# Understanding Advanced Bluetooth Angle Estimation Techniques for Real-Time Locationing

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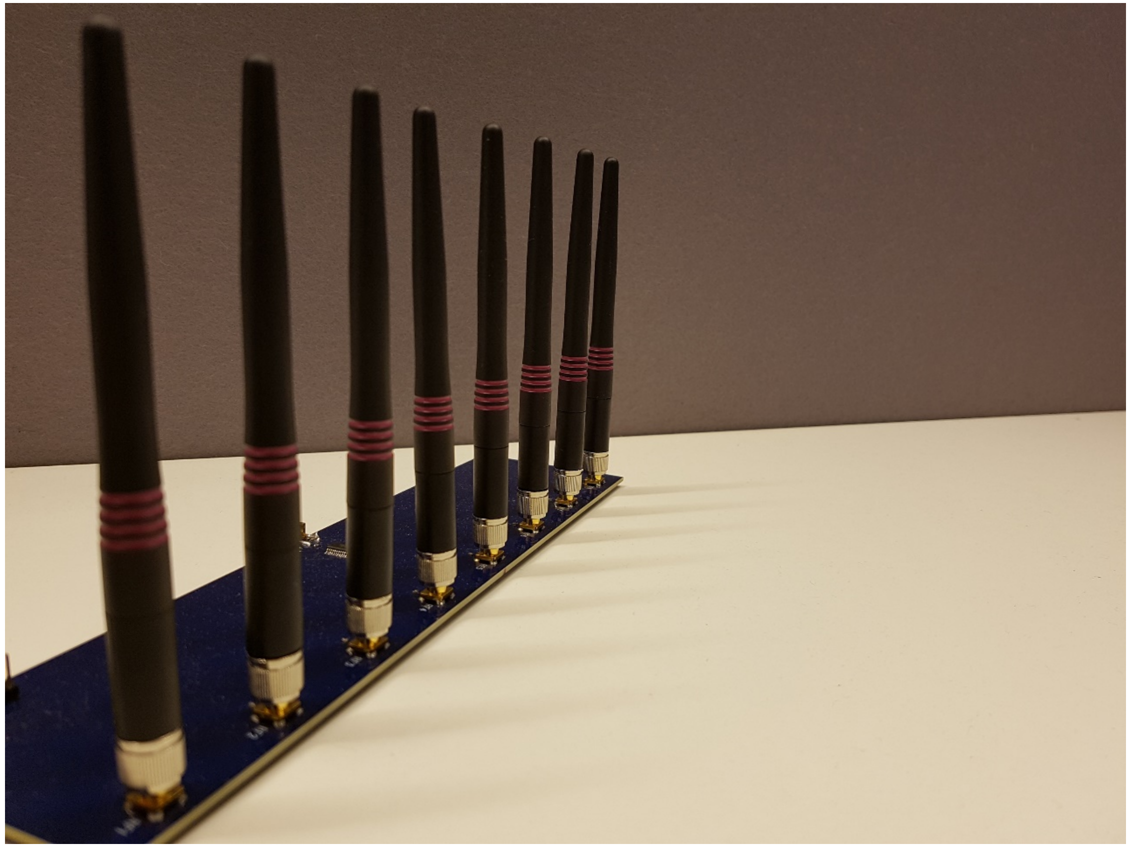
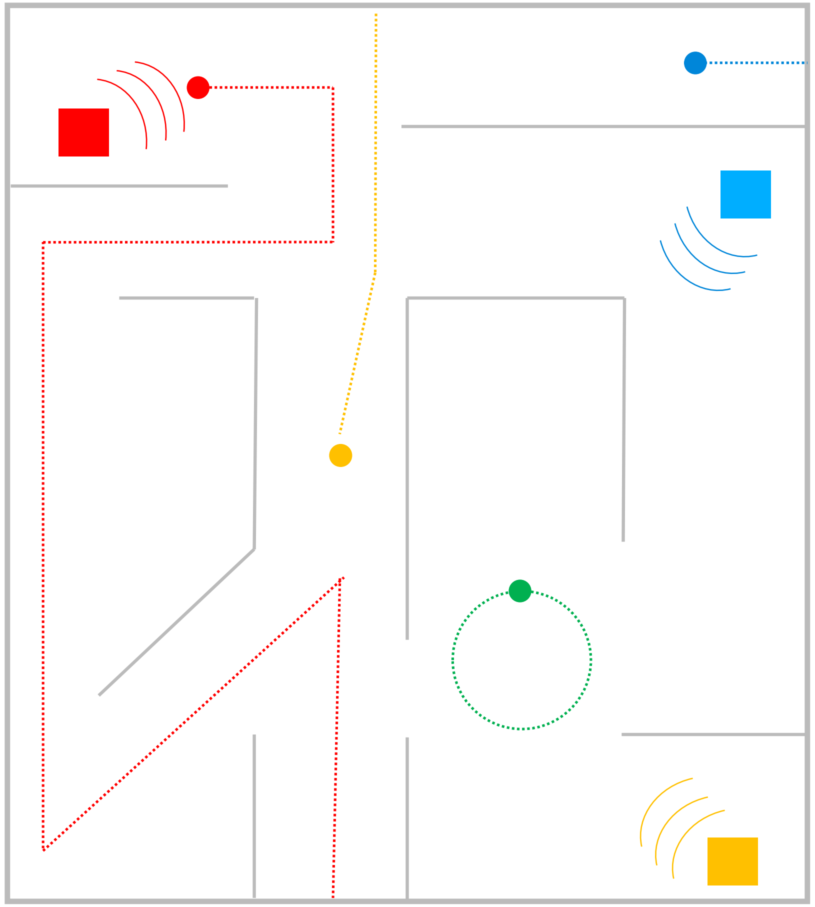


