CMPE58C: Sp. Tp. Mobile Location Tracking & Motion Sensing

Radio-Based Positioning

Can Tunca

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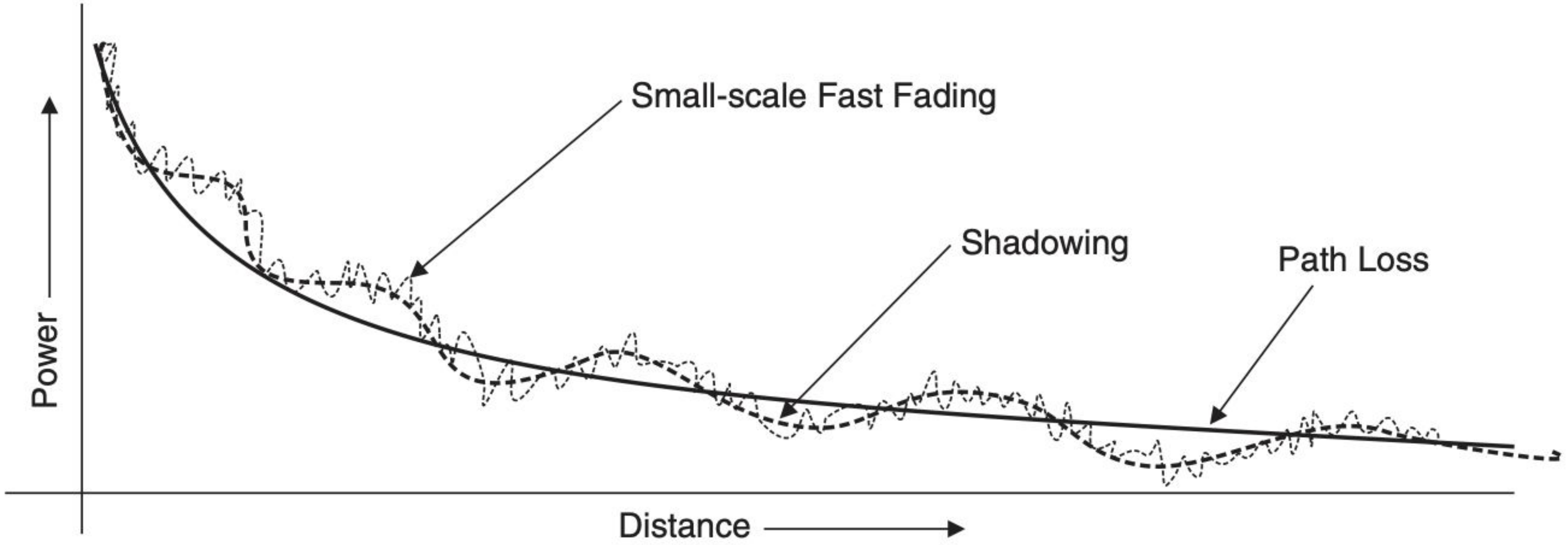
Fall 2022

Lecture Overview

- Technologies we'll focus on
  - BLE (Bluetooth 4.0+)
  - WiFi
  - UWB
  - 5G
- Techniques we'll explore or revisit
  - RSS-based positioning
  - Time-of-flight (especially RTT)
  - TDoA (time difference of arrival)
  - AoA (angle of arrival)
  - Fingerprinting
- Also…
  - A brief overview of signal propagation and fading
  - How to compute position via lateration? (Least Squares)

NOTE: Throughout the slides, we'll refer to **MS** as mobile station (device-to-be-located) and **BS** as base station (infrastructure)

Signal Propagation



Path Loss: Friis

- Free-space path loss: **Friis** equation

$$\alpha_{\text{loss}} = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$$

distance

path loss in dB

wavelength

- Assumes isotropic antennas (unidirectional propagation from a sphere)
- Assumes zero antenna gain: Loss is usually less than this value
- Ignores a lot of factors: Unrealistic, but still helpful...
- Other empirical models: Hata, Walfish–Hikegami, Ergec...
    - Based on measurements in large-scale urban environments
    - Not really applicable to small-scale indoor environments (except Ergec?)

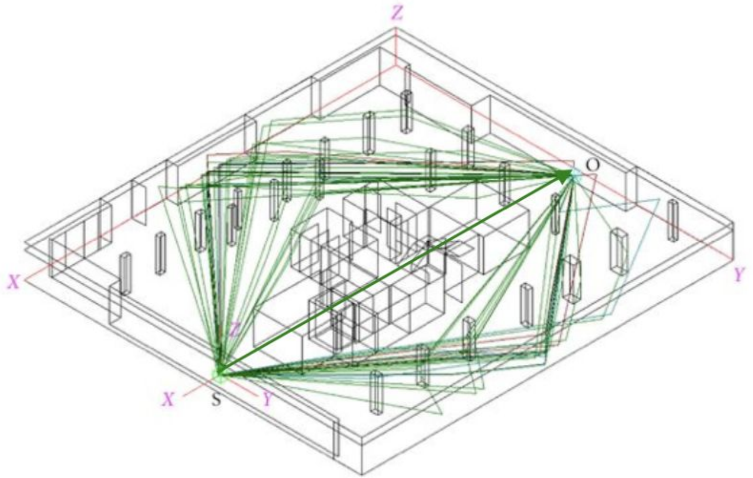
Path Loss: Ergec

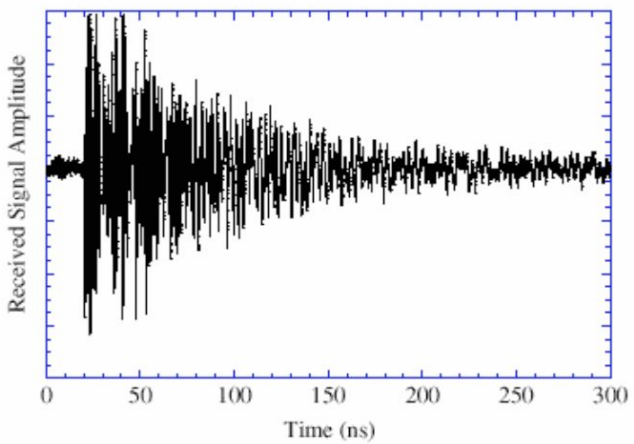
$$\Delta p_{\text{loss}} = \alpha_{\text{loss}} + 10\beta \log\left(\frac{d}{d_0}\right) + \eta_{\text{shad}}, \qquad d > d_0,$$

- α_{loss} is loss at $\boldsymbol{d_0}$ based on Friis
- β is the empirical path loss exponent
- A more empirical and realistic extension of Friis
  - Has a well-adopted place in RSS-based techniques, especially for indoors

Shadowing and Multipath

- Very difficult to model (even if we know the environment)
- Usually assumed to be non-existent in RSS-based techniques…
- Or modelled as a Gaussian distribution





BLE (Bluetooth Low Energy)

- aka **Bluetooth 4.0**: distinct from classic Bluetooth (physical layer, protocols…)
- Popularized for positioning by **iBeacon**
- Radio characteristics
  - ISM band: 2.400–2.4835 GHz (unlicensed, shared by many other tech…)
  - 40 x 2 MHz channels: a narrow-band technology
  - Up to 2 Mbps data rate
  - Very low energy (up to 100 times lower than classic Bluetooth, depending on use case)
  - Low range: up to 100 meters in LOS, typically much lower than this
- The primary positioning mode is RSS-based **(RSS: Received Signal Strength)**
  - Measure signal strength in the form of RSSI
  - Turn into ranging estimates (distance)
  - Trilateration
- BLE 5.1 introduces angle-of-arrival (AoA)! (we'll come back to this)

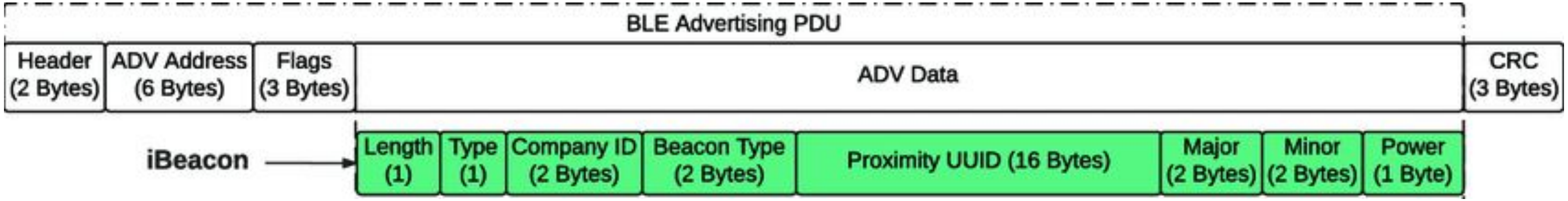
iBeacon

- Introduced by Apple in 2013
- What really popularized BLE for positioning
- Actually a protocol, operates on BLE application layer (does not include HW or physical layer change)
- Designed to be used by devices called beacons
    - Battery operated
    - Low cost (5-20$)
    - Long battery life: > 3 years!

iBeacon: Protocol

- iBeacon is a **one-way** protocol
  - Beacons advertise, receivers pick up
  - Receivers position themselves (device-based architecture)
  - Proximity or RSS-based positioning
- Beacon BLE radio is the same
  - It usually supports both transmission and reception
  - But two-way communication is only used for configuration
- An **application layer** protocol
  - Any BLE-capable device can implement it
  - Android: You are free to do anything with BLE packages
  - iOS: Has more restrictions, but provides a standard way of decoding iBeacon readings
  - Also supports background functionality (i.e. app is in BG, phone is in pocket)

