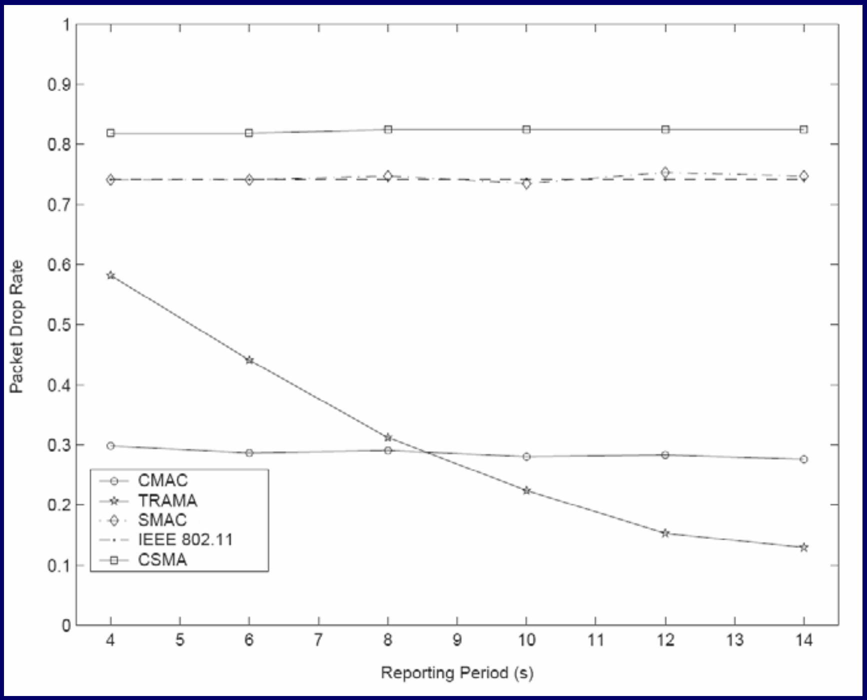


- ***Source function:*** **Transmit event information**
- ***Router function:*** **Forward packets from other nodes in the multi-hop path to the sink**
- **Two Components**
  - ***Event MAC (E-MAC)***
  - ***Network MAC (N-MAC)***

