COMP6733 IoT Design Studio

Time and Space Synchronisation

This Lecture

- Groups and project allocation have been released.
  - https://webcms3.cse.unsw.edu.au/COMP6733/23T2/resources/86678
- Lab 3
  - BLE with Laptop and Ranging
- LPWAN
- Localisation

Motivation

- IoT aim to provide information on the spatial-temporal characteristics of the physical world
- Each observation is a tuple of the form <S,T,M> where
  - S = spatial location
  - T = time
  - M = sensor measurement
- Location can be specified by
  - Geographic co-ordinate system
    - (Longitude, Latitude) or (Longitude, Latitude, Altitude)
  - Local co-ordinate system
    - (x,y), (x,y,z) etc.

Localization

A system service that establishes spatial relations between nodes

- sensor data without location information are often meaningless (a temperature is too hot, but where?)
- devices need to know where they are for actuation (turn on the sensor near the window…)
- mapping of sensor data to internet (google maps)
- required by other services (geographic routing)
- ranging, localization, tracking

What can you do with the location information?

- Location based service
  - Local search, Uber, Deliveroo…
- To provide location stamps
- To monitor the spatial evolution of a diffuse phenomenon
  - To track a chemical/radioactive plume
- To track objects / animals
- Navigation
- To perform spatial query

Virtual fencing

Demo: Localization in Action I

Demo: Localization in Action II

Some localization methods

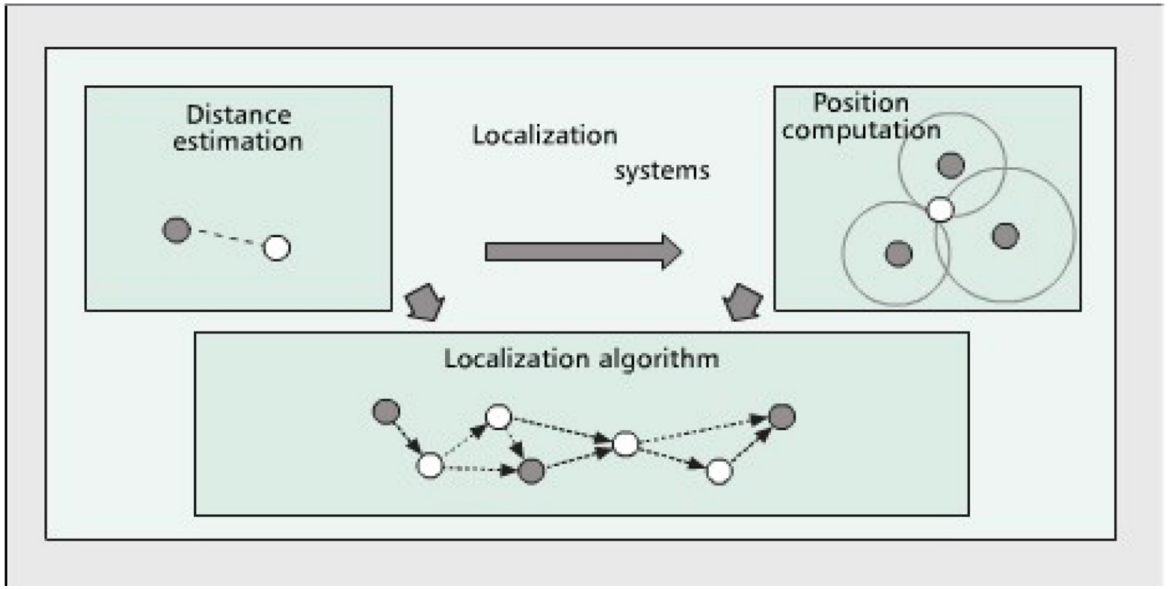
- Manual location
  - Sensor locations are manually recorded
  - Issues?
- Localisation by mobile phone towers
  - Accuracy of 100m

$$\sigma_{\hat{\tau}}^2 \geq \frac{c^2}{4\pi^2 B^2 \, E_s/N_0}\left(1 + \frac{1}{E_s/N_0}\right)$$

  - Accuracy too low?
- GPS
  - Operated by the US Government
  - 31 geo-stationary satellites (at altitude of about 20,000km)
  - High accuracy (few meters) with good light of sight
  - Similar systems: Galileo, NAVIC

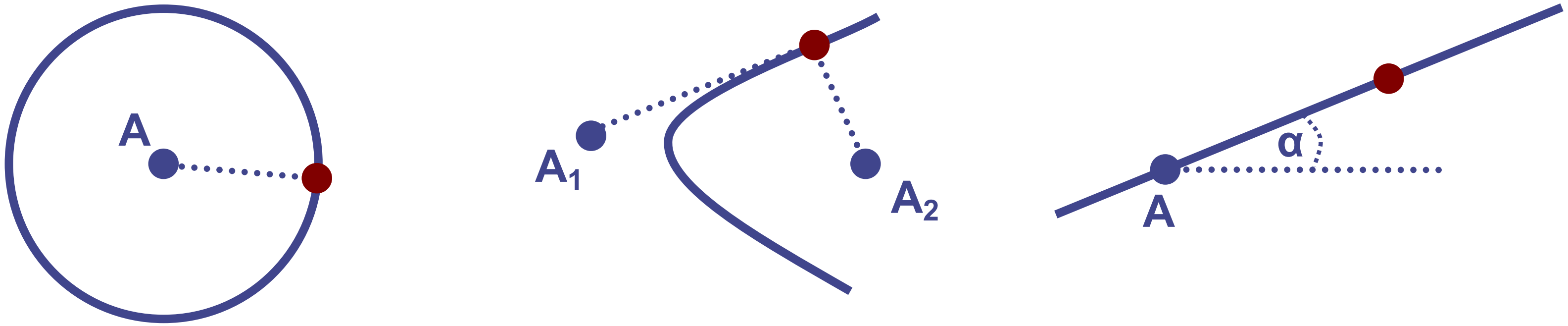
Localization Framework

- Distance Estimation: Estimation position/angle related parameters between two nodes
- Position Computation: Computing a node's position based on available information and anchor node positions
- Localization Algorithm: Manipulating available information in order to localize other nodes in the network



Relative position estimation

- Determine low-level spatial relations between nodes
- Impose geometric constraints on the location of a node

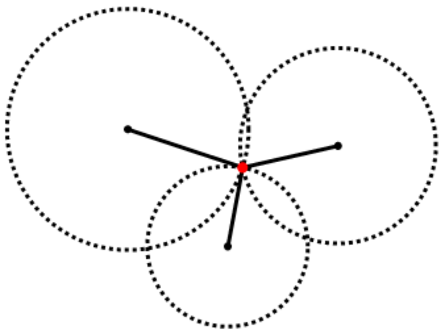


distance | distance difference | angle

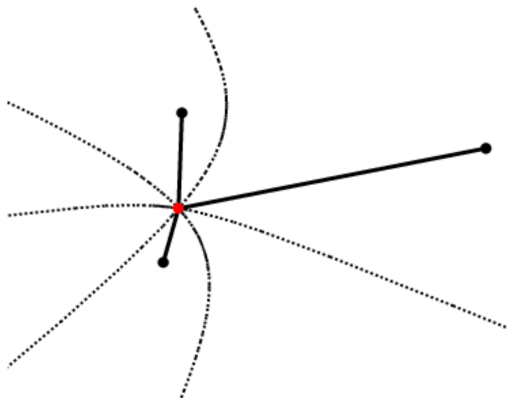
Position Computation

- Establish a common coordinate system across the network
- Absolute or relative

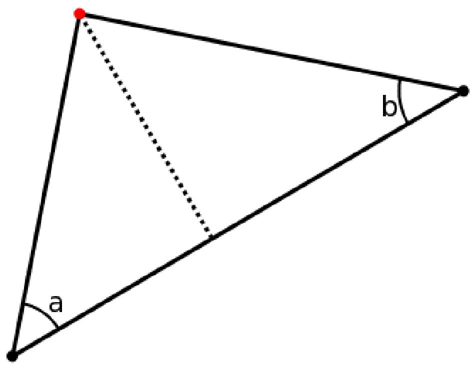
distance



distance difference



angle

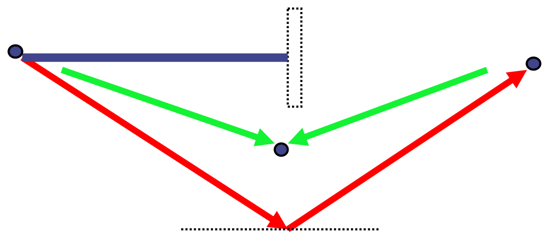


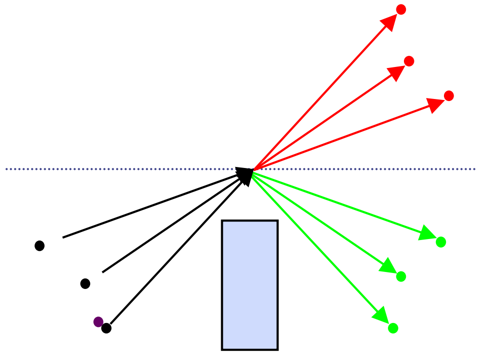
trilateration (or multilateration)

triangulation

Challenges: Real-world Signal Propagation

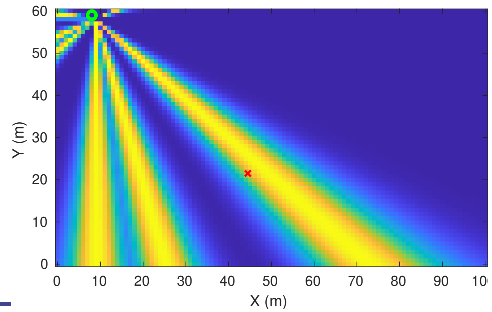
- Signals attenuate at different rates in air, water, solids
- Signals reflect from objects
- Non-line of sight problems