iBeacon: Packet structure

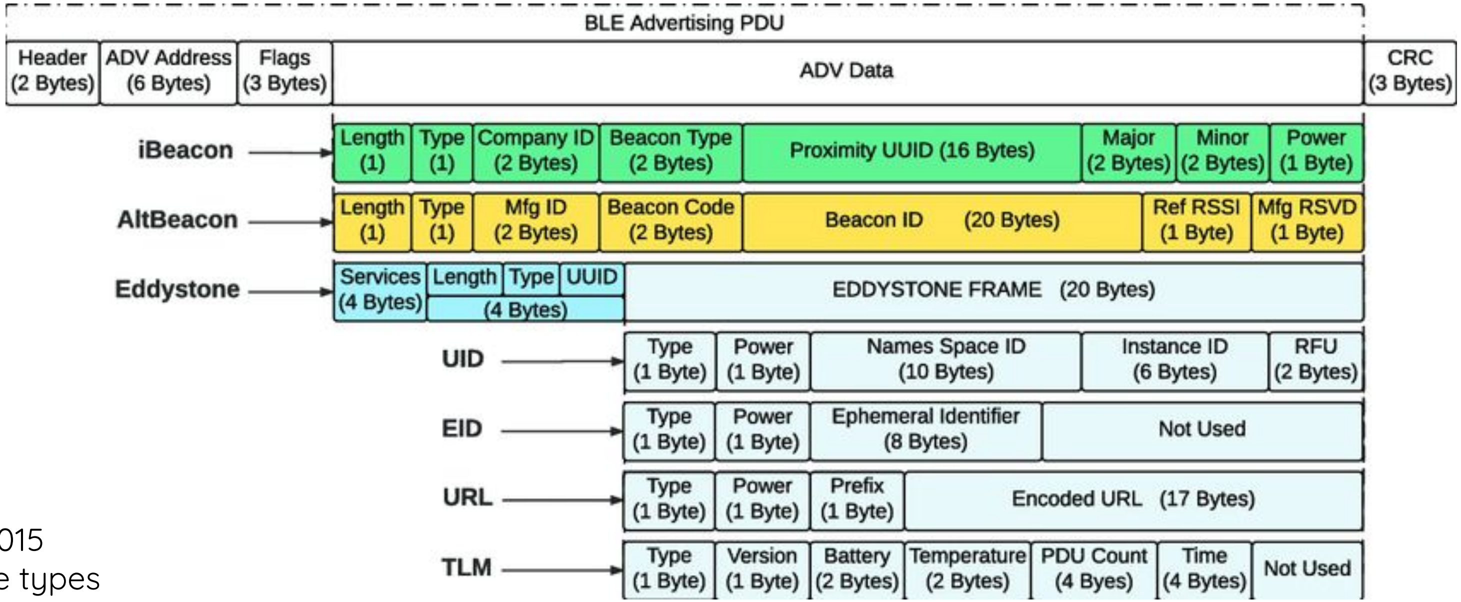


- First 6 bytes is the prefix; usually fixed (some definitions also include Flags, 3 + 6 = 9 bytes)
- **UUID + major + minor** denotes the id of a beacon
  - Could then be matched to a lookup table with id -> beacon location
  - iOS requires scanned UUIDs to be specified beforehand (a limit of 20 UUIDs)
  - So we are mostly left with major + minor to embed id (32 bits)
  - Apple suggests using major for buildings, minor for individual beacons in that building (but you are free to encode anything, even the coordinates themselves!)
- Reference power byte (aka RSSI calibration or RSSI@1m)
  - Optional field
  - RSSI measured 1 meter away from the beacon, to serve as a reference

iBeacon: Configurable parameters

- Advertisement interval
  - Influences battery consumption
  - Typically below 1 seconds (> 1Hz)
- Transmission power
  - Not to be confused with reference power
  - Actual physical transmission power
  - Can influence range, although may make closer RSS readings undistinguishable
  - Influences battery consumption
- Reference power
  - This is also a parameter, if you choose to set it and use it on the receiving device
  - Intended use case: Measure avg. RSSI at 1 meter, record it to the beacon to be advertised
  - Has no physical effect
  - Can serve as a guide for turning RSSI into distance (we'll see how)

iBeacon: Alternative protocols



Eddystone

- By Google in 2015
- Different frame types
- More flexibility, but didn't stick...

AltBeacon

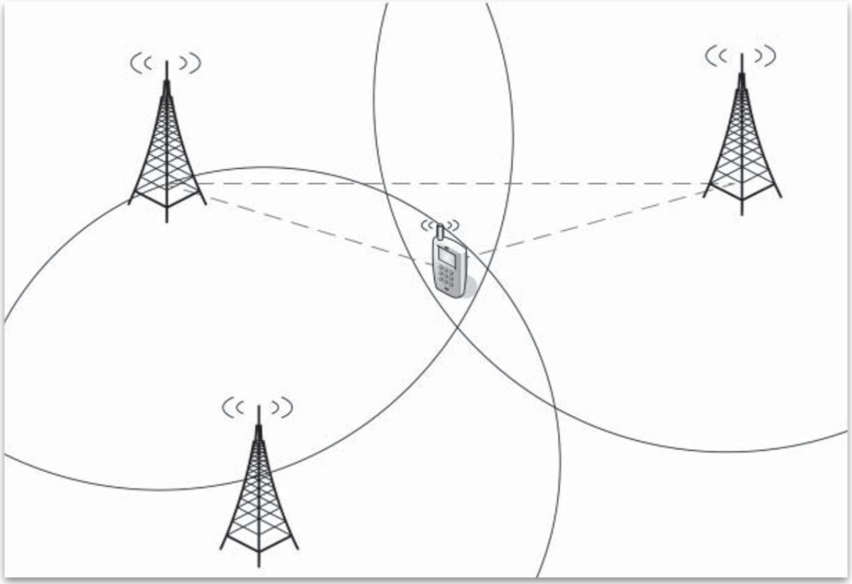
- An open community specification in 2014

RSSI

- **Received signal strength indicator**
- A relative value (depends on the receiver)
- Very vendor/chipset dependent (can’t compare two values from different HW)
- Usually measured in dBm (decibels referenced to one milliwatt)
- Can be used for lateration if we can get distance estimates...
- Not ideal for accurate positioning, but we don’t have anything else...

Next: A detour for some theory...

Lateration



Principle: Intersection of circles (spheres in 3D case)
They usually don't intersect! (measurement errors)
Trilateration: Special case with 3 BSs

Trilateration: Least Squares

actual MS position (what we are trying to estimate)

distance measurement between MS and BS_i

$$z_i = h_i(X) + \eta_i$$

noise (error)

a model mapping actual to measured
(usually a non-linear function)

Least Squares aims to minimize sum of squared residuals (errors):

$$\mathcal{J}(X) = \sum_{i=1}^{n} \eta_i^2 = \sum_{i=1}^{n} [z_i - h_i(X)]^2$$

$$\hat{X} = \arg\min_X \{\mathcal{J}(X)\}$$

Trilateration: Least Squares

- $h_i(X)$ is non-linear
- Non-linear Least Squares involves optimization (no closed form solution)
  - Find an estimate
  - Calculate a gradient
  - Iterate
- Search algorithms can be used (gradient descent, simulated annealing...)
- There is a method to make $h_i(X)$ linear if we don't need optimal...

Trilateration: Linearized Least Squares

We need a model in the form: $\mathcal{H}(X) = HX$

($X = [x, y]^{\mathrm{T}}$ is the MS position)

ranging estimates:

$$d_i^2 = (x_i - x)^2 + (y_i - y)^2$$

subtracting an estimate from a specific BS:
(this is the actual linearization trick!)

$$d_i^2 - d_1^2 = x_i^2 + y_i^2 - x_1^2 - y_1^2 - 2x(x_i - x_1) - 2y(y_i - y_1)$$

can now be written in the form

$$HX = B,$$

$$H = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \\ \vdots & \vdots \\ x_n - x_1 & y_n - y_1 \end{bmatrix},$$

$$B = \frac{1}{2} \begin{bmatrix} \left(d_1^2 - d_2^2\right) + \left(x_2^2 + y_2^2\right) - \left(x_1^2 + y_1^2\right) \\ \left(d_1^2 - d_3^2\right) + \left(x_3^2 + y_3^2\right) - \left(x_1^2 + y_1^2\right) \\ \vdots \\ \left(d_1^2 - d_n^2\right) + \left(x_n^2 + y_n^2\right) - \left(x_1^2 + y_1^2\right) \end{bmatrix}.$$

solvable by $X = (H^{\mathrm{T}}H)^{-1}H^{\mathrm{T}}B.$

Computing distance from RSSI

- Further simplification of Ergec:

$$P_t - P_r = 10\beta \log_{10} d$$

transmission power

reception power

path loss exponent

distance (to be estimated)

- Reorganized into the final formula:

RSSI

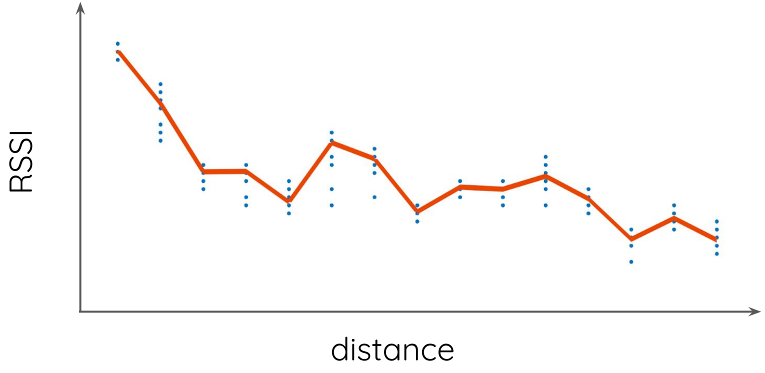
Calibration RSSI at a known distance (typically 1 m)

$$d = 10^{\frac{-(P_r - P_c)}{10\beta}}$$

some typical values

Environment	**Path loss exponent (β)**
Free space	2
Urban area	2.7 - 3.5
Suburban area	3 - 5
Indoor (LOS)	1.6 - 1.8 (multipath can be constructive!)

Reality about RSSI



Real measurements!
Each point is averaged over 1 minute
Result wouldn't change even if longer!

Signals greatly affected by environmental factors

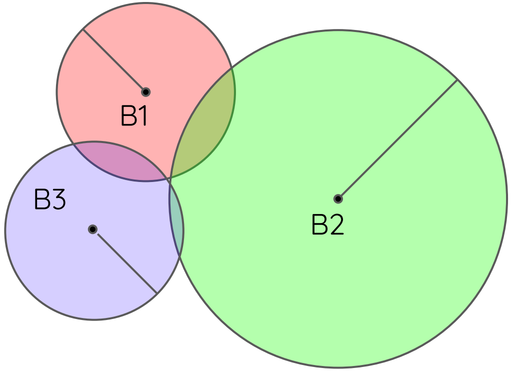
- Blocked by some objects, reflected by others
- Even humans can affect the signal
- The effects are indeterminate!

Signal homogeneity is not always achievable

- Different placements, brands, enclosures (access points, lighting fixtures, battery beacons...)
- Even same HW/chipset/radio have variations

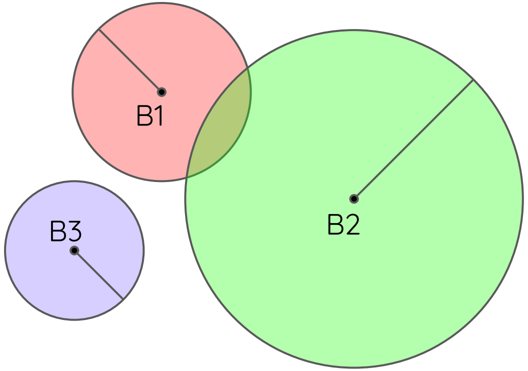
Least Squares is still good, but may have some disadvantages...

