Mobile and Ubiquitous Computing
2022-2023
MEIC/METI - Alameda & Taguspark

Location I & II

Contents

- Basic definitions
- GPS and Differential GPS
- Infrared and ultrasonic
- Wi-Fi and Cellular
- Others
- Location-Based Applications and Services
- Challenges and opportunities

Type of location solutions:
- Triangulation, ToF, AoA, etc.
- Proximity
- Scene analysis (fingerprinting, modelling)

Introduction

- Location is at the core of a number of **high-value applications** including:
  - emergency response, navigation, asset tracking, ground surveying, and many others

- The **market for GPS products and services** alone was aprox. **US$200 billion in 2015**

- **Location** is also commonly used to **infer other contexts**:
  - **symbolic location** is often a good **proxy for activity** (e.g., grocery store is indicative of shopping)
  - **social roles and interactions** can be learned from **patterns of colocation**, and
  - **physical activities and modes of transportation** can often **be inferred from the changes in coordinate-based location**

Basic Definitions

- Location:
  - **symbolic** - symbolic location encompasses abstract ideas of where something is: kitchen, room 609, on a train arriving at Lisbon, etc.
  - **physical** - physical location provides coordinates such as latitude and longitude

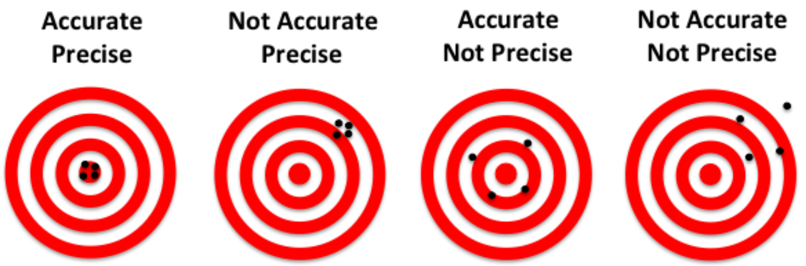
- Accuracy and Precision:
  - some inexpensive GPS receivers can locate positions to within 10 meters for approximately 95 percent of measurements.
  - **correction is accuracy.**
  - **variability is precision.**

- To assess the **scale of a location system**, we consider:
  - its **coverage area per unit of infrastructure**, and
  - the **number of objects the system can locate per unit of infrastructure per time interval**

- Infrastructure **cost**

- Per-client **cost**

- Privacy:
  - location of a user is **obtained locally or on a central service.**



Outdoor Location: GPS

GPS Context (1/2)

- NAVSTAR Global Positioning System (GPS) is by far **the most widely** used outdoor location technology.
- It is estimated that in 2020, the number of **GPS chipsets** approached **three billion**
- Dates:
  - the U.S. Department of Defense **approved the project in 1973**
  - the system was declared **fully operational in 1995**
  -
- Cost:
  - **development** of GPS has been reported at **$14 billion**
  - its **annual operation** and maintenance cost is estimated at **$500 million**
  -
- It is a **passive one-way** ranging system where all signals are transmitted by earth-orbiting **satellites**, and **position determination happens at the receivers**
- It provides:
  - worldwide coverage
  - scales to an unlimited number of users,
  - preserves user privacy
  - supports a range of location services with accuracies that range from several meters to a few millimeters

GPS Context (2/2)

- Different types of GPS receivers vary in pricing:
  - from a **hundred dollars** for an inexpensive mass market model, to
  - tens of **thousands of dollars** for the more accurate kinematic solutions used for land surveying

- GPS was designed as a dual-use technology for both **military** and **civilian** use:
  - to maintain an accuracy advantage for the military, the original GPS design included a feature known as **Selective Availability**
  - it added **intentional noise** to the signals to degrade the accuracy of civilian GPS models

- Shortage of military-grade GPS receivers during the first Persian Gulf War in **1991**:
  - the U.S. Pentagon **disables Selective Availability** for the duration of the war,
  - and used **civilian receivers** to make up the shortfall

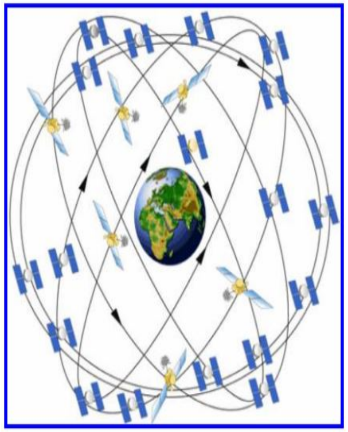
- Selective Availability was:
  - permanently **discontinued in May of 2000**, and
  - in **September 2007**, the U.S. Government announced its decision to **eliminate the feature** from future GPS satellites

- In December of **2004**:
  - the U.S. government reiterated its commitment to provide **GPS access free of direct user fees** for civil, commercial, and scientific uses

Architecture (1/3)

- It consists of three distinct parts:
  - a constellation of Earth-orbiting **satellites** that broadcast a continuous ranging signal,
  - **ground stations** that update the satellites' coordinate projections and clocks and,
  - the **receivers** that use the GPS signals to estimate their position

- Earth-orbiting satellites:
  - **31 satellites** organized into **six non-geostationary circular orbits** 26,560 km above the Earth with a **12-h period**
    - full GPS coverage requires **24 GPS satellites**
    - the **additional satellites** operate as **active spares** to **accommodate occasional maintenance downtime** and to assure **system robustness**



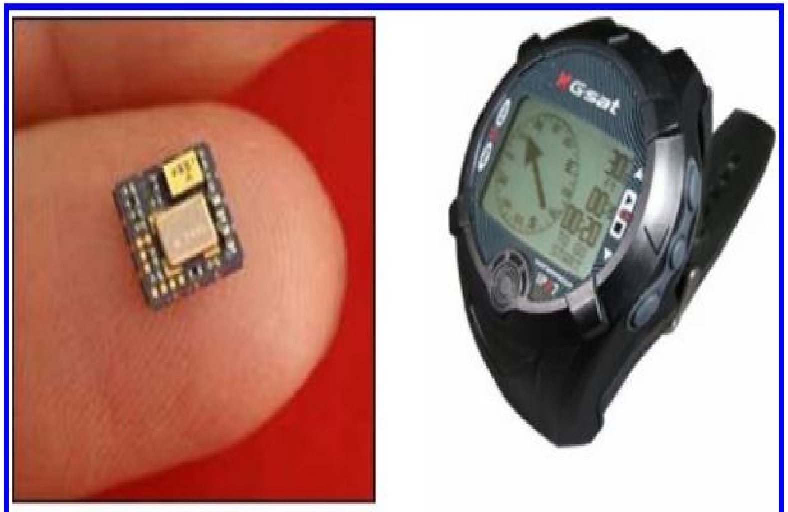
Architecture (2/3)

- Ground stations:
  - responsible for **monitoring satellite positions** and providing satellites with **clock corrections and satellite orbit updates**
  - there are enough ground monitoring stations to allow **each satellite to be simultaneously tracked by at least two monitoring stations**
  - simultaneous satellite tracking improves the precision of orbit calculations **increasing localization accuracy**

Architecture (3/3)

- GPS receivers:
  - determine their position by **simultaneously tracking at least 4**, but commonly up to 12, satellites
  - can be **augmented with other sensors** (e.g. altimeters, accelerometers, and gyroscopes) to compensate for gaps in GPS coverage

- Receivers:
  - the original mobile units tested by the **U.S. Army in the 1970s weighed approx. 12kg** and filled a backpack
  - today, typically around the **size of a cell phone**, and new single chip GPS implementations have made form factors as small as a wristwatch as possible

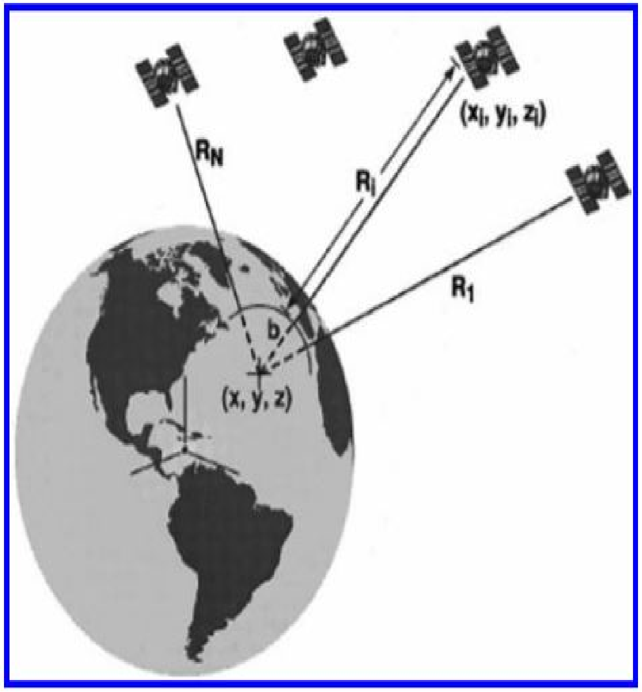


(a) (b)

Algorithm (1/3)

- Supported by all GPS receivers and allows the receiver to:
  - **estimate its position in three dimensions** (latitude, longitude, altitude)

- Location estimated:
  - computed from the **estimated positions of the satellites** and the **ranges from the receiver to those satellites**
  -



- **Satellite locations are learned from the broadcasts from the satellite**:
  - **Ri is the distance between the receiver and satellite i,**
  - it is inferred by measuring the **transit time of the signal between the satellite and the receiver and multiplying by the speed of light**

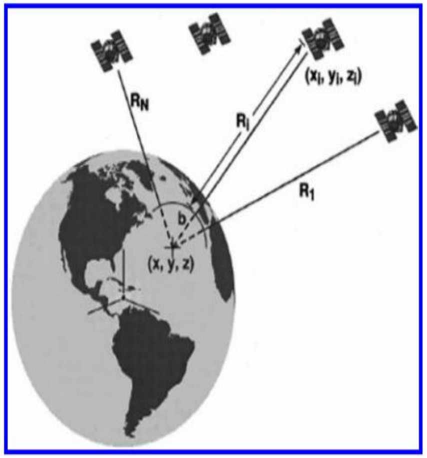
Algorithm (2/3)

- Measuring the signal transit time accurately requires:
  - the satellite and receiver's **clocks to be tightly synchronized**
- In practice, the use of **low-cost crystal oscillators in the receiver** introduces:
  - a bias that makes the distance from the satellite appear **shorter or longer than the real value**
  - the receiver-induced bias will be the **same across all of the satellites**
  - **satellite** induced clock bias is less of an issue because of their **extremely accurate atomic clocks**
  - thus, the effect of the **receiver's clock bias can be removed** by treating it as an extra unknown in the location calculation

Algorithm (3/3)

- The **receiver's location** in three-dimensional space (x, y, z) and **receiver clock bias b** is determined by solving the following equation for at least four satellites (just three satellites would be required with perfect clocks):

$$R_i = \sqrt{(x_i - x^2) + (y_i - y)^2 + (z_i - z)^2} - b$$



It requires at least **four satellites** (as opposed to the **three satellites that would be required with perfect clocks**)

- In cases where more than four satellites signals are available to the receiver:
  - the **redundant data** is used to try to **identify and eliminate error** in the location estimate

- Commercial GPS units using this basic algorithm estimate location with **median accuracy of around 10 m**

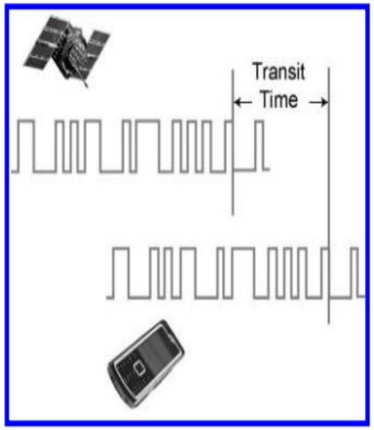
Algorithm - Satellite Range Estimation

- To allow the **distance between the satellite and the receiver** to be estimated:
  - GPS satellites **transmit radio signals modulated** by pseudorandom noise **(PRN) codes**,
  - such codes consist of **binary sequences** that appear to be randomly generated but are **specific** to each satellite and **known** by the receiver.