CMAC Performance

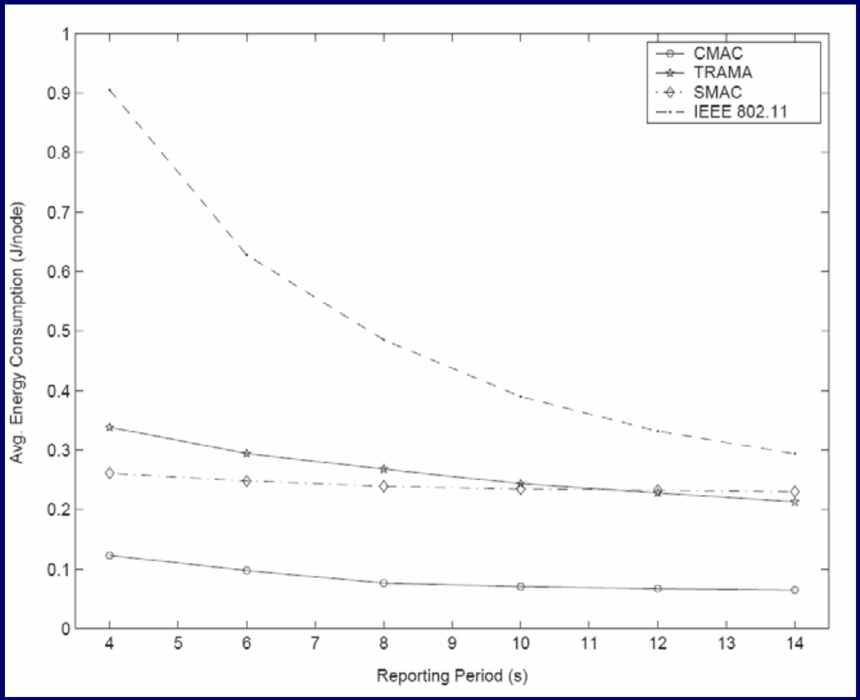


Medium Access Delay



Packet Drop Rate

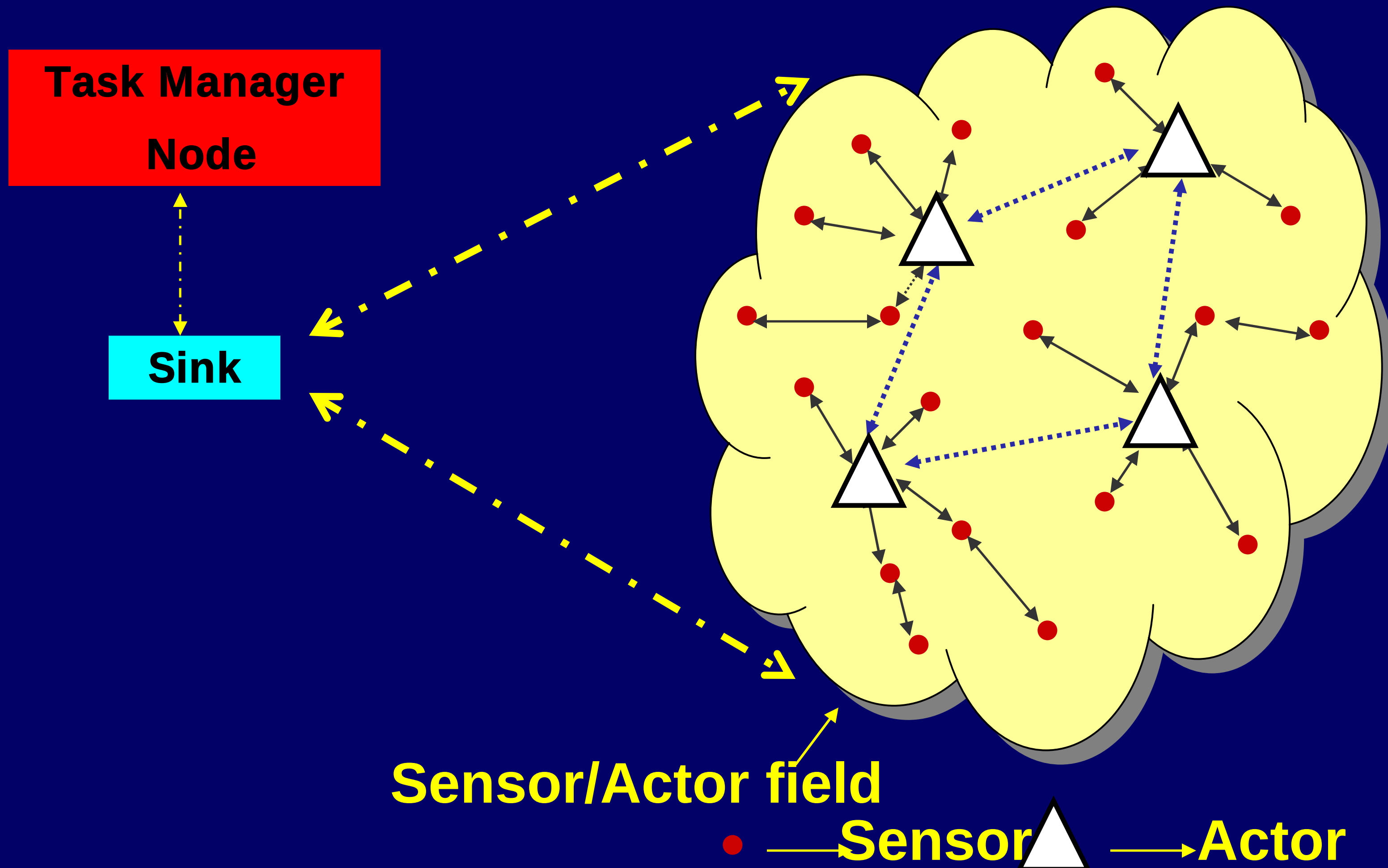
CMAC Performance



Avg. Energy Consumption

Wireless Sensor and Actor Networks

I.F. Akyildiz and I. H. Kasimoglu,
"Wireless Sensor and Actor Networks: Research Challenges",
Ad Hoc Networks Journal (Elsevier), October 2004.



