# Programming Ubiquitous Things 2023/24 - Spring 2024 - UiO

## Location

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- Introduction and some basic definitions
- GPS and Differential GPS
- Infrared and Ultrasonic Location Systems
- Location Estimation with 802.11
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# 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 is more than **US$200 billion**
- **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 location**






# Basic Definitions

- Location:
  - **symbolic** - symbolic location encompasses abstract ideas of where something is: kitchen, room 609, on a train arriving at Oslo central station, 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 (grain size, accuracy) for approximately 95 percent (precision) of measurements
  - **grain size is accuracy**
  - **percentage 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**
- Privacy:
  - location of a user is **obtained locally or on a central service**
- Infrastructure **cost**
- Per-client **cost**

# GPS







## GPS Basics (1/2)

- AVSTAR Global Positioning System (GPS) is by far **the most widely** used location technology
- Huge market for GPS products and services:
  - 2001/2015 was 15 billion euros/140 billion euros
- It was estimated that by 2020, the number of **GPS chipsets** approaches **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** 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 Basics (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 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**:
  - 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
  - in **September 2007**, the U.S. Government announced its decision to **eliminate the feature** from future GPS satellites






# 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**

- Normally, location GPS based services require a **monthly extra-fee**

# Video Example (1/3) – how it works

https://www.youtube.com/watch?v=nBT-KT6ASsc&t=1s findster







# Video Example (2/3) – GPS accuracy

https://www.youtube.com/watch?v=gIGxAC0rTiA&list=PLSFsgkVB0kB5Eedibl5GF4tClBEhkKVoj&index=4&ab_channel=Findster

# Video Example (3/3) – MAZE proprietary protocol

https://www.youtube.com/watch?v=59k-ZjKTtQY&list=PLSFsgkVB0kB5Eedibl5GF4tClBEhkKVoj&index=5&ab_channel=Findster

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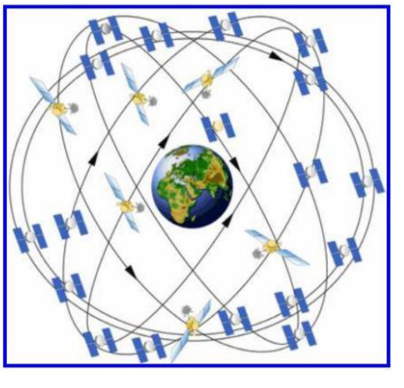
# Architecture (1/3)

- 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 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**



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# 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**


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# 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 aprox. 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



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# Why GPS was Developed (1/5)

- Soviet Union launched the **first artificial satellite** (Sputnik 1) in 1957
- Two American physicists (William Guier and George Weiffenbach) at Johns Hopkins Univ. in the Applied Physics Lab. (APL) decided to **monitor its radio transmissions**:
  - they realized that, because of the Doppler Effect, they could **pinpoint where the satellite was along its orbit**
  - the Director of the APL gave them access to their UNIVAC to do the **heavy calculations** required

- Early the next year, Frank McClure, the deputy director of the APL, asked Guier and Weiffenbach to investigate the inverse problem:
  - **pinpointing the user's location, given the satellite's**
  - at the time, the Navy was developing the submarine-launched **Polaris missile**, which **required them to know the submarine's location**
  - this led them at APL to develop the **TRANSIT** system
  - in 1959, ARPA (renamed DARPA in 1972) also played a role in TRANSIT






# Why GPS was Developed (2/5)

- TRANSIT was first successfully tested in 1960:
  - it used a **constellation of five satellites**, and
  - could provide a **navigational fix approximately once per hour**
- In 1967, the U.S. Navy developed the **Timation** satellite:
  - it proved the feasibility of placing **accurate clocks in space**, a technology required for GPS
- In the 1970s, the ground-based **OMEGA** navigation system:
  - became the **first worldwide radio navigation system**
- Limitations of these systems drove the need for a more universal navigation solution with greater accuracy

- Although there were wide needs for accurate navigation in military and civilian sectors:
  - almost none of those was seen as justification for the **billions of dollars it would cost** in research, development, deployment, and operation of a constellation of navigation satellites
  - during the **Cold War arms race**, the nuclear threat to the existence of the United States was the need that did justify this cost in the view of the United States Congress
  - this deterrent effect is **why GPS was funded** and is also the reason for the **ultra-secrecy at that time**

# Why GPS was Developed (3/5)

- The nuclear triad:
  - consisted of the United States Navy's **submarine-launched ballistic missiles** (SLBMs), along with United States Air Force (USAF) **strategic bombers**, and **intercontinental ballistic missiles** (ICBMs)
  - considered vital to the nuclear deterrence posture, **accurate determination of the SLBM launch position** was a force multiplier
- Precise navigation:
  - would enable United States ballistic missile submarines to get an **accurate fix of their positions before they launched their SLBMs**
  - the USAF, with two thirds of the nuclear triad, also had r**equirements for a more accurate and reliable navigation system**
  - the U.S. Navy and U.S. Air Force were developing their own technologies in parallel to **solve what was essentially the same problem**
- To increase the survivability of ICBMs, there was a proposal to use mobile launch platforms (comparable to the Soviet SS-24 and SS-25):
  - the need to **fix the launch position** had similarity to the SLBM situation