**Agenda**

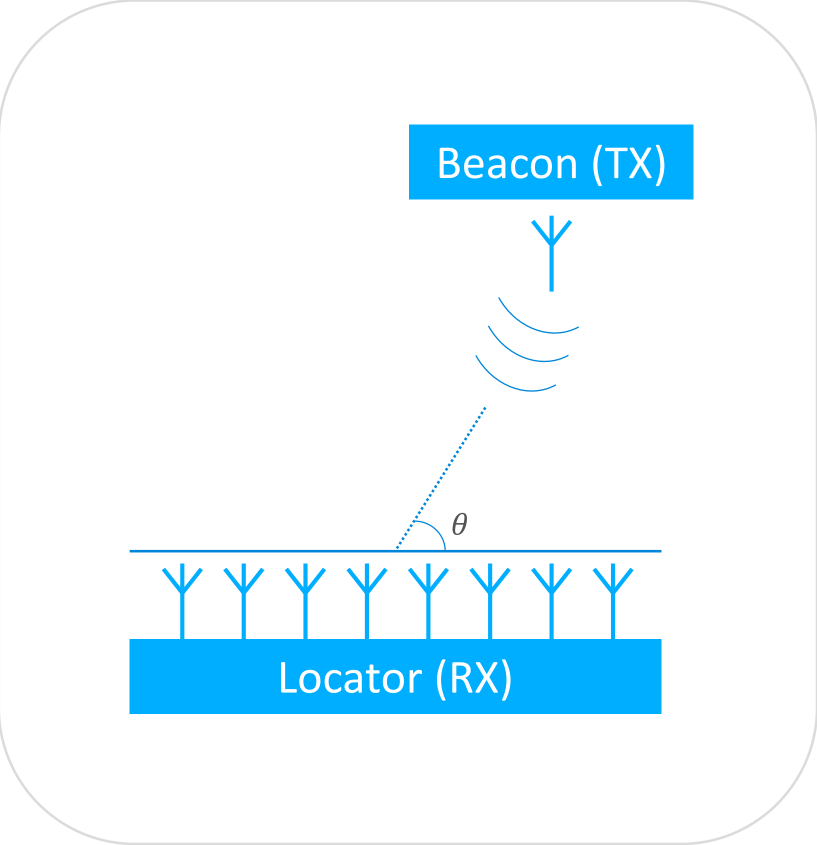
- Motivation – What and Why?
- History of Direction Finding
- Bluetooth AoA
- Bluetooth AoD
- Example applications
- Challenges
- Some Comparative Positioning Technologies
- Antenna Arrays
- Direction of Arrival Theory
- Summary

