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Tracking Individuals

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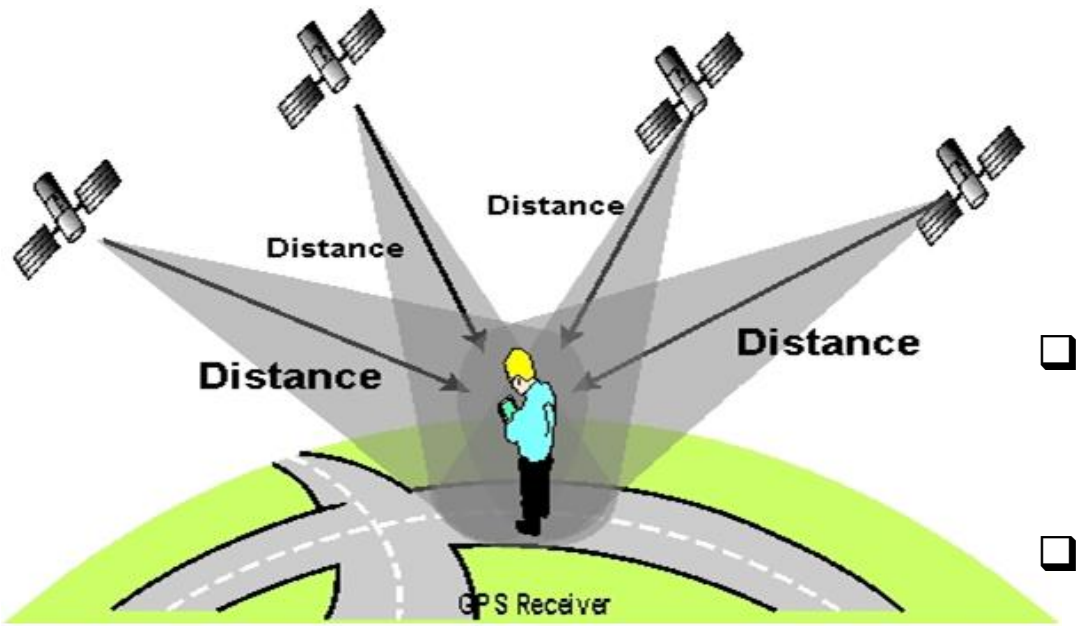
Outline

- GPS
- Bluetooth
- Wi-Fi
- Cellular Telephony
- BSSID/Cell-ID Positioning Systems
- Trilateration
- Multilateration
- RSSI
- TDOA
- Fingerprinting
- Camera-based Positioning
- Information Use

Localization

- What is the purpose of localization?
  - Localization of individuals
  - Localization of assets
- Who performs the localization?
  - Individuals
  - Organizations
  - Third Parties
- Where is the localization performed?
  - Outdoors
  - Indoors

GPS Localization (Outdoors)

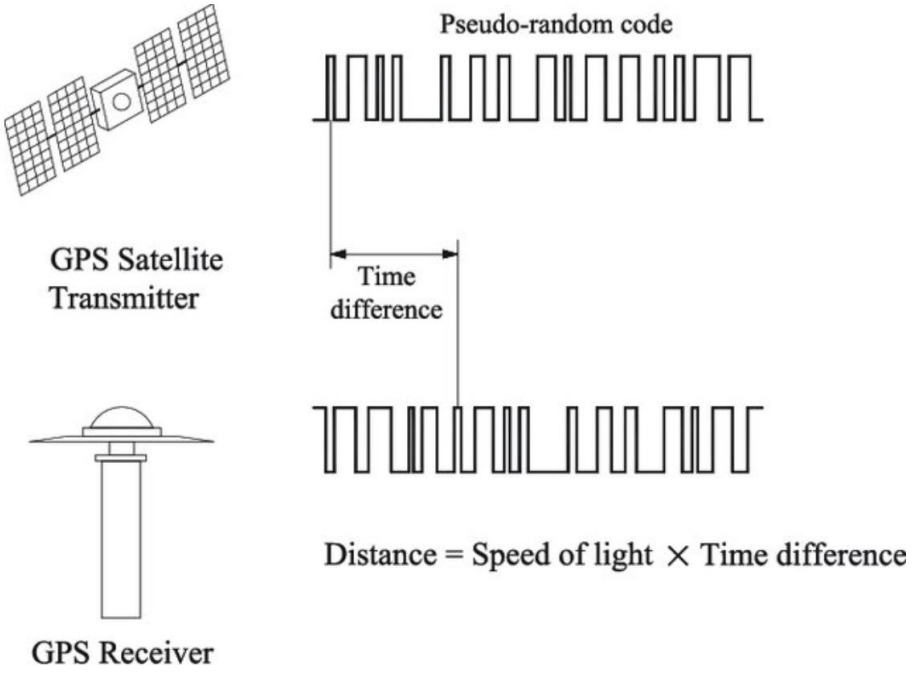


Source: https://owaysonline.com/global-positioning-system-on-ships/

- Global Positioning System (GPS): true position within 10 m for 90% of all measurements
- Based on atomic clocks
- Uses radio signals
- Requires Line-of-Sight (LOS)
- Purpose: navigation

How Does the GPS Work?

- GPS satellite Medium Earth Orbit (MEO)
- Transmission Power 44.8 W
- GPS satellites send pseudo-random sequences over the radio, e.g., the L1 (1575.42 MHz) and L2 (1227.60 MHz) channels
- Due to the signal propagation, the signal arrives at the receiver with a delay



Source: Im SB, Hurlebaus S, Kang YJ. Summary review of GPS technology for structural health monitoring. Journal of Structural Engineering. 2013 Oct 1;139(10):1653-64.

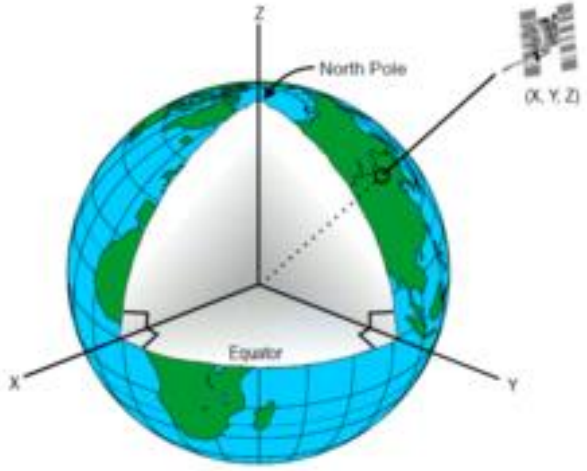
Position & Clock Drift Estimated

$$P^1 = \left((x^1 - x)^2 + (y^1 - y)^2 + (z^1 - z)^2 \right)^{1/2} + c\tau - c\tau^1$$

$$P^2 = \left((x^2 - x)^2 + (y^2 - y)^2 + (z^2 - z)^2 \right)^{1/2} + c\tau - c\tau^2$$

$$P^3 = \left((x^3 - x)^2 + (y^3 - y)^2 + (z^3 - z)^2 \right)^{1/2} + c\tau - c\tau^3$$

$$P^4 = \left((x^4 - x)^2 + (y^4 - y)^2 + (z^4 - z)^2 \right)^{1/2} + c\tau - c\tau^4$$



Source: Wikipedia

- $P^1, \ldots, P^4$ – distances measured to satellites 1,…, 4
- $(x^1, y^1, z^1), \ldots, (x^4, y^4, z^4)$ – positions of satellites 1,…, 4
- c – speed of light
- $\tau^1, \ldots, \tau^4$ – clock drift at the satellite

Source: Blewitt G: Basics of the GPS technique: observation equations. Geodetic Applications of GPS, p. 15, 1997.