Wireless Sensor and Actor Networks (WSANs)

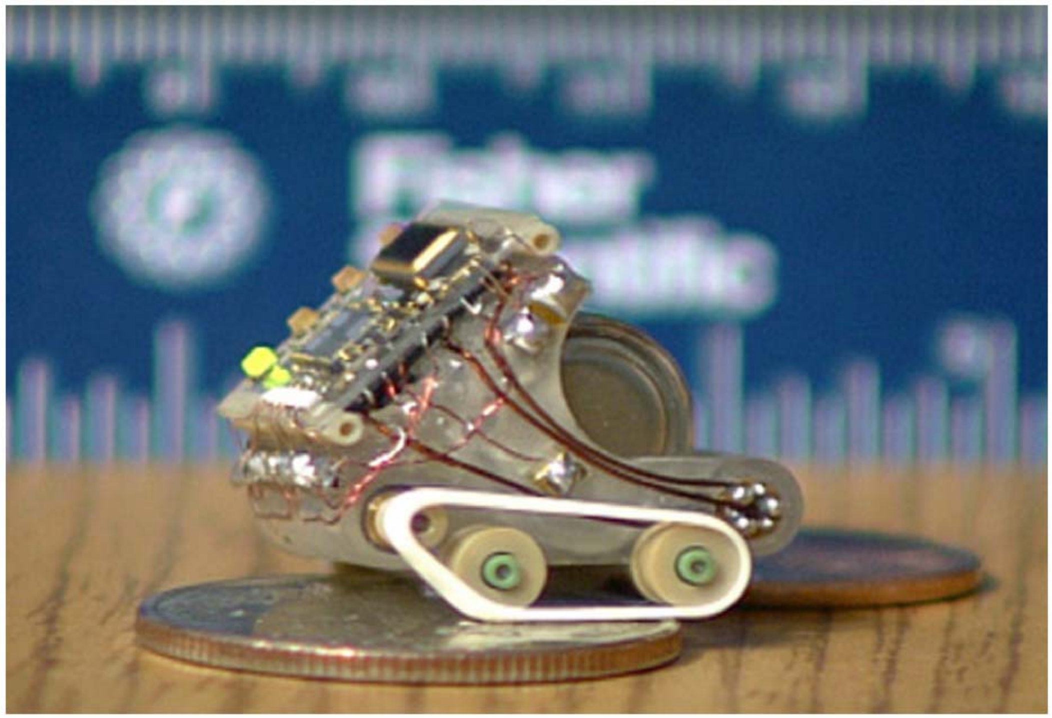
- Sensors
  - Passive elements sensing from the environment
  - Limited energy, processing and communication capabilities
- Actors
  - Active elements acting on the environment
  - Higher processing and communication capabilities
  - Less constrained energy resources (Longer battery life or constant power source)

- *Sensors + Actors* ⟶ *WSANs*

Sub-Kilogram Intelligent Tele-robots (SKITs): Networked Robots having Coordination & Wireless Communication Capabilities

Robotic Mule: Autonomous Battlefield Robot designed for the Army

Mini-Robot
(developed at Sandia National Laboratories)



