18-452/18-750
Wireless Networks and Applications
Lecture 22: Sensor Networks

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http://www.cs.cmu.edu/~prs/wirelessS20/

Announcements

- P2 checkpoint 1 is due today.
  - » E-mail it to me
  - » There is a sign up sheet for meetings posted on Canvas
  - » Includes zoom link
- Survey talk drafts are due next week, Monday or Wednesday
  - » Schedule is now on the web page
  - » The Monday lecture will run long so we complete the surveys in 2 lecture slots

Some Thoughts about Surveys

- **Many students use the google templates, which as generally a disaster (24pt)**
  - » No slide numbers
  - » Tiny font sizes (12pt) – I want to be bigger! (18pt)
  - » 50%-80% of the slide is empty
  - » Use the space wisely!
- **Outline generally looks like:**
  - » Background: why useful, challenges, design options, etc.
  - » Discussion on the three papers:
    - – What is the key idea – this should be clear (figure!)
    - – Some sample results illustrating benefits
    - – Do not use terminology specific to the paper
  - » Personal opinion on pros or cons (global or per paper)

Outline

- Example applications
- Early sensor networks
  - » Power management
  - » Routing
  - » Efficient data collection
- Today's sensor networks

Based on slides by Prof JP Hubaux (EPFL), Lama Nachman (Intel), Revathy Narayanan (CMU)

Wireless Sensor Networks (WSN)

- Wireless sensors have limited compute, energy, memory, and bandwidth resources, but:
- Sensing capabilities → Can observe properties the physical world
- CPU and actuators → Can control some aspects of the physical world
- Small physical size → Can be embedded throughout the physical environment
- Basis for "Cyber physical" systems, "Internet of Things"

Architecture for Wireless Sensor Networks

- There is no such thing!
- Early systems: highly specialized, relatively small-scale deployments
  - » Home security systems, HVAC systems, security, …
- Later systems: focus on scaling, conserve battery, collaboration between sensors
  - » A lot of research on multi-hop ad hoc networks that reduce energy consumption
- Today: trend towards more general, highly scalable, very low energy systems
  - » Must be easy to deploy and maintain

WSN Applications

- Commercial Applications
  - » Light/temperature control
  - » Precision agriculture (optimize watering schedule)
  - » Asset management (tracking freight movement/storage)
- Monitoring tools supporting Scientific Research
  - » Wild life Habitat monitoring projects Great Duck Island (UCB), James Reserve (UCLA), ZebraNet (Princeton.
  - » Building/Infrastructure structure (Earthquake impact)
- Military Applications
  - » Shooter Localization
  - » Perimeter Defense (Oil pipeline protection)
  - » Insurgent Activity Monitoring (MicroRadar)

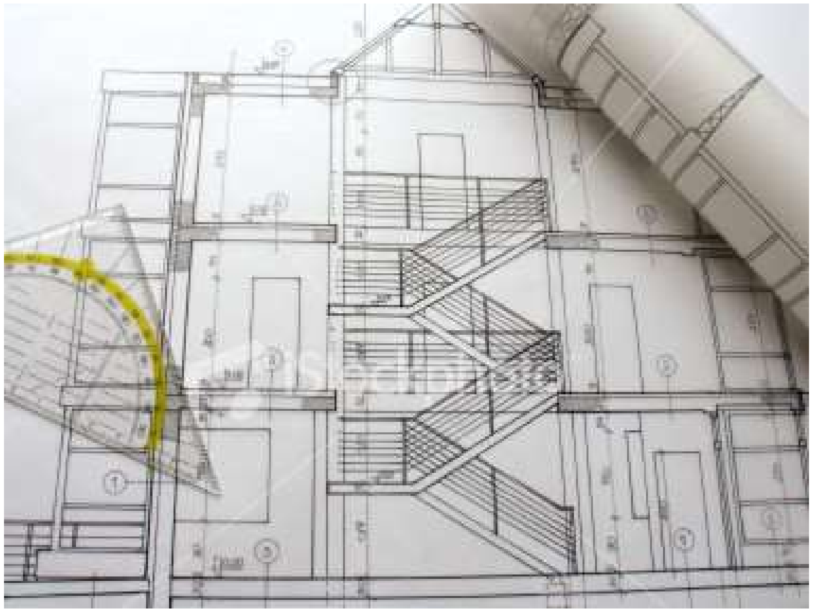
Cold Chain Management

- Supermarket chains need to track the storage temperature of perishable goods in their warehouses and stores.
- Tens if not hundreds of fridges should be monitored in real-time
- Whenever the temperature of a monitored item goes above a threshold
  - » An alarm is raised and an attendant is warned (pager, sms)
  - » The refrigeration system is turned on
- History of data is kept in the system for legal purpose
- Similar concept can be applied to pressure and temperature monitoring in
  - » Production chains, containers, pipelines

Home automation

- **Temperature management**
  - » **Monitor heating and cooling of a building in an integrated way**
  - » **Temperature in different rooms is monitored centrally**
  - » **A power consumption profile is to be drawn in order to save energy in the future**

- **Lighting management:**
  - » **Detect human presence in a room to automatically switch lights on and off**
  - » **Responds to manual activation/ deactivation of switches**
  - » **Tracks movement to anticipate the activation of light-switches on the path of a person**



- **Similar concept can be applied to**
  - » **Security cameras, controlling access, …**

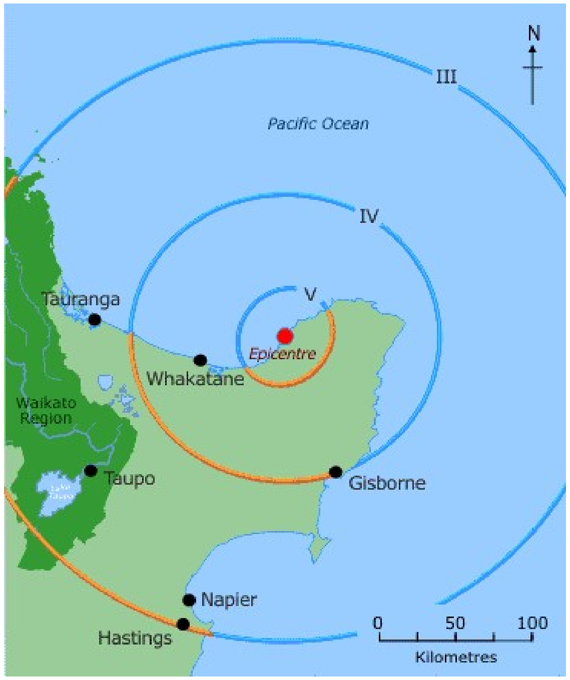
Precision Agriculture Management

- Farming decisions depend on environmental data (typically photo-synthesis):
  - Solar radiation
  - Temperature
  - Humidity
  - Soil moisture
- Data evolve continuously
- over time and space
- A farmer's means of action to influence crop yield :
  - Irrigation
  - Fertilization
  - Pest treatment
- To be optimal, these actions should be highly localized (homogenous parcels can be as small as one hectare or less)

- Environmental impact is also to be taken into account
  - Salinization of soils, groundwater depletion, well contamination, etc.

