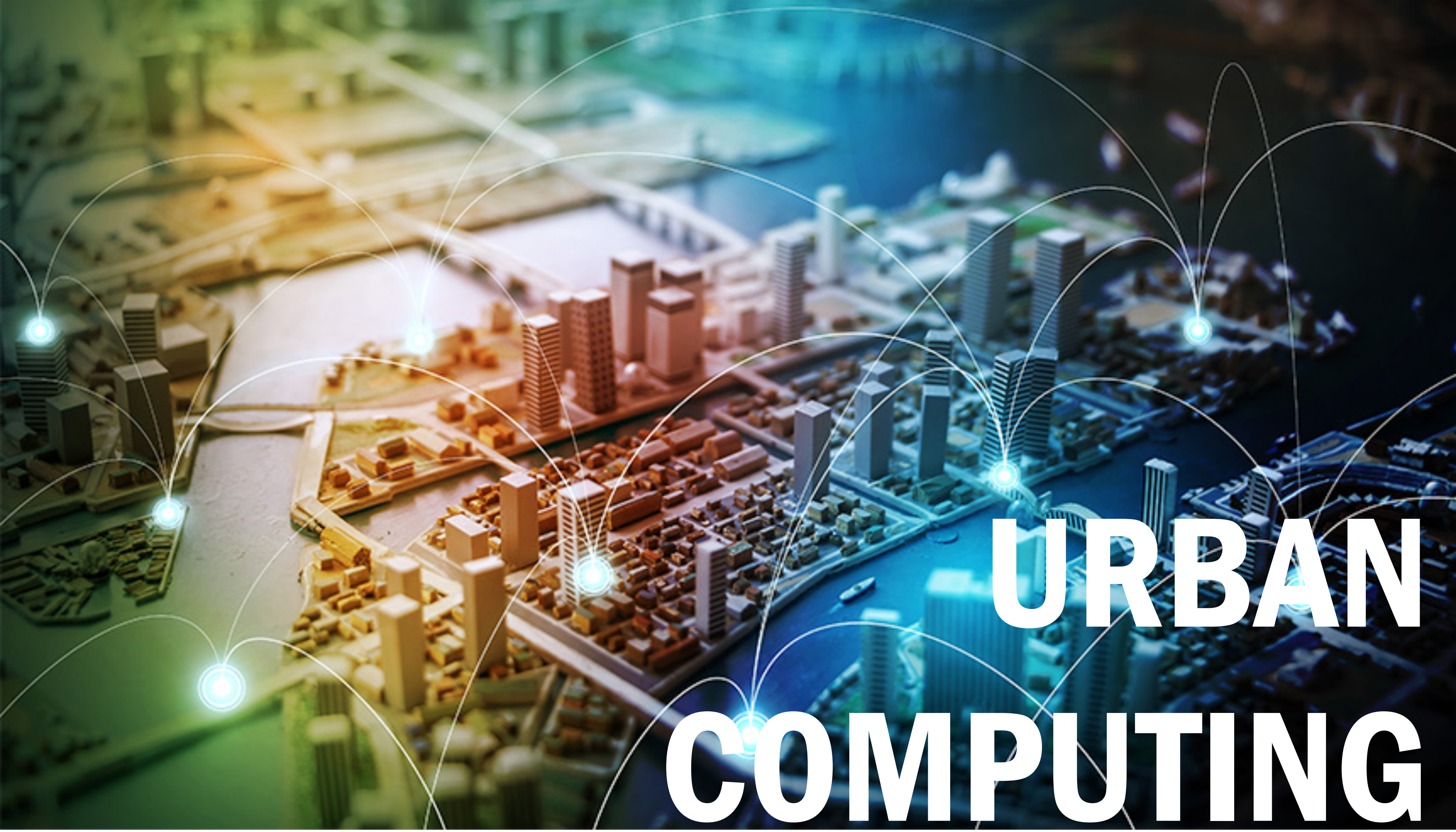

URBAN COMPUTING

Image credit: smart-energy.com

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AI6128 Urban Computing

Lecture 2

Urban Sensing

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Content

- Sensors
- Urban sensor networks
- Urban sensing applications
- Sensor network design

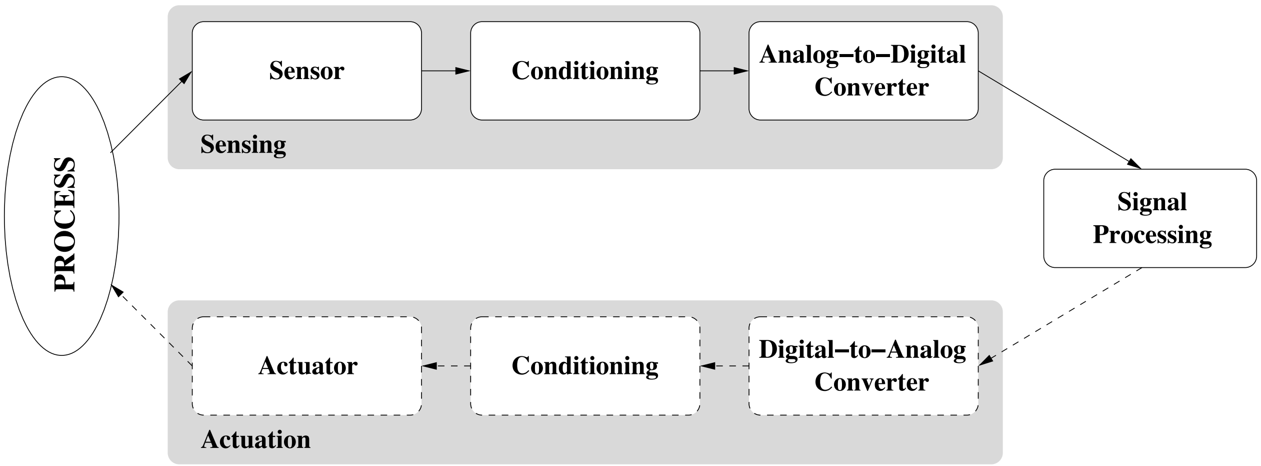
Sensors

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)

Data Acquisition

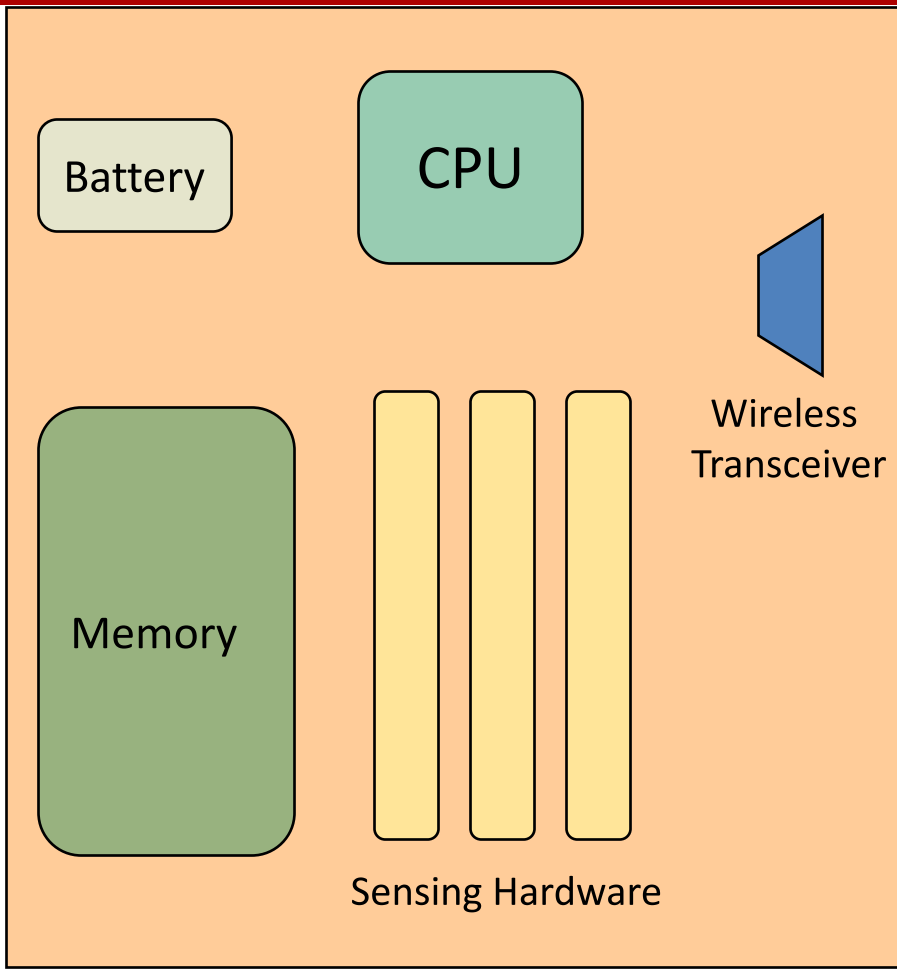


- Sensor captures phenomena in the physical world (process, system, plant)
- Signal conditioning prepares captured signals for further use (amplification, attenuation, filtering of unwanted frequencies, etc.)
- Analog-to-digital conversion (ADC) translates analog signal into digital signal
- Digital 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 Classification

Type	Examples
Temperature	Thermistors, thermocouples
Pressure	Pressure gauges, barometers, ionization gauges
Optical	Photodiodes, phototransistors, infrared sensors, CCD sensors
Acoustic	Piezoelectric resonators, microphones
Mechanical	Strain gauges, tactile sensors, capacitive diaphragms, piezoresistive cells
Motion, vibration	Accelerometers, mass air flow sensors
Position	GPS, ultrasound-based sensors, infrared-based sensors, inclinometers
Electromagnetic	Hall-effect sensors, magnetometers
Chemical	pH sensors, electrochemical sensors, infrared gas sensors
Humidity	Capacitive and resistive sensors, hygrometers, MEMS-based humidity sensors
Radiation	Ionization detectors, Geiger-Mueller counters

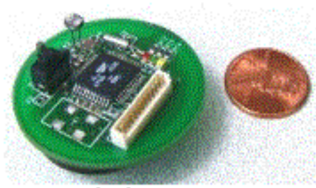
Wireless Sensors

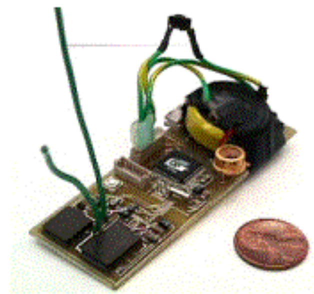


- Enabled by recent advances in MEMS technology
- Integrated wireless transceiver
- Limited in
  - Energy
  - Computing capability
  - Storage
  - Transmission range
  - Bandwidth

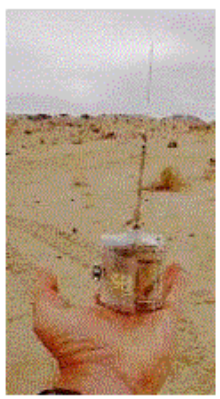
Wireless Sensors (cont'd)

Modern Sensor Nodes


UC Berkeley: COTS Dust


UC Berkeley: COTS Dust

UC Berkeley: Smart Dust


UCLA: WINS


Rockwell: WINS


JPL: Sensor Webs

Mote: A small wireless sensor node, part of a larger network

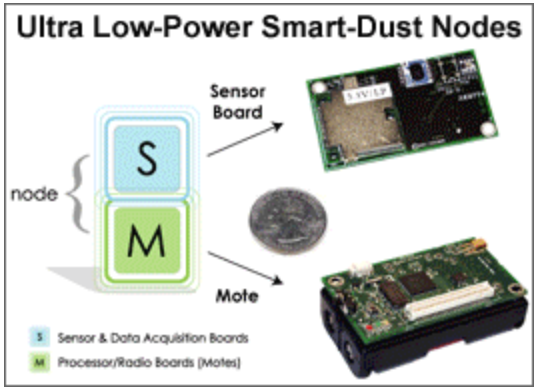
TelosB Mote

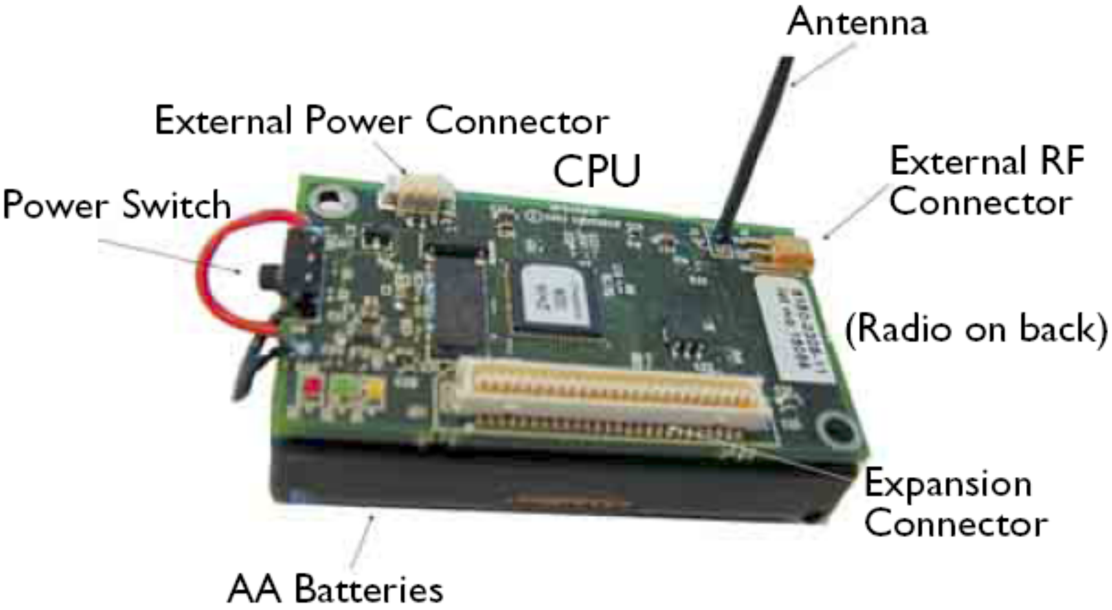
- The overall architecture of a sensor node consists of:
  - The sensor node processing subsystem running on sensor node main CPU
  - The sensor subsystem and
  - The communication subsystem