# Motivation



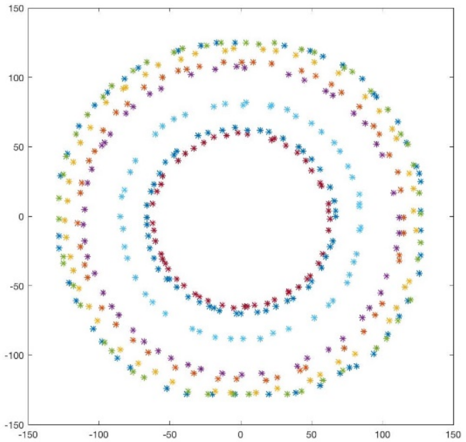
- The term Real-Time Locationing (RTLS) ?
  - Target is to get real-time estimates of object positions (or angles), in this case using RF-waves
  - GPS vs indoor locationing
  - Bluetooth Angle of Arrival and Angle of Departure are upcoming technologies
- Why Real-Time Location?
  - Find or track assets/people
  - Find yourself
  - IoT’s best friend – new applications not yet invented…
- History of direction finding methods goes back over 100 years
  - Direction finding technology is already used in many applications like medical equipment, aviation, security applications, military …

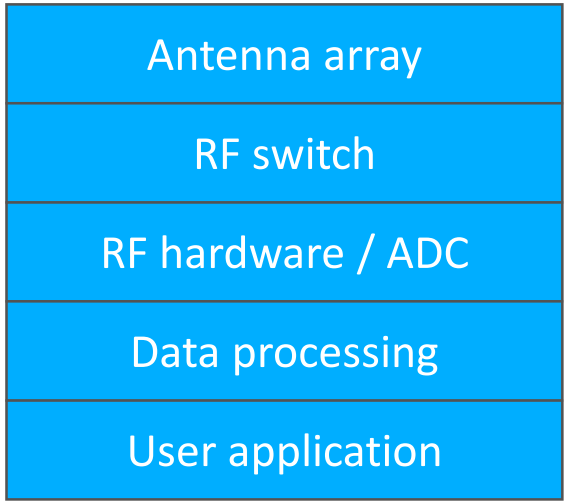
# Bluetooth Angle of Arrival – Basic Idea 1/2




- The Bluetooth AoA/AoD specifications developed by the Bluetooth SIG are mature but not yet final.
  - We'll talk about general concepts and will not refer to the spec
- General idea: In Angle of Arrival the tracked device is sending a special beacon signal using 1 antenna
- Receiver devices called locators
  - Have multiple antennas arranged in an array
  - Take IQ-samples from the received signal while sequentially switching the currently active antenna
  - Angle of arrival estimate is calculated based on the input data
- Antennas in the receiving array will (theoretically) see phase differences because of different line-of-sight distances to the TX
  - Light speed vs. wave length vs. antenna distance
  - In practice not easy: multi-path and antenna array properties