- GPS receivers continually **compare the signals they are receiving** with a **locally generated replica of the satellite's PRN code**:
  - the time **delta between the received signal and the local PRN code** represents the **signal's travel time**
  - range is computed by simply **multiplying the travel time by the speed of light** (299,729,458 m/s)

- The use of orthogonal PRN codes allows all GPS satellites to use the same frequencies:
  - while still allowing receivers to differentiate their transmissions
  - and tracking them in parallel

- The **theoretical accuracy of GPS** ranging is:
  - **3 m** for the civilian
  - **0.3** m for the military



Algorithm - Satellite Coordinate Estimation

- The GPS receiver obtains the satellite's coordinates from a **navigation message** which is also modulated on 1,575 and 1,227 MHz signals

- The **message is encoded within the PRN** code at the low bit rate of 50 bits per second

- The navigation **message is 37,500 bits long** and **takes 12.5 min to transmit**

- The **message contains all of the relevant information** about the GPS constellation:
  - the coordinates of the satellites as a function of time,
  - satellite clock correction parameters,
  - a satellite directory,
  - constellation health status, and
  - parameters for ionospheric error correction

- To speed location calculation at the GPS receiver:
  - the **satellite coordinates and clock offset are repeated** in the navigation message **every 30s**

Errors and Biases – Ranging Errors

- Satellite's **atomic clocks are very stable**:
  - Still can **accumulate up to 17 ns of error per day**, which translates to a **range error of 5 m**
  - To correct for this, the **satellite clock is continually monitored by the ground monitoring stations**, and **clock corrections are periodically transmitted**

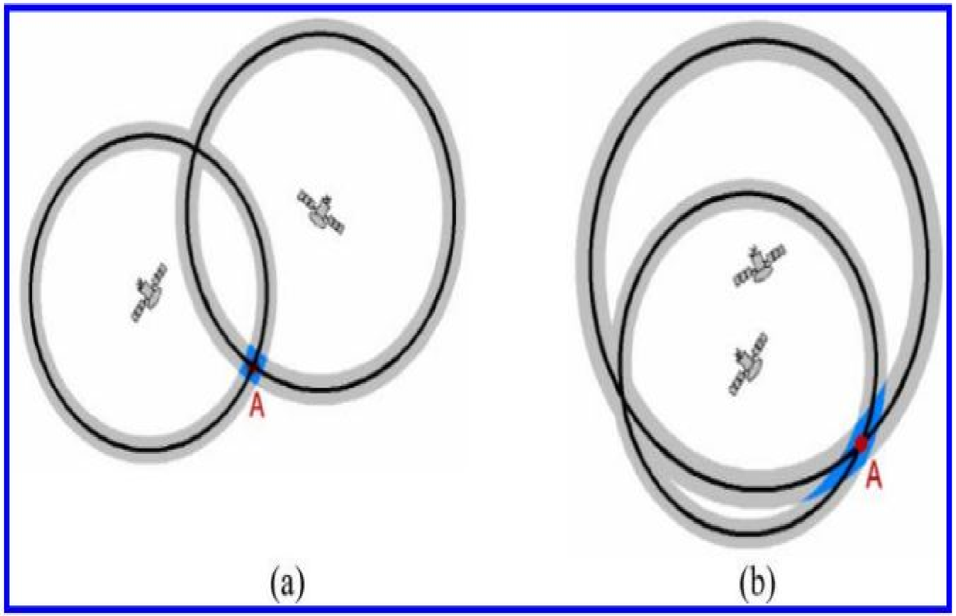
- **Satellite coordinates errors**:
  - On the order of **2 m**
  - Result of the **failure of the satellite position models** to account for all forces acting on the satellite
  - This can be **eliminated almost completely** by using precise orbit data (accurate within a few centimeters) that is made available over the Internet

- Ionospheric delay is the dominant source of GPS ranging error:
  - Interaction of the GPS signal with ionized gases in the upper atmosphere,
  - **Varies** with **time of day**, **time of year**, **solar flare activity**, and the **angle of entrance of signal** that affects the length of the path through the ionosphere
  - **Models** of ionospheric delay have been developed, leaving a **residual delay with a 4-m mean**

Errors and Biases – Satellite Geometry Errors

- The quality of the GPS location estimation depends on:
  - how well the tracked **satellites are spread across the sky**, and
  - in general, **satellite geometry improves as the distance between satellites increases**

- The **size of the uncertainty area** where the receiver could be located **decreases**, as the **distance between the satellites increases** (see blue bands in the figure)



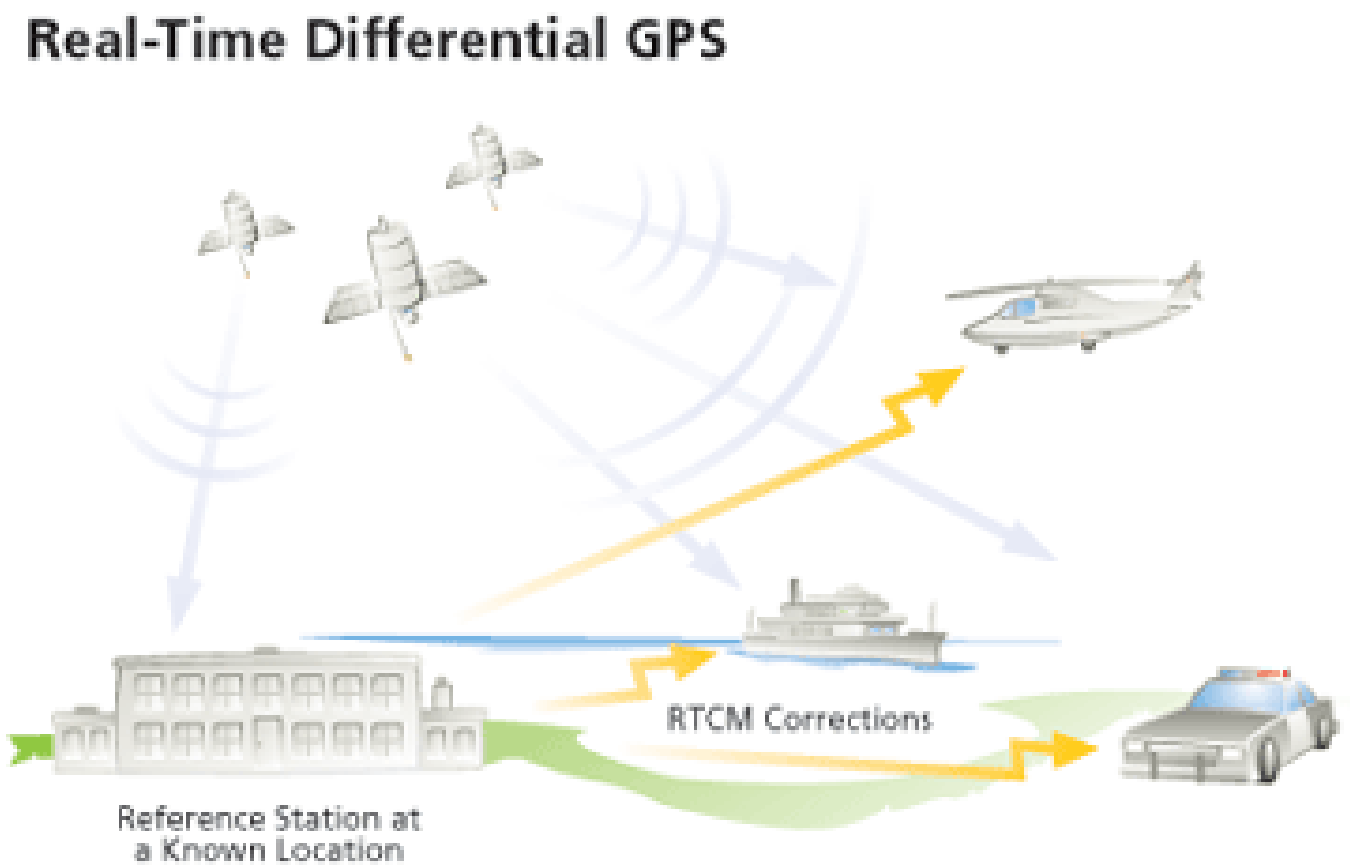
GPS Drawbacks

- Accurate GPS localization **requires an unobstructed view of at least four satellites**

- GPS signals do not penetrate well through walls, soil, and water:
  - thus, the system **cannot be used inside buildings**, **underground** (e.g., inside a mine or tunnel), or for **subsurface marine navigation**

- Signal can also be obstructed by large buildings in the so-called **urban canyons**

Real-Time Differential GPS



Main Idea of Differential GPS

- **Differential GPS takes advantage** of the fact that
  - satellite clock and coordinate **errors**, as well as ionospheric and tropospheric **delays** exhibit **high temporal and spatial correlation** and are **very similar even hundreds of kilometers apart**

- Thus, differential techniques **take advantage of this** by:
  - coordinating **multiple GPS receivers that simultaneously track the same satellites**
  - by having **one or more GPS receivers fixed at known positions**, the observed **errors** from those receivers **can be transmitted to nearby roving GPS receivers**
  - these **roving units are then able to reduce their error** in proportion to their proximity to the site at which the correction was measured

Real-Time Differential GPS

- Real-time differential GPS (**DGPS**) is a:

relative positioning technique that provides **sub-meter accuracy**

A fixed receiver determines the DGPS corrections by **comparing its measured satellite ranges** with ranges computed using its **known coordinates** and **the satellite coordinates** obtained from the **navigation message**

The **DGPS corrections are then transmitted** over a ground- or satellite-based wireless link to the rover

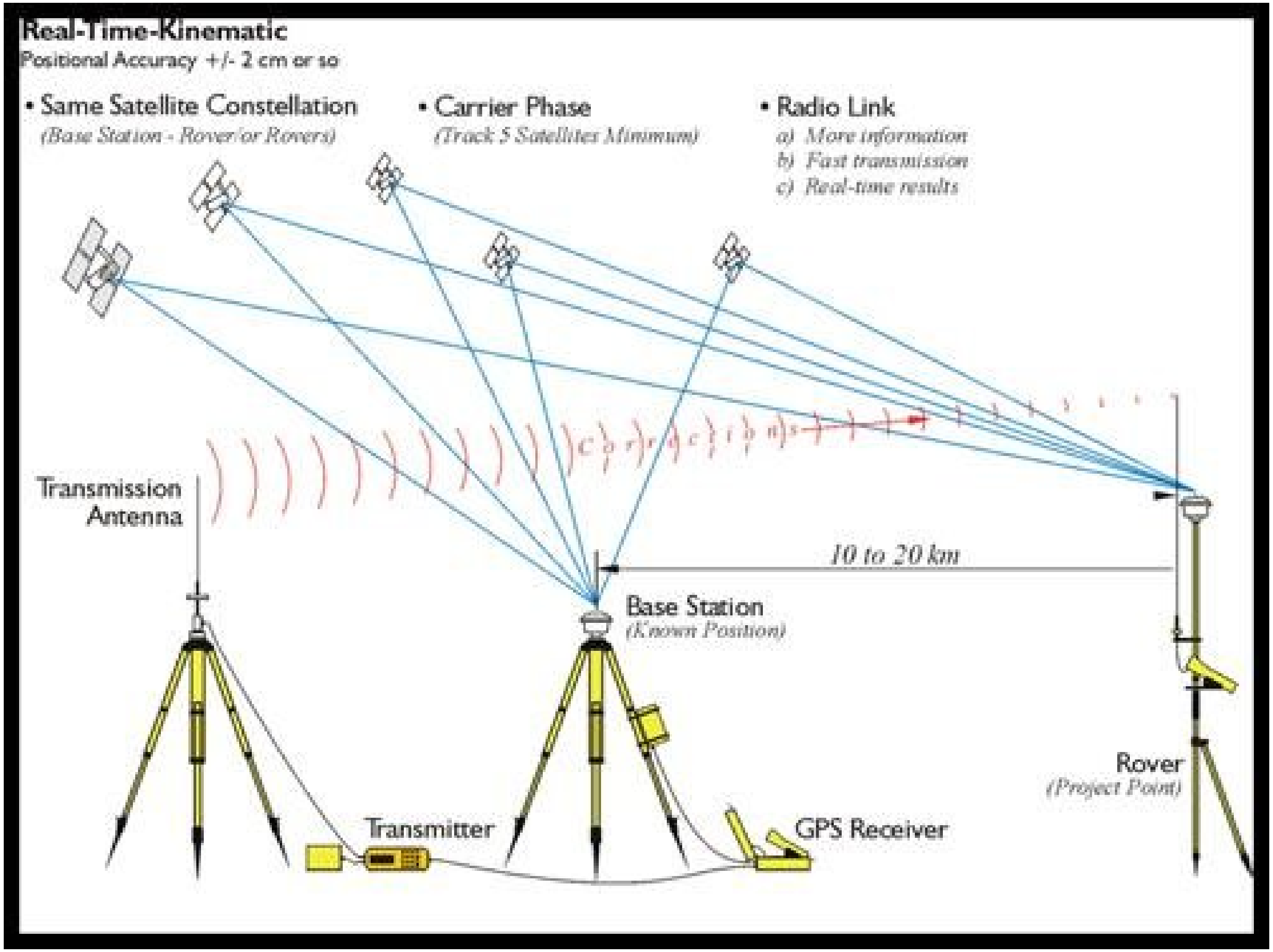
The **rover uses them to adjust** its ranging measurements