Earthquake detection

- The occurrence of an earthquake can be detected automatically by accelerometers
- Earthquake speed: around 5-10km/s
- If the epicenter of an earthquake is in an unpopulated area 200km from a city center, instantaneous detection can give a warning up to 30 sec before the shockwave hits the city
- If a proper municipal actuation network is in place:
  - » Sirens go off
  - » Traffic lights go to red
  - » Elevators open at the nearest floor
  - » Pipeline valves are shut
- Even a warning of a few seconds, can reduce the effects of the earthquake
- Similar concept can be applied to
  - » Forest fire, landslides, etc.



Economic Forecast

- **Industrial Monitoring** (35% – 45%)
  - Monitor and control production chain
  - Storage management
  - Monitor and control distribution
- **Building Monitoring and Control** (20 – 30%)
  - Alarms (fire, intrusion etc.)
  - Access control
- **Home Automation** (15 – 25%)
  - Energy management (light, heating, AC etc.)
  - Remote control of appliances
- **Automated Meter Reading** (10-20%)
  - Water meter, electricity meter, etc.
- **Environmental Monitoring** (5%)
  - Agriculture
  - Wildlife monitoring
- Other areas:
  - Performance monitoring in sports
  - Patient monitoring in health/medicine
  - Wireless sensor in vehicular networks

Recent forecast: 7 Billion $ by 2026

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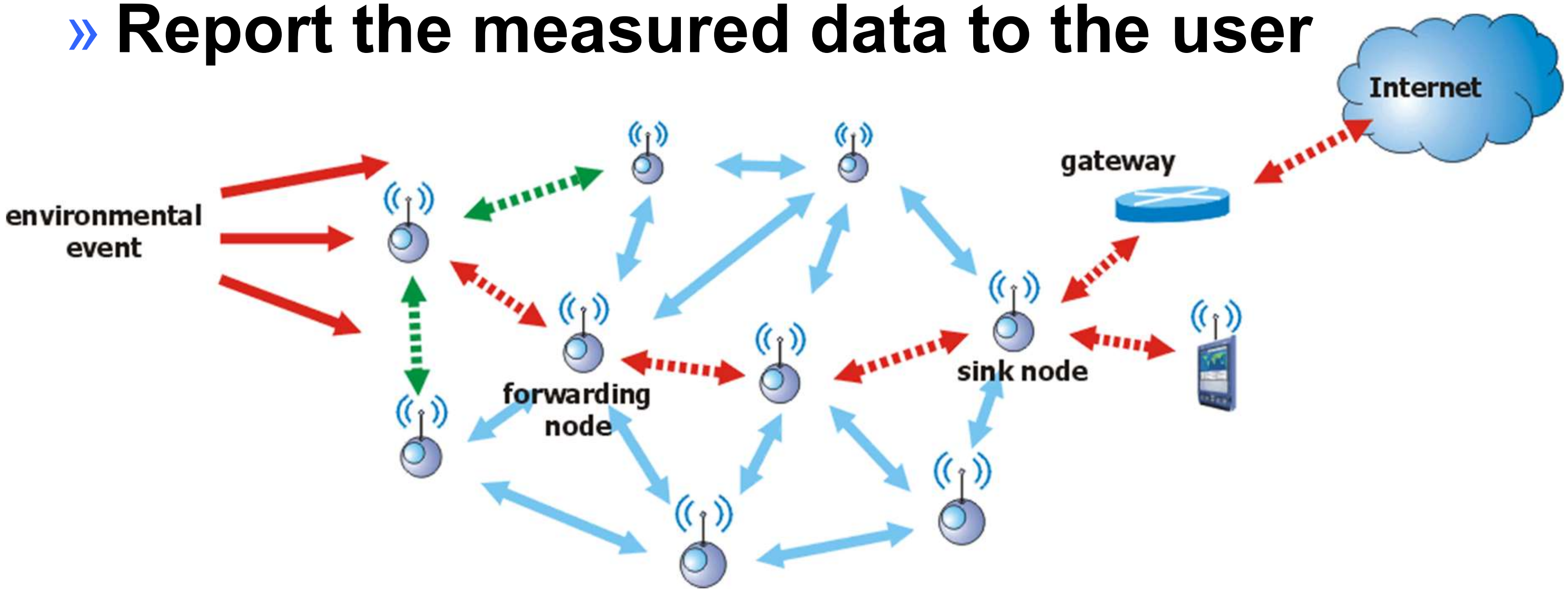
WSN Characteristics and Design Issues

- Characteristics
  - » Distributed data collection
  - » Many-to-one (rarely peer-to-peer)
  - » Limited mobility
  - » Data collection (time and space resolution)
  - » Event detection
- Design issues
  - » Low-cost (hardware and communication)
  - » Extended life-time – long battery life
  - » Reliable communication
  - » Efficient integrated data processing
  - » Hybrid network infrastructure
  - » Security

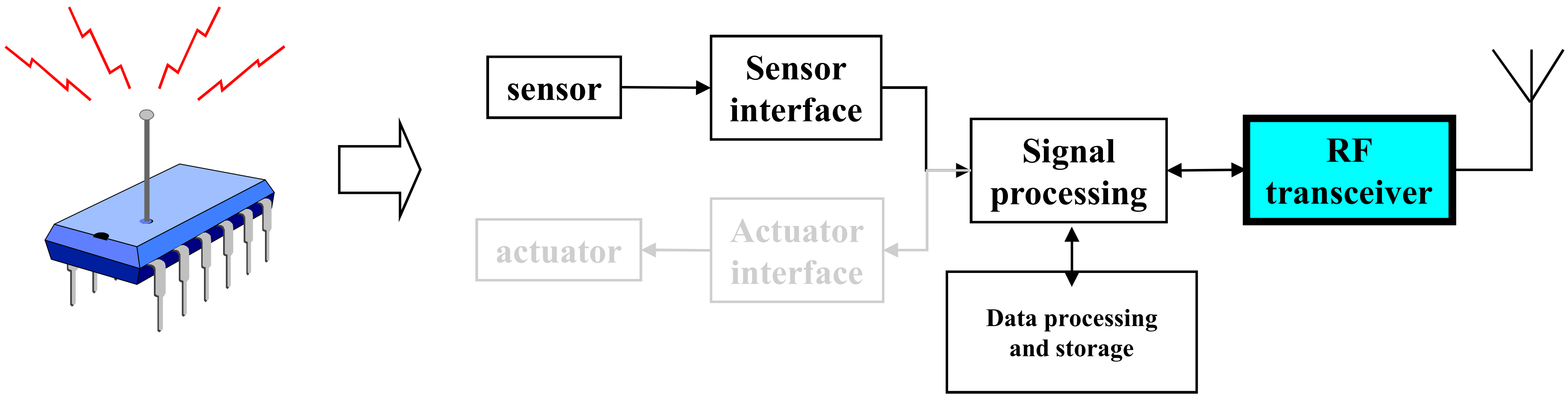
Wireless helps but may not be required!