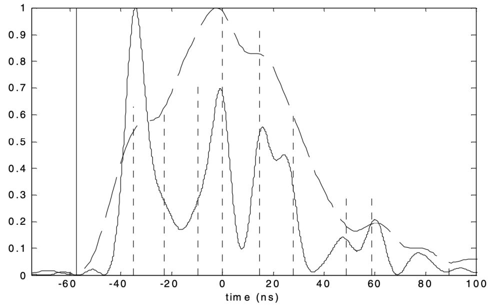




caused by reflection in the environment

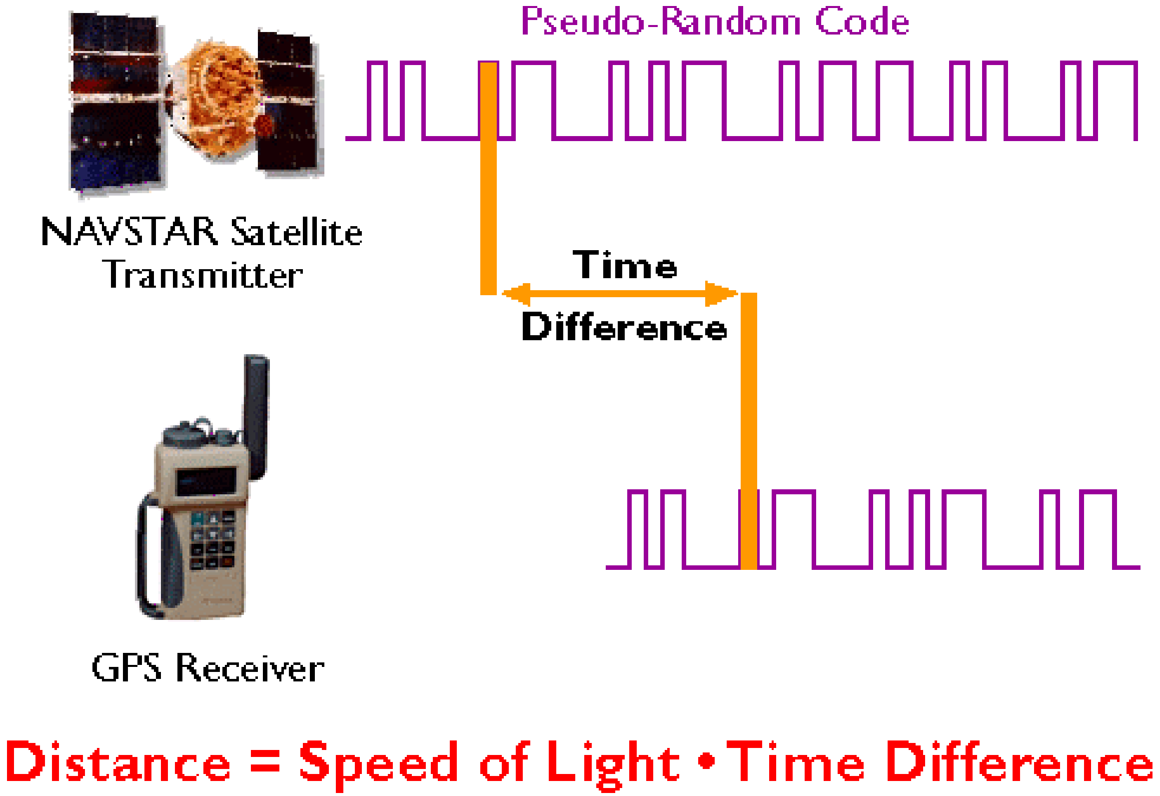
can't be always resolved locally





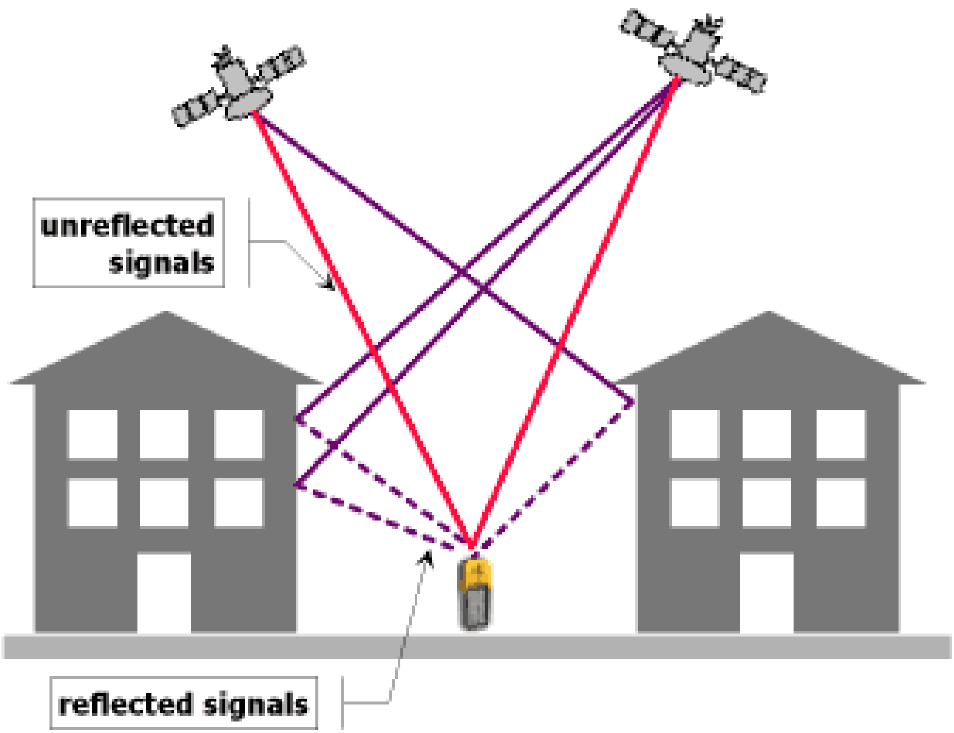
Estimating distances – Time of Arrival (ToA)

- If anchors and nodes are sychronised in time
  - Anchor emits a pulse or a characteristic signal
  - Use time of transmission, propagation speed, time of arrival to compute distance
- GPS uses ToA to calculate distance



Requirements of ToA

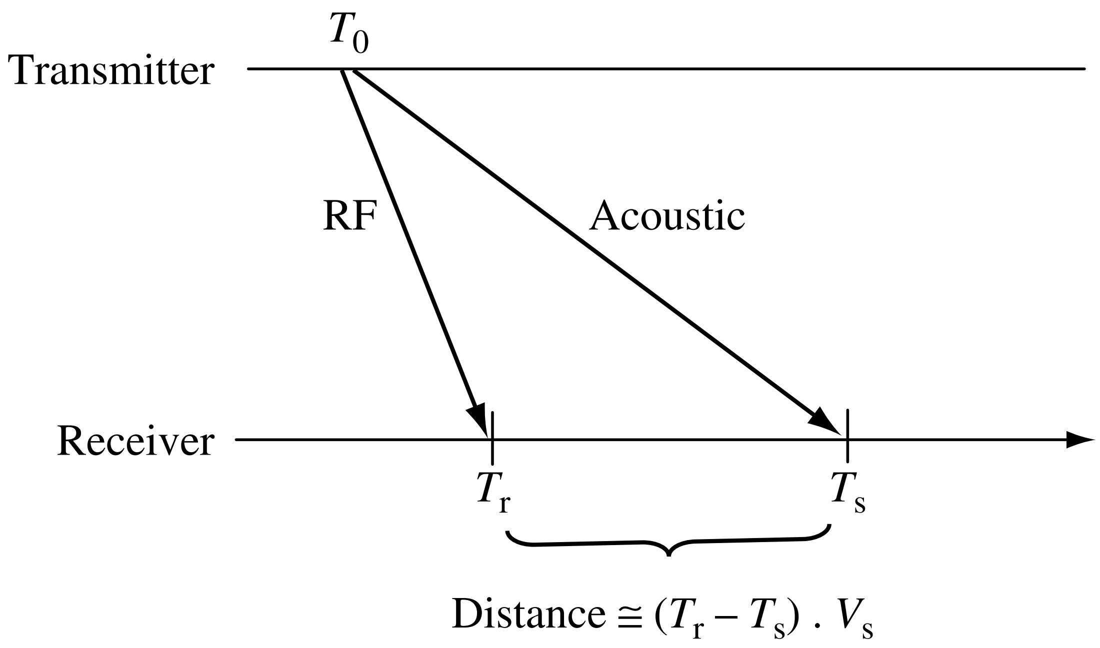
- Tight time synchronisation
  - Synchronisation error => wrong distance estimate
- Line-of-sight to the anchors
  - Not always possible
  - Multi-path effect can cause error in estimating time of arrival



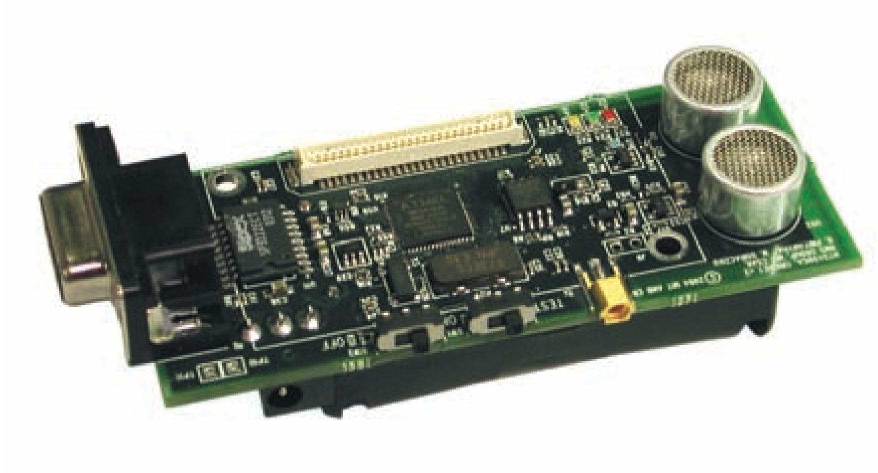
Estimating distances – TDoA

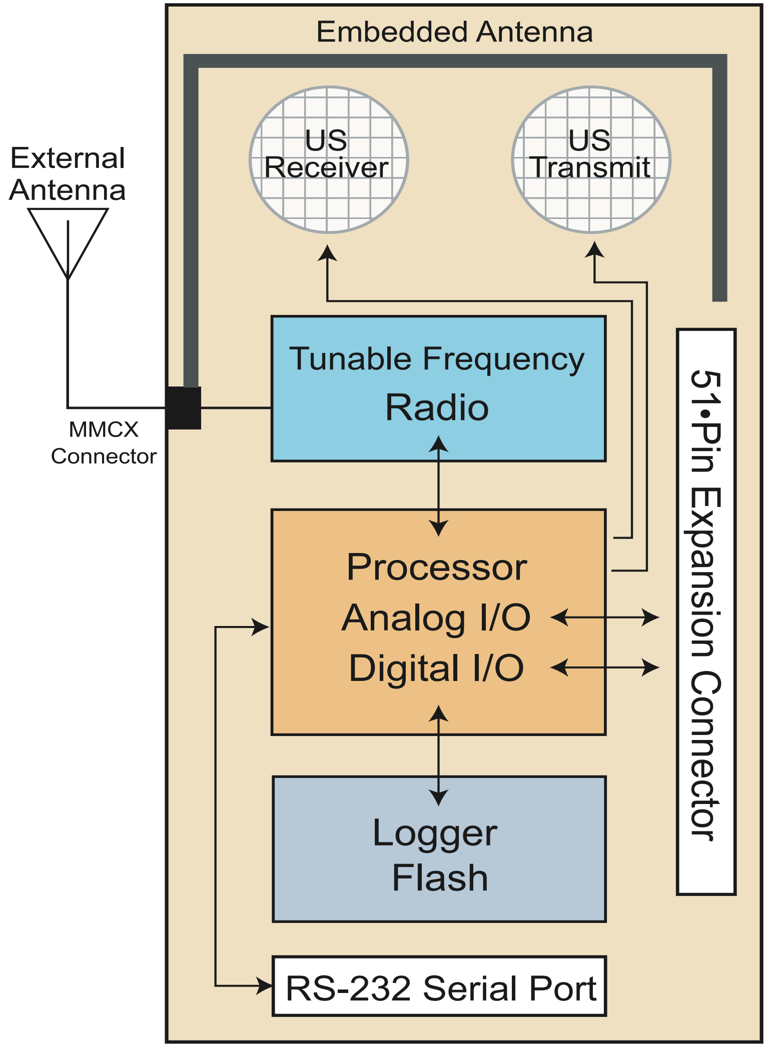
Time Difference of Arrival (TDoA)

- Use two different signals with different propagation speeds
- Example: ultrasound and radio signal
  - Propagation time of radio negligible compared to ultrasound
- Compute difference between arrival times to compute distance
- Problem: Calibration, expensive/energy-intensive hardware



The Cricket motes estimate distance using ToDoA

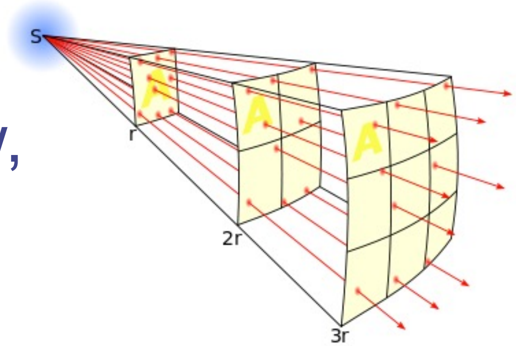




MCS410CA Block Diagram

RSSI Ranging

- RSSI (Radio Signal Strength Indicator): value provided by radio chips indicating power of the received signal
- Signals attenuate with a predictable rate
- Free space propagation (inverse square law, surface of a sphere)



$$P_r = \frac{P_t A_r}{4\pi r^2}$$

- In reality, mutlipath, fading, and shadowing effects result in a law more like

$$P_r \propto \frac{P_t}{r^\alpha}, \text{ where } 2 \le \alpha \le 6$$

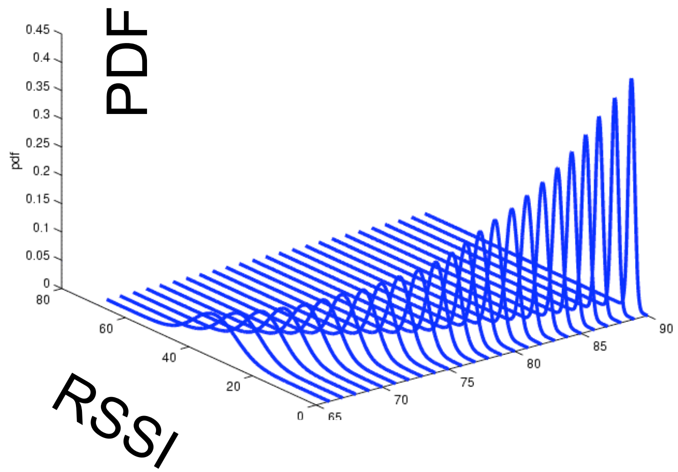
- Many multipath and shadowing models exist (Raleigh, Rice, lognormal, ...) for different settings and materials

RSSI Ranging

1. Transmit at a known power, measure the received power (RSSI)
2. Use a propagation model to calculate distance d

Transmiter **Receiver**

$$P_{\text{recv}} = c\frac{P_{\text{tx}}}{d^{\alpha}} \Leftrightarrow d = \sqrt[\alpha]{\frac{cP_{\text{tx}}}{P_{\text{recv}}}}$$



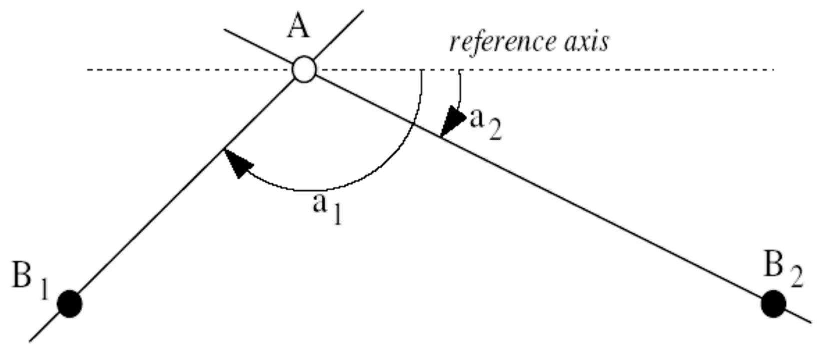
Errors:

- Need to calibrate the model
- Unpredictable channel variations
- Error increases with distance
- Differences in hardware, etc

Angle Estimation

- determine relative angle to a transmitting road
- both ultrasound and radio signals have been used (acoustic or radio antenna arrays)

triangulation

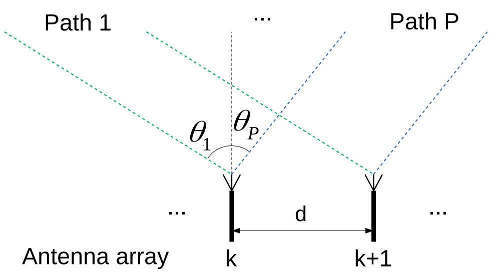


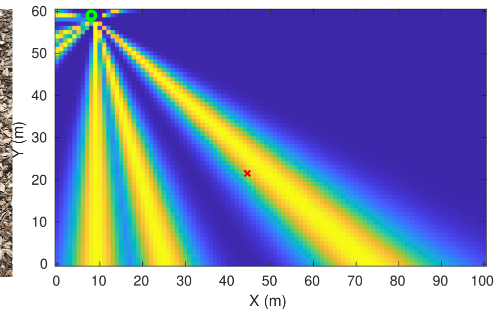
Two approaches:

1. nodes transmit directional signals
2. complex antenna array, or multiple ultrasonic receivers determine the angle of arrival

cons:

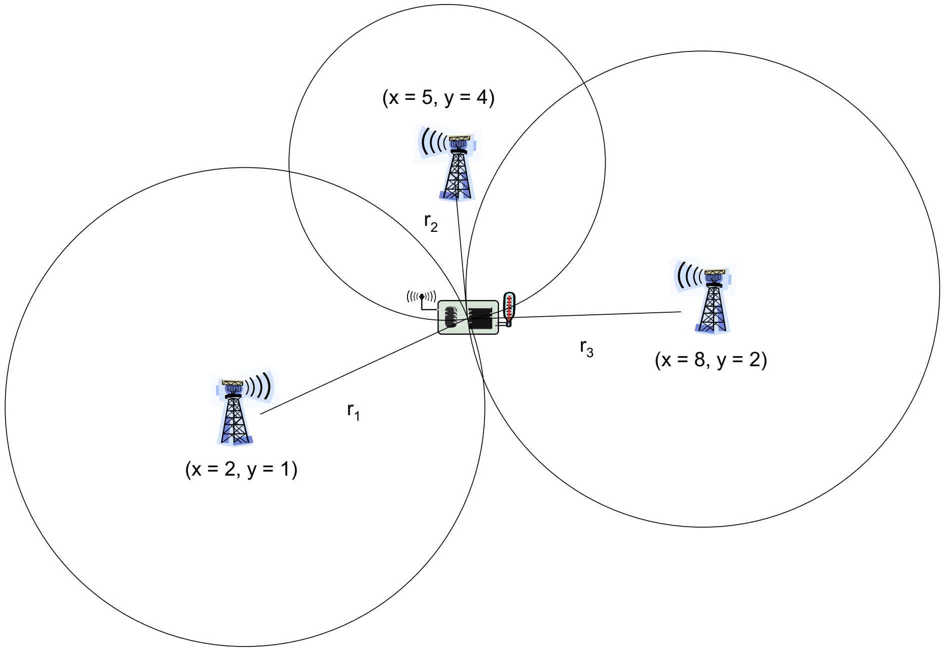
- acoustic signals are susceptible to echoes
- radio signals require powerful hardware

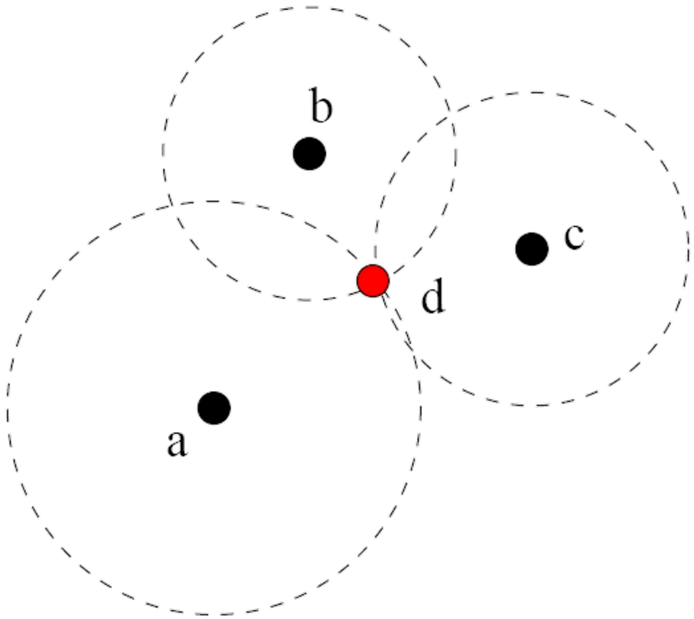




Tri/Multi-lateration

- Anchors advertise their coordinates & transmit a reference signal
- Other nodes use the reference signal to **estimate** distances to anchor nodes





Trilateration

- Assuming distances to three points with known location are exactly given
- Solve system of equations (Pythagoras!)
  - (x_i, y_i) : coordinates of ***anchor point*** i, r_i distance to anchor i
  - (x_u, y_u) : unknown coordinates of node

$$(x_i - x_u)^2 + (y_i - y_u)^2 = r_i^2 \text{ for } i = 1, \ldots, 3$$

  - Subtracting eq. 3 from 1 & 2:

$$(x_1 - x_u)^2 - (x_3 - x_u)^2 + (y_1 - y_u)^2 - (y_3 - y_u)^2 = r_1^2 - r_3^2$$

$$(x_2 - x_u)^2 - (x_{\cancel{2}\,3} - x_u)^2 + (y_2 - y_u)^2 - (y_{\cancel{2}\,3} - y_u)^2 = r_2^2 - r_3^2.$$

  - Rearranging terms gives a linear equation in (x_u, y_u)!

$$2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$$

$$2(x_3 - x_2)x_u + 2(y_3 - y_2)y_u = (r_2^2 - r_{\cancel{2}\,3}^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)$$

Trilateration as matrix equation

- Rewriting as a matrix equation:

$$2\begin{bmatrix} x_3 - x_1 & y_3 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{bmatrix}\begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) \\ (r_2^2 - r_{\cancel{2}\,3}^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2) \end{bmatrix}$$

- Example: $(x_1, y_1) = (2,1)$, $(x_2, y_2) = (5,4)$, $(x_3, y_3) = (8,2)$,
  $r_1 = 10^{0.5}$, $r_2 = 2$, $r_3 = 3$

$$2\begin{bmatrix} 6 & 1 \\ 3 & -2 \end{bmatrix}\begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} 64 \\ 22 \end{bmatrix}$$

=> $(x_u,y_u) = (5,2)$

Trilateration with distance errors

- What if only distance estimation $r_i^0 = r_i + \varepsilon_i$ available?
- Use multiple anchors, overdetermined system of equations

$$
2\begin{bmatrix} x_n - x_1 & y_n - y_1 \\ \vdots & \vdots \\ x_n - x_{n-1} & y_n - y_{n-1} \end{bmatrix} \begin{bmatrix} x_u \\ y_u \end{bmatrix} =
\begin{bmatrix} (r_1^2 - r_n^2) - (x_1^2 - x_n^2) - (y_1^2 - y_n^2) \\ \vdots \\ (r_{n-1}^2 - r_n^2) - (x_{n-1}^2 - x_n^2) - (y_{n-1}^2 - y_n^2) \end{bmatrix}
$$

- Use (x_u, y_u) that minimize mean square error, i.e, $||\mathbf{Ax} - \mathbf{b}||_2$

Minimize mean square error

- Look at square of the of Euclidean norm expression (note that $||\mathbf{v}||_2^2 = \mathbf{v}^{\mathrm{T}}\mathbf{v}$ for all vectors v)

$$||\mathbf{Ax} - \mathbf{b}||_2^2 = (\mathbf{Ax} - \mathbf{b})^{\mathrm{T}}(\mathbf{Ax} - \mathbf{b}) = \mathbf{x}^{\mathrm{T}}\mathbf{A}^{\mathrm{T}}\mathbf{Ax} - 2\mathbf{x}^{\mathrm{T}}\mathbf{A}^{\mathrm{T}}\mathbf{b} + \mathbf{b}^{\mathrm{T}}\mathbf{b}$$

- Look at derivative with respect to x, set it equal to 0:

$$2\mathbf{A}^{\mathrm{T}}\mathbf{Ax} - 2\mathbf{A}^{\mathrm{T}}\mathbf{b} = 0 \Leftrightarrow \mathbf{A}^{\mathrm{T}}\mathbf{Ax} = \mathbf{A}^{\mathrm{T}}\mathbf{b}$$

  - ***Normal equation***
  - Has unique solution (if A has full rank), which gives desired minimal mean square error

- Essentially similar for angulation as well

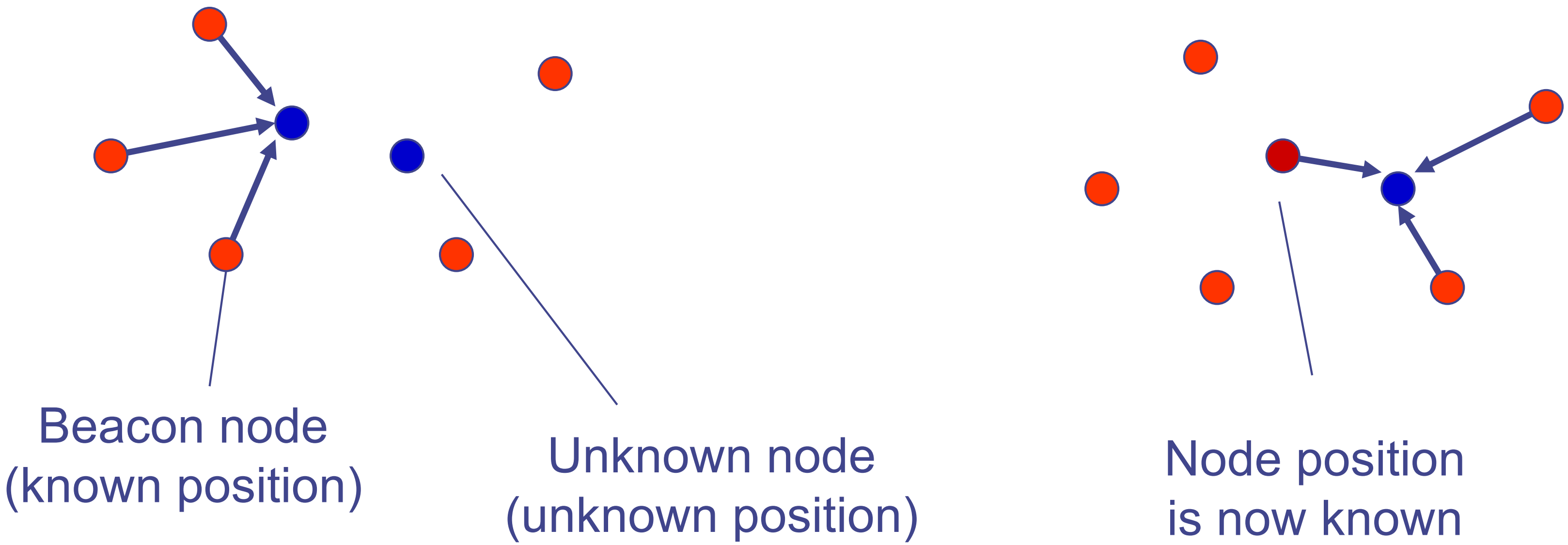
Trilateration and multilateration

- Trilateration
  - Use the distances from 3 different anchors to determine the location on a plane or (x,y) co-ordinates
  - GPS uses distance from 3 different satellites to determine (longitude, latitude)

- If you want to determine (x,y,z) co-ordinates of a node, what is the minimum number of anchors that you need?

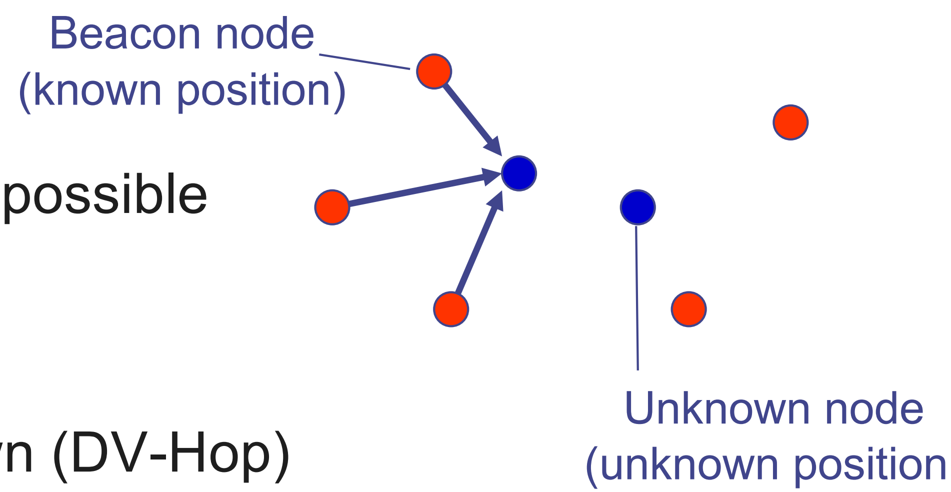
- Many localisation methods use trilateration or multilateration, the differences are how distance to anchors is estimated