- 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)

MICAz Mote

- MTS310 sensor board
  - Acceleration
  - Magnetic
  - Light
  - Temperature
  - Acoustic
  - Sounder





MICAz follows IEEE 802.15.4 Zigbee standard with direct sequence spread spectrum radio and 256kbps data rate

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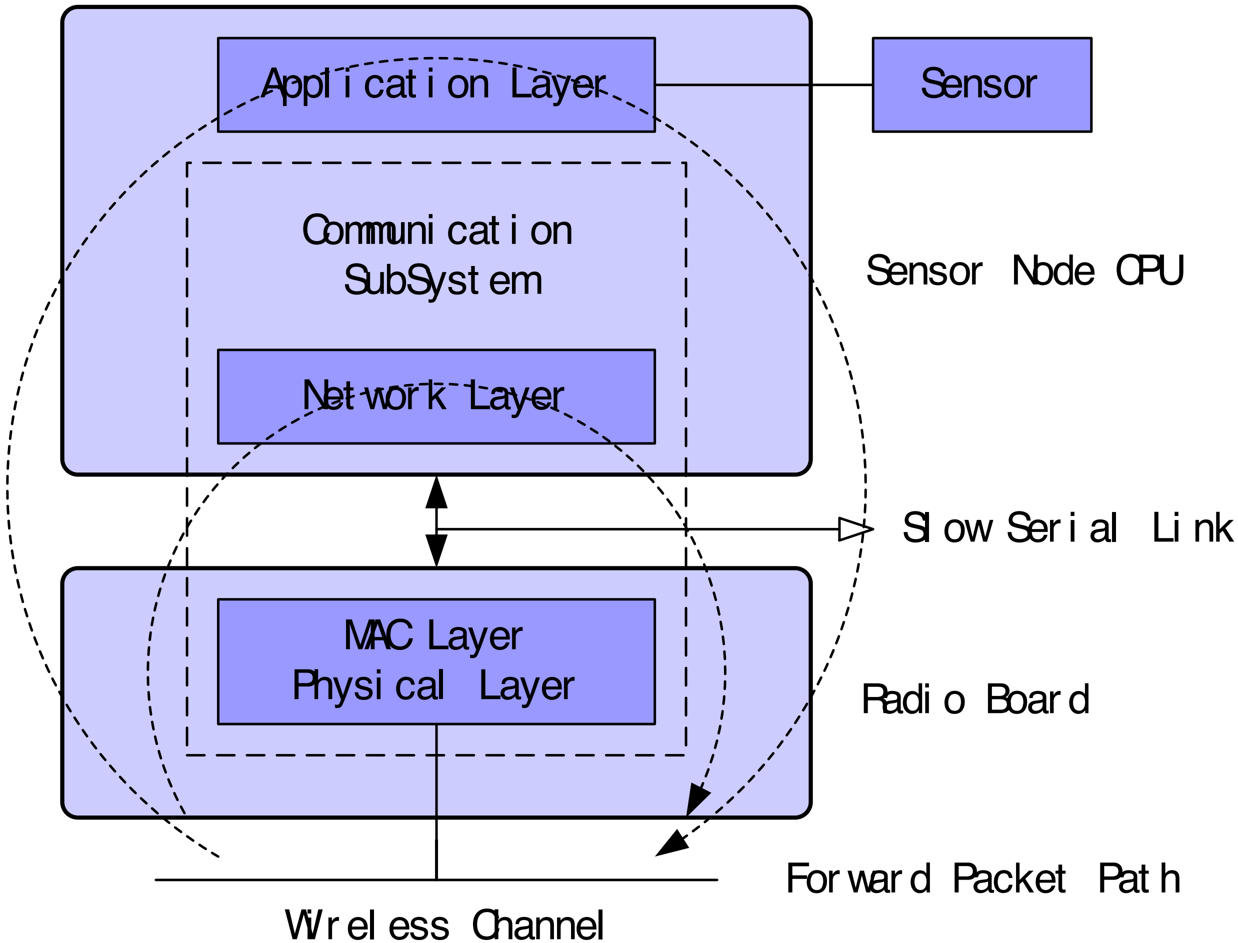
TI SensorTag

- ARM Cortex-M3 SoC
  - 32bit MCU
  - CC2650 Wireless (Bluetooth, Zigbee)
  - Temperature, movement, humidity, pressure, optical
  - Can be bought on Amazon (~S$70)

Software Architecture of Wireless Sensor



Smartphone

- Massive deployment
- A sensor-rich device

IMU: Intertial measurement unit:

Accelerometer,
Gyroscope,
Magnetometer (can differentiate between magnetic reading in indoor settings)

camera

part of home button in old models. no longer used

Image credit: https://www.mdpi.com/1424-8220/19/9/2164/htm

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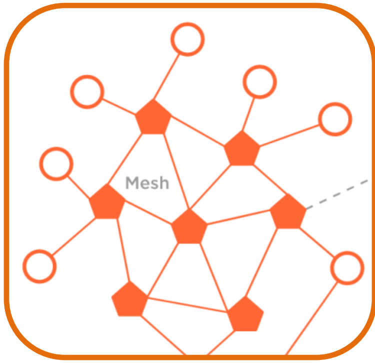
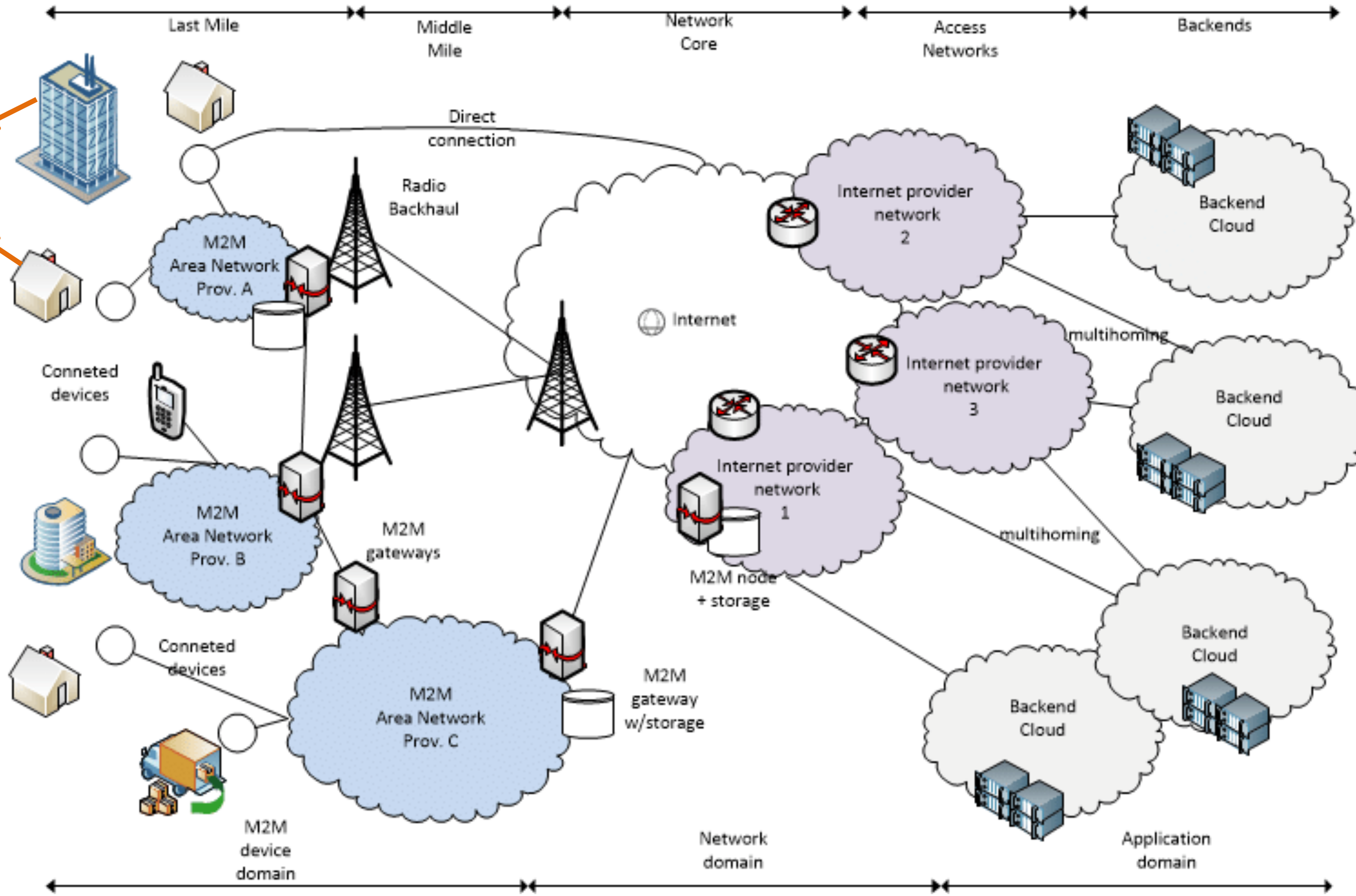
Urban Sensor Networks

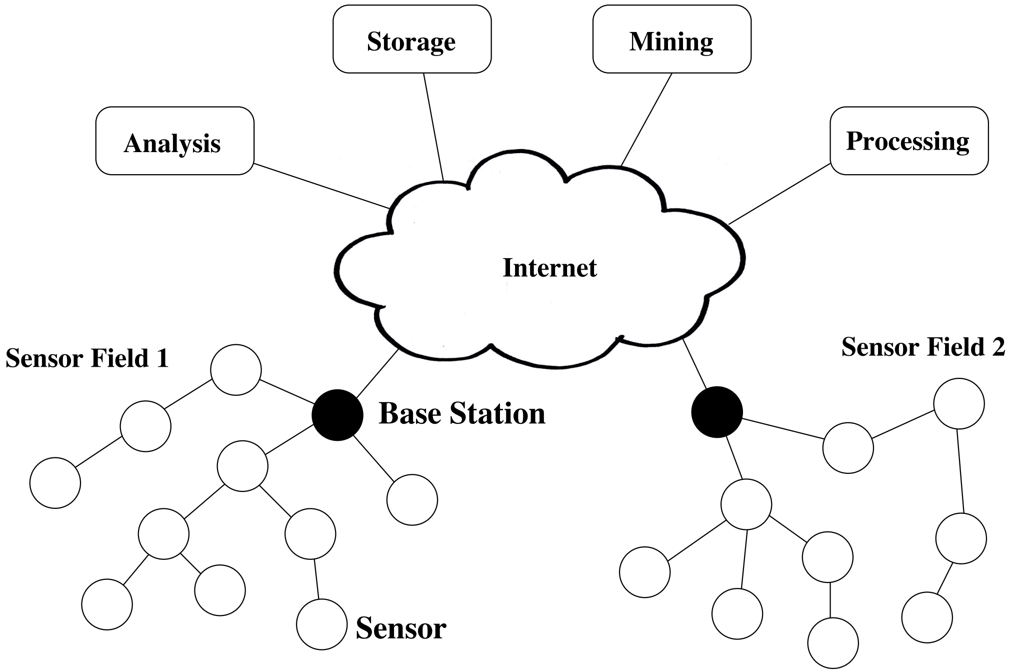
The Big Picture



Wireless Mesh



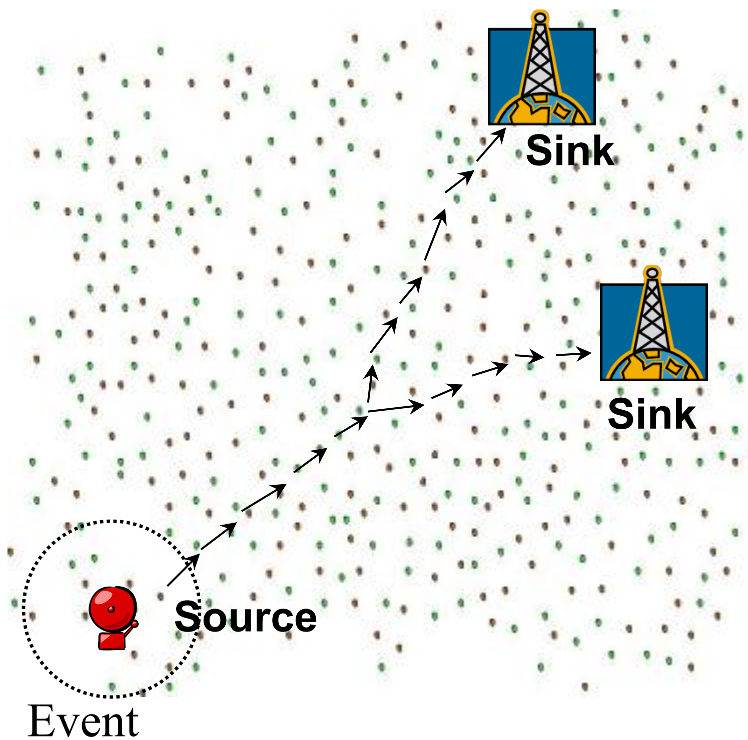
Wireless Sensor Network (WSN)



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

Common Network Architecture

- Sensor nodes are responsible for
  - Detection of events
  - Observation of environments
  - Relaying of third party messages
- Information is generally gathered at sinks
  - Sinks are responsible for higher level processing and decision making



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 network

History of WSN

- DARPA:
  - Distributed Sensor Nets Workshop (1978)
  - Distributed Sensor Networks (DSN) program (early 1980s)
  - Sensor Information Technology (SensIT) program
- UCLA and Rockwell Science Center
  - Wireless Integrated Network Sensors (WINS)
  - Low Power Wireless Integrated Microsensor (LWIM) (1996)
- UC-Berkeley
  - Smart Dust project (1999)
  - Concept of “motes”: extremely small sensor nodes
- Berkeley Wireless Research Center (BWRC)
  - PicoRadio project (2000)
- MIT
  - µAMPS (micro-Adaptive Multidomain Power-aware Sensors) (2005)