Trilateration: Theory vs. Reality



Theory

The circles intersect perfectly
(or almost perfectly)

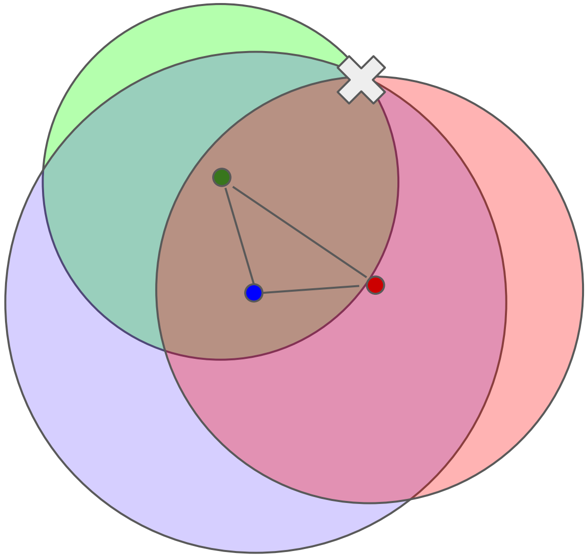


Reality!

The circles do not intersect at all
Usually not even possible to correct by
a common factor! (unlike in GPS)

Trilateration: Theory vs. Reality

- Theoretically possible to get a position estimate outside the BS triangle
- Can be a blessing
  - What if device is really there?
- Can be a curse
  - If device is not there, the search space gets pretty big
  - Risk of divergence/fluctuations
  - Especially given unreliability of RSSI



Trilateration: A simpler alternative

- **Weighted average**

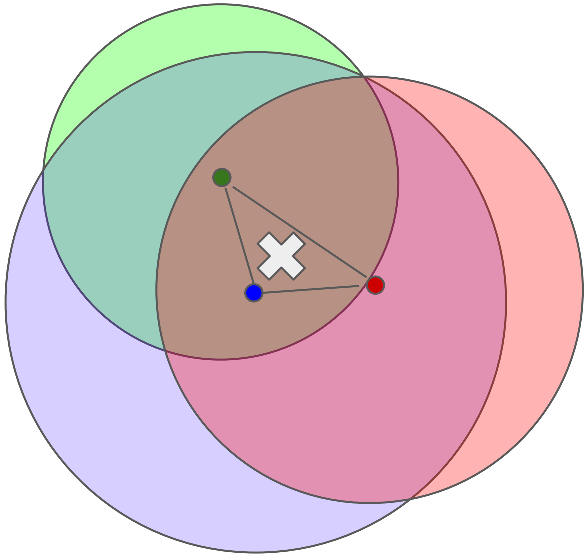
$$x = \frac{1}{n}\sum_i w_i x_i$$

$$y = \frac{1}{n}\sum_i w_i y_i$$

where

X_i ith BS position

X MS position



- Analogy: Each BS pulling proportional to its weight
- Weight could be something simple as
  - 1/distance OR 1/distance$^{\beta}$
  - The exponent here has an effect similar to path loss exponent
  - Or anything else! (measurement freshness, signal reliability...)
- More stable but cannot produce an estimate outside the convex hull...
  - Need special infrastructure design (search space contained in hull)

BLE/iBeacon Summary

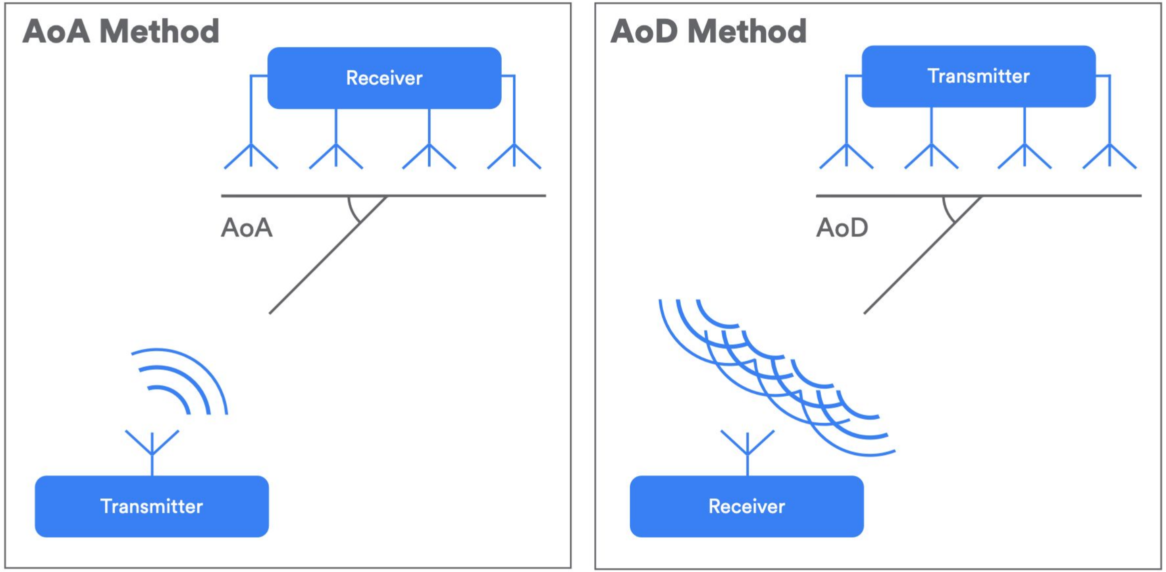
✅ Strengths

- Low cost
- Very widespread, difficult to find a commercial device without BLE capability
- Low energy (long-lasting batteries)
- Supports both ranging-based and proximity-based approaches
- Simple device-based infrastructure

❌ Weaknesses

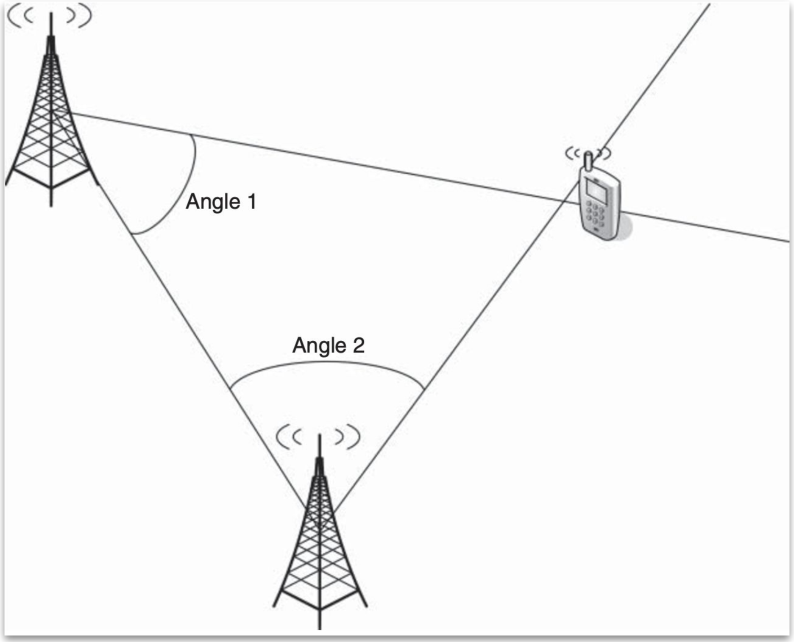
- RSSI is very unreliable
- Best achievable accuracy is 1-3 meters (usually much worse)
- Needs infrastructure: Cheap but needs to be dense (typically 1 beacon per $40m^2$)
- Topology must be designed according to the positioning method

BLE 5.1



- Two new modes:
  - Angle-of-Arrival (AoA)
  - Angle-of-Departure (AoD)
- Requires antenna arrays (beacons don’t have it!)
  - Requiring base stations more like Access Points

Angulation



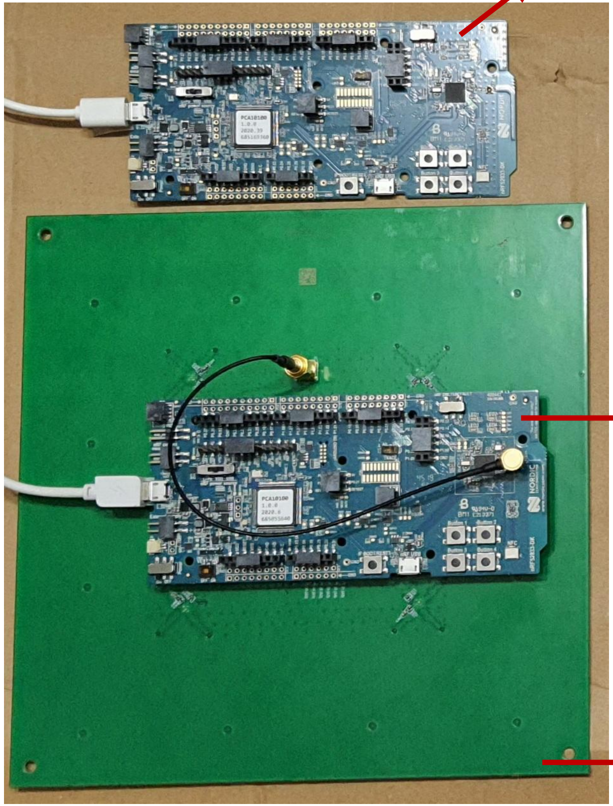
Principle: Intersection of lines at measured angles

2 BSs are enough (as opposed to lateration and hyperbolic)

Triangulation: Special case with 2 BSs (**not 3**, 2 are enough to make a triangle!)

BLE 5.1: An example - Nordic nRF52833 Dev Kit

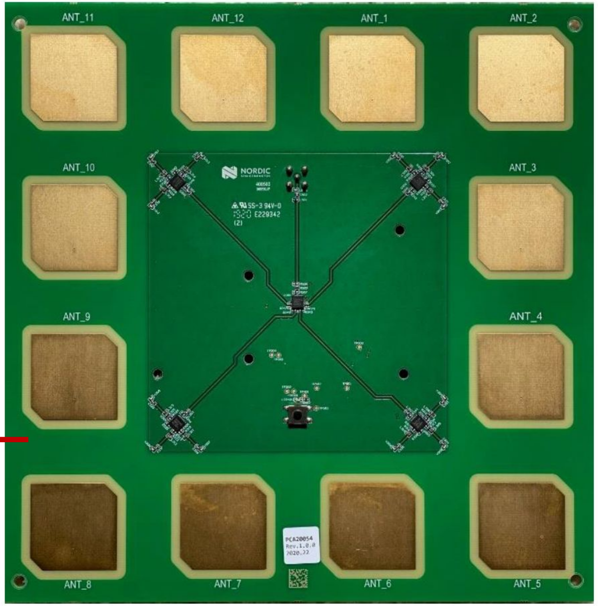
Tag board



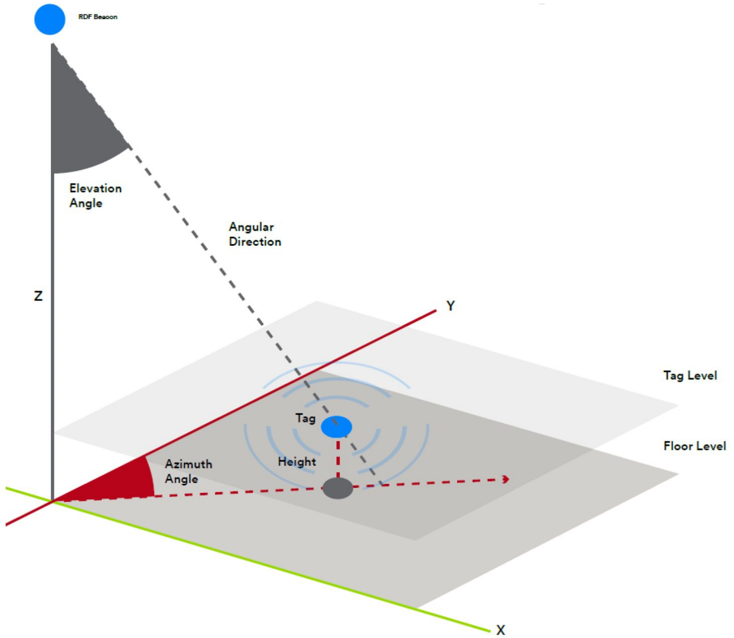
Locator board (BS)

