URBAN COMPUTING

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AI6128 Urban Computing

Lecture 3

Localization & Time Acquisition

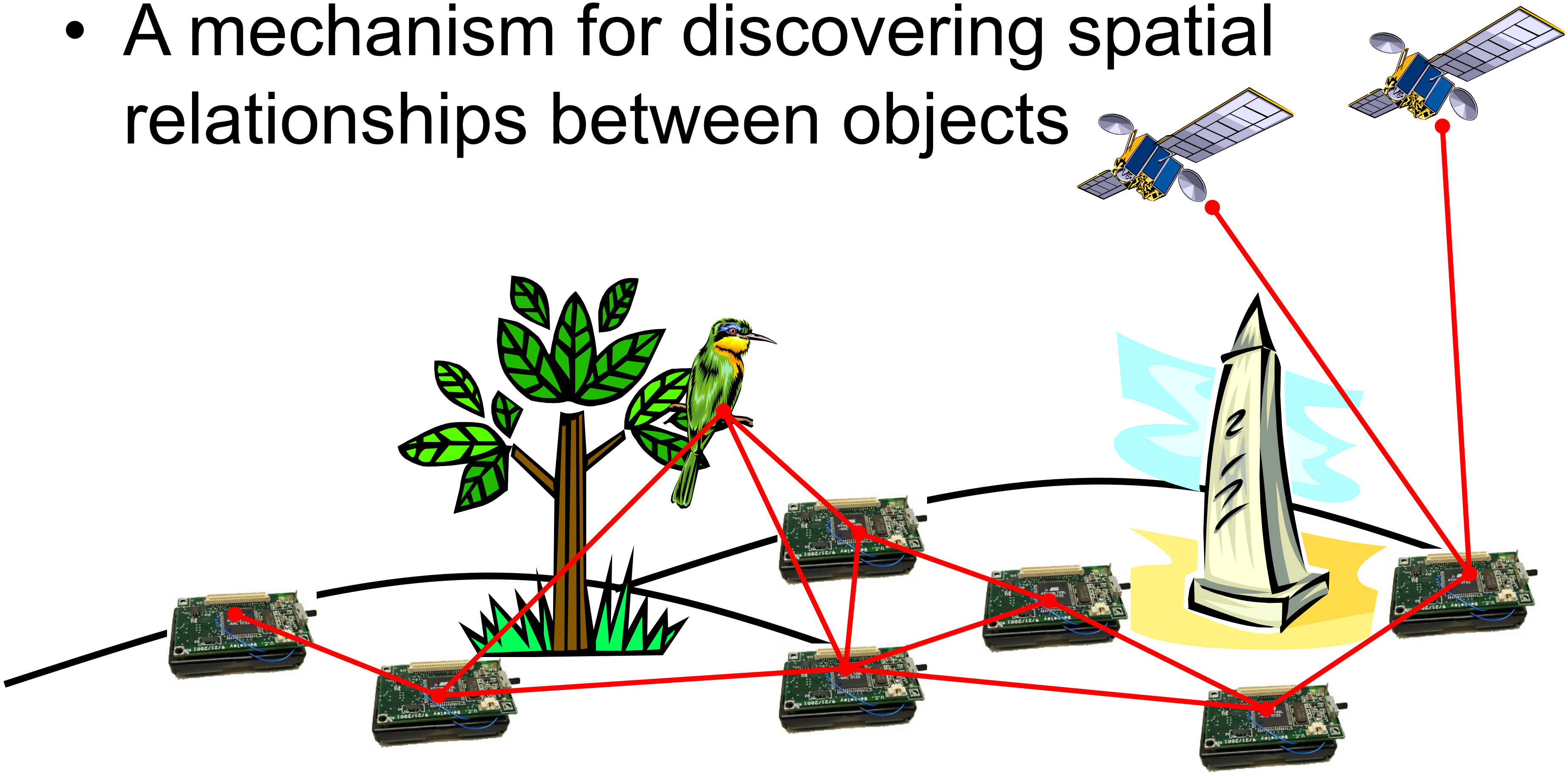
Content

- Introduction to localization
- Localization approaches
- GPS
  - Outdoor localization and time acquisition
- Indoor localization
- Indoor time acquisition

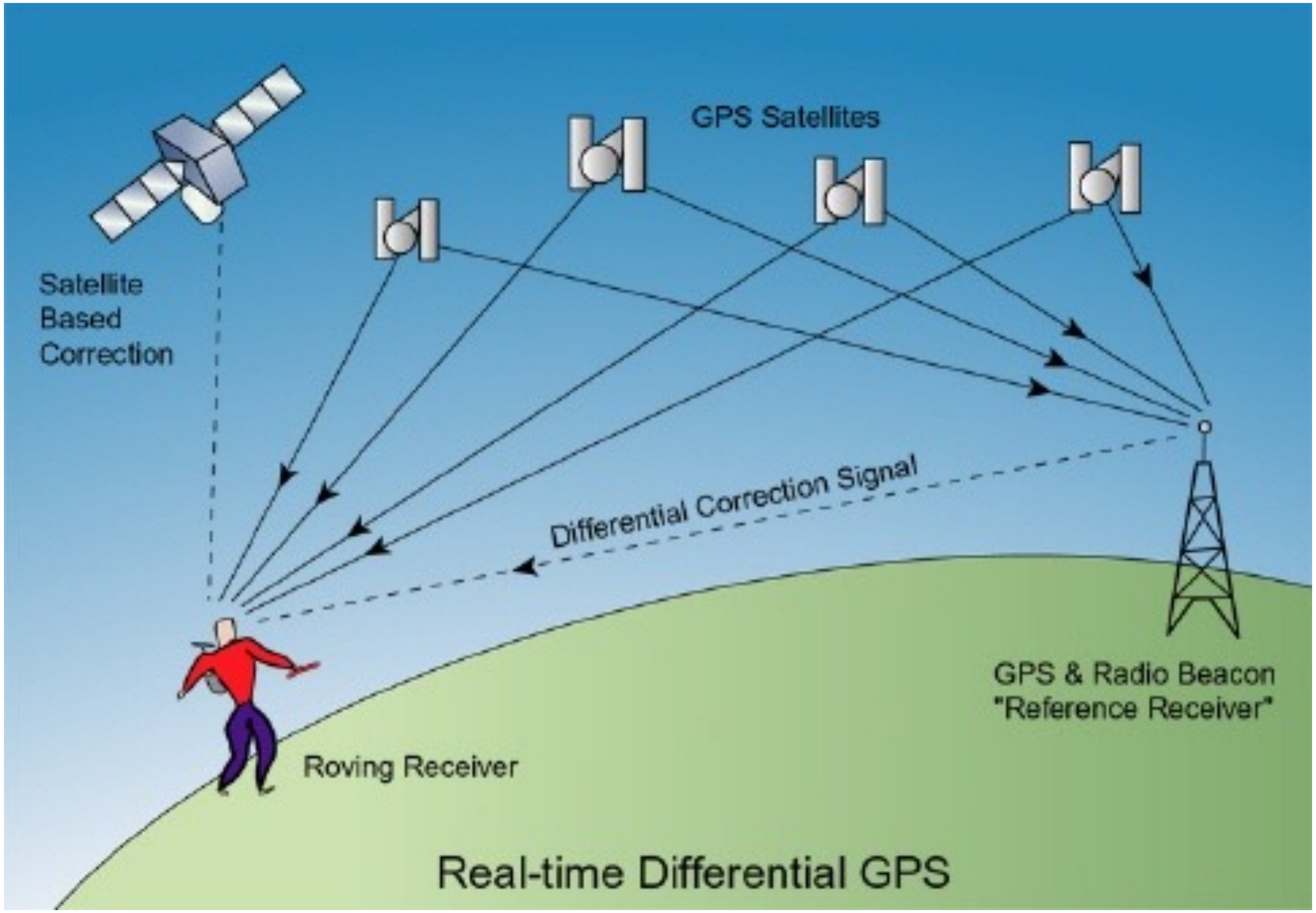
Introduction to Localization

What is Localization

- A mechanism for discovering spatial relationships between objects

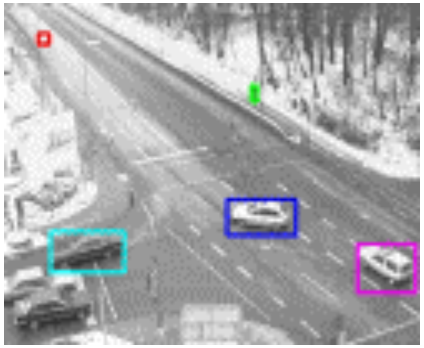


Location Tracking



Urban Applications

- Navigation
- Surveillance
  - Track real-time positions of buses
  - Crowd monitoring (for social security)
- Location-based services (LBS)
  - 911, location-based search, etc
- Location-based authentication



Broader Applications

- Scientific applications
  - Air/water quality monitoring, environmental studies, wild animal tracking, biodiversity
- Military applications
- Resource selection (server, printer, etc)
- Sensor networks
  - Geographic routing
- New applications enabled by availability of locations

Localization Research

- Well studied topic (3,000+ PhD theses??)
- Application dependent
- Research areas
  - Technology
  - Algorithms and data analysis
  - Visualization
  - Evaluation

Properties of Localization

- Physical position vs symbolic location
- Absolute vs relative coordinates
- Centralized vs decentralized computation
- Precision
- Cost
- Scalability
- Limitations

Location Information Representation

- Absolute
  - Geographic coordinates (Lat: 33.98333, Long: -86.22444)
- Relative
  - 1 block north of the main building
- Symbolic
  - High-level description (home, bedroom, office)

No One Size Fits All

- Ideal solution doesn't exist
  - Accurate
  - Low-cost
  - Easy-to-deploy
  - Ubiquitous (indoor, outdoor)
- Application needs determine technology

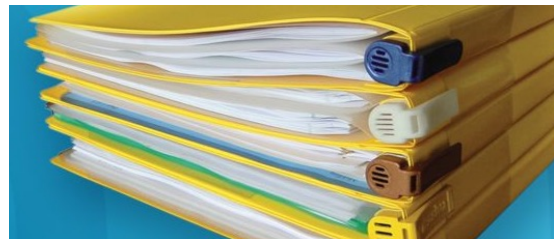
Examples

- Motion capture
  - cm or mm accuracy
- Car navigation system
  - sub-m or m accuracy
- Finding a lost object
  - Fine-grained symbolic location (in backpack)
- Weather information
  - City-level accuracy
- Printing a document
  - Room-level symbolic location

Lots of Technologies


GPS

WiFi Beacons


Ultrasound


Floor pressure


VHF Omni Ranging


Ad hoc signal strength

Laser range-finding


Stereo camera

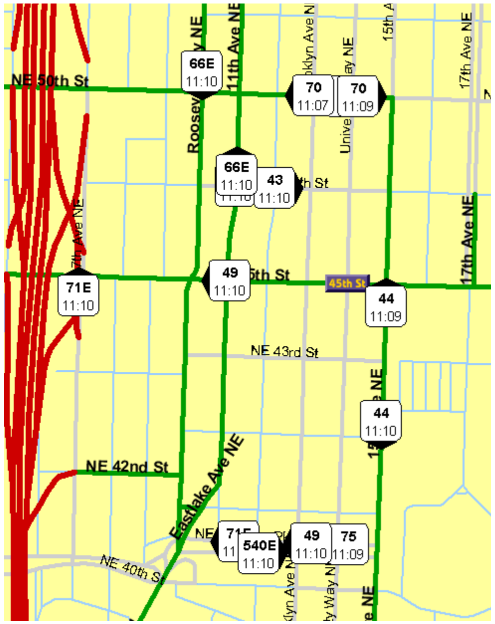

Ultrasonic time of flight


Array microphone

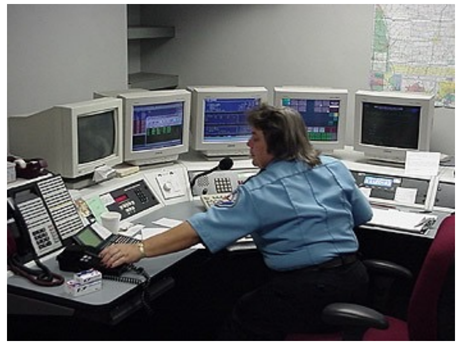

Physical contact


Infrared proximity

Some Outdoor Applications



Bus view



E-911

Car Navigation

Child tracking

Some Indoor Applications

Elder care

Localization Approaches

Approaches for Determining Location

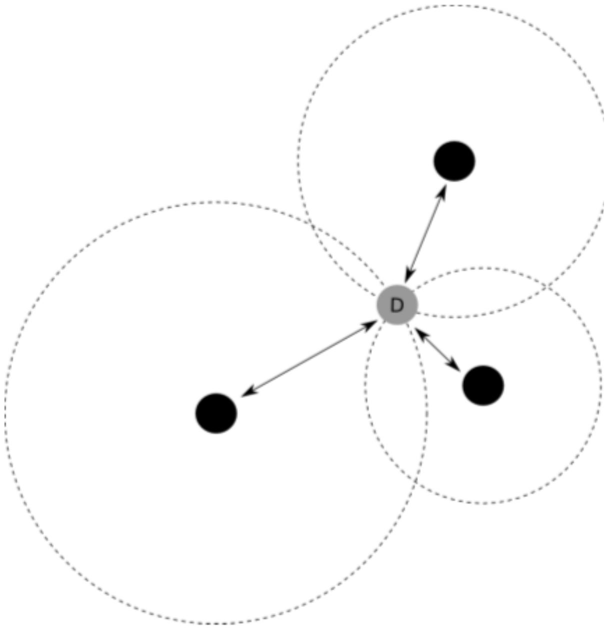
- Localization algorithms
  - Proximity
  - Lateration
    - Received signal strength indicator (RSSI)
    - Time-of-arrival (ToA), time difference of arrival (TDoA)
  - Angulation
  - Fingerprinting

Proximity

- Simplest localization technique
- Closeness to a reference point
  – It can be used to decide whether a node is in the proximity of an anchor
  – Based on loudness, physical contact, etc
- Can be used for positioning when several overlapping anchors are available
  – Centronoid localization

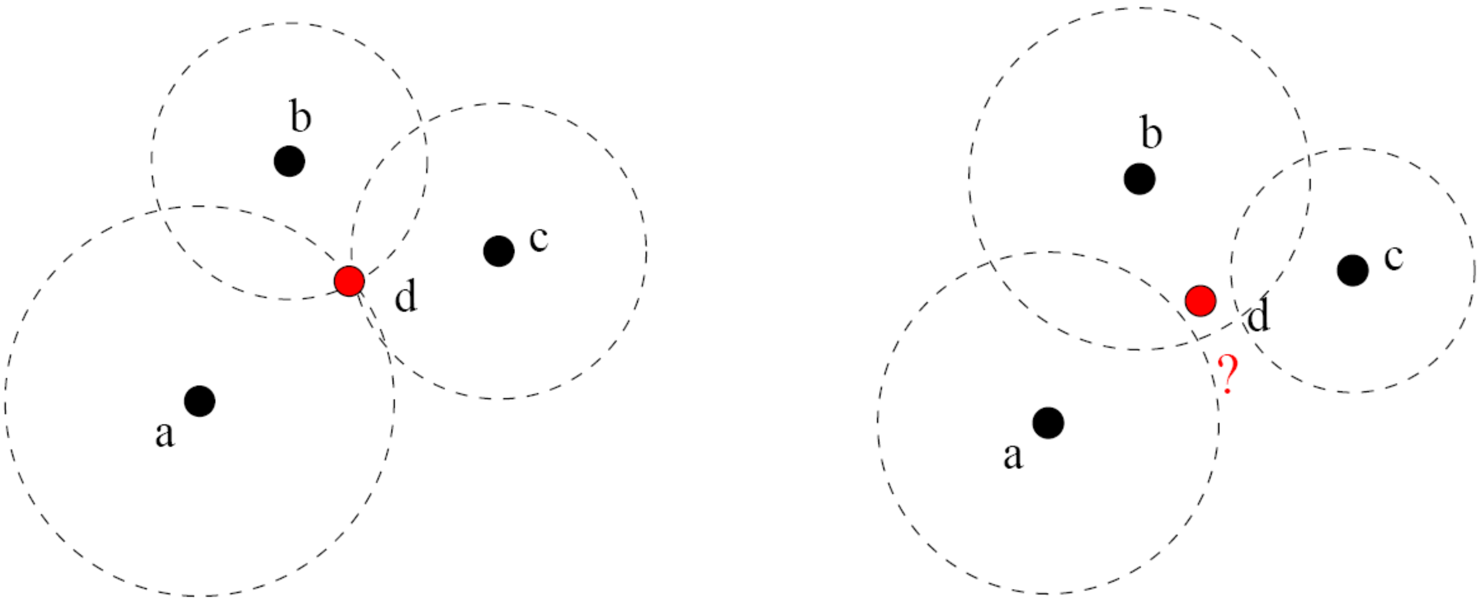
Lateration

- Measure distance between device and reference points
- 3 reference points needed for 2D
  - Trilateration
- 4 for 3D



Noisy Distance Measurements

- Distance measurements are noisy!

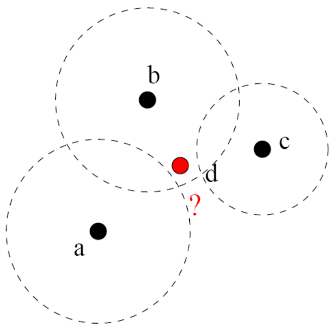


Optimization Problem

- Solve an optimization problem: minimize the mean square error

$$d^* = \arg\min_d (D(d,a) - \tilde{D}_{da})^2 + (D(d,b) - \tilde{D}_{db})^2 + (D(d,c) - \tilde{D}_{dc})^2$$

a, b, c: 2D position of anchors (known)
d: 2D position of target (unknown)
D(x, y): Euclidean distance between x and y
D_{xy}: noisy distance measurement between x and y



- Incorporate more anchors to reduce impact of noises

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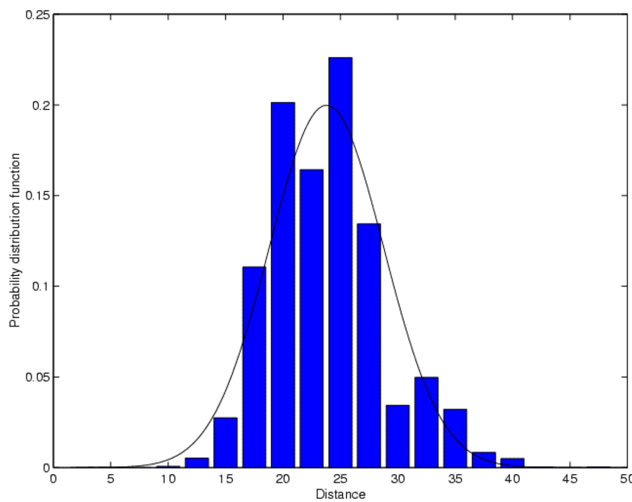
Estimating Distance: RSSI

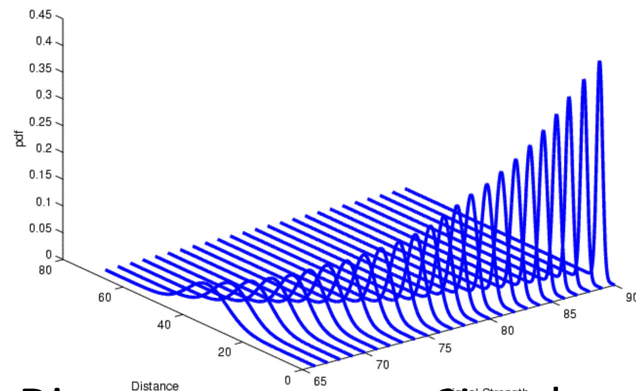
- Received signal strength indicator (RSSI)
  - Send out signal of known strength, use received signal strength and path loss coefficient to estimate distance

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

  - Problem: highly error-prone process



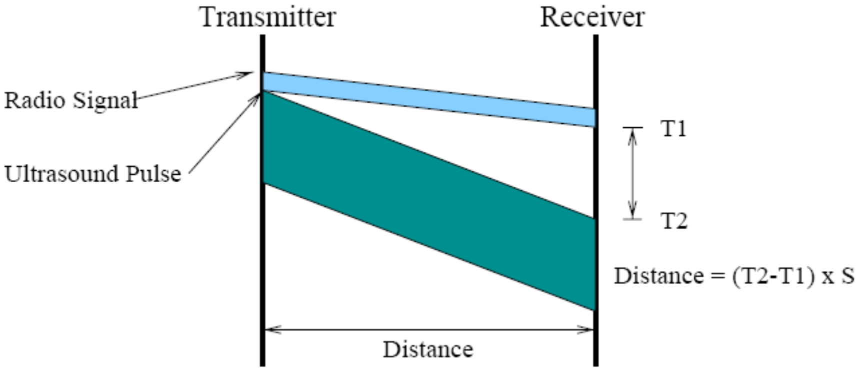
Distance



Distance Signal strength

Estimating Distance: Other Means

- Time of arrival (ToA)
  - Use time of transmission, propagation speed, time of arrival to compute distance
  - Problem: exact clock synchronization
- Time difference of arrival (TDoA)
  - Use two different signals with different propagation speeds
  - Example: ultrasound and radio



    - Propagation time of radio negligible compared to ultrasound
    - Compute difference between arrival times to compute distance
    - Problem: calibration, expensive/energy-intensive hardware

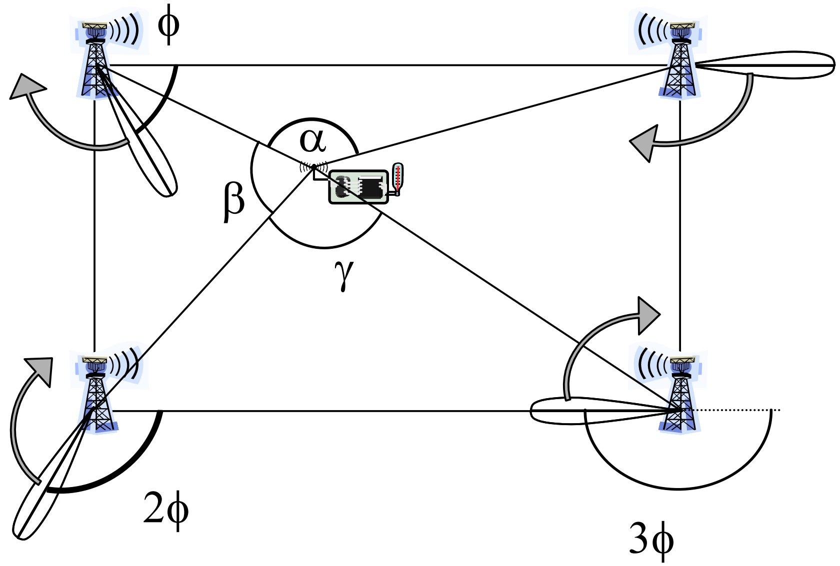
Lateration vs Angulation

- When distances between entities are used, the approach is called lateration
- When angles between nodes are used, one talks about angulation