# Why GPS was Developed (4/5)

- In 1960, the Air Force proposed a radio-navigation system called **MOSAIC** (MObile System for Accurate ICBM Control)
- A follow-on study, Project 57, was worked in 1963:
  - it was "**in this study that the GPS concept was born**“
- That same year, the concept was pursued as Project 621B, which had:
  - "many of the attributes that you now see in GPS“, and
  - promised increased accuracy for Air Force bombers as well as ICBMs
- Updates from the **Navy TRANSIT system were too slow for the high speeds of Air Force operation**

# Why GPS was Developed (5/5)

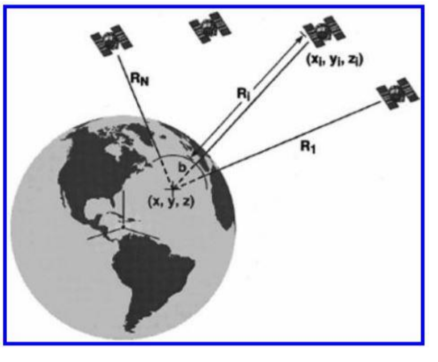
- The Naval Research Laboratory (NRL) continued making advances with their Timation (Time Navigation) satellites:
  - first launched in 1967,
  - second launched in 1969, with the
  - third in 1974 carrying the first atomic clock into orbit,
  - and the fourth launched in 1977
- Another important predecessor to GPS came from a different branch of the US military:
  - in 1964, the United States Army orbited its first **Sequential Collation of Range (SECOR) satellite** used for geodetic surveying
  - it included **three ground-based transmitters at known locations** that would send signals to the satellite transponder in orbit
  - a fourth ground-based station, at an undetermined position, could then use those signals to fix its location precisely
  - the last SECOR satellite was launched in 1969






# Algorithm (1/3)

- Supported by all GPS receivers and allows the receiver to:
  - **estimate its position in three dimensions** (latitude, longitude, altitude)
  - by **tracking four or more satellites**
- 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 satellites**:
  - **Ri is the distance between the receiver and satellite i**,
  - location 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

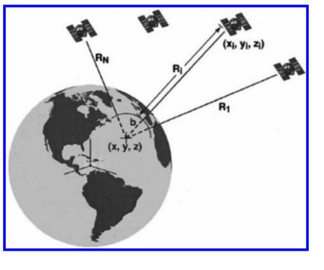





# Algorithm (3/3)

- 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:

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




- 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
  - this is typically done using a least-squares estimation or with a Kalman filter

# Errors and Biases – Ranging Errors

- **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**

- **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

- 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**

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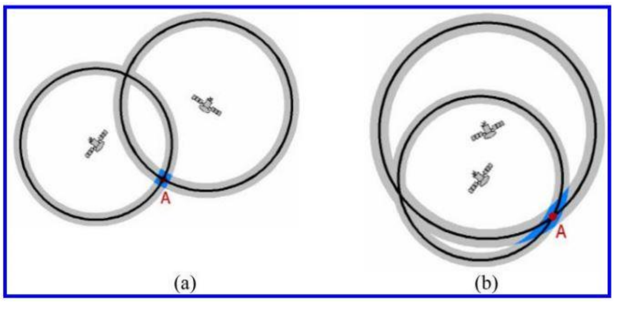
# Errors and Biases – Satellite Geometry Errors

- 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)







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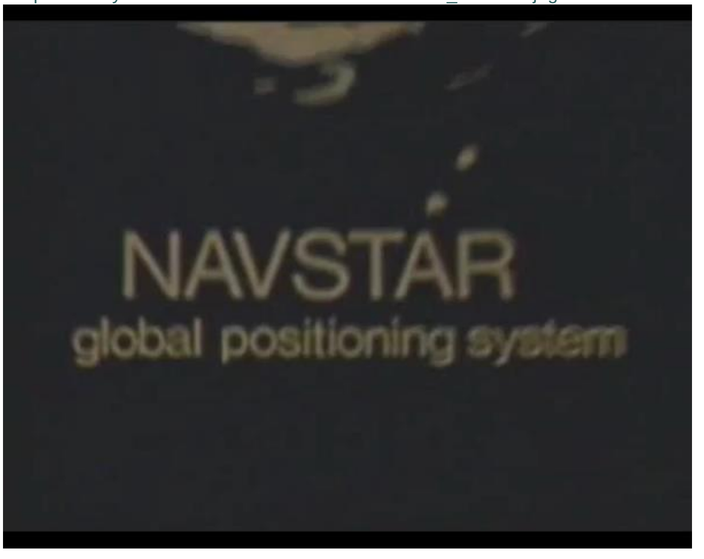
# Initial Video (Navstar was the initial name of GPS)

https://www.youtube.com/watch?v=zYkJL2JAFr4&ab_channel=jaglavaksoldier










# Differential GPS

# Main Idea of Differential GPS

- **Differential GPS takes advantage** of the fact that
  - satellite clock and satellite 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

Where such accuracy and precision (sub-meter using the differential GPS) would be really required?