Low Flying Helicopter Platform

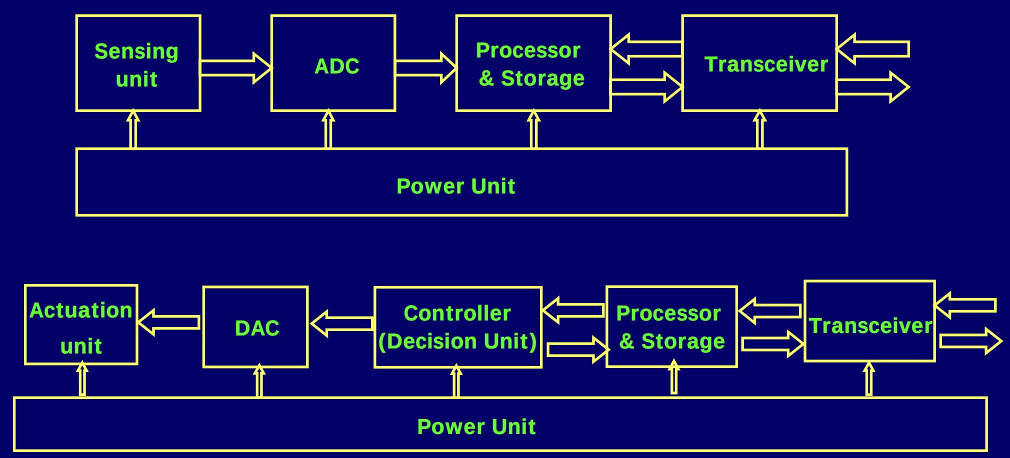
Photo courtesy of Sebastian Thrun

Figure 2. Sebastian Thrun's Aerial Mapping Helicopter

Components of Sensor & Actor Nodes

Sensor Node

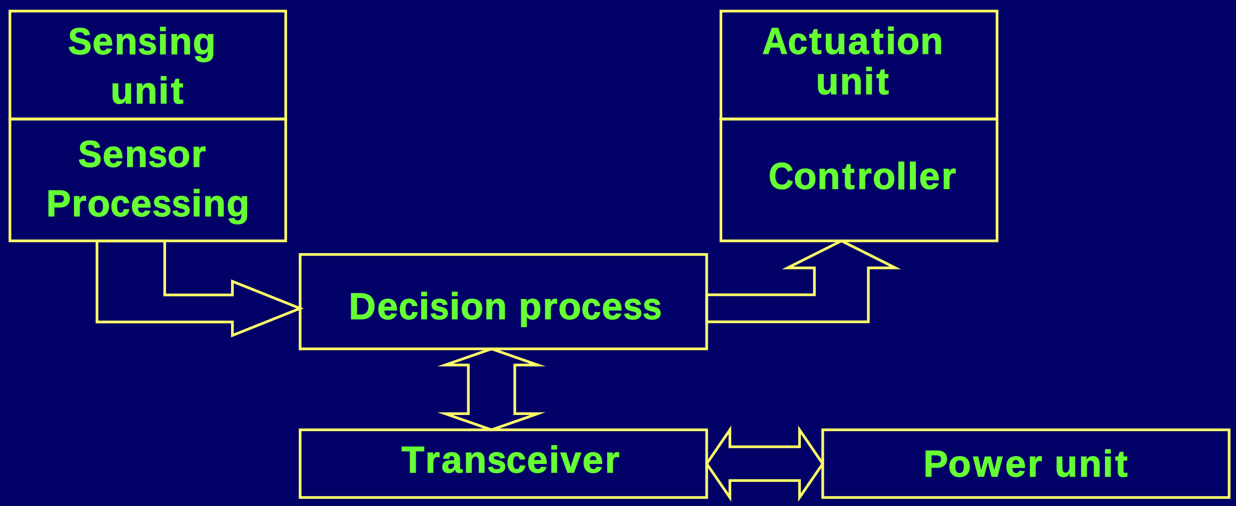
Actor Node



- **Actor Node Operation**
  - Actors receive digital data from sensors
  - Digital data is processed
  - Controller generates action commands based on data
  - Digital action command is converted to analog signal
  - Action is performed

Components of Sensor & Actor Nodes

- **Some applications use *integrated sensor/actor nodes*.**



WSAN Applications

- Environmental Applications:
  - Detecting and extinguishing forest fire.
- Microclimate control in buildings:
  - In case of very high or low temperature values, trigger the audio alarm actors in that area.
- Distributed Robotics & Sensor Network:
  - (Mobile) robots dispersed throughout a sensor network
- Battlefield Applications:
  - Sensors detect mines or explosive substances
  - Actors annihilate them or function as tanks

WSANs vs. Wireless Sensor Networks

- **Real-time requirements for timely actions**
  - Rapidly respond to sensor input (*e.g.*, fire application)
  - To perform right actions, sensor data must be valid at the time of acting

- **Heterogeneous Node Deployment**
  - Sensors → *Densely deployed*
  - Actors → *Loosely deployed* due to the different coverage requirements and physical interaction methods of acting task