DGPS is offered both as a local and a wide-area service

Real-Time Differential GPS – examples

- Maritime DGPS:
  - it consists of a **network of stations installed at lighthouses along coastal areas** in several countries around the world
  - each station operates by independently **broadcasting real-time DGPS corrections** (285- to 325-kHz frequency band)
  - these corrections are **available at no cost**, but **require a GPS receiver augmented** to receive the corrections
  -
- Wide Area Augmentation System (WAAS):
  - it is a wide-area DGPS implementation that determines GPS range errors at **25 ground base stations**
  - these corrections are **broadcast from four geostationary satellites**
  - measurements from 27 U.S. airports show that WAAS provides **accuracy of 1.8 m at least 95%** of the time
  -
- Others:
  - European Geostationary Navigation Overlay System (EGNOS)
  - Japan’s Multifunctional Transport Satellite Augmentation System (MSAS)
  - India’s GPS and GEO Augmented Navigation (GAGAN)

Real-Time Kinematic GPS



Real-Time Kinematic GPS

- GPS variant that achieves **centimeter accuracy**
- It uses an **alternative technique for satellite ranging**:
  - it is based on **measuring the number of fractional and full signal cycles** that happen between the satellite and the receiver
  - the range is then **computed by multiplying this value by the carrier's wavelength**
  - while the fraction of the last cycle is easy to determine, the **number of full cycles is ambiguous**
  - this ambiguity can be resolved by taking **simultaneous measurements at two receivers** (there are several techniques)
- After receiving the **base's coordinates and measurements** and **resolving the ambiguity**:
  - roving RTK receivers obtain **centimeter-level positioning accuracy**
- RTK is used in applications that require **extreme accuracy**:
  - surveying, aircraft landing, and maritime construction
- High-end RTK systems cost **tens of thousands of euros** and **require line of sight between the coordinating GPS receivers**

Comparison

☆☆☆★ worst

☆☆★★

☆★★★

★★★★ best

Technology	Basic GPS	GPS + WAAS	Real-time Kinematic GPS
Accuracy	★★☆☆ 3D coordinates with 10 m median accuracy	★★★☆ 3D coordinates with 2 m median accuracy	★★★★ 3D coordinates with 10 cm accuracy
Coverage	★★★☆ Outdoors with clear view of 4+ GPS satellites	★★☆☆ Outdoors in USA — Requires clear view of 4+ GPS satellites and a WAAS satellite	★☆☆☆ Outdoors with 4+ GPS satellites and requires line-sight between mobile unit and surveyed unit
Infrastructure cost	★★★★ $14 B US initial cost + $500 M US yearly for global coverage	★★★★ WAAS satellites needed in addition to GPS constellation	★☆☆☆ Beyond GPS constellation, requires calibrated, surveyed ground unit
Per-client cost	★★★☆ GPS antenna and chipset required	★★★☆ GPS antenna and WAAS-capable chipset required	★☆☆☆ Special RTK unit required
Privacy	★★★★ Location is estimated passively on the GPS unit	★★★★ Location is estimated passively on the GPS unit	★★★★ Location is estimated passively on the GPS unit
Well-matched use cases	Outdoor navigation for land, sea and air, emergency response, turn-by-turn driving directions, outdoor mapping/information/tour guide services, personell/pet tracking, fitness/activity tracking, gaming	Outdoor navigation for land, sea and air, emergency response, turn-by-turn driving directions, outdoor mapping/information/tour guide services, personell/pet tracking, fitness/activity tracking, gaming	Outdoor navigation requiring extreme accuracy, surveying, aircraft landing, maritime construction

Indoor Location: Infrared and Ultrasonic Location Systems

Infrared and Ultrasonic Location Systems

1) Active Badge
2) Walrus
3) Cricket
4) Active Bat

Introduction (1/2)

- **Light and sound**:
  - move freely in open space.
  - are both largely **blocked by the materials** such as walls, curtains, and partitions that humans use to define the borders of their living spaces.

- These two types of signals are **well suited for indoor location systems**:
  - they can determine **which room a user is** in with high accuracy.

- High relevance of room-level location information for many **context-aware applications and services**:
  - While applications like navigation require absolute locations,
  - many others rely instead on the semantics associated with a room name or room type.
  - A location system with a median accuracy of 0.5 m may seem more desirable than a system which is only able to determine which room a user is in.
  - However, you may rethink this assessment once you consider that the former system may incorrectly infer that the user is in the adjoining kitchen 25% of the time, when in fact they are in the hallway.

Introduction (2/2)

- Possible indoor location approaches:
  - use **infrared or ultrasound beacons and listeners** to determine a location
  - the **beacons may be embedded in the environment**, and the **listeners remain mobile or vice-versa**
  - use **radio signals** to coordinate the location estimation
  - rely on the **ultrasound or infrared signals**
  - Provide symbolic room-level accuracy or
  - use **time-of-arrival** or **angle-of-arrival** to determine the user's location within the room with **5–10 cm accuracy.**

Room-Level Localization via Proximity - ActiveBadge

- The **first indoor location system** was the **Active Badge**:
  - developed in **1990** at the Olivetti Research Laboratory
  - **The badge** is the beacon; the **receiver** is in the room.
  - Determines the room in a building where people are located by having **each person wear a small (40-g) badge-like device that sends a unique pulse-width** modulated infrared code every 15 s
  - **these codes are received by base stations** mounted on the ceilings of offices, hallways, and meeting rooms
  - **base stations decode the received infrared signals** and forward the decoded **badge-IDs to a centralized location server** using the building's wired networking infrastructure
  - because **base stations are mounted in known locations**
    and because the **signals rarely propagate beyond a single room**,
    the **server can infer** with high probability in which room the badge is beaconing
  - because the infrared **badges take only 0.1s to transmit their unique code**, collisions between simultaneously beaconing badges are unlikely

Room-Level Localization via Proximity- ActiveBadge

- Infrared signals are **easily blocked by fabric**:
  - the badges need to be worn on the **outside of people's clothing**

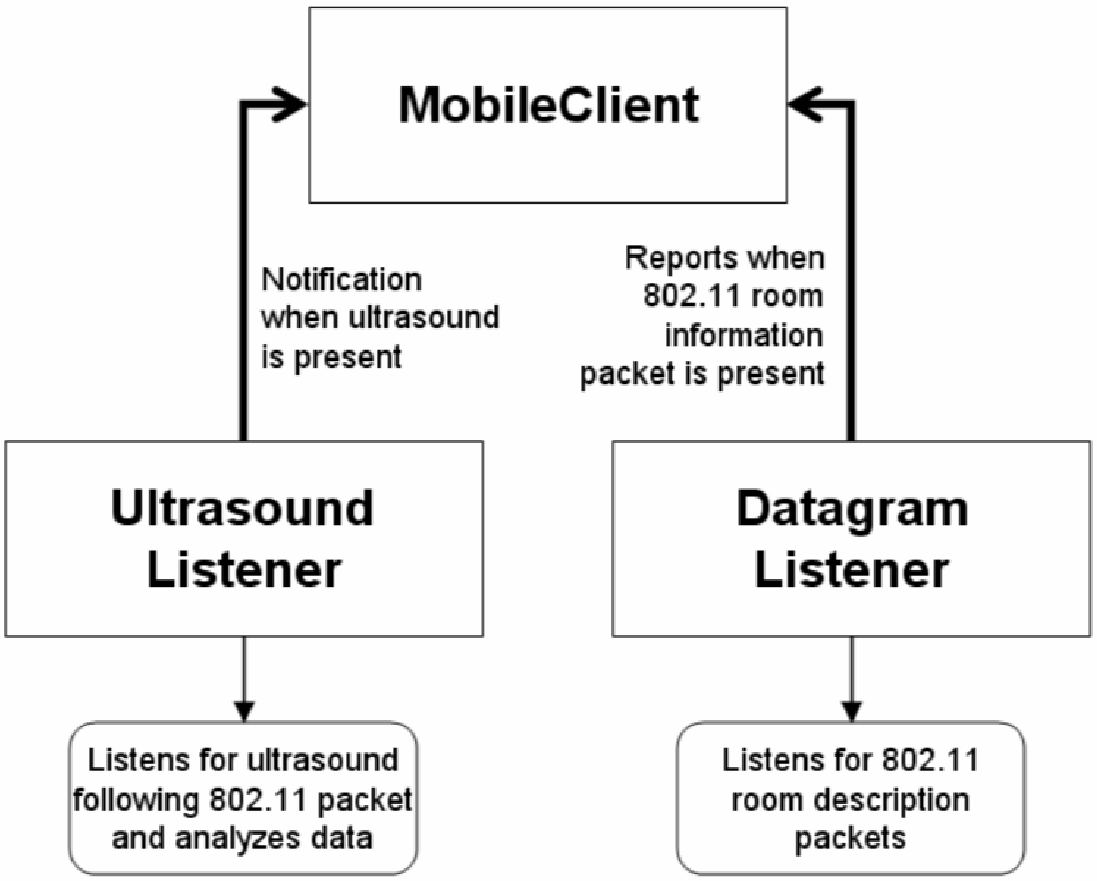
- Badges clipped to belts or pockets were often **obscured by tables and desks** when people were seated:
  - "**clipped to a breast pocket**" emerged as the best position in which to wear the Active Badge

- Simple design and use of low power parts enable:
  - an Active Badges to **run for more than a year** before requiring the batteries to be changed

- **Simplicity** in design and architecture:
  - commercial infrared badge systems as those sold by Versus have changed little in the nearly 20 years since the Active Badge system was developed

- Disadvantages:
  - **requires specialized infrastructure** in the form of base stations to listen for badge IDs
  - **requires users to purchase and carry the badge itself**

Room-Level Localization via Proximity- WALRUS



Room-Level Localization via Proximity- WALRUS

- WALRUS uses **PC and PDA speakers and microphones** to **send and receive ultrasonic signals** to convey proximity:
  - PCs are the ultrasound and radio **beacons**; badges are the **receivers** (mic and wireless)
  - it **does not encode the room's ID** using the ultrasonic signal
  - **it encodes the room's ID using a radio side channel**
  - the **PCs that are serving as beacons** periodically emit a 10-ms pulse of 21-kHz ultrasound
  - at the same time, **PCs send an 802.11 datagram containing the rooms' identifying** information
  - as the **ultrasounds and radio datagram are transmitted at the same time**, WALRUS **clients do not need to constantly monitor their microphones**
  - rather, **they can listen for an 802.11 datagram and, only when received, listen for an ultrasound signal**

- Given that there is no actual data encoded in the ultrasound:
  - **the client's audio task is reduced to simply looking for sufficient energy** in the 21-kHz band to denote proximity
  - this also extended the useful range of the ultrasound signals generated by the beacons to 13 m in their experiments