- 3 reference points needed for 2D
  - Triangulation

Determining Angles

- Directional antennas
  - On the node
  - Mechanically rotating or electrically “steerable”
  - On several access points
    - Rotating at different offsets
    - Time between beacons allows to compute angles



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Fingerprinting

- Mapping solution
- Address problems with multipath
- Better than modeling complex signal propagation pattern

SSID (Name)	BSSID (MAC address)	Signal Strength (RSSI)
linksys	00:0F:66:2A:61:00	18
starbucks	00:0F:C8:00:15:13	15
newark wifi	00:06:25:98:7A:0C	23

Fingerprinting (cont'd)

- Easier than modeling
- Requires a dense site survey
- Usually better for symbolic localization

- Performance depends on
  - Spatial differentiability
  - Temporal stability

- Concepts and methods introduced
- Now, systems
  - Global positioning system (GPS)
  - Indoor time acquisition systems
  - Indoor location sensing systems

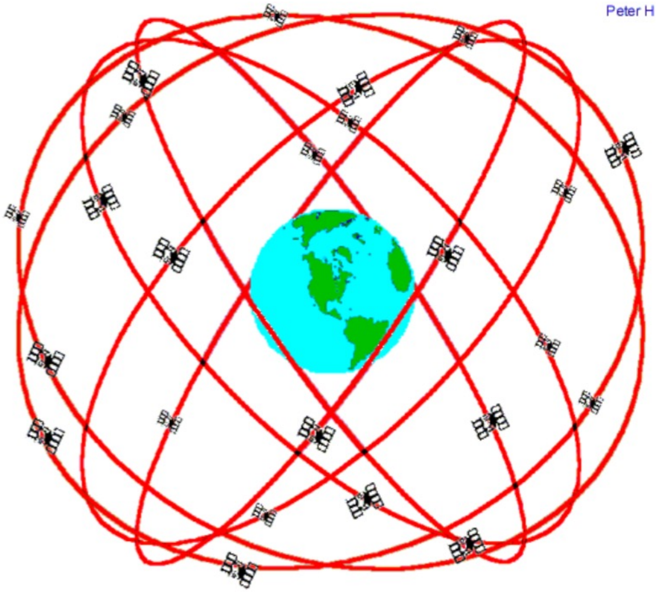
GPS

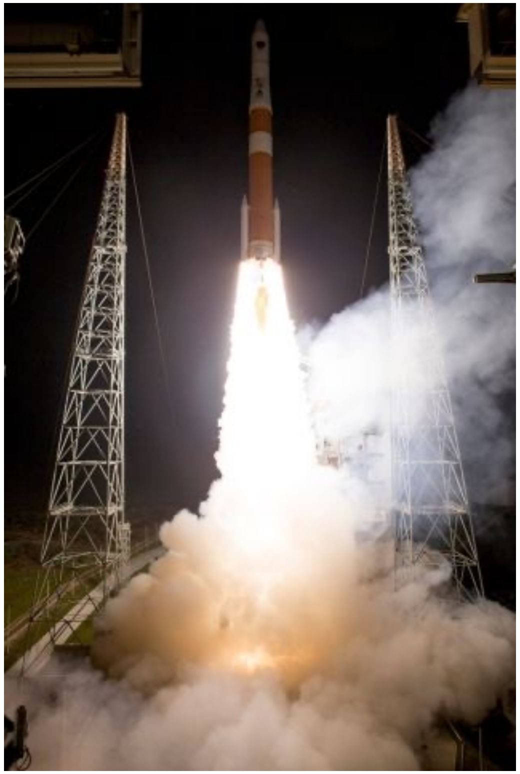
What is GPS?

- Original intent: to develop an all-weather, 24-hour, truly global navigation system to support the armed forces of U.S. and its allies
  – Total investment by U.S. military to date is over $10 billion
- Now freely available to all users
  – Civil applications grow rapidly, far more than military uses
  – U.S. military however still operates several “levers” that control the performance of GPS
- Must have sounded like magic 50 years ago

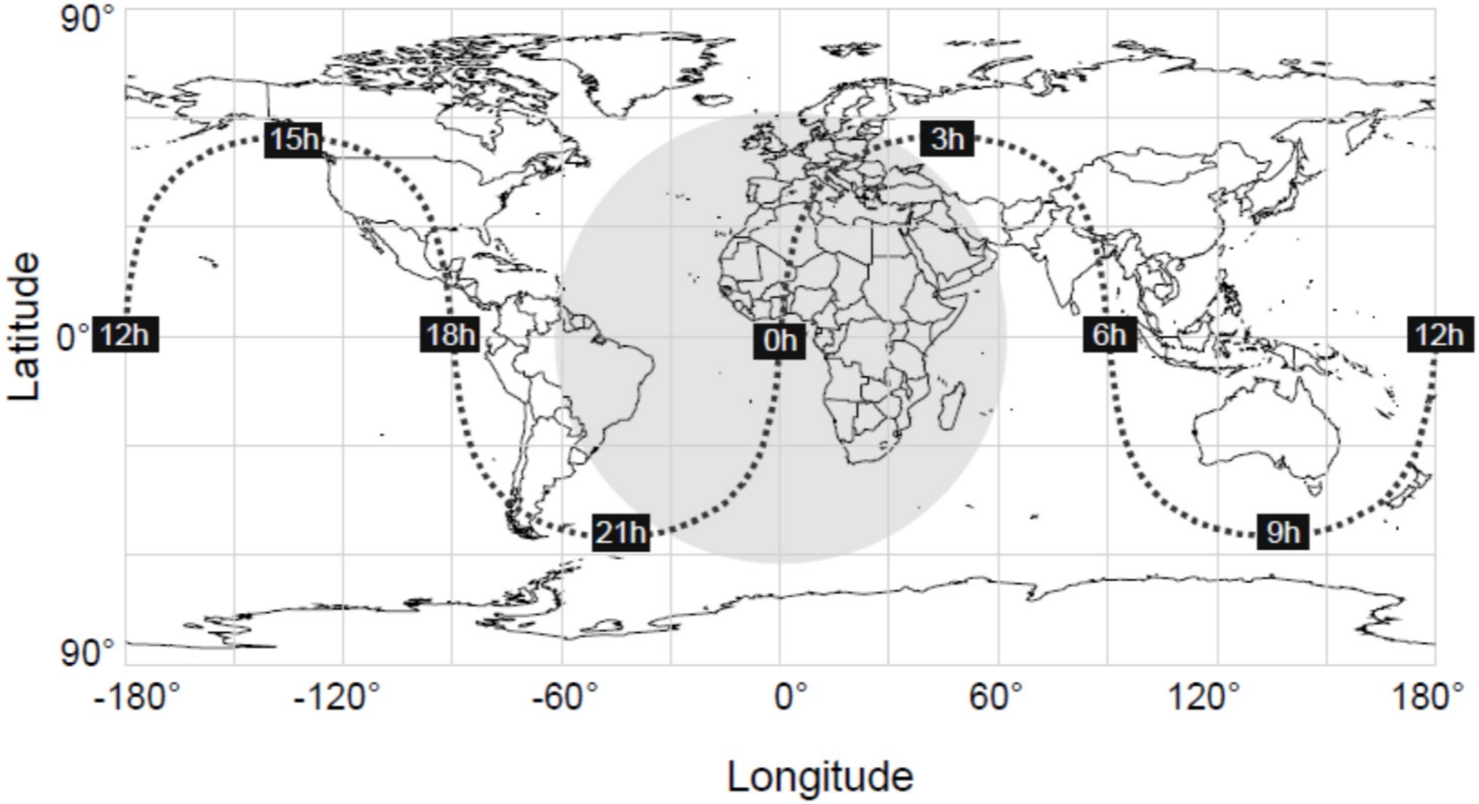
The Launch

- US DoD sponsored project puts satellites into orbit
  - First sat launched in 1978
  - 24 sats by mid 1990s
  - 30 sats currently





GPS Constellation

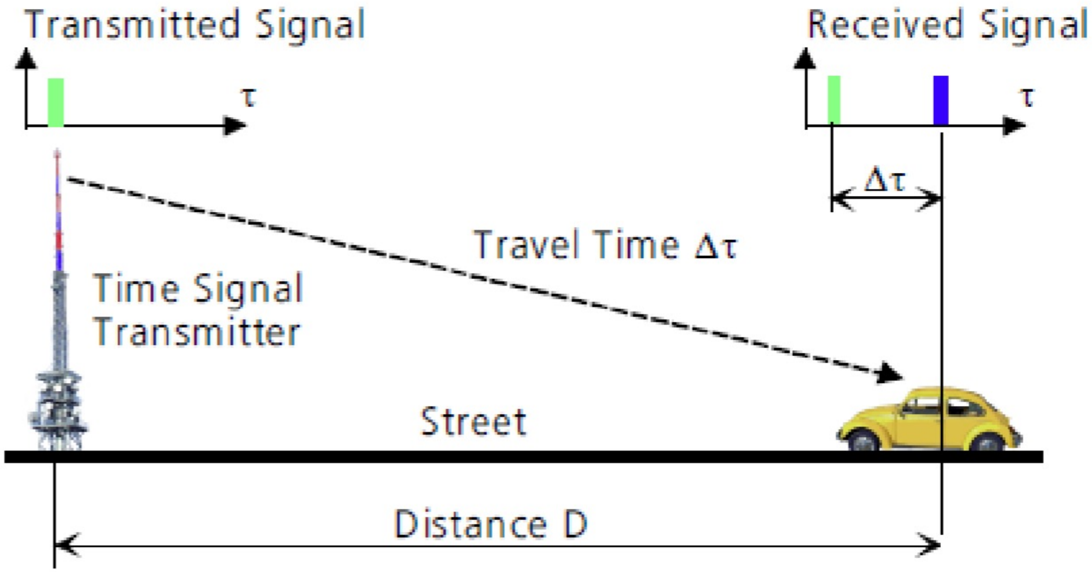


- All GPS sats in 6 medium earth orbits
- Orbital period: 12 hours

Localization Approach

- Trilateration based on ToA

If sat and receiver have synchronized clock:



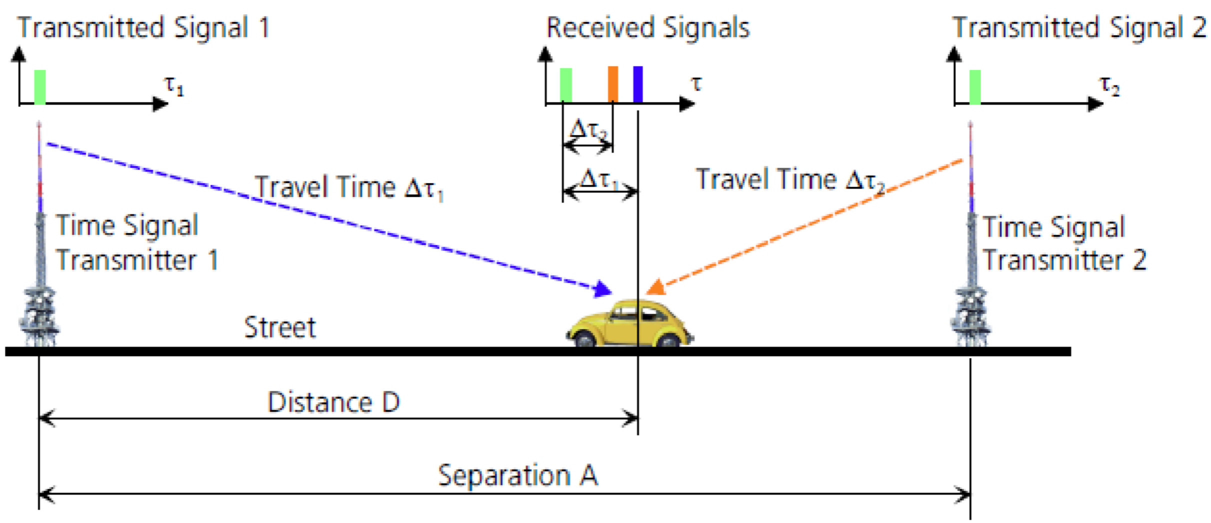
$$\text{distance} = \Delta\tau \times 3 \times 10^{8}\,\text{m/s}$$

Curse from Clock

- Needs very accurate clock synchronization
  - Clock error of 1 microsec, distance error of 300m!
- GPS sats have very accurate atomic clocks
- GPS receivers don’t have atomic clocks
  - “Cursed clock”: a typical user device’s crystal-based clock drifts for about 50 microsec per second

Lift the Curse (1D Case)

- Trilateration based on TDoA



t_{r1}: receiver's clock value on sat1's signal arrival

t_{r2}: receiver's clock value on sat2's signal arrival

ts: sats' signal transmission time instant

δ: receiver's clock error (unknown)

c: speed of light

unknown

$$\begin{cases} (t_{r1} - \boxed{\delta} - t_s)\cdot c = \boxed{D} \\ (t_{r2} - \boxed{\delta} - t_s)\cdot c = A - \boxed{D} \end{cases}$$

Lift the Curse (3D Case)

- If three sats seen

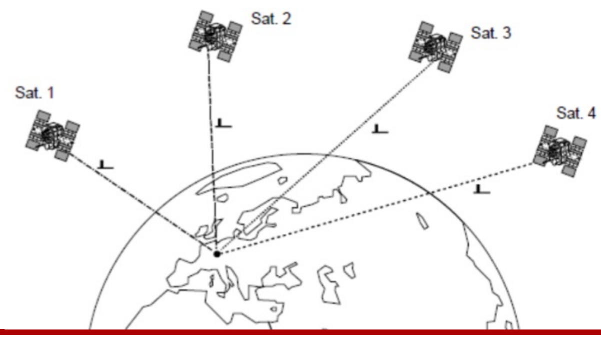
$$\begin{cases} (t_{r1} - \boxed{\delta} - t_s)\cdot c = |\boxed{p_r} - p_{s1}| \\ (t_{r2} - \boxed{\delta} - t_s)\cdot c = |\boxed{p_r} - p_{s2}| \\ (t_{r3} - \boxed{\delta} - t_s)\cdot c = |\boxed{p_r} - p_{s3}| \end{cases}$$

pr: receiver position (x, y, z), 3 unknowns
ps1: Sat1 position, known
4 unknowns, 3 equation: under-determined

- If four sats seen

$$\begin{cases} (t_{r1} - \boxed{\delta} - t_s)\cdot c = |\boxed{p_r} - p_{s1}| \\ (t_{r2} - \boxed{\delta} - t_s)\cdot c = |\boxed{p_r} - p_{s2}| \\ (t_{r3} - \boxed{\delta} - t_s)\cdot c = |\boxed{p_r} - p_{s3}| \\ (t_{r4} - \boxed{\delta} - t_s)\cdot c = |\boxed{p_r} - p_{s4}| \end{cases}$$

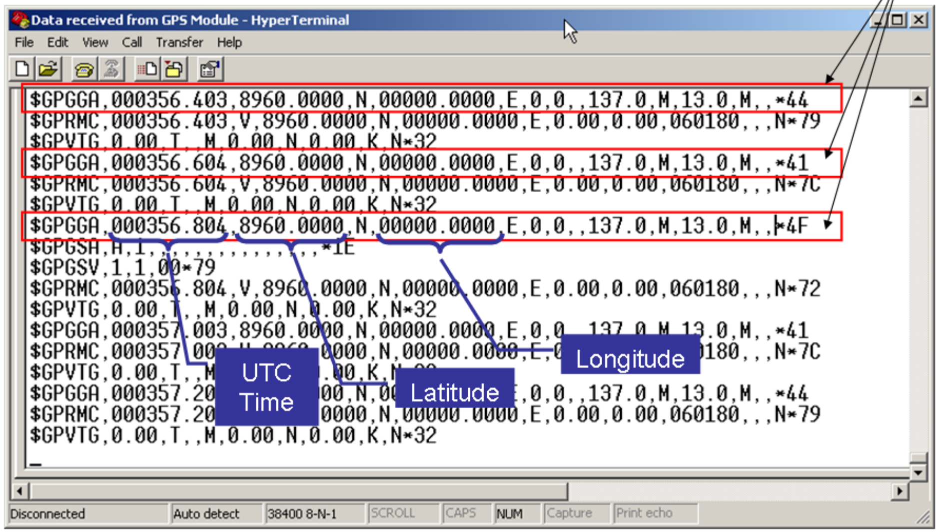
4 unknowns, 4 equation: determined!
GPS receiver needs to see at least 4 sats in the sky!



GPS Accuracy

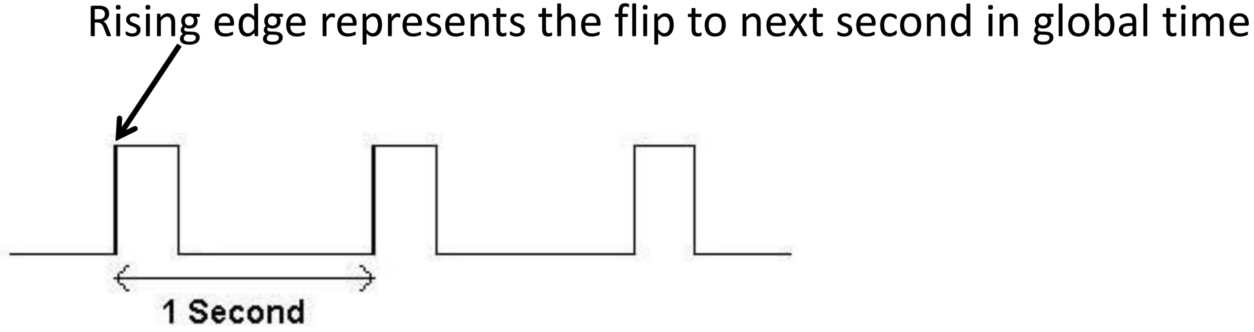
- Location and coarse time
  - Given in NMEA (National Marine Electronics Association) format
  - Location accuracy: 0.5 ~ 5 m
  - Time accuracy: sub-second

GGA NMEA Messages

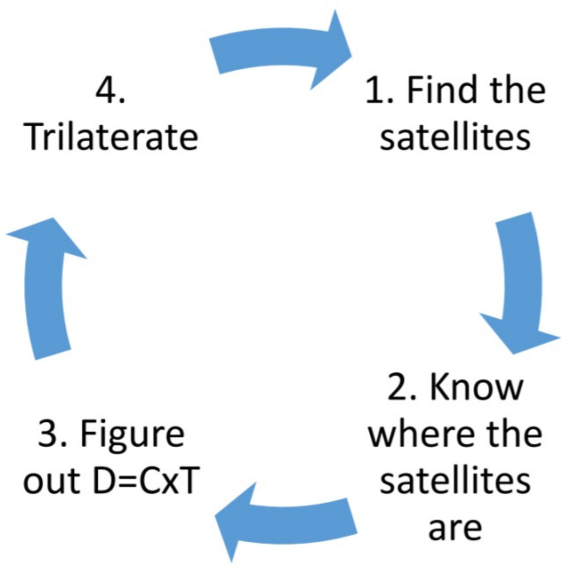


GPS Accuracy (cont'd)

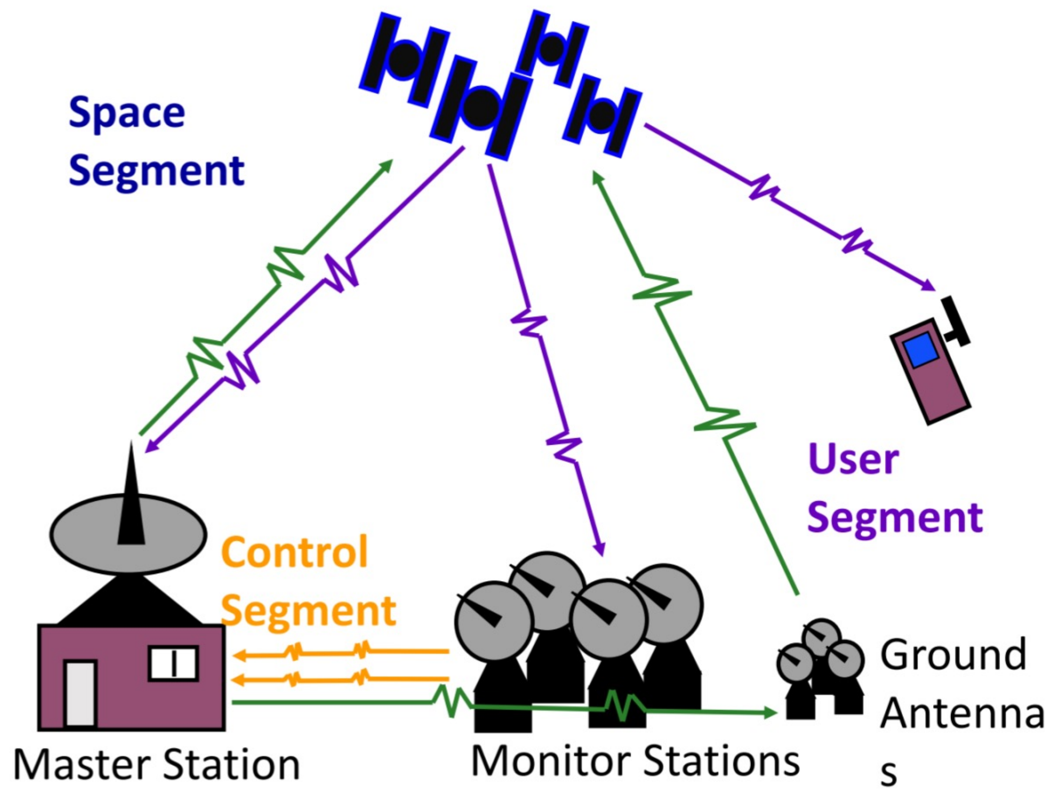
- Precise time
  - Second flip given by PPS (pulse per second)
  - Accuracy: nanosecond to microsecond (depending on grade of the receiver)
  - PPS + coarse time = precise time