History of WSN (cont'd)

- Recent commercial efforts
  - Crossbow (www.xbow.com)
  - Memsic (www.memsic.com)
  - Sensoria (www.sensoria.com)
  - Worldsens (worldsens.citi.insa-lyon.fr)
  - Dust Networks (www.dustnetworks.com)
  - Ember Corporation (www.ember.com)

WSN Communication

- Characteristics of typical WSN:
  - Low data rates (comparable to dial-up modems)
  - Energy-constrained sensors

High to Low Energy Usage:
Cell
WiFi
BT (Classic Bluetooth)
Zigbee / BLE (Bluetooth Low energy)
RFID / NFC

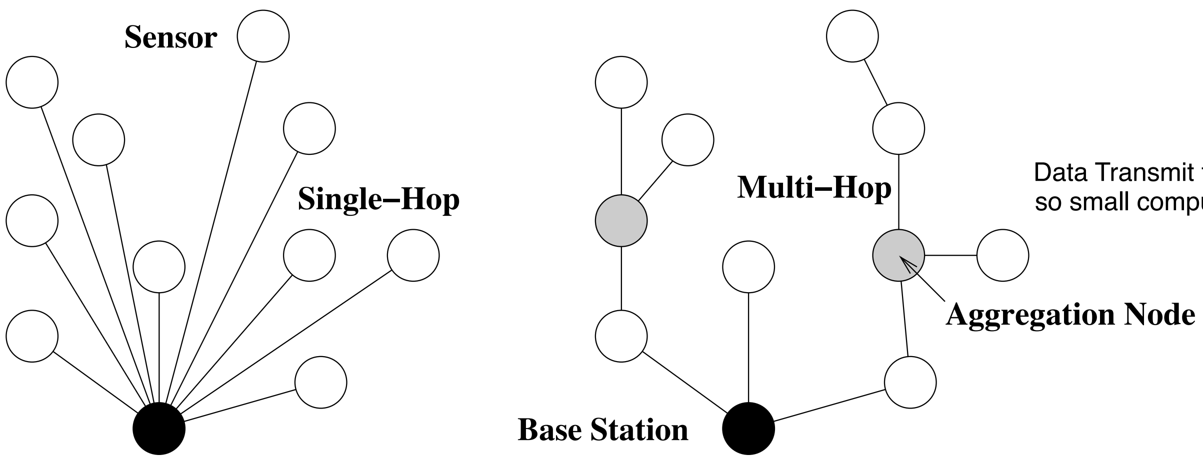
- IEEE 802.11 (Wi-Fi) family of standards
  - Most widely used WLAN protocols for wireless communications in general
  - Can be found in early sensor networks or sensors networks without stringent energy constraints

- IEEE 802.15.4 (Zigbee) 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 (multi-hop)
  - May reduce power consumption and allows for larger coverage
  - Introduces the problem of routing

threshold < P_receiver = P_transmitter / d^2



Data Transmit through aggregation:
so small computation on node itself

Challenges of WSN

- Energy efficiency
- Networking
- Decentralization
- Design constraints
- Security

WSN Challenge: Energy Efficiency

- 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

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

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WSN Challenge: Energy Efficiency (cont'd)

- 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

Comparison of Energy Sources

	Power (Energy) Density	Source of Estimates
Batteries (Zinc-Air)	1050 -1560 mWh/cm^3 (1.4 V)	Published data from manufacturers
Batteries(Lithium ion)	300 mWh/cm^3 (3 - 4 V)	Published data from manufacturers
Solar (Outdoors)	15 mW/cm^2 - direct sun 0.15mW/cm^2 - cloudy day.	Published data and testing.
Solar (Indoor)	.006 mW/cm^2 - my desk 0.57 mW/cm^2 - 12 in. under a 60W bulb	Testing
Vibrations	0.001 - 0.1 mW/cm^3	Simulations and Testing
Acoustic Noise	3E-6 mW/cm^2 at 75 Db sound level 9.6E-4 mW/cm^2 at 100 Db sound level	Direct Calculations from Acoustic Theory
Passive Human Powered	1.8 mW (Shoe inserts >> 1 cm^2)	Published Study.
Thermal Conversion	0.0018 mW - 10 deg. C gradient	Published Study.
Nuclear Reaction	80 mW/cm^3 1E6 mWh/cm^3	Published Data.
Fuel Cells	300 - 500 mW/cm^3 ~4000 mWh/cm^3	Published Data.

With aggressive energy management, ENS might live off the environment.

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Energy Management

- Actuation energy is the highest
  - Strategy: ultra-low-power “sentinel” nodes
    - Wake-up or command movement of mobile nodes
- Communication energy is the next important issue
  - Strategy: energy-aware data communication
    - Adapt the instantaneous performance to meet the timing and error rate constraints, while minimizing energy/bit
- Processor and sensor energy usually less important

MICA mote Berkeley

Transmit	720 nJ/bit	Processor	4 nJ/op
Receive	110 nJ/bit	~ 200 ops/bit	

WINS node RSC

Transmit	6600 nJ/bit	Processor	1.6 nJ/op
Receive	3300 nJ/bit	~ 6000 ops/bit	

II-29

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WSN Challenge: Networking

- 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

WSN Challenge: Networking (cont'd)

- 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

WSN Challenge: Networking (cont'd)

- 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

WSN Challenge: 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 Challenge: Design Constraints

- Many hardware and software limitations affect the overall system design

- Examples include:
  - Low processing speeds (to save energy)
  - Low storage capacities (to allow for small form factor and to save energy)
  - Lack of I/O components such as GPS receivers (reduce cost, size, energy)
  - Lack of software features such as multi-threading (reduce software complexity)

WSN Challenge: Security

- Sensor networks often monitor critical infrastructure or carry sensitive information, making them desirable targets for attacks
- Attacks may be facilitated by:
  - Remote and unattended operation
  - Wireless communication
  - Lack of advanced security features due to cost, form factor, or energy
- Conventional security techniques often not feasible due to their computational, communication, and storage requirements
- As a consequence, sensor networks require new solutions for intrusion detection, encryption, key establishment and distribution, node authentication, and secrecy

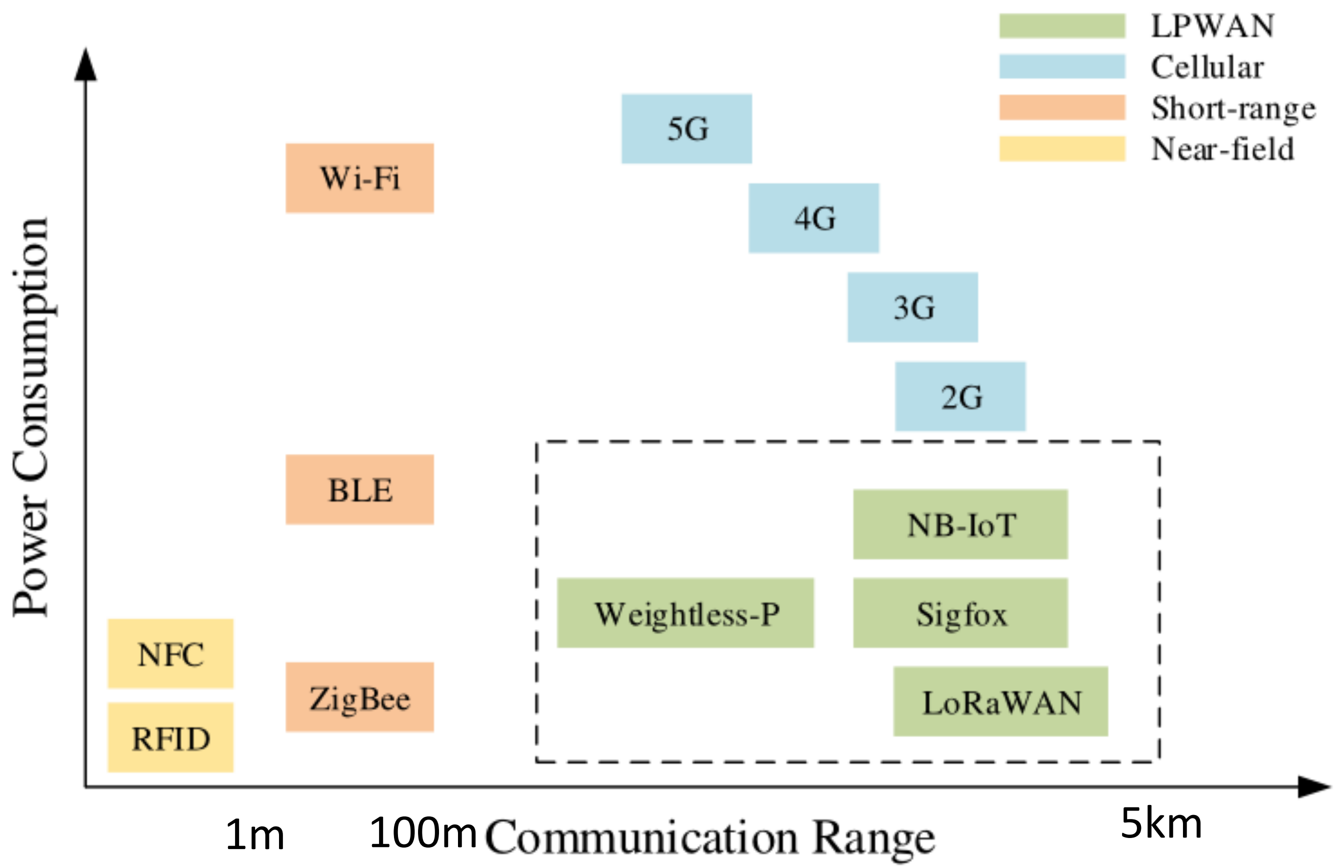
Comparison

Traditional Networks	Wireless Sensor Networks
General-purpose design; serving many applications	Single-purpose design; serving one specific application
Typical primary design concerns are network performance and latencies; energy is not a primary concern	Energy is the main constraint in the design of all node and network components
Networks are designed and engineered according to plans	Deployment, network structure, and resource use are often ad-hoc (without planning)
Devices and networks operate in controlled and mild environments	Sensor networks often operate in environments with harsh conditions
Maintenance and repair are common and networks are typically easy to access	Physical access to sensor nodes is often difficult or even impossible
Component failure is addressed through maintenance and repair	Component failure is expected and addressed in the design of the network
Obtaining global network knowledge is typically feasible and centralized management is possible	Most decisions are made localized without the support of a central manager

New Development: LPWAN

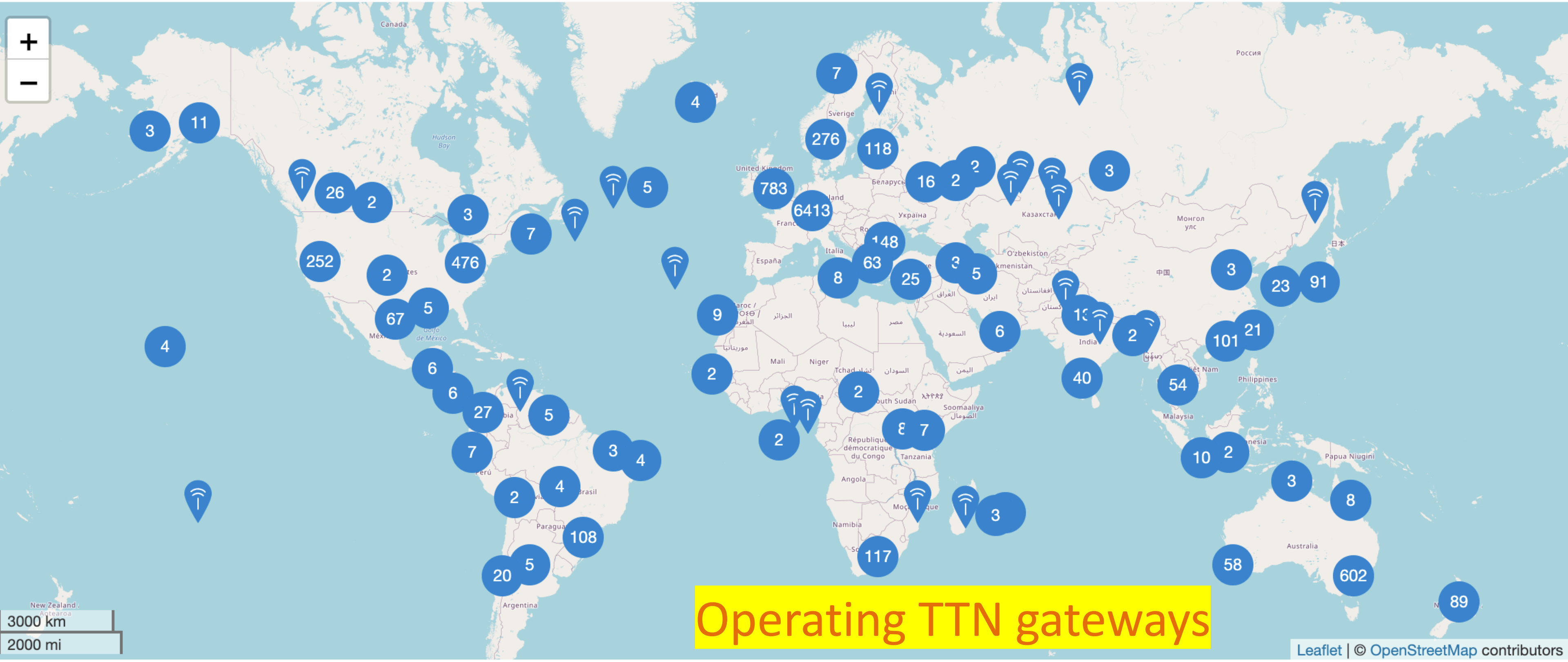
- Low-power wide-area networking (LPWAN)
  - Long Range (LoRa) and LoRaWAN
  - Narrowband IoT (NB-IoT)
  - Sigfox
  - Weightless-P
  - etc

Technology Position



Forming Global Ecosystem

- LoRaWAN-based The Things Network (TTN)