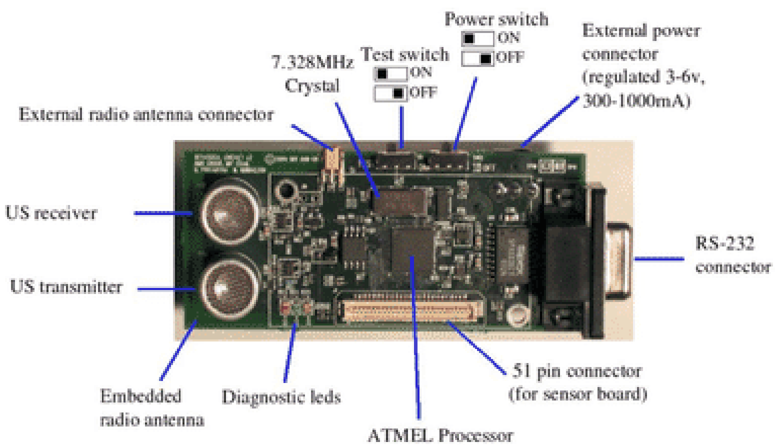
Room-Level Localization via Proximity- WALRUS

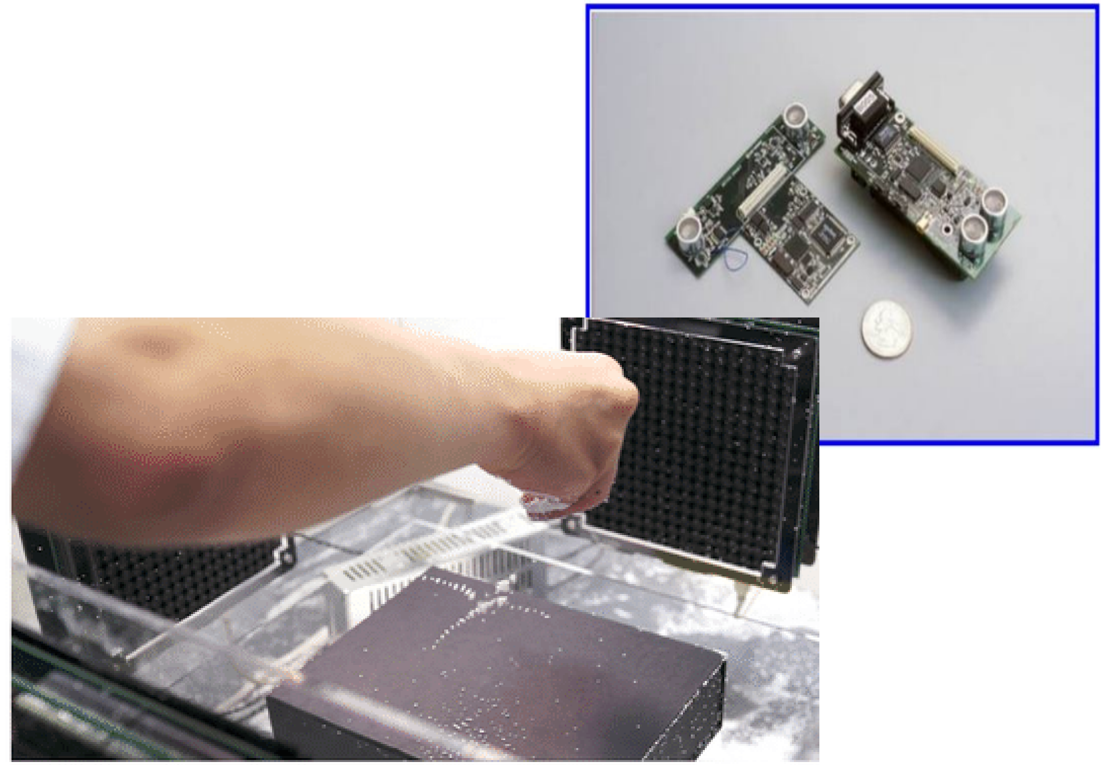
- The mobile client component is designed to run whenever it hears an 802.11 location packet:
  - it **records audio** from the microphone for enough time for a typical room size (e.g., 50-100ms can handle a good sized room of 18m maximum dimension at 25°C)
  - it then **looks for energy** in the received audio in a small band around 21KHz:
    - if there is a signal there, then **it is likely the device is in the room that generated the last location** information-bearing 802.11 packet
    - conversely, **if there is no energy at 21KHz, then it is likely that the device is in a different room**
    - several readings over a few seconds can quickly provide a high-confidence room-level location estimate
    - note that the client device only expends energy on ultrasound detection when it hears an 802.11 location packet; the rest of the time, it performs no ultrasound calculations at all

Room-Level Localization via Proximity- WALRUS

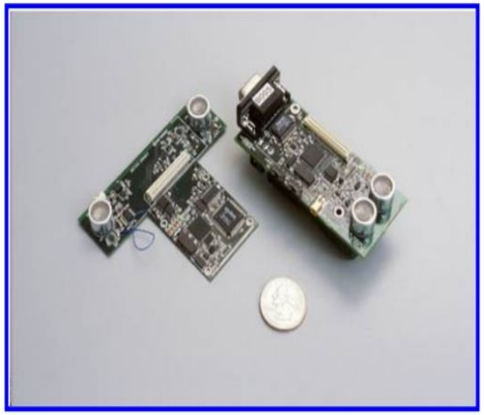
- Because **beaconing PCs are not coordinated** in WALRUS:
  - there is the potential for **client devices to receive the radio datagram from one beacon and associate it with the ultrasound from a different beacon**, in effect, incorrectly identifying which room it is in
  - the **experiments show that while this is unlikely** when only a small number of WALRUS beacons are within 802.11 range of each other, by the time **the number of beacons grows to 25**, the **error rate increases to more than 50%**
  - this issue can be addressed by **using a central coordinator to schedule the PC beacons**

Sub-room Accuracy – Cricket





Sub-room Accuracy With Ultrasonic Time of Flight

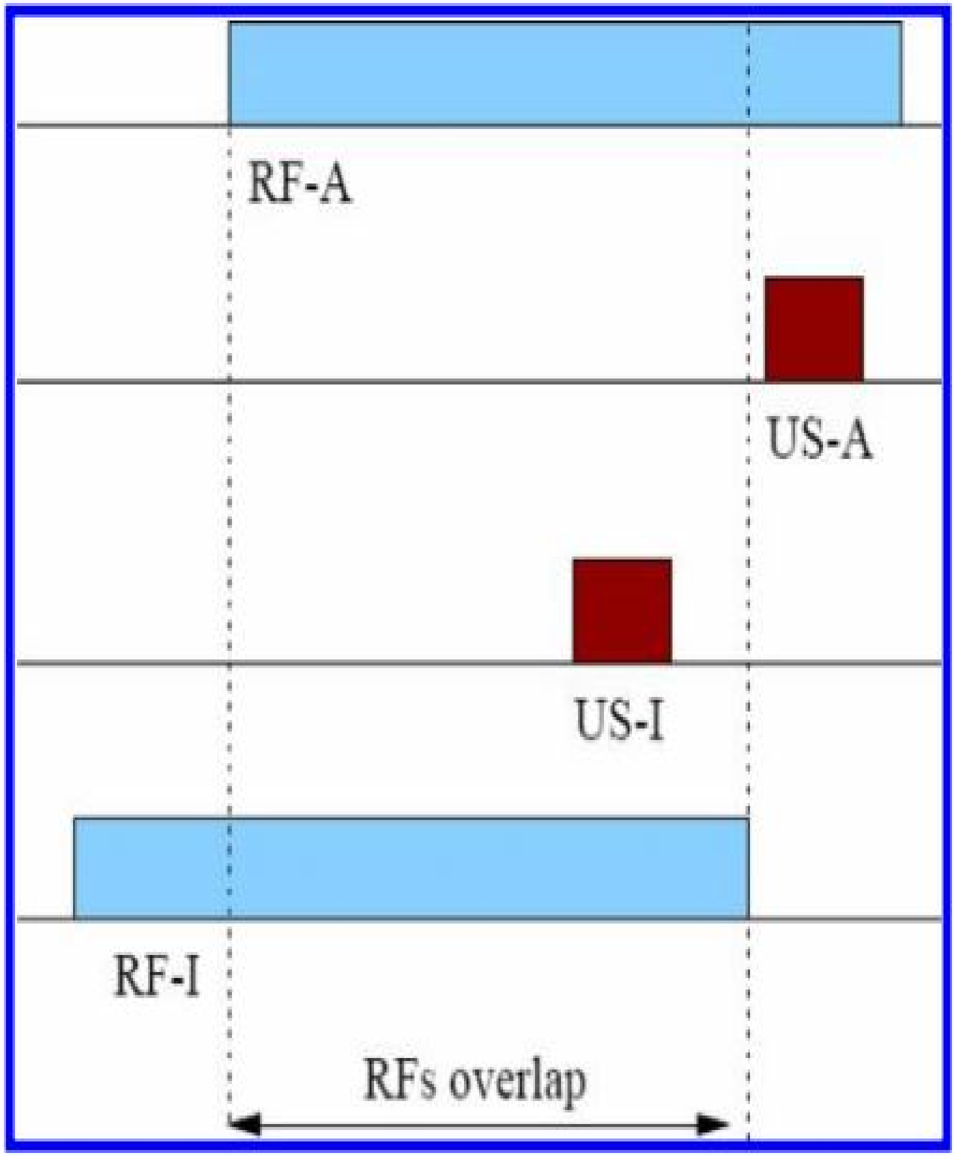


- The **Cricket** system:
  - developed as part of the MIT Oxygen project
  - sought to enable **sub room-level location using ultrasound**, and
  - to do it in a **privacy preserving, decentralized fashion**
  - **badges** are the receivers/listeners; **beacons** are the infra-structure

- **Beacons are placed on ceilings** or high on the walls in the environment and **advertise their identity using a combination of RF and ultrasound**:
  - **Cricket beacons encode their identity using RF** and **send ultrasound pulses** containing no digital data (similar to WALRUS)
  - Cricket designers wanted to be able to place multiple Cricket beacons in a single room to allow Cricket listeners to figure out which part of the room (which seat at the table, which work area, which bed, etc.) the user was occupying

- Provides positioning precision to within 1m² regions within a room (since the ultrasound does not travel through walls).