GPS Overview



Repeat, repeat, repeat



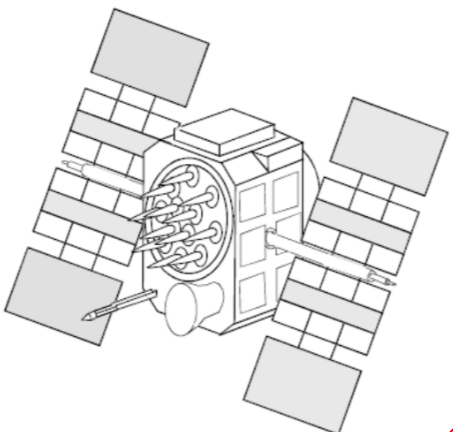
Data Broadcast from GPS Sat

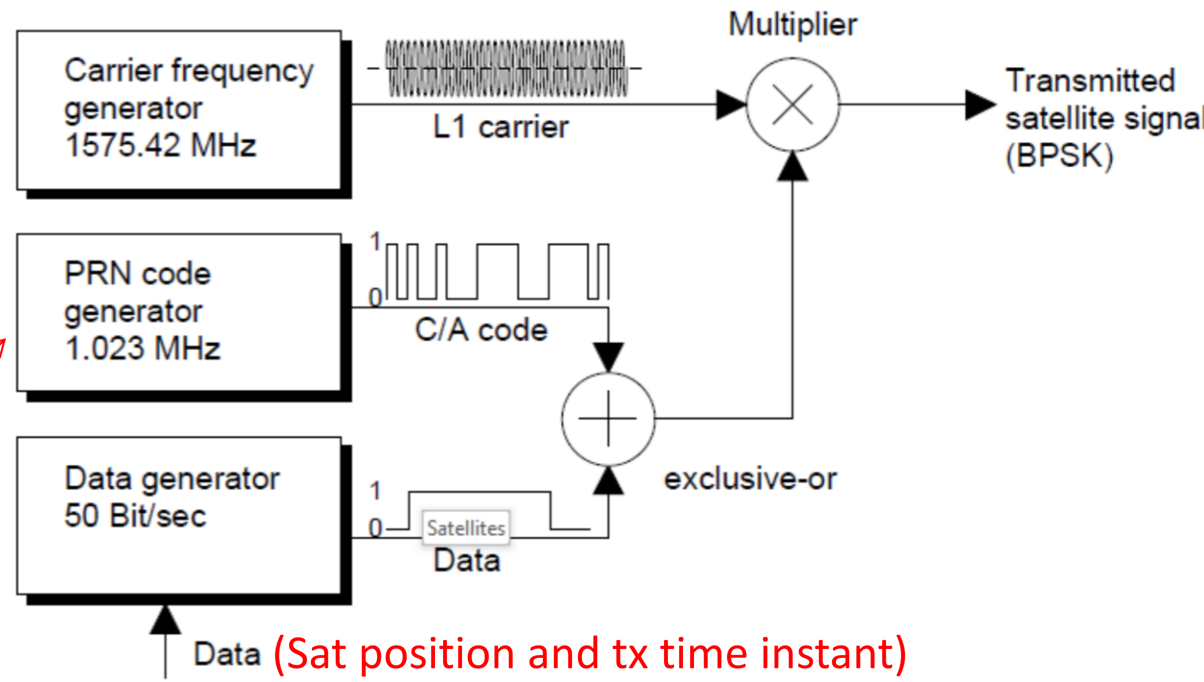
$$\begin{cases} (t_{r1} - \delta - \boxed{t_s}) \cdot c = | p_r - \boxed{p_{s1}} | \\ (t_{r2} - \delta - \boxed{t_s}) \cdot c = | p_r - \boxed{p_{s2}} | \\ (t_{r3} - \delta - \boxed{t_s}) \cdot c = | p_r - \boxed{p_{s3}} | \\ (t_{r4} - \delta - \boxed{t_s}) \cdot c = | p_r - \boxed{p_{s4}} | \end{cases}$$

Data to be broadcast from GPS sats
Receiver solves the equations based on the data

- One-way communications
  - Downlink broadcasts from GPS sats
  - No uplink
- How to enable simultaneous broadcasts from multiple GPS sats?
  - CDM (code division multiplexing)

GPS Data Modulation





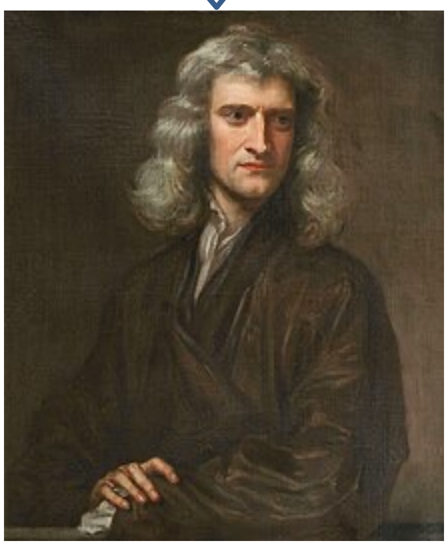
For receiver to decouple data from different sats

Each GPS satellite transmits a unique signature assigned to it. This signature consists of a Pseudo Random Noise (PRN) Code of 1023 zeros and ones, broadcast with a duration of 1ms and continually repeated.

From Newton to Einstein

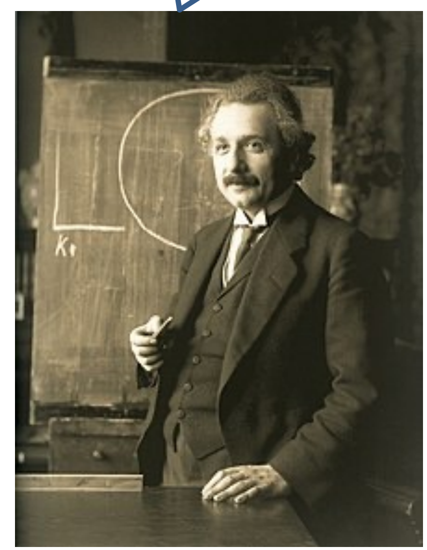
- Time & space are absolute
- Time, space, mass are independent

- Time & space are relative
- Time, space, mass are coupled



Isaac Newton (1643-1727)

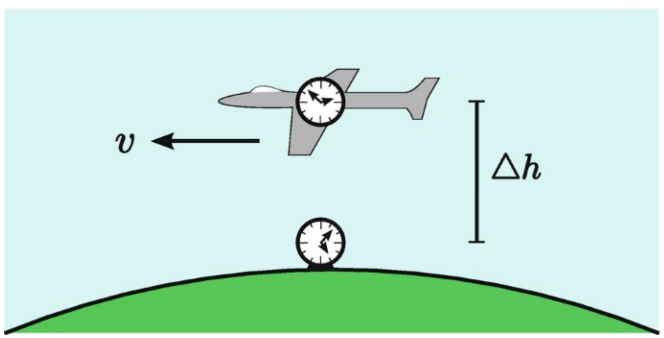
Newton's theory is an approximation of the theory of relativity for systems of low-speed/-mass objects

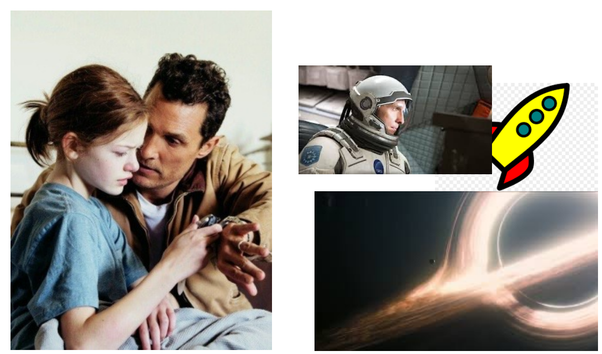


Albert Einstein (1879-1955)

Relativity-Theoretical Effects

- Special theory of relativity
  - Impact of speed on time and space
- General theory of relativity
  - Impact of gravitation on time and space





From movie "Interstellar"

Time dilation

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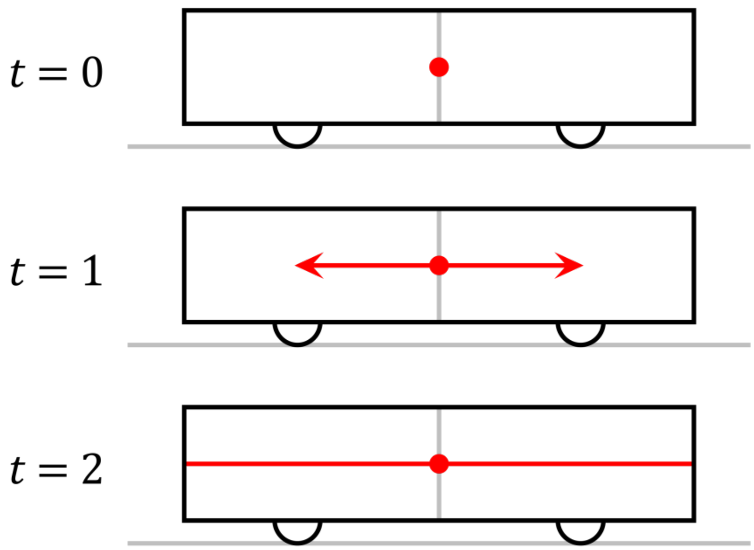
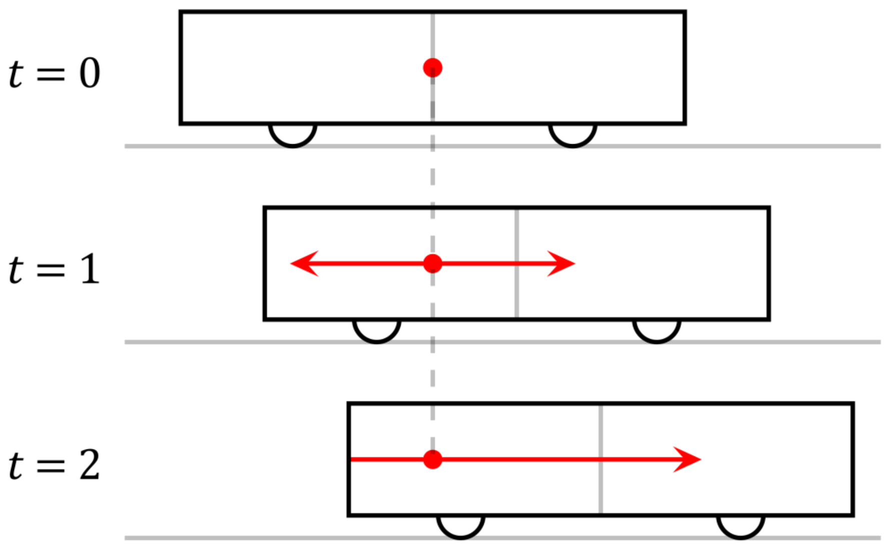
Example: Relativity of Simultaneity

Basis: Speed of light is a constant.

(First verified by Michelson & Morley in 1887)



The train-and-platform experiment from the reference frame of an observer on board the train.



Reference frame of an observer standing on the platform.

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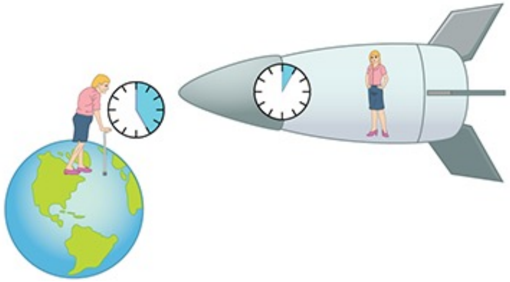
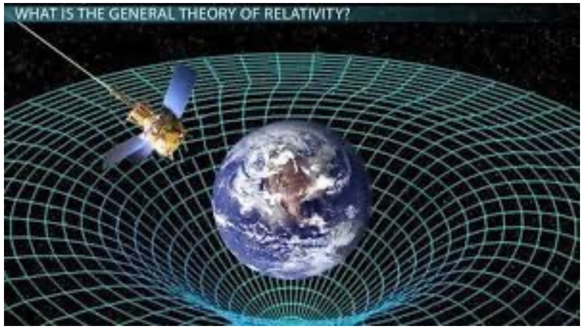
GPS Needs to Consider Relativity

- Special theory of relativity
  - GPS satellite speed: 14,000 km/h = 16 x speed of flight = 0.000013c
  - Dilation factor: 1.0000000001, i.e., GPS satellite's time advances more slowly



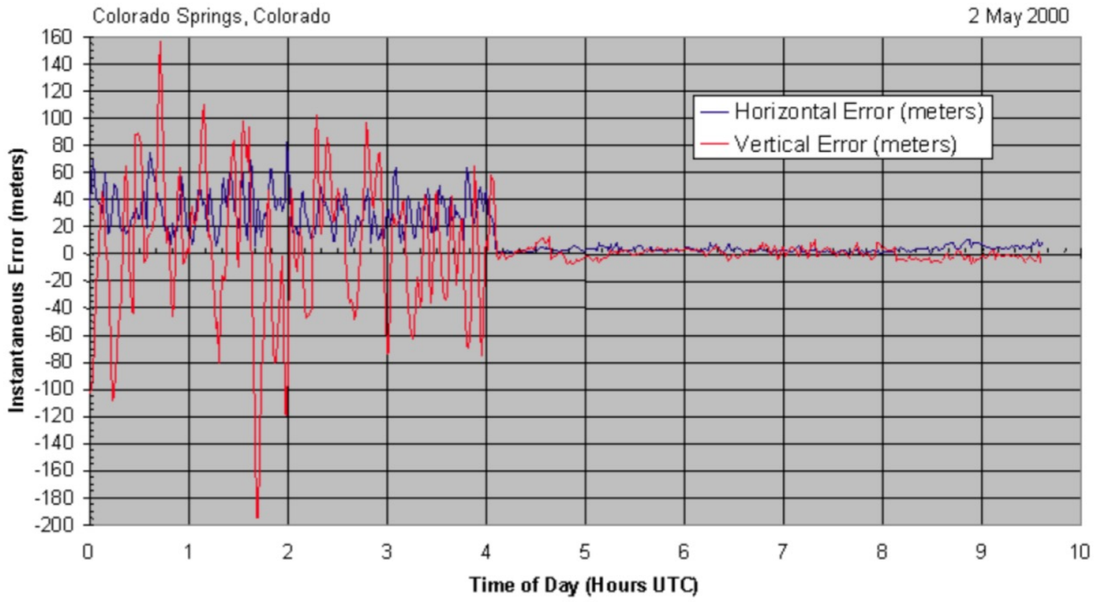
- General theory of relativity
  - GPS satellite altitude: 20,180 km
  - Due to weaker gravitational force, GPS satellite's advances faster



Overall, GPS satellite's time advances 38 microseconds faster per day than earth ground's time, leading to 10 km/day localization drift

Historical Event of GPS

- "The decision to discontinue Selective Availability is the latest measure in an ongoing effort to make GPS more responsive to civil and commercial users worldwide... This increase in accuracy will allow new GPS applications to emerge and continue to enhance the lives of people around the world."
  ---- President Bill Clinton, May 1st 2000



Other GNSS Systems

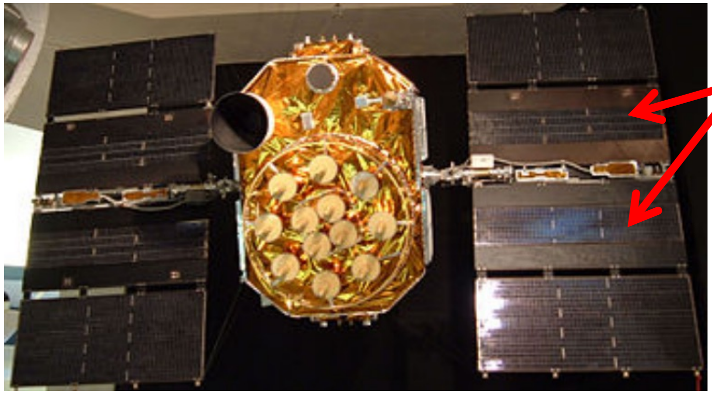
- Global Navigation Satellite System

Visit https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg to see an animation of the different GNSS systems

System	BeiDou	Galileo	GLONASS	GPS	NavIC	QZSS
Owner	China	European Union	Russia	United States	India	Japan
Coverage	Global	Global	Global	Global	Regional	Regional
Coding	CDMA	CDMA	FDMA & CDMA	CDMA	CDMA	CDMA
Altitude	21,150 km (13,140 mi)	23,222 km (14,429 mi)	19,130 km (11,890 mi)	20,180 km (12,540 mi)	36,000 km (22,000 mi)	32,600 km (20,300 mi) – 39,000 km (24,000 mi)[33]
Period	12.63 h (12 h 38 min)	14.08 h (14 h 5 min)	11.26 h (11 h 16 min)	11.97 h (11 h 58 min)	23.93 h (23 h 56 min)	23.93 h (23 h 56 min)
Rev./S. day	17/9 (1.888...)	17/10 (1.7)	17/8 (2.125)	2	1	1
Satellites	BeiDou-3: 28 operational (24 MEO 3 IGSO 1 GSO) 5 in orbit validation 2 GSO planned 20H1 BeiDou-2: 15 operational 1 in commissioning	26 in orbit 22 operational 6 to be launched[34]	24 by design 24 operational 1 commissioning 1 in flight tests[35]	30,[36] 24 by design	3 GEO, 5 GSO MEO	4 operational (3 GSO, 1 GEO) 7 in the future
Frequency	1.561098 GHz (B1) 1.589742 GHz (B1-2) 1.20714 GHz (B2) 1.26852 GHz (B3)	1.559–1.592 GHz (E1)1.164–1.215 GHz (E5a/b) 1.260–1.300 GHz (E6)	1.593–1.610 GHz (G1) 1.237–1.254 GHz (G2)1.189–1.214 GHz (G3)	1.563–1.587 GHz (L1) 1.215–1.2396 GHz (L2)1.164–1.189 GHz (L5)	1176.45 MHz(L5) 2492.028 MHz (S)	1575.42MHz (L1C/A,L1C,L1S) 1227.60MHz (L2C) 1176.45MHz (L5,L5S) 1278.75MHz (L6)[37]
Status	Basic nav. service by 2018 end to be completed by H1 2020[34]	Operating since 2016 2020 completion[34]	Operational	Operational	Operational	Operational
Precision	1m (Public) 0.01m (Encrypted)	1m (Public) 0.01m (Encrypted)	4.5m – 7.4m	5m (no DGPS or WAAS)	1m (Public) 0.1m (Encrypted)	1m (Public) 0.1m (Encrypted)
System	BeiDou	Galileo	GLONASS	GPS	NavIC	QZSS

Limitation of GPS

- GPS signals cannot be received indoors
- GPS sats have to limit the signal Tx power
  - Power generation from solar array: 0.4-2.9kW similar to power consumption of a GSM base station
  - Altitude of about 20,000km, in contrast to a few km from a GSM base station



Solar array:
Cannot generate enough power to get its signal penetrate buildings

An unlaunched GPS sat on display at San Diego Air & Space Museum

Indoor Localization

Indoor Localization Systems

- Olivetti Research Ltd Active Badge (proximity)
  - IR
- AT&T Active Bat
  - Ultrasonic
- MIT Cricket
  - RF + ultrasonic
- Microsoft Research RADAR
  - Wi-Fi RSSI
- Duke SurroundSense (symbolic)
  - Sound, color/light, movement, Wi-Fi SSID
- Gatech PowerLine Positioning (room-level)
  - Powerline active emission
- Oxford/UIUC/NTU Powerline SLAM
  - Powerline passive emission + geomagnetic
- NTU RoomRecognize (room-level)
  - Near-ultrasonic echo
- Device-free localization
  - Instrumented floor, motion detector, computer vision

High variety
(no one size fits all)

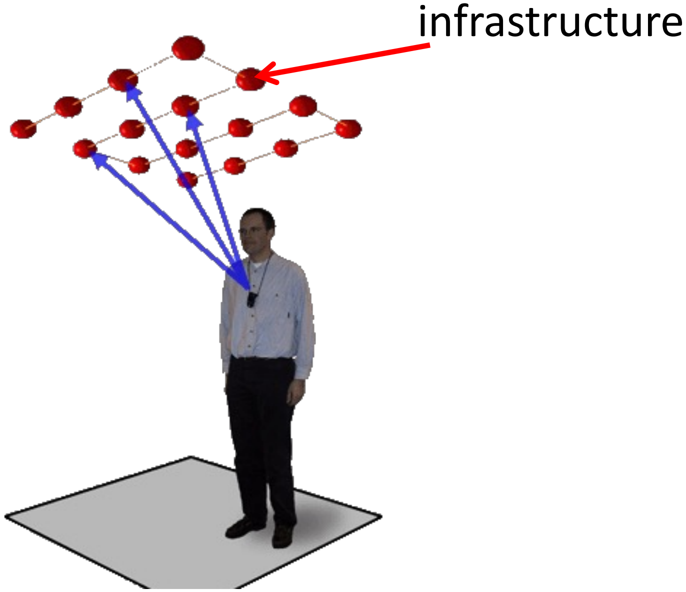
Fragmented
(no unified, integrated solution)

Active Badge (1992)

- Promixity-based solution
  - Every badge periodically sends unique identifier via IR Infrared
  - Receivers store received ID on a server
  - Infrastructure knows target position

Active Bat (2002)

- Lateration based on ultrasonic signal's time-of-flight
- 3cm resolution
- Infrastructure knows target position