Iterative Multilateration: Solution for Multi-hop



Multi-hop range estimation

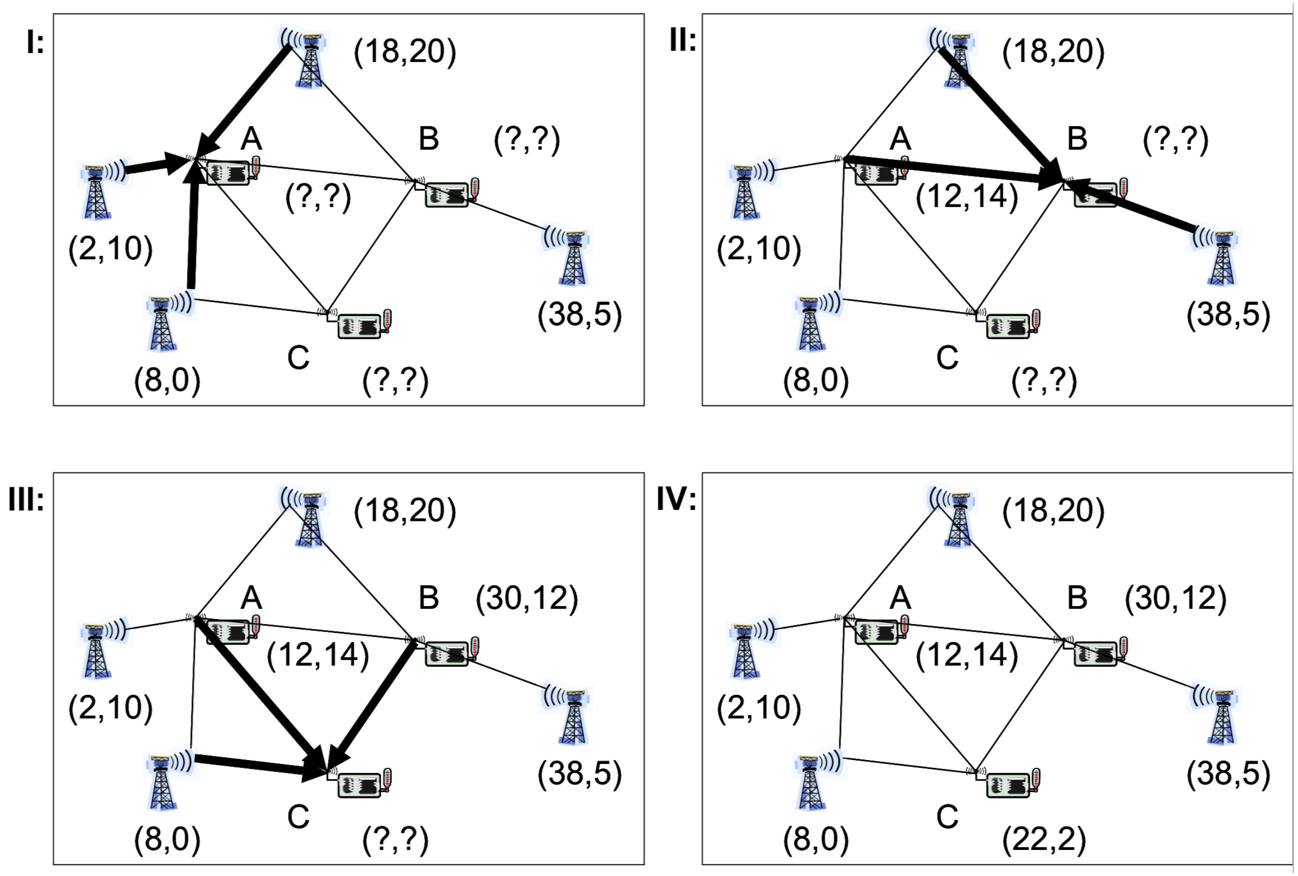
- How to estimate range to a node to which no direct radio communication exists
  - No RSSI, TDoA, etc.
  - But multi-hop communication is possible



- Idea 1: Count # of hops
  - Assume length of one hop known (DV-Hop)
  - Start by counting hops between anchors, divide known distance
- Idea 2: If range estimate between neighbors exist, use them to improve total length of route estimation in previous method (DV-Distance)

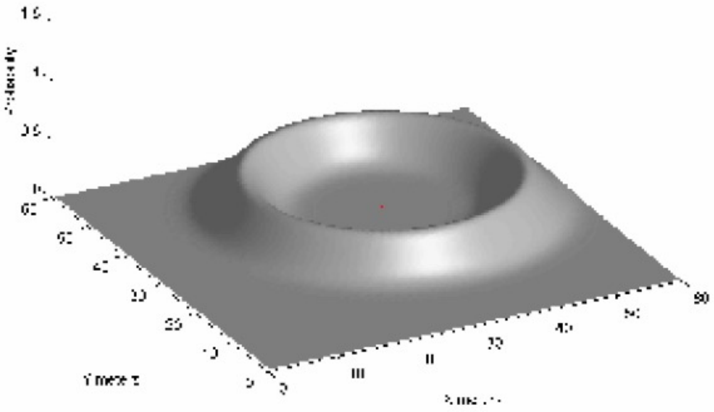
Iterative Multilateration

- Assume some nodes can hear at least 3 anchors, but not all
- Let more and more compute position estimates, spread position knowledge in the network
- Problem: errors can accumulate

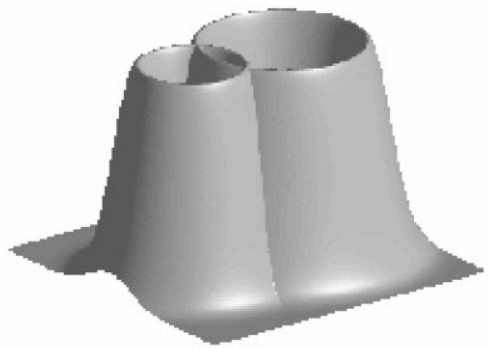


Probabilistic Position Description

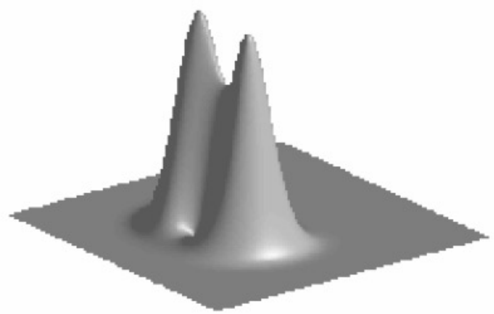
- Similar idea to previous one, but accept problem that position of nodes is only probabilistically known
  - Represent this probability explicitly, use it to compute probabilities for further nodes



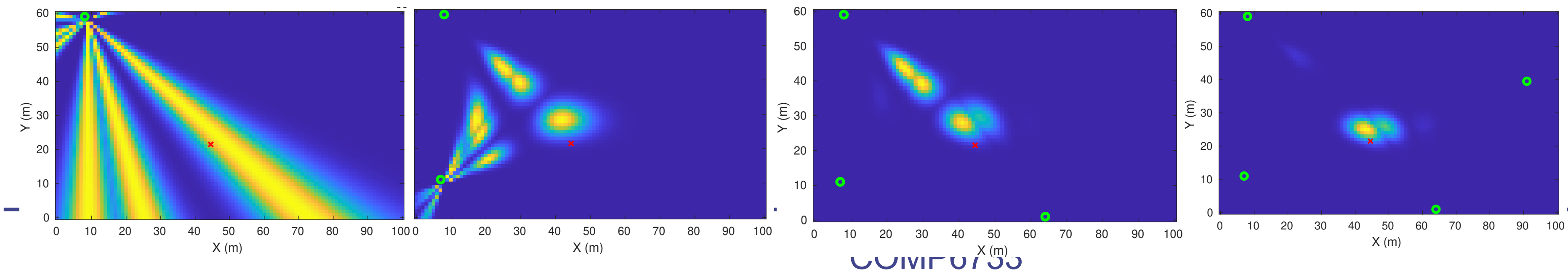
Probability Density function of a node position after receiving a distance estimate from one anchor



Probability Density function of two distance measurements from two independent anchors



Probability Density function of a node after intersection two anchor's distance measurements



Localization Techniques: Range Free

- estimate locations without explicit ranging measurements
- limited accuracy but low cost

Example: iBeacon

- Provide location awareness for apps
- Bluetooth low energy
- Operations:
  - iBeacon base stations broadcast their own unique identification number to the local area.
  - Software on a receiving device (smartphone) may then look up the iBeacon and perform various functions.

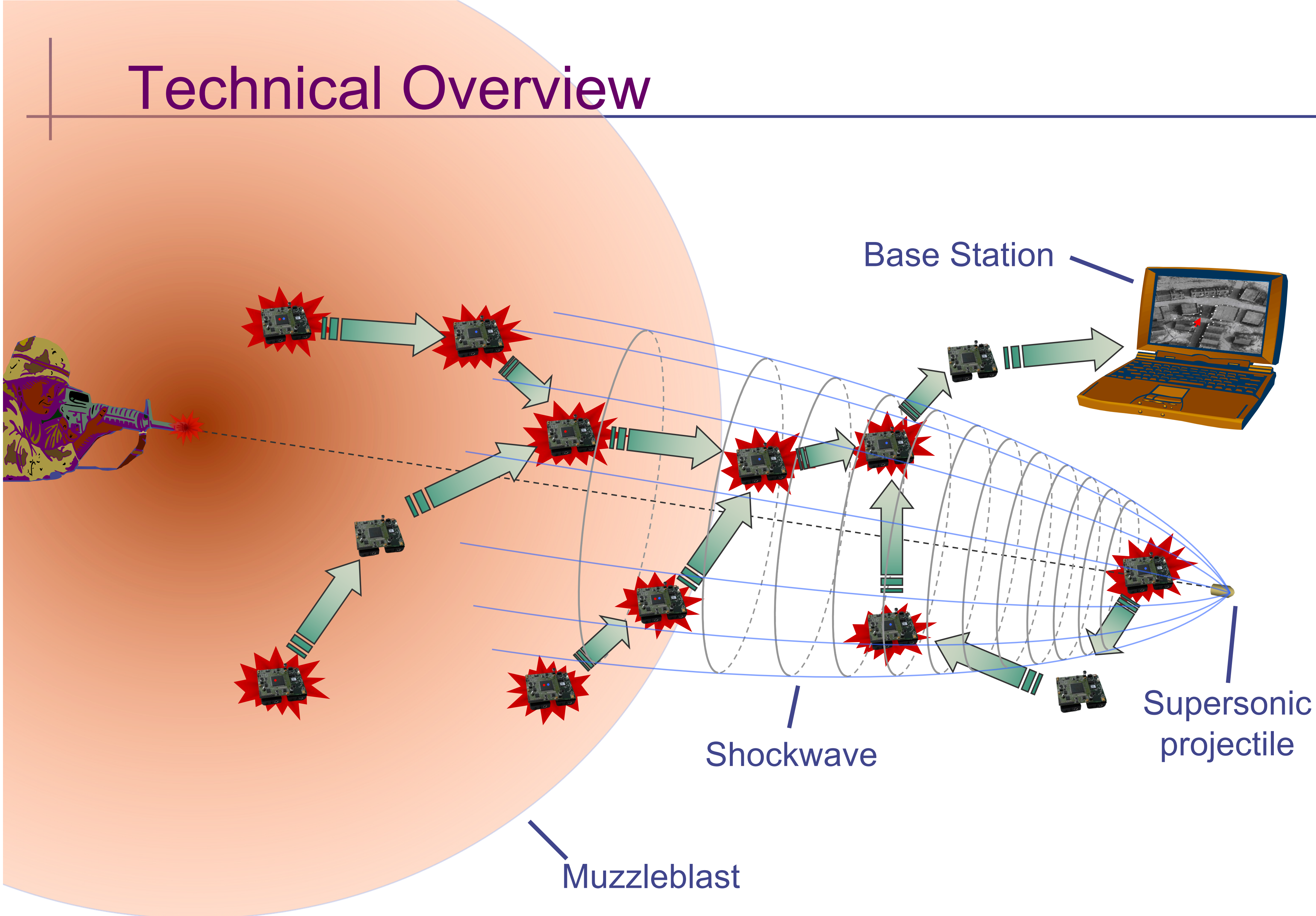
- Location of the tag = Location of the reader that hears the response
- The distance between transmitting beacon and receiving devices can be approximated into 3 distinct ranges
  - Immediate, Near and Far

Example: Countersniper IoT System

- Task: detect a shot and localize shooter on the map in real time
- Real system: deployed and tested at Ft. Benning, GA, USA
- Hard problem in urban space due to multipath and limited line of sight (shots inside buildings, behind cars, …)

- 60 sensors covering 100x40m
- Performance:
  - Avg 3D accuracy: ~1 m
  - Avg 2D accuracy: ~0.6 m
  - Latency: <2 seconds

Technical Overview



2.5D Display, Single shot

Video

Time synchronisation --- background

- Coordinated Universal time (UTC)
  - Primary time standard
  - Within 1 second of mean solar time at 0 degree longitude

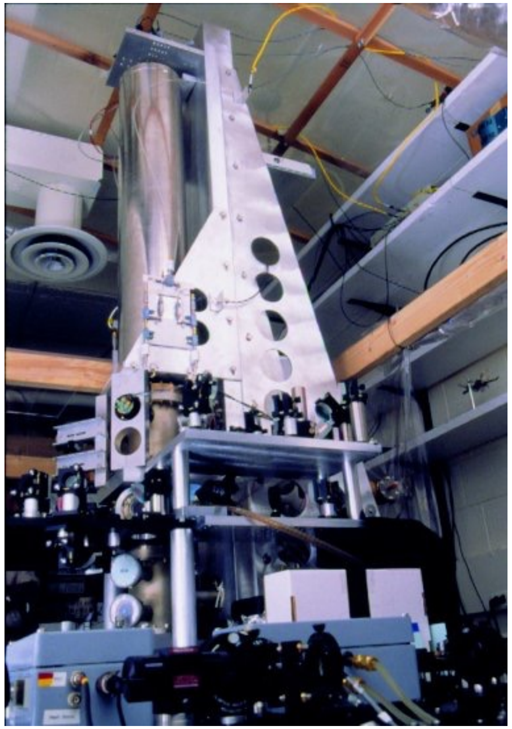
- Greenwich Mean Time (GMT)
  - mean solar time at the Royal Observatory in Greenwich, London
  - Same as UTC (UTC supersedes GMT)

Time ball in Greenwich: drops at 1300 GMT (since 1883)

Atomic Clock

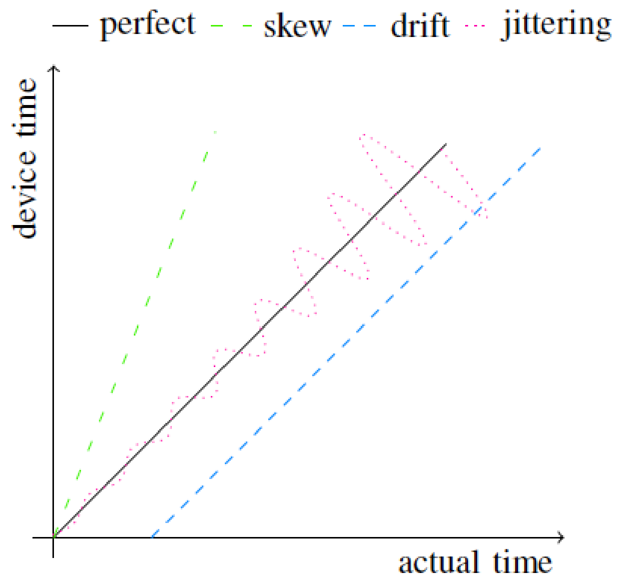
- Uses electron transition frequency in the microwave, optical or UV range of EM spectrum as a frequency standard for its timekeeping element
- Accurac depends on (i) temperature of the sample atoms and (ii) frequency and intrinsic width of the electronic transition
- Typical accuracy is of order of 10^{-9} sec

"You're late!"