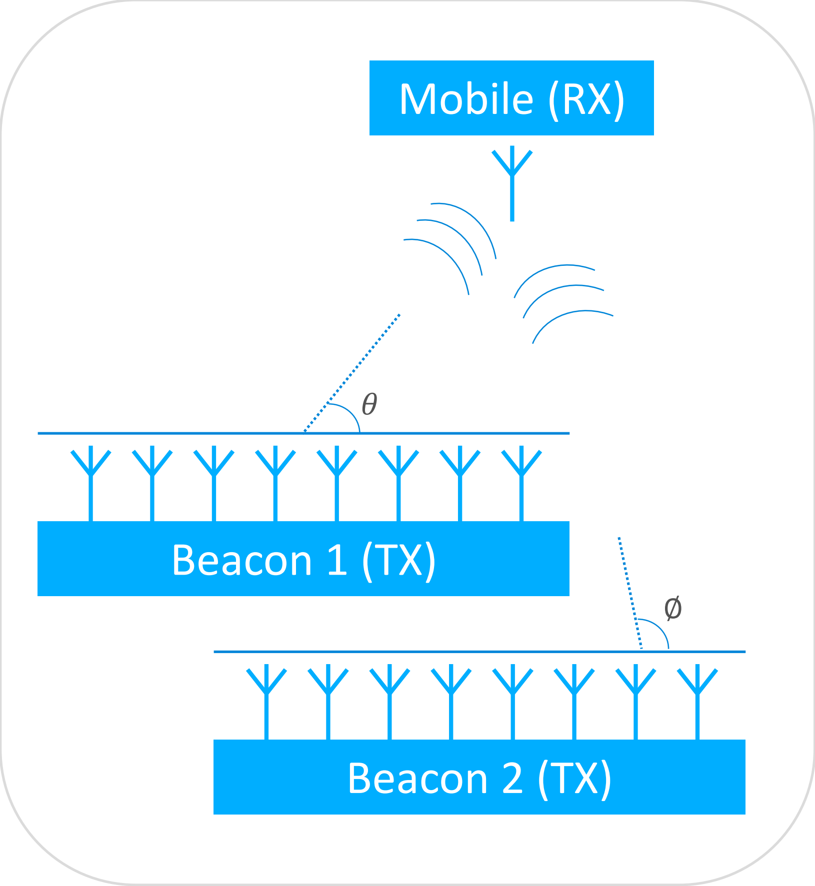
# Bluetooth Angle of Arrival – Basic Idea 2/2




- One IQ-sample is a pair of in-phase and quadrature-phase samples.
- The AoA-calculation algorithm takes in the IQ-data and calculates an estimate for the arrival angle.
  - Phase and amplitude information
- In Bluetooth, control data related to the positioning is transferred over the traditional data channel.

# Bluetooth Angle of Departure – Basic Idea

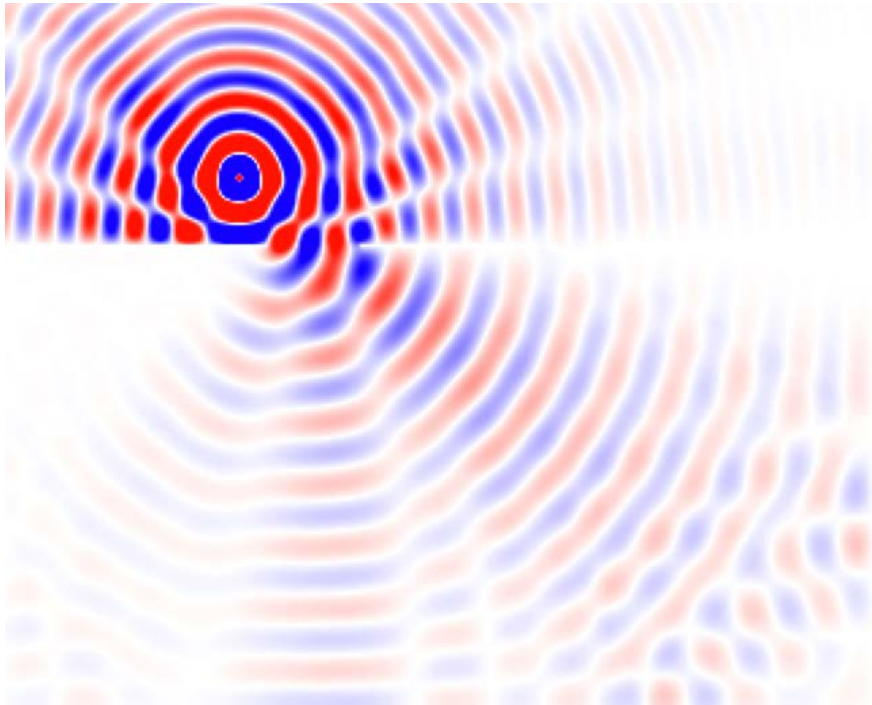



- In Angle of Departure, the fundamental idea of measuring phase differences is the same but device roles are swapped
  - The tracked device is using only one antenna. Beaconing devices use multiple antennas.
- From the application point of view, the fundamental difference to Angle of Arrival