## 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 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 dollars** and **require line of sight between the coordinating GPS receivers**






# Enhancements and Other GPSs

- The next generation of GPS satellites are being deployed:
  - include **new PRN codes** that will enable civilian receivers to correct for the ionospheric effects that account for a large portion of the GPS error
- The **performance** of DGPS receivers is currently **limited by user equipment and multipath errors:**
  - as such, it is not expected to be affected by GPS modernization
- Other GPSs:
  - motivation is the reluctance to **base critical infrastructure on a service controlled by the armed forces of a foreign nation**

# Other GPSs

- **GLONASS** was originally deployed by the Soviet Union:
  - by 2010, GLONASS had achieved 100% coverage of Russia's territory and in October 2011, the full orbital constellation of 24 satellites was restored, enabling full global coverage

- The **Galileo** system is a 30-satellite location system under development by the European Union:
  - it will be under **full civilian control** under a public–private partnership
  - the EU owns the physical system as a public asset, and a concessionaire deals with day-to-day system operation
  - its architecture also allows for regional and local augmentation to improve service
  - it was expected to become **operational** sometime **between 2011 and 2013**
  - in July 2018, 26 of the planned 30 active satellites were in orbit
  - the complete 30-satellite Galileo system (24 operational and 6 active spares) was expected by 2021

- The planned improvements to GPS and GLONASS and the advent of Galileo:
  - over the next 5 to 10 years, there will **be up to 80 satellites available for positioning**
  - this will lead to the introduction of **multisystem receivers** (dual GPS/GLONASS receivers are already available)

- It is estimated that:
  - **combining GPS, GLONASS, and Galileo**, a ground-based receiver should always be able to **see 21 satellites** except at extreme latitudes **compared to just 6 for the GPS-only solution**
  - a combined **GPS and Galileo system** should have a **median error of approximately 1.5 m**






# Comparison


| Technology | Basic GPS | Differential GPS | 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 |

# Infrared and Ultrasonic Location Systems



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## What are infrared and ultrasonic location systems good for ?



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# Introduction (1/2)

- **Light and sound**:
  - they 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 an application like navigation requires 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 he is in the hallway



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# Introduction (2/2)

- Solutions presented:
  - use **infrared or ultrasound beacons and listeners** to determine a location
  - the **beacons may be embedded in the environment**, and the **listeners are mobile and vice-versa**
  - use **radio signals** to coordinate the location estimation
  - rely on the **ultrasound or infrared signals**
  - some provide symbolic room-level accuracy
  - can use **proximity** or **time-of-arrival** or **angle-of-arrival** to determine the user's location within the room with **room-5–10 cm accuracy**



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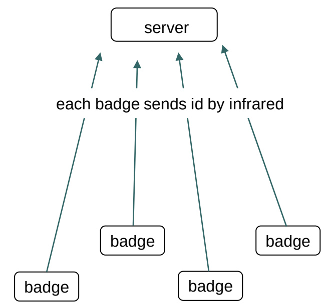
# Room-Level Localization via Proximity - ActiveBadge

- The **first indoor location system** was the **Active Badge**:
  - developed in **1990** at the Olivetti Research Laboratory
- 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 0.1 s to transmit their unique code**, collisions between simultaneously beaconing badges are unlikely






There is fundamental problem with ActiveBadge (infrared signals) which is...

# 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 in pockets or belts 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
- More disadvantages:
  - **requires specialized infrastructure** in the form of base stations to listen for badge IDs
  - **requires users to purchase and carry the badge itself**
- Some nice features:
  - simple design and use of low power parts enable:
    - an Active Badge 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 since the Active Badge system was developed



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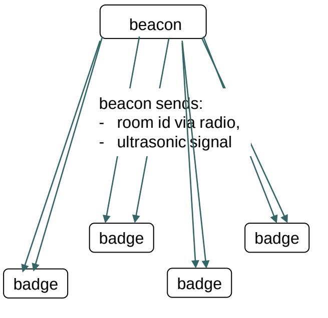
# Room-Level Localization via Proximity – WALRUS (1/2)

- WALRUS uses **PC/PDA speakers and microphones** to **send/receive ultrasonic signals** to convey proximity:
  - it **does not encode the room's ID** using the ultrasonic signal, just **proximity**
  - **it encodes the room's ID using a radio side channel (802.11 datagram),** i.e, **PCs send an 802.11 datagram containing the rooms' identifying** information
  - the **PCs that are serving as beacons** periodically emit a 10-ms pulse of 21-kHz ultrasound
  - 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**



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# Room-Level Localization via Proximity – WALRUS (2/2)

- 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 connote proximity
  - this also extended the useful range of the ultrasound signals generated by the beacons to 13 m in their experiments
- 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**