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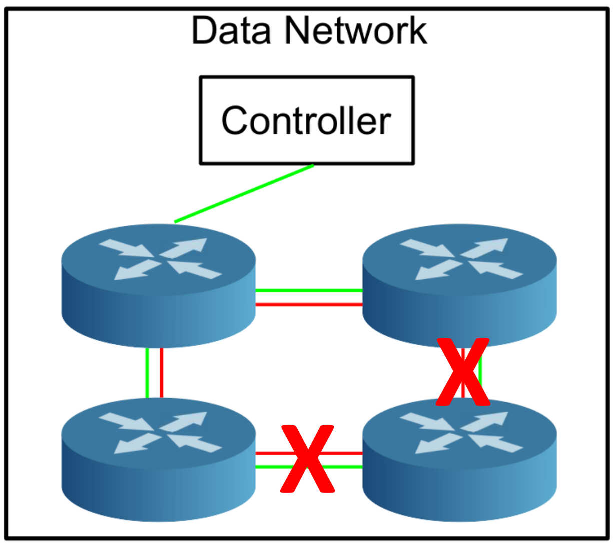
Using LoRa to Tackle Networking Challenges

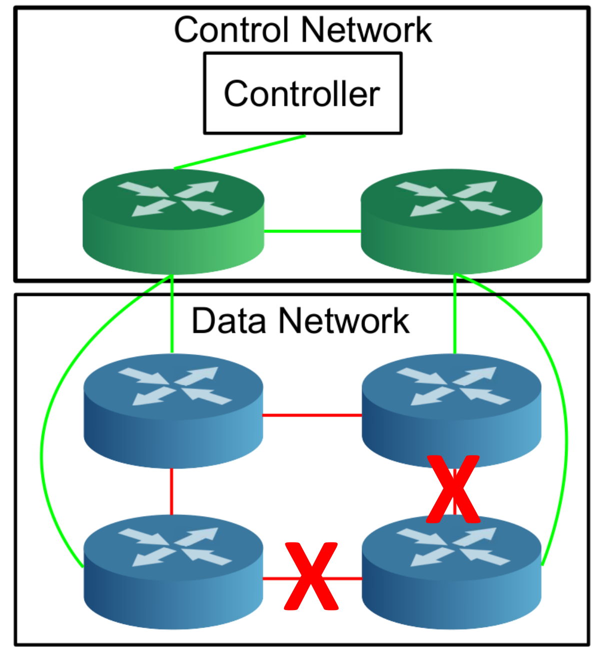
- Mission-critical applications are moving towards centralized network management
  - WirelessHART (used in >8,000 industrial systems)
  - ISA100.11a standard

In-band vs. Out-of-Band Network Management

In-band control plane



Out-of-band control plane



Undesirable coupling

- Lose control in data-plane failures

No coupling

- Simple and resilient

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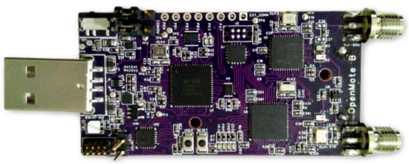
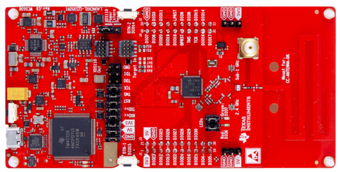
LPWAN-based Control Plane

- LPWAN's kilometers communication range
  - One-hop control plane
  - Good manageability

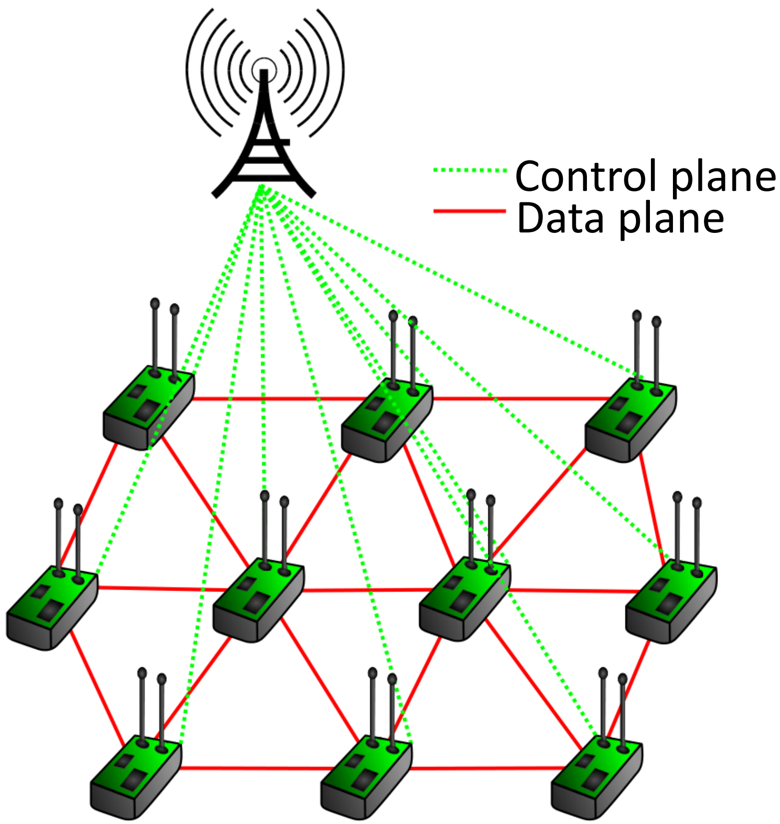
- Dual-radio devices are increasingly available



Openmote: Sub-GHz, 2.4 GHz



Simplelink: Sub-GHz, Zigbee, BLE



Urban Sensing Applications

Urban Sensing Applications

- Structural health monitoring
- Traffic sensing
- Pipeline monitoring

Structural Health Monitoring

- Motivation
  - Events:
    - On August 2, 2007, a highway bridge unexpectedly collapsed in Minnesota
    - Nine people were killed in the event
    - Potential causes: wear and tear, weather, and the weight of a nearby construction project
    - In fact, the BBC reported (August 14, 2007) that China had identified more than 6,000 bridges that were damaged or considered to be dangerous
  - These accidents motivate wireless sensor networks for monitoring bridges and similar structures

Structural Health Monitoring (cont'd)

- Motivation:
  - Traditional inspections:
    - Visual inspection ➔ everyday
      - Labor-intensive, tedious, inconsistent, and subjective
    - Basic inspections ➔ at least once a year
    - Detailed inspection ➔ at least every five years on selected bridges
    - Special inspections ➔ according to technical needs
      - The rest require sophisticated tools ➔ expensive, bulky, and power consuming

Local and Global Inspections

- Local inspection techniques focus on detecting highly localized, imperceptible fractures in a structure
  - Requires:
    - a significant amount of time
    - the disruption of the normal operation of the structure
- Global inspection techniques aim to detect a damage or defect that is large enough to affect the entire structure
  - Researcher have been developing and testing wireless sensor networks as global inspection techniques

Wisden by USC

- First prototype to employ WSN for monitoring structural health
  - Installing a large scale wired data acquisition system may take several weeks and is quite expensive
  - ***First deployment*** - *for conducting seismic experiments*
    - on an imitation of a full-scale 28×28 square foot hospital ceiling
    - the overall weight which the ceiling supports is approximately 12,000 pounds
  - ***Second deployment***
    - 25 nodes (a tree topology) and a 16 bit vibration card
    - a high-sensitive triaxial accelerometer is attached to the vibration card
    - designed for high-quality, low-power vibration sensing
    - the task of the network was to reliably send time-synchronized vibration data to a remote sink over a multi-hop route
      - NACK
      - hop-by-hop scheme

Golden Gate Bridge Monitoring (Berkeley)

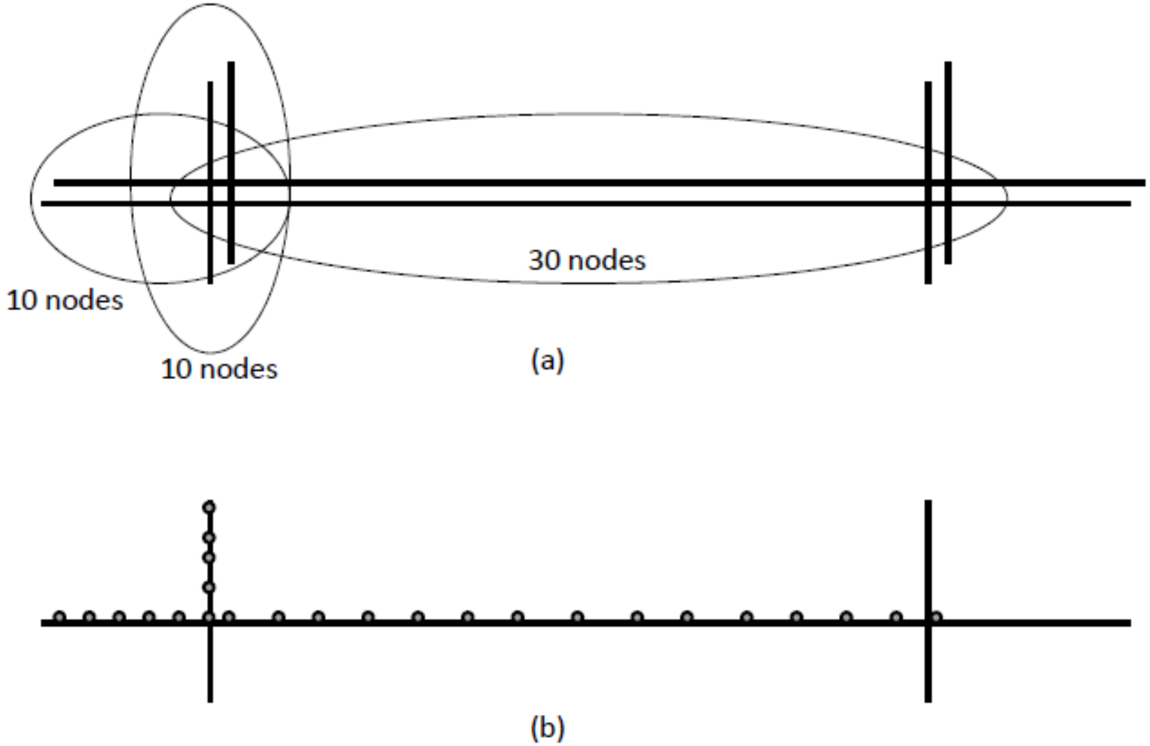
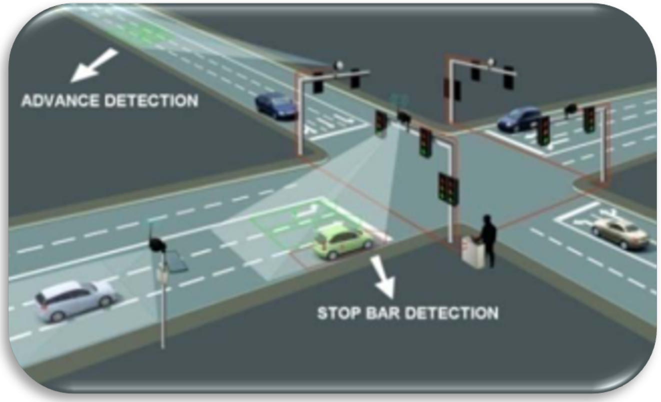


Figure: The deployment scenario on the Golden Gate Bridge

Golden Gate Bridge Monitoring (cont'd)

- 64 wireless sensor nodes deployed on this bridge
- The network monitors ambient vibrations synchronously
  - 1 KHz rate, ≤10μs jitter, accuracy=30μG, over a 46 hop network
- The goal of the deployment:
  - 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

Traffic Sensing



- Motivation:
  - Ground transportation is a vital and a complex socio-economic infrastructure
  - It is linked with and provides support for a variety of systems, such as supply-chain, emergency response, and public health
  - The 2009 Urban Mobility Report reveals that in 2007, congestion caused urban Americans to
    - travel 4.2 billion hours more
    - purchase an extra 2.8 billion gallons of fuel
  - Congestion cost is very high - $87.2 billion; an increase of more than 50% over the previous decade

Traffic Sensing (cont'd)

- Motivation:
  - Building new roads is not a feasible solution for many cities
    - lack of free space
    - high cost of demolition of old roads
  - One approach: put in place distributed systems that reduce congestions
    - Gather information about the density, sizes, and speed of vehicles on roads
    - Infer congestions
    - Suggest alternative routes and emergency exits

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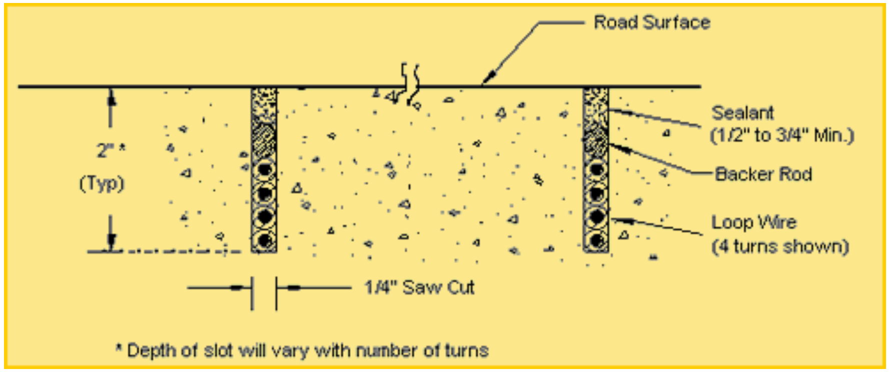
Inductive Loops