NSIT-F1

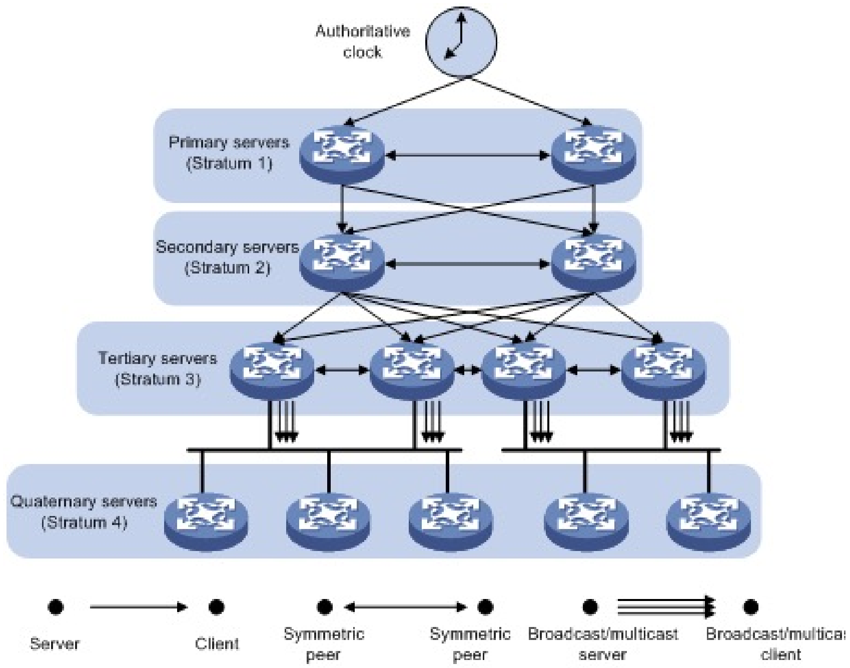
Clock skew and drift

- Most computing devices are equipped with a hardware oscillator assisted computer clock
- The frequency of the oscillator determines the rate at which this clock runs
- The clock can “drift” with time
- Various factors: internal (e.g., processor utilization) or external (e.g., temperature)



Network Time Protocol

- Developed in 1979
- Arguably the longest running, continuously operating, ubiquitously available protocol in the Internet
- Current version: NTPv4
- Uses UDP, port 123
- Hierarchical semi-layered organization
- Stratum 0: high precision devices such as atomic clocks, GPS, etc.
- 64 bit timestamp: 32 bit for seconds and 32 bits for fractional seconds
- NTPv4 introduced 128 bit timetstamp

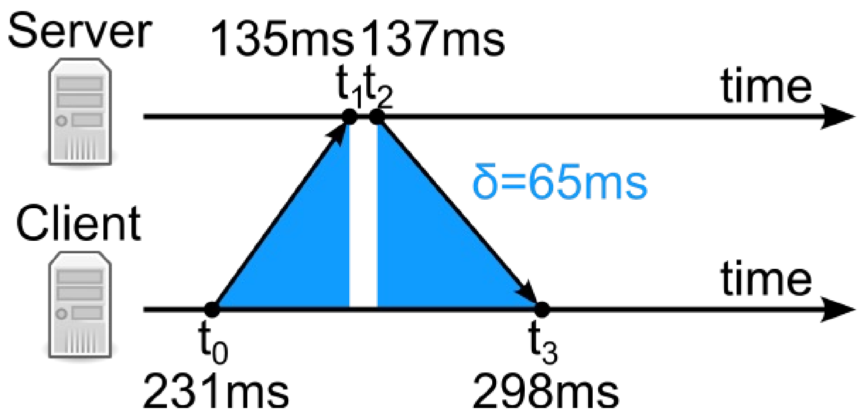


Clock Synchronization Algorithm

- NTP client regularly polls 3 or more servers of diverse networks
- Client computes its time offset and round-trip delay as:

$$\theta = \frac{(t_1 - t_0) + (t_2 - t_3)}{2}$$

$$\delta = (t_3 - t_0) - (t_2 - t_1)$$



- Advanced filtering and statistical analysis to reduce errors
- NTP can usually maintain time to within tens of milliseconds over the public Internet, and can achieve better than one millisecond accuracy in local area networks under ideal conditions
- Asymmetric routes and network congestion can cause errors of 100 ms or more

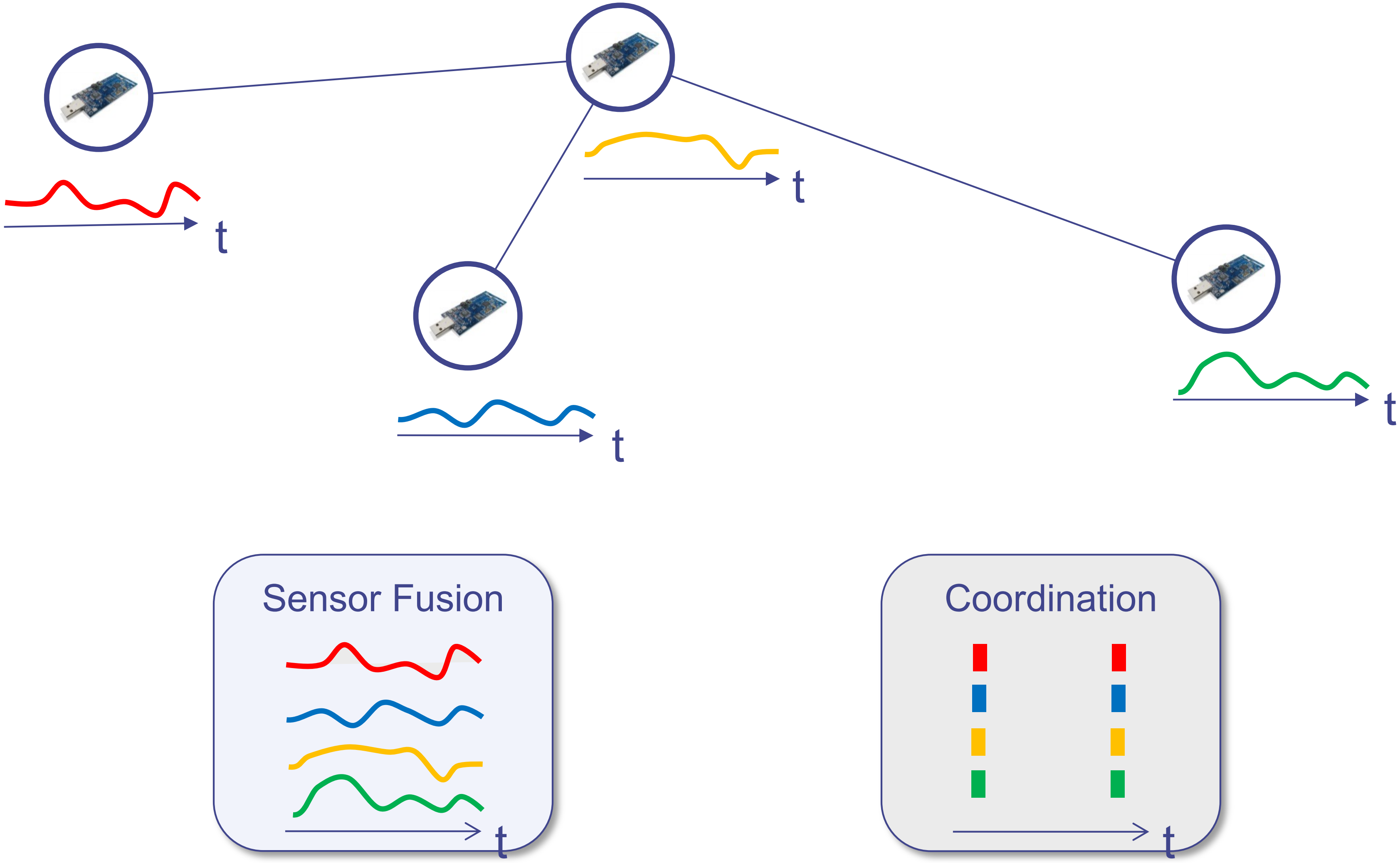
NTP (more)

- An estimated 25 million Network Time Protocol (NTP) servers and clients are deployed all over the world.
- NTP software has been ported to almost every workstation and server platform available today - from PCs to supercomputers and embedded systems, even home routers and battery backup systems.
- Global reach
  - In the US, USNO and NIST operate multiple public NTP primary servers directly synchronized to national standard cesium clock ensembles and GPS.
  - Government agencies in many other countries and on all continents (including Antarctica) operate public NTP primary servers.
  - National and regional service providers operate public NTP secondary servers synchronized to the primary servers.
  - US Government agencies, including US Weather Service, US Treasury Service, IRS and FAA operate their own NTP networks.
  - Private and public institutions, including universities, broadcasters, financial institutions and corporations operate their own NTP networks.
  - NTP is on the seabed, Navy warships, NASA Shuttle missions and planned for the Mars Internet.

Clock Synchronization

http://www.youtube.com/watch?v=W1TMZASCR-I

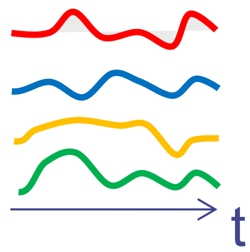
Time in Distributed IoT devices



How Accurate Time Do We Need?

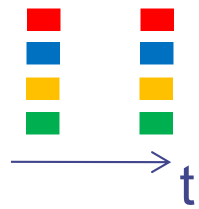
Temporal relationships in sensor data

- Events with timestamps (in acoustics, 30us)
- Data with timestamps (Golden Gate needs 10us)
- Delay measurements for distance estimation/location
  - Audio/sound/noise propagation: Accuracy 1ms - 10ms
  - Radio propagation: Accuracy 10ns - 1us



Coordinated actuation of sensors

- Sampling sensors at the exact same time
- Radio channel access using TDMA: a few us



Three Perspectives of Synchronization

- Relative timing
  - Relies on ordering of messages and events. It is sufficient if the network can correctly determine in event 1 occurred before event 2
  - Simplest
- Relative timing in which network clocks are independent of each other and the nodes keep track of drift and offset
  - Node keeps its drift and offset in correspondence to neighboring node.
  - Nodes can synchronize their local time with another nodes local time at any instant
- Global Synchronization
  - Constant global timescale throughput the network
  - Complex

Global Clock Sources

Radio Clock Signal:

- Clock signal from a reference source (atomic clock) is transmitted over a long wave radio signal
- Transmission range up to 2000 km
- Accuracy limited by the distance to the sender
- Special antenna/receiver hardware required

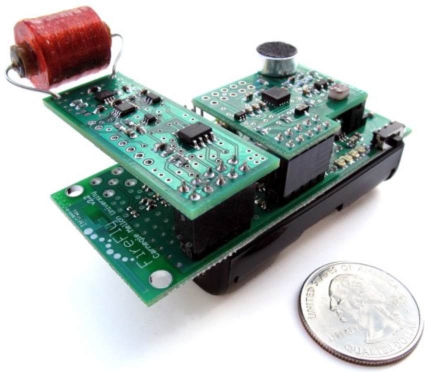
Global Positioning System (GPS):

- Satellites continuously transmit own position and time code
- Line of sight between satellite and receiver required
- Special antenna/receiver hardware required

Clock Sources (2)

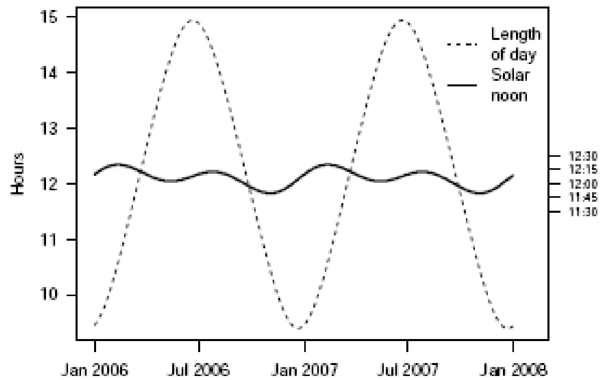
AC power lines:

- Use the magnetic field radiating from electric power lines
- AC power line oscillations are extremely stable (10^{-8} ppm)
- Power efficient, consumes only 58 μW
- Single communication round required to correct phase offset after initialization