GPS Summary

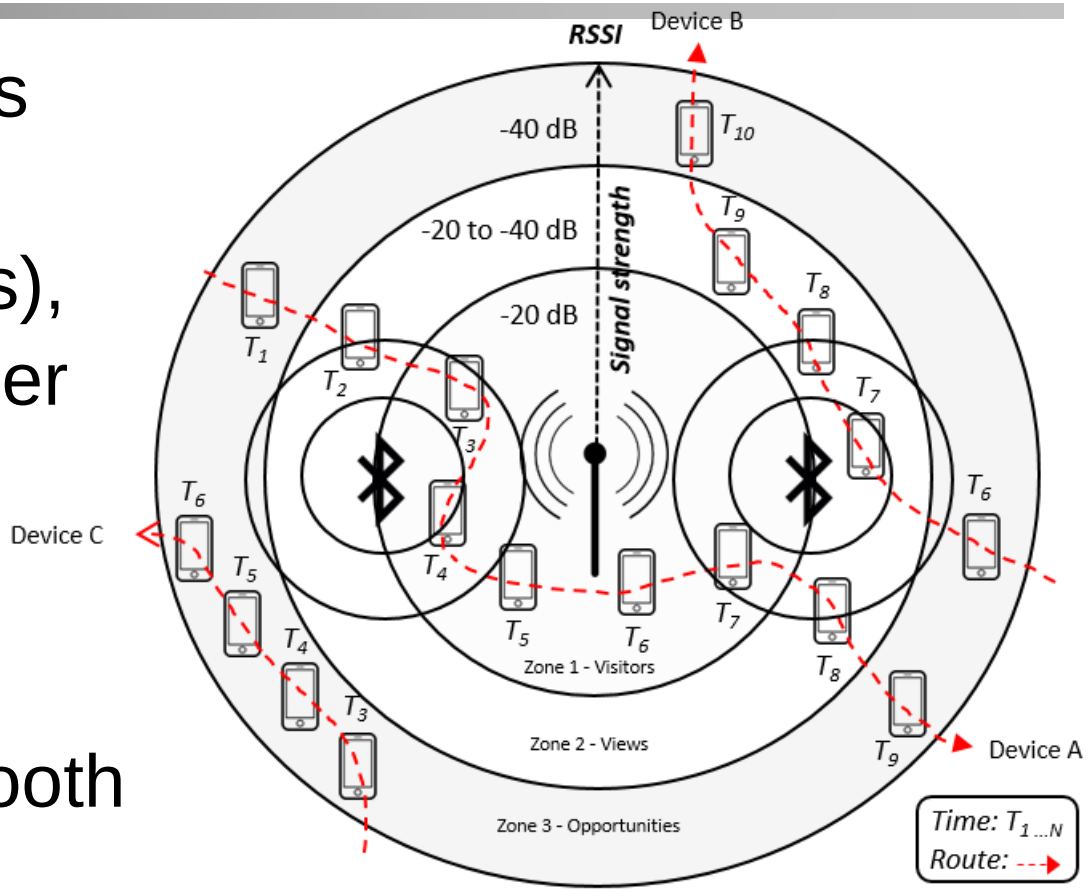
- Computing is local on the receiver
- C/A & P-code used for distance estimation
- User-centric localization technology
- Uses radio signals for position estimation
- Requires a specialized receiver, (i.e., does not send any signals).
- Requires LOS, therefore, cannot be used indoors
- Localization is:
  - Individual/asset-centric
  - Performed by users (resp. assets) themselves
  - Suited for outdoor applications

Other Localization Techniques

- Individual/asset-centered localization
  - Localization is performed on a device belonging to the individual
  - The information on the location does not have to be necessarily shared with third parties,
- Organization-based localization
  - For example, in network localization in Mobile Telephony
  - Typically, the user has a contractual agreement with a given organization (or not!)
- Third Party Localization
  - Performed by third parties, no contractual agreements,
  - WiFi, Bluetooth, Cameras

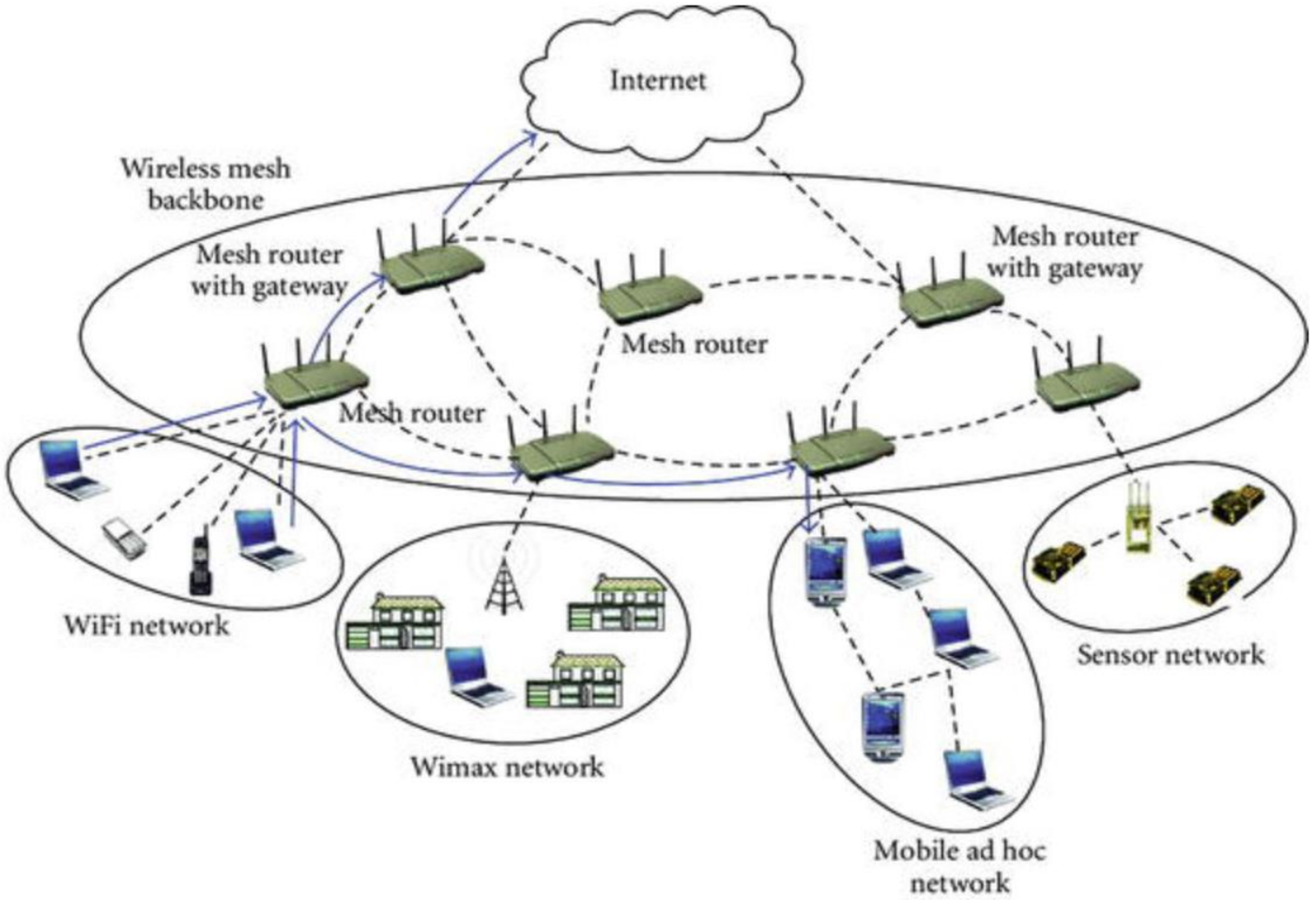
Wi-Fi / Bluetooth Localization

- The lack of GPS indoors (i.e., signals do not propagate through walls), causes the need for other localization techniques
- For example, Wireless Fidelity (Wi-Fi) or Bluetooth could be used instead