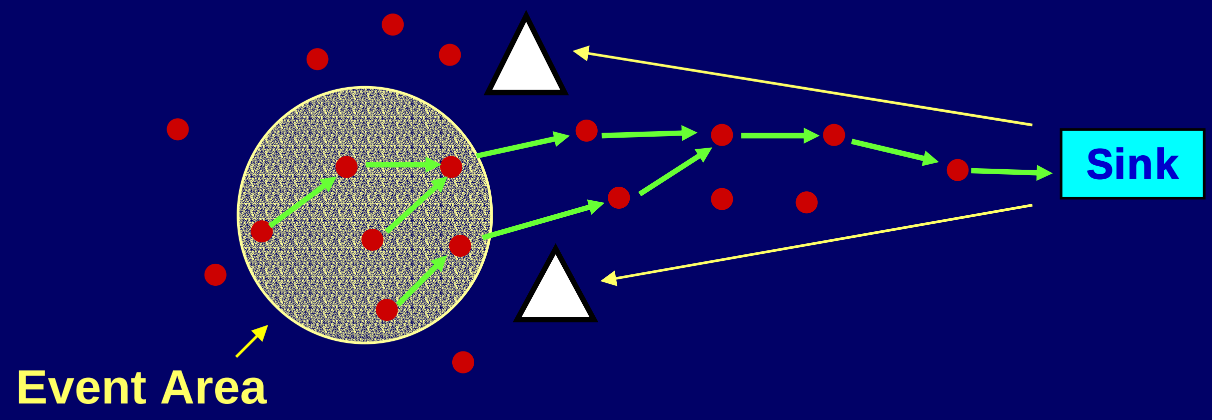
WSANs vs. Wireless Sensor Networks

- **Coordination Requirement**
  - A need for distributed local coordination mechanism
    - Sensor-Actor Coordination
    - Actor-Actor Coordination

- **High Node Mobility**
  - Especially actors may be mobile (i.e., robots)
  - Protocols should support mobility

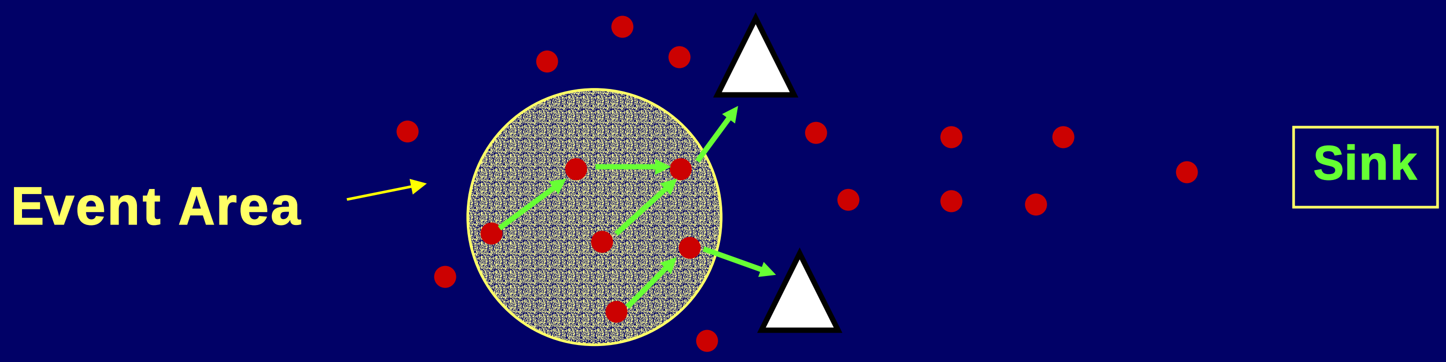
WSAN Communication Architecture

Semi-Automated Architecture



- *Sensors→Sink→Actors*
- Requires manual intervention at sink
- No sensor-actor and actor-actor coordination needed
- Similar to the conventional WSN architecture