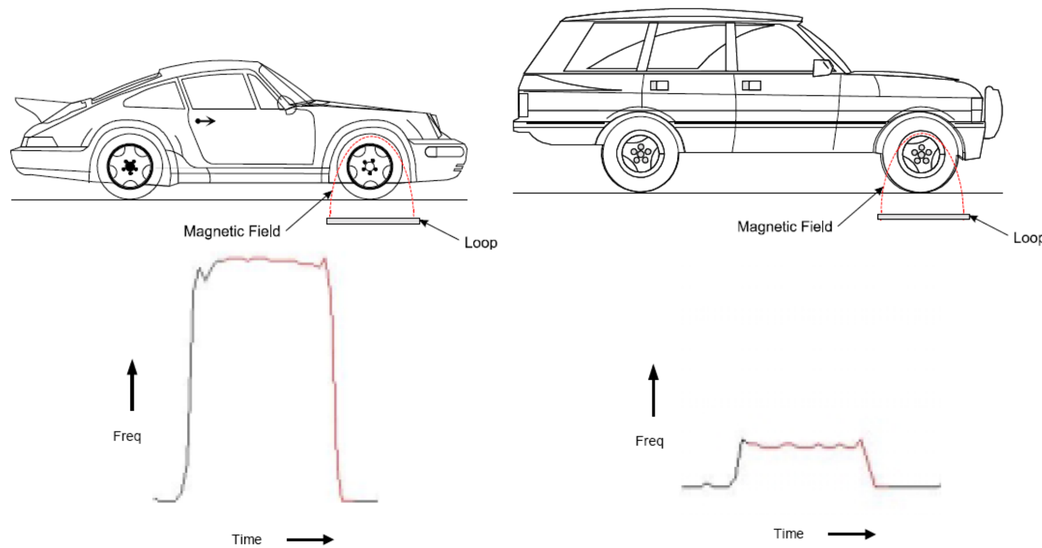
- In-road sensing devices
- Advantages:
  - Unaffected by weather
  - Provide direct information



- How does it work:
  using Faraday's induction law
  - A coil of wire (several meters in diameter, passes an electric current through the coil)
  - Buried under the road and connected to a roadside control box
  - Magnetic field strength can be induced as a result of a current and the speed and the size of passing vehicles

Magnetic Sensing

- Magnetic sensors can determine the direction and speed of a vehicle
  - A moving vehicle can disturb the distribution of the magnetic field
    - by producing its own magnetic field
    - by cutting across it
- The magnitude and direction of the disturbance depends on
  - The speed, size, density and permeability of the vehicle



Magnetic Sensing (cont'd)

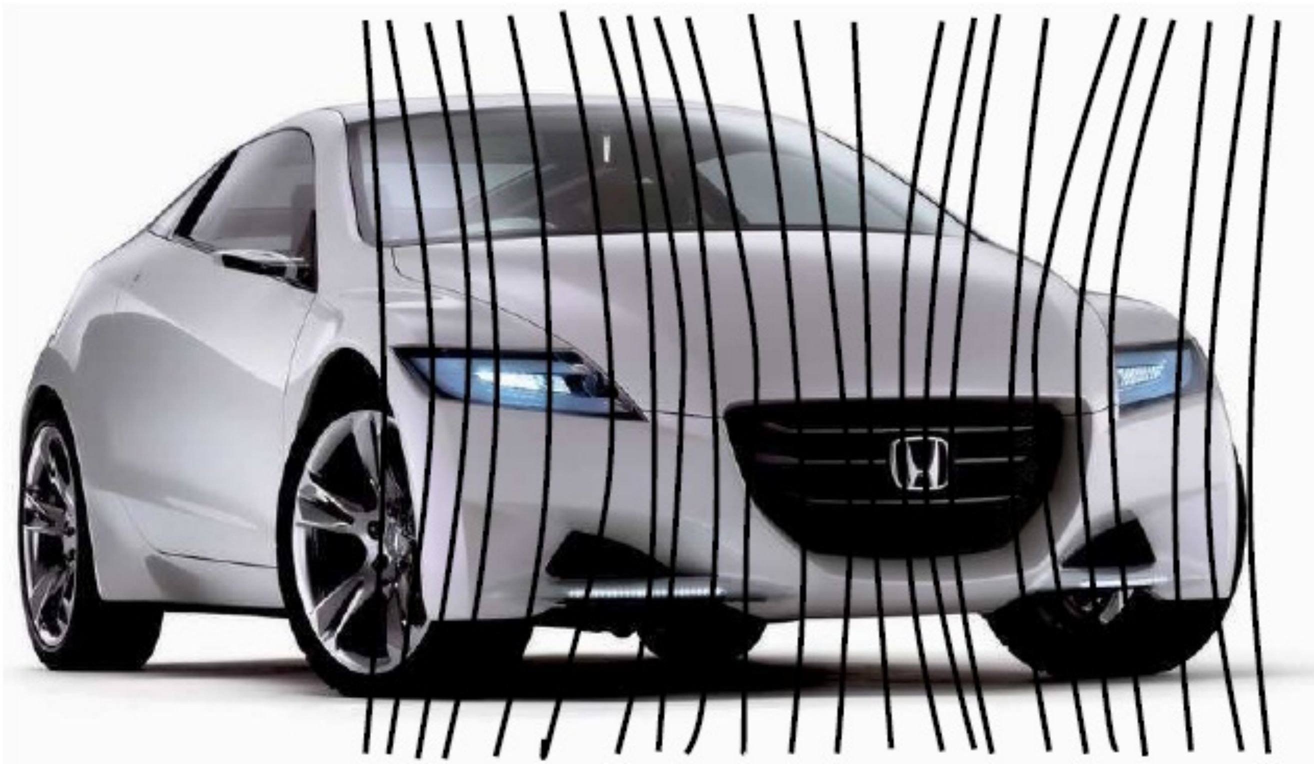


Figure: Detection of a moving vehicle with an ARM magnetic sensor (Caruso and Withanawasam 1999)

Magnetic Sensing (cont'd)

- Almost all road vehicles *contain* a large mass of steel
- The magnetic *permeability of steel* is much *higher* than the surrounding air
- Steel has the capacity to *concentrate* the *flux lines* of the Earth's magnetic field
- The concentration of magnetic flux varies *as the vehicle moves*; it can be detected from a distance of up to *15m*
- The field variation reveals a *detailed* magnetic signature
- It is possible to distinguish between different types of vehicles

Pipeline Monitoring

- Objective: monitoring gas, water, and oil pipelines
- Motivation:
  - Management of pipelines presents a formidable challenge
    - Long length, high value, high risk
    - Difficult access conditions
    - Requires continuous and unobtrusive monitoring
  - Leakages can occur due to excessive deformations
    - Earthquakes
    - Landslides
    - Collisions with an external force
    - Corrosion, wear, material flaws
    - Intentional damage to the structure

Pipeline Monitoring (cont'd)

- To detect leakages, it is vital to understand the characteristics of the substance the pipelines transport
  - fluid pipelines generate a hot-spot at the location of the leak
  - gas pipelines generate a cold-spot due to the gas pressure relaxation
  - fluid travels at a higher propagation velocity in metal pipelines than in a Polyvinyl Chloride (PVC)
  - a large number of commercially available sensors to detect and localize thermal anomalies
    - fiber optics sensors
    - temperature sensors and
    - acoustic sensors

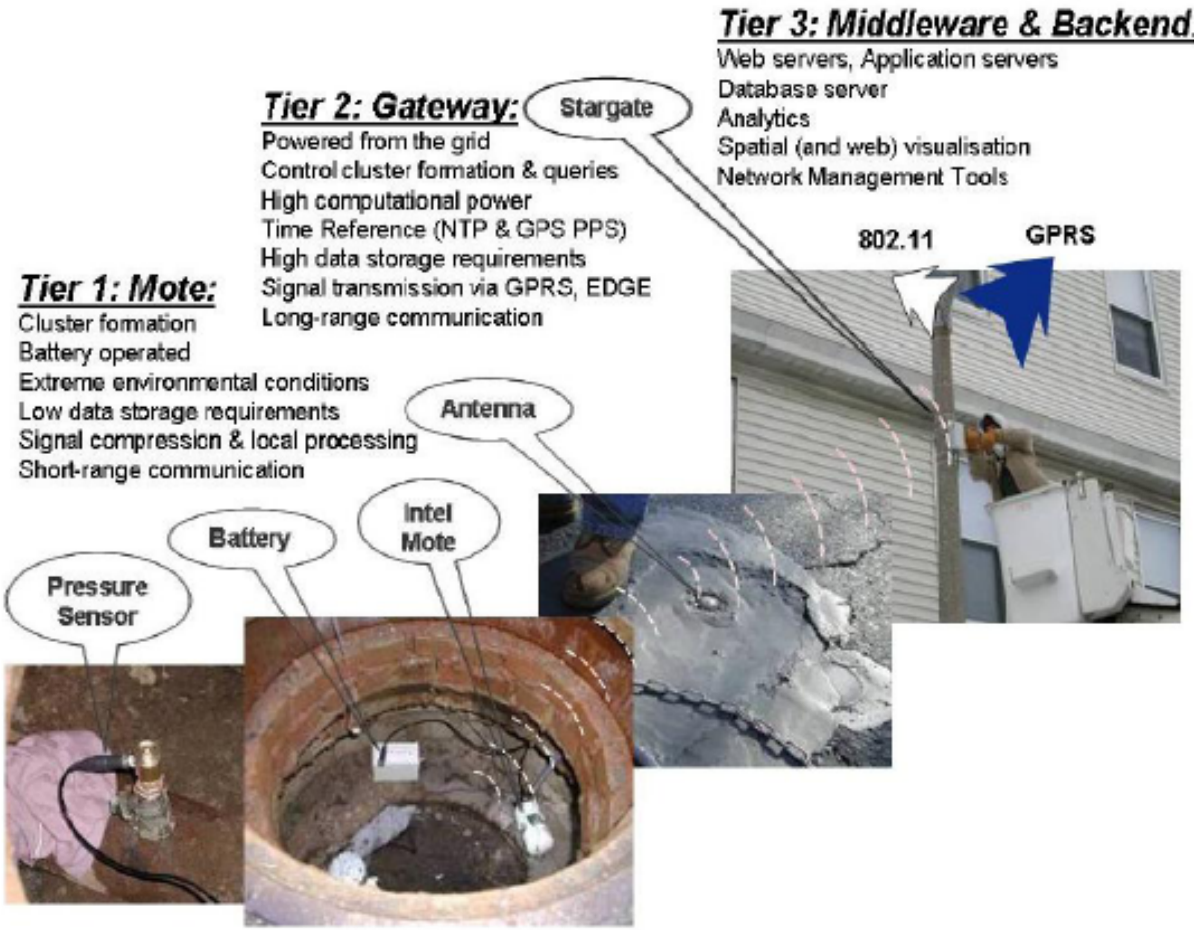
PipeNet (Stoianov et al. 2007)

- Motivation:
  - sewerage systems convey domestic sewage, rainwater runoff, and industrial wastewater to sewerage treatment plants
  - historically, these systems are designed to discharge their content to nearby streams and rivers
  - subsequently, combined sewer overflows are among the major sources of water quality impairment
  - nearly 770 large cities in the US, mainly older communities, have combined sewer systems

PipeNet (cont'd)

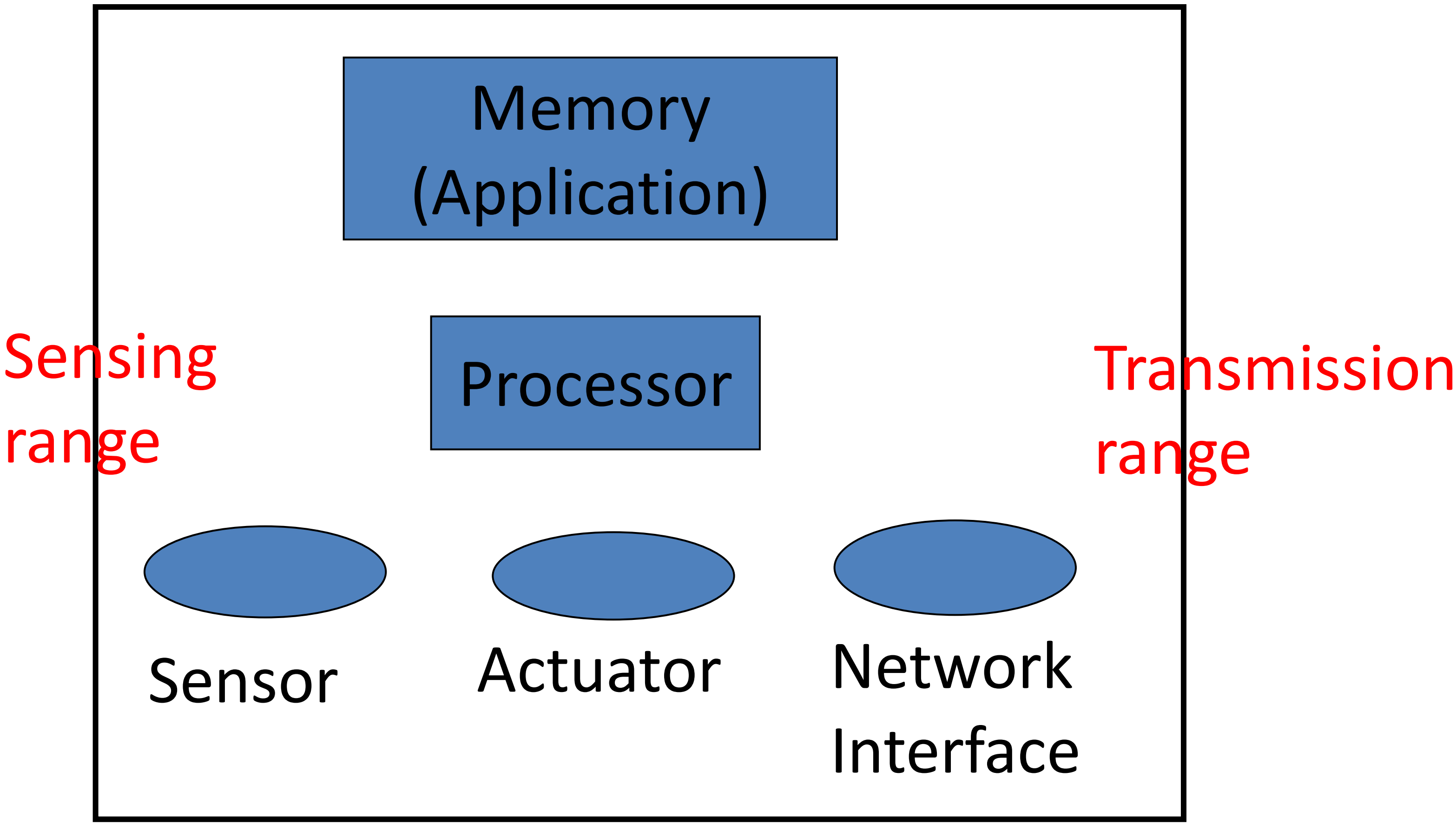
- The PipeNet prototype has been developed to monitor water pipelines in urban areas
- The task is to monitor:
  - Hydraulic and water quality by measuring pressure and pH
  - Water level in combined sewer systems
  - Sewer collectors and combined sewer outflows