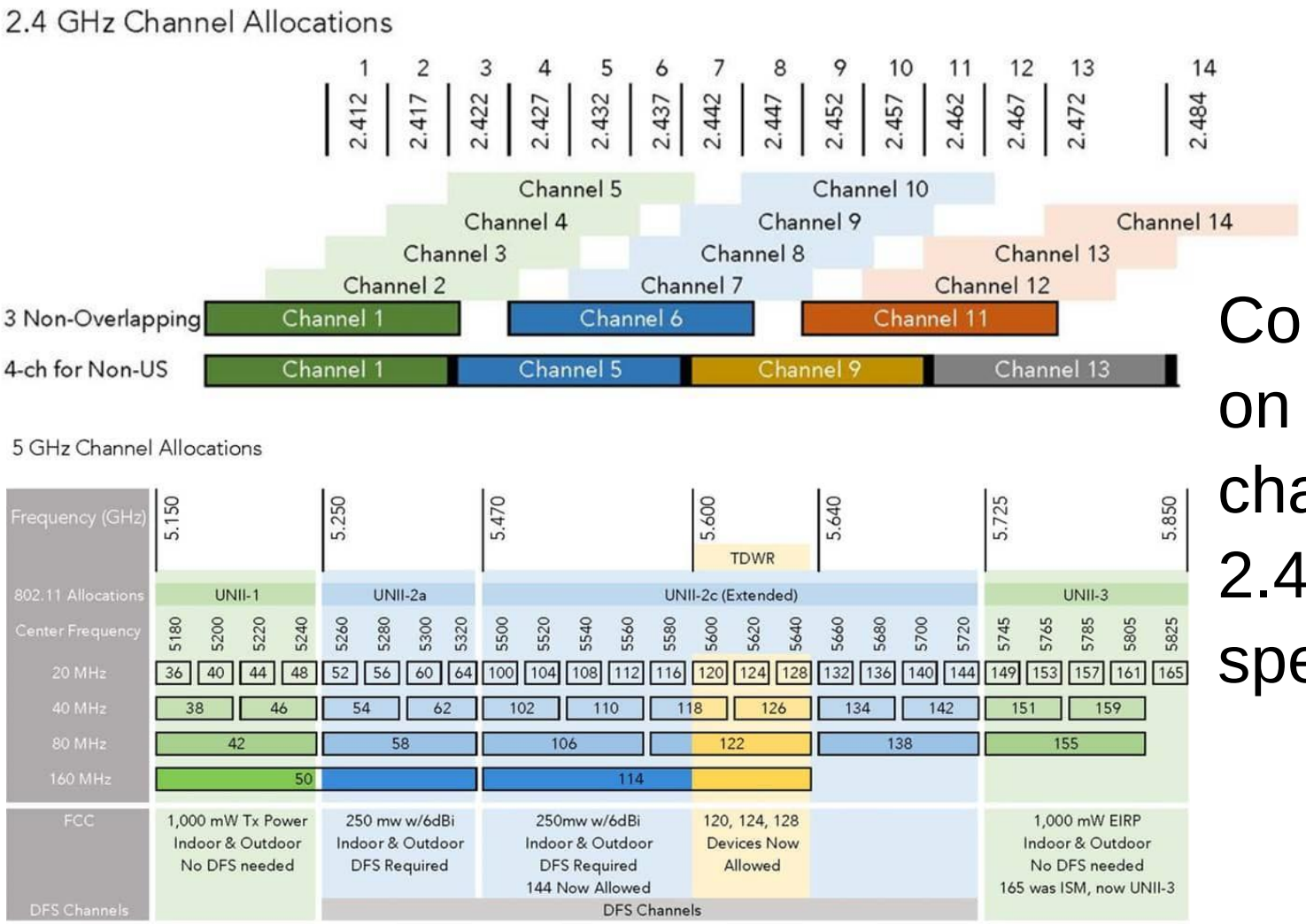
Source: https://www.csg.uzh.ch/csg/en/research/PasWITS.html

Wireless Networks (IEEE 802.11)



Source: https://www.openpr.com/news/2078480/wireless-mesh-network-market-showing-13-94-cagr-growth-to-2025

Wi-Fi Communication Channels



Communication on a single channel in the 2.4 or 5 GHz spectrum range

Source: Wireless LAN Professionals

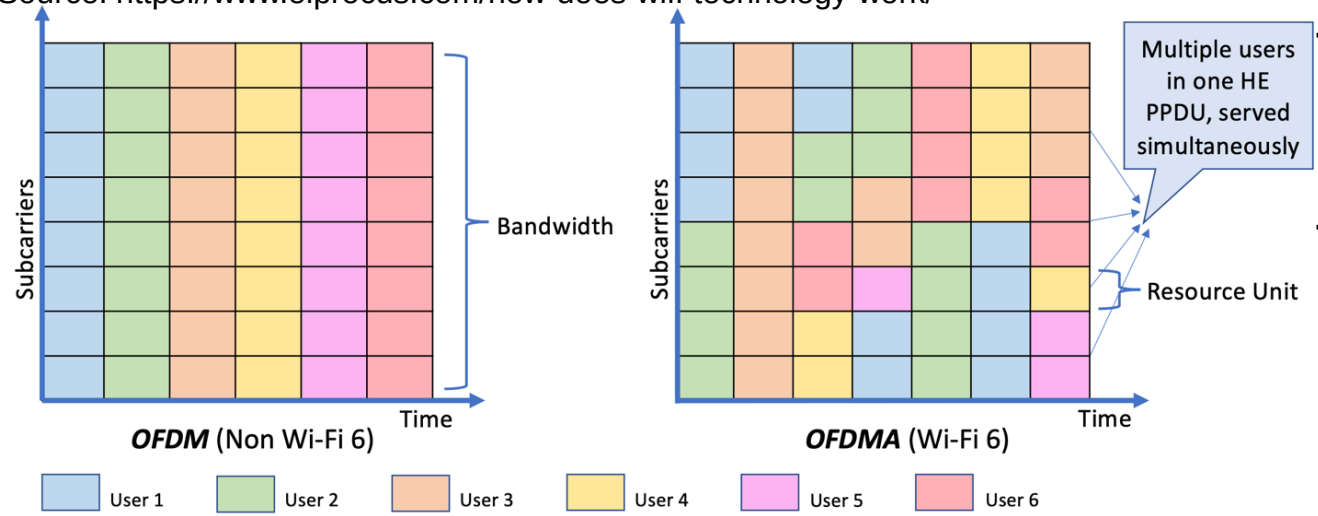
Wi-Fi Communication Basics

AP = BSSID

Wireless stations exchange IEEE 802.11 frames

Source: https://www.oreilly.com/library/view/80211-wireless-networks/0596100523/ch04.html

Source: https://www.elprocus.com/how-does-wifi-technology-work/



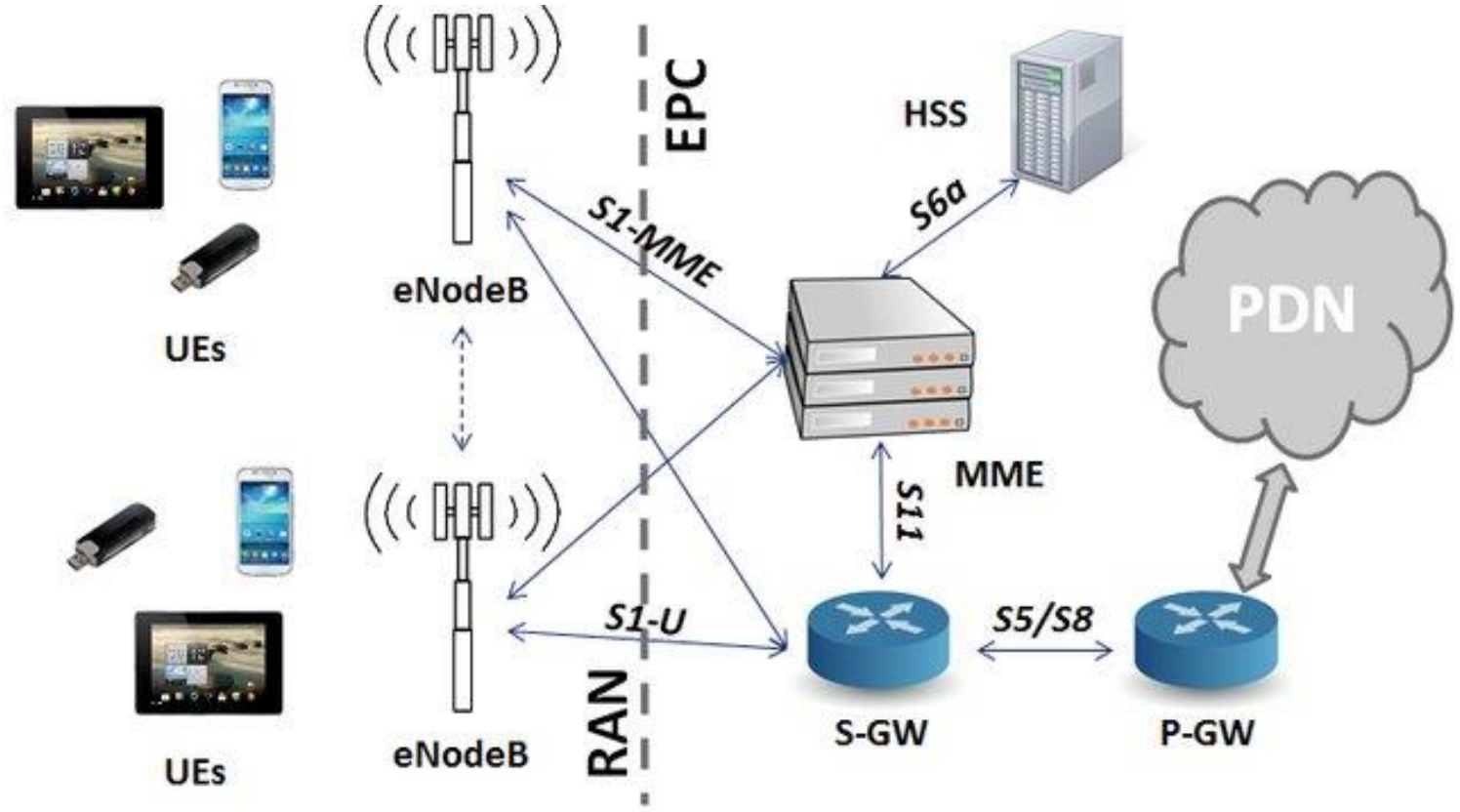
through the wireless channel shared in time and frequency