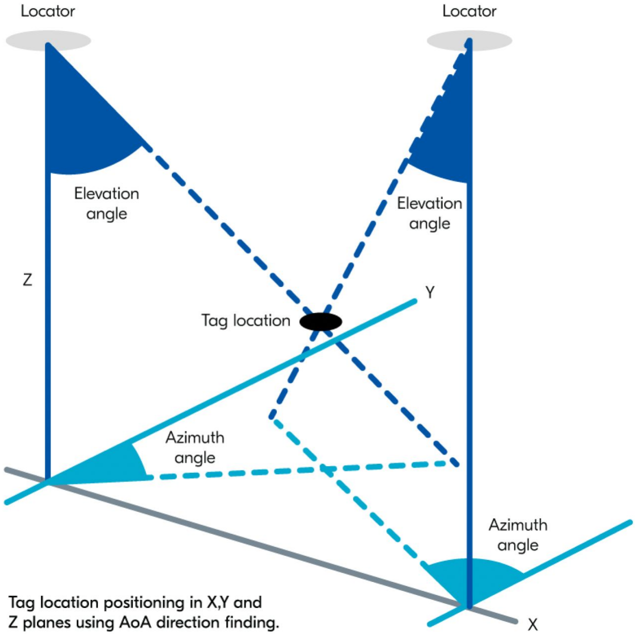
Antenna Array
Front side

Antenna Array
Rear side



BLE 5.1: 3D Angulation





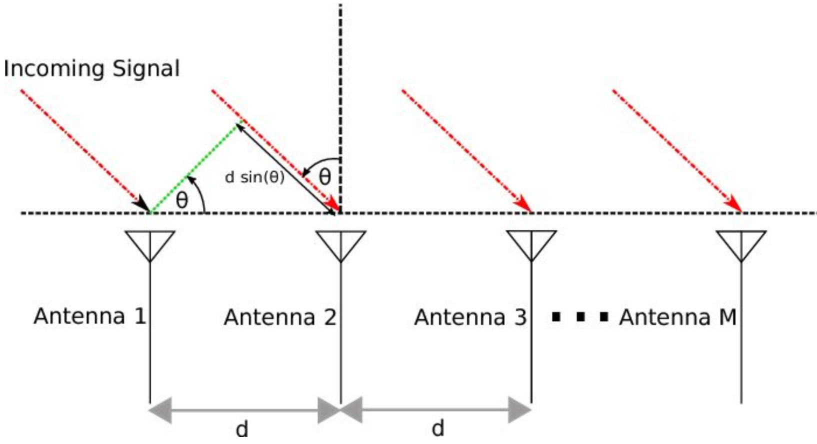
- Antenna arrays are usually able to measure both **azimuth** and **elevation** angles
- A single antenna may be enough!

- 2 or more BS's could be used to increase accuracy
- No need to know tag height

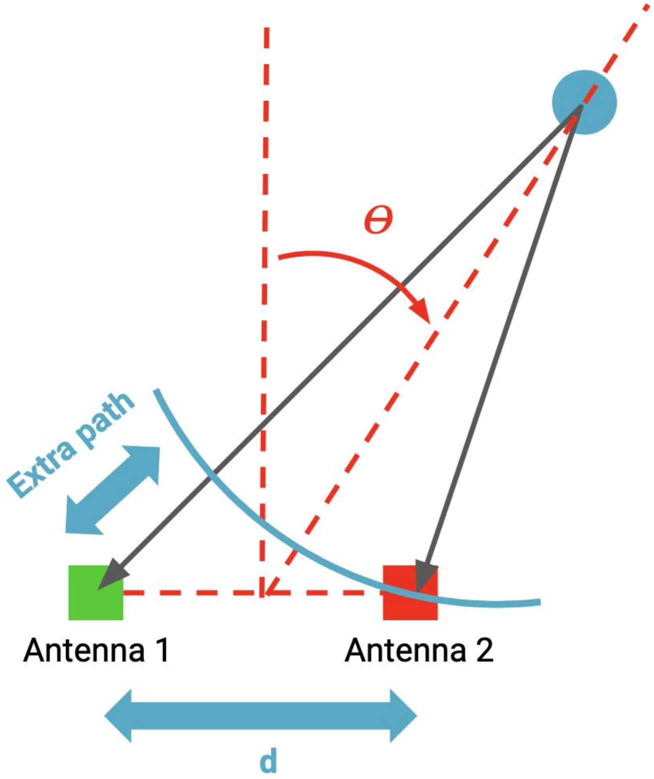
BLE 5.1: How to compute angle?

Preamble (1 or 2 octets)	Access-Address (4 octets)	PDU (2-258 octets)	CRC (3 octets)	Constant Tone Extension (16 to 160 μs)

- Principle: Measuring signal phase difference at different points on antenna
- Constant Tone Extension (CTE)
  - A bit sequence included at the end of each packet
  - 16-160 μs long
  - A series of modulated 1s (no whitening)
  - Transmitted at a constant wavelength
  - Phase difference measured via a technique called In-Phase and Quadrature (IQ) Sampling
- Also called PDoA (phase difference of arrival)

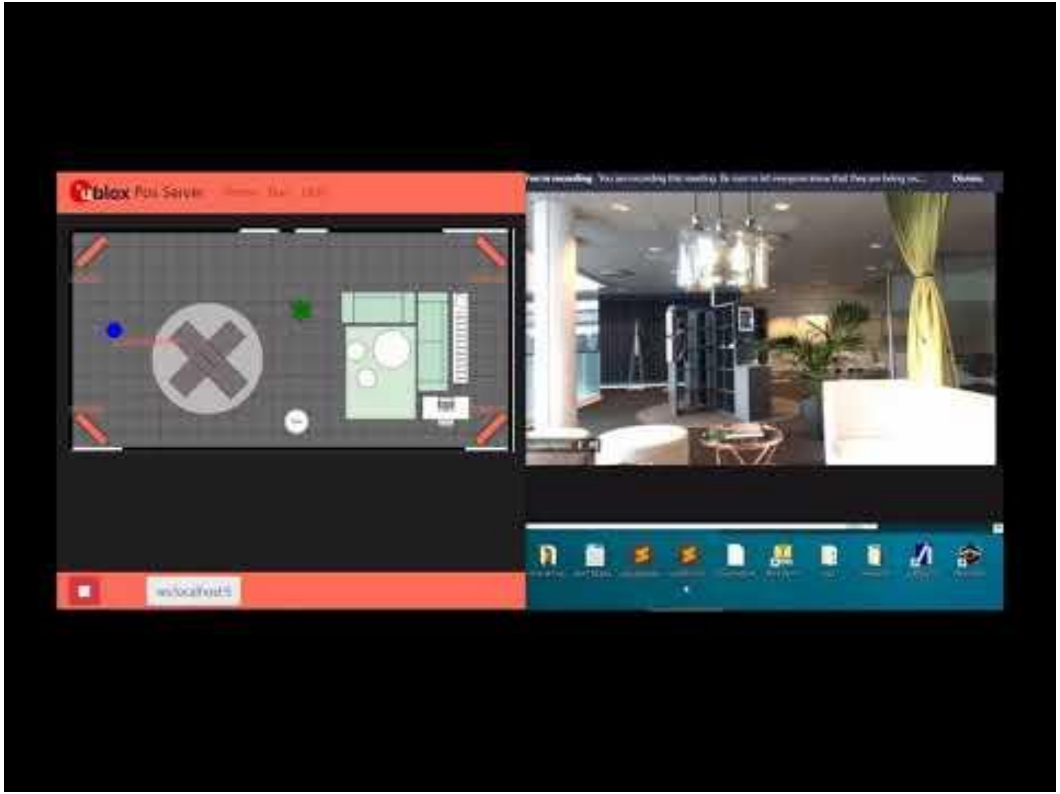


Some considerations on antenna arrays



- When θ = 0 no phase diff (paths are the same)
- When θ = π/2 path difference is antenna separation (d)
- **We should set d = λ/2 for optimal (half a wavelength)**
- If we make d longer there will be multiple θ corresponding to same phase difference
- We can make d shorter, but measuring phase difference will be more difficult (need to be more precise)
- λ (wavelength) for 2.4GHz is 12.5 cm: That's why those antennas are big!