PipeNet (cont'd)



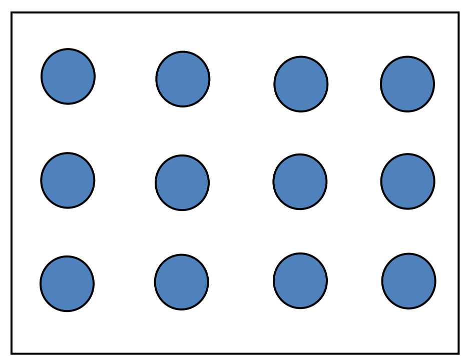
Sensor Network Design

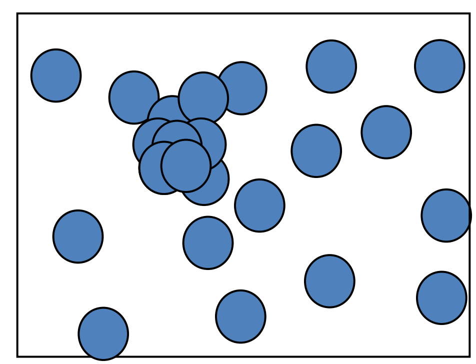
Sensor Node


Memory (Application)
Processor
Sensing range
Transmission range
Sensor
Actuator
Network Interface

Overview

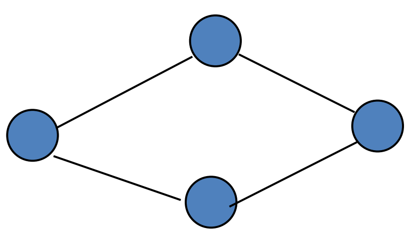
- Sensor network deployment
  - How to deploy sensors over a field?
    - Deterministic, planned deployment
    - Random deployment
  - Desired properties
    - Connectivity
    - Coverage





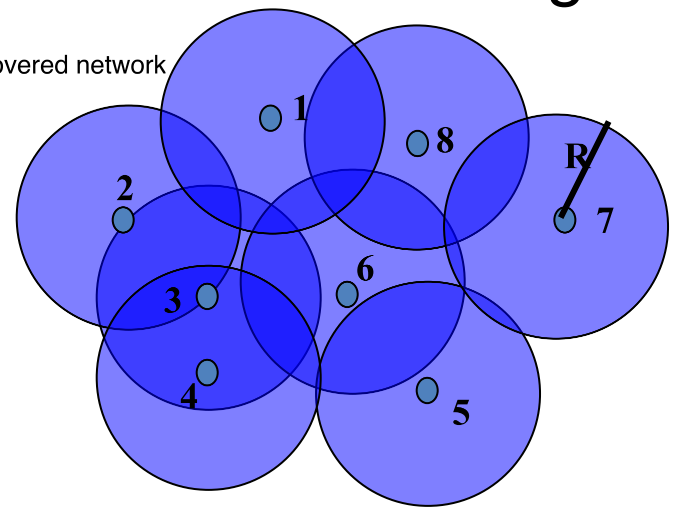
Connectivity & Coverage

- The sensor network is connected
  - K-connected: there are at least k distinct paths between any two nodes
- Every point is covered
  - K-covered: any point is within the sensing ranges of at least k sensors



A 2-connected network

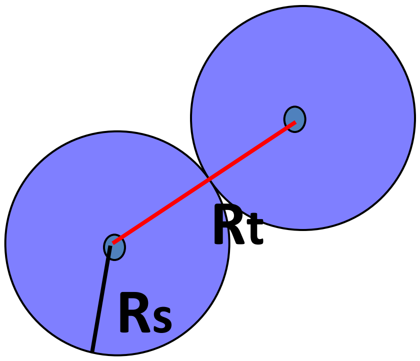
1 covered network



Coverage & Coverage: not independent, not identical

- If region is continuous, $R_t \geq 2R_s$:
  region is covered ➡ network is connected
  (proved in 2003)

Transmission (Communication) is larger than 2 times the sensing distance.



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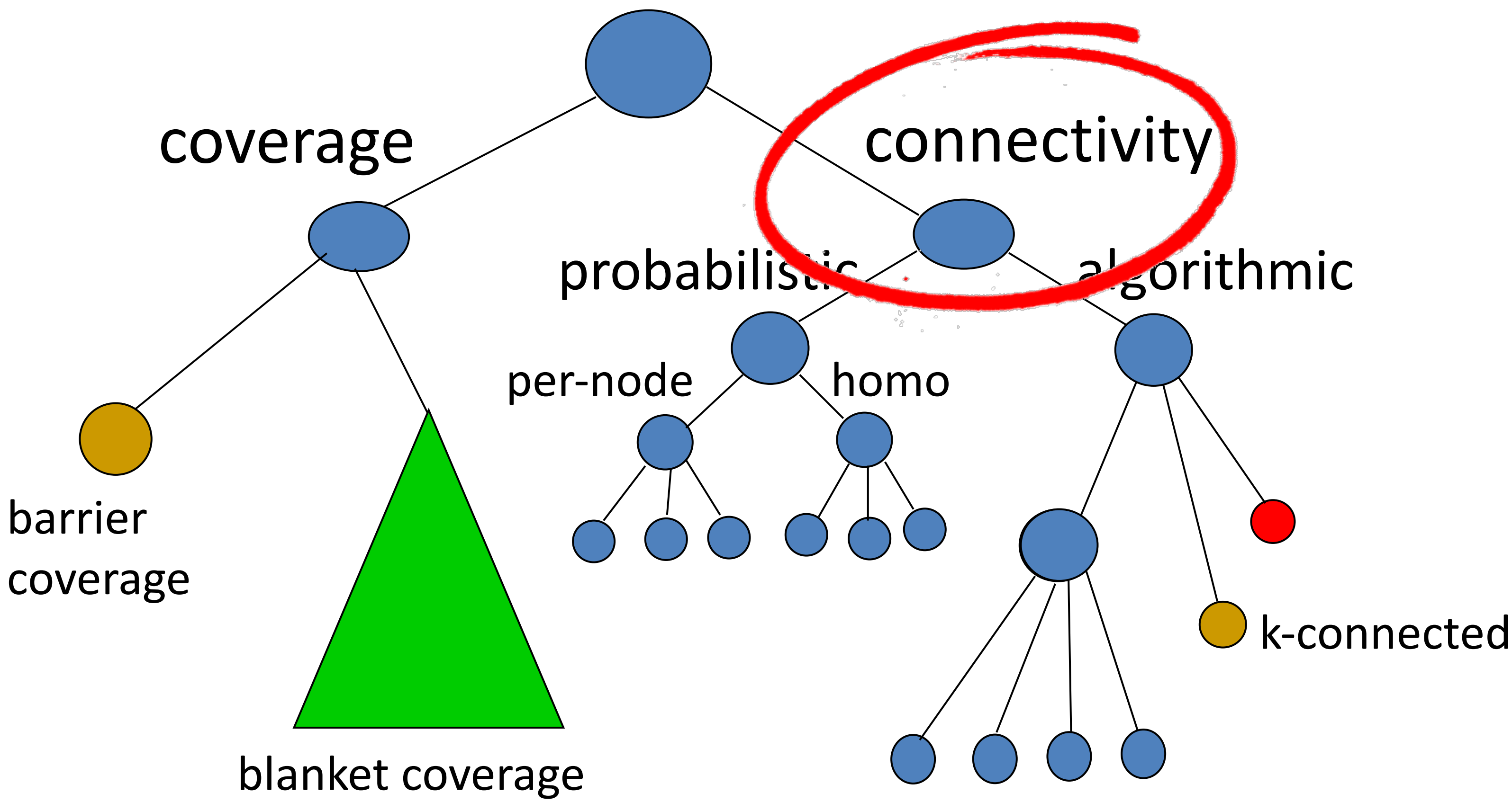
Problem Space



Power Control for Connectivity

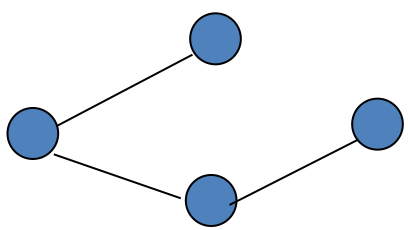
- Adjust transmission range (power)
  - Resulting network is connected
  - Power consumption is minimum

- Transmission range
  - Homogeneous
  - Node-based

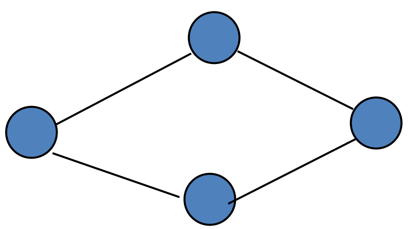
Power Control for K-connectivity

- For fault tolerance, k-connectivity is desirable
- K-connected network
  - At least K distinct paths between any two nodes
  - With k-1 nodes removed, the network is still connected

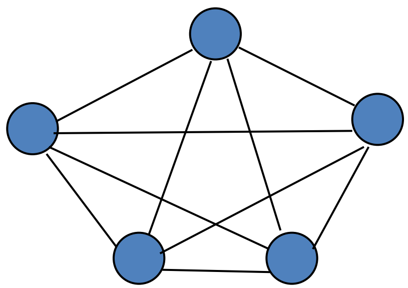
If any k-1 nodes are removed the remaining nodes are still k connected.



1-connected



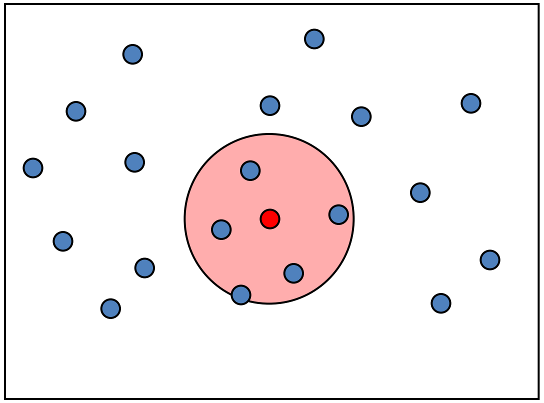
2-connected



3-connected

Two Types of Approaches

- Probabilistic
  - How many neighbors are needed?
- Algorithmic
  - Construct a network with desired connectivity
  - (skipped in this course)



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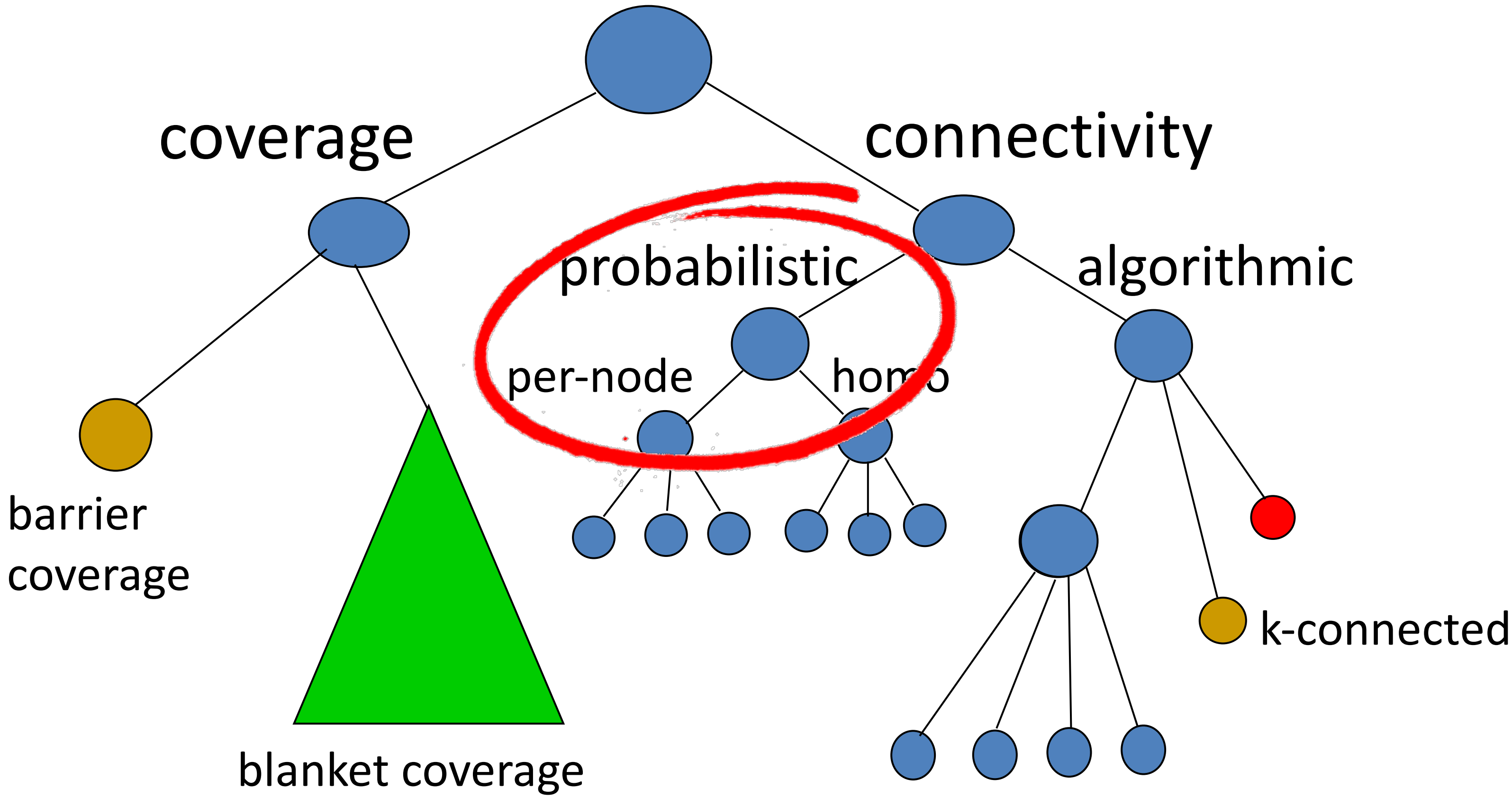
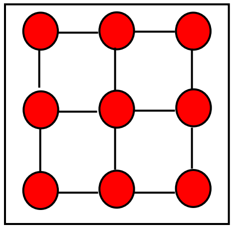
Problem Space