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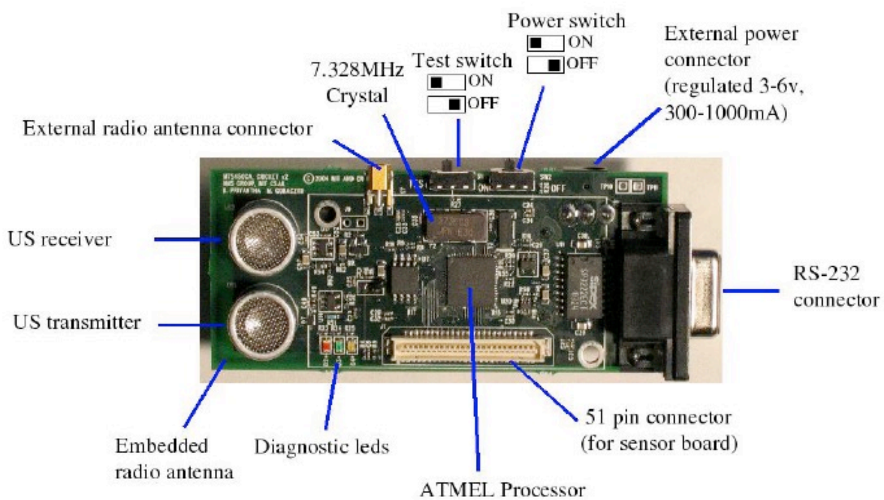
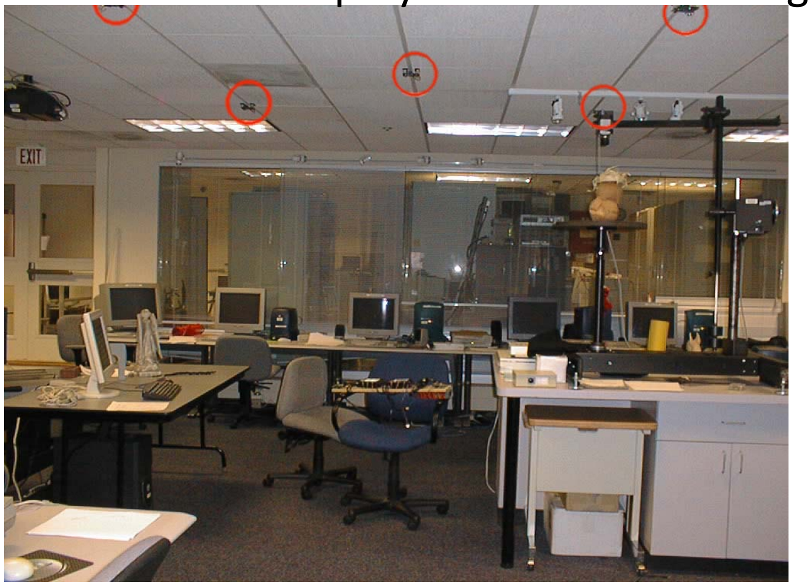
Cricket (2004-2006)

- RF+ultrasound: TDoA (thus distance)
- Cheap: US$10 per node
- Two modes: beacon, listener



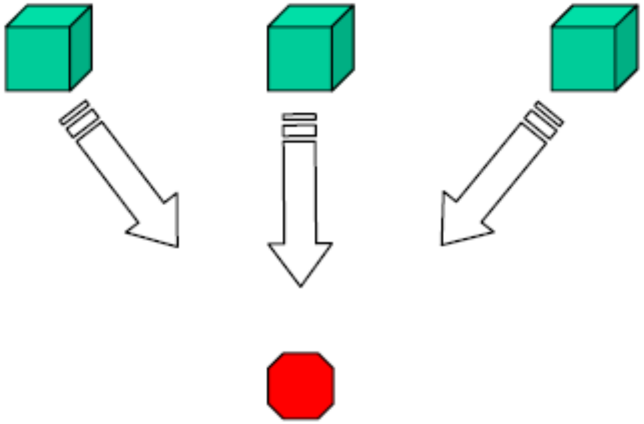
Infrastructure deployed at MIT lab ceiling



Cricket: Passive Mobile

- Only mobile knows its own position
  - Fixed nodes at known positions periodically transmit their location (or identity) on a wireless channel, and passive receivers on mobile devices listen to each beacon.
  - Privacy-preserving

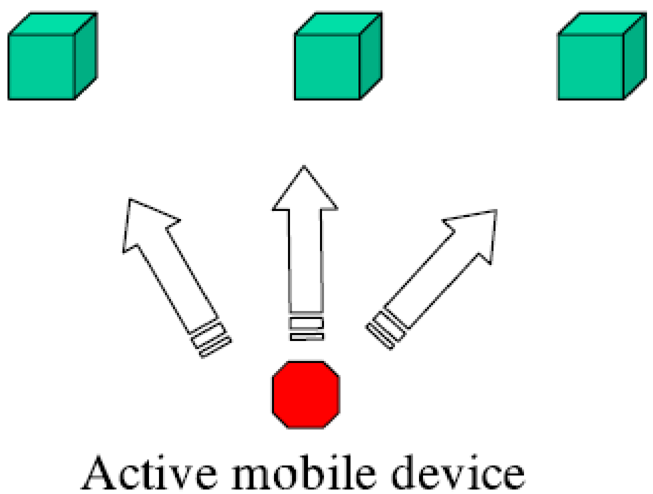
Similar to GPS



Passive mobile device

Cricket: Active Mobile

- Infrastructure knows mobile's position
  - An active transmitter on each mobile device periodically broadcasts a message on a wireless channel.



Cricket: Summary

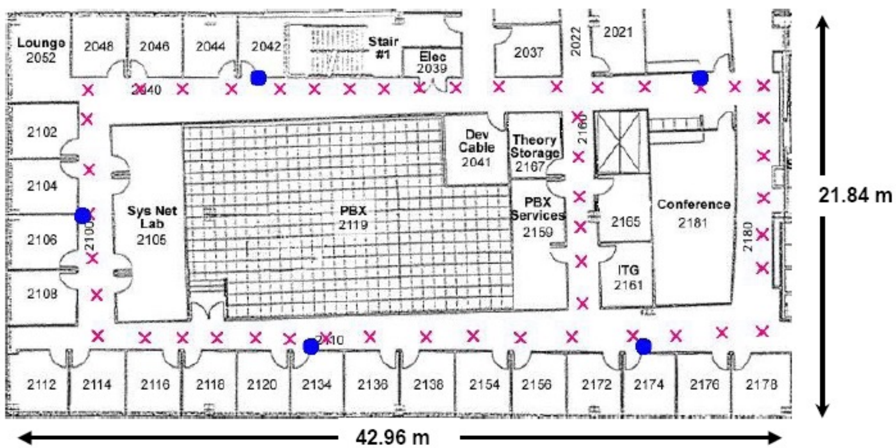
	Advantages	Disadvantages
Passive mobile	• Privacy • Decentralized and scalable (infinite mobiles) • Acceptable accuracy at low speeds	• Reduced accuracy at higher speeds (about 1m/s) Suffers from synchronization problems. It is difficult in indoor scenario
Active mobile	• Good accuracy No need for synchronization	• Centralized, reduced scalability (a single mobile at a time) • Privacy concern • Beacon nodes need network

Drawback

- Active Badge, Active Bat, Cricket require dedicated infrastructures
  - High deployment cost / overhead

RADAR (2000)

- Trilateration based on distances estimated from Wi-Fi RSS
- Uses the existing Wi-Fi infrastructure
- Basis for most today's usable system (e.g., Google Map)



RADAR (cont'd)

- Authors show Wi-Fi can be used to track objects
- Localization error: 2 ~ 8 meters
- Drawback
  - For small errors, dense Wi-Fi APs needed
  - Needs in-situ RSS profiling
    Not a plug-and-play system

A Large Body of RSS-Based Systems

Radio Frequency Identification (RFID)	LANDMARC [INFOCOM'04], Wang et al. [INFOCOM'07], Seco et al. [IPIN'10]
Bluetooth	Ficsher et al.[CWPNC'04], PlaceLab [Pervasive'04], Pei et al. [JGPS'10]
Wireless Sensor	Chang et la. [Sensys'08], Chung et al. [MobiSys'11], Pirkl et al. [UbiComp'12]
GSM	Otsason et al. [UbiCom'05]
Wireless Local Area Network (WLAN)	RADAR [INFOCOM'00], Horus [MobiSys'05], Chen et al.[Percom'08]

A Large-Body of RSS-Based Systems (cont'd)

- Applied on smartphones

➢ Wi-Fi on smartphone

Chintalapudi et al. [MobiCom'10], OIL [MobiSys'10], WiGEM [CoNexts'11]

Improve accuracy

➢ Wi-Fi + other sensing modalities

Zee[MobiCom'12], UnLoc[MobiSys'12], WILL[INFOCOM'12],

LiFS[MobiCom'12], ABS[MobiSys'11], Liu et al.[MobiCom'12],

SurroundSense [MobiCom'09], Escort [MobiCom'10]

Let's Step Back

- Symbolic localization can be very useful

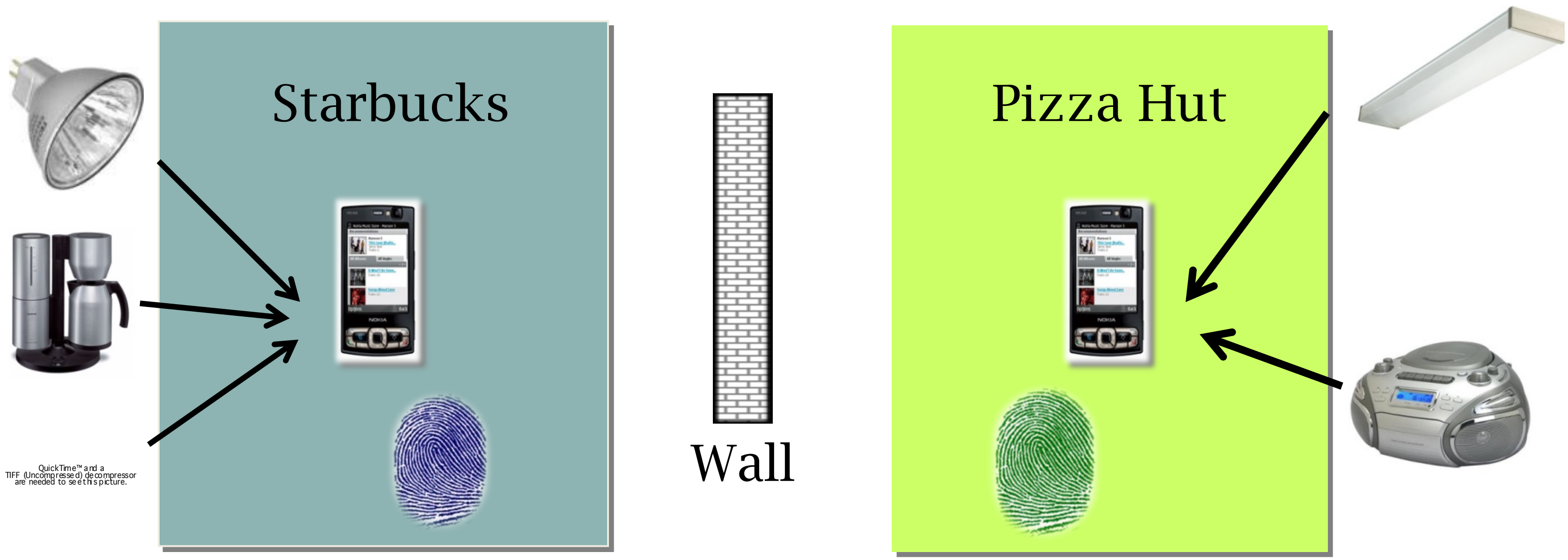
The dividing-wall problem

SurroundSense (2009)

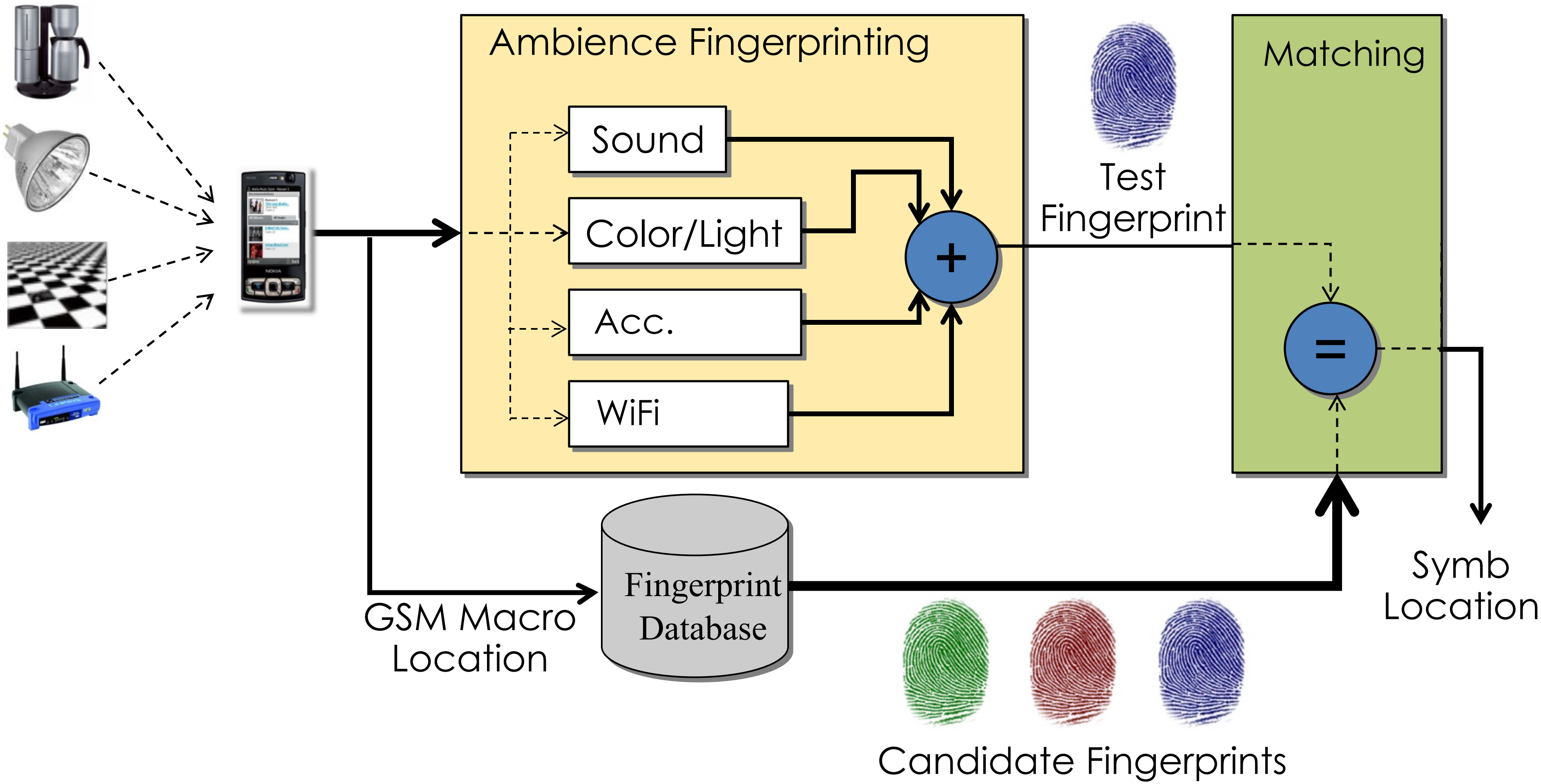
- It is possible to identify the symbolic location by sensing the ambient
  - Sound, light, color, user movement, Wi-Fi

SurroundSense: Fingerprint

- Multi-dimensional fingerprint
  - Based on ambient sound / light / color / user movement / Wi-Fi SSID



SurroundSense: Architecture



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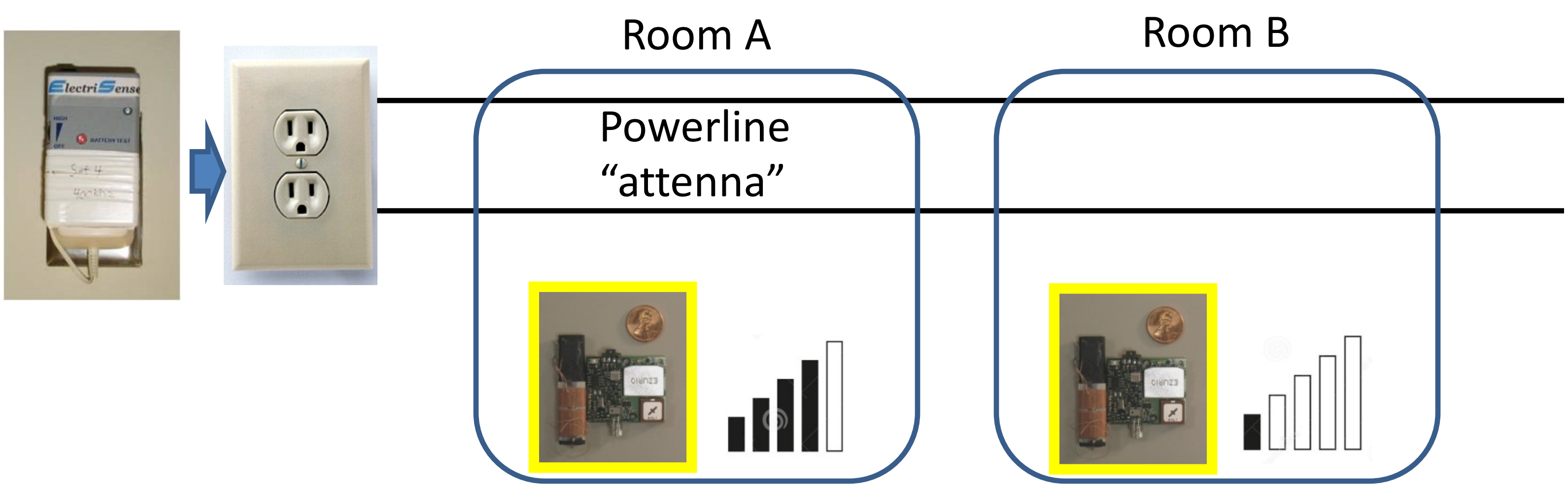
SurroundSense: Results & Limitations

- Results
  - 89% accuracy in identifying business locations

- Limitations
  - Non-business locations are less diverse
  - Ambient varies over time
  - Phone can sense opportunistically (e.g., in pocket)
  - Labor-intensive fingerprint database construction
    - Can be mitigated by crowdsourcing

PowerLine Positioning (2006)

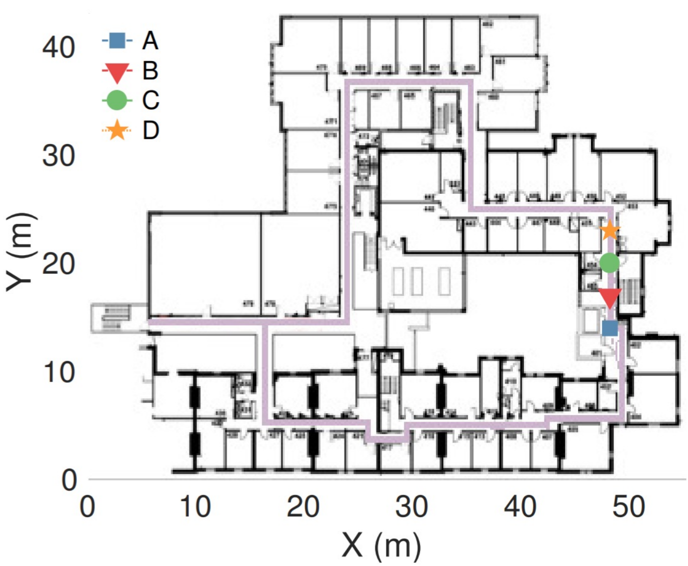
- Room-level localization
  - Inject signal into household powerline
  - Mobile detects signal radiated from powerline

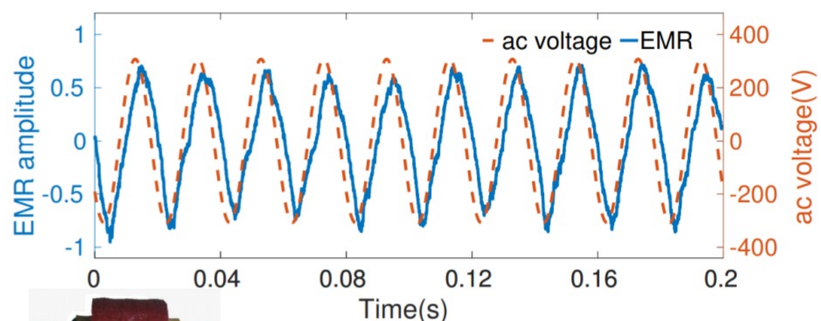


Received signal strength is room-dependent

Powerline SLAM (2018)

- Powerline generates passive magnetic radiation at 50Hz or 60Hz
- Radiation amplitude varies with location





Electromagnetic radiation sensor tuned to 50Hz

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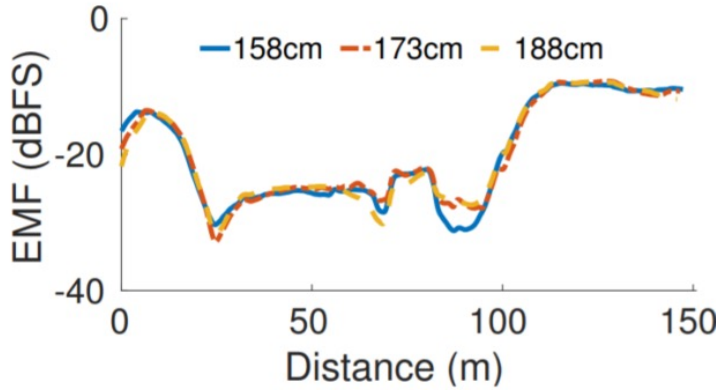
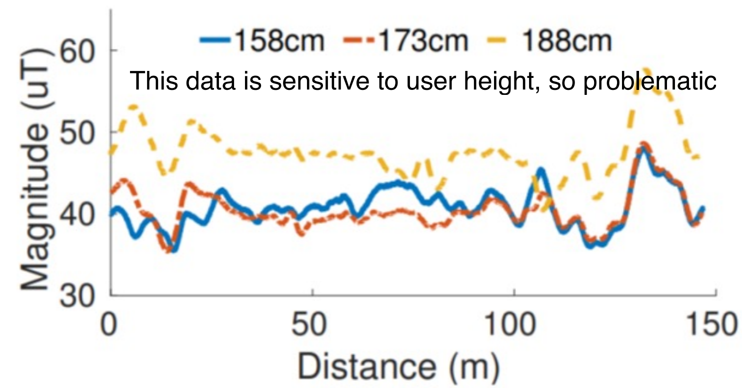
Powerline SLAM (cont'd)



Powerline radiation



Geomagnetic

- Powerline electromagnetic radiation
  - Not affected by user heights
  - But affected by working states of nearby electrical appliances
- Geomagnetic measurement
  - Not affected by electrical appliances
  - But affected by user heights
- Combining both achieved 4m localization accuracy in office building