Source: https://blogs.cisco.com/networking/wi-fi-6-ofdma-resource-unit-ru-allocations-and-mappings

Wi-Fi Localization

- Mostly indoor setups, but can work outdoors too
- Both Access Points (AP) and Stations send data
  - Users can localize themselves, by observing signals from APs of known positions nearby
  - Network can localize a user (MAC) who sends data
  - Third parties can localize users (MACs), who send data
  - Third parties can localize users, who actively probe for networks, but do not send send data yet (MAC).

Mobile Networks (2-5G)



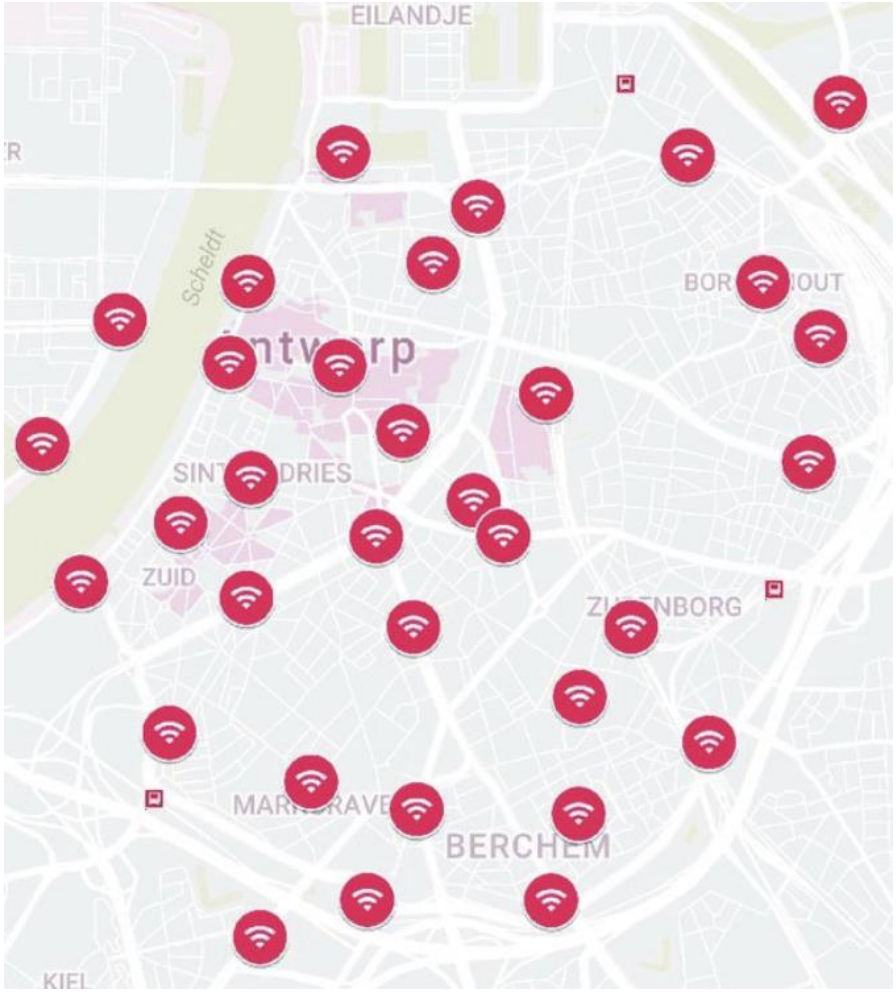
J. Jermyn, R. P. Jover, I. Murynets, M. Istomin and S. Stolfo, "Scalability of Machine-to-Machine systems and the Internet of Things on LTE mobile networks," *2015 IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Boston, MA, 2015, pp. 1-9, doi: 10.1109/WoWMoM.2015.7158142

Mobile Localization

- Mostly outdoors, but can be used indoor too
- Both Cells and User Equipment (UE) send data
  - Users can localize themselves, by observing signals from APs nearby
  - Network can localize a user who sends data
  - Third parties cannot localize users as the privacy is better protected
    - Based on random identifiers, user identification rarely sent, however a plain-text International Mobile Subscriber Identity (IMSI) sent sometimes unprotected in 2G-4G networks
    - Tracking based on impersonating legitimate cells and deploying IMSI catchers.

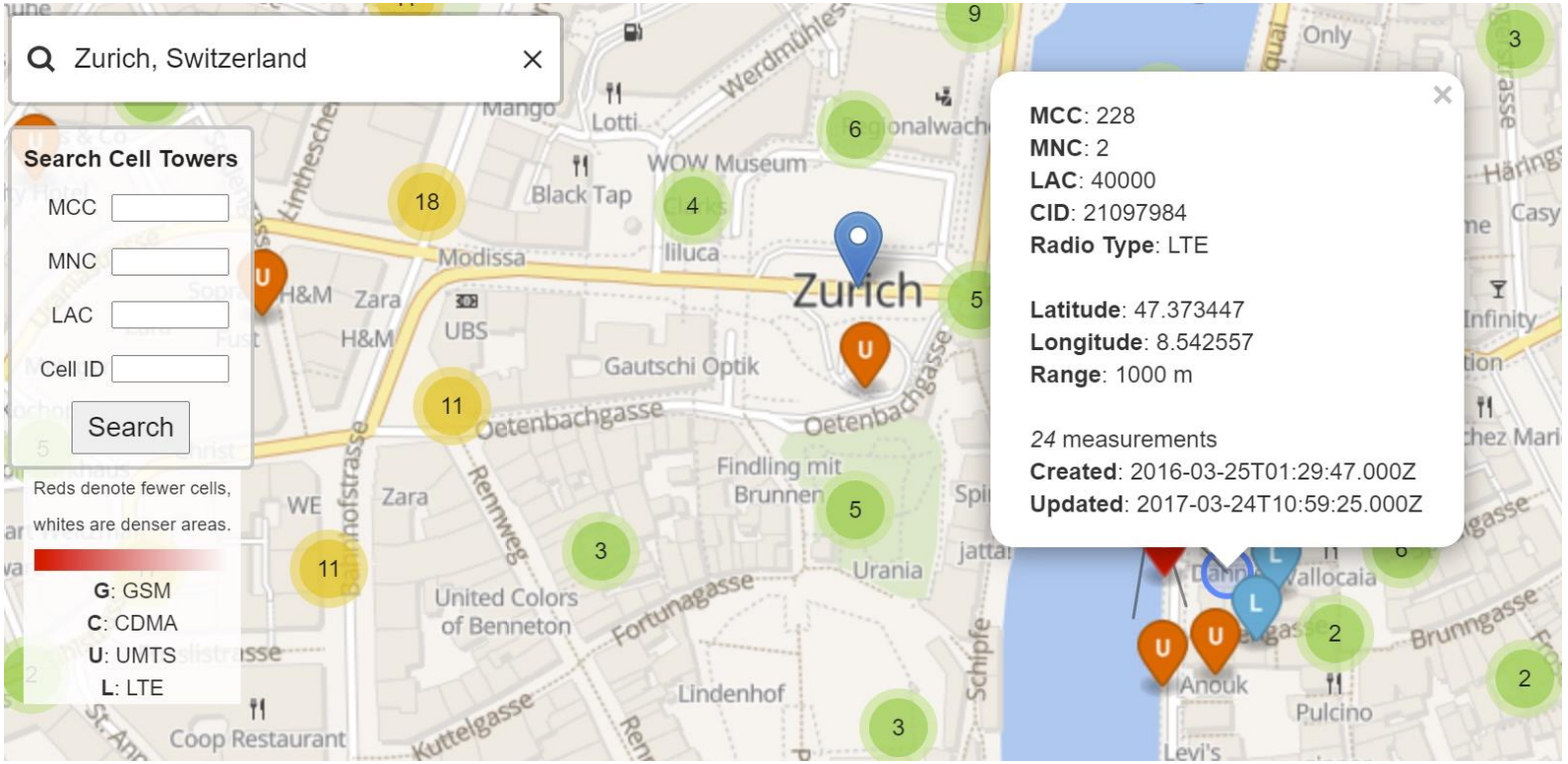
Wi-Fi Positioning System (WPS)

- BSSID-based Wi-Fi location system
- The database contains APs (BSSIDs) with known geographical location
- Translates BSSIDs received by the user to location estimates
- Accuracy ~100 m



Source: Janssen T, Weyn M, Berkvens R. Localization in low power wide area networks using wi-fi fingerprints. Applied Sciences. 2017 Sep;7(9):936.