Sunlight:

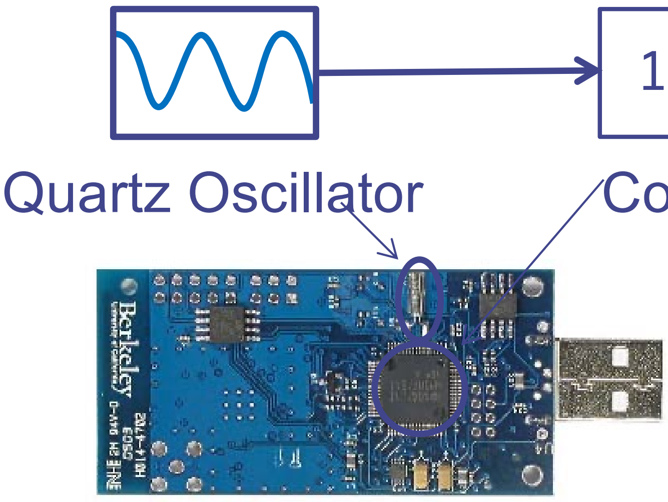
- Using a light sensor to measure the length of a day
- Offline algorithm for reconstructing global timestamps by correlating annual solar patterns (no communication required)

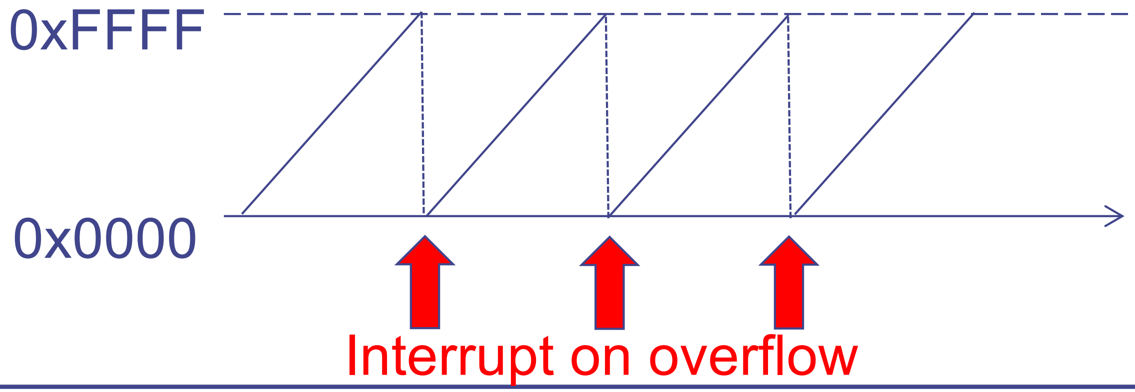


IoT Node Clocks

Hardware Clock

- Quartz Crystal or RC-Oscillator = a circuit that uses mechanical resonance to generate electric signal with precise frequency (typ. Freq. of 10kHz – 10MHz)
- 8/16/32-bit counter register
- Overflow occurs when counter reaches its maximum value





IoT Node Clocks (2)

Notation

- A counter represents the passing of time:

$$H_i(t)$$

- OS maintains Software Clock by scaling and offsetting a counter:

$$C_i(t) = \alpha H_i(t) + \beta$$

- Clock resolution: 1 counter unit (e.g., 30.5us for 32kHz clock)
- Clock precision: consistency of clock frequency (5ppm)
- Clock accuracy: difference from nominal frequency (50ppm)

Clock Drift and Skew

Computer clocks tend not to be in perfect agreement

- **Clock skew/offset**: the difference between times on two clocks

$$|C_i(t) - C_j(t)| \mathrel{!=} 0$$

- **Clock drift**: clocks count time at different rates

$$dC_i/dt \mathrel{!=} dC_j/dt$$

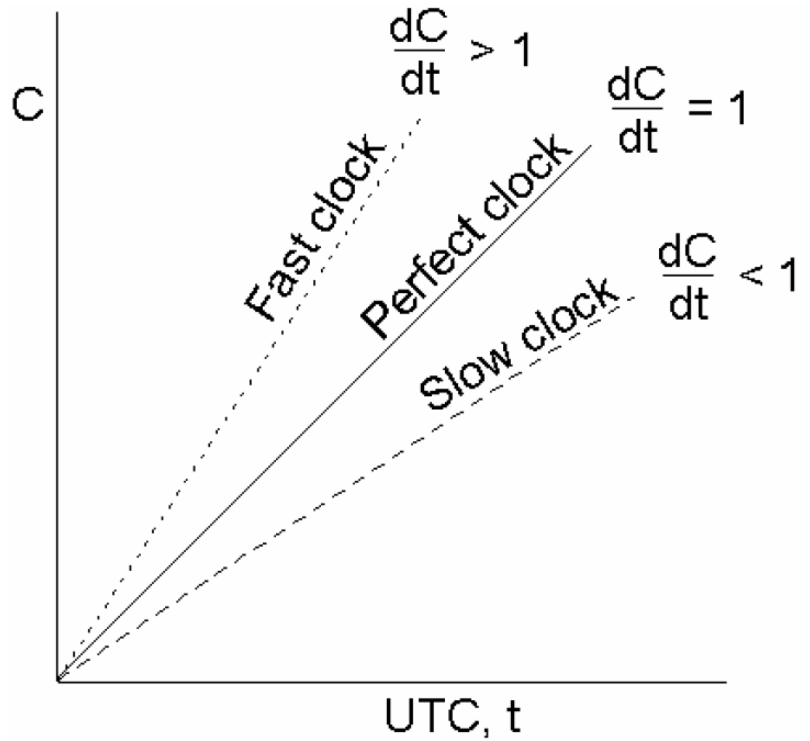
Clock Drift

Clock makers specify a maximum drift rate ρ ppm

- Cheap crystals drift by ~1sec in 2 days (10^{-5} secs/sec)
- Clock drift is often given in parts-per-million (e.g. 10 ppm)

By definition:

$$1-\rho \leq dC/dt \leq 1+\rho$$

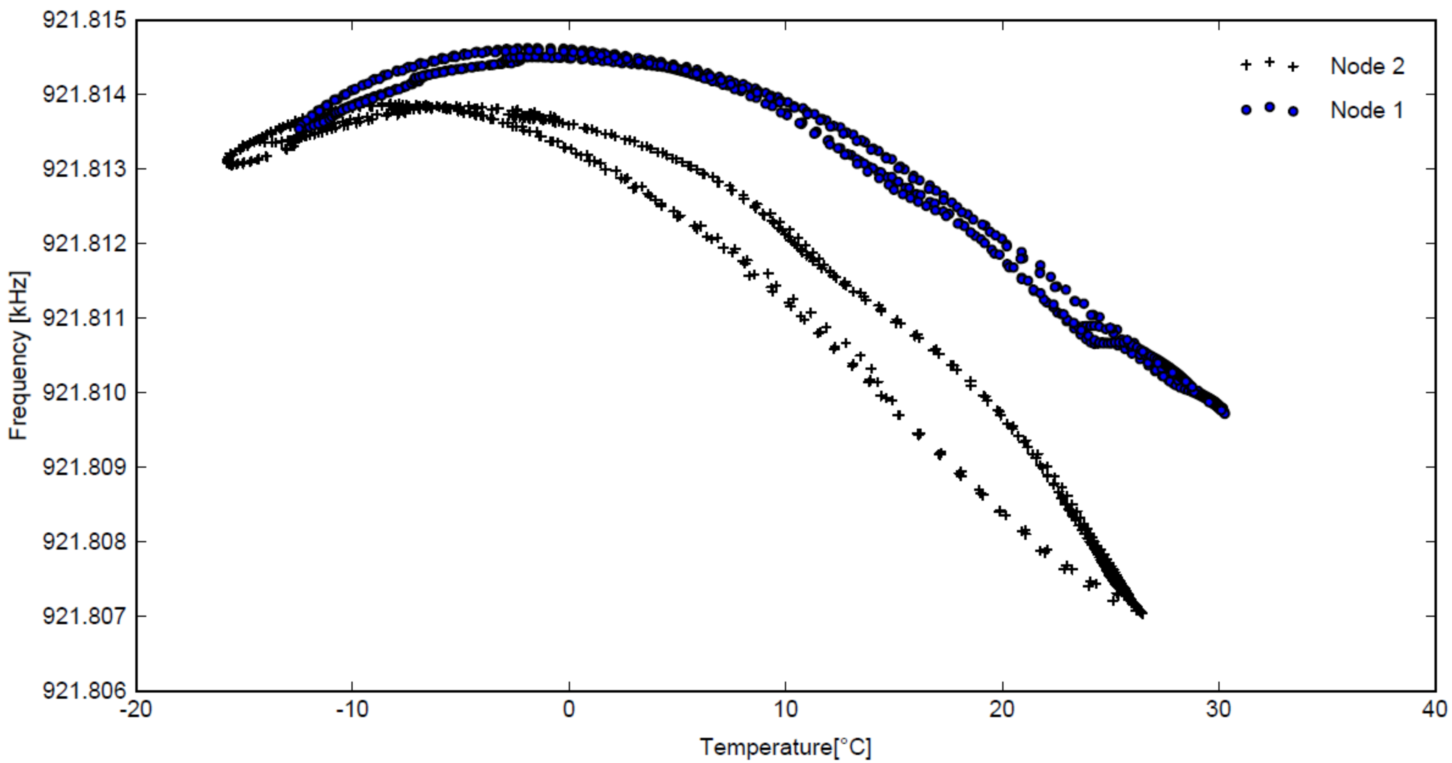


Clock drifts depend on:

- manufacturing defects,
- temperature, and
- power supply variation

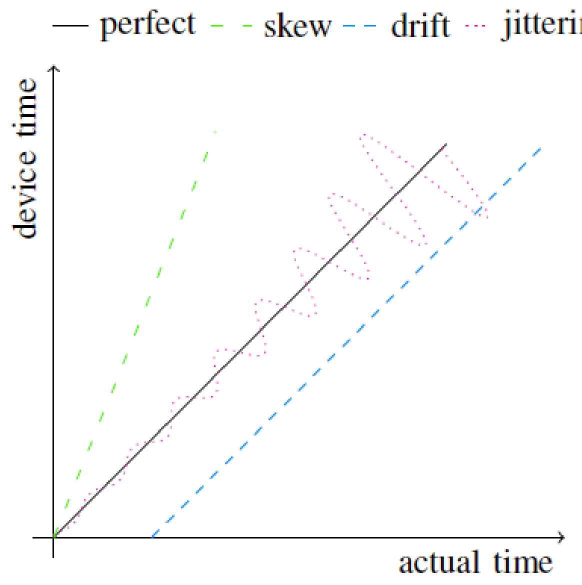
Clock Drift: Temperature

Dependency on Temperature: Mica2 nodes



Clock skew and drift

- Most computing devices are equipped with a hardware oscillator assisted computer clock
- The frequency of the oscillator determines the rate at which this clock runs
- The clock can "drift" with time
- Various factors: internal (e.g., processor utilization) or external (e.g., temperature)

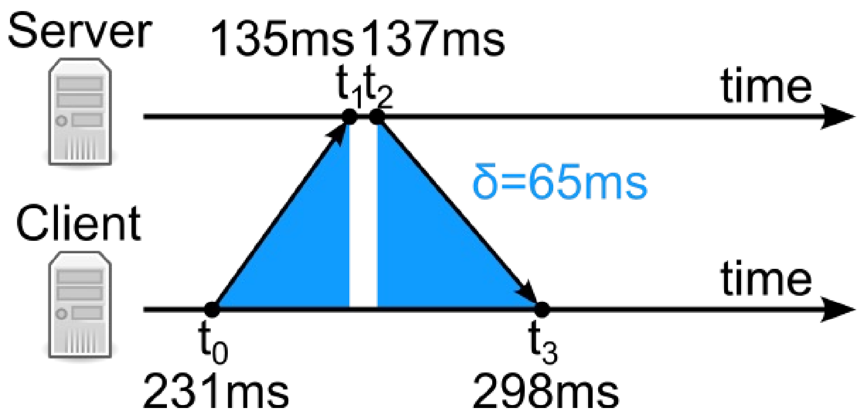


Clock Synchronization Algorithm

- NTP client regularly polls 3 or more servers of diverse networks
- Client computes its time offset and round-trip delay as:

$$\theta = \frac{(t_1 - t_0) + (t_2 - t_3)}{2}$$

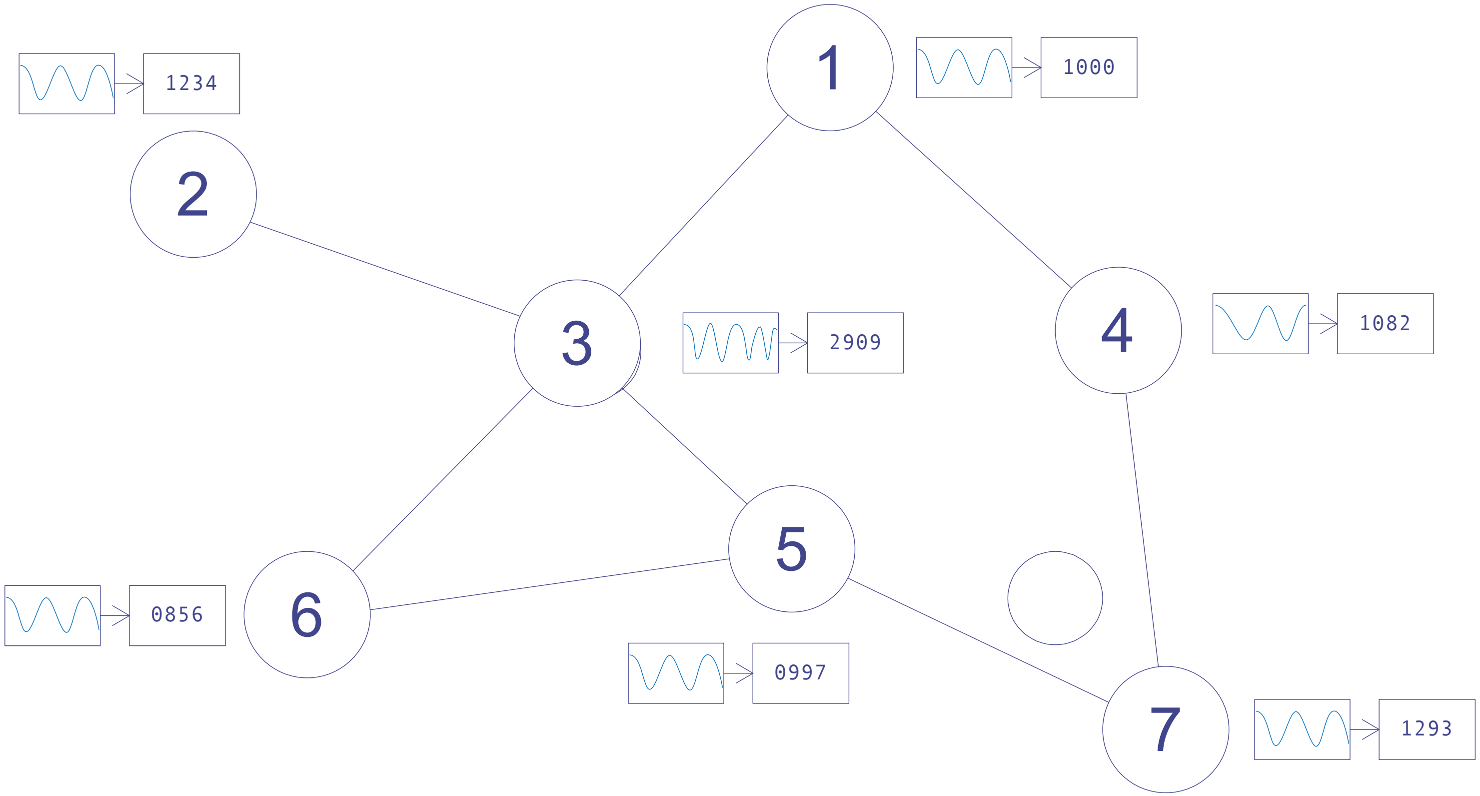
$$\delta = (t_3 - t_0) - (t_2 - t_1)$$



- Advanced filtering and statistical analysis to reduce errors
- NTP can usually maintain time to within tens of milliseconds over the public Internet, and can achieve better than one millisecond accuracy in local area networks under ideal conditions
- Asymmetric routes and network congestion can cause errors of 100 ms or more

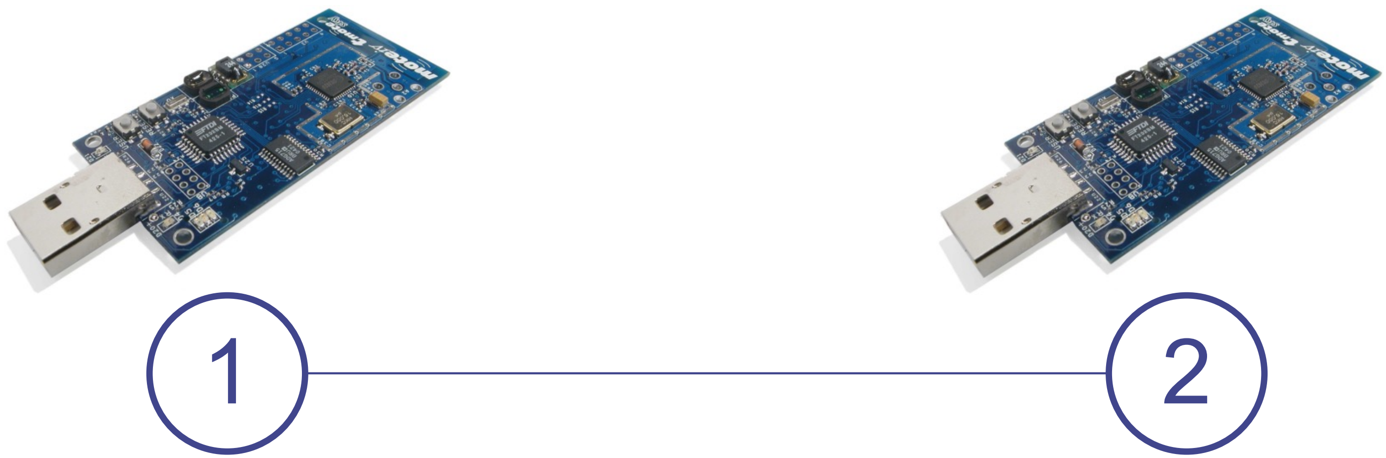
Time Synchronization

The main objective is to determine relative drifts and offsets of the clocks of different IoT nodes



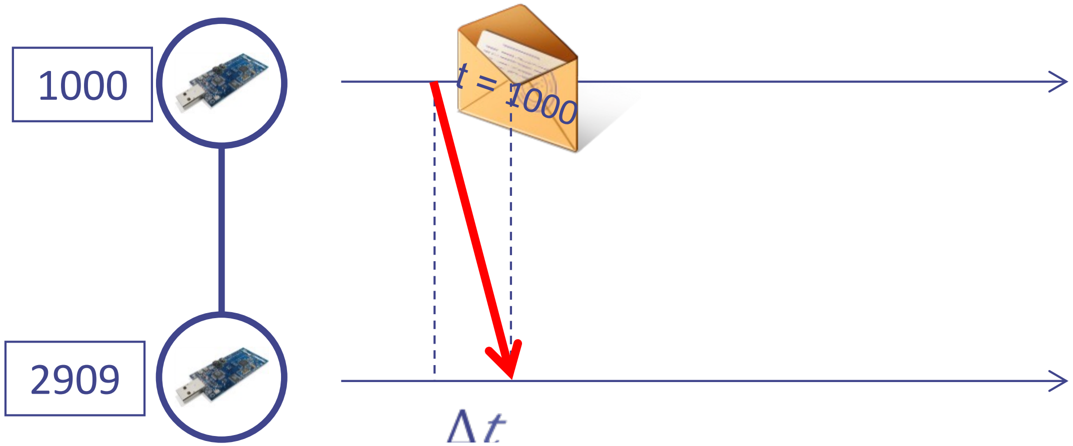
Clock Synchronization: Single-Hop

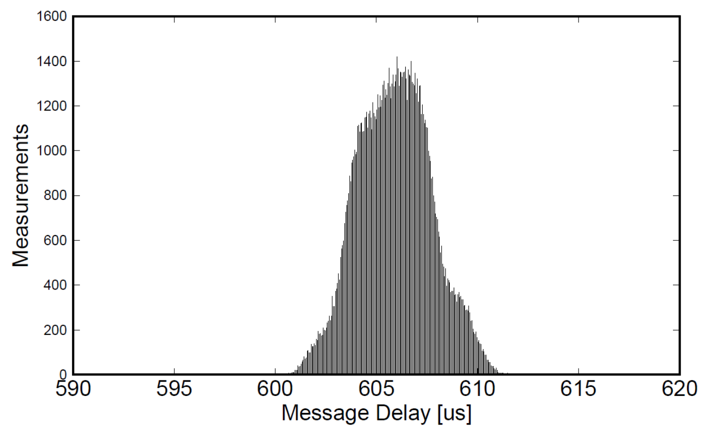
How do we synchronize the clocks of **two** IoT nodes?



Time Transfer: Radio Packets

Radio packets provide a common reference point for time Synchronisation

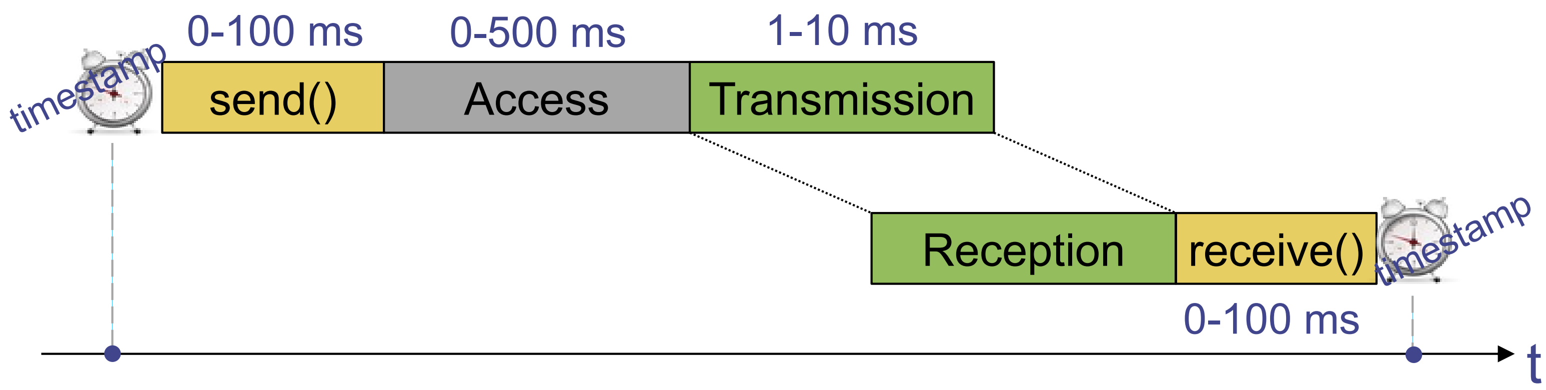




Messages Experience Jitter in the Delay

Problem: Jitter in the message delay

- Various sources of errors (deterministic and non-deterministic)

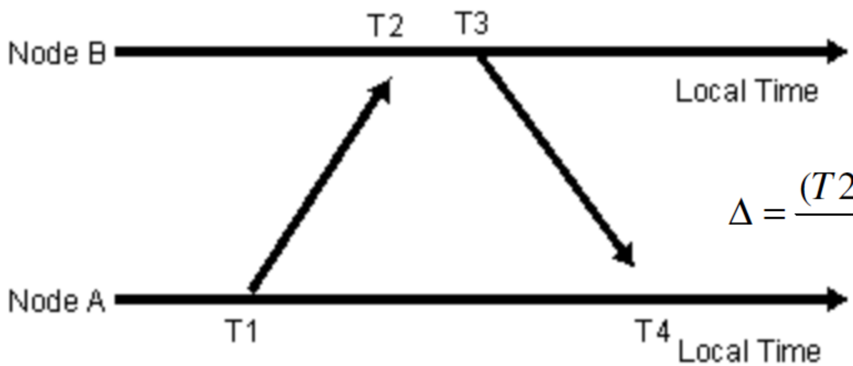


- Time-stamping at the MAC layer can increase precision and reduce jitter

Timing Sync Protocol for sensor networks (TPSN)

- Sender-receiver based synchronization that uses a tree to organize the network topology
- Phase 1: Level discovery
  - Root node with high precision clock (e.g. GPS)
  - Nodes will learn how many hops (levels) they are away from root by exchanging discovery messages
- Phase 2: Synchronization
  - Initiated by the root
  - Propagates down the levels

T2 = T1 + d + Δ



$$\Delta = \frac{(T2 - T1) - (T4 - T3)}{2}; d = \frac{(T2 - T1) + (T4 - T3)}{2}.$$

S. Ganeriwal, R. Kumar and M, Srivastava, “Timing-Sync Protocol for Sensor Networks”

Results

	TPSN	RBS
Average error (in µs)	16.9	29.13
Worst case error (in µs)	44	93
Best case error (in µs)	0	0
Percentage of time error is less than or equal to average error	64	53