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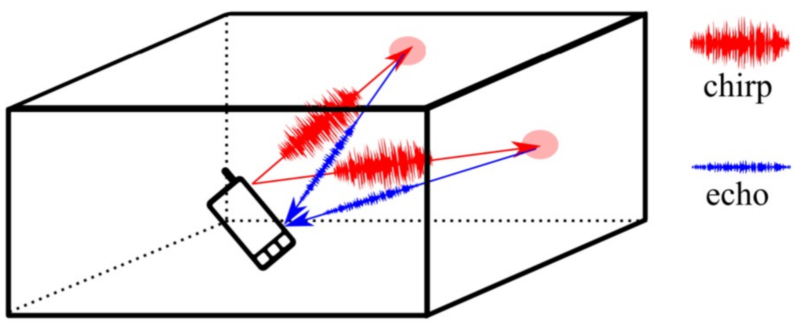
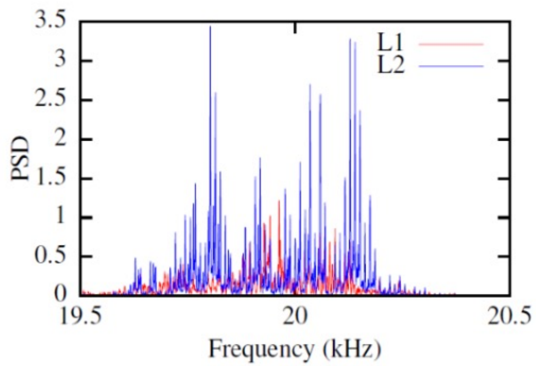
Powerline Sensing: Limitations

- Powerline electromagnetic radiation sensors are not available on today's off-the-shelf mobile devices
- Labor-intensive fingerprint database construction

RoomRecognize (2018)

- A smartphone can recognize the room it is located in based on echos responding to a near-ultrasound (inaudible) chirp
- 97% accuracy in recognizing 50 rooms





Power spectral density of echos in two rooms

RoomRecognize: Limitations

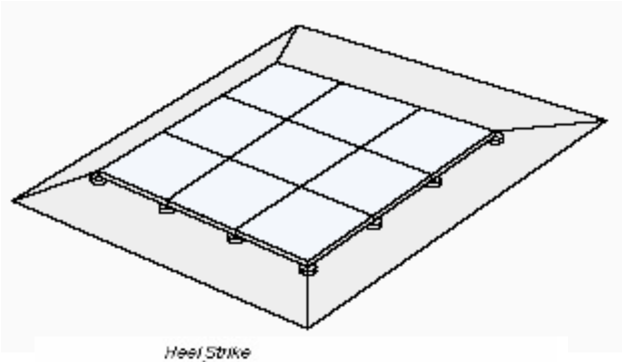
- Requires fingerprint database construction
- Can be affected by nearby moving people

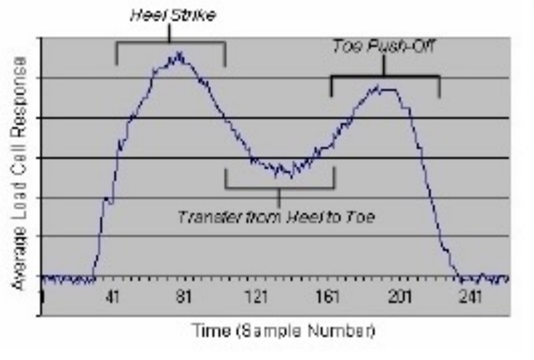
Device-Free Localization

- All above systems require the user to carry a device (a customized device or a smartphone)
- Device-free localization
  - User doesn't carry any device
  - User localized unobtrusively

Instrumented Floor

- Load sensors to detect footstep
- Hard to identify users





Motion Detector

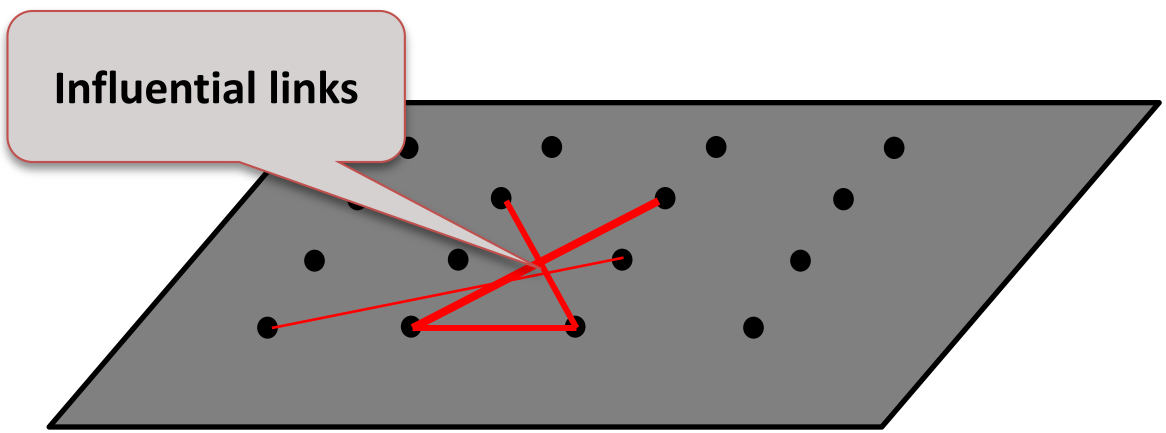
- Low-cost
- Proximity
- Hard to identify users

Surveillance Camera

- Require significant communication and computation resources
- Subject to occlusion
- Privacy-breaching
  - Only applicable in public space

Radio Links

- An object will affect the radio links (e.g., Bluetooth)
- Limitations
  - Requires dense deployment of radio devices
  - Hard to address multiple objects



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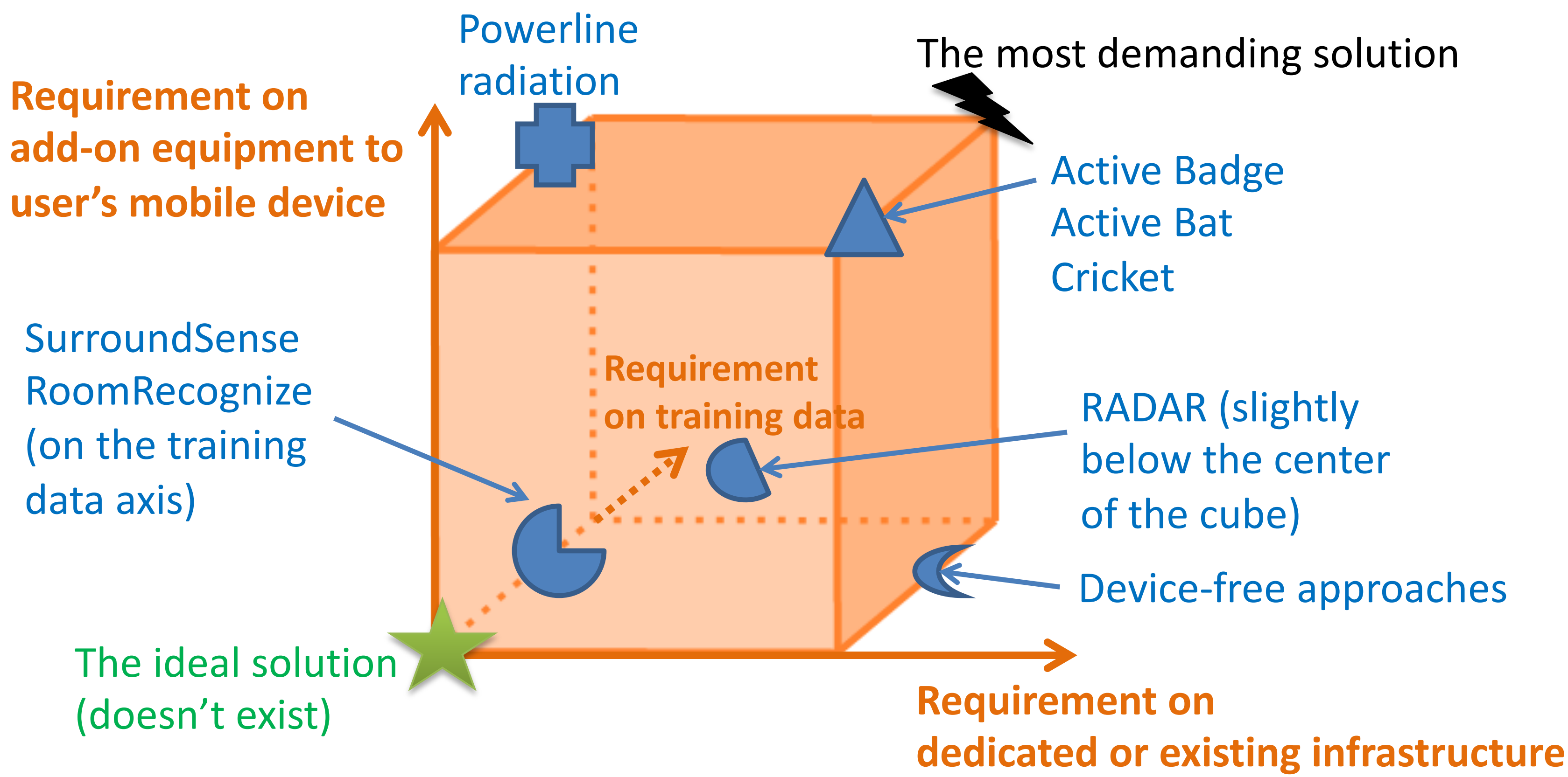
Indoor Localization: Summary

- 30 years research to move within this requirement cube



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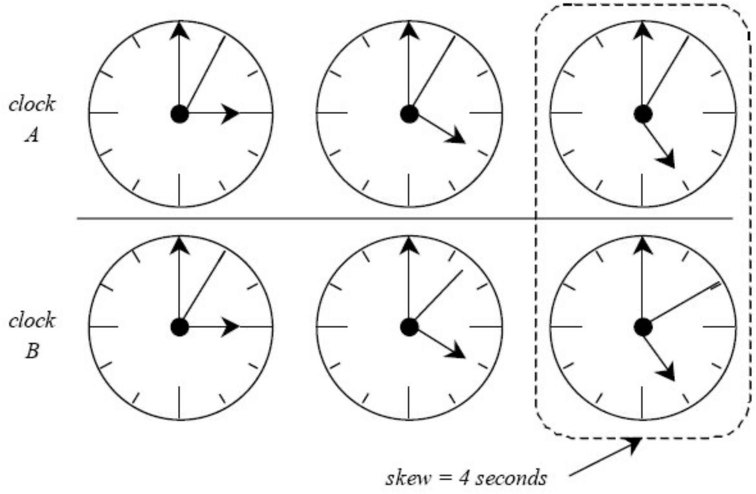
Indoor Time Acquisition

Concepts on Time

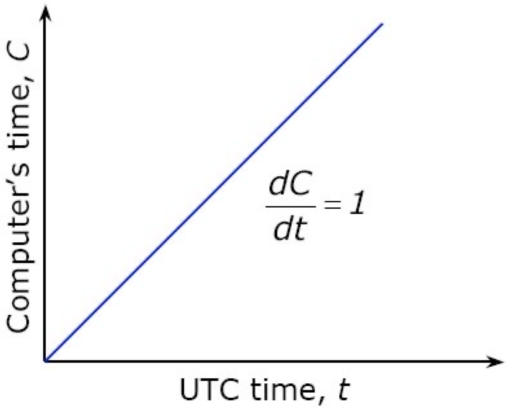
- Newtonian time (absolute time)
  - We don't consider Einstein's relativity because indoor electronic devices don't move too fast
  - Einstein's relativity needs to be considered for GPS sats because they move very fast
  - We also don't consider the problem of what is time (theoretical physicists also find hard to define time; what we need is merely how to measure time)
- Global time: UTC (Universal Coordinated Time)
  - Singapore is in UTC+8
- Units
  - 1 second = 10^3 milliseconds = 10^6 microseconds

Concepts on Clock

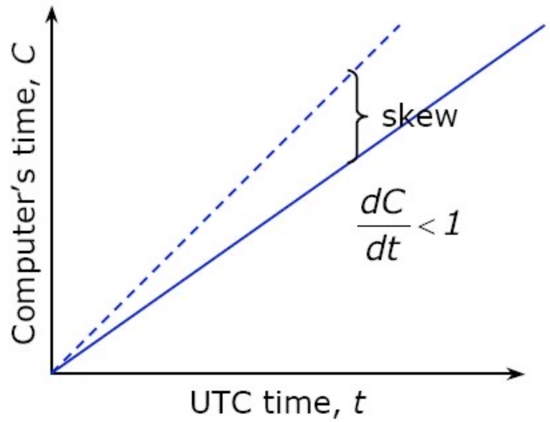
- Clock drift
  - The phenomenon that clocks tick at different rates
    - Ordinary quartz clocks drift by 1 ~ 50ppm
      i.e., 1 ~ 50 microseconds per second
- Clock skew (offset)
  - Difference between two clocks at a time instant



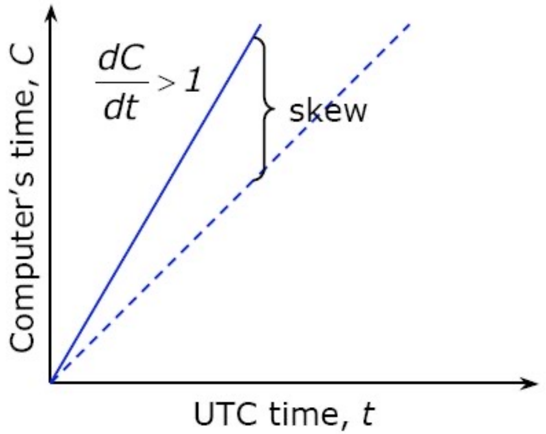
Clock Drifts



Perfect clock



Slow clock



Fast clock

Objective

- Keep an indoor device's clock synchronized with UTC all the time
  - Data generated by the device can then be timestamped using its clock
- Easy and hard
  - Easy for moderate accuracy (e.g., seconds)
  - Hard for high accuracy (e.g., microseconds)

Typical Accuracy

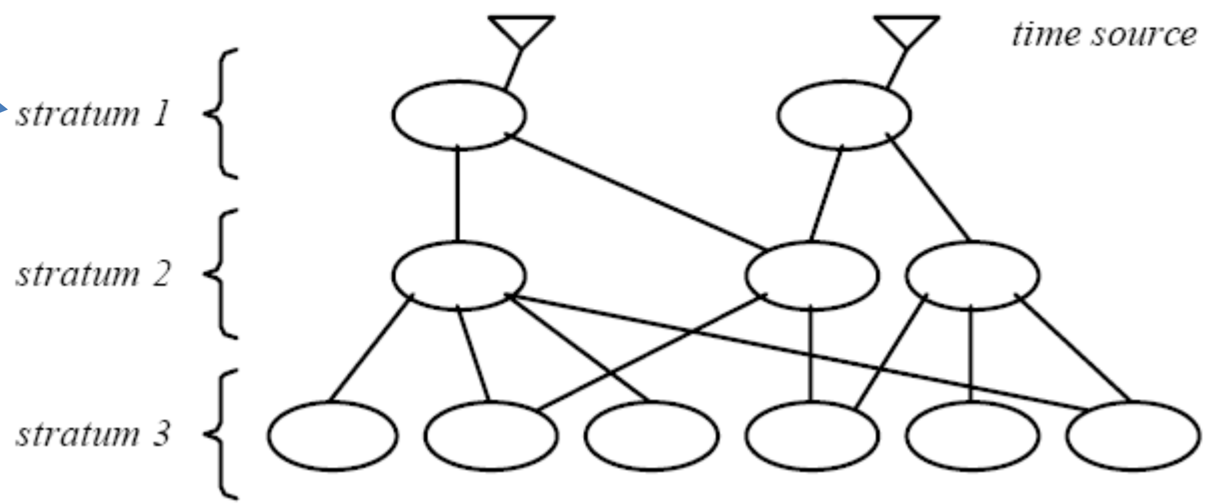
- Attach GPS receiver to urban IoT node
  - Without PPS: sub-second
  - With PPS (through serial port): microsecond
- Attach WWVB and DCF77 radio receiver
  - ± 3 milliseconds
- Attach GOES (Geostationary Operational Environmental Satellites) receiver
  - ± 0.1 milliseconds

- Impractical for every urban IoT device
  - Cost, size, convenience, environment

Network Time Protocol (NTP)

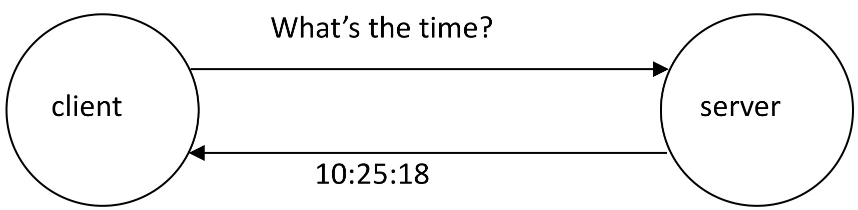
- Developed in 1991, a foremost means for networked devices nowadays
- A synchronization hierarchy

Nodes connected directly to accurate time source (e.g., GPS receiver)



A Naïve Approach

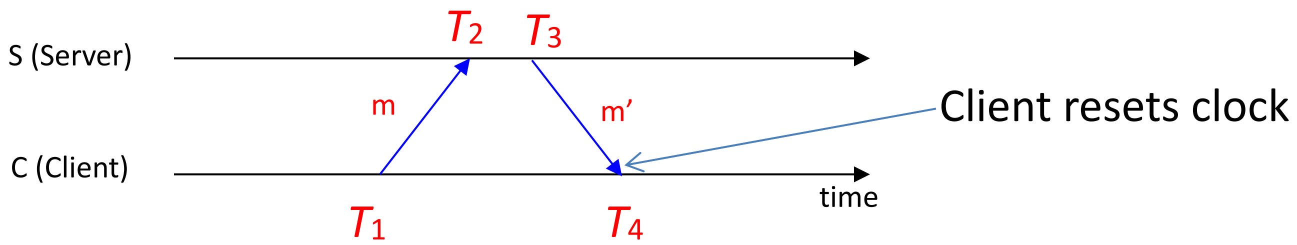
- Simplest synchronization technique
  - Issue a remote procedure call to obtain time
  - Set time



Does not consider network and processing latencies

NTP Synchronization

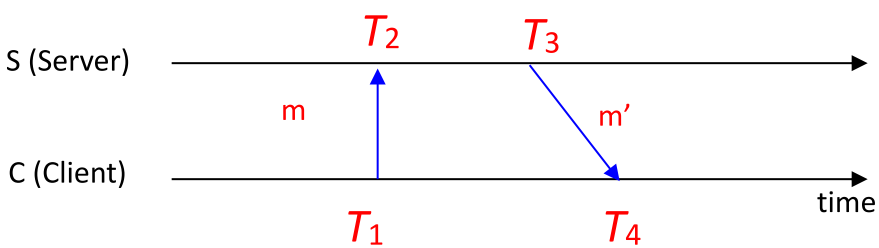
- Addresses processing delay and symmetric network delays



  - Total network delay $D = (T_4 - T_1) - (T_3 - T_2)$
  - Clock offset of C relative to S is $O = C_c(t) - C_S(t) = T_1 + D / 2 - T_2$
  - Client resets clock: $T_4 - O$

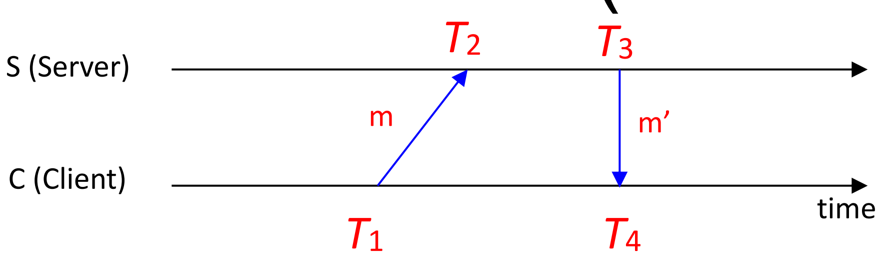
Clock Offset Estimation Error

- Zero error when the two network delays are identical
- Extreme case 1 (zero delay for request)



Error = D / 2

- Extreme case 2 (zero delay for reply)



Error = - D / 2

NTP Errors

- Error increases with link asymmetry
- Error bound increases with total network delay

$$-\color{red}{D} / 2 \leq \text{Error} \leq \color{red}{D} / 2$$

- In practice, NTP error also depends on the accuracy of timestamping network packet transmission and arrival
  - There is a delay from the NTP code asks the OS to transmit the packet to when the packet is actually transmitted

Typical NTP Errors

- Ethernet
  - Milliseconds
- Wireless link (Wi-Fi, Bluetooth)
  - Milliseconds to hundreds milliseconds
  - Depends on how busy the channel is
- NTP is inefficient for ToA-based ranging
  - Error over ultrasound: 0.34m ~ 200m
  - Error over RF: more than 300km

Higher Sync Accuracy

- Obtain the times when the packet is actually transmitted and received
  - Access the hardware interrupt from the network interface card (NIC) and radio chip
  - Microsecond accuracy can be achieved on wireless link
    - 1 microsecond error: 300m ranging error
    - Nanosecond accuracy is in general needed for RF-based ranging
  - Not all NICs and radio chips provide hardware interrupts on packet events

Learning Objectives

- Localization approaches
  - Read the approaches of proximity, lateration, augulation, RSSI, ToA/TDoA, fingerprinting
- GPS
  - Understand principle, requirement, limitation
- Indoor localization
  - Read the advantages and disadvantages of various approaches
- Indoor time acquisition
  - Understand sources of NTP error
  - Calculate NTP error bound

Research Case Studies: Accurate & Secure Time in a City (not examinable)