Cricket



Sub-room Accuracy With Ultrasonic Time of Flight

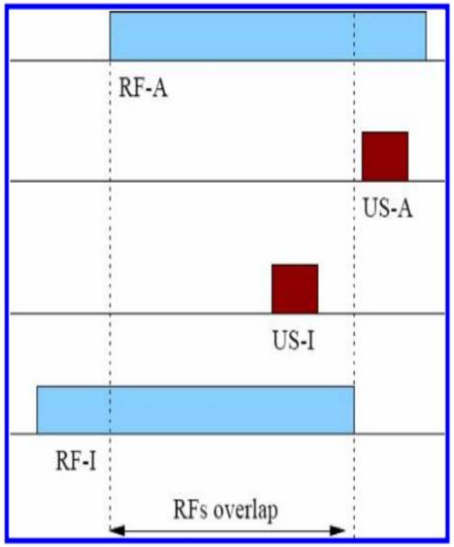
- To do this, the Cricket system:
  - ultrasound travels very slowly (in room-temperature air, sound travels at only 0.34 m/ms.)
  - on receiving the radio ID from a beacon, **Cricket listeners not only listen for an ultrasound pulse, but time how long it takes to arrive**
  - because the radio signal travels almost instantaneously relative to the ultrasound:

the delay between start of the radio transmission and the observation of the ultrasound pulse is a close approximation of the time of flight of the ultrasound which can, in turn, be **converted into an estimate of the distance the ultrasound travelled**

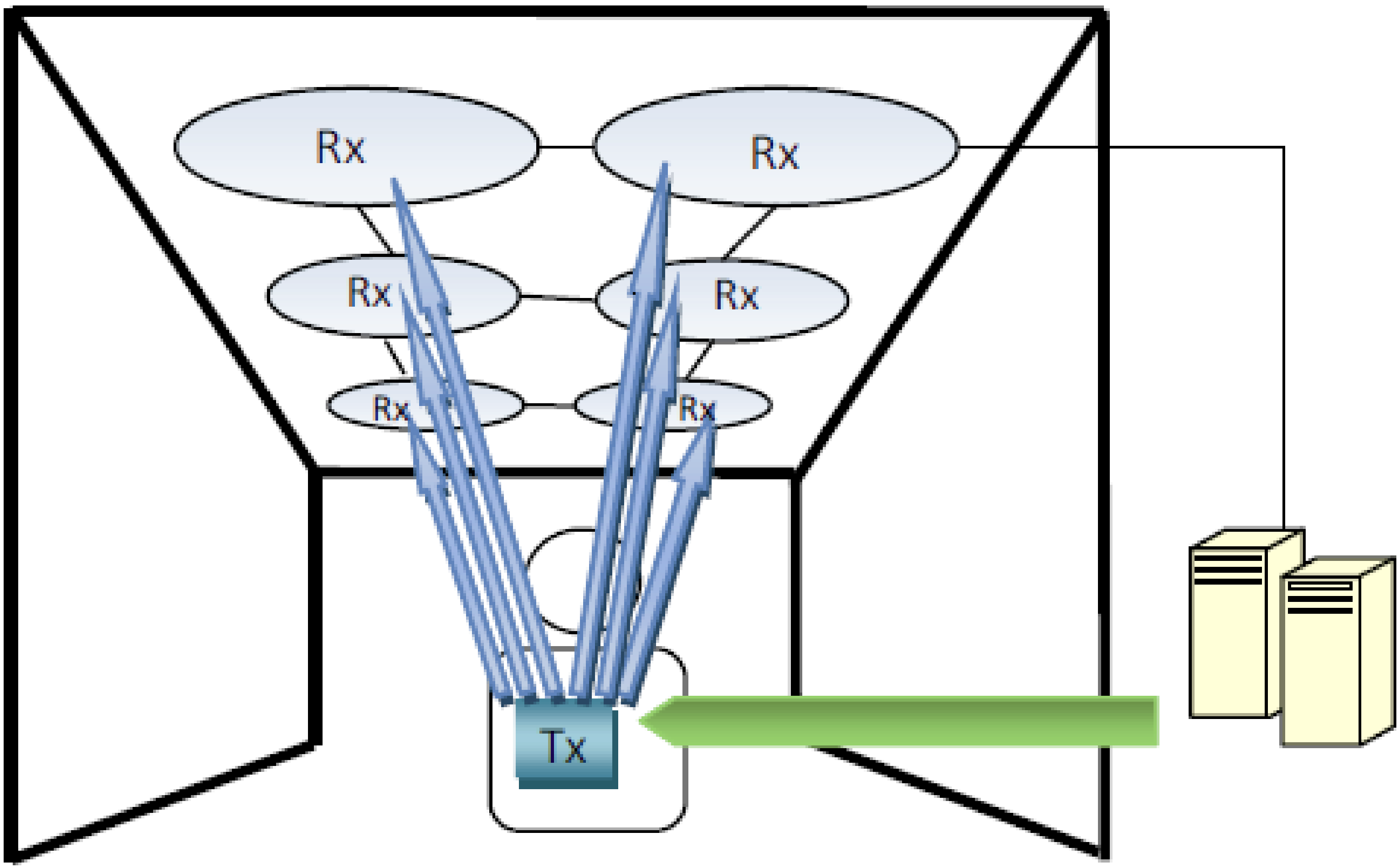
  - by **estimating and comparing the distances of the beacons being observed**, a Cricket **listener can accurately predict which beacon is the closest**
- Thus, Cricket can be used as:
  - a **room-level location system**, when **beacons are sparsely deployed**, and
  - a **sub room location level system**, when **multiple beacons are placed in a room**
- Subsequent extensions to Cricket show that:
  - with **sufficient beacon density**, their system could **determine location within several centimeters** and **orientation to within 5°**

Sub-room Accuracy With Ultrasonic Time of Flight

- Preventing listeners from associating the ultrasound pulse from one beacon with the radio broadcast from another:
  - given that the **maximum effective ultrasonic range of the Crickets is 10 m**, the Crickets beacons intentionally transmit their ID using a **slow radio encoding that takes as long as ultrasound takes to propagate 10 m**
  - this ensures that the **radio transmission from each cricket beacon fully overlaps the flight of the ultrasound pulse** from the same source
  - this overlap guarantees that **at the time a listener receives an ultrasonic pulse from a beacon, it will still be receiving that beacon's ID via radio**
  - this allows the **listeners to detect (and ignore) the RF collision** that would occur **if two or more ultrasound packets were in flight at the same time**
  - this ensures that pulses will never be incorrectly associated with the wrong beacon ID
  - to reduce the chance that these collisions occur, **Cricket beacons randomize the time between transmissions** (e.g. beacons wait between 150 and 350 ms between broadcasts)



Absolute Location With ToF – Active Bat



Absolute Location With Time of Flight

- The goal is to estimate with **high accuracy** the absolute location of a device within a room:
  - e.g., 110 cm south, 50 cm east, and 35 cm up from the northwest corner of Conference Room 206
- Badges are the **beacons**; **receivers** are in the infra-structure

- The Active Bat system:
  - was developed by AT&T Research in 1999
  - it uses ultrasound receivers to localize small (35 g) pager-like devices called Bats in three-dimensional space
  - it is extremely accurate, estimating location correctly within 5 cm 50% of the time and within 9 cm 95% of the time
- Like Cricket:
  - Bats are located by measuring the travel time of an ultrasonic pulse
- In contrast to Cricket:
  - Bats emit the ultrasonic pulses, and receivers in the infrastructure listen for and time the pulse's travel

Absolute Location With ToF – Active Bat

- Accuracy of the Active Bat system derives from:
  - its **dense deployment of ultrasound receiver units**
- In the original AT&T deployment:
  - **100 ceiling-mounted receivers were used in a 100-m2 office**
  - this density makes it likely that a **Bat's pulse would be heard by at least three** and likely many more receivers
- To estimate location:
  - **receivers pool their time-of-flight observations to a central server** that performs multilateration (a generalization of trilateration)
  - **location** is estimated from three or more ranging estimates from known locations
- Similar to Cricket:
  - reflections of ultrasound are common, and
  - the Bat system uses the redundancy of the grid of receivers to reject these reflections as outliers

Absolute Location With ToF – Active Bat

- The Active Bat system is sufficiently accurate that:
  - it is possible to place multiple Bats on a rigid object and,
  - by measuring the Bat's location, reconstruct not only the object's **location** but also its **orientation**

- Experiments in which two **Bats were** attached to a rigid object **22 cm apart** showed:
  - **orientation could be estimated within 10° over 80% of the time**

- The accuracy of the Bat system is dependent:
  - not only on the **density of ultrasound receivers**, but also
  - on **centimeter-accurate knowledge of each receiver's location**

- Active Bat system is centrally coordinated

- Bats wishing to be tracked register their interest with a central service via radio:
  - this service employs a slotted schedule to ensure that, at most, one Bat at a time has an ultrasonic pulse in flight
  - the system designers determined that ultrasonic reverb can take up to 20 ms to die off in an indoor environment
  - thus, they use a schedule with 50 slots per second

Absolute Location With ToF – Active Bat

- At the start of a slot:
  - the **central server requests (via radio) that the Bat with a given ID send an ultrasound pulse**
  - then, **the server records the elapsed time and ID of each receiver that reports having heard the pulse**

- At the end of the slot:
  - **the server can compute the distance estimates** and,
  - **using the receiver's locations, can estimate the Bat's location**

- The Bat system:
  - does not need to employ a uniform schedule, and
  - Bats assigned to people can be localized with a higher frequency than those attached to less mobile objects like printers

Comparison

Technology	Infrared proximity (e.g., Active Badge)	Ultrasound proximity (e.g., WALRUS)	Ultrasound TOF (e.g., Active Bat)
Accuracy	★★★☆ Room ID with high accuracy	★★★☆ Room ID with high accuracy	★★★★ 3D location with 5 cm accuracy
Coverage	★★☆☆ Indoor only in room fit with IR receiver/beacon	★★☆☆ Indoor only in room fit with ultrasonic beacons	★★☆☆ Indoor only in room fit with ultrasonic infrastructure
Infrastructure cost	★★☆☆ Infrared receiver or beacon required for each room	★★☆☆ 1 or more ultrasonic receiver or beacon required for each room	★☆☆☆ Requires dense array of ultrasonic receivers
Per-client cost	★★★☆ Inexpensive IR badge/dongle required	★★★★ Software only solution on device with microphone	★★★☆ Inexpensive ultrasonic badge/dongle required
Privacy	★★★★ If localization is performed on the client. Otherwise ★★☆☆ Opt-out easy by removing badge	★★★★ Localization is performed by mobile client	★★☆☆ Localization is performed by infrastructure. Opt-out easy by removing badge
Well-matched use cases	Asset and personnel tracking, indoor mapping/ navigation/tour guides	Asset and personnel tracking, indoor mapping/ navigation/tour guides	Asset and personnel tracking, tangible UIs, fine-grained info services

Location Estimation With 802.11

Introduction

- Estimating location with 802.11 was **first proposed in 2000**:
  - since then, many variants have been developed.

- At their most basic, **all of these systems work the same way**:
  - 802.11 radios and their supporting drivers allow a device to scan for nearby 802.11 APs
  - regardless of the variant of 802.11 (a, b, g, n) or whether encryption is enabled, these scans return a list of the nearby APs and their unique IDs called MAC addresses
  - all of the 802.11 location systems capitalize on the fact that 802.11 access points have limited range (typically less than 100 m), and **if a device can hear an access point**, **it knows that it is in the vicinity of that access point.**

- If a **device can see more than one AP**:
  - it can **estimate its own location more precisely**, and additional information, such as **received signal strength and packet loss rate**, can be used to improve the accuracy of location estimates further.

Introduction

- The appeal of using 802.11 for location estimation is strong:
  - **nearly all mobile devices** have built-in 802.11
  - AP density is high, e.g. over a **half-million known mapped 802.11 access points** in the Tokyo metropolitan area
  - densities of this kind raise the possibility of **high-coverage indoor/outdoor location with no additional location infrastructure**

- This near-pervasive client hardware and infrastructure for doing 802.11-based location is the reason why dozens of such location systems have been developed

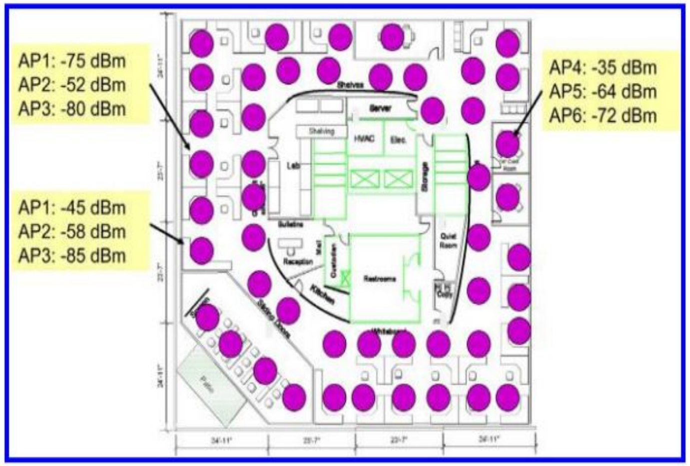
- To allow client devices to discover and associate with an access point:
  - the 802.11 protocol includes **beacon frames that APs can send to alert clients to their presence**
  - the frequency with which these beacon frames are sent varies by model of AP and commonly **ranges from tens to hundreds of beacon frames per second**
  - these frames **contain the human readable SSID of the network** "Joe's hotspot" and the **MAC address of the AP** and whether the **AP is running encryption or not**

- **Client** devices can:
  - passively **learn about nearby APs** by listening for a small window of time on each of the 802.11 channels
  - alternatively, **clients also have the option of initiating an active scan** by sending a probe request which prompts access points to reply with a probe response very similar to a beacon frame

