18-452/18-750
Wireless Networks and Applications
Lecture 23: Sensor Networks

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http://www.cs.cmu.edu/~prs/wirelessF18/

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

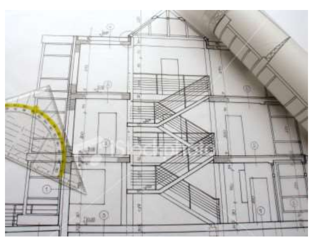
- Commercial Applications
  - » Light/temperature control
  - » Precision agriculture (optimize watering schedule)
  - » Asset management (tracking freight movement/storage)
- Monitoring tools supporting Scientific Research
  - » Wild life Habitat monitoring projects Great Duck Island (UCB), James Reserve (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



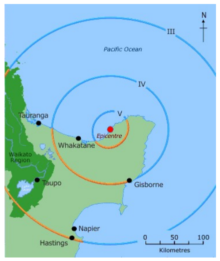
- Similar concept can be applied to
  - » Security cameras, controlling access, …

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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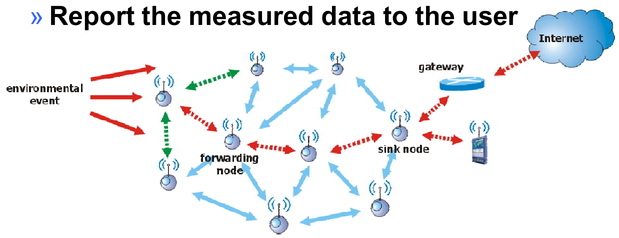
WSN Characteristics and Design Issues

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

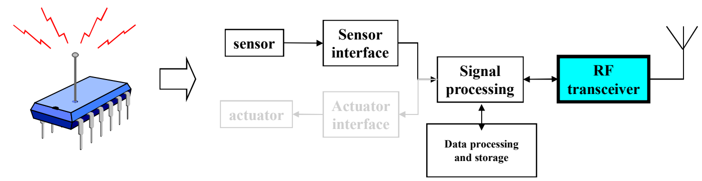
Wireless helps but may not be required!

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



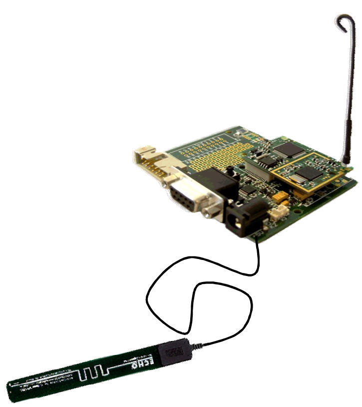
Sensor Node architecture



- 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

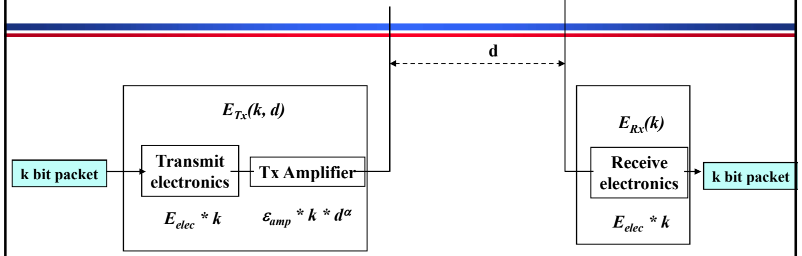
Design Issue: Low-cost

- 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



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

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

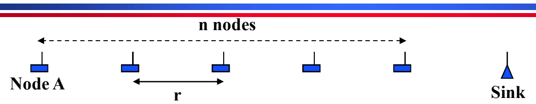
Typical values:

$\alpha = 2…6$

$E_{elec} = 50$ 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: $E_{multi\text{-}hop} = n*E_{Tx}(k, d = r) + (n-1)* E_{Rx}(k)$

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

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

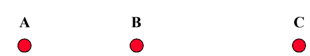
Assuming $\alpha = 3, r = 10m$, we get $E_{multi-hop} < E_{direct}$ as soon as $n \geq 2$

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:

$td^{\alpha}_{AB} + td^{\alpha}_{BC} + c$

Relay region

Relay region:

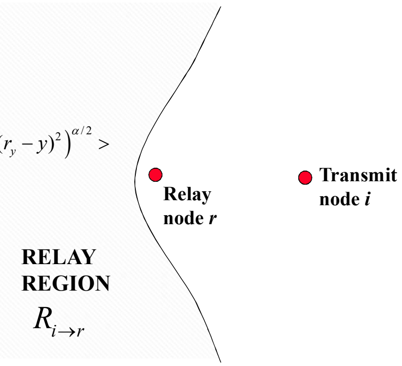
$$R_{i\to r} \equiv \{(x,y) \mid P_{i\to r\to(x,y)} < P_{i\to(x,y)}\}$$

We can expand this to:

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

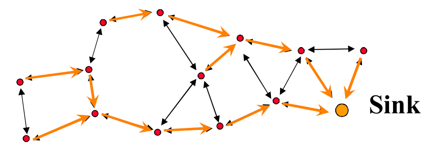
$$t\left((i_x-x)^2+(i_y-y)^2\right)^{\alpha/2} - t\left((r_x-x)^2+(r_y-y)^2\right)^{\alpha/2} >$$

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



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

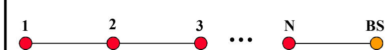


Load-balancing

- 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

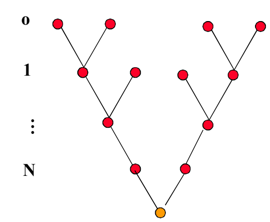
P_{pr} : Average processing power consumption

$P_T(k)$: 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

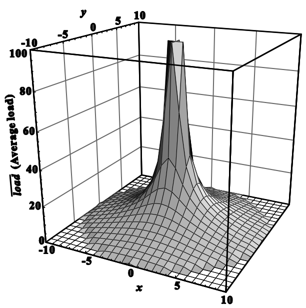
$F(d) \ge 2^d$

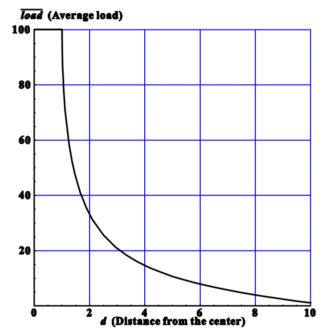
$P(d) \ge P_{tx} + 2^d (P_{tx} + P_{rx})$

P grows exponentially with distance from leaf node

Load balancing

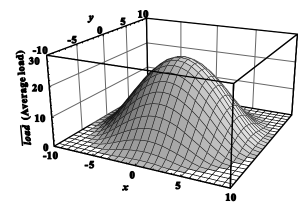
- Power consumption increases at least linearly when nodes are closer to the sink
- Typical case is much worse

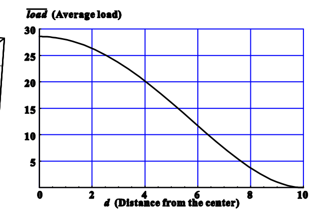




Use Mobility for Load-balancing

- 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

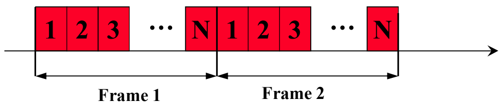
Medium-Access Control

- 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 http://research.cens.ucla.edu/people/estrin/resources/conferences/2002jun-Ye-Estrin-Energy.pdf

Synchronous MACs

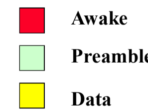
- TDMA (similar to cellular networks)

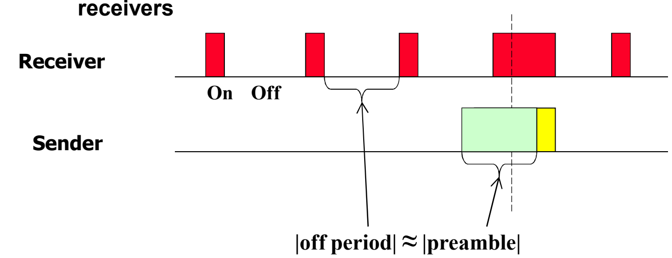


- Shortcomings
  - » Necessity to organize nodes in clusters and cluster hierarchies
  - » High control traffic cost
- Possible solution
  - » Each node maintains two schedules
    - – Its parent schedule
    - – The schedule it sets for its children
  - » Beacons are used to compensate for clock drifts