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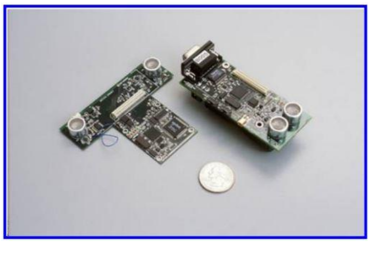
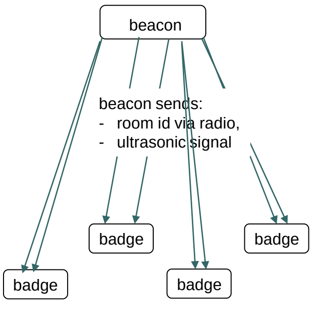
# Cricket - Ultrasonic Time of Flight (1/2)

- 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**
- **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**





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# Cricket - Ultrasonic Time of Flight (2/2)

- Ultrasound travels very slowly (in room-temperature air, sound travels at only 343 m/sec = 0.343 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 traveled**
- 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**, it can **determine location within several centimeters** and **orientation to within 5°**



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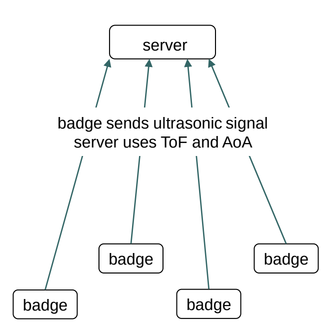
# Absolute Location with ToF and AoA – Active Bat (1/4)

- Goal:
  - 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
- The Active Bat system:
  - was developed by AT&T Research in 1999 uses **ultrasound receivers** to localize small (35 g) pager-like devices called Bats in three-dimensional space
  - it uses **Time of Flight (ToF) and Angle of Arrival (AoA)**
  - it is extremely accurate, estimating location correctly
  - within 5 cm, 50% of the time - 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**
  - **receivers in the infrastructure listen** for and time the pulse's travel



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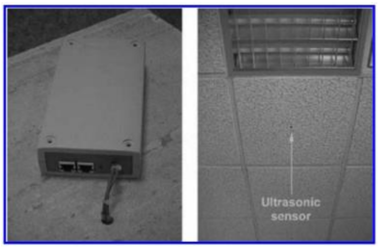
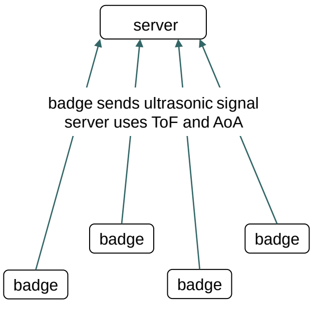
# Absolute Location with ToF and AoA – Active Bat (2/4)

- **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 multi-lateration (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



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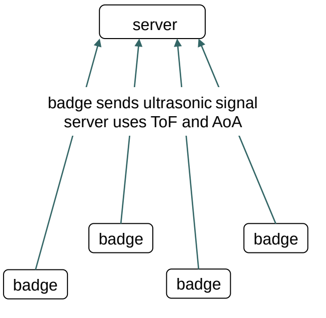
# Absolute Location With ToF and AoA – Active Bat (3/4)

- 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:
  - on the **density of ultrasound receivers**
- Active Bat system is **centrally coordinated**; **bats** wishing to be tracked **register their interest** with a central service via radio




- It employs a slotted schedule to ensure that, at most, one Bat at a time has an ultrasonic pulse in flight
- Ultrasonic reverb can take up to 20 ms to die off in an indoor environment
- Thus, it uses a schedule with 50 slots per second



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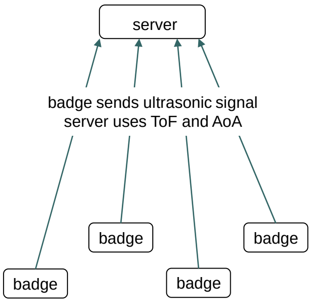
# Absolute Location With ToF and AoA – Active Bat (4/4)

- 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



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# comparison

design and performance



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# Comparison - design

| System | Location Technology | Sender of ID (IR: Infrared US: ultrasound) | Inference avoidance / detection | Location computed by |
|---|---|---|---|---|
| Active Badge | Infrared | badge ID by IR | Collision detection | Server |
| WALRUS | Ultrasound+RF | beacon ID by RF | None | Client |
| Cricket | Ultrasound+RF | beacon ID by RF | Collision detection | Client |
| Active Bat | Ultrasound+RF | Bat ID by RF | Central schedule | Server |



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# Comparison - performance


| 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 |



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# Indoor Location – An Example

https://www.youtube.com/watch?v=wtBERi7Lf3c BLE indoor location



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# Location Estimation with 802.11



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# Introduction (1/2)

- 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 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**
- **Lighthouse** metaphor: → proximity
  - if you can see the lighthouse, you know you're getting close to shore
- If a **device can see more than one AP**: → signal strength
  - 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



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# Introduction (2/2)

- The appeal of using 802.11 for location estimation is strong:
  - **nearly all mobile devices** have built-in 802.11
  - many **known mapped 802.11 access points**
  - high densities raise the possibility of **high-coverage indoor/outdoor location with no additional location infrastructure or cost**
- 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 hotpot" 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



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# Introduction (2/2)

- The appeal of using 802.11 for location estimation is strong:
  - **nearly all mobile devices** have built-in 802.11
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## Signal Strength Fingerprinting and Signal Strength Modelling

- To allow client dev ...
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# Signal Strength Fingerprinting



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# 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 to not change between the time of mapping and the location estimation

**Wardriving** is the act of searching for Wi-Fi wireless networks by a person in a moving vehicle, using a portable computer, a smartphone or a personal digital assistant (PDA).