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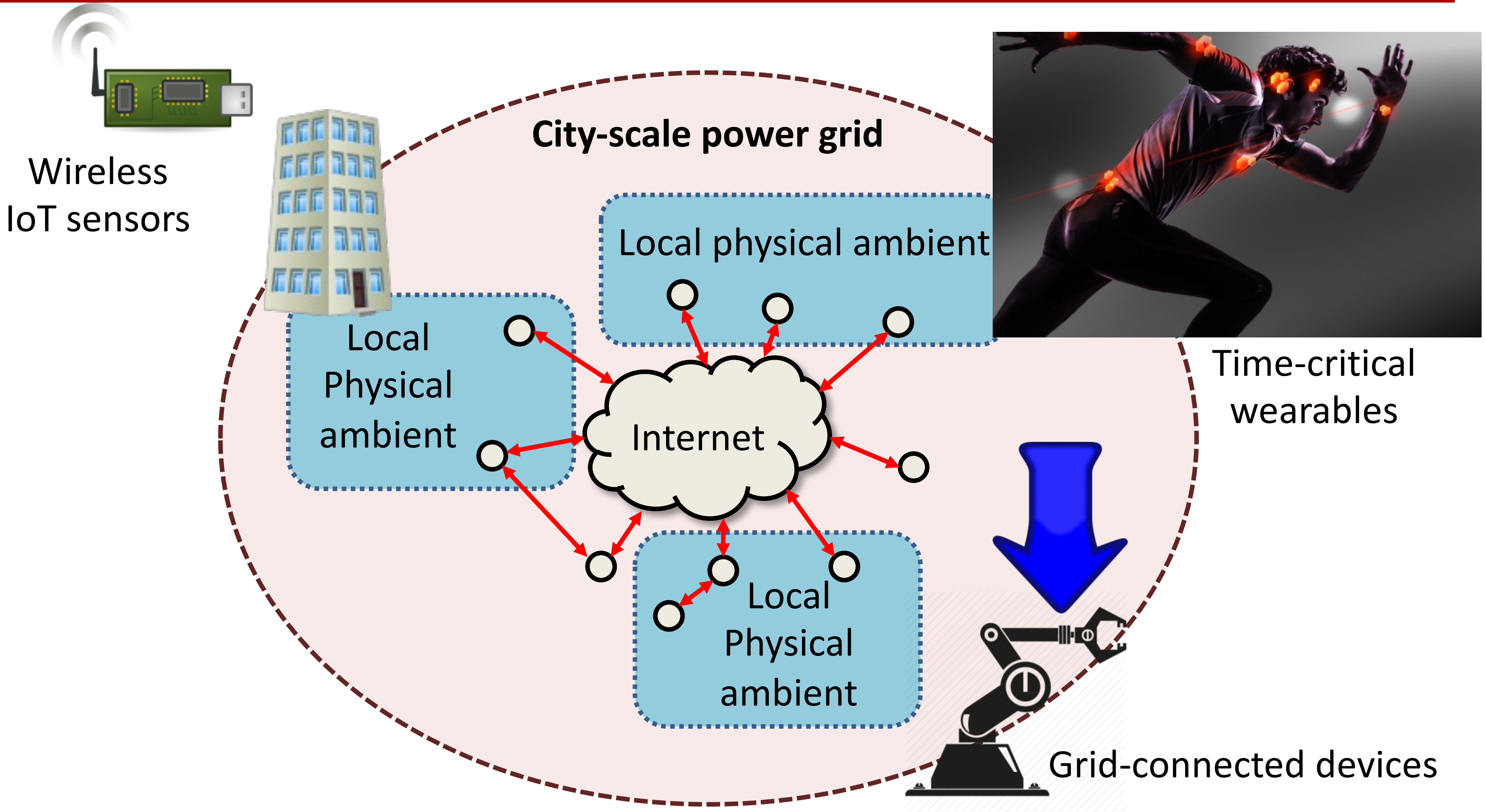
Time Keeping in Urban IoT

Power Grid as Time Source



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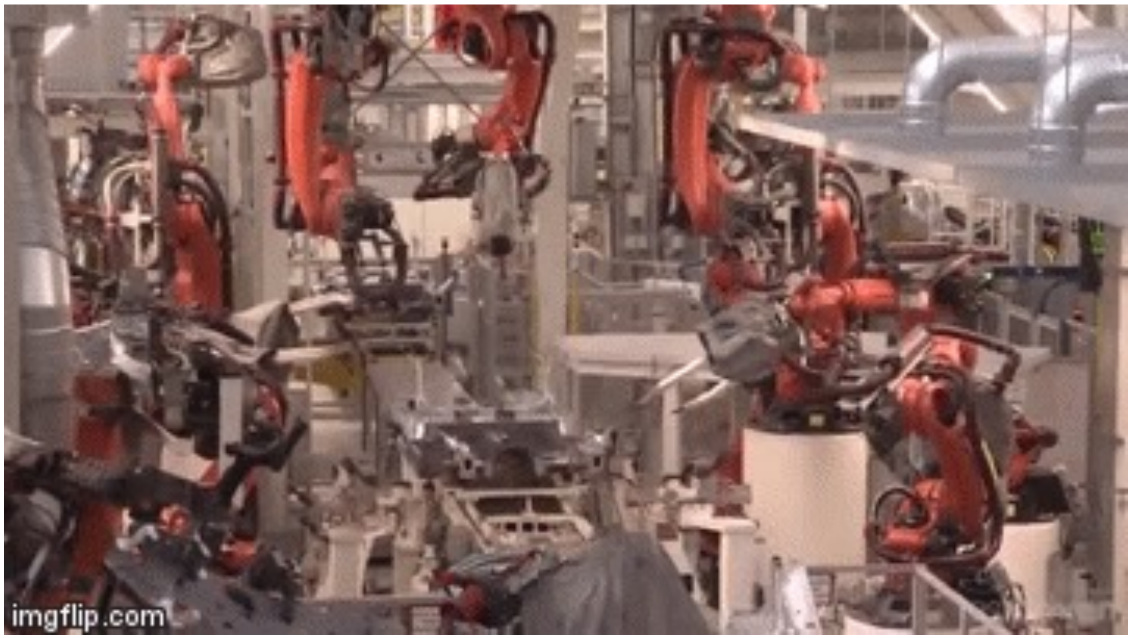
Clock Synchronization in Industrial IoT

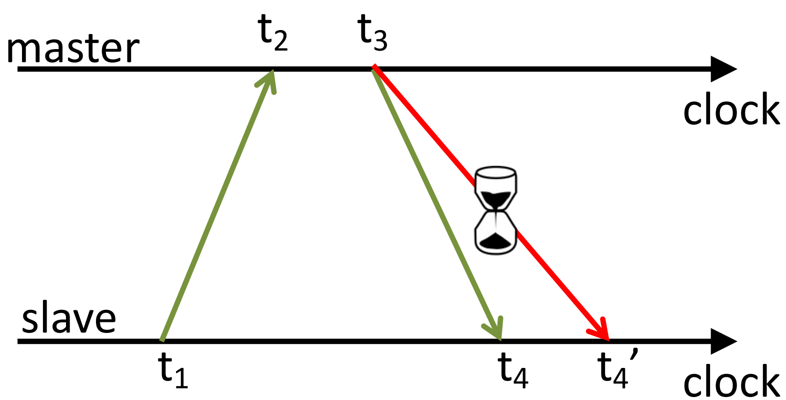


Roboteam

- Industrial systems need accurate clock sync
  - ms or even μs accuracy
- Desynchronization
  - Degrade system performance, cause damage

Clock Sync Security

- GPS
  - Not scalable, vulnerable to wireless spoofing
- Message exchange based protocols (NTP, PTP, …)
  - Vulnerable to packet delay attack [RFC 7384]
    Implemented in wired/wireless networks
  - No pure cryptographic solution

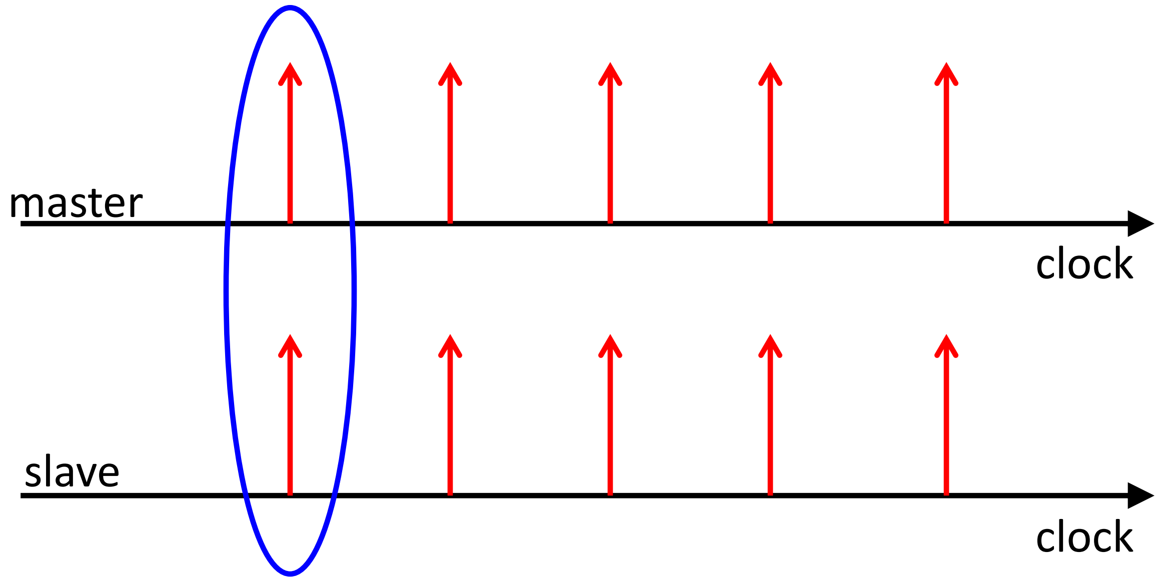


Symmetric link assumption

$$\text{oneway delay} = \frac{RTT}{2} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2}$$

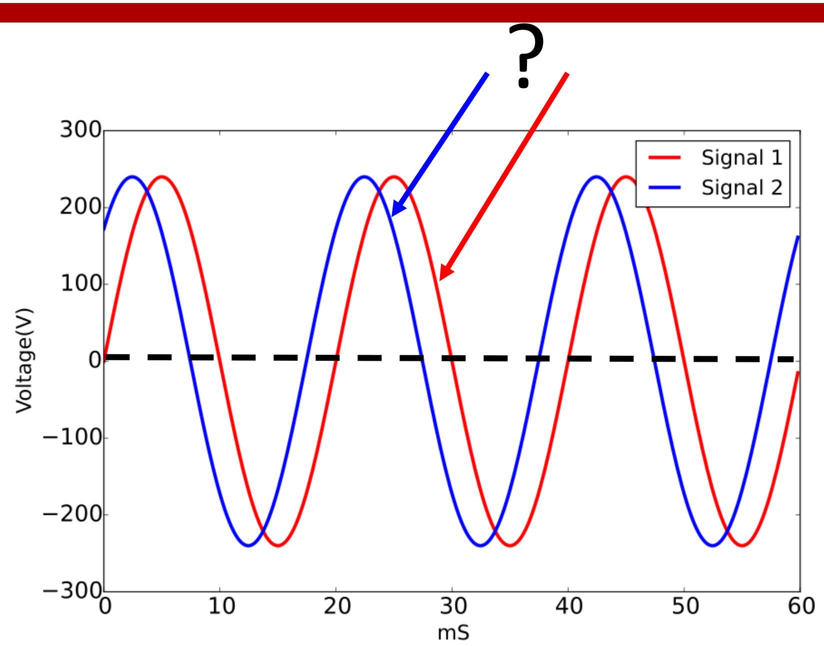
$$\text{introduced offset error} = \frac{t_4' - t_4}{2}$$

Secure Sensing-Based Clock Sync



- Common periodic impulses from physical ambient
  - **Synchronous:** Impulses occur at the same time
  - **Securely synchronizable:** Correspondence between two impulses w/o measuring network delays

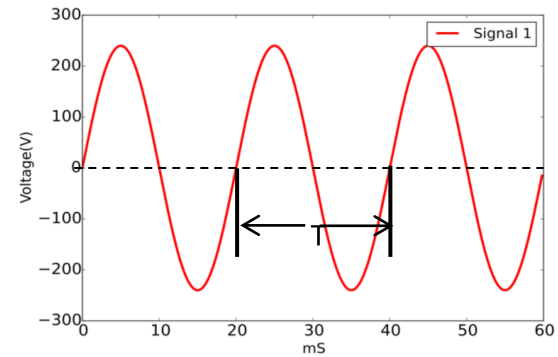
Electric Network Voltage (ENV)

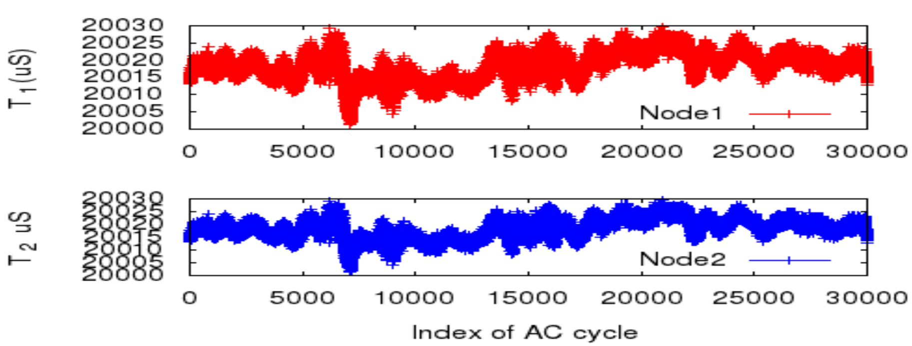


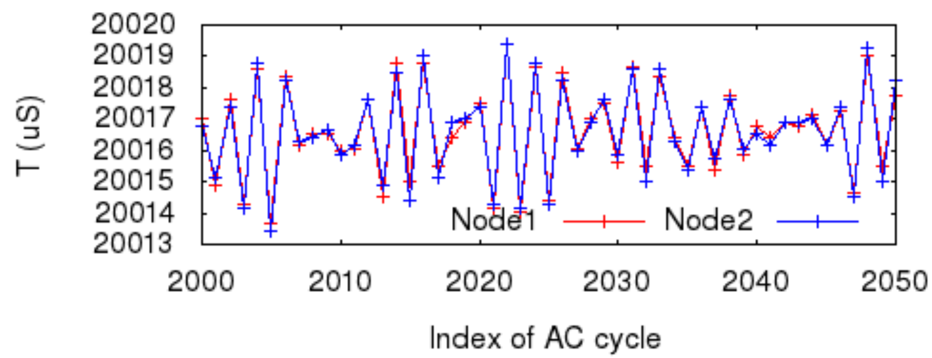
- Synchronous
  - 100 µs offset over 10 km
- Hard to compromise
  - Inject large energy to distort 50Hz ENV
  - Modify power network?
- **Securely synchronizable?**

Time Fingerprint (TiF)

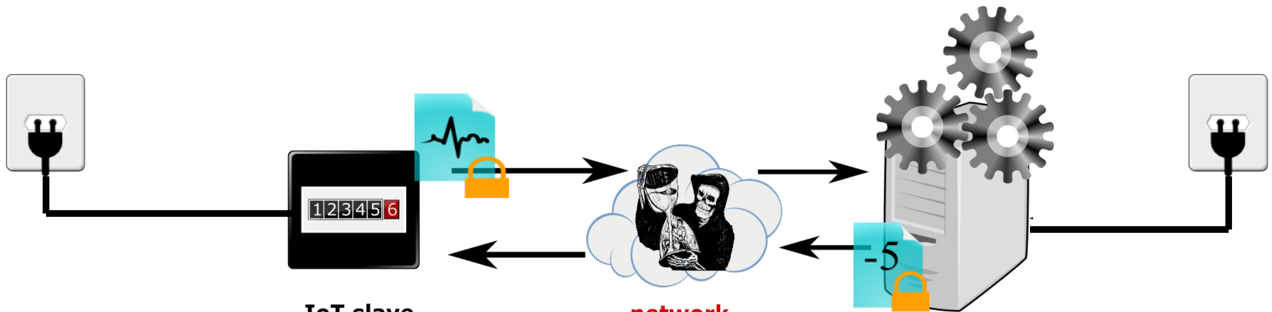
- TiF: a sequence of cycle lengths
  - TiF form fluctuates randomly
  - Nodes in an area observe similar forms





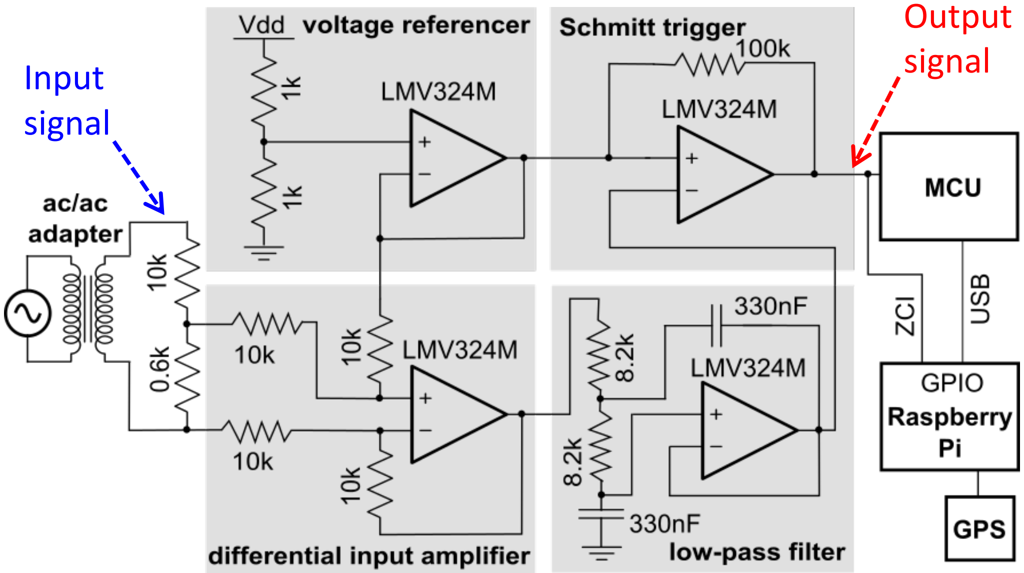


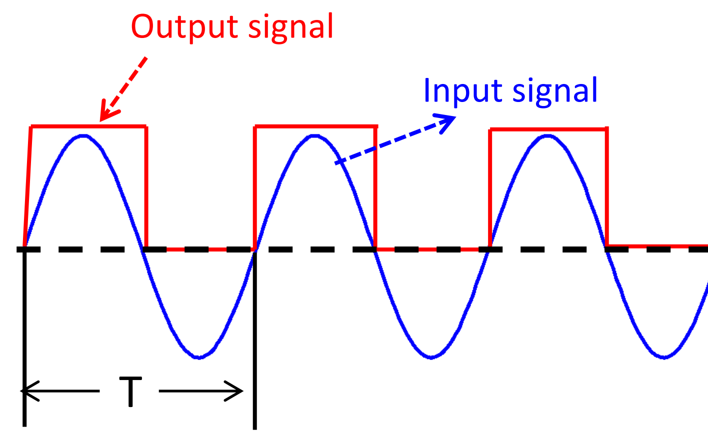
TiF-based Clock Sync

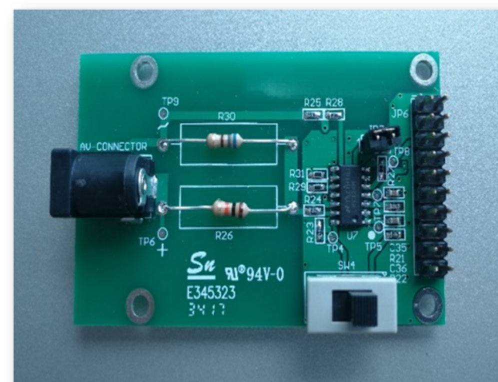


- Master-slave architecture
  - Master: record TiF trace with global timestamp
  - Slave: transmits a timestamped TiF
- Does not measure network transmission delay
  - Immune to packet delay attack

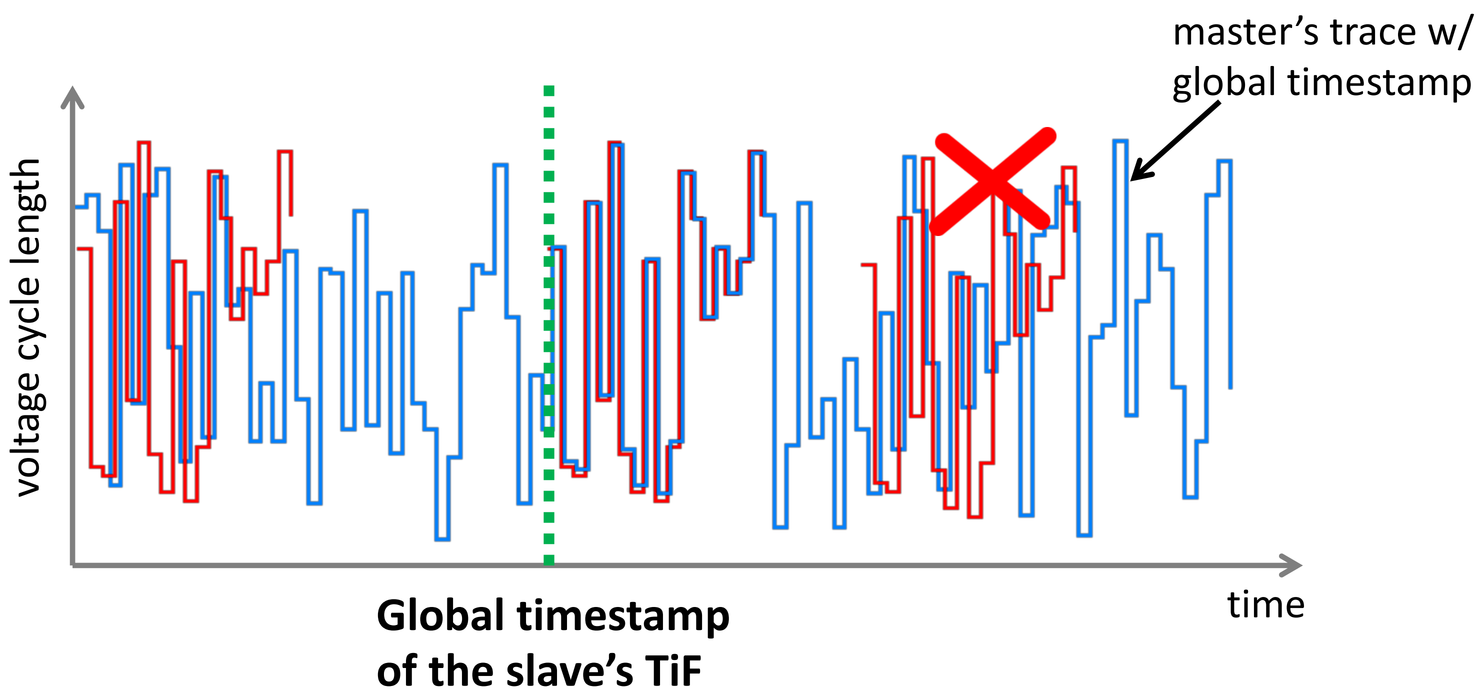
TiF Capture


Input signal
ac/ac adapter
Output signal
Vdd
voltage referencer
1k
1k
LMV324M
Schmitt trigger
100k
LMV324M
10k
0.6k
10k
10k
10k
10k
LMV324M
differential input amplifier
330nF
8.2k
8.2k
LMV324M
330nF
low-pass filter
MCU
ZCI
USB
GPIO
Raspberry Pi
GPS