Cell ID-based Location Systems



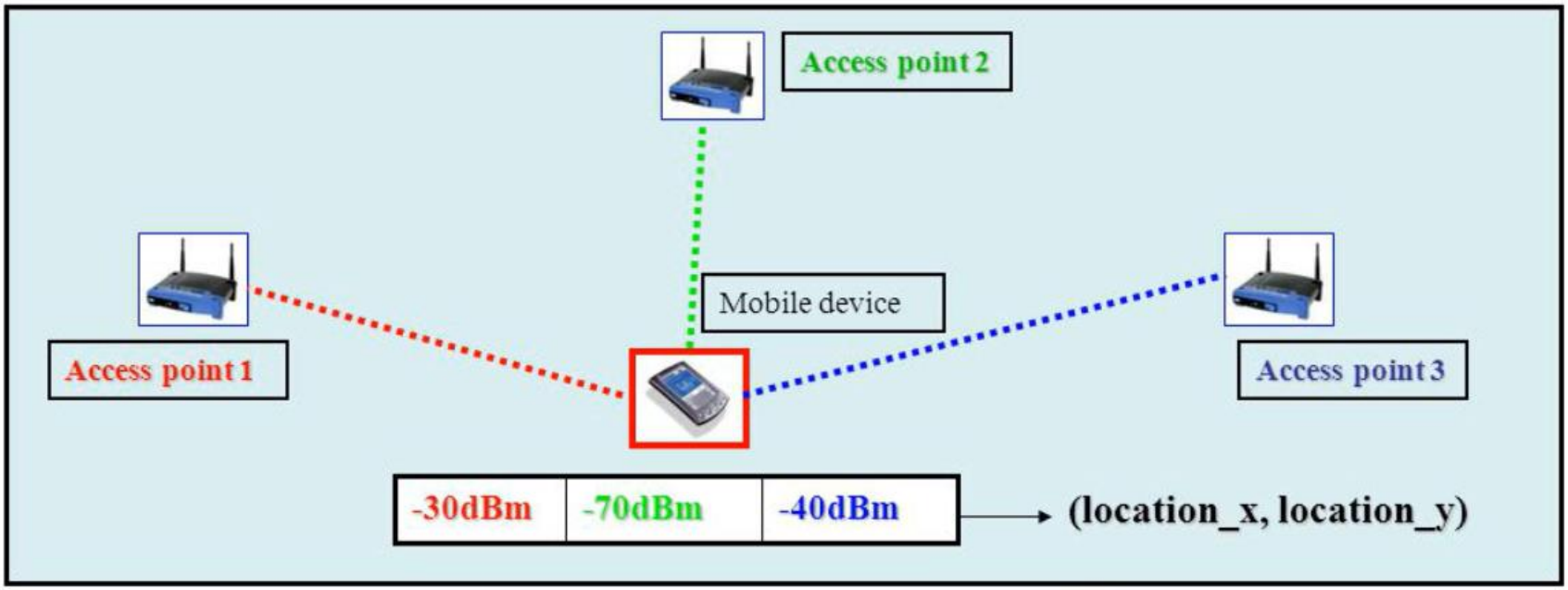
Source: www.opencellid.org

- Every Cell is Recognized by Mobile Country Code (MCC), Mobile Network Code (MNC), Location Area Code (LAC), Cell-ID (CID).

WPS / Cell-ID

- Typically, those are passive scans allowing for individual centric localization
- The mobile device can just passively scan spectrum looking for known location anchors, e.g., Mobile Access Points (APs) in Wi-Fi or Cells in Mobile Telephony.
  - Cells are recognized by MCC, MNC, LAC, CID
  - Mobile APs are recognized by BSSID
- The accuracy of this method is at the level of the coverage of a given device, a couple of hundred meters

In Network Localization



Pan SJ, Zheng VW, Yang Q, Hu DH. Transfer learning for wifi-based indoor localization. In Association for the advancement of artificial intelligence (AAAI) workshop 2008 Jul 13 (Vol. 6). The Association for the Advancement of Artificial Intelligence Palo Alto.

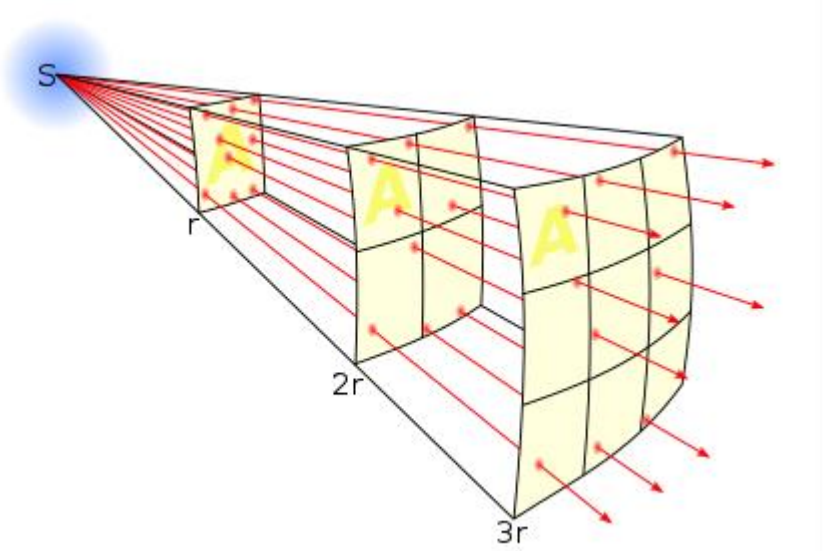
- Where is the user?
  - Can be performed by the user
  - Can be performed by the network in its premises

In Network Localization Performance

- Based on propagation models, the algorithm tries to estimate the true position of the user
- Some estimates are based on the distance estimation from Mobile Access Points, e.g., Received Signal Strength Indicator (RSSI).
- Other Techniques try to map the information on radio conditions in a given place (fingerprints), to later estimate the position of the user. The current radio situation of the user is compared with the map and the position is estimated.
- Accuracy ~ 1…10 m

Path-Loss Model (1)

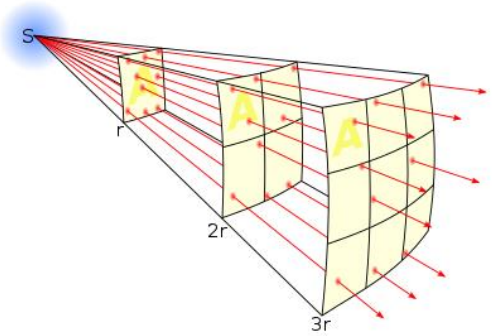
- Intensity of the beam decreases with the distance from the source
  - $I = \frac{P_t}{4\pi d^2}$
- The antenna captures signal proportionally to its aperture
  - $P_r = \frac{P_t}{4\pi d^2} \times A$



Source: https://www.wikiwand.com/en/Free-space_path_loss

Path-Loss Model (2)

- Power received at distance d_0
  - $P_r(d_0) = \frac{P_t}{4\pi d_0^2} \times A$
- Power received at distance d
  - $P_r(d) = \frac{P_t}{4\pi d^2} \times A$