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What are the main drawbacks of Signal Strength Fingerprinting ?



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# Signal Strength Fingerprinting – Radar (1/2)

- 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 a 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)



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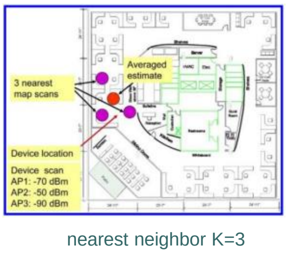
# Signal Strength Fingerprinting – Radar (2/2)

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


nearest neighbor




nearest neighbor K=3



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## 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**
- 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 (1/2)

- 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 electromagnetic 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**
  - fingerprinting **does not scale well**



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## Signal Strength Fingerprinting – Conclusion (2/2)

- 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 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**



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# 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 (1/3)

- 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:
  - has 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**



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# Signal Strength Modeling - Active Campus (2/3)

- It succeeded in achieving high coverage:
  - **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** as 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



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# Signal Strength Modeling - Active Campus (3/3)

- The Active Campus location system used an **AP database** storing:
  - latitude, longitude, and floor number for each known access point
- In the tests:
  - average estimation **accuracy of 22 m outdoors and 11 m indoors**
  - **AP densities observed indoors** are bigger than **outdoors** is why there is higher accuracy indoors,
  - indoor obstructions effectively reduced AP ranges and shrank 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



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# Signal Strength Modeling – PlaceLab (1/2)

- What if we want to use ActiveCampus **outside the campus** ?
  - PlaceLab 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**

**Wardriving** is the act of searching for Wi-Fi wireless networks by a person in a moving vehicle, using a portable computer, smartphone or personal digital assistant (PDA).



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## Signal Strength Modeling – PlaceLab (2/2)

- The observation of Place Lab was that:
  - war driving tools 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**
- 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 PlaceLab yielded accuracy numbers 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**

**Wardriving** is the act of searching for Wi-Fi wireless networks by a person in a moving vehicle, using a portable computer, smartphone or personal digital assistant (PDA).



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## Signal Strength Modeling – AP Database (1/2)

- Active Campus and PlaceLab **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**

**Wardriving** is the act of searching for Wi-Fi wireless networks by a person in a moving vehicle, using a portable computer, smartphone or personal digital assistant (PDA).



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## Signal Strength Modeling – AP Database (2/2)

- 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 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, PlaceLab 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



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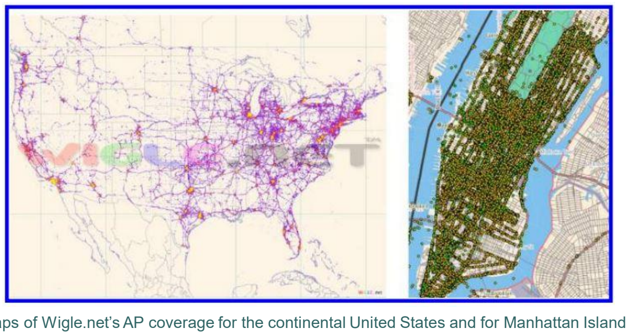
## Signal Strength Modeling – Conclusion

- 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



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# Location Estimation with 802.11 - Privacy Considerations



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## Privacy Considerations (1/2)

- 802.11 location systems have been architected in various ways and this has an impact on the privacy guarantees they offer their users
- The privacy of 802.11 location systems can be excellent if:
  - it is implemented entirely with passive radio reception and client-side computation
- Such client-side approach is used by:
  - PlaceLab, Ekahau, and others
- Other systems have, for various reasons, implemented some of the functionality in the infrastructure:
  - lessening a client's privacy guarantees
- E.g., the original RADAR system was actually implemented by having:
  - APs listen for packets from clients and then pool their observations to make an estimate of the client's location



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# Privacy Considerations (2/2)

- Skyhook Wireless and Active Campus:
  - run a small client-side program that performs the network scan,
  - the results of which are shipped to a central server that performs the location estimation
- On the upside, such an approach:
  - allows the client software to be minimal and the AP database to be both centrally maintained and safe guarded
- On the downside, such an approach:
  - it both requires the client to have network connectivity to do location estimation and compromises the user's privacy



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# Location Estimation With 802.11 - Comparison