WSAN Communication Architecture
Automated Architecture



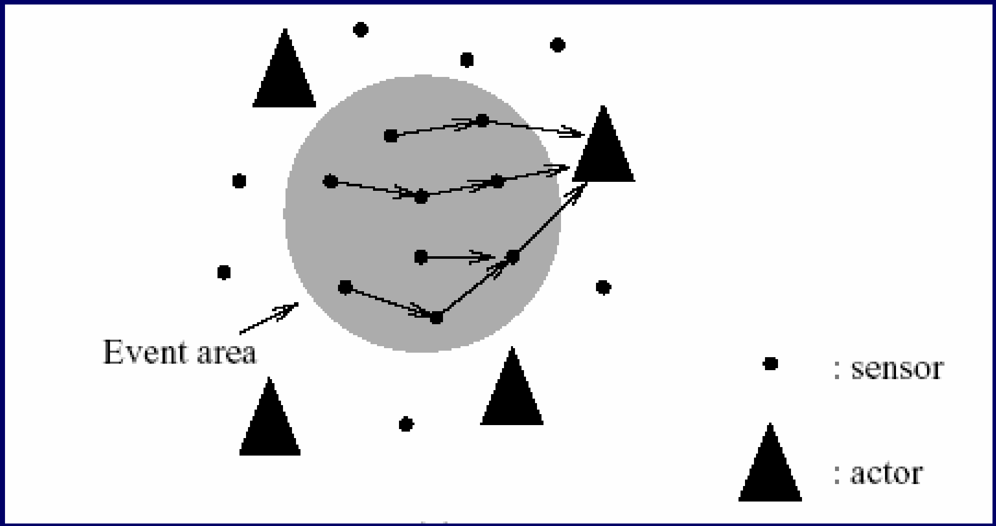
- *Sensors→Actors*
- No intervention from sink is necessary
- Localized information exchange
- Low latency
- *Distributed sensor-actor and actor-actor coordination required*

Effective Sensor-Actor Coordination

- **Transmission of sensor readings from sensors to actors**
- **Local coordination to provide efficient data transmission**
- **Challenges:**
  - Which sensor(s) communicate with which actor(s)
  - How this communication occurs (i.e. single-hop or multi-hop)
  - What are the requirements of this communication (i.e., real-time, energy efficient)

Effective Sensor-Actor Coordination

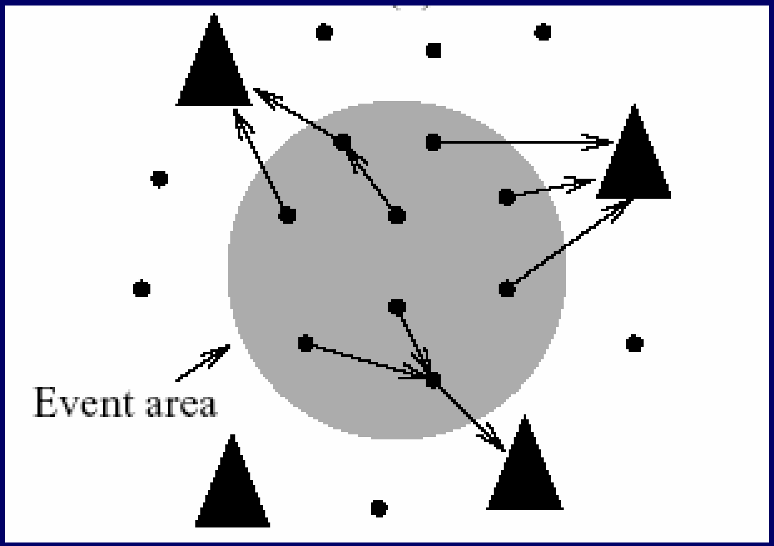
- **Single-Actor vs. Multi-Actor**
  - **Single-Actor**



  - *Selection of the most appropriate actor*
  - *To select, sensors need to coordinate with each other*

Effective Sensor-Actor Coordination

– **Multi-Actor**



- *Clustering is required*
- *Sensors only need to coordinate with sensors within some neighborhood to form clusters or groups*

Effective Actor-Actor Coordination

- **Why is Actor-Actor Communication necessary?**
  - Actor receiving sensor data may not act on event due to small action range
  - One actor may not be sufficient, so trigger other nearby actors
  - Multiple actors receiving same event data must communicate for proper and adequate action
  - In case of multiple events, task allocation required
- **Challenges:**
  - *Which actor(s) should execute which action(s)?*
  - *How should multi-actor task allocation be done?*