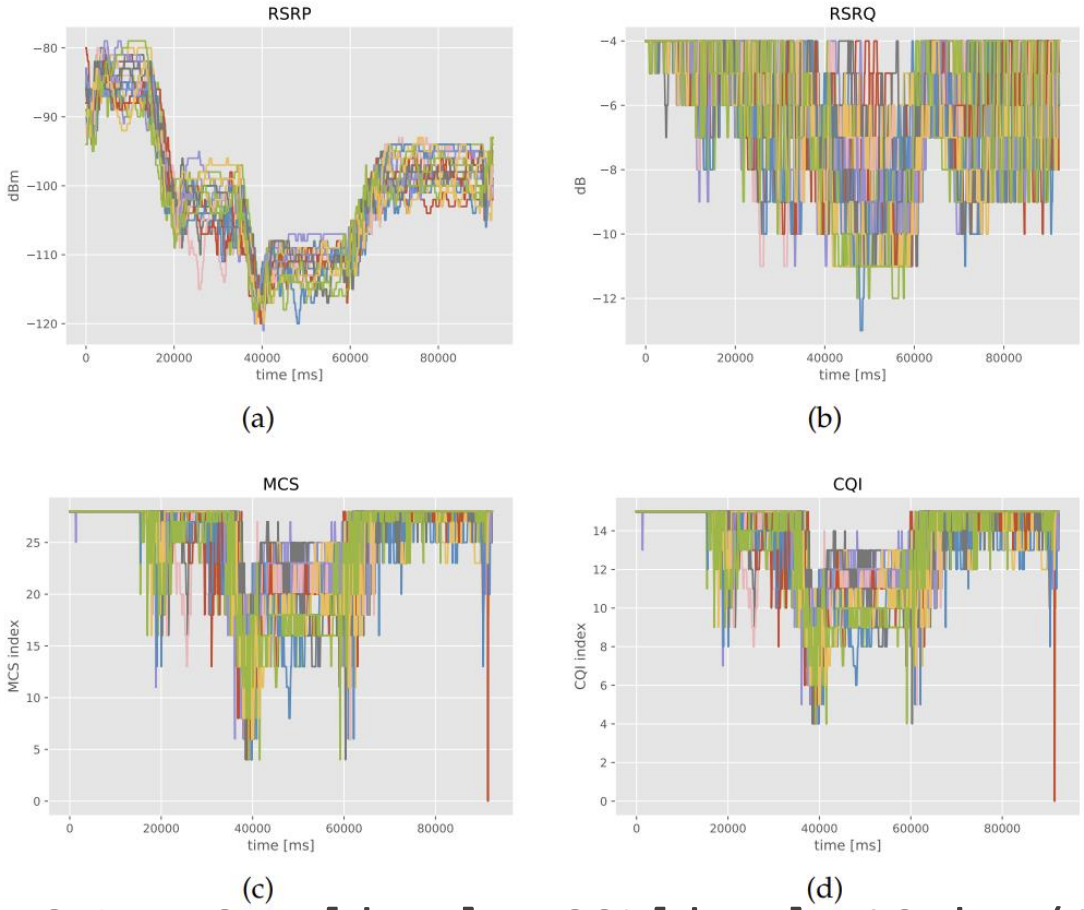
Source: https://www.wikiwand.com/en/Free-space_path_loss

$$\boxed{P_r(d)\ [\text{dBm}]} = 10 \log \frac{\frac{P_t}{4\pi d^2} \times A}{1\ \text{mW}} = 10 \log \left(\frac{\frac{P_t d_0^2}{4\pi d^2 d_0^2} \times A}{1\ \text{mW}} \right) =$$

$$10 \log \left(\frac{\frac{P_t}{4\pi d_0^2} \times A}{1\ \text{mW}} \right) - 10 \times 2 \log \left(\frac{d}{d_0} \right) =$$

$$\boxed{P_r(d_0)\ [\text{dBm}]} - 10 \times n \log \left(\frac{d}{d_0} \right), \text{ where } n = 2.$$

RSSI in LTE



- Different Metrics in 4G in spite of mobility.
- First, the user goes away from the eNB
- Then, they start approach the eNB

SNR: RSRP [dBm]= RSSI [dBm] - 10×log (12 × N)

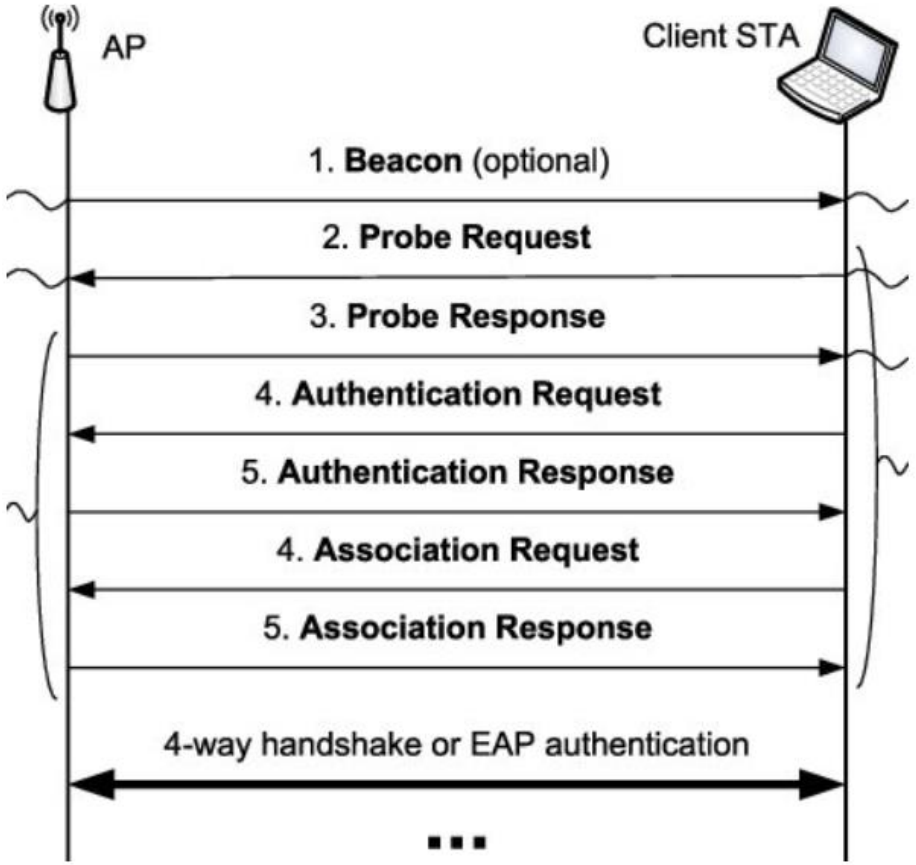
Remo Röthlisberger: Video Delivery with Multi-Access Edge Computing (Bachelor Thesis), University of Bern 2019.

Passive Probing in Wi-Fi

- An Access Points sends its beacons once every 100 TUs, where 1 TU is equal to 1024 µs.
- Passive Probing is a slow process. For all 2.4 GHz channels it would require more than 1 s to search for all AP in the neighborhood.
- Active Probing has to be used to search for nearby APs.

Active Probing in Wi-Fi

- To save energy, mobile devices actively search for AP in the vicinity.
- The probe request is a special Wi-Fi frame (with MAC address) sent through the air.
- It can be intercepted by all APs and third parties in the neighborhood.
- To avoid tracking switch off Bluetooth /Wi-Fi completely.
- Alternatively, activate MAC address randomization
- Big Networks such as Amazon, Apple (e.g, AirTag), etc. can track users and revert the MAC address to Identity relation.

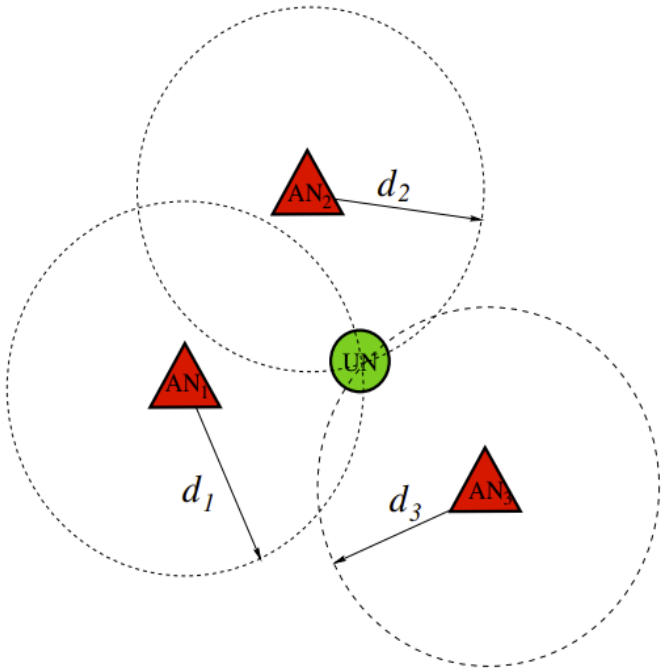


Lindqvist J, Aura T, Danezis G, Koponen T, Myllyniemi A, Mäki J, Roe M. Privacy-preserving 802.11 access-point discovery. In Proceedings of the second ACM conference on Wireless network security 2009 Mar 16 (pp. 123-130).