Second Generation Wireless Sensor Network

- Numerous sensor devices
  - » Modest wireless communication, processing, memory capabilities
  - » Form Ad Hoc Network (self-organized)
    - – Uses short-range wireless technologies
  - » Report the measured data to the user



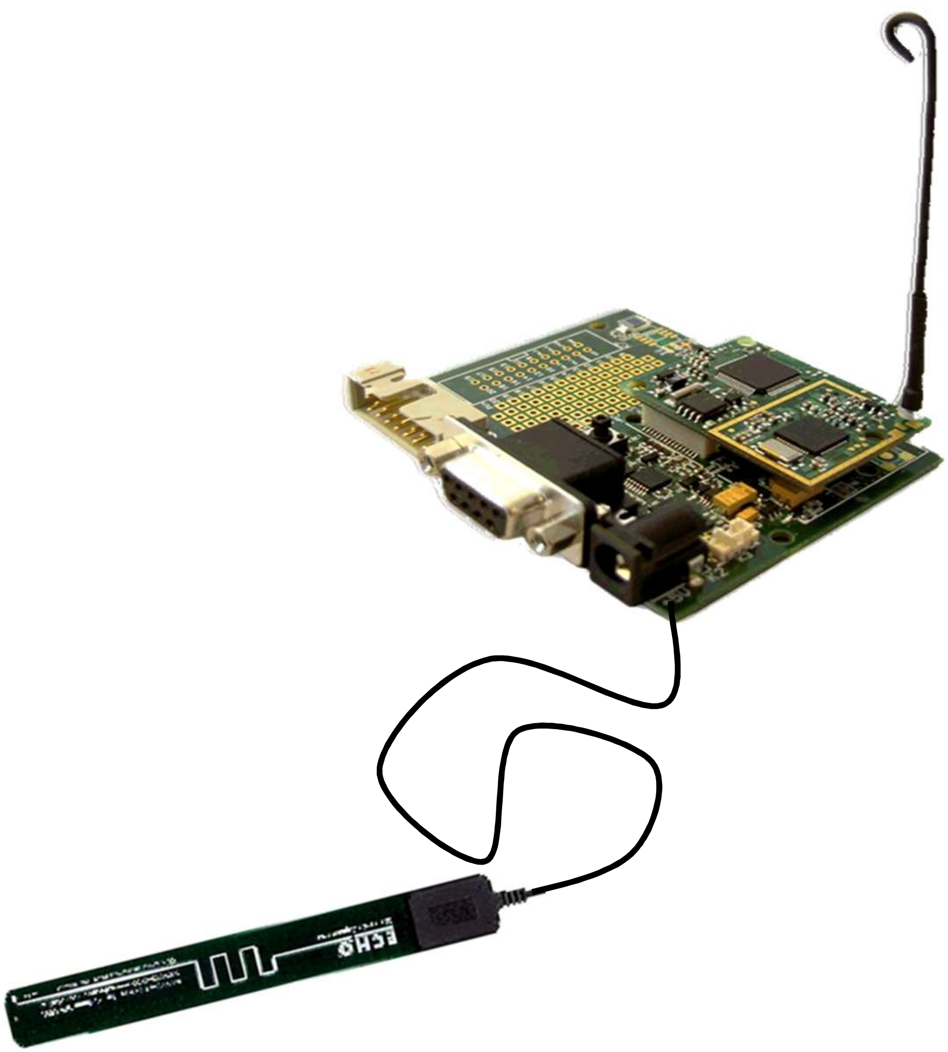
Sensor Node architecture



- A sensor node can be an *information source*, a *sink* and a *router*
- Autonomous ⇒ *low-power*
- Combine *sensing*, *signal conditioning*, *signal processing*, *control* and *communication* capabilities

(courtesy of Swiss Center for Electronics and Microelectronics, Neuchâtel)

Example of a Low Power Transceiver: Tinynode™



- 868 MHz multi-channel transceiver
- 8 MHz µ-Controller
- 10KB RAM
- 48 kB Program space
- 512 External Flash
- 115 kbps data rate
- 3 V supply voltage
- Current consumption
  - » Transmit 33 mA
  - » Receive 14 mA
  - » Sleep < µA
- -121 dBm sensitivity
- Radio range 200m (outdoor)
- 39 MHz quartz reference

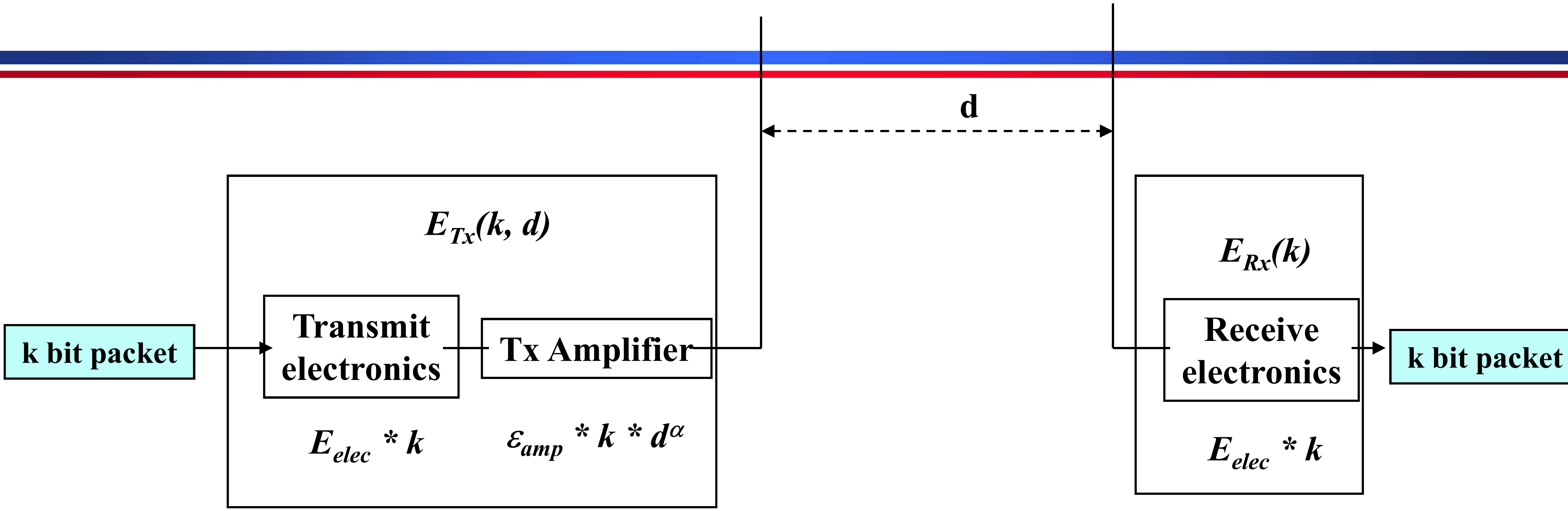
Design Issue: Low-cost

- **Hardware**
  - » Low-cost radio
  - » Low cost internal clock
  - » Limited storage and processing capabilities
  - » Not tamper-proof
  - » May have to withstand tough environmental conditions
- **Communication**
  - » Cannot rely on existing pay-per-use cellular infrastructure
  - » Use unlicensed spectrum to reach a “gateway”, which has internet connectivity
    - – Wired, WiFi, drive-by, cellular, …

Design Issue: Power Management

- Traditional metrics for network optimization: bandwidth, latency, economics ($$), …
- Wireless sensor networks: power efficiency
  - » Energy-efficient routing
  - » Load balancing to distribute power consumption
  - » In network aggregation to reduce traffic load
  - » Minimize up-time of sensors
- Requires new network technologies
  - » Different routing algorithms
  - » New MAC protocols