BLE 5.1 AoA Example



BLE 5.1 AoA Summary

✅ Strengths

- Sub-meter accuracy
- Still uses BLE, receiver devices will be mostly compatible
  (not all phones in the market have BLE 5.1 capabilities yet, but the trend is upwards)

❌ Weaknesses

- BS is more complicated than simple beacons (antenna arrays)
- High cost
- LOS requirement for optimal operation
- High density topology requirement (antenna arrays have limited usable angles and ranges)
- Topology needs to be carefully planned

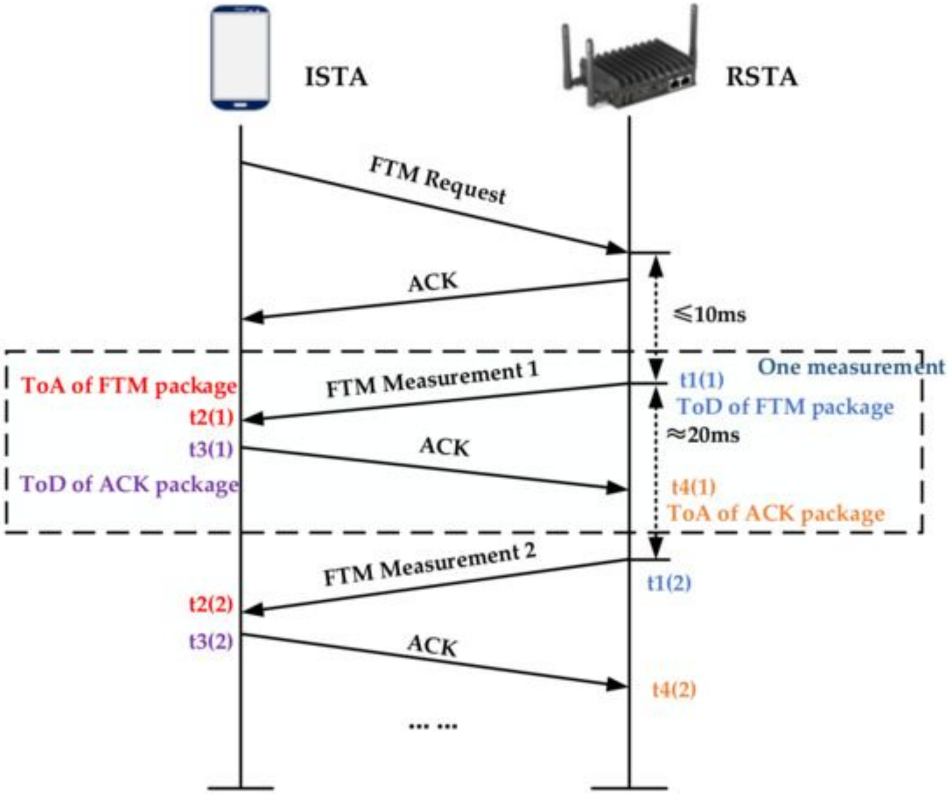
WiFi

- Very similar signal characteristics to BLE
  - They both live in the ISM band
- RSS-based methods are equivalently possible…
  - But not as ideal since WiFi BS's are APs which are not battery-operated!
  - Infrastructure cost is high
- AoA is also possible, the same principles can be used…
- A big advantage is that there are APs in many places already!
  - Topology not designed for positioning though…
  - Not as dense as we'd like
  - LOS is hard to come by, especially to make AoA possible

WiFi FTM

- What if there was a way to get time-of-flight?
- ToF requires synced base stations (remember GPS)
  - Access points do not have atomic clocks...
- TDoA also requires synced transmissions
  - Either BSs transmit at the same time (very difficult)
  - or MS transmits and location is calculated at the BSs (distributed system, complex)
- A solution: Round Trip Time (RTT)
  - Kind of like ping pong...
- **Fine Time Measurements:** IEEE 802.11mc

WiFi FTM: The Protocol



- ISTA: Initiating station (MS)
- RSTA: Receiving station (BS)
- MS already knows t_2 and t_3
- **FTM Measurement 2** contains t_1 and t_4
- After that point MS can compute RTT:

$$RTT = (t_4 - t_1) - (t_3 - t_2)$$

$$distance = RTT * c / 2$$

- Doesn't matter if MS and BS clocks are different! (time differences measured on the same device)
- Multiple measurements could be taken for more accurate results

WiFi FTM Summary

✅ Strengths

- Better than RSS-based
- WiFi is a widely adopted tech that will be around for quite some time (even though not all devices support 802.11mc yet)
- Existing hardware (APs) could be potentially used (not all have 802.11mc)

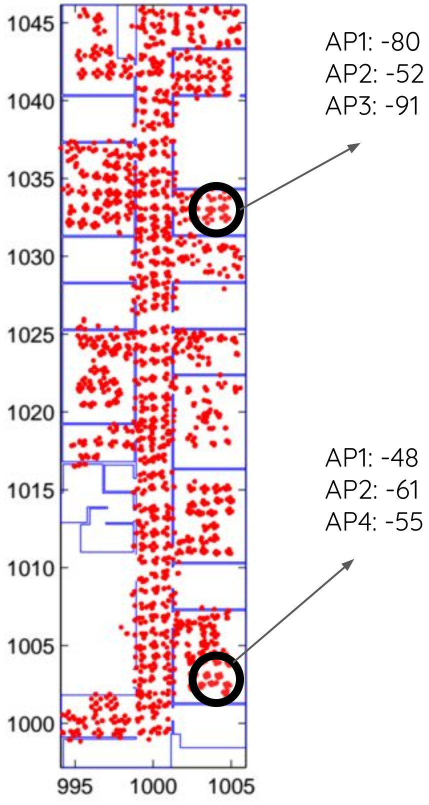
❌ Weaknesses

- Sub-meter is still rarely possible
- Requires LOS
- Very susceptible to multipath
- Frequency/band not really suitable for timing measurements (We'll see why when we explore UWB...)
- Costly hardware in case of no existing infrastructure
- iOS is very limited for WiFi-related developer APIs (Apple can implement something themselves though...)

BLE and WiFi are everywhere…

- There are lots of devices around transmitting BLE and WiFi
- Existing infrastructure, especially for WiFi
- Stationary equipment like computers, TVs, kitchen appliances, all broadcast BLE or similar
- Do we really need to install dedicated hardware?

Radio Fingerprinting



- Principle: What if we could learn what the signals look like at a known location?
- Conduct an offline survey, measuring signal properties at known locations (quite like training)
- Typically measuring signal strength (RSSI)
- Possible measurement strategy
  - Build a comprehensive grid covering all localizable space
  - Take multiple measurements over a substantial time at a single point (instantaneous may be misleading)
  - Store averages in a database (DB)
- The result is a *fingerprinting map*

Fingerprinting: Online Inference

- How to find MS position at a given time? (We'll use WiFi as an example)
- MS scans APs and builds a measurement vector m
- Find the **nearest neighbor**: Point in database closest to m
- We need a distance metric: Could be Euclidean or something else...
- i.e. for every measurement point in DB (ith measurement, jth AP):

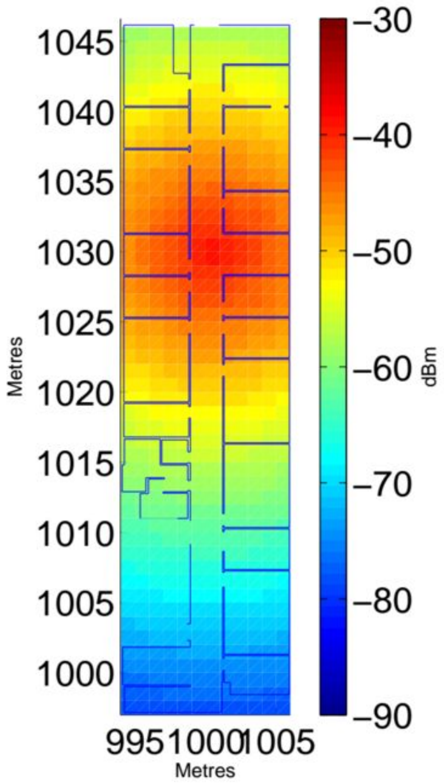
$$D^i_{euclidean} = \sqrt{\sum_{j=0}^{A} |m_j - \hat{s}^i_j|^2}$$

- Return the position associated with measurement i
- Could be extended to kNN (k-nearest neighbors)

How to handle missing values?

- How to compare **[(AP1: -30), (AP2: -52), (AP3: -95)]** and **[(AP1: -30), (AP2: -52)]**
- Maybe AP3 is not ON at that time, or we simply didn't hear it
- Naive distance approach gives a value of 95! (even though it should be closer as -95 is a very low value)
- A common approach is to set all unseen APs to receiver sensitivity (the lowest value a receiver can pick up), e.g. -100
  - **[(AP1: -30), (AP2: -52)]** becomes **[(AP1: -30), (AP2: -52), (AP3: -100)]**
  - The difference is 5, which is much better
- What if an AP that we should be hearing strongly is not there? (maybe it is defective)
  - A much more difficult problem, some approaches exists but all have caveats...

Fingerprinting: Regression Maps



- We can use regression to fill in the gaps
- A continuous regression map for each AP
- Machine Learning methods are also usable
  - For example: Train a neural network with surveyed points
  - It can output a reference vector for any queried point
  - Or it can even tell you the MS position directly given the measurement vector!
  - A good premise, but may be less stable than kNN...

Fingerprinting: The Reality

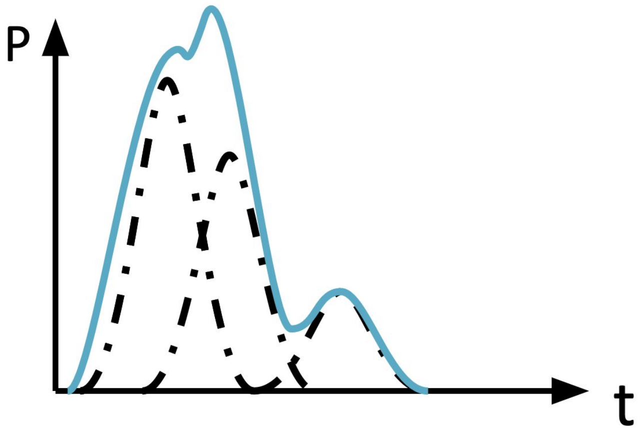
- Fingerprinting is very promising in theory
  - No need to deploy any hardware: Opportunistic positioning
  - But the reality is quite different...
- Even the smallest change in the environment may have a significant effect on the radio map
  - Try moving a chair or a desk...
- People are also serious signal blockers (water absorbs signal pretty well)
  - The way a person carries the device matters, other people around matter
- Signal sources also change
  - AP configurations change, devices go offline, get replaced...
- Offline survey is susceptible to errors
  - You have to know your true position to add it to DB (a chicken & egg situation)
- Scanning is time-consuming at MS
  - Need to wait for all APs to have a complete measurement vector
    (especially considering MS is just sniffing, no active requests/connections)

UWB

- Ultra-wideband
- An umbrella term for bandwidth > 500 MHz (a huge value!)
- Typically in 3.1 - 10.6 GHz range
- The premise is high data rate, low energy, but low range
- Started appearing in high end phones
- A sequence of pulses rather than traditional modulated sine wave...
- Very good for timing

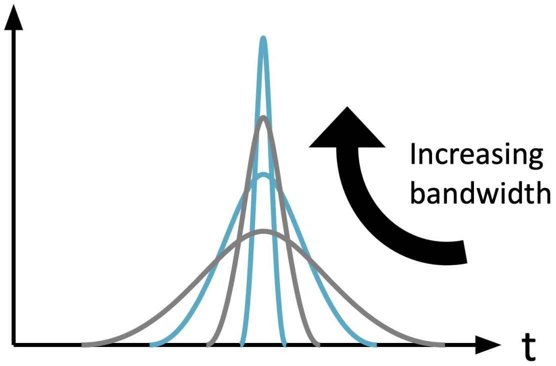
Timing signals in narrow-band

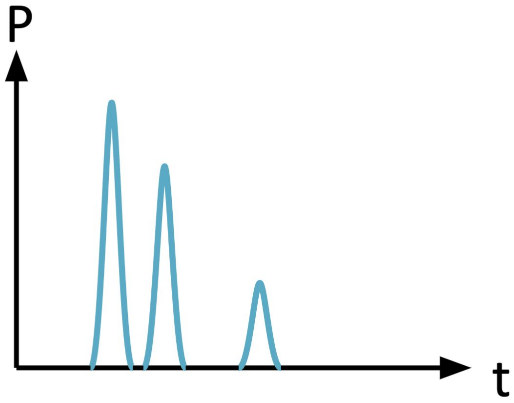
- Multipath makes it impossible to deduce when the direct signal arrived
- Every transmission has a finite width in time domain
- The width is comparable to the time between reflected signals
- Signals merge together and peaks are eroded



UWB Pulses

- Increased bandwidth increases time granularity and “rising edge”
- Transmit more info in less time
- Pulses are very narrow: no more than 2ns
- Being able to distinguish multipath and determine first pulse





Doesn’t UWB interfere with other tech?