Signal Strength Fingerprinting

Signal Strength Fingerprinting - Idea

- Location estimation using radio fingerprints involves **two phases**:
  - the **mapping phase**, and the
  - **location estimation phase**



- Mapping phase:
  - a **site survey is performed**, in which the visible APs and their observed signal strengths are recorded along with the location in which the observation was taken
  - to provide good coverage, the radio map readings typically span the entire physical space
  - to provide good accuracy, the **readings need to be of sufficiently high density**; typically, a reading is collected every few square meters

- Given this radio map, estimating location is straightforward:
  - a **client in an unknown location performs a radio scan** and estimates its **location to be the place on the radio map whose scan most closely matches its observation**
  - **spatial variation** ensures that there will be enough variety in the radio environment to distinguish places from each other
  - **temporal consistency** means these distinctions are likely not to change between the time of mapping and the location estimation

Signal Strength Fingerprinting - Radar

- The first 802.11 location system, RADAR, was developed at Microsoft Research
- RADAR and the other systems like it are the most accurate 802.11-based location techniques:
  - capable of tracking device with **1- to 3-m accuracy** depending on the environment
  - it takes advantage of two properties of the 802.11 signals observed by client devices:
    - spatial variability
    - temporal consistency
- Due to the short range of 802.11 and the way signals are blocked and reflected by obstructions in the environment:
  - the **strength with which an AP is observed varies considerably spatially**, even over distances as small as a meter (we have all observed this when we found we could not get good network connection in one place, and we moved over one seat, and the connection improved drastically)
  - the **strength of an 802.11 signal tends to be temporally consistent** (if a given seat at a table is a good place to establish a connection to a particular AP today, it will likely be a good place to connect in a few minutes, the next day, or the next month)

Signal Strength Fingerprinting - Radar

- Radar:
  - builds a map of the radio environment by collecting location-tagged "**radio fingerprints**", and
  - later uses this map to perform localization of mobile 802.11 devices
  - as most other similar systems, it uses the Euclidean distance in **signal space** as a measure of the similarity of the two radio scans

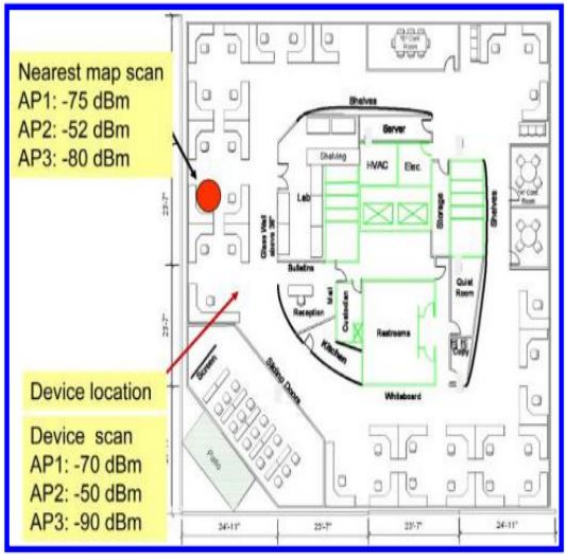
- For example, the distance in signal space for the pair of scans is

$$\sqrt{5 \cdot 5 + 2 \cdot 2 + 10 \cdot 10} = 11.4$$

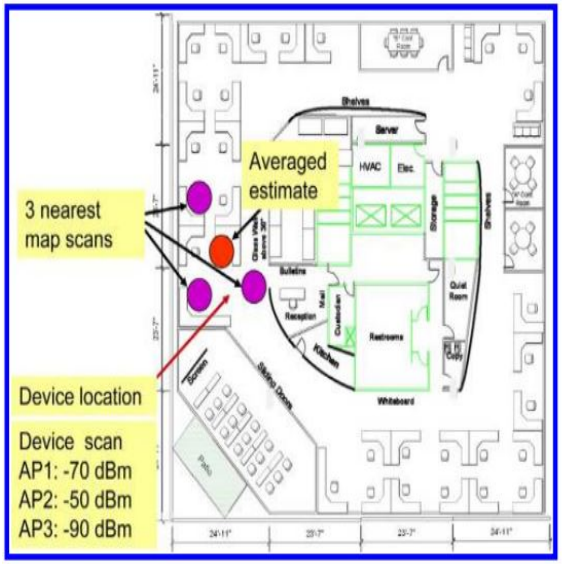
AP	Scan 1	Scan 2	Difference
AP1	-70 db	-75 db	5 db
AP2	-50 db	-52 db	2 db
AP3	-90 db	-80 db	10 db

Signal Strength Fingerprinting - Radar

- The simplest algorithm for estimating location is called **nearest neighbor**:
  - the device's location is estimated to be the location of the mapping scan with the **smallest Euclidian distance from the client's scan**



nearest neighbor



nearest neighbor K=3

- Because there is some fluctuating interference from objects and radio sources:
  - **accuracy can be improved** by using more sophisticated algorithms
  - some systems including RADAR, smooth out variations by **averaging the locations of the K closest mapping scans** in Euclidian space
  - small K of 2–4 has been shown to yield good results

Signal Strength Fingerprinting - Accuracy

- The accuracy of any location system based on 802.11 radio fingerprinting is dependent on a number of factors:
  - **density** of the radio fingerprint map
  - **obstacles** in the mapped area

- E.g. the RADAR system was evaluated in:
  - a **1000-m2** office environment
  - with **70 fingerprint** locations,
  - averaging **4 m distance between neighboring fingerprints** and
  - yielded a **median localization error of 3 m** (versus a median error of 16 m for random)

- E.g. Horus and the commercial system Ekahau report:
  - **accuracies of 1 m** or better using **radio maps with 1–2 m between readings** on average

- A 2006 study using cars with GPS to collect 802.11 data showed that:
  - with a **mean distance of 10 m between fingerprints**,
  - it was possible to **estimate location with 15-m accuracy**

Signal Strength Fingerprinting - Accuracy

- Location systems are often used by people carrying mobile devices:
  - effect of human bodies on the accuracy of a fingerprinting location system

- To mitigate the effect of bodies attenuating the 802.11 signals:
  - RADAR’s fingerprint maps were constructed with **four fingerprints from each location**,
  - with the person doing the mapping facing each of N, S, E, and W

- Rationale for taking these directional readings is:
  - to capture in the radio map **both different locations**,
  - and the **different ways a person may occlude the signals**

- With all four readings included in the radio map:
  - RADAR achieved **median accuracy of 3 m**
  - independent of the user orientation
  - when the fingerprint map was constrained to **only the north collected readings** and testing was done while **facing south**, errors increased by more than **60%**

Signal Strength Fingerprinting - Conclusion

- The **effects of human occlusion on accuracy are indeed significant**
- Other systems have **varied in the number of mapping scans** performed at each location:
  - in the case of maps generated from moving clients, from 1 to as many as 100
- The strength of 802.11 fingerprinting is that **it is a sampling technique**:
  - it does not need to understand where the APs are,
  - what the physical environment looks like, or
  - how 2.4-GHz signals propagate
- It works by simply:
  - creating an **approximate snapshot of the radio environment**, and
  - later sampling that snapshot
- Its simplicity is also its weakness:
  - site surveys are **brittle,** AP location changes are not that rare.
  - fingerprinting does not scale well.

Signal Strength Fingerprinting - Conclusion

- The radio maps produced by the site surveys are brittle:
  - if an **access point is moved**, the map needs to be recollected for the space within range of this AP,
  - even if the move is as insignificant as from the top of a filing cabinet to the desk beside it
  - as a result, fingerprinting systems are **best suited for spaces in which some degree of control over the radio infrastructure can be maintained** such as office spaces, hospitals, and other similar buildings or small campuses

- Fingerprinting does not scale well:
  - keeping a complete, up-to-date radio map for an office building or even a technology park might be fine, but
  - it is **not feasible at the scale of countries**, **states**, or even **large cities**
  - fingerprint maps can be collected sparsely with a predictable loss in accuracy in exchange for density reduction

- Other possible approach is to **model radio signal propagation**

Signal Strength Modeling

Signal Strength Modeling - Idea

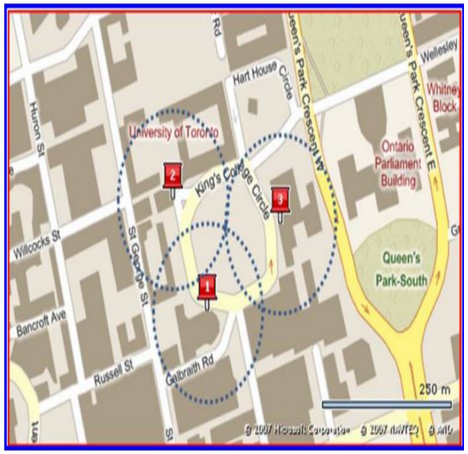
- At their core, all these systems take advantage of the same principle:
  - as **radio signals propagate in predictable ways**,
  - a **device's location can be predicted by modeling the propagation of the radio signals the device has observed**

- Models vary greatly, but all ask the same question:
  - "Based on what I know about the access points just observed, where is the device most likely to be?"

SSID	MAC	RSSI	Encrypted?
Capital City WiFi	00:0f:34:ab:0c:e0	-66 dB	No
First Security Trust	00:0f:f7:0c:e9:c0	-78 dB	Yes
First Security Trust	00:0f:f7:0c:4f:03	-105 dB	Yes

- Simplistic radio model:
  - assume that "**802.11 APs have a range of 100 m**"

- This model, combined with these AP locations, leads to the (perhaps incorrect) inference that:
  - the **client device is somewhere in the intersection of the three 100-m circles** centered at the coordinates of the three



Signal Strength Modeling - Active Campus

- The first wide-area deployment of an 802.11 location system was done:
  - as part of the **Active Campus** project
  - on the **University of San Diego** campus in 2002

- One of the goals was:
  - to offer **location-based social networking services** to students,
  - a campus-wide **indoor/outdoor location system**

- The campus:
  - have pervasive 802.11 coverage,
  - but was far **too large to perform a fingerprinting site survey**

- One resource at the team's disposal:
  - recent inventory recording the physical locations of the university's 1000 access points

- With this data set:
  - developed algorithms to use this AP map to approximate a device's location given an 802.11 scan

Signal Strength Modeling - Active Campus

- It succeeded in achieving high coverage with **accuracy in the wide-area of approximately 20 m**

- Basic trade-offs in using a modeling-based approach:
  - 1) it makes **simplifying assumptions** that make the computation easier at the cost of **decreased accuracy**
  - we are assuming that all APs can be heard from the same distance in all directions (which is almost never true)

  - 2) even if we wanted to use a **more sophisticated model**, **we could not do so** if the AP database did not give us additional key parameters such as transmit strength or degree of obstruction that the model needed
  - this creates a **strong coupling** between the **content of the AP database**, the **complexity of the radio model**, and the resulting accuracy of the location estimation

Signal Strength Modeling - Active Campus

- The Active Campus location system used an **AP database** storing:
  - latitude, longitude, and floor number for each known access point
- It used the **observed signal strength from each access point to estimate the client's distance from that AP**
- The **client's latitude and longitude** were estimated by:
  - **combining these distance estimates** using an average that heavily weighted the distance estimate from the strongest AP
- In the tests:
  - Average estimation **accuracy of 22 m outdoors and 11 m indoors**
  - **AP densities observed indoors** are bigger than **outdoors** which is why there is higher accuracy indoors,
  - although it was also likely due in part to indoor obstructions effectively reducing AP ranges and shrinking the set of likely client locations
- User's floor always estimated to be the floor of the AP with the strongest received signal:
  - due to the heavy attenuation of concrete floors and ceilings, this technique yielded the correct floor 95% of the time