Simple Model for Energy Consumption



$$E_{Tx}(k, d) = E_{elec} * k + \varepsilon_{amp} * k * d^{\alpha}$$

$$E_{Rx}(k) = E_{elec} * k$$

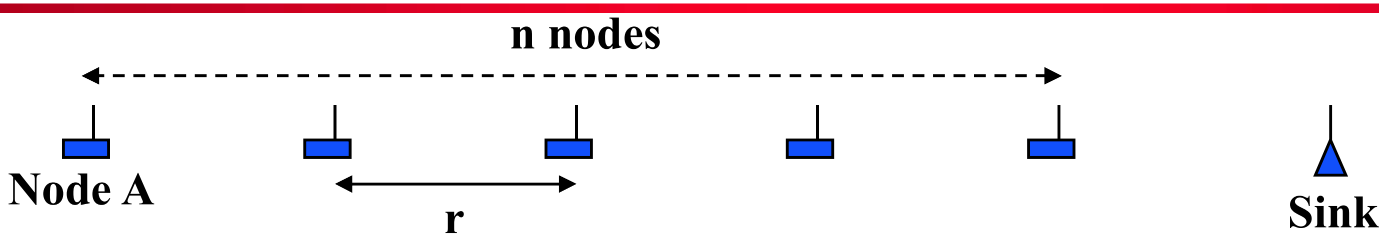
Typical values:

$\alpha = 2 \ldots 6$

$E_{elec} = 50\ nJ/bit$

$\varepsilon_{amp} = 100\ pJ/bit/m^{\alpha}$

Energy-efficient Routing : Example



Transmitting a single *k*-bit message from node A (located at distance nr from Sink) to Sink:

Direct transmission: $E_{direct} = E_{Tx}(k, d = n*r) = E_{elec} * k + \varepsilon_{amp} * k * (nr)^{\alpha} = k(E_{elec} + \varepsilon_{amp}\, n^{\alpha} r^{\alpha})$

Multi-Hop Transmission: $E_{multi\text{-}hop} = n*E_{Tx}(k, d = r) + (n\text{-}1) * E_{Rx}(k)$

$$= n(E_{elec} * k + \varepsilon_{amp} * k * r^{\alpha}) + (n\text{-}1) * E_{elec} * k = k((2n\text{-}1)E_{elec} + \varepsilon_{amp}\, n r^{\alpha})$$

MultiHop routing requires *less* energy than direct communication if: $\frac{E_{elec}}{\varepsilon_{amp}} < \frac{r^{\alpha}(n^{\alpha-1} - 1)}{2}$

Assuming $\alpha = 3, r = 10m$, we get $E_{multi-hop} < E_{direct}$ as soon as $n \geq 2$

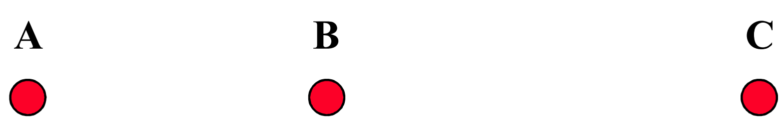
Minimum Energy in a More General Wireless Network

- **Problem: for an arbitrary set of nodes, find (in a fully distributed way) the minimum cost spanning tree to and from a given *sink* node**
- **Assumptions**
  - » **Each node knows its own exact location (e.g., using GPS)**
  - » **The power decreases with distance according to a power law with a known and path loss exponent α**
  - » **Each node can communicate with another node located at an arbitrary distance**
  - » **Nodes do not move**
  - » **Slightly different power model**

sending: td^{α}

receiving: c

- **Example:**



Power to send from A to C via B:

$$td_{AB}^{\alpha} + td_{BC}^{\alpha} + c$$

Relay region

Relay region:

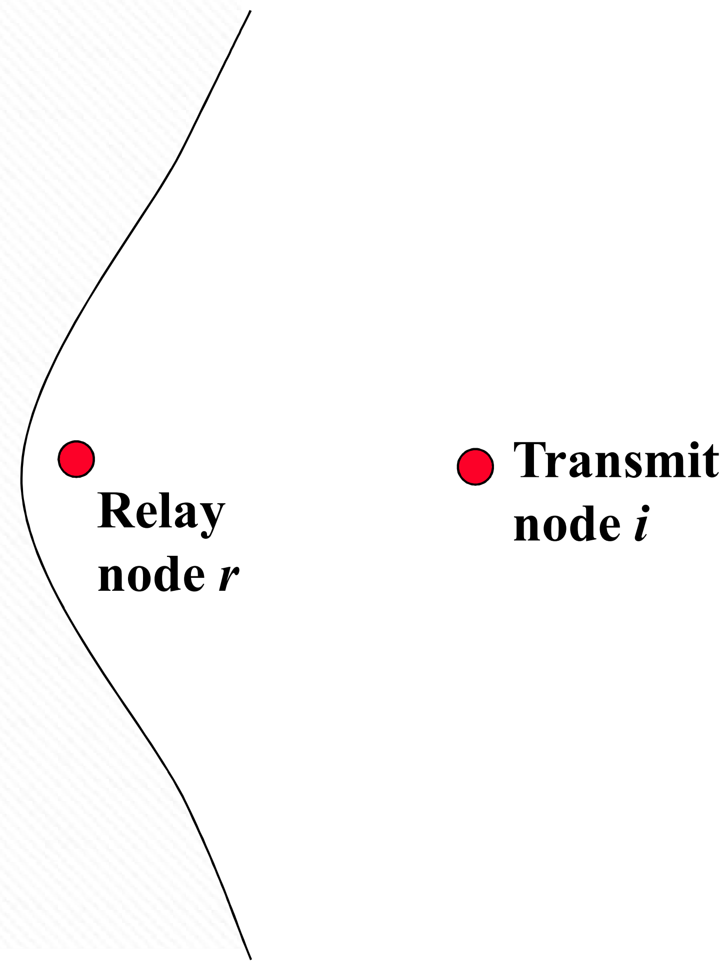
$$R_{i\to r} \equiv \{(x,y) \mid P_{i\to r\to(x,y)} < P_{i\to(x,y)}\}$$

We can expand this to:

$$td^{\alpha}_{i,r} + td^{\alpha}_{r,(x,y)} + c < td^{\alpha}_{i,(x,y)}$$

$$t\left((i_x - x)^2 + (i_y - y)^2\right)^{\alpha/2} - t\left((r_x - x)^2 + (r_y - y)^2\right)^{\alpha/2} >$$

$$t\left((i_x - r_x)^2 + (i_y - r_y)^2\right)^{\alpha/2} + c$$

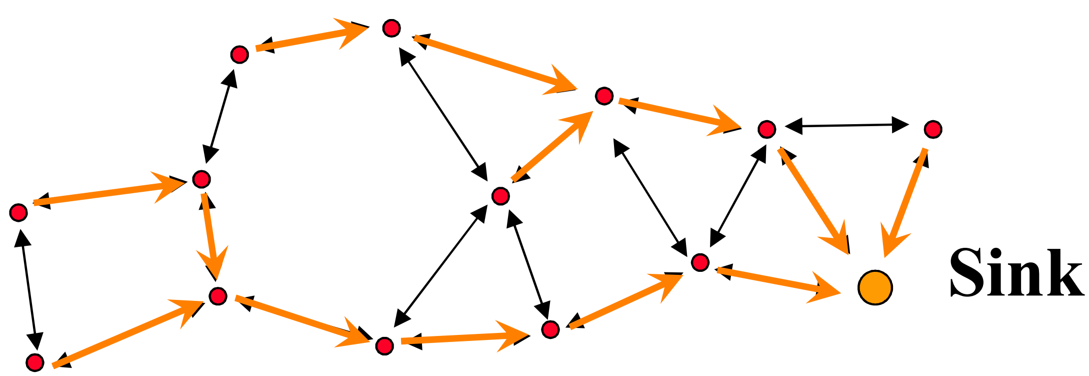


RELAY REGION

$R_{i\to r}$

Distributed Network Protocol

- Finds the minimum power topology for a stationary set of nodes with a single sink
- Assumption: each node is equipped with a GPS-receiver and transmits its position to its neighbors
- The protocol proceeds in 2 phases:
  1. Each node computes its own enclosure
  2. Each node computes its optimal cost distribution