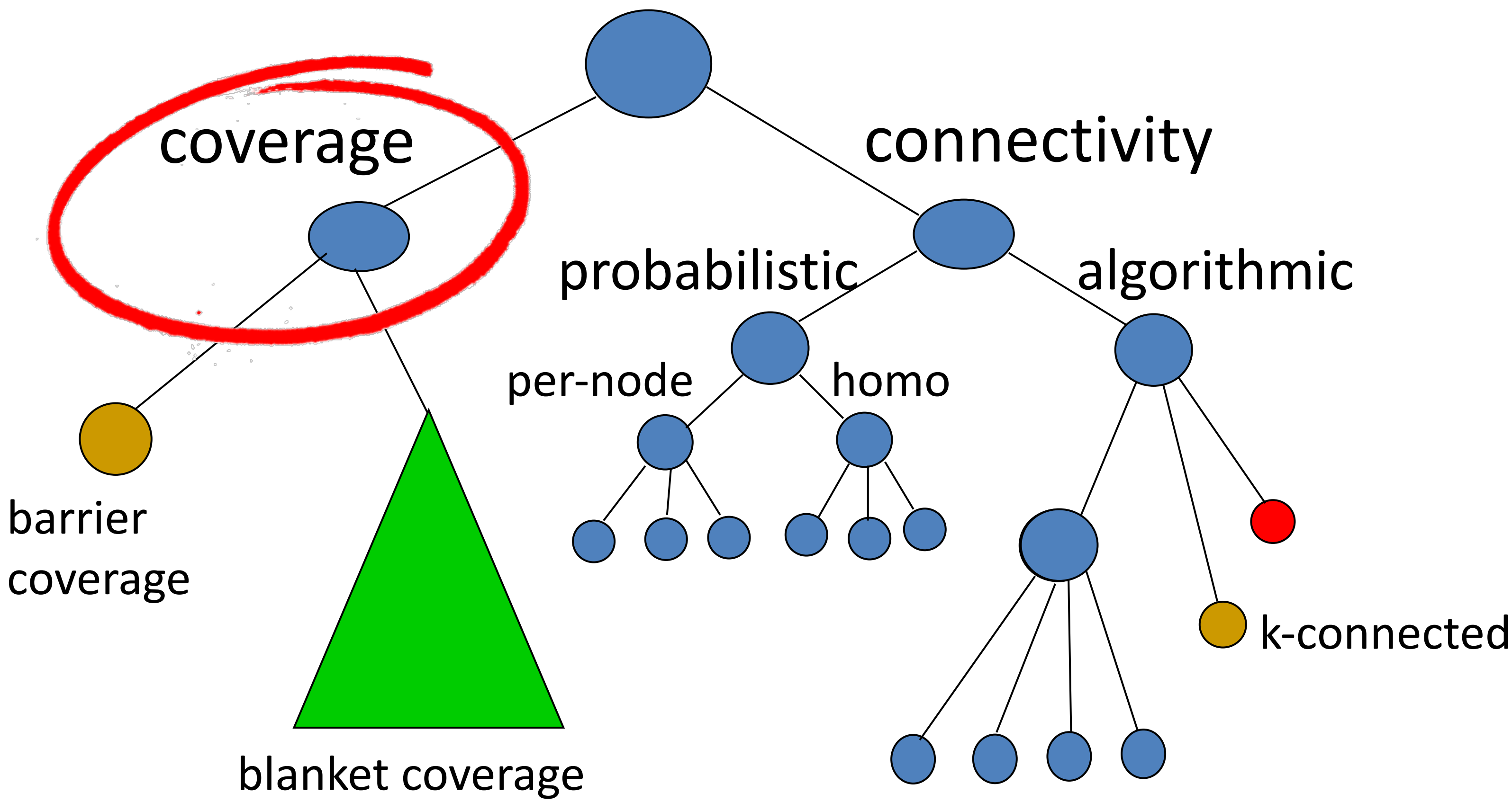
How Many Neighbors Needed?

- Deterministic / regular deployment
  - Easy



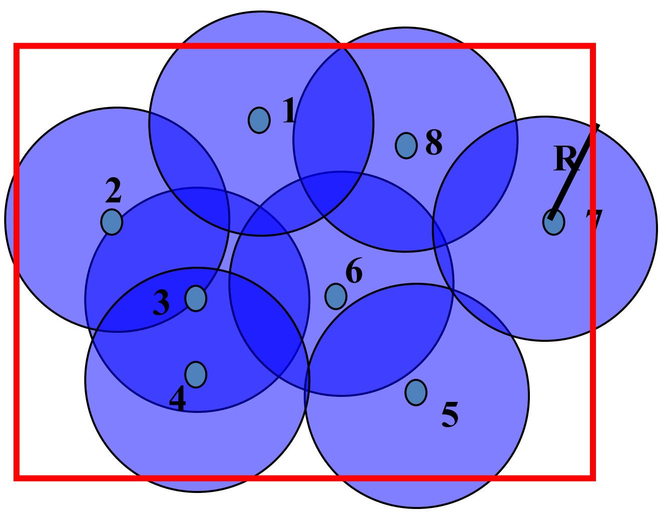
- Random deployment (2D Poisson process)
  - N: number of nodes deployed in a region
  - For whatever k value
    k-connectivity requires N → infinity
  - Xue & Kumar 2002: If each node has 5.1774 $\log_{10}N$ neighbors, network is 1-connected when N → infinity

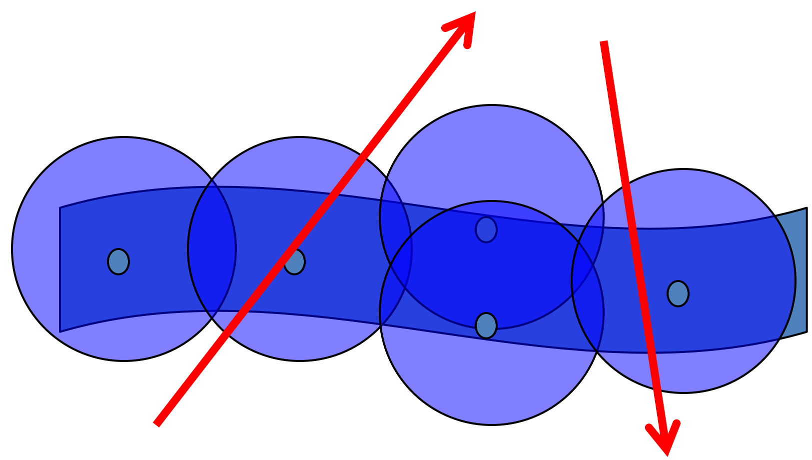
Problem Space



Blanket vs Barrier Coverage

- Blanket coverage
  - Whether an entire area is covered by sensors
  - Application: event detection
- Barrier coverage (skipped in this lecture)
  - With a barrier of sensors, whether any crossing path is covered by sensors
  - Application: moving object detection





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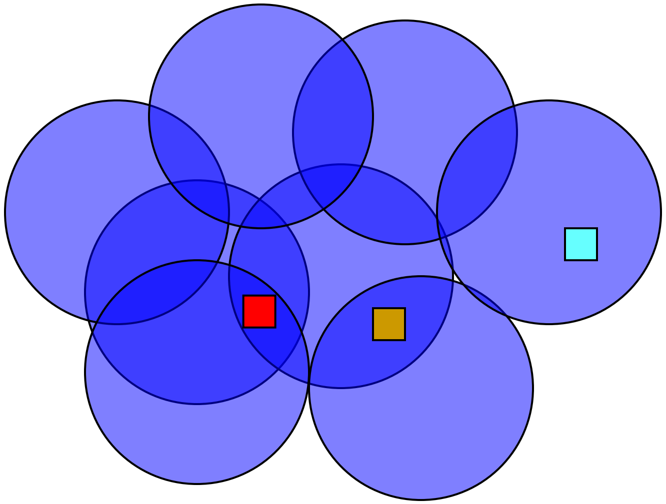
K-coverage

- 1-covered
- 2-covered
- 3-covered

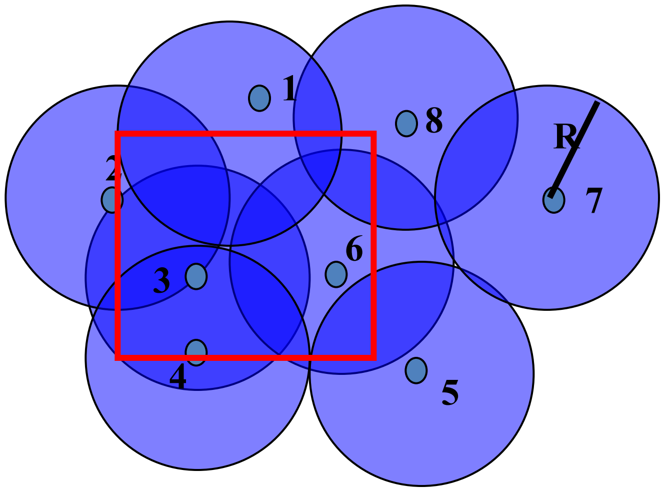


K-Coverage Problem

- Given: region, sensor deployment, integer k
- Question: Is the entire region k-covered?

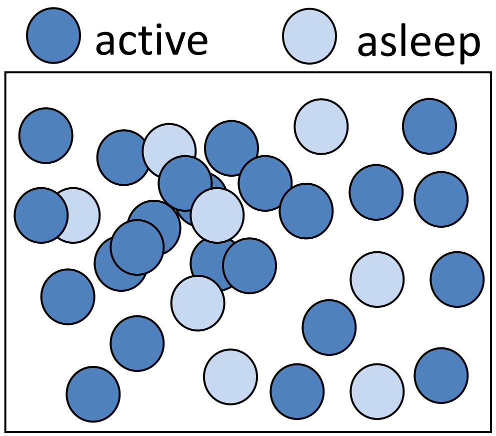
- Find results in

  C. Huang and Y. Tseng, “The coverage problem in a wireless sensor network,” In WSNA, 2003.



How to Achieve K-Coverage

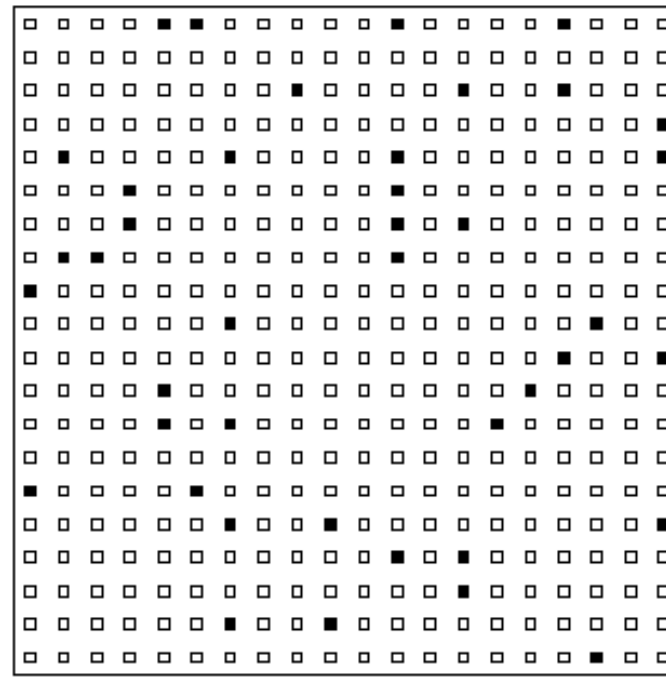
- How many sensors needed?
  - Depends on
    - Deployment method
    - Sensing range
    - Sensor failure rate
    - Others



- Density and topology control
  - Given a deployment, turn on/off sensors to maximize lifetime subject to k-coverage

Sensor Grid Coverage (Shakkottai et al. 2003)

- Active □
- Asleep ■
- p: active probability
- r: sensing range
- Necessary and sufficient condition for 1-coverage?