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## Comparison

worst
★☆☆☆
★★☆☆
★★★☆
★★★★
best

| Technology | 802.11 signal-strength fingerprinting (e.g., RADAR) | 802.11 signal-strength modeling (e.g., Place Lab) | 802.11 proximity (e.g., GUIDE) |
|---|---|---|---|
| Accuracy | ★★★☆ 2D coordinates with 1-3 m median accuracy | ★★☆☆ 2D coordinates with 10-20m median accuracy | ★☆☆☆ Location accuracy dependant on AP density |
| 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. | ★★★☆ Anywhere with 802.11 coverage and an AP, location map. |
| 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. | ★★★★ No additional infrastructure is needed beyond 802.11 APs. |
| Per-client cost | ★★★★ Software-only solution for devices with 802.11 NICs. | ★★★★ 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. | ★★★★ 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 | Outdoor tour guides, nearby resource advertisement, activity tracking |



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# Cellular-Based Systems



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# 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 providing 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 / radio modeling / assisted GPS / fingerprinting**
- Each type of location system has a different trade-off between:
  - **ease of deployment, coverage, and accuracy**





# Cellular-Based Systems – Cell ID-Based (1/2)

- 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)

# Cellular-Based Systems – Cell ID-Based (2/2)

- The sytem 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 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)
  - **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**



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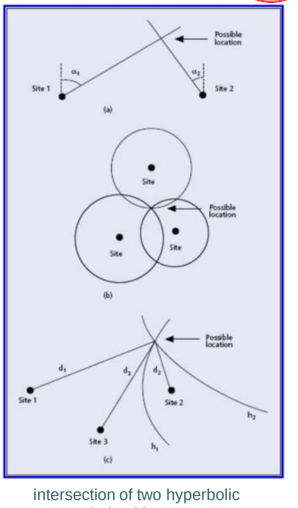
# Cellular-Based Systems – Radio Modelling (1/6)

- A **variety of location systems based on modeling** 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 **modeling 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**




intersection of two hyperbolic curves derived from measurements to three base stations:
- (a) angle of arrival;
- (b) time of arrival;
- (c) time difference of arrival



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# Cellular-Based Systems – Radio Modelling (2/6)

- **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 on 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 cells
  - provides a **higher degree of privacy to users**, as time-difference is measured and the location estimated on the user's local device



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# Cellular-Based Systems – Radio Modelling (3/6)

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



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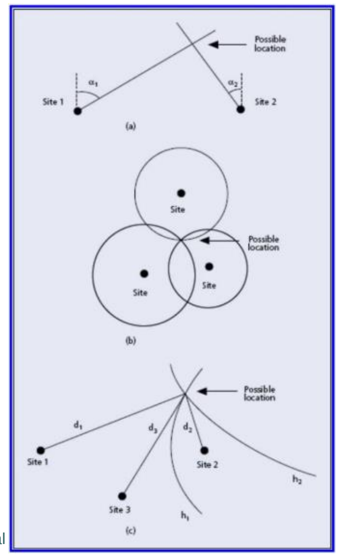
## Cellular-Based Systems – Radio Modelling (4/6)

- 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




intersection of two hyperbolic curves derived from measurements to three base stations:
- (a) angle of arrival;
- (b) time of arrival;
- (c) time difference of arrival



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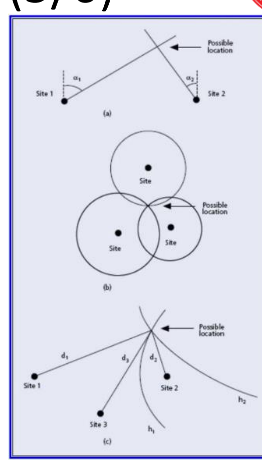
## Cellular-Based Systems – Radio Modelling (5/6)

- 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
  - that is why **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;
- (c) time difference of arrival



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# Cellular-Based Systems – Radio Modelling (6/6)

- 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., PlaceLab system, which complements their 802.11 signal models with a model that predicts tower distance based on received signal strength

- In Place Lab:
  - **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**



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# Cellular-Based Systems – Signal Strength Fingerprinting (1/2)

- Signal strength fingerprinting is an empirical location technique that involves:
  - a "training" or "mapping" phase in which a radio map of the environment is constructed by collecting a series of fingerprints in multiple location

- A radio fingerprint reflects some property, commonly as the signal strengths, of a group of radio sources that are heard at a specific location

- Once the training phase is complete:
  - **a client can determine its location by looking for the closest matches of the current measurement to the set of measurements collected in the training phase**



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## Cellular-Based Systems – Signal Strength Fingerprinting (2/2)

- This solution is **very similar to the fingerprinting systems based on 802.11** but there are 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, **radio maps for cellular systems will degrade**
  - due to shorter range, **802.11 fingerprinting is more accurate** than cellular fingerprinting given the same number of radio sources



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## Cellular-Based Systems – Comparison

- Three location services: Cell-ID, TDOA
- 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



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# Cellular-Based Systems – Comparison


| Technology | GSM signal-strength fingerprinting | GSM TOF and signal-strength modeling | GSM/CDMA proximity |
|---|---|---|---|
| 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) |
| 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 |
| 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 |
| Per-client cost | ★★★★ Software only solution | ★★★★ Software only solution | ★★★★ Software only solution |
| 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 |
| Well-matched use cases | Asset and personnel tracking in indoor environments, indoor mapping/navigation/tour guides | Social networking, emergency response, neighorhood-scale information access, fitness tracking, outdoor mapping / navigation | Regional information access (weather, traffic, etc.) |



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# Global Overview (techniques)

AOA is the angle and distance calculated relative to two or multiple reference points through the intersection of direction lines between the reference points.