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

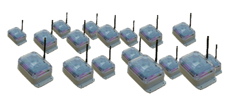
- Push toward LPWAN wireless technologies
  - » Technology specifically designed for low power sensors with low duty cycle
  - » Transmission range of kilometers simplifies deployment – fewer base stations required
- New types of MAC technologies
  - » Early sensor networks typically based on 802.15 type standards (e.g., Zigbee)
  - » New MACs are simpler and specific for low power and low throughput
    - – E.g., Aloha style protocols

LPWAN's potential

sub-GHz ISM band
chirp spread-spectrum (CSS)

10km Range

Low Data Rate
(0.25 kbps – 27 kbps)



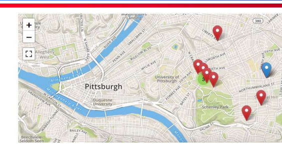
Thousands of devices per gateway

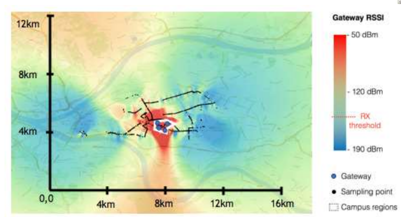
5+ Year Battery Life

Charm: Exploiting Geographical Diversity Through Coherent Combining in Low-Power Wide-Area Networks Adwait Dongare, Revathy Narayanan, Akshay Gadre, Artur Balanuta, Anh Luong, Swarun Kumar, Bob Iannucci, Anthony Rowe, IPSN 2018

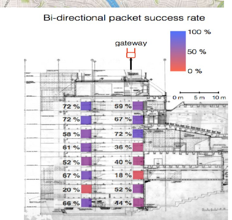
Is this realistic?

Deployment of 4 outdoor gateways + multiple indoor gateways



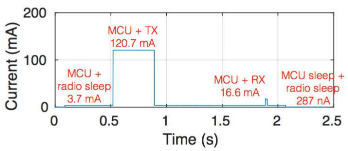


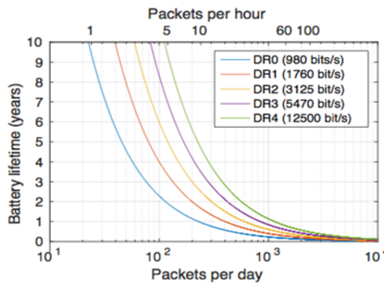
Coverage < 10km with islands of isolated coverage



Worse within buildings

Device Power Analysis

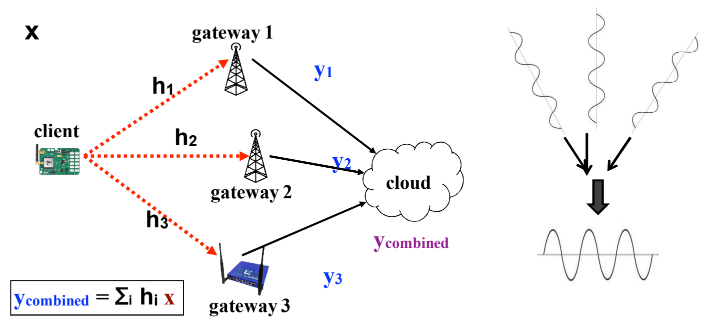




- Wireless radio transmission dominates the energy budget.
  - » Microcontrol unit power low
- Ensuring faster transmission can reduce the power drain.
- Can we do better by using multiple cooperating basestations?
  - » Reduce distance to sensors
  - » Obtain multiple copies of each packet

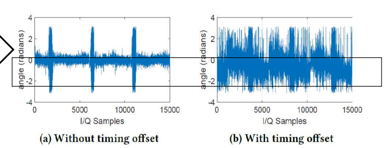
Charm

A system that allows coherent combination of signals received at multiple LP-WAN gateways