Signal Strength Modeling - PlaceLab

- What if we want to use ActiveCampus **outside the campus**?
  - Place Lab employed a simple radio model based on an average of the latitude and longitude of the observed access points weighted by signal strength
- The key contribution of Place Lab was:
  - an access point database could be quickly built using a technique known as "**war driving**"
- War driving is:
  - **finding 802.11 networks by driving around** in a car equipped with a GPS and an 802.11 device that is continually scanning and logging
  - by **post-processing the log**, the GPS and 802.11 readings can be correlated to produce a cloud of locations in which a given AP was observed
  - using a **model of signal propagation**, this cloud of geo-tagged radio observations can be used to **estimate the 802.11 access point's physical location**
- The observation of Place Lab was that:
  - war driving tools such as NetStumbler and Kismet that were primarily being used to allow people to find open networks could also be used to quickly build AP databases for 802.11 location systems

Signal Strength Modeling - PlaceLab

- The strength of this approach is that;
  - war driving **maps all observable access points**,
  - regardless of whether they are in a school, a business, or a private residence,
  - and independent of whether their traffic is encrypted or not
- This allowed Place Lab to provide coverage beyond that of a managed network:
  - it was the first system to potentially offer city or country scale 802.11-based location
- Experiments with Place Lab yielded accuracy numbers very similar to those of Active Campus:
  - in the neighborhood with the sparsest AP distributions, Place Lab has a median accuracy of 23 m, while in the densest, it had accuracies of 15–20m

Signal Strength Modeling – AP Database

- Active Campus and Place Lab illustrate two popular means of constructing an access-point database
- The advantage of the Active Campus approach is accuracy:
  - knowing an AP's location on a floor plan or a building schematic allows someone to estimate the AP's absolute location within a meter of its true location
- The downside of the Active Campus approach is that it only works when a network manager knows the location of their networking hardware:
  - note that this does not completely eliminate the possibility of achieving wide area or high coverage with this technique
  - cities deploying metropolitan-scale WiFi programs or even national "hotspot" providers like T-Mobile likely know the location of their APs
- War driving:
  - allows vast swaths of terrain to be quickly mapped at the cost of reduced accuracy in the AP location estimates

Signal Strength Modeling – AP Database

- In war driving, the errors in AP placement come from a variety of sources:
  - GPS is being used to record the location of radio observations, and **GPS itself has an 8 to 10m median error**

  - this is compounded by the **error introduced by the modeling** used to predict AP location from the set of observations

  - another source of error comes from that fact that all of the **popular war-driving programs ignore altitude** and estimate AP location in just latitude and longitude
  - while this may not introduce significant error for APs in one- or two-story buildings, Place Lab found that it had a **significant effect in downtown areas with tall buildings**

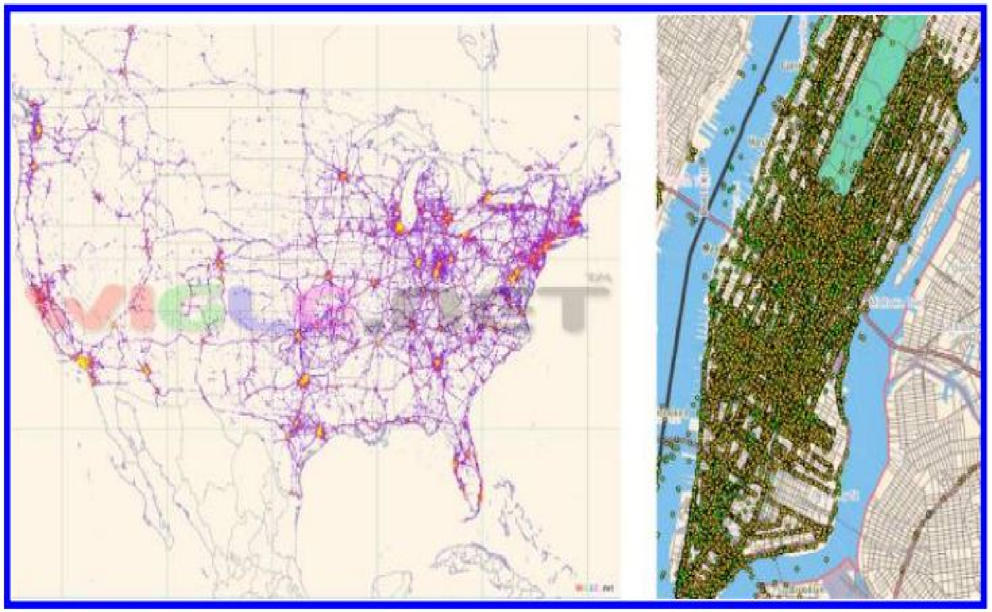
  - APs are **deployed, decommissioned, or moved** on a regular basis in the mapped area
  - this gives the data from a war drive an unpredictable, temporal fragility that a map of centrally controlled infrastructure could determine and even control

- Observations:
  - a comparison of war-driven AP locations to the true location of five APs in a residential area found a **median error of 26 m**
  - larger study of over 500 APs on Dartmouth campus - median error of **40 m for war-driven** AP estimates

Signal Strength Modeling – Conclusion

- Despite the drawbacks:
  - war driving has been far and away the largest source of AP data for location estimation
  - the commercial location system by Skyhook Wireless and Navizon employ nationwide war driving in the United States to build their AP maps

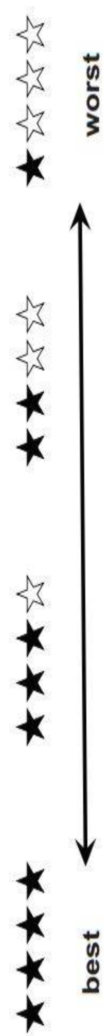
- In the public domain, the user-contributor war-driving repository "Wigle" contains the location of over 11 million APs



maps of Wigle.net's AP coverage for the continental United States and for Manhattan Island

Location Estimation With 802.11 - Comparison

Comparison



Technology	802.11 signal-strength fingerprinting (e.g., RADAR)	802.11 signal-strength modeling (e.g., Place Lab)
Accuracy	★★★☆ 2D coordinates with 1-3 m median accuracy	★★☆☆ 2D coordinates with 10-20m median accuracy
Coverage	★★☆☆ Building to campus scale. Requires 802.11 coverage and radio map. Best accuracy achieved when 3+ APs are visible.	★★★☆ Areas with 802.11 coverage and radio map. Best accuracy achieved when 3+ APs are visible.
Infrastructure cost	★★☆☆ No additional infrastructure is needed beyond 802.11 APs. Creating radio map is time intensive and new/moved APs require remap.	★★★☆ No additional infrastructure is needed beyond 802.11 APs. Creating radio maps is less work than for fingerprinting.
Per-client cost	★★★★ Software-only solution for devices with 802.11 NICs.	★★★★ Software-only solution for devices with 802.11 NICs.
Privacy	★★★★ when localization is performed on the client. ★☆☆☆ when localization is performed in the infrastructure.	★★★★ when localization is performed on the client. ★☆☆☆ when localization is performed in the infrastructure.
Well-matched use cases	Asset and personnel tracking in indoor environments, indoor mapping/navigation/tour guides	Social networking, tour guides, indoor/outdoor navigation/tour guides, fitness/activity tracking

Cellular-Based Systems

Cellular-Based Systems - Introduction

- The development of location systems based on mobile phone technology was originally driven by:
  - the U.S. Federal Communication Commission E911 mandate, and
  - its European Community counterpart E112 to locate mobile phone calls to assist in the delivery of emergency services

- In addition, the wide adoption and ubiquitous connectivity of cellular phones makes them tempting platforms for the delivery of location-based services:
  - advertising, recommendation systems, and gaming

- A localization system based on cellular signals, such as GSM or CDMA, has the key advantages that:
  - it leverages the phone’s existing hardware, and
  - can potentially provide location estimates anywhere voice service is available

- A number of mobile phone-based location systems have been developed, and they can be grouped into four categories:
  - cell ID-based approaches,
  - methods based on radio propagation modeling,
  - assisted GPS, and
  - surveying techniques based on radio fingerprinting

- Each type of location system strikes a different trade-off between ease of deployment, coverage, and accuracy

Cellular-Based Systems – Cell ID-Based

- A mobile-phone base station is typically equipped:
  - with a number of directional antennas that
  - define sectors of coverage or cells,
  - each of which is assigned a unique cell ID

- Cell ID-based location is a simple technique where:
  - the position of the mobile phone is estimated based on the ID of the cell currently providing service to the device

- Cell ID-based location is usually implemented on the network side, and its key advantage is:
  - it works for all phones, as no handset modifications are required

- Accuracy depends on the size of the cell, ranging:
  - from 150 m for microcells in urban cores to 30 km for cells in rural settings

- Such accuracy may be sufficient for some applications:
  - e.g. weather and traffic reports, but
  - falls short of the requirements for other application such as street navigation and the E911 guidelines (as these require a cell phone handset to be localized within 50 m 66% of the time)
  - accuracy can be improved by including in the position a calculation of the round-trip time (RTT)

Cellular-Based Systems – Cell ID-Based

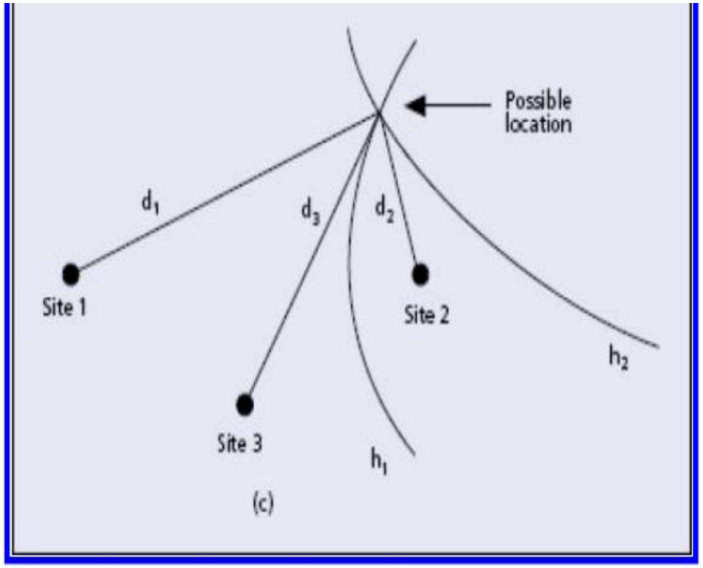
- The system by Laasonen is an example of a cell-ID based system:
  - it was implemented purely on the handset without network cooperation
  - it monitors the ID of the GSM cell the handset receives service from and uses the transition between cells to recognize the common places that a user goes to
  - it does not attempt to estimate absolute location, but rather assigns symbolic locations (e.g. Home and Grocery Store)
  - thus, it does not need to know the coordinates of the cell towers
  - the privacy improvement in this “handset-only” approach is marginal, as current protocols require the mobile phone to register with the cell tower to obtain the cell ID

Cellular-Based Systems – Radio Modelling

- A variety of location systems based on modelling of GSM and CDMA radio signals have been developed:
  - most are based on time-of-flight measurements (rather than signal strength)

- The underlying techniques used for computing ranges to cell towers depend on the specifics of the GSM or CDMA physical layer:
  - but the positioning algorithms used by GSM and CDMA are in fact very similar

- The main radio modelling positioning methods provided by GSM and CDMA systems are based on Time Difference of Arrival (**TDOA**) trilateration:
  - handset position is estimated by intersecting hyperbolic lines derived by taking differences between time measurements from pairs of base stations



Cellular-Based Systems – Radio Modelling

- TDOA requires base stations to be tightly synchronized:
  - this is not an issue for CDMA networks (follow a synchronous protocol)
  - in GSM, this requires the deployment of additional network elements to determine the clock difference between base stations
  - this information is then provided to the handset who uses it to calibrate the measurements from neighboring base stations

- TDOA can be implemented either on the **network** or the **client**

- Network-based approach:
  - three or more base stations **compare observations to determine the time differences** at which handset transmissions are heard at the cell towers
  - has the advantage that **it does not require modifications to the handset** hardware, and as a result, it works for existing, deployed handsets

- Client-based implementation:
  - the **handset measures the time differences in the arrival of training sequences** or pilot symbols transmitted by three or more stations
  - provides a **higher degree of privacy to users**, as time-difference is measured and the location estimated on the user's local device base stations