TOA is the time taken by a signal to arrive at a receiver from a fixed transmitter, with the transmitter as the reference point

TDOA determines the relative position of a mobile transmitter based on the difference in the propagation time of arrival of the transmitter and multiple reference points or sensors

Signal properties are geometrical parameters consisting of metrics such as angle, distance and signal to measure an object's position using calculations

Angle of Arrival (AOA)

Time of Arrival (TOA)

Time Difference of Arrival (TDOA)

Received Signal Strength Indication (RSSI)

RSSI is a measure of the power level of the RSS present in a radio infrastructure that can be used to estimate the distance between mobile devices

Signal Properties

Location Techniques

**Both the signal property and the location algorithm work together to determine the location of an object. The location algorithm processes the signal property and outputs a location.**

Scene Analysis or Fingerprinting collects information or features from a scene or observation and then estimates the location of an object by matching or comparing the collected information with the one in an existing database

Location Algorithms

Location algorithms translate the recorded signal properties into distances and angles, and then computes the actual position of a target object

Triangulation

Trilateration

Proximity

Scene Analysis/ Fingerprinting

Triagulation: The location of an object is determined by calculating the position of a transmitter based on the angle and distance relative to two known reference points

Trilateration: The distance measurements relative to three known reference points are used to determine position by computing the attenuation of the transmitted signal

Proximity: The location of an object is the same as the closer antenna



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## Global Comparison – signals properties and location algorithms

| Signal property | Measurement metric | Pros | Cons |
|---|---|---|---|
| Angle of Arrival (AOA) | Angle-based | High accuracy at room level | Complex, expensive and low accuracy at wide coverage |
| Time of Arrival (TOA) | Distance-based | High accuracy | Complex and expensive |
| Time Difference of Arrival (TDOA) | Distance-based | High accuracy | Expensive |
| Received Signal Strength Indication (RSSI) | Signal-based (RSS) | Low cost | Medium accuracy |

| Positioning algorithm | Signal property | Pros | Cons |
|---|---|---|---|
| Triangulation | AOA | Simple, low-cost and high accuracy at room level | Complex, expensive and low accuracy at wide coverage |
| Trilateration | TOA/TDOA | High accuracy | Complex and expensive |
| Proximity | RSSI | High accuracy | Complex and expensive |
| Scene analysis/fingerprinting | RSSI | High performance | Complex, expensive, medium accuracy and time consuming |



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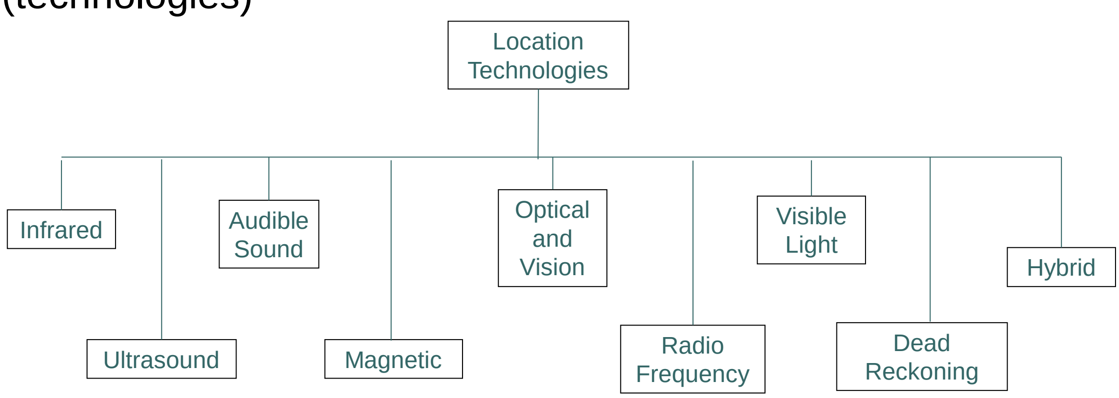
## Global Overview (technologies)



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# Other Approaches



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## Other Approaches – Introduction

- The location technologies we have described thus far:
  - vary in cost, coverage, and accuracy,
  - all are used in commercial location systems, and
  - all have reached wide-scale adoption in one or more application niches
- There are, however, **many other location technologies that have not gotten beyond the research laboratory or the prototype stage**
- There are **others**, too, that have been **largely perfected**, but due to **small coverage or exceptionally high cost** have not moved beyond a few highly **specialized niches**
- Some systems:
  - have 1 mm average error, and the least, with almost 100 km average error
  - eliminate the need for people to carry beacons or listeners and instead use a person's visual appearance, noise profile, or ground reaction forces to track them through an environment
  - in addition to the GPS, 802.11, and cell-phone-based system, there are many other radio-based systems based on both standard and custom protocols ranging in spectrum from 33 kHz up to 7 GHz