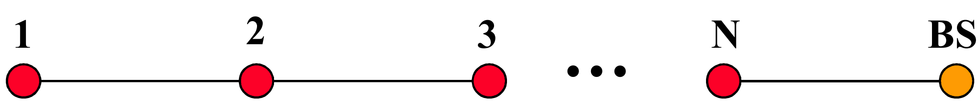


Load-balancing

- **Assumption: in a multi-hop many-to-one sensor network, the data collection follows a spanning tree.**
- **Power consumption due to transmission/reception grows exponentially from the leaves to the root of the tree**
- **Consequence: the power sources of the nodes close to the sink deplete faster. Since they relay all the network's traffic, they pull the network lifetime down.**

Load-balancing

Line topology



P_{tx} : Average transmission power consumption

P_{rx} : Average reception power consumption

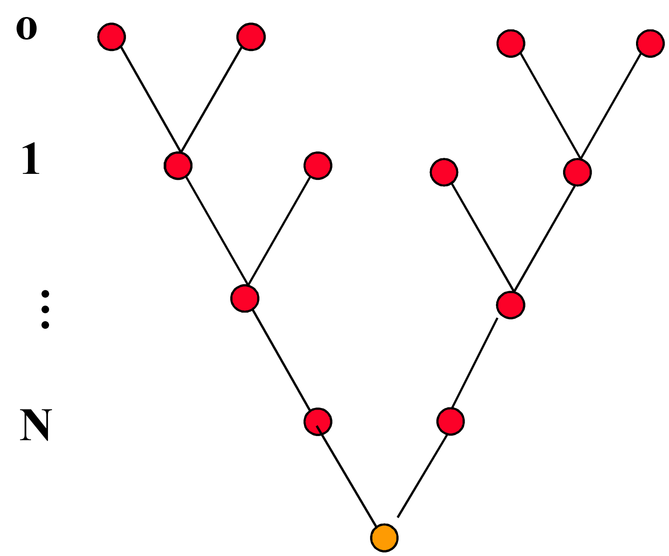
P_{pr} : Average processing power consumption

$P_T(k)$: Total power consumption of node k

$P = P_{pr} + P_{tx} + (k-1)(P_{tx} + P_{rx})$

P grows linearly with the distance from the leaf node

Tree topology



d : distance from leaf

F : number of messages forwarded

P : Power consumption

Assumptions:

1) all nodes have either 0 or $n_k > 2$ children

2) all leaves are at the same distance from the sink

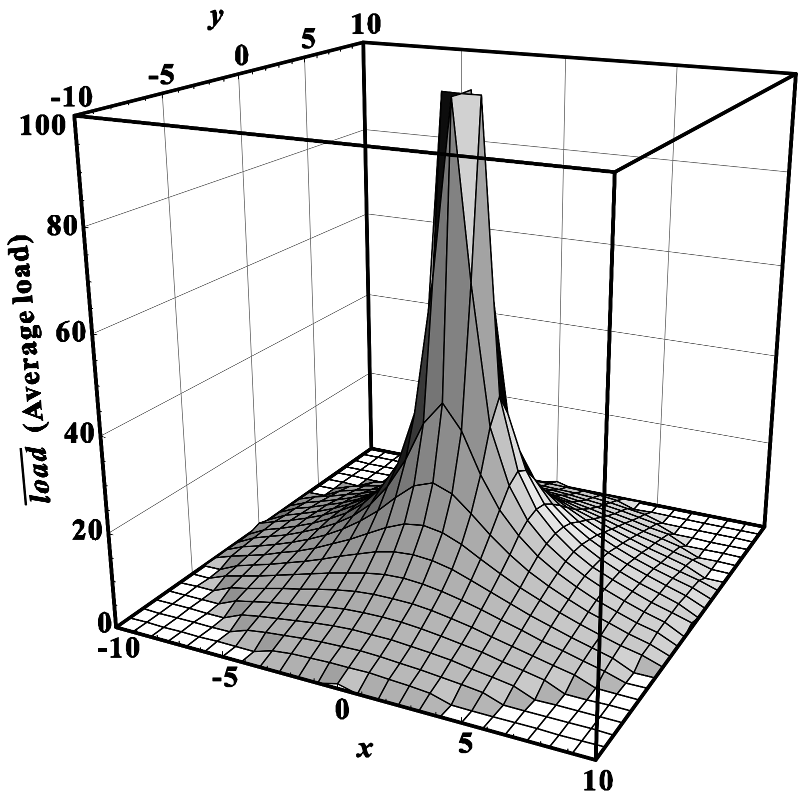
$F(d) \geq 2^d$

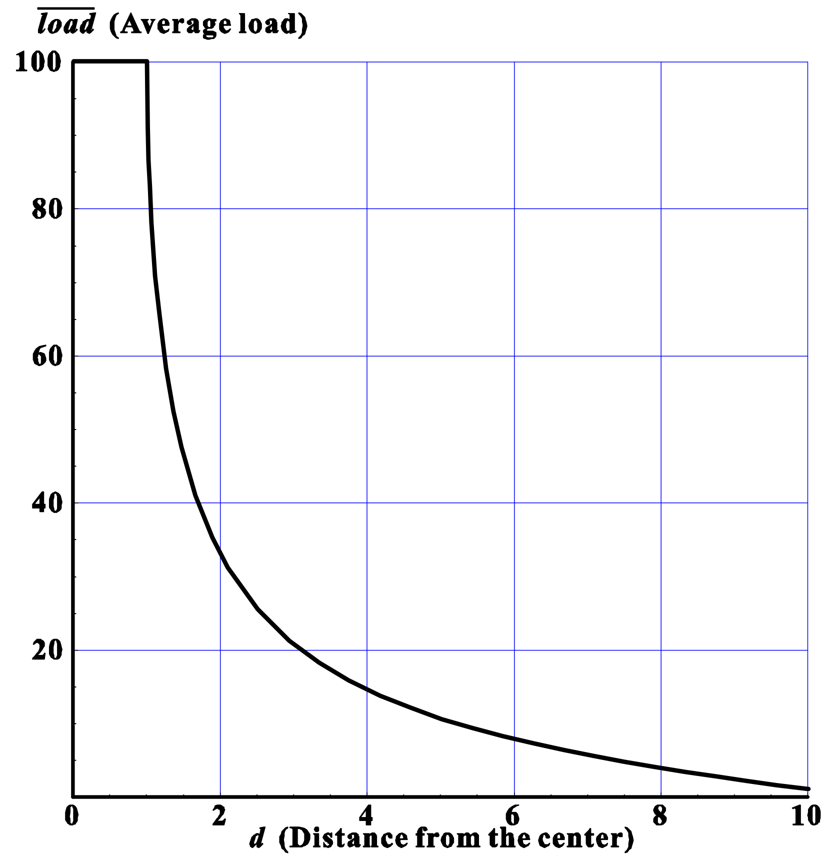
$P(d) \geq P_{tx} + 2^d (P_{tx} + P_{rx})$