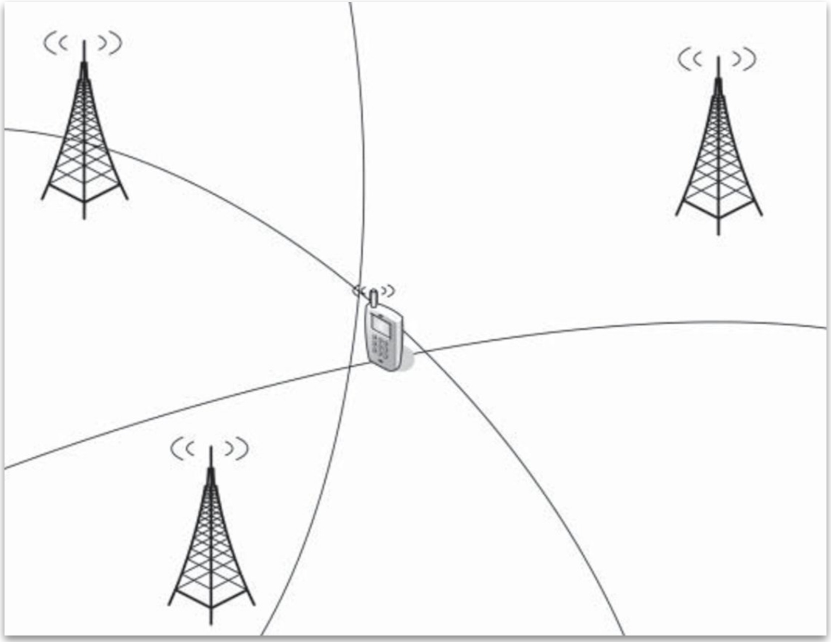
Doesn’t UWB interfere with other tech?

- UWB is attempting to use a big portion of the licensed frequency spectrum, so cannot allocate a dedicated part to it
- UWB is an **underlay** system
  - Its power is below the noise floor of any narrowband technology
  - Hiding data in the noise (remember GPS)
- Hence can coexist peacefully with other tech

UWB: Modes

- TWR (Two Way Ranging)
  - Essentially the same thing as RTT, two-way communication required
  - Same method as WiFi FTM, but much more accurate
  - No need for BS time sync, position can be computed at MS
- TDoA (time difference of arrival)
  - MS transmits, BSs pick up and calculate position
  - The hyperbolas are more likely to intersect due to accuracy!
- Even AoA is possible
  - The antenna can be smaller since UWB typically operates at higher frequencies!

Hyperbolic Localization (TDoA)



Principle: Intersection of hyperbolas

They usually don't intersect! (measurement errors)

Least Squares is a possible method for TDoA too

UWB Summary

✅ Strengths

- Sub-meter accuracy (as low as 10cm)
- Many different modes, suitable for different topologies and architectures
- Small antenna and chipsets
- Low power (not as low as BLE though)
- Can penetrate walls better than narrowband

❌ Weaknesses

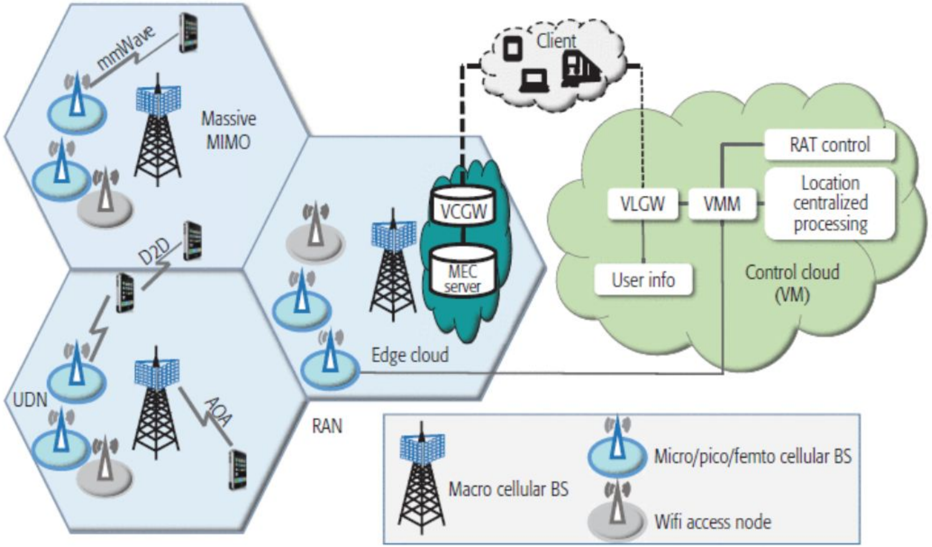
- Adoption has been slow (only flagship smartphones have it with limited developer APIs)
- Medium-high cost (may go down)
- There are many UWB variants, poor standardization (Apple also has a variant which may take over)
- LOS is still required for optimal operation (despite better penetration)
- Short range

Cellular Positioning

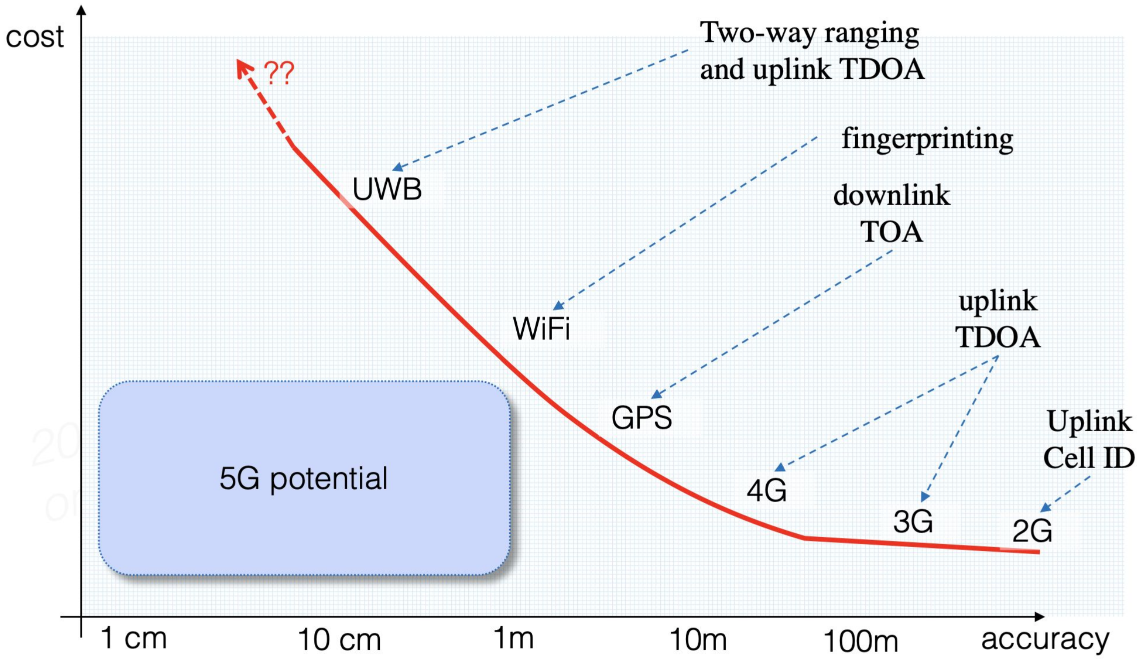
- Cellular networks need the user positions to improve quality of service
- Even the earliest cellular network (2G) have some location capabilities
- Especially important for mobility
  - Cellular networks are designed for communications to/from mobile users
  - Handover management: Which cell to take over?
- Why cells?
  - Cells are areas that are covered by one or more base stations
  - Neighboring cells usually use different frequencies/channels to avoid interference
  - Network should at least know the cellular occupancy of each user (which cell?)

Cellular Positioning: Frequently Used Terms

- BS: Base Station
- UE: User Equipment (MS)
- Uplink: From UE to BS
- Downlink: From BS to UE
- RAN: Radio Access Network
- UDN: Ultra Dense Network
- MIMO: Multiple Input Multiple Output
- gNB: Same as BS in scope of 5G

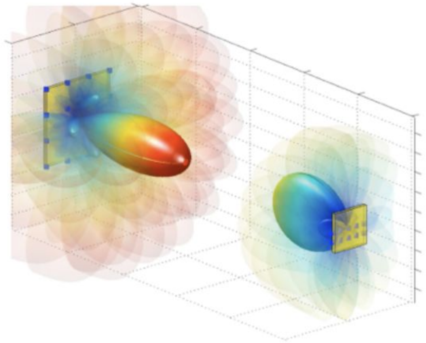


5G: The Premise

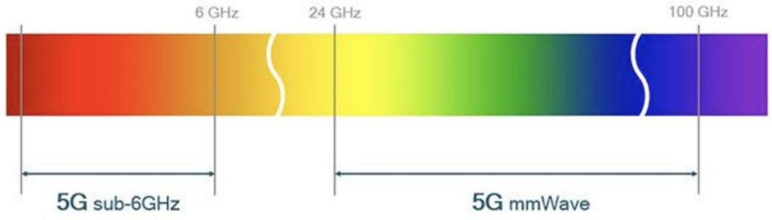


- It can be argued that it is low cost since existing hardware will be used, but is it enough for sub-meter accuracy?
- Accuracy demands special hardware (AoA, mmWave...)

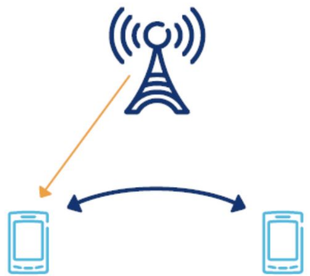
5G in a nutshell...