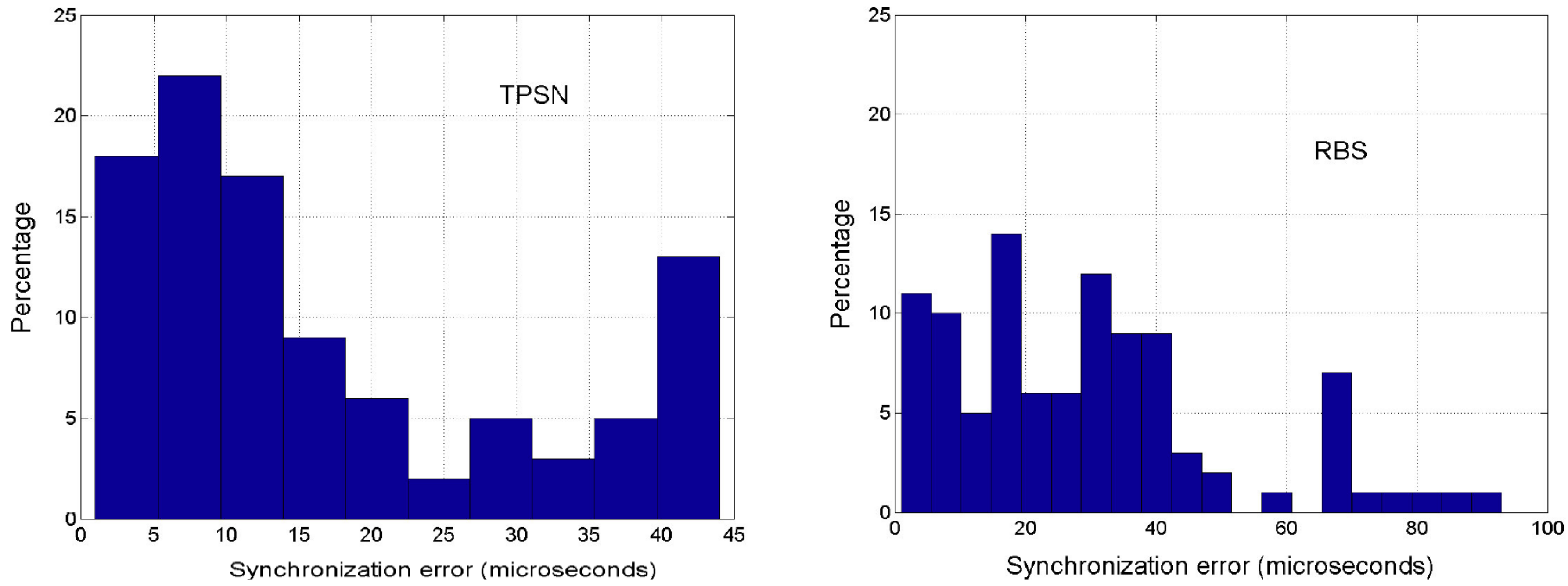
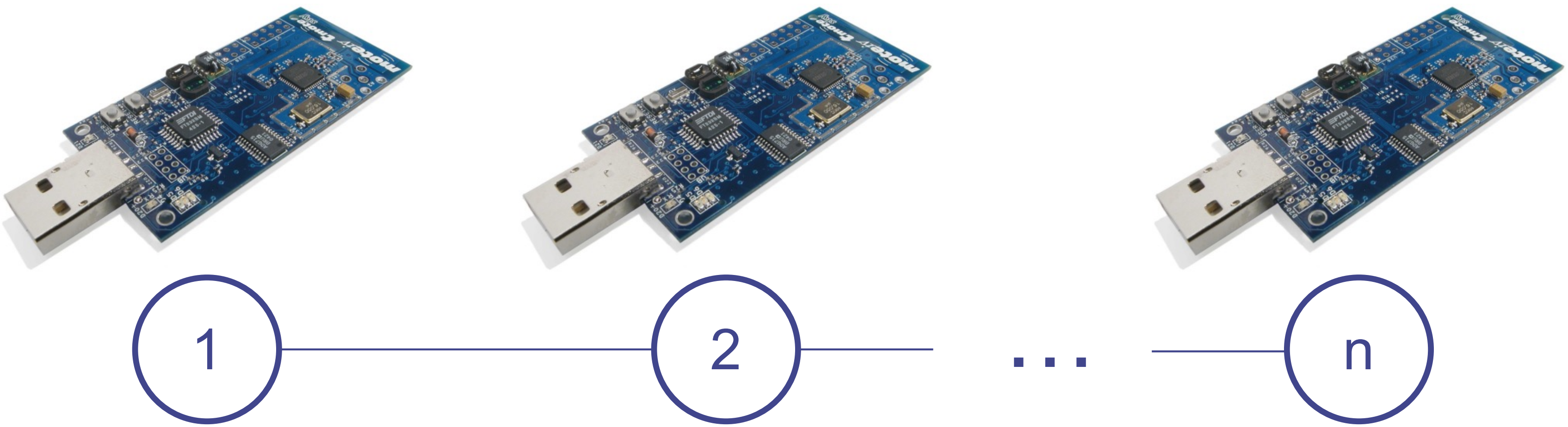


Figure 5: Histogram of Synchronization error (only magnitude)

Clock Synchronization: Multi-Hop

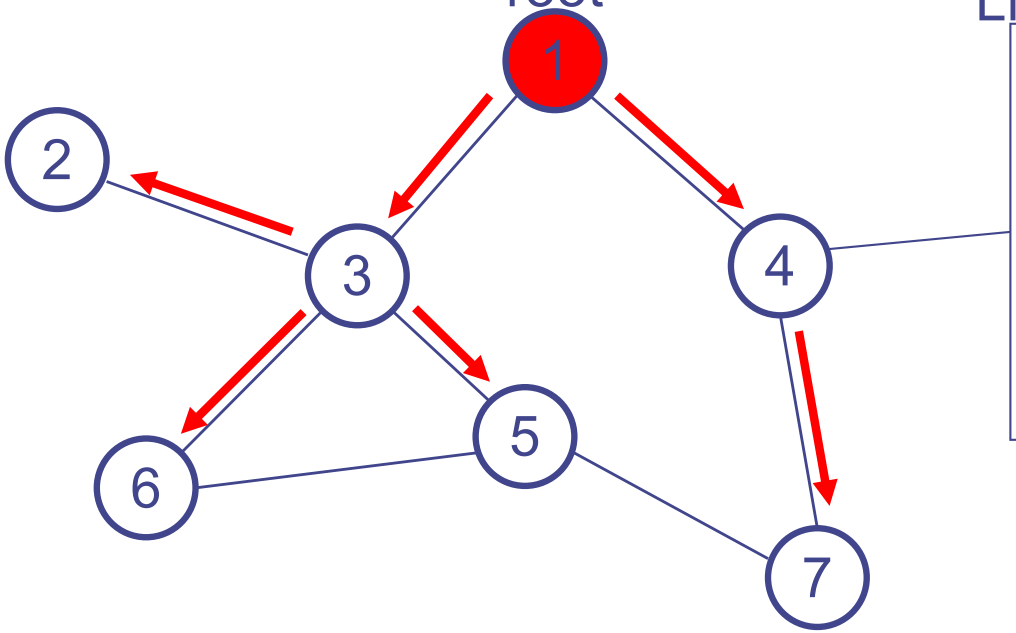
How do we synchronize the clocks of **many** IoT nodes?



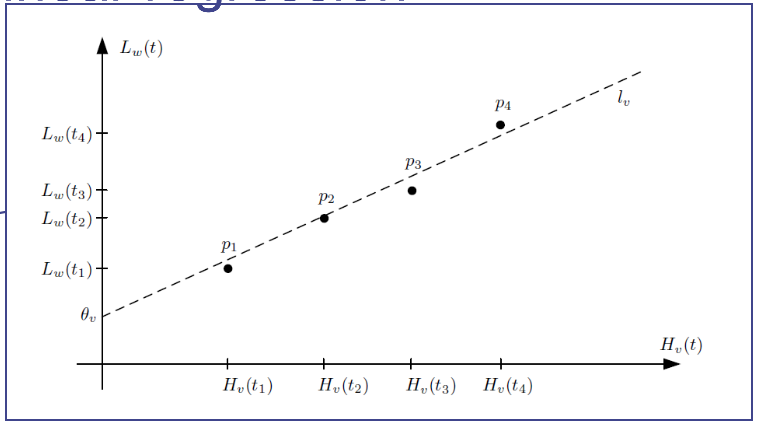
Multi-hop Synchronisation with FTSP

Flooding Time Synchronization Protocol (FTSP)

- Hierarchical clock synchronisation: reference clock (root node)
- Forward estimation of reference clock using periodic beacons



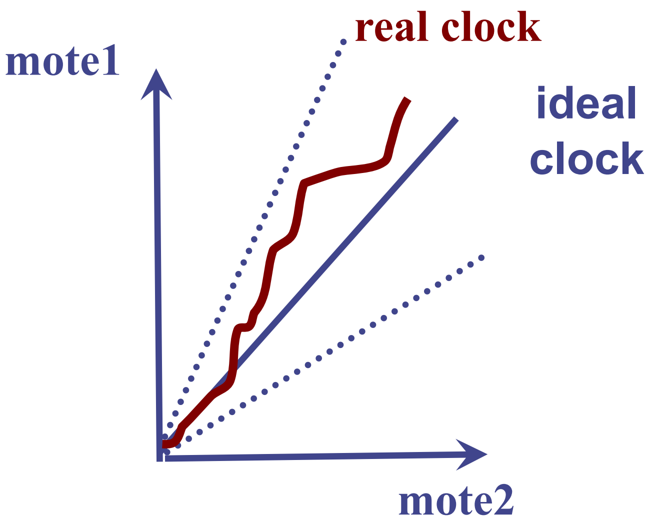
Linear regression

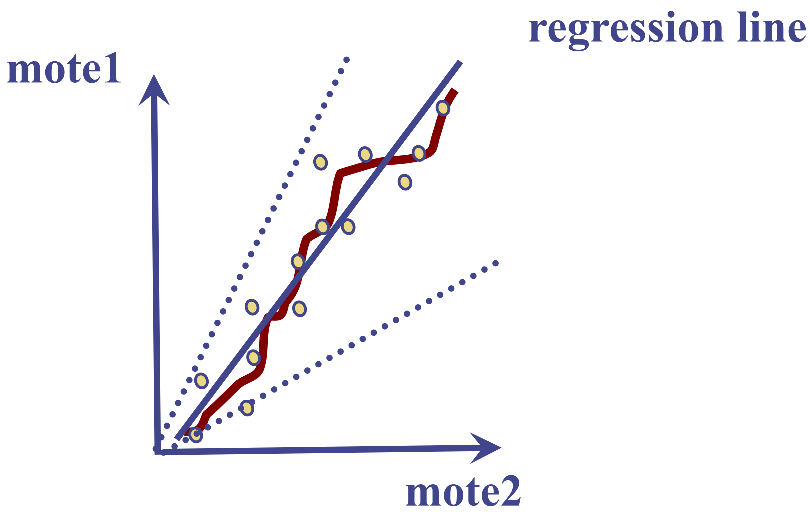


Continuous Synchronization

Relative drift synchronization:

- most commonly, both rate and offset of the local clocks of 2 nodes is estimated
- synchronization in rounds: a popular method is linear regression
- For nodes n_i, n_j a linear relation $C_i(t) = \alpha C_j(t) + \beta$ is postulated
- α, β are determined by minimizing square differences of the times





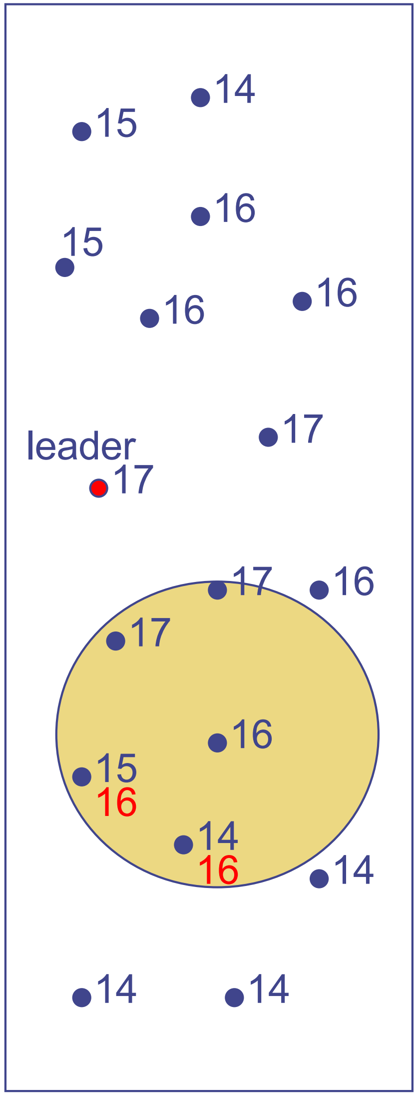
Flooding Time Synchronization Protocol (FTSP)

Overview

- Leader = node with the smallest ID
- Global time = leader's local time
- No hierarchy is maintained, each node periodically broadcasts a timesync packet
- Sequence numbers
  - to distinguish old and new timestamp
  - only increased by the leader

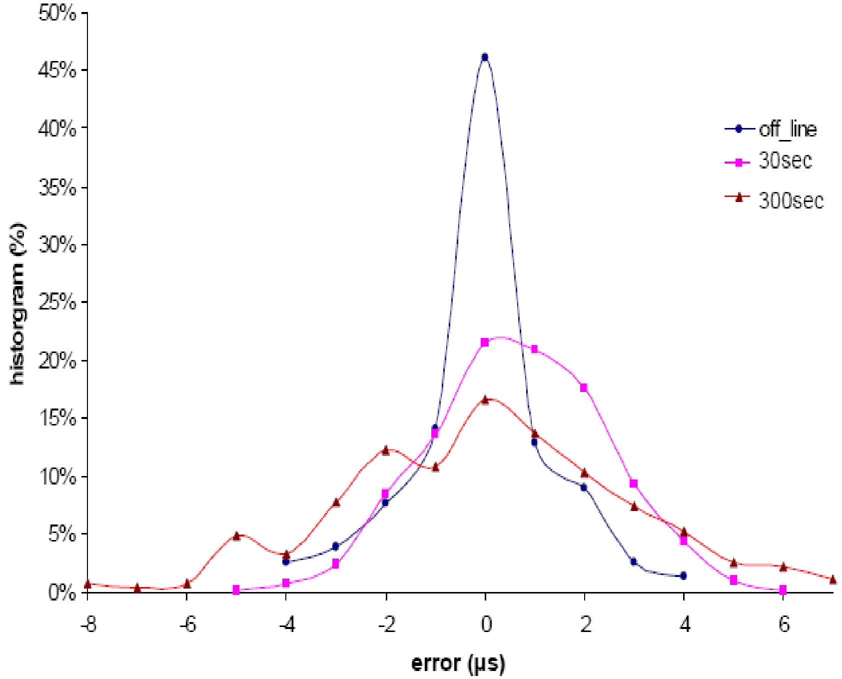
Robustness

- If leader fails, a leader election protocol is employed
- Nodes can enter and leave the network, links can fail, topology can change



sequence numbers

Linear Regression



The distribution of the errors of linear-regression

Continuous accuracy of a few µs is possible using LR.

Summary

- Space Synchronization (localization)
- Time synchronization
- References on the website