P grows exponentially with distance from leaf node

Load balancing

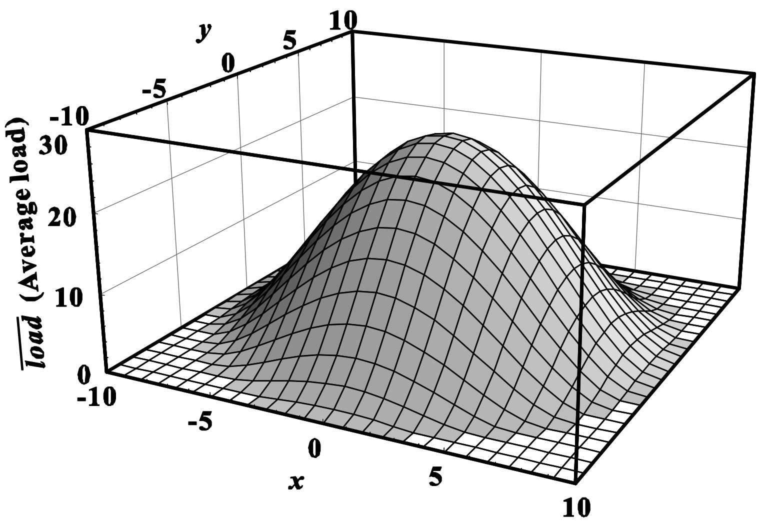
- Power consumption increases at least linearly when nodes are closer to the sink
- Typical case is much worse

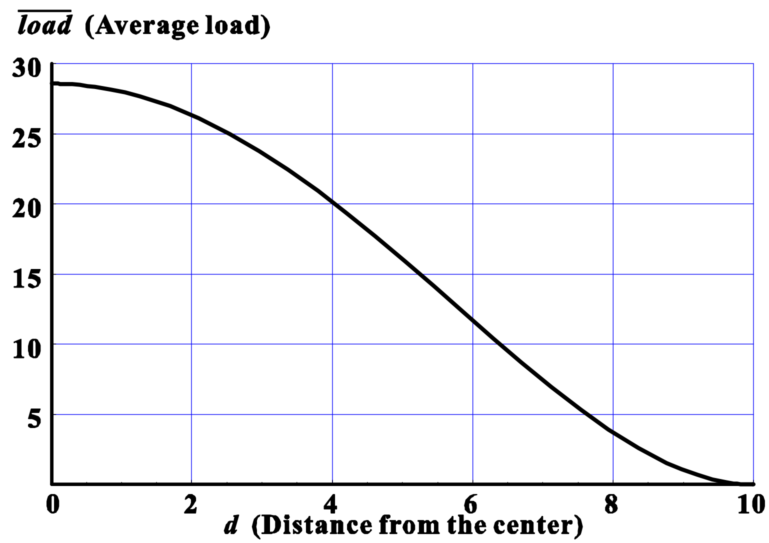




Use Mobility for Load-balancing

- Move the base station to distribute the role of “hot spots” (i.e., nodes around the base station) over time
- The data collection continues through multi-hop routing wherever the base station is, so the solution does not sacrifice latency





In-network Data Aggregation

- To mitigate cost of forwarding, compute relevant statistics along the way: *mean*, *max*, *min*, *median* etc.
- Forwarding nodes aggregate the data they receive with their own and send one message instead of relaying an exponentially growing number of messages
- Issues
  - » Location-based information (which nodes sent what) is lost
  - » Distributed computation of statistics
    - – *mean*: node needs to know both the mean values and the sizes of samples to aggregate correctly
    - – *median*: only an approximated computation is possible
- Especially useful in a query-based data collection system
  - » Queries regard a known subset of nodes
  - » Aggregation function can be specified

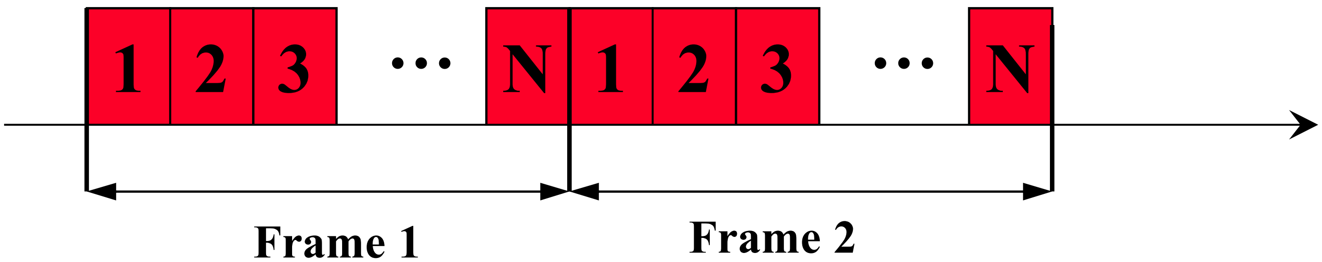
Medium-Access Control

- MAC attributes:
  - » Collision avoidance
  - » Energy efficiency
  - » Scalability and adaptivity
- Nodes transmit very intermittently, but once a transmission is taking place, we must ensure that the intended receiver is awake so it can receive packet.
- Current-consumption in receive state or in radio-on idle state are comparable
- Idle state (idle listening) is a dominant factor in power consumption

Goal is to put nodes to sleep most of the time, and wake them up only to receive a packet