Cellular-Based Systems – Radio Modelling

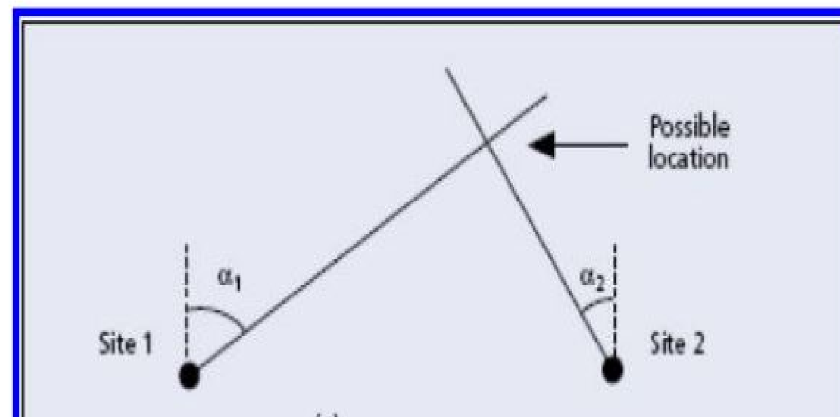
- TDOA **accuracy ranges between 50 and 500 m** depending on interference, system geometry, and multipath effects:
  - handsets in close proximity to a base station may suffer from **interference** issues where the strong signal of the nearby base station prevents the handset from hearing the transmission of neighbouring nodes
  - this problem is more pronounced for CDMA systems, where different towers transmit on the same frequency, than on GSM networks, where towers are allocated different frequencies
  - to alleviate, base stations stop transmission for short idle periods that enable the handset to measure other neighbouring nodes

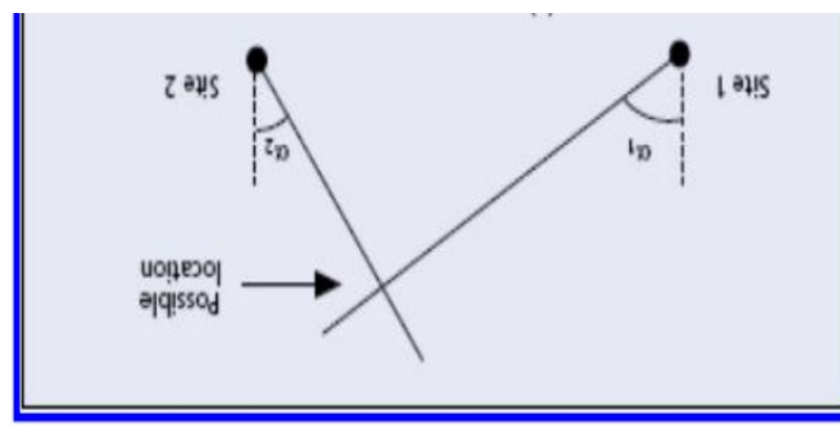
- **Multipath effects**, resulting from signal reflecting on obstacles degrade the accuracy of the technique by lengthening the perceived distance to the base station

Cellular-Based Systems – Radio Modelling

- In addition to TDOA, GSM, and CDMA also provide positioning methods based on angle or arrival (AOA) and time of arrival (TOA)

- AOA is a method that determines position by electronically steering a directional antenna or an antenna array:
    - handset position is determined using triangulation, by intersecting a minimum of two directional lines of bearing



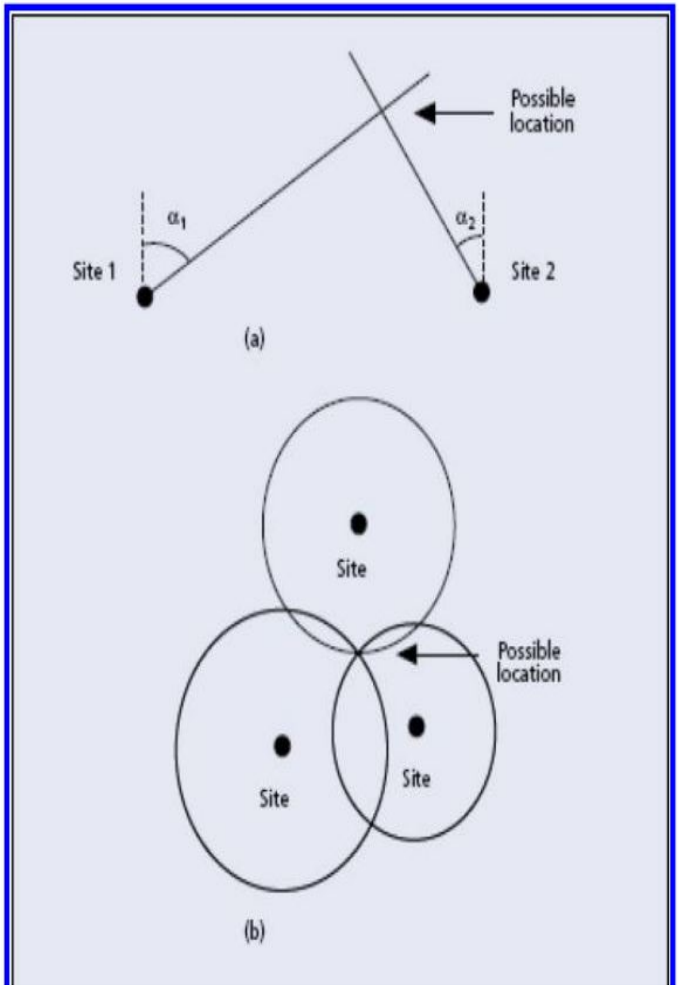


Cellular-Based Systems – Radio Modelling

- The most significant drawback and advantage of AOA is:
  - it **requires specialized antennas and receivers**, which limits this approach to network-based implementations
  - it has the advantage that **it does not require system-wide synchronization** and is **more robust to multipath** propagation effects

- In TOA, the handset position is determined by intersecting range circles:
  - TOA systems can be implemented at either the network or the client

- A significant downside of TOA systems is that:
  - the measuring device has to have accurate knowledge of the time of transmission to determine the signal propagation time
  - note that TDOA systems get around this requirement by taking the difference between measurements



intersection of two hyperbolic curves derived from measurements to three base stations:

- (a) angle of arrival;
- (b) time of arrival;

Cellular-Based Systems – Radio Modelling

- GSM and CDMA location systems based on the measurement of **received signal strength** have also been developed:
  - it is less common than time-based approaches, as it typically achieves lower performance
  - e.g. Place Lab system, which complements their 802.11 signal models with a GSM model that predicts tower distance based on received signal strength

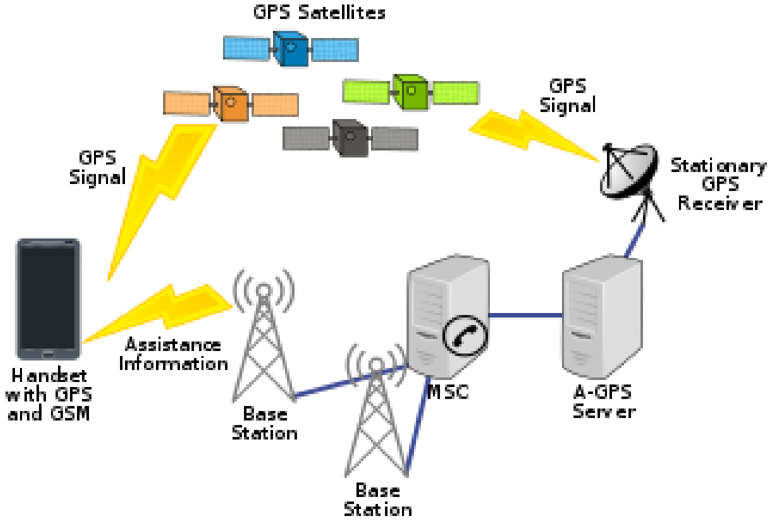
- In Place Lab:
  - GSM cell tower locations are estimated using war-driving tools similar to those used to estimate 802.11 base station locations
  - e.g. in three Seattle neighborhoods, Place Lab achieved median accuracy between 100 and 200 m depending on building and tower density; more densely populated neighborhoods, which tend to have a higher concentration of base stations, had better accuracy
  - the handset-based approach enables location determination without the need for cooperation from the network operator but requires the mobile to store a database of tower locations

Cellular-Based Systems – Signal Strength Fingerprinting

- This solution is very similar to the fingerprinting systems based on 802.11 but there are with some differences:
  - due to higher coverage, cellular fingerprinting has the **potential to work in more places** than 802.11 fingerprinting
  - because cell towers are more dispersed across the covered area, a cellular-based localization system would **still work in situations where a building's electrical infrastructure has failed**
  - the significant expense and complexity of cellular base stations result in a network that **evolves slowly** and is only **reconfigured infrequently**
  - while this lack of flexibility (and high configuration cost) is certainly a drawback for the cellular system operator, it creates a stable environment, and **radio maps for cellular systems will degrade at a slower rate** than those based on 802.11
  - due to shorter range, **802.11 fingerprinting is more accurate** than cellular fingerprinting given the same number of radio sources

Cellular-Based Systems – A-GPS

- A-GPS:
  - Provides GPS satellite information to accelerate and bootstrap mobile phone location.
  - Provides accuracy in the tens of meters, but is still only available on a fraction of mobile handsets



- A-GPS and TDOA complement each other to a large extent:
  - A-GPS is expected to perform best in rural and suburban environments where few obstructions provide for good satellite visibility; in this environment, however, low base station density leads to poor TDOA performance
  - conversely, in downtown areas and other dense urban environments, TDOA has higher coverage than A-GPS, as it works (albeit at reduced accuracy) indoors and in other obstacle-rich environments

Cellular-Based Systems – Comparison

- Three location services: Cell-ID, TDOA, and A-GPS

- Each of these types of location services strikes a different trade-off between:
  - ease of deployment, coverage, and accuracy

- Cell ID provides:
  - the lowest accuracy, but
  - because it does not require additional hardware on the network side, it is the one method that is universally supported by all network providers

- TDOA:
  - provides higher accuracy, but
  - because it requires changes to the network, the handset, or both, it is not yet universally supported

Cellular-Based Systems – Comparison

Technology	GSM signal-strength fingerprinting	GSM TOF and signal-strength modeling	GSM/CDMA proximity	Assisted GPS (A-GPS)
Accuracy	★★★☆ 2D coordinates with 4 m median accuracy in dense cell environment	★★☆☆ 3D coordinates with 100 - 200 m accuracy	★☆☆☆ Accuracy dependant on cell tower density (150 m – 30 km)	★★☆☆ 3D coordinates with 10 -150 m accuracy depending on number of GPS satellites visible
Coverage	★★☆☆ Building to campus scale. Requires cell network coverage and radio map. Best accuracy when 3+ cells are visible	★★★☆ Areas with GSM coverage and radio map. Best accuracy when 3+ cells are visible	★★★★ Anywhere with cell coverage and cell-to-location map	★★★☆ Outdoors with 4+ GPS satellites or indoors with cell network support + view of 1+ GPS satellite
Infrastructure cost	★★★☆ No additional infrastructure is needed beyond cell network. Creating radio map is time intensive	★★★★ No additional infrastructure is needed beyond cell network and map of tower locations	★★★★ No additional infrastructure is needed beyond cell network and map of tower locations	★★★☆ Beyond GPS constellation, requires deployment of fixed GPS receivers
Per-client cost	★★★★ Software only solution	★★★★ Software only solution	★★★★ Software only solution	★★★☆ GPS antenna and chipset required for handset
Privacy	★★☆☆ Even if location is computed on client device, the network still tracks a handset's associated cell	★★☆☆ Even if location is computed on client device, the network still tracks a handset's associated cell	★★☆☆ Even if location is computed on client device, the network still tracks a handset's associated cell	★★☆☆ Even if location is computed on client device, the network still tracks a handset's associated cell
Well-matched use cases	Asset and personnel tracking in indoor environments, indoor mapping/navigation/tour guides	Social networking, emergency response, neighborhood-scale information access, fitness tracking, outdoor mapping / navigation	Regional information access (weather, traffic, etc.)	Emergency response, indoor/outdoor information/tour guide services, personnel/pet tracking, activity tracking, gaming