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# Other Approaches – Systems

- Instrumented surfaces (base location estimation on something physical and fundamental):
  - Smart Floor, Magic Carpet
  - load sensors placed in the floor are likely to be robust, unobtrusive, and low-maintenance,
  - whereas some of these systems are **limited in their handling of multiple occupancy situations**, they can correctly detect occupancy and thus still work well for occupancy-based services
  - they **can be easily used into an existing home or office space** (assuming the elevated floor is OK)
- Vision:
  - it is one of the few approaches that **do not require instrumenting or tagging** the entity to be located
  - mobile (e.g., robotic navigation) / fixed cameras (e.g., track the location of the people that appear on camera ),
  - visual tags (e.g., 2-D barcodes designed to be easily recognized by cameras)
- Laser range finders, Audible sound, Internet protocol measurement, Magnetic field strenght, Radio frequency identification tags, Radio from FM to ultrawide band, etc.



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# Other Approaches - Comparison


| Technology | Smart floors | Vision with fixed cameras | Vision + 2D tags | IP measurement |
|---|---|---|---|---|
| Accuracy | ★★★★ 2D location with 10 – 20 cm accuracy (person may not be IDed) | ★★★☆ 3D location with 10 – 100 cm depending on camera density | ★★★★ 3D location with 1 cm accuracy when observed from < 2 m away | ★☆☆☆ 2D location with 70-200 km accuracy |
| Coverage | ★★☆☆ In rooms fit with in-floor sensors. Performs poorly with multiple users in room | ★★☆☆ Indoor/outdoor in view of camera | ★★☆☆ Indoor/outdoor in view of camera | ★★★★ worldwide for any networked computer device |
| Infrastructure cost | ★☆☆☆ Cost of retrofitting for load sensors prohibitive | ★★☆☆ Requires networked cameras in each room | ★★☆☆ Requires networked cameras in each room | ★★★★ uses existing IP network |
| Per-client cost | ★★★★ Requires no user instrumentation | ★★★★ Requires no user instrumentation | ★★★☆ Requires 2D tags on objects / people to be tracked | ★★★★ Requires no extra hardware or software |
| Privacy | ★★☆☆ User's location known, but identity often not | ★☆☆☆ Video surveillance among worst intrusions on privacy | ★☆☆☆ Video surveillance among worst intrusions on privacy | ★★★★ No addition information released |
| Well-matched use cases | Assisted living, HVAC/smart home control | Asset and personnel tracking, security / surveillance | Asset and personnel tracking | National/regional information and advertisement delivery |



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## Other Approaches - Comparison

★☆☆☆ worst
★★☆☆
★★★☆
★★★★ best

| Technology | Magnetic field strength | RFID with fixed readers and mobile tags | Ultra-wide band radio TOF/AOA | TDOA from digital TV |
|---|---|---|---|---|
| Accuracy | ★★★★ 3D location with 1 mm accuracy | ★★★☆ Room (or area of room) with high accuracy | ★★★★ 3D location with 15 cm accuracy | ★★☆☆ 3D coordinates with 10-20 m median accuracy |
| Coverage | ★☆☆☆ User must be within 3 meters of transmitter | ★★☆☆ Indoor in room fit with readers | ★★☆☆ Indoor in range of UWB listeners | ★★★★ indoor/outdoor in range of TV towers |
| Infrastructure cost | ★☆☆☆ transmitters cost $50k+ US | ★☆☆☆ Long-range RFID readers required for each room | ★★☆☆ Requires 2+ UWB listeners | ★★★★ piggybacks timing info on existing TV signals |
| Per-client cost | ★☆☆☆ Users fit with costly magnetic sensors | ★★★★ Each object / person requires inexpensive tag | ★★★☆ UWB badge required | ★★★☆ antenna and chipset required |
| Privacy | Not a factor for such specialized systems | ★★☆☆ Locations tracked by infrastructure. Opt-out by removing tag | ★★☆☆ Locations tracked by infrastructure. Opt-out by removing badge | ★★★★ Location is estimated passively on the local unit |
| Well-matched use cases | Motion capture for video games and animated media (cartoons) | Asset and personnel tracking, indoor mapping/ navigation/tour guides | Asset and personnel tracking, indoor mapping/ navigation/tour guides | Social networking, assisted living, activity tracking |



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# Location-Based Applications and Services



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# Location-Based Applications and Services

- Navigation and way-finding
- Asset tracking
- Emergency response
- Geofencing
- Location-based content and search
- Social networking
- Health and wellness
- Gaming and entertainment










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# Conclusions

- It’s a hot topic

- Much more is expected in the near future:
  - applications
  - security
  - technologies
  - behaviour changes
  - social impact
  - etc.

- Stay tuned !



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