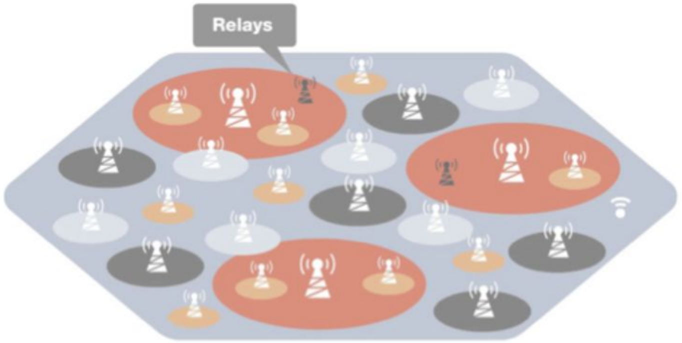
Large antenna arrays
Directional transmission



High frequency carriers
Larger bandwidth



Device-to-device communication



Network densification

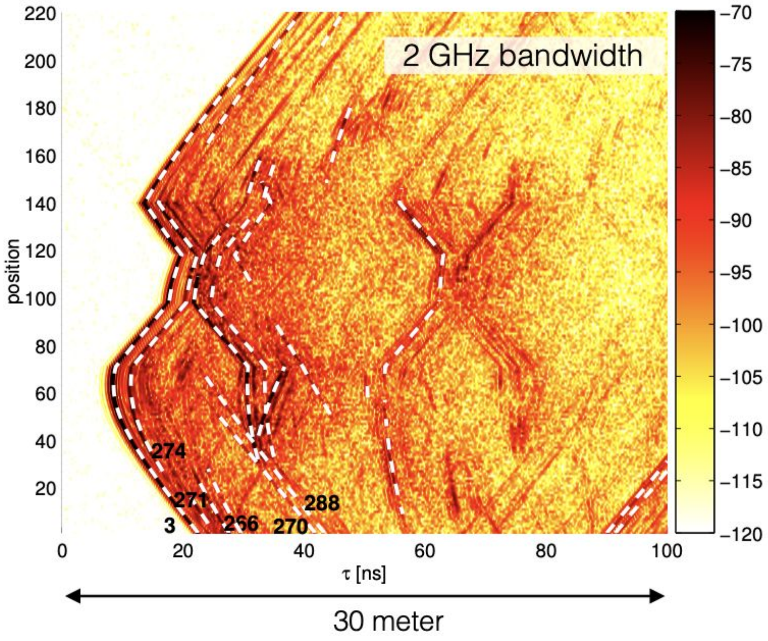
5G: High carrier frequencies

- Higher path loss, but countered by antenna array gains
- Less shadowing since severe penetration loss
  - Can be a bit counter-intuitive, but…
  - Receiving a shadowed signal is worse than not receiving it at all
- Multipath fading: No diffraction, limited scattering, little reflection
- In summary: Communication channel is dominated by LOS
  - Good because what we can pick up is clean
  - Bad because we need to maintain LOS between BS and UE

5G: Large bandwidths

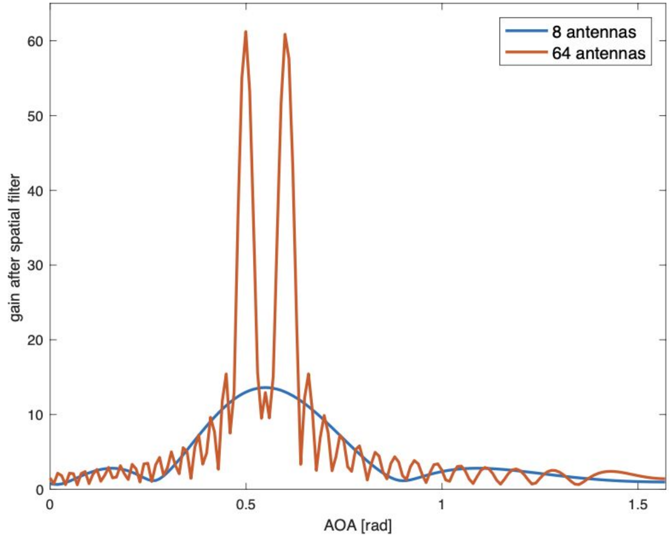
- Larger bandwidth leads to better delay (hence distance) estimation accuracy
- Multipath components are easier to resolve
- Two paths are resolvable when

$$|\tau_1 - \tau_2| \times B \gg 1$$



5G: Larger number of antennas

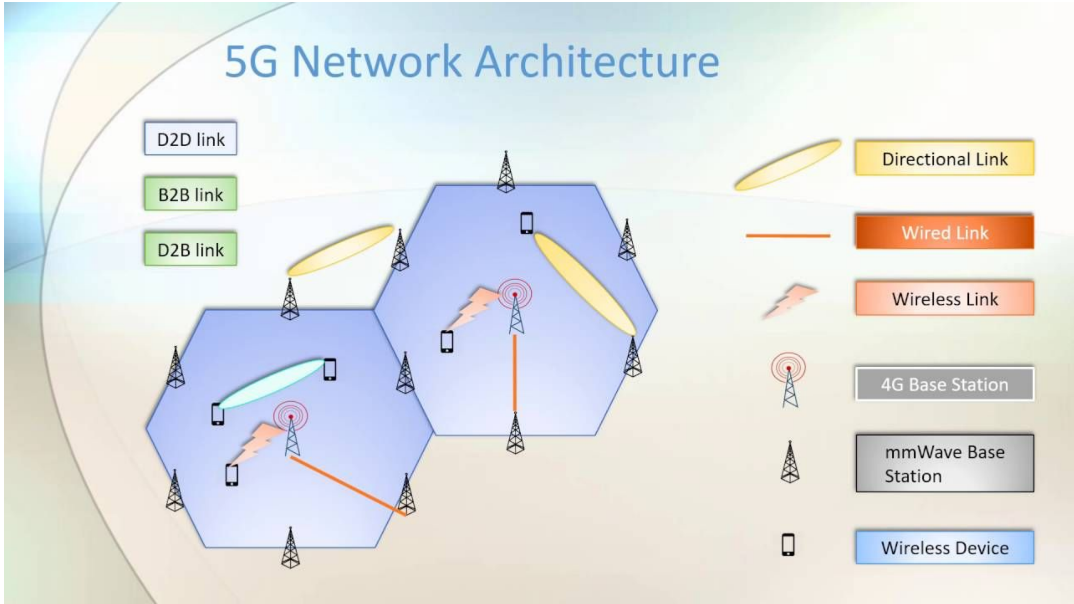
- i.e. larger antenna arrays
- Larger receiving antennas: Better AoA resolvability
- Larger transmitting antennas: Better AoD resolvability, smaller beamwidth (we'll revisit beamforming)
- aka Massive MIMO



Directionality increases,
but so does gain!

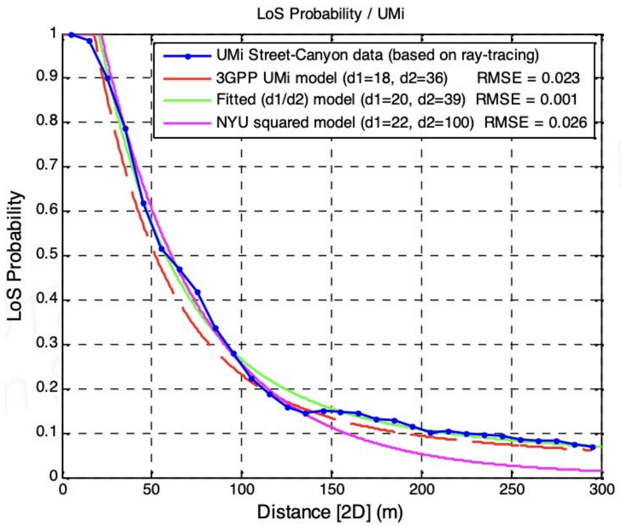
5G: Device-to-device communication

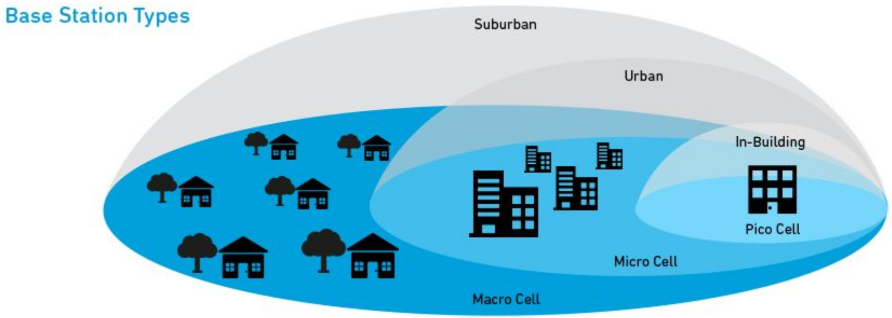
- 5G will have side links (extra links between devices)
- Can improve both accuracy and coverage
- Enables cooperative positioning methods
- 5G has a special focus on IoT
- Possible links
  - D2D
  - D2B (mmWave or traditional)
  - B2B (wired)



5G: Network densification

- Many base stations of different size and capabilities
- Higher chance of LOS at shorter distances
- For communication we might not need LOS, but it is crucial for positioning!
- Also called Ultra Dense Network (UDN)
    - Small: micro-cell
    - Smaller: pico-cell
    - Smallest: femto-cell



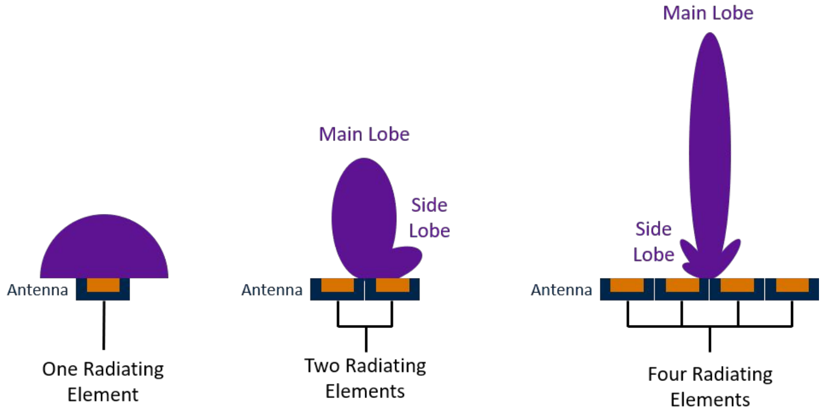


Cell Type	Output Power (W)	Cell Radius (km)	Users	Locations
Femtocell	0.001 to 0.25	0.010 to 0.1	1 to 30	Indoor
Pico Cell	0.25 to 1	0.1 to 0.2	30 to 100	Indoor/Outdoor
Micro Cell	1 to 10	0.2 to 2.0	100 to 2000	Indoor/Outdoor
Macro Cell	10 to >50	8 to 30	>2000	Outdoor