Output signal
Input signal
T

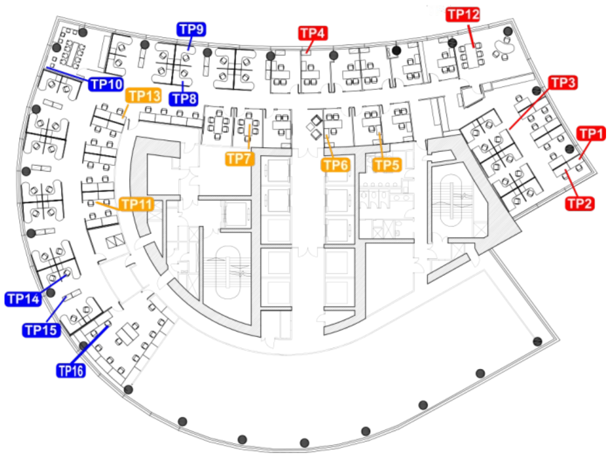


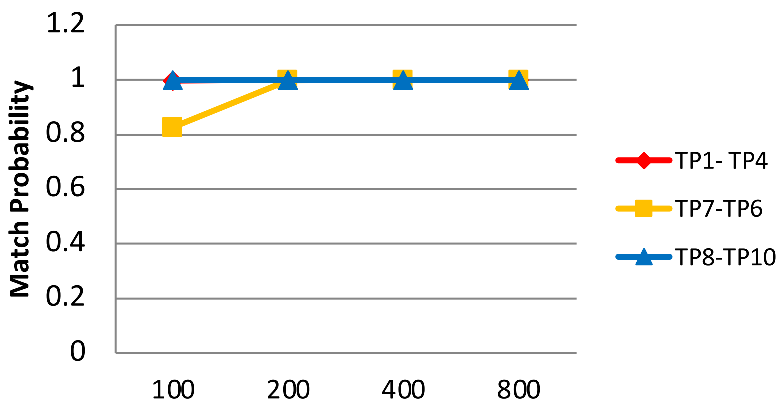
TiF Matching



Measurement (1)

- Evaluation method
  - Synchronize master and slave using GPS for ground truth
  - Metric: probability of correct matching
  - Find length of TiF to “ensure” no matching errors





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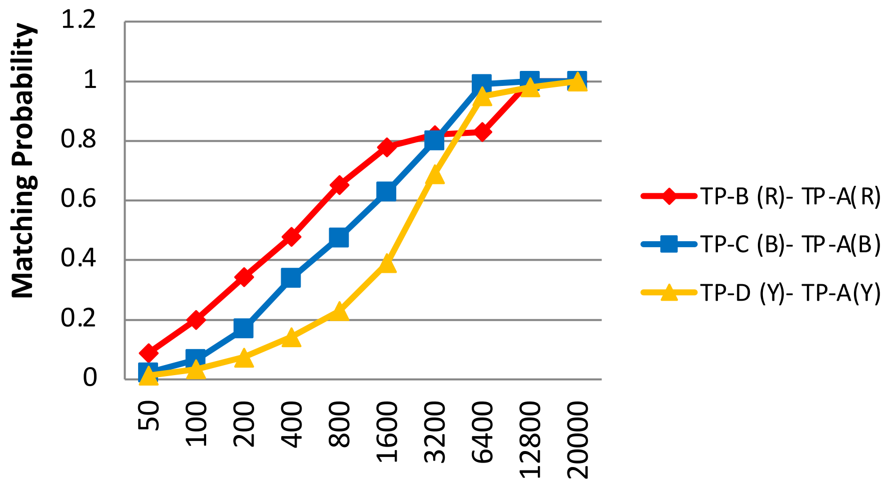
TiF Length

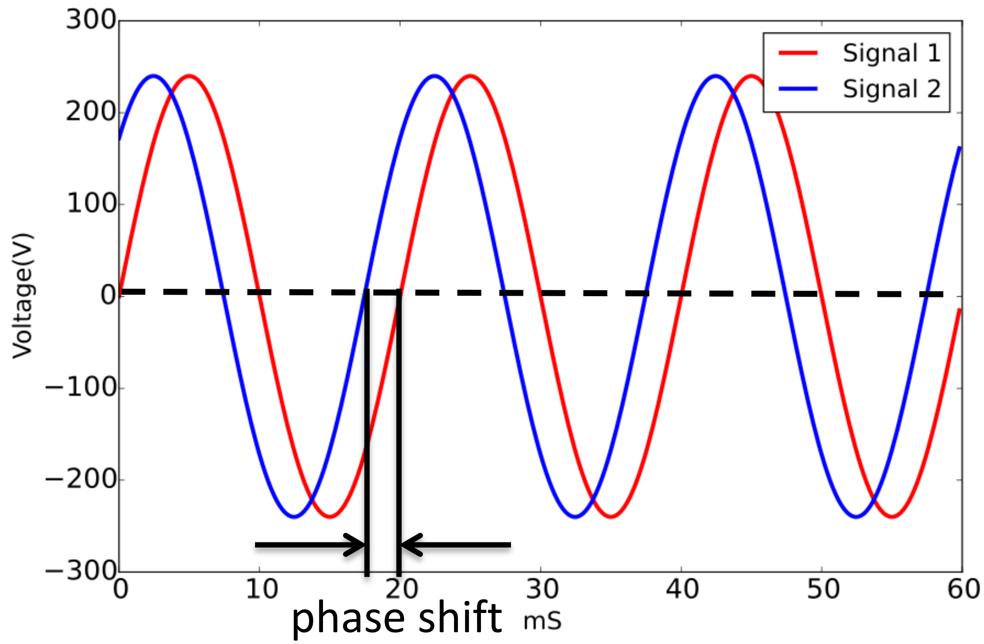
Measurement (2)



TiF Length

TiF Length

Synchronization Accuracy

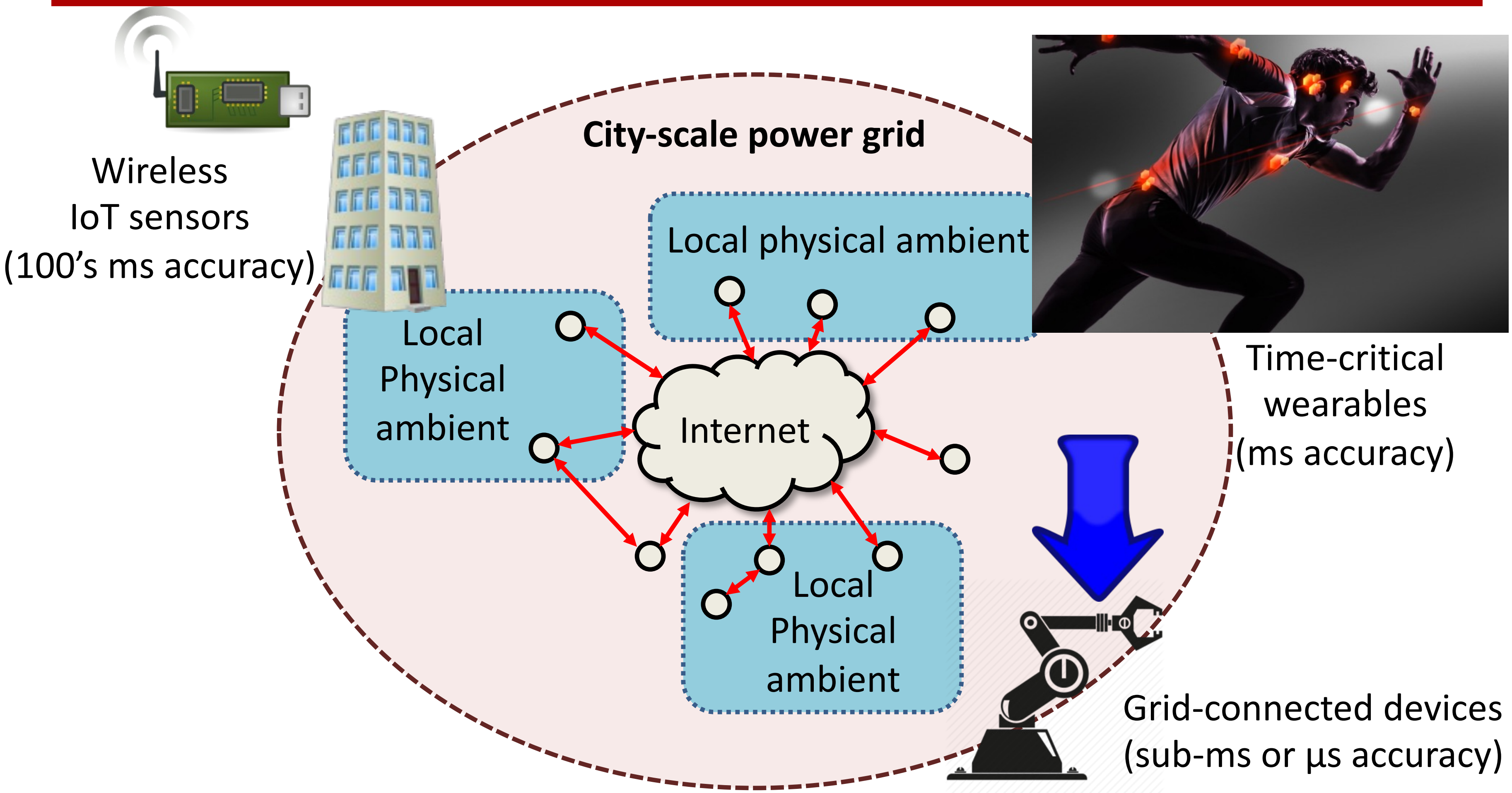


- 10 km
  - 100 μs
- Within same building
  - 10 μs

Summary

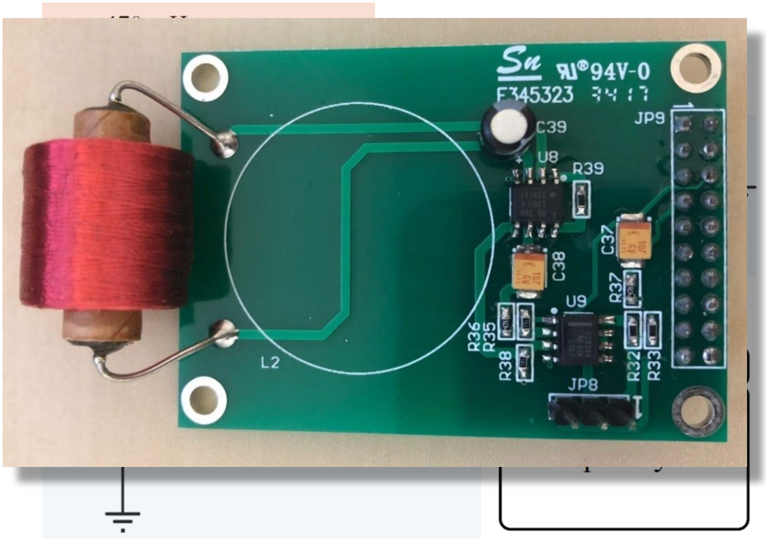
- Our approach
  - Use **imperfections** of periodicity
  - Address packet delay attack

Accurate & Secure Time in a City

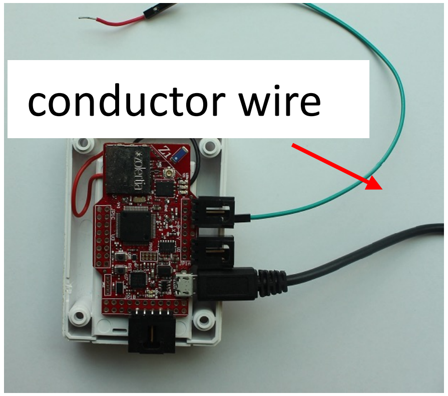


Extension to Electromagnetic Radiation (EMR)

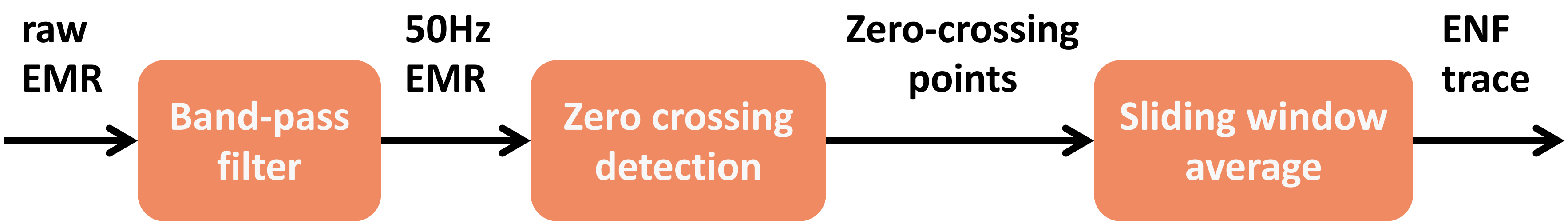
- Customized sensor
  - Raspberry Pi
  - Audio card @ 44.1kHz
  - ***A tank circuit + conditioning***

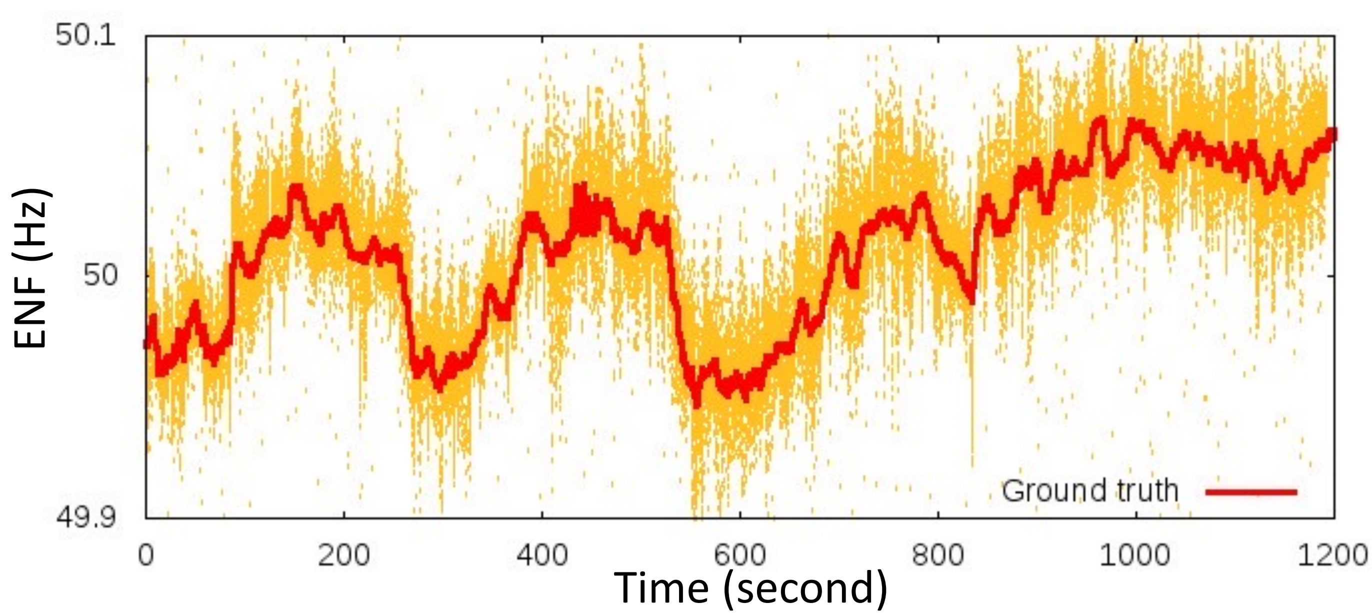


- Off-the-shelf mote
  - Z1 (MSP430)
  - Built-in ADC @3.7kHz
  - Antenna: ***conductor wire***



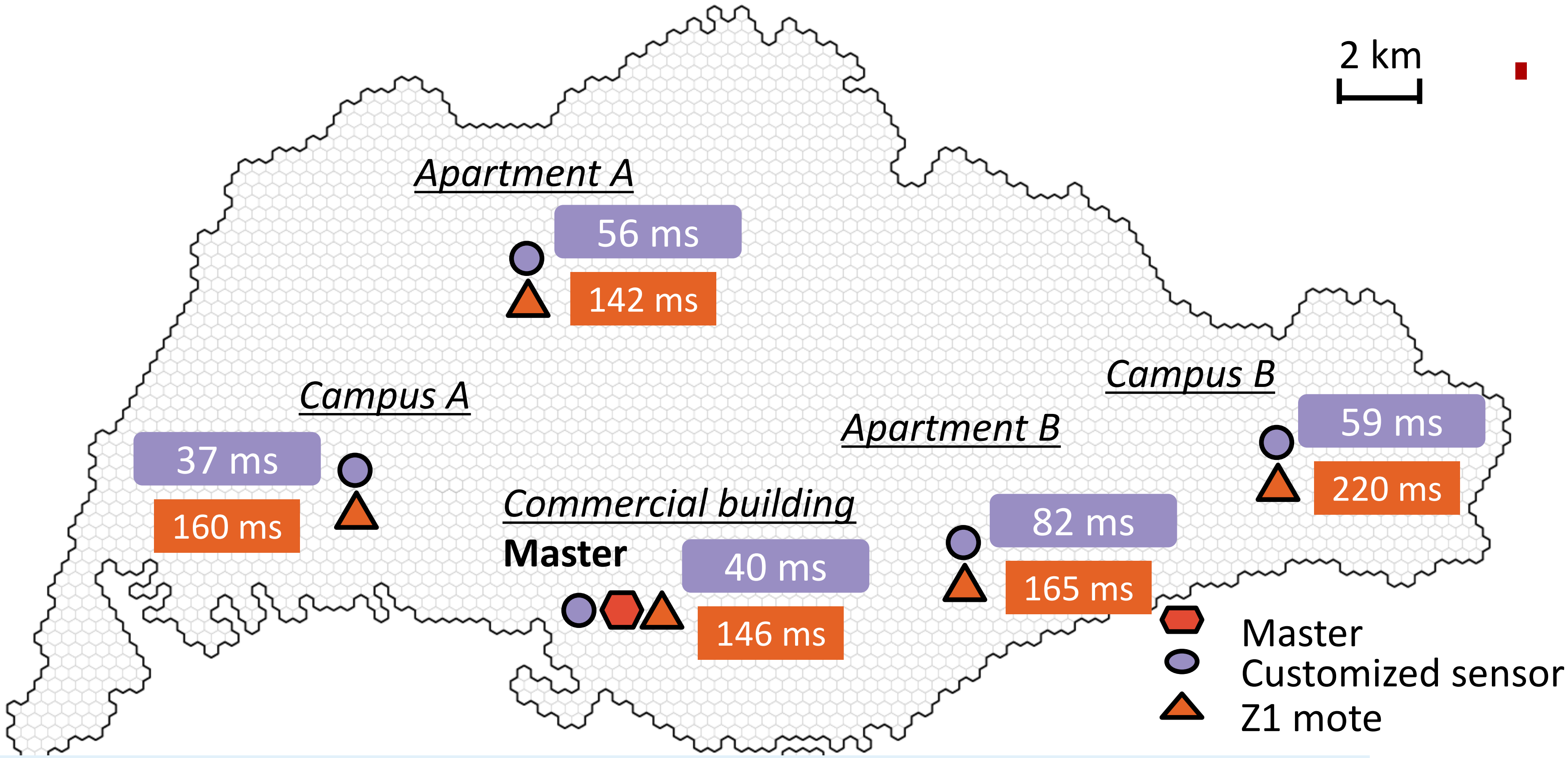
ENF-based TiF Extraction





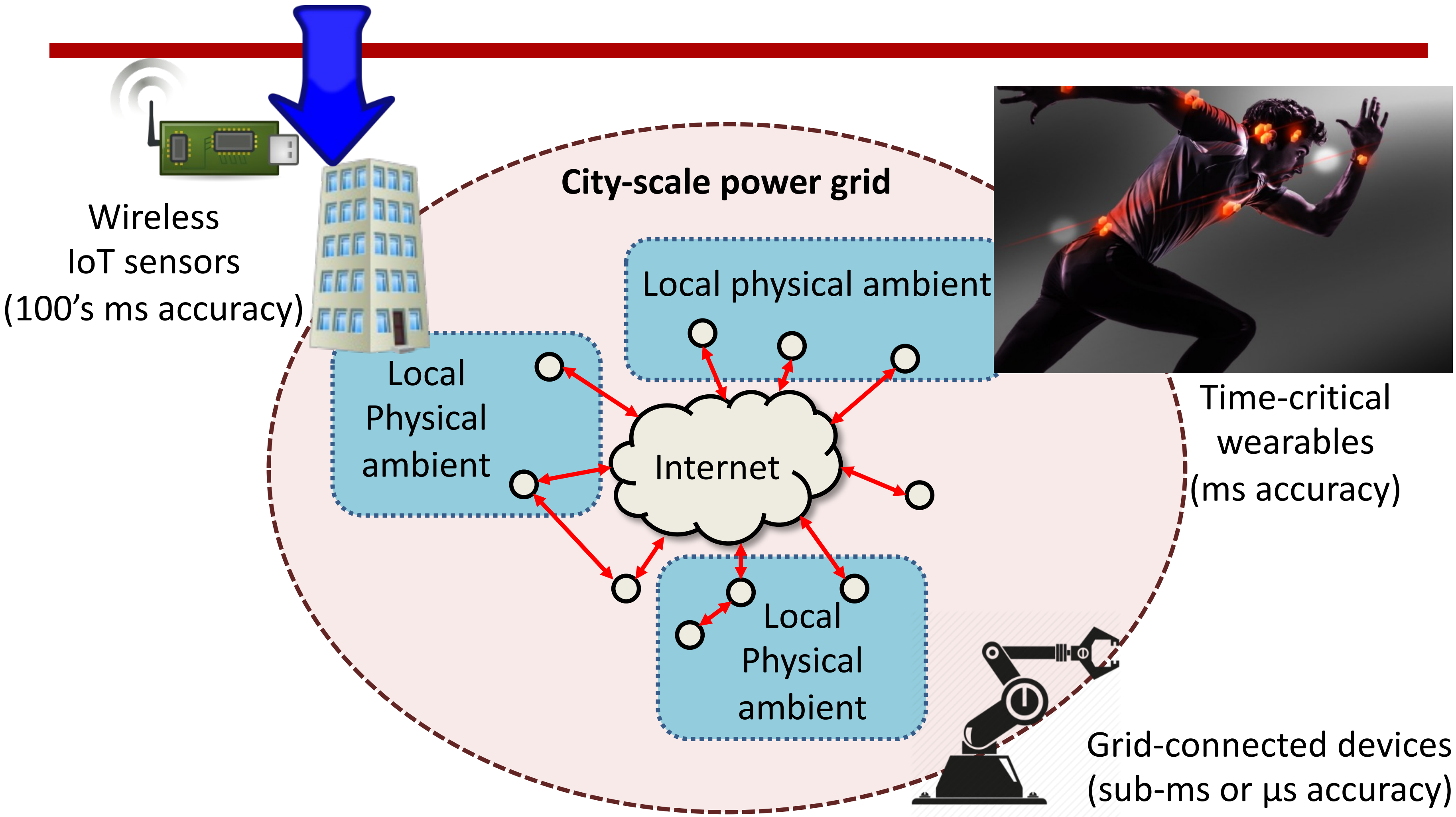
Mean error = 0.0007 Hz RMSE = 0.044 Hz

Evaluation in Singapore



- Numbers: median decoding errors
- Customized sensor gives **lower decoding error**
- **No significant impact** of distance on decoding error