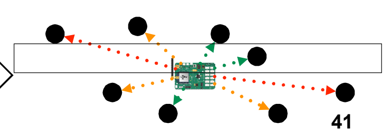


Challenges

- Limited backhaul bandwidth → Maximum datarate:10Gbps
- Absence of precise time synchronization



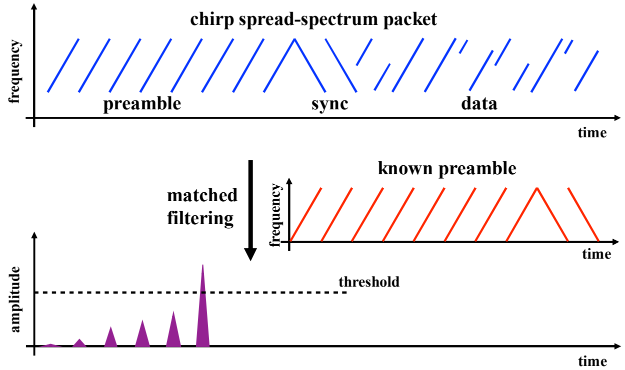
- Large number of streams are difficult to scale



How does Charm resolve each of these challenges?

Challenges	Charm's Solution
Limited backhaul bandwidth	Local packet detection
Precise time synchronization	Phase based synchronization
Data from a large number of gateways	Selective combination based on geographic location and signal quality.

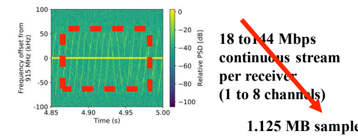
Local Packet Detection



Uses only the preamble and sync header

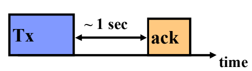
Effect of local detection

- Two-phase protocol
  - » Local packet detection - simplify synchronization requirements
  - » Upload samples only when required - saves bandwidth



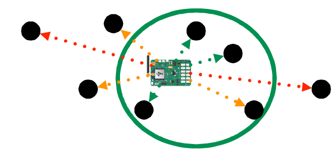
Phase based synchronization

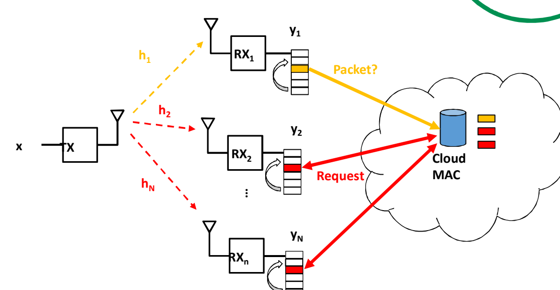
- Synchronization is achieved as a two step process.
  - » Coarse synchronization- based on GPS clocks/ NTP → Up to few milliseconds
  - » Fine synchronization- iterating over smaller set of samples → Up to a single sample
- LoRaWAN 1 sec Ack - weaker latency requirements



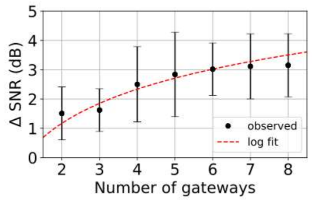
Selective combination of signals

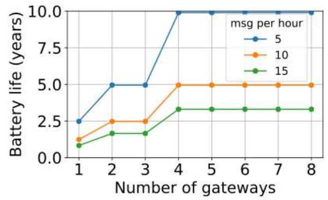
Selective combination is based on location and signal quality - improve scalability





Benchmark: Improved Network And Device Performance





Combined signal SNR increases logarithmically

Results into improved battery life on client devices

Conclusion

- **WSNs are an emerging technology which will continue to grow exponentially in the coming years**
- **This new communication paradigm introduces a new set of design constraints**
  - » **They must be extremely low-cost**
    - – **Both to purchase and to operate**
  - » **They must be extremely energy efficient (lifetime: years)**
    - – **Hardware design**
    - – **Routing and topology mechanisms**
    - – **Specialized Medium Access Control mechanisms**
  - » **Despite their low-cost and power management features, they must implement reliable communication protocols**
  - » **They must integrate versatile middleware, data processing**
  - » **They often rely on a hybrid network infrastructure**