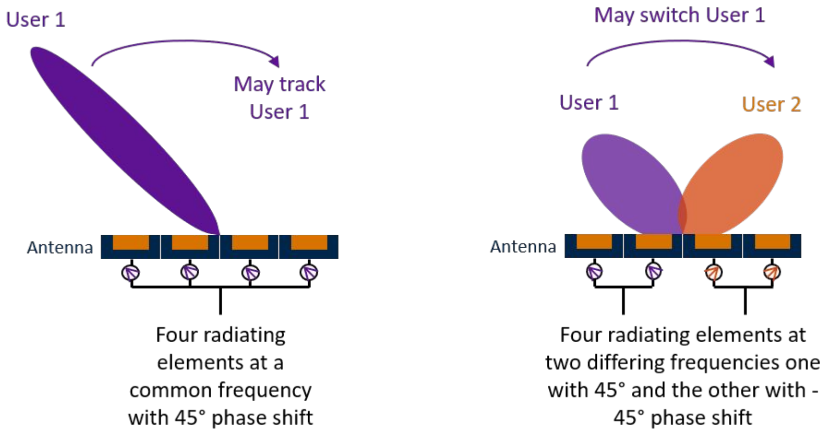
qorvo

5G: Beamforming

- Directional signal transmission, possible via antenna arrays!
- Via controlling the phase and relative amplitude of the signal at each transmitter
- Constructive and destructive interference strengthens the desired direction while weakening others



More antennas give more directionality

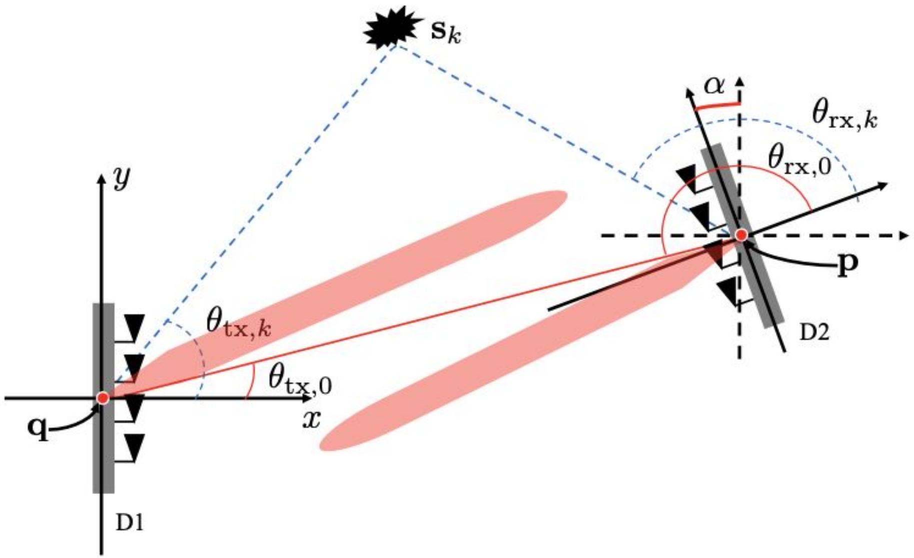


It is possible to generate beams with different directions at different channels

5G: Initial Access Problem

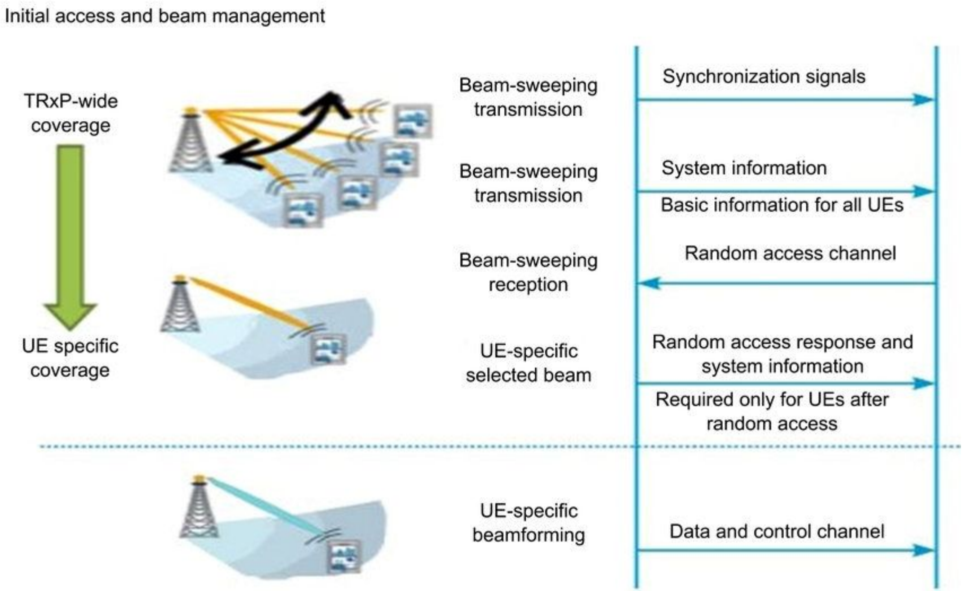
- Beamforming enables high SNR and high data rates, but where to point the beam initially?
- Beam-sweeping and beam-refinement

  1. Transmit beams in every direction (each beam at a different time)
  2. UE selects the best beam and knows when the next beam with the same direction will arrive
  3. Responds at the next iteration
  4. BS further refines beam with a similar procedure



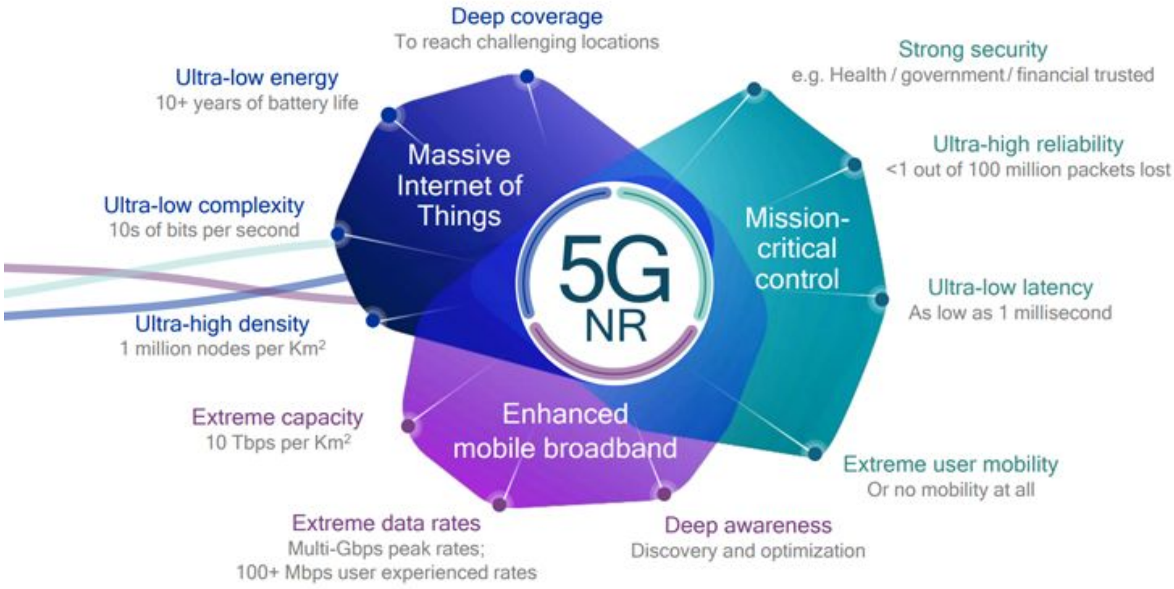
5G: Initial Access Problem

- Alternatively, use out-of-band position information
- i.e. Rough location info communicated beforehand
    - Could be GPS, could be simple trilateration
    - Does not need to be so accurate
- Can be used to improve the Initial Access (IA) process (Reducing beam-sweep angle)

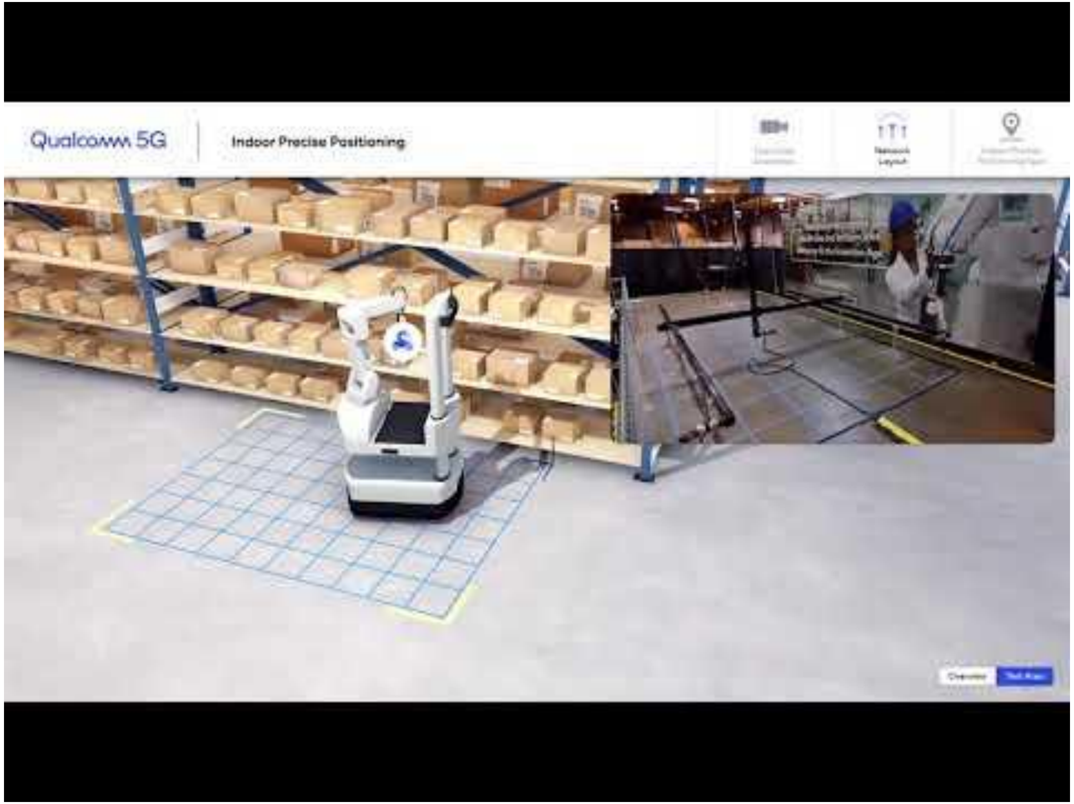


5G NR

- Stands for **5G New Radio**
- 5G is the standard, NR is the actual tech
- As in 4G and LTE, 3G and UMTS



5G Positioning Example



5G Summary

✅ Strengths

- Sub-meter accuracy with mmWave
- Operators are invested in this
- Position improves communication, communication improves position
- AoA is required for beamforming which increases data rates (more incentive!)
- Envisions interconnectivity with a wide range of devices (not just phones!)

❌ Weaknesses

- High infrastructure needs (it is not there yet!)
- LOS requirements for high accuracy
- High cost (but may be worth it?)
- Operators may choose to go sub-6GHz for lower cost (demanding use cases are not there yet)
- mmWave 5G is supported by only flagship phones today (will increase)