Effective Actor-Actor Coordination

- **Single-Actor Task vs. Multi-Actor Task**
  - *Single-Actor Task*
    - How is single actor selected?
  - *Multi-Actor Task*
    - What is the optimum number of actors performing actions?
    - Selection of most fit actors among the capable actors for that task

Effective Actor-Actor Coordination

- **Centralized Decision vs. Distributed Decision**
  - ***Centralized Decision***
    - Action decisions are taken in an organized way
    - Selection of the actor functioning as decision unit
    - *High latency*
  - ***Distributed Decision***
    - Local coordination
    - Timely actions
    - *High power consumption*

WSAN Protocol Suite

- *Management Plane*
  - Manages power, mobility and node failure problems.
- *Coordination plane*
  - Determines sensor/actor coordination based on data received from other planes.
- *Communication Plane*
  - Receives commands from the coordination plane and then performs communication.

Management Plane

- ***Power Management Plane***
  - Manages how a node uses its power.
- ***Mobility Management Plane***
  - Detects the movements of nodes to provide network connectivity.
- ***Fault Management Plane***
  - Refers to the detection and resolution of node problems.

Coordination Plane

- **Sensors Coordination**
  - to achieve higher-level sensing task
  - to determine nodes which will not transmit data due to applied MAC protocol
  - to perform multi-hop routing and data aggregation
  - to select actors which data will be sent to
- **Actors Coordination**
  - to select actors which act on the event area

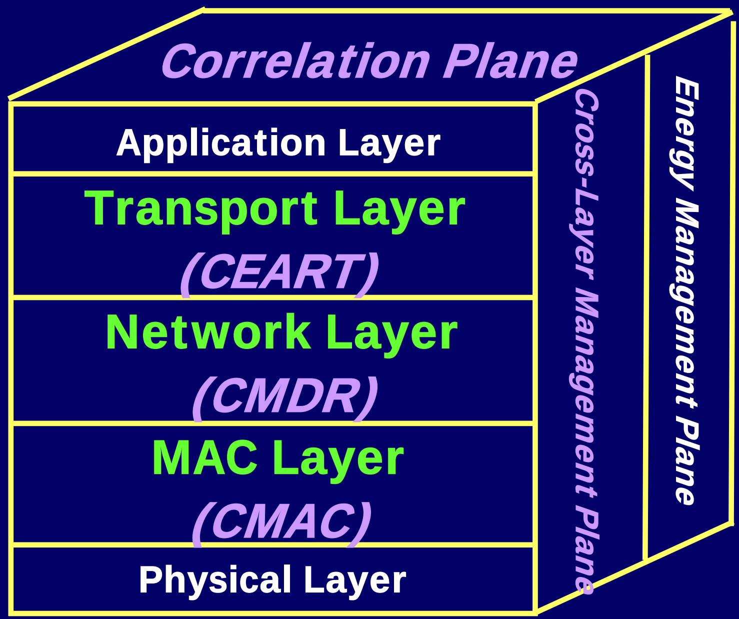
Communication Plane

- **Transport:**
  - *Event reliability* required for sensor-actor communication
  - *Conventional reliability* required for actor-actor communication
  - Both cases have REAL-TIME requirements.
- **Routing:**
  - Optimum paths both from sensors to actor(s) and from actors to actors
  - Supporting real-time and prioritization to provide actions to be performed on time.

Communication Plane

- ***MAC:***
  - Both ***energy efficiency*** and ***QoS*** (i.e. timeliness) guarantees
  - ***Adaptation*** to actor mobility
- **Cross-Layering**
  - Layering approach sub-optimal and inflexible for WSANs.
  - Cross layer approach provides effective sensing, data transmission and acting.

Correlation-Based Advanced Protocols for WSAN



GOAL:

- Develop *theoretical correlation framework*
- EXPLOIT SPATIAL/TEMPORAL CORRELATION
  - High node density → *Spatial Correlation*
  - Event characteristics → *Temporal Correlation*
- Develop *advanced collaborative correlation-based energy-efficient protocols based on theory*