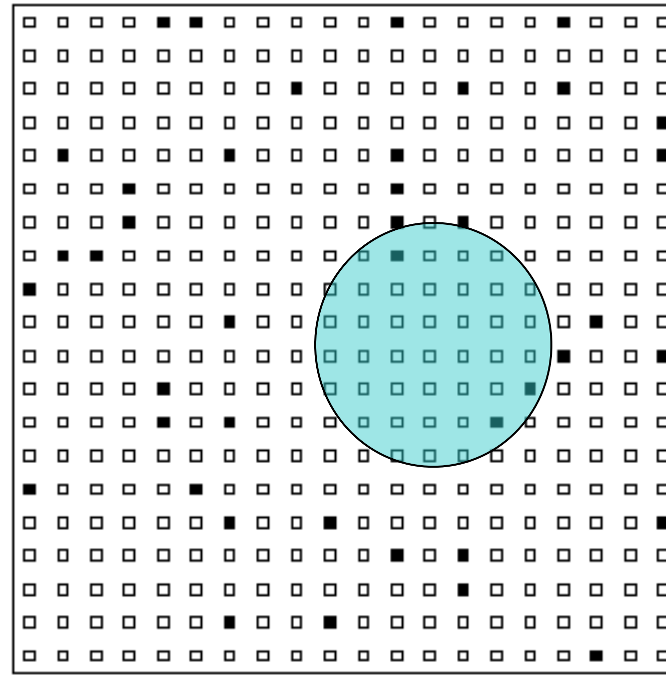


n nodes on grid points

Conditions for Asymptotic Coverage

Necessary:	$$\lim_{n\to\infty} \frac{\boxed{np\cdot\pi r^2}}{\log n} \geq 1$$
Sufficient:	$$\lim_{n\to\infty} \frac{\boxed{np\cdot\pi r^2}}{\log n} > 4$$

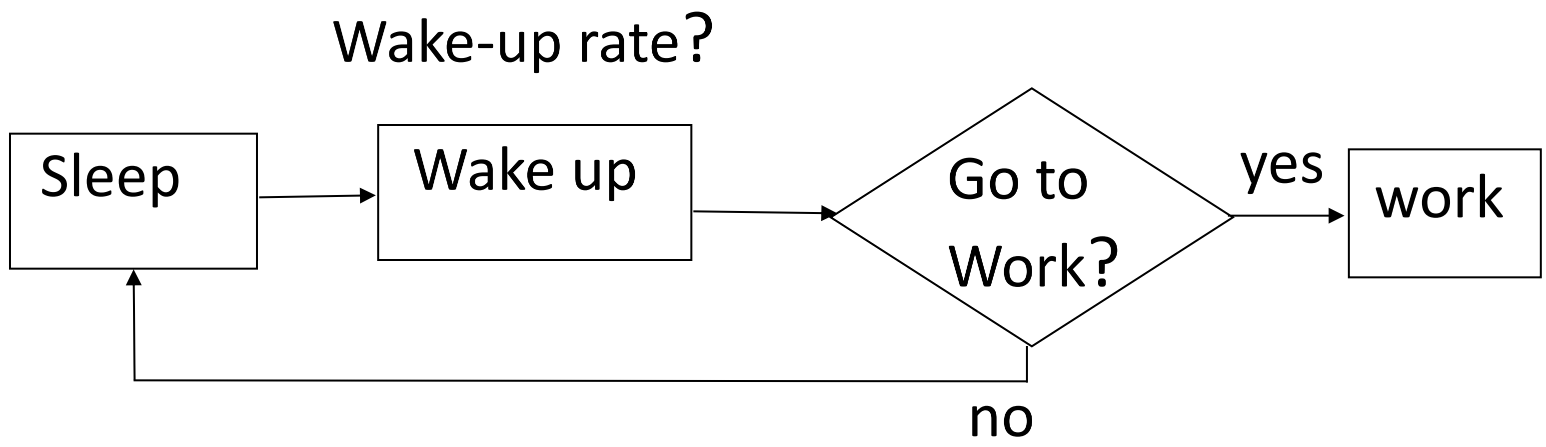
$\boxed{np\cdot\pi r^2}$ = expected # of active sensors in a sensing disk.



n nodes on grid points

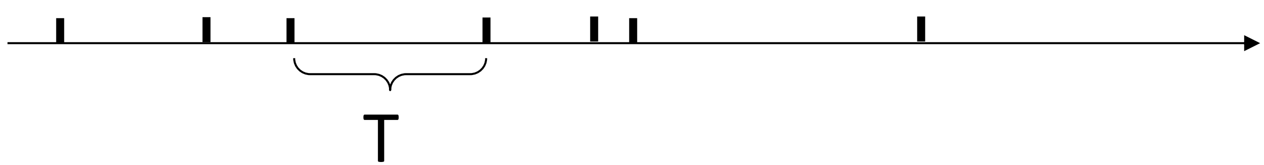
PEAS Protocol for Density Control (Ye et al. 2002)

- How often to wake up?
- How to determine whether to work or not?



Inter Wake-up Time

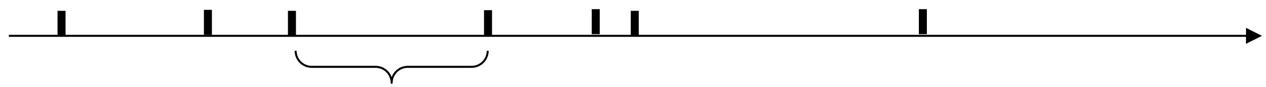
- Wake-up follows Poisson process
  - At any time instant, the node wakes up with a certain probability such that there are averagely λ wake-ups per unit time
  - Inter wake-up time T is a random variable following exponential distribution



Pdf: $f_T(t) = \lambda \exp(-\lambda t)$

Nodes' Independent Wake-ups

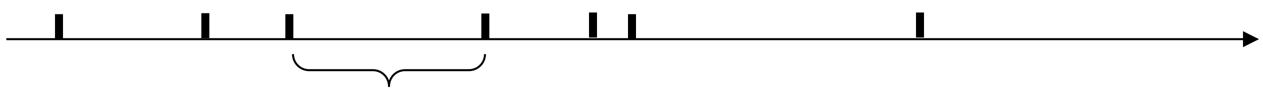
A



Pdf: $f_T(t) = \lambda \exp(-\lambda t)$

Average inter wake-up time: $1/\lambda$

B



Pdf: $f_T(t) = \lambda' \exp(-\lambda' t)$

Average inter wake-up time: $1/\lambda'$

A + B: $f_T(t) = (\lambda + \lambda') \exp(-(\lambda + \lambda')\, t)$

Average inter wake-up time: $1/(\lambda + \lambda')$

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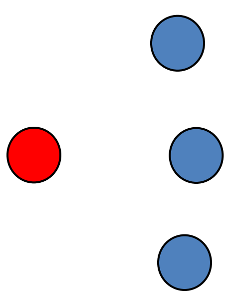
PEAS: Wake-up Rate Adjustment

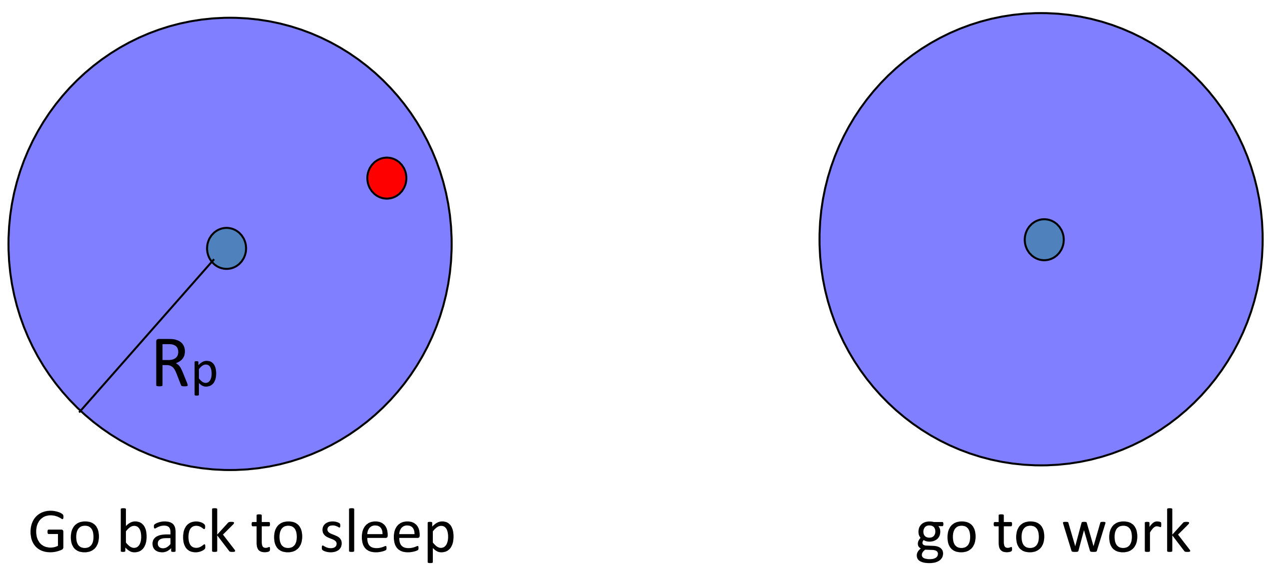
- Working node knows
  - Desired total wake-up rate λ_d
  - Measured total wake-up rate λ_m
- When a node wakes up, adjusts its λ by

$$\lambda \mathrel{*}= \lambda_d / \lambda_m$$ (in C language)

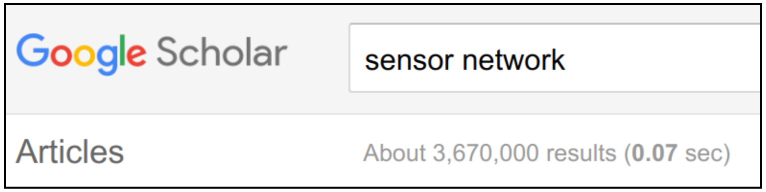


PEAS: Go to Work or Return to Sleep?

- Depends on whether there is a working node nearby



Networked Sensing: Big Picture



3.6 million research articles!

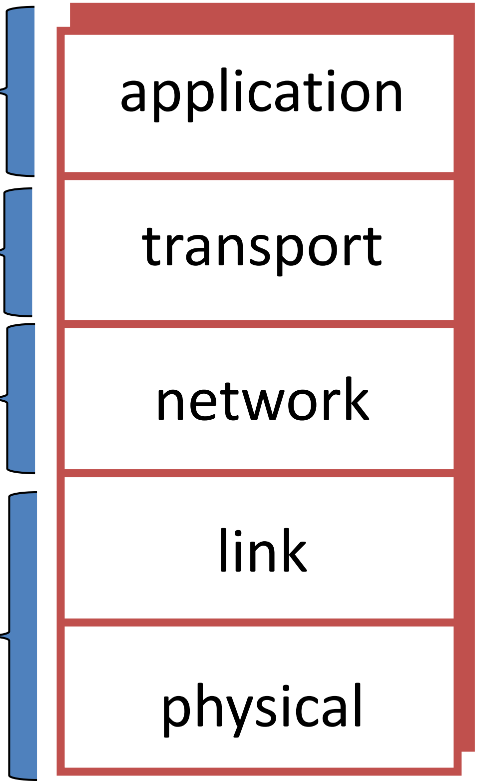
Touched

Untouched: data dissemination, etc

Touched on coverage and connectivity control
Untouched: clustering, routing, addressing, etc
These problems addressed from 2000-2010 roughly

MAC, error correction, communication modulation, etc
These problems addressed from 2005-2015 roughly

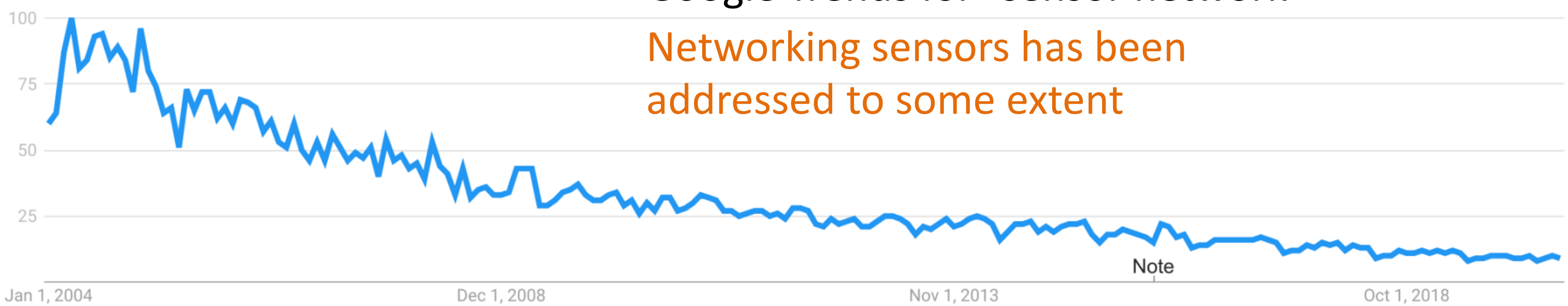
Internet protocol model



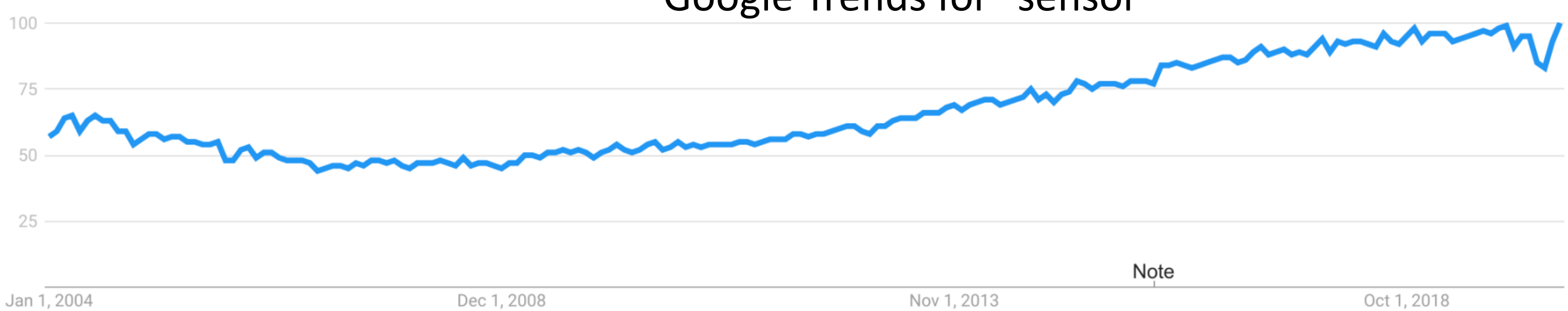
Trends in Sensing

Google Trends for “sensor network”

Networking sensors has been
addressed to some extent



Google Trends for “sensor”



Sensing in general becomes sustainably more important from 2008 given the increasing cyber-physical interactions

Learning Objectives

- Sensors
  - Understand the components of wireless sensors
- Urban sensor networks
  - Understand benefits and challenges of multi-hop networking
- Urban sensing applications
  - Understand the types of sensors used
- Sensor network design
  - Understand the concepts of coverage and connectivity
  - Understand approaches to coverage/connectivity control