Synchronous MACs

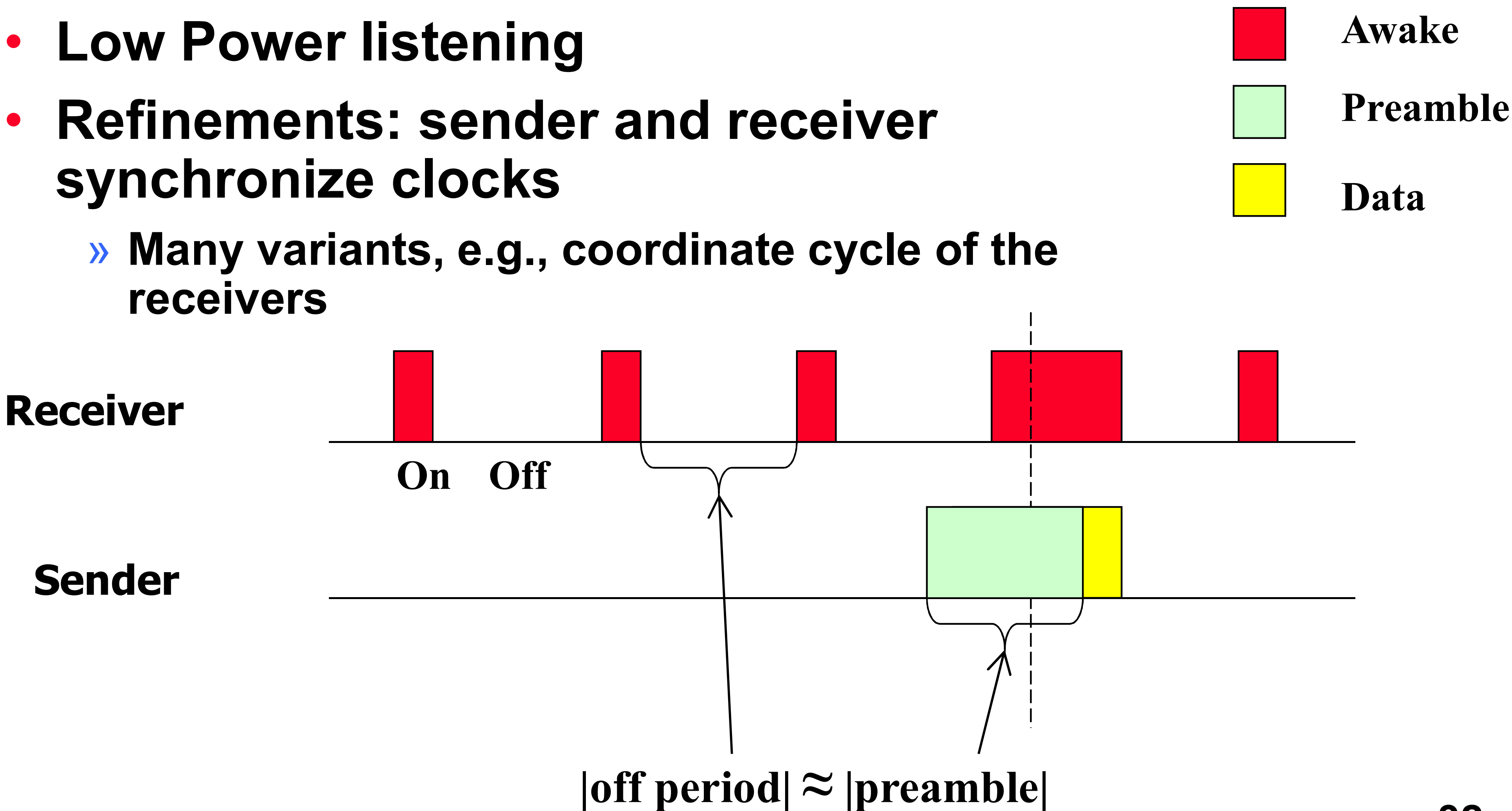
- TDMA (similar to cellular networks)



- Shortcomings
  - » Necessity to organize nodes in clusters and cluster hierarchies
  - » High control traffic cost
- Possible solution
  - » Each node maintains two schedules
    - – Its parent schedule
    - – The schedule it sets for its children
  - » Beacons are used to compensate for clock drifts

Asynchronous: B-MAC

- Asynchronous
- Low Power listening
- Refinements: sender and receiver synchronize clocks
  - » Many variants, e.g., coordinate cycle of the receivers



Design Issue: Efficient Data Collection

- Many-to-one communication paradigm
- Multi-hop communication based on tree topology
  - Nodes select one parent to send their data packets
  - Traffic volume increases near the root: impacts battery life time and possibly network performance
- Aggregate packets before sending them
  - Reduces the number of packets near the root
  - In low duty cycle network, gain may be substantial
- Aggregate information using simple operations
  - Max, min, average, …
- Price to pay: loss of real-time

Delay Tolerant Network with Data Mules

- Clusters are not directly connected by a network to the server
- Cluster heads store data from the cluster nodes
- "Data mules" collect the data periodically
  - » Cars, robots, plane, etc.
- When a cluster-head detects a mule, it uploads to it the data it had in store

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Today's Sensor Networks

- Push toward diverse set of low-power wireless technologies
  - » Differ in MAC, licensed/unlicensed, range, power, target bit rates, …
- New types of MAC technologies
  - » IEEE WiFi and PAN technologies: both WiFi and PAN
    - – Zigbee, Bluetooth Low Energy, 802.11ah
  - » Cellular: LTE-M, NB-IoT
  - » Industry-driven technologies using diverse PHY and MAC protocols
    - – LoRa, Sigfox, Z-Wave, …
    - – Protocols can be as simple as Aloha
- RFIDs, e.g., DASH7

WiFi HaLow – 802.11ah

- Low power version of WiFi operating in the unlicensed 900 MHz band (2017)
  - » Increased range (1km), lower transmit power
- Based on 802.11a/g but uses 1 MHz channels
  - » 26 channels; can do channel bonding up to 16 MHz
  - » Transmit rates in range of 0.3 to 347 Mbps
- Support for relaying, limiting contention, and power save mode
  - » Relays: increase AP coverage; increase bit rates thus reducing paper
  - » Contention-free periods for AP-stations, timed access
  - » Sectorization: groups of nodes can only send in certain time windows, e.g., to reduce hidden terminal effects

IEEE PAN - ZigBee

- 802.15.4 PHY layer is used by Zigbee (2003) and some non-IEEE protocols
  - » Defined for the 900 MHz and 2.4 GHz unlicensed bands
- Uses Direct Sequence Spread Spectrum
- MAC uses CSMA-CA
- Can create star and point-to-point topologies
  - » See PAN lecture
- Targets low-bandwidth, relatively short range applications
  - » Up to 250 Kbps, range 10-100 m
  - » 127 byte packets

Bluetooth Low Energy

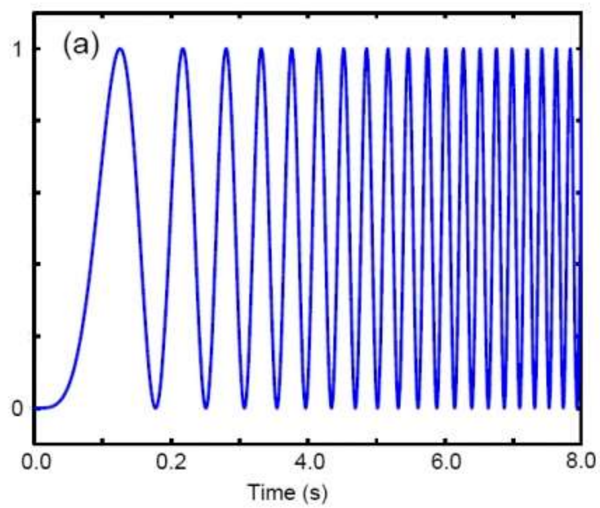
- Lower power consumption and cost than Bluetooth but similar transmissions range
- Not backwards compatible with Bluetooth
  - » Uses the same 2.4 GHz frequencies to radio can be shared
- Uses frequency hopping on 40 2-MHz channels
  - » Compared to 79 1-MHz channels for Bluetooth classic
  - » Also some differences in the frequency hopping
  - » Similar modulation (Gaussian frequency shift keying)
- Targets applications with low bit rates
  - » PHY rates up to 1 Mbps (2 Mbps for Bluetooth 5)
  - » Data rates much lower: up to 0.5 Mbps for Bluetooth 5