Localization Techniques

- Trilateration
- Multilateration
- Triangulation
- Angle of Arrival
- Time of Arrival
- Time Difference of Arrival
- Received Signal Strength Indicators (RSSI)
- Fingerprinting

Trilateration – Position Estimation in 2D



- Three equations to be solved:

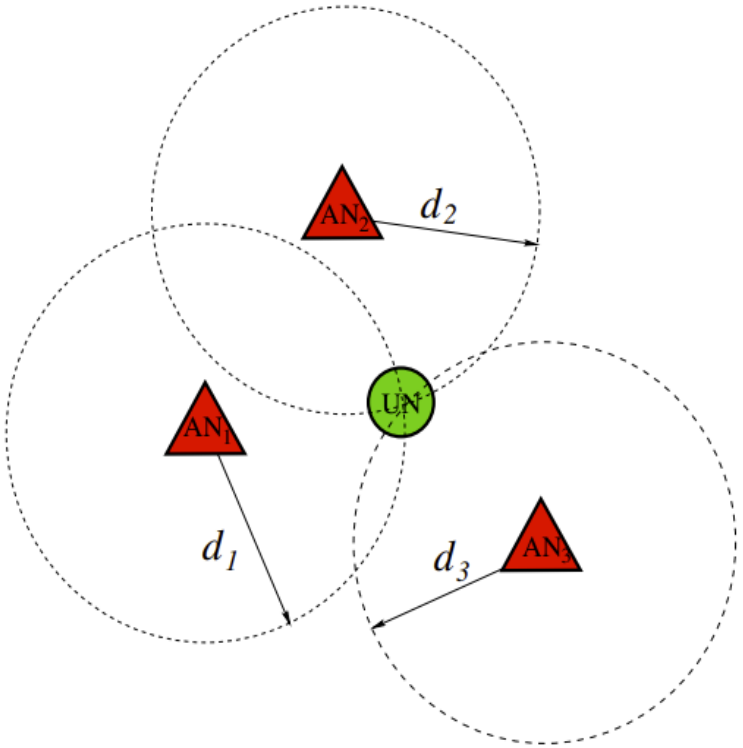
$$(x-x_1)^2 + (y-y_1)^2 = (d_1)^2$$
$$(x-x_2)^2 + (y-y_2)^2 = (d_2)^2$$
$$(x-x_3)^2 + (y-y_3)^2 = (d_3)^2$$

- The solution to first two equations provides us with two points at the crossing of two circles

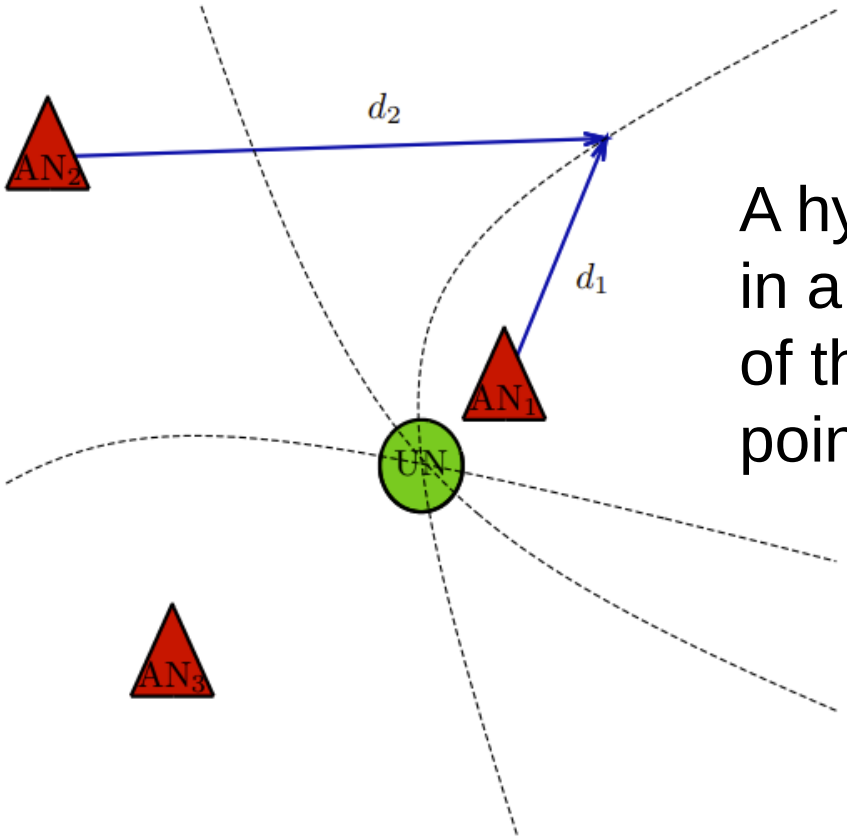
The third equation is given to select one of those points

Estimate User's Position (RSSI)

- Measure the received signal RSSI [dB]
- Evaluate the distance using the free space path loss
- $P(d) = P(d_0) - 10\, n \log (d/d_0) - X_\sigma$
- n: path loss index, X_σ: noise
- Mobile Telephony Provides different estimates, e.g., RSSI, RSRP, RSRQ



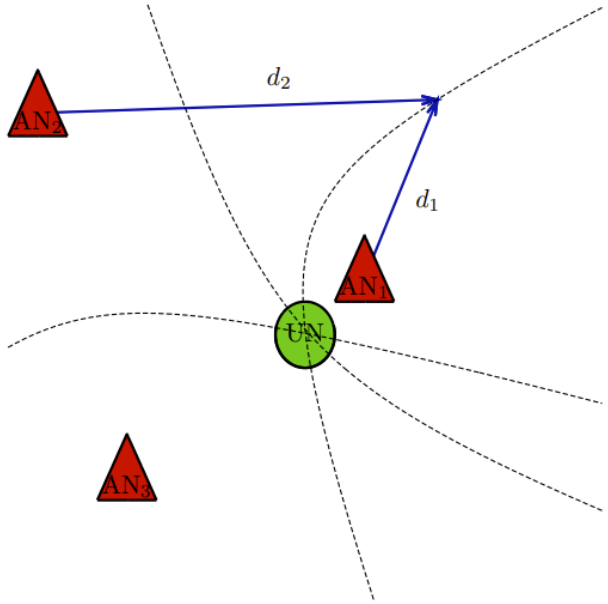
Multilateration



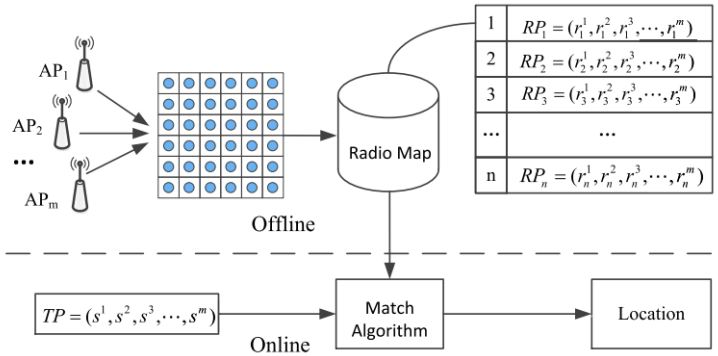
A hyperbola is "the set of all points in a plane such that the difference of the distances from two fixed points (foci) is constant".