Commercial Viability of WSN Applications

- ***XSILOGY Solutions*** **is a company which provides wireless sensor network solutions for various commercial applications such as tank inventory management, stream distribution systems, commercial buildings, environmental monitoring, homeland defense etc.**

  http://www.xsilogy.com/home/main/index.html

- ***In-Q-Tel*** **provides distributed data collection solutions with sensor network deployment.**

  http://www.in-q-tel.com/tech/dd.html

- ***ENSCO Inc.*** **invests in wireless sensor networks for meteorological applications.**

  http://www.ensco.com/products/homeland/msis/msis_rnd.htm

- ***EMBER*** **provides wireless sensor network solutions for industrial automation, defense, and building automation.**

  http://www.ember.com

Commercial Viability of WSN Applications

- *H900 Wireless SensorNet System(TM),* the first commercially available end-to-end, low-power, bi-directional, wireless mesh networking system for commercial sensors and controls is developed by the company called *Sensicast Systems*. The company targets wide range of commercial applications from energy to homeland security.

  http://www.sensicast.com

- *The Sensor-based Perimeter Security* product is introduced by a company called *SOFLINX Corp.* (a wireless sensor network software company)

  http://www.soflinx.com

- *XYZ On A Chip: Integrated Wireless Sensor Networks for the Control of the Indoor Environment In Buildings* is another commercial application project currently performed by Berkeley.

  http://www.cbe.berkeley.edu/research/briefs-wirelessxyz.htm

Commercial Viability of WSN Applications

- *The Crossbow* wireless sensor products and its environmental monitoring and other related industrial applications of such as surveillance, bridges, structures, air quality/food quality, industrial automation, process control are introduced.

  http://www.xbow.com

- *Japan's Omron Corp* has two wireless sensor projects in the US that it hopes to commercialize in the near future. *Omron's Hagoromo Wireless Web Sensor project* consists of wireless nodes equipped with various sensing abilities for providing security for major cargo-shipping ports around the world.

  http://www.omron.com

- Possible business opportunity with a big home improvement store chain, Home Depot, with Intel and Berkeley using wireless sensor networks

  http://www.svbizink.com/otherfeatures/spotlight.asp?iid=314

Commercial Viability of WSN Applications

- *Millennial Net* builds wireless networks combining sensor interface endpoints and routers with gateways for industrial and building automation, security, and telemetry
  http://www.millennial.net
- *CSEM* provides sensing and actuation solutions
  http://www.csem.ch/fs/acuating.htm
- *Dust Inc.* develops the next-generation hardware and software for wireless sensor networks
  http://www.dust-inc.com
- *Integration Associates* designs sensors used in medical, automotive, industrial, and military applications to cost-effective designs for handheld consumer appliances, barcode readers, and wireless computer input devices
  http://www.integration.com

Commercial Viability of WSN Applications

- *Melexis* produces advanced integrated semiconductors, sensor ICs, and programmable sensor IC systems.
  http://www.melexis.com

- *ZMD* designs, manufactures and markets high performance, low power mixed signal ASIC and ASSP solutions for wireless and sensor integrated circuits.
  http://www.zmd.biz

- *Chipcon* produces low-cost and low-power single-chip 2.4 GHz ISM band transceiver design for sensors.
  http://www.chipcon.com

- *ZigBee Alliance* develops a standard for wireless low-power, low-rate devices.
  http://www.zigbee.com

What are the Current Showstoppers?

- WHAT IS THE MOST EFFICIENT WAY TO REALIZE COMMUNICATION????
- Do we need all fancy protocols?
- Follow the TCP/IP Stack, i.e., keep the Strict Layer Approach ???
- Or Interleave the Layer functionalities???
- Cross Layer Optimization

DEMOS Applications

- Clear Demonstration of Testbeds and Realistic Applications

- Not only data or audio but also video as well as integrated traffic.

Basic Research Needs for Sensor Networks

- **An Analytical Framework for Sensor Networks**

  → Find a Basic Generic Architecture and Protocol development which can be tailored to specific applications.

FURTHER OPEN RESEARCH ISSUES

- **Research to *integrate WSNs into NGWI***
  e.g., interactions of Sensor and AdHoc Networks or Sensor and Satellite or any other combinations…

- **Explore the SENSOR-ANTISENSOR NETWORKS**

Need for Realistic Applications

SOME OF OUR EFFORTS IN BWN LAB @ GaTech

- **SpINet → for Mars Surface**
- **Airport Security → Sensors/Actors**