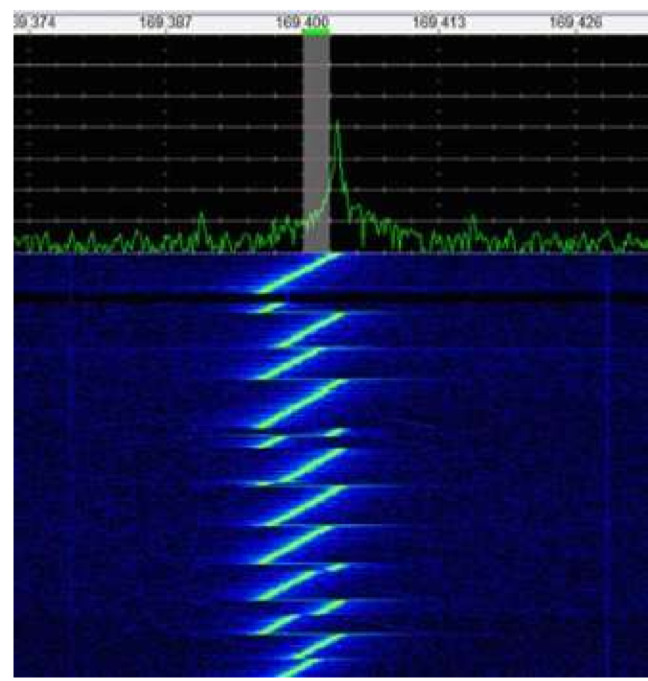
Low Power Cellular

- Narrowband – IoT (NB-IoT) – 2016
  - » Focus on indoor coverage, low bitrates, dense deployments
  - » Two categories with different performance
  - » Uplink typically faster: 16-159 kbps vs 26-127 kbps
- LTE-M machine type communication - 2016
  - » High bandwidth including voice, mobility
  - » Lower latency but higher cost compared with NB-IoT
  - » Uplink 1-7 Mbps – Downlink 1-4 Mbps
- Both standards are defined by 3GPP
- Simple node design: single antenna, SISO
  - » Half duplex: always for NB-IoT, optional for LTE-M

Low-Power Wide-Area Networks (LPWAN)

- Longer range to simplify deployment
  - » "Metropolitan" area – cite-wide sensor network
  - » Star topology, up to 10 km of range
- Based on spread spectrum across 125+ KHz band
  - » Chirp spread spectrum
- Sub-GHz bands
  - » 900 MHz in US
- Low throughput
  - » 0.25-27 Kbps
  - » Payload up to 243B
- Aloha protocol
  - » What about capacity?



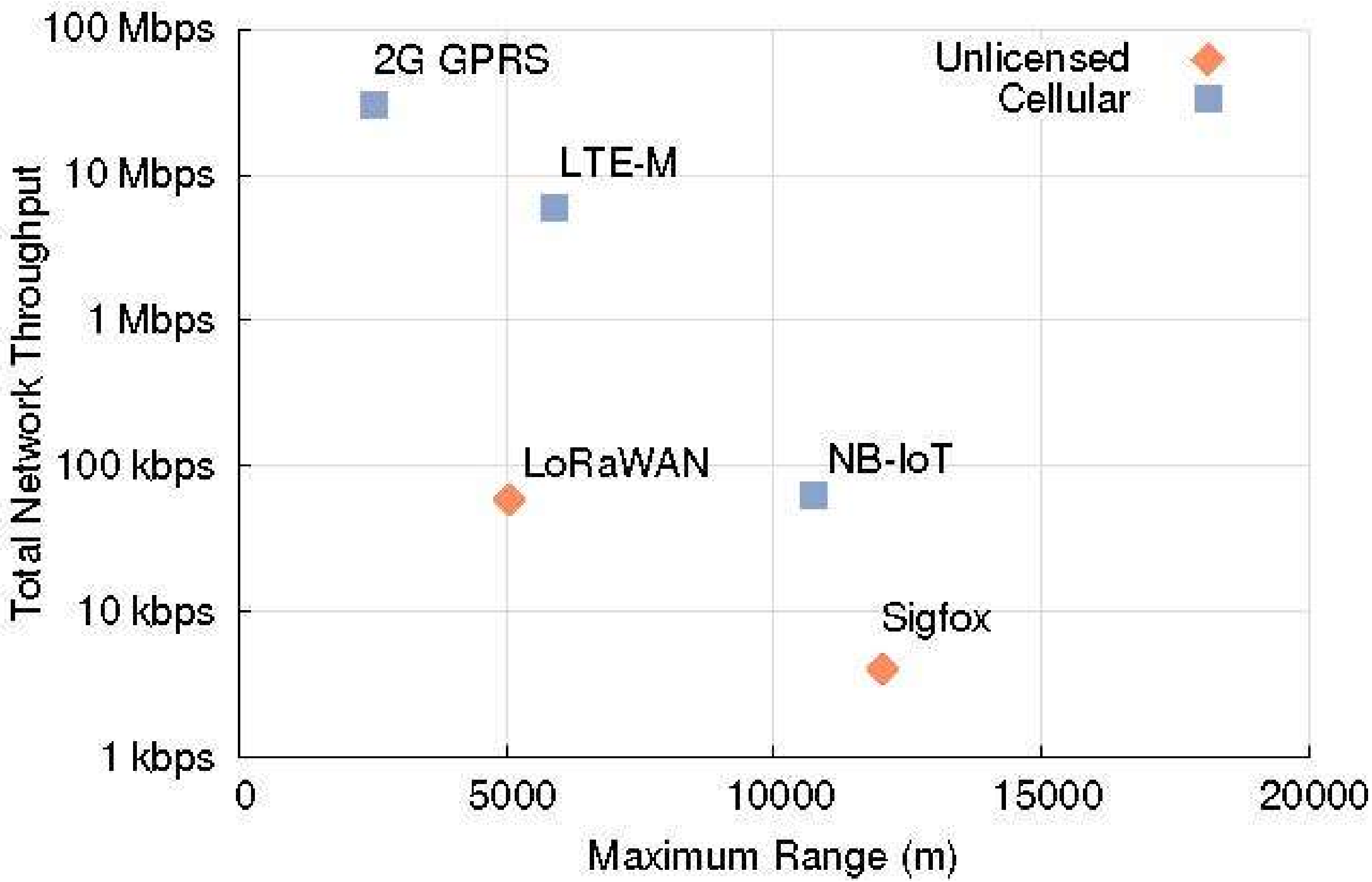


https://www.link-labs.com/blog/what-is-lora

SigFox

- **Ultra-narrowband technology:**
  - » Transmits in 200 Hz in 200 KHz of sub-GHz spectrum
  - » Low data rate 100s of bits/sec
  - » Uses differential BPSK – phase modulation
- **Based on Aloha protocol: transmitter picks a carrier frequency; received decodes full band**
- **Very basic protocol: small packets, no encryption, single bit rate**
  - » Payload is 12 bytes uplink, 8 bytes downlink
- **Also uses star topology**
- **Radios are cheaper than LoRaWAN**
  - » With roughly double the range

Comparison
Throughput versus Range



"Challenge: Unlicensed LPWANs Are not Yes the Path to Ubiquitous Connectivity", Branden Ghena et. al., ACM Mobicom'19

https://dl.acm.org/doi/10.1145/3300061.3345444

Power Efficiency

Network Technology	Average Power (uW) 84 Bytes Per 1 Hour	84 Bytes Per 4 Hours	200 Bytes Per 24 Hours	1000 Bytes Per 24 Hours
Sigfox (155 dB)	110	29	11	56
LoRaWAN (143 dB)	12	3.0	1.1	5.1
LTE-M (144 dB)	50	25	12	13
LTE-M (164 dB)	2200	620	150	440
NB-IoT (144 dB)	62	22	13	15
NB-IoT (164 dB)	1800	520	100	240

Max range

Good Signal