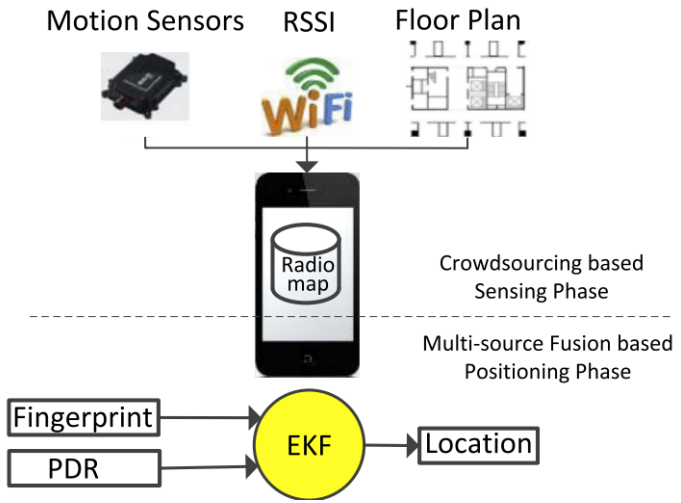
TDoA based Localization

- The time difference between beacon signals arriving has to be measured
- All anchor nodes have to be synchronized
- The distance estimated through the equation
  - $c\,\delta T = \delta d_{xy} = |\, d_x - d_y \,|$



Fingerprinting

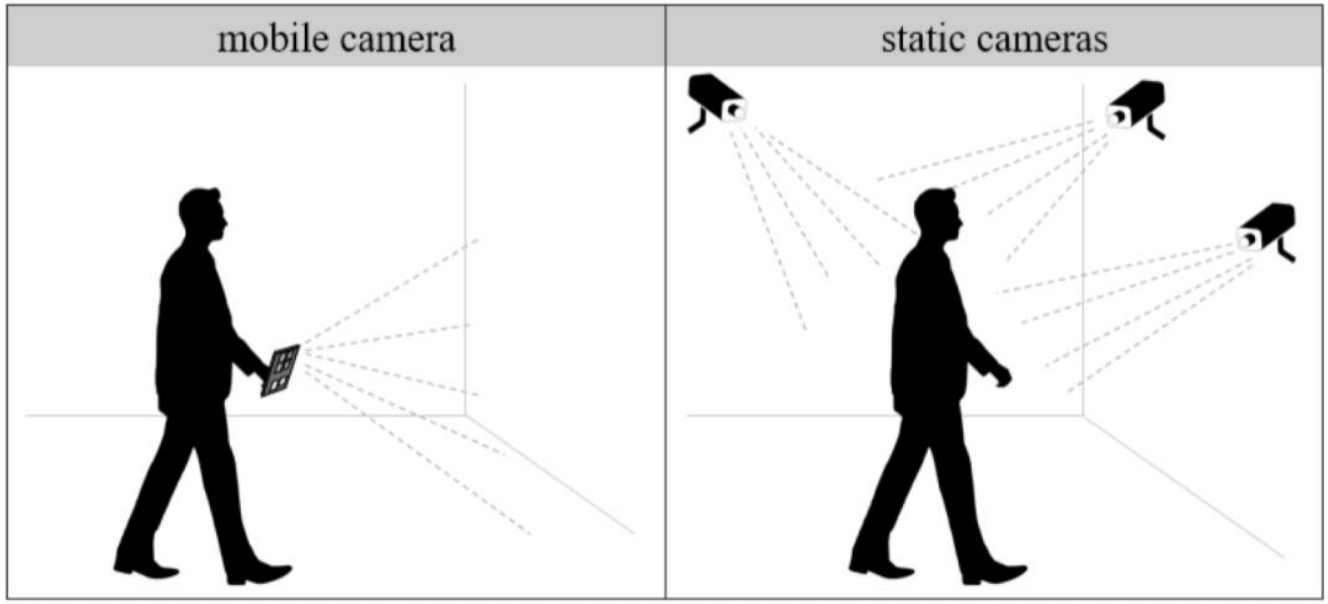




Source: Zhao W, Han S, Hu RQ, Meng W, Jia Z. Crowdsourcing and multisource fusion-based fingerprint sensing in smartphone localization. IEEE Sensors Journal. 2018 Feb 12;18(8):3236-47.

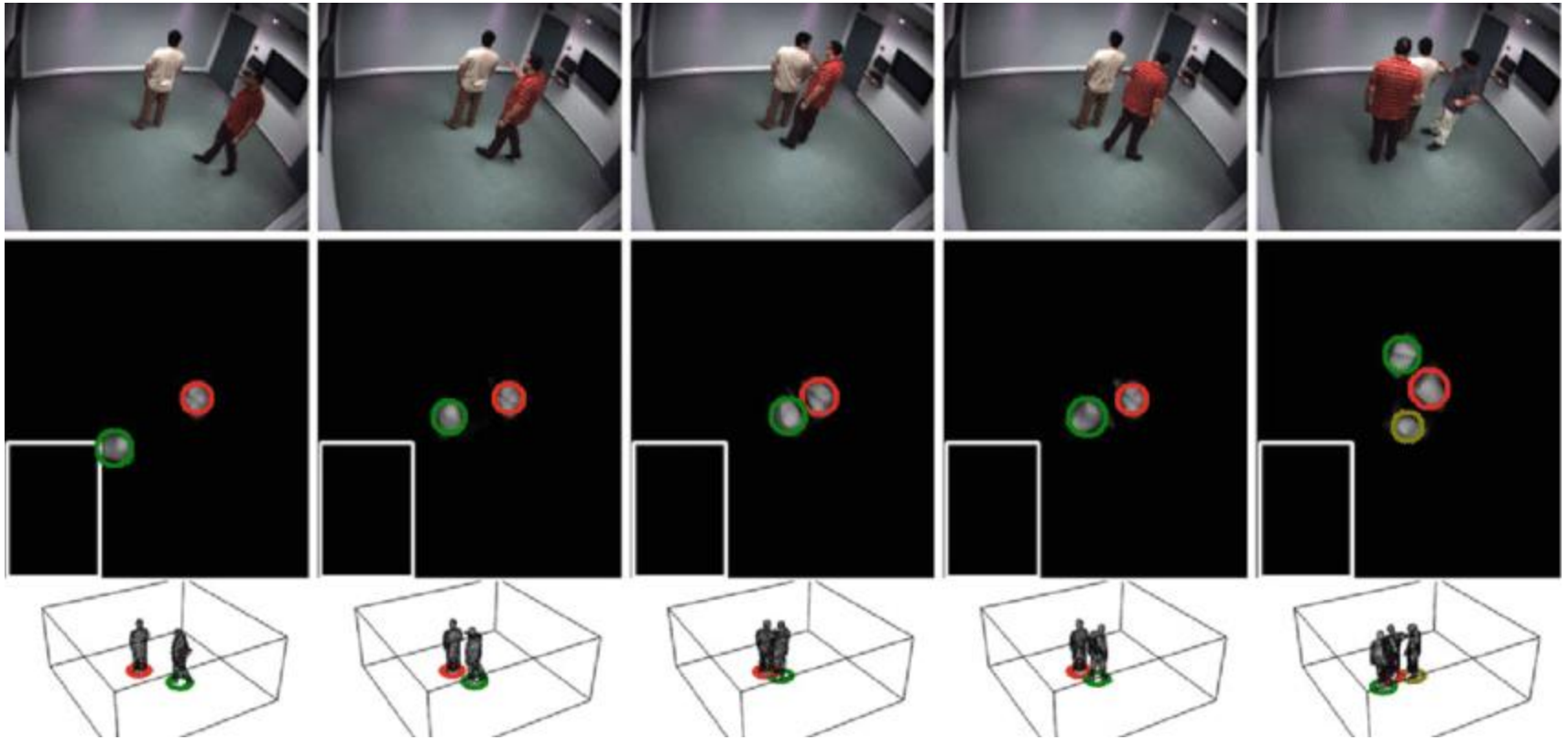
- Create a radio-map for various locations (might be expensive, and lengthy)
- Take a sample
- Use k-nearest neighbor algorithm to estimate the position
- Combine with other sources of location and smoothen the results

Camera-based Localization



- Can be performed for the benefit of the user
- Can be performed by an organization
- Can be performed by a third party

Indoor Localization



Source: Grammenos D, Drossis G, Zabulis X. Public Systems Supporting Noninstrumented Body-Based Interaction. InPlayful user Interfaces 2014 (pp. 25-45). Springer, Singapore.

Thermal Sensor Localization

Source: https://ecl-ips.com/blog/avigilon-h4-thermal-cameras/

- Various types of sensors might be used to perform localization of people and assets.

Mobility Prediction

- Use historical data on localization of users for user mobility prediction
  - Gathering data from telco operators
  - Using mobility datasets provided online
    - https://www.idiap.ch/dataset/mdc
  - Gathering data in running projects
    - https://www.csg.uzh.ch/csg/en/research/PasWITS.html
- Use the historical data for mobility prediction to improve congestion estimation and provide better adapted services!

Q/A