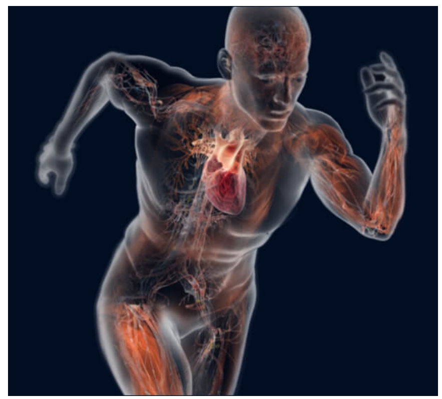
Accurate & Secure Time in a City



NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Tight Clock Sync for Wearables

Synchronized audio Streams [PATENT US 20150092642 A1]



Muscle fatigue & activation monitoring [UbiComp’15, IPSN’16]

(Multi-user) gaming [atomicbands]

Universal Clock Sync for Wearables

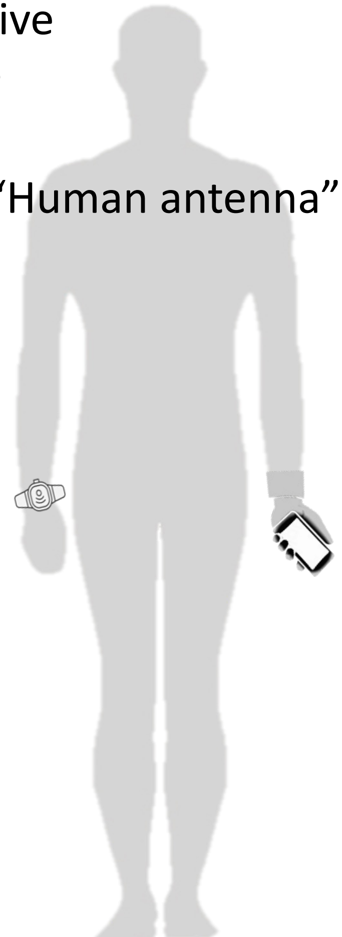
Highly customized
for certain hardware

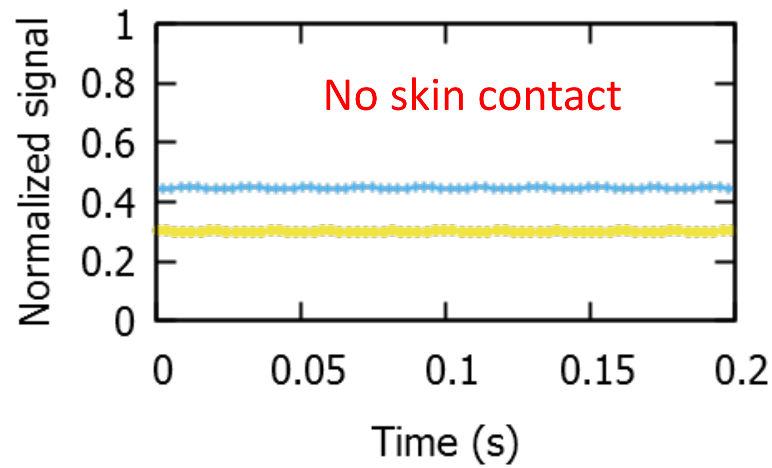
vs.

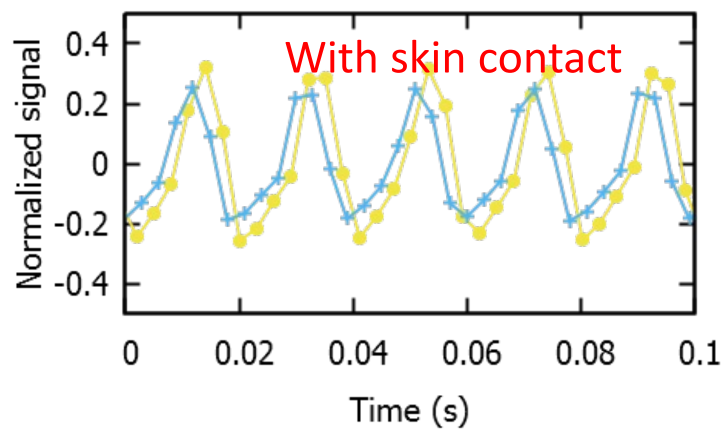
Diversified platforms

As Apps developers, can we tightly sync diversified wearables?

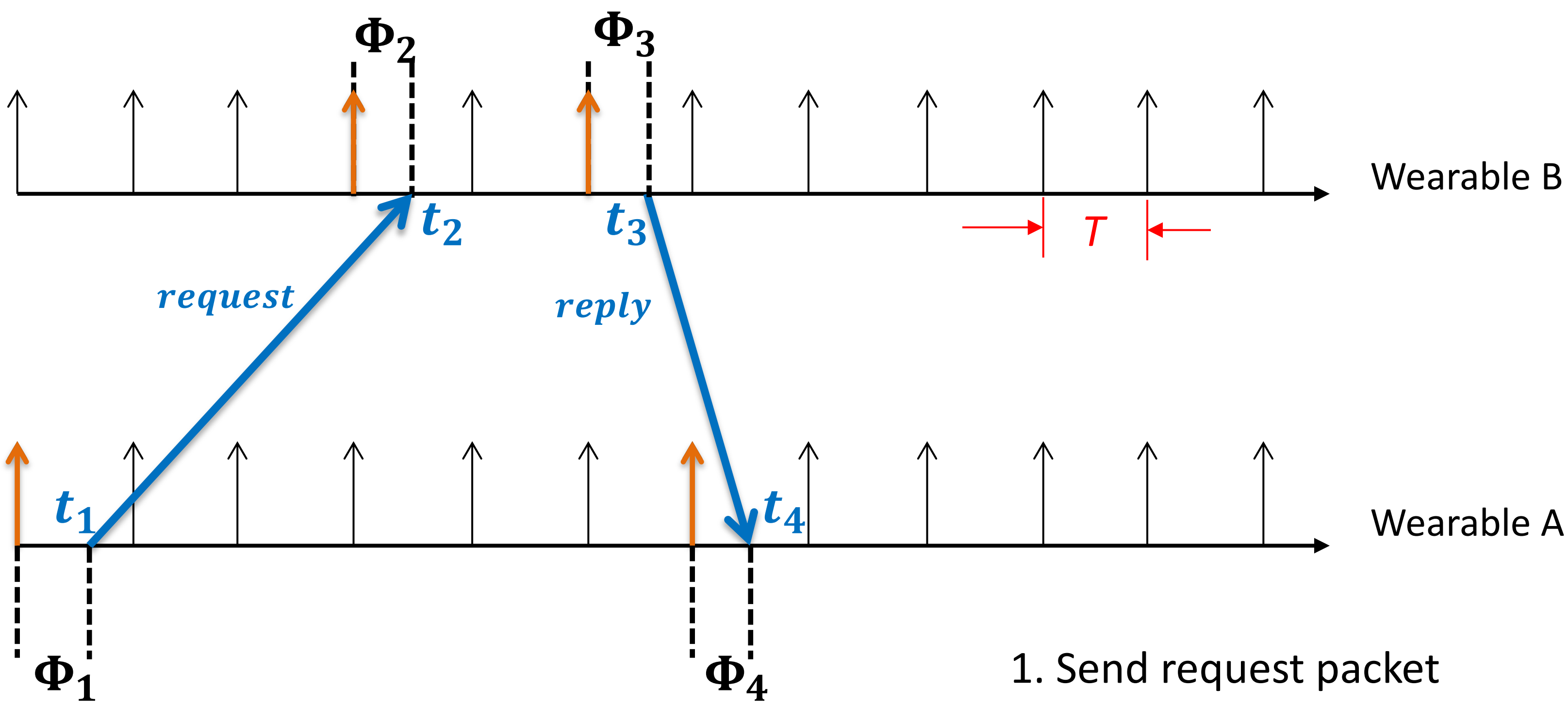
Human Antenna Effect





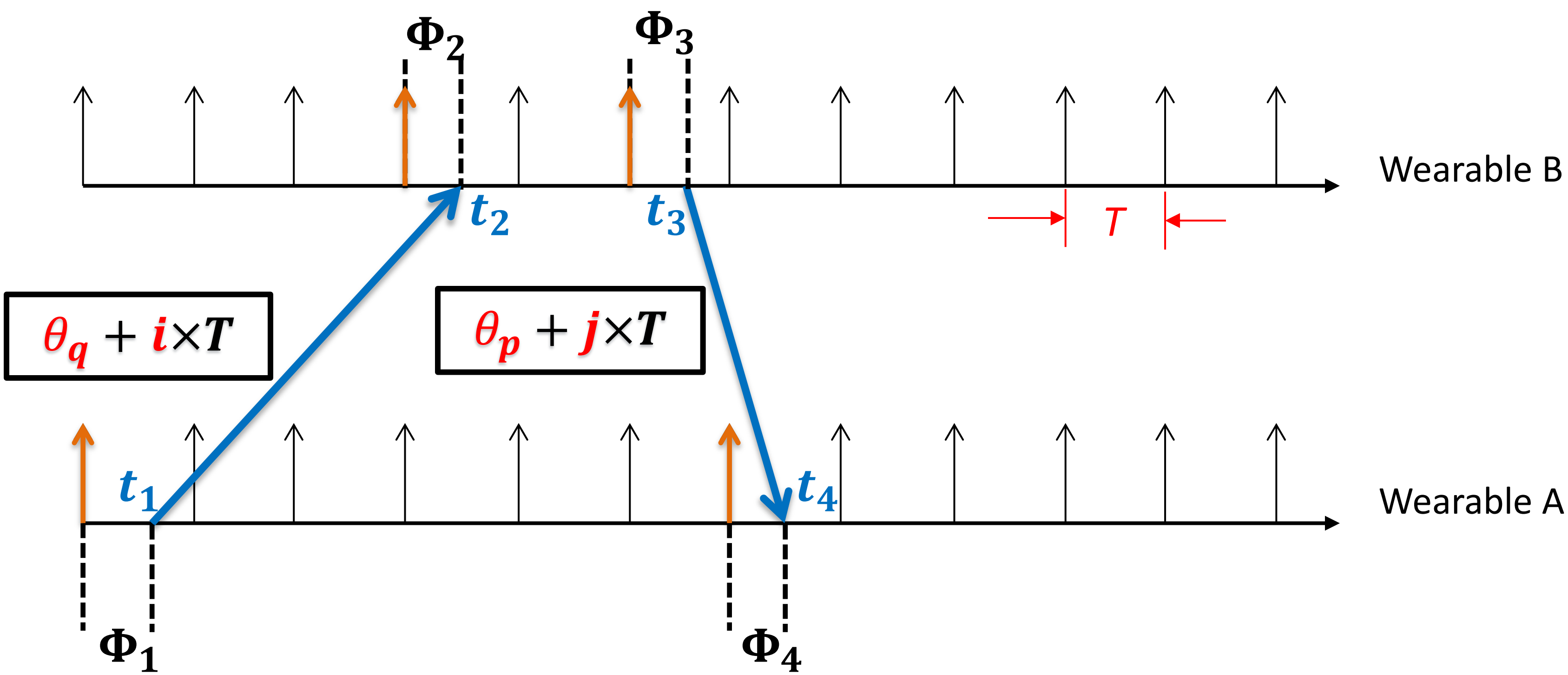


TouchSync: Protocol



1. Send request packet
2. Send reply packet
3. Compute phases

TouchSync: Phase Difference

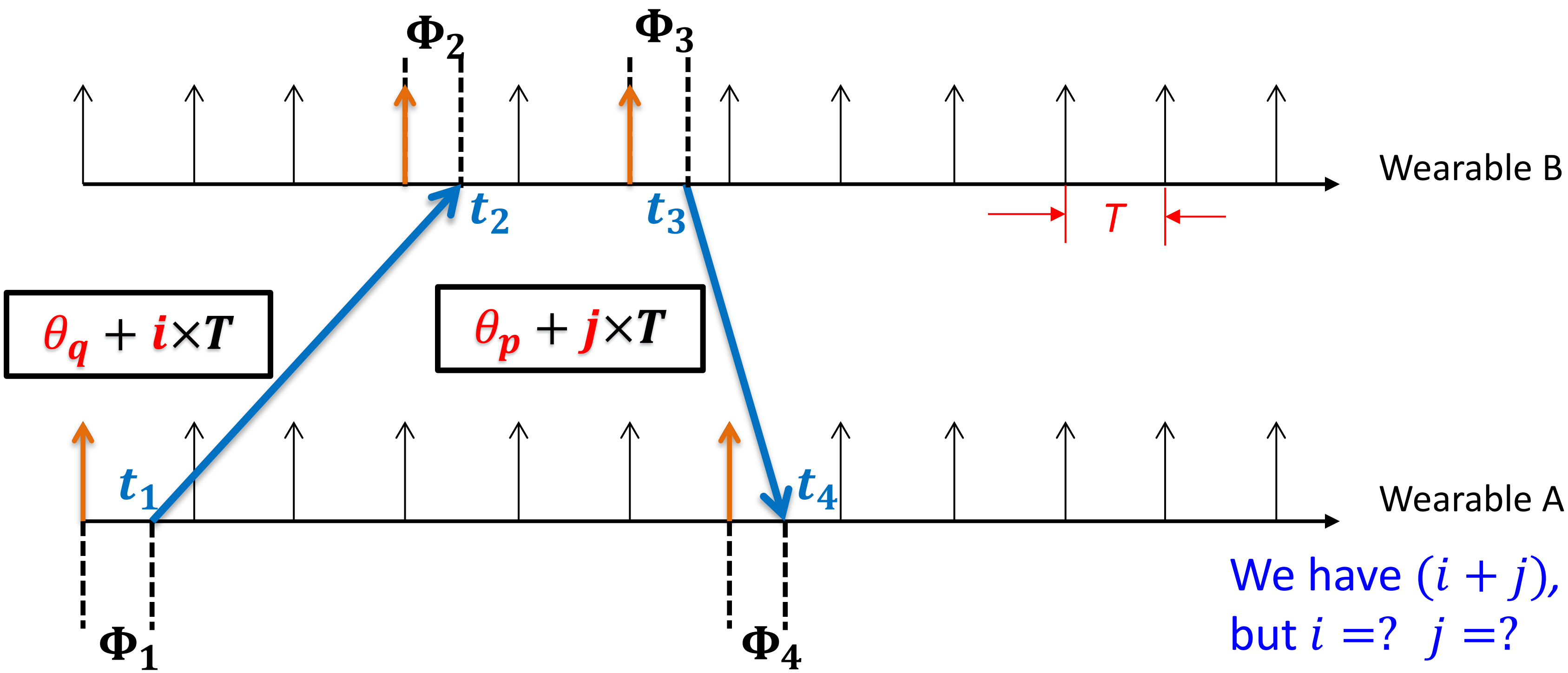


Phase difference during fly:

Request message: $\theta_q = \Phi_2 - \Phi_1$

Reply message: $\theta_p = \Phi_4 - \Phi_3$

TouchSync: Integer Ambiguity

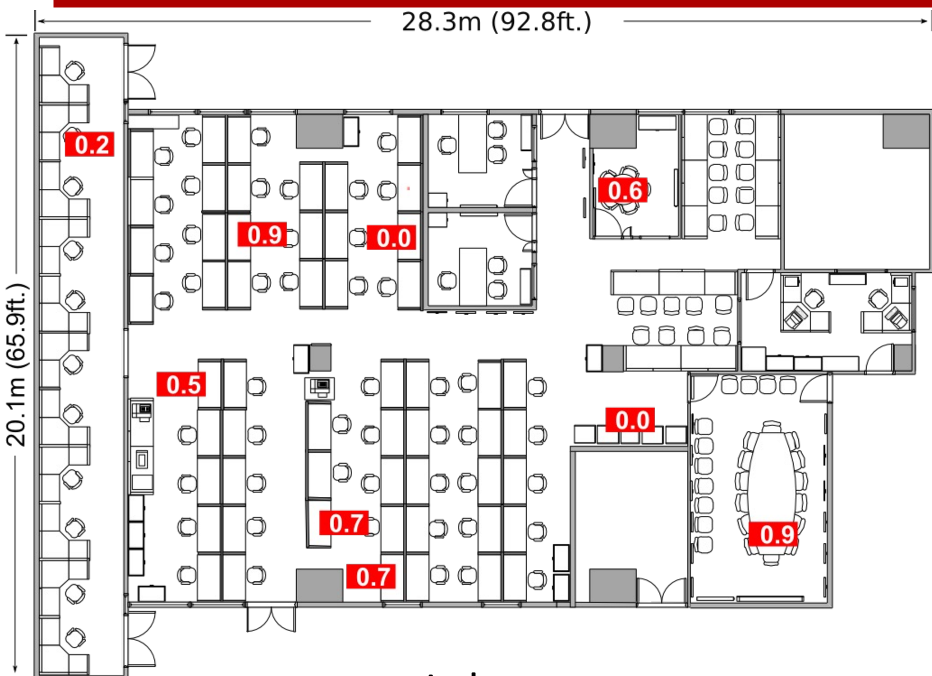


We have $(i+j)$,
but $i = ?$ $j = ?$
(Integer Ambiguity)

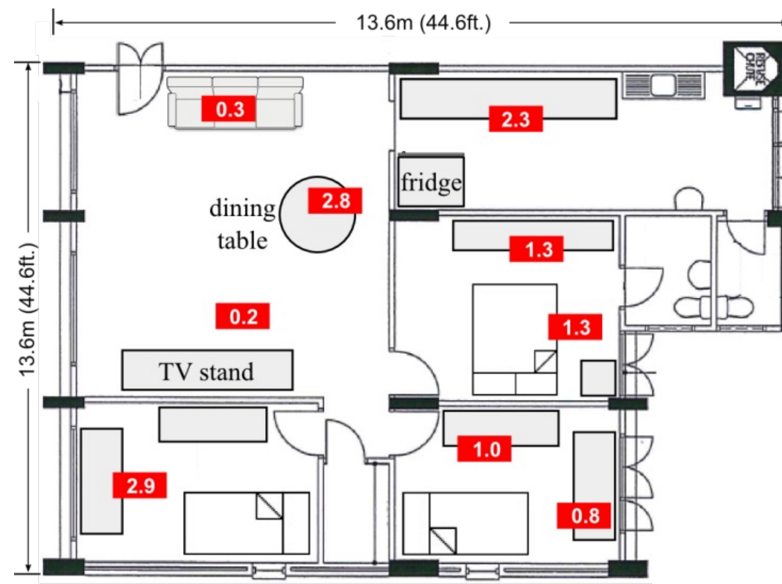
Round Trip Time (RTT) $= (\theta_q + \theta_p) + (i + j) \times T = (t_4 - t_1) - (t_3 - t_2)$

Solve ambiguity by multiple rounds of sync with clock offset as common unknown

TouchSync on Same Body



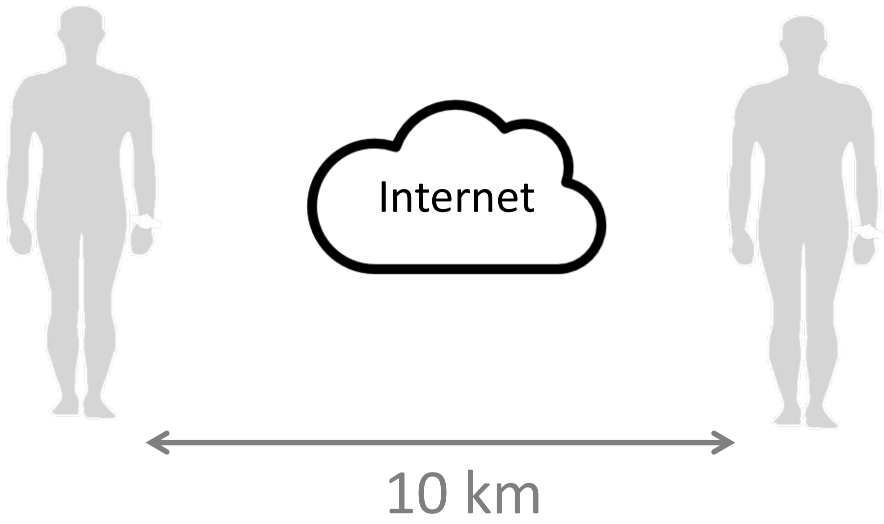
Lab



Home

- Lab, home, office, corridor
  - 51 experiment positions
- Average error: **0.78 ms**

TouchSync over Internet



- Settings
  - Communication over a ngrok tunnel
  - Each wearable synchronized to a local GPS receiver for groundtruth
- Sync error ≤ **7 ms**

Summary

- Use power grid properties for resilient time
  - Power socket: sub-ms accuracy *[RTSS'16]*
  - EMR: sub-s accuracy *[IPSN'17]*
  - Skin electric potential: ms accuracy *[SenSys'17]*

[RTSS'16] Sreejaya Viswanathan, Rui Tan, David Yau. Exploiting Power Grid for Accurate and Secure Clock Synchronization in Industrial IoT.

[IPSN'17] Yang Li, Rui Tan, David Yau. Natural Timestamping Using Powerline Electromagnetic Radiation.*

[SenSys'17] Zhenyu Yan, Yang Li, Rui Tan, Jun Huang. Application-Layer Clock Synchronization for Wearables Using Skin Electric Potentials Induced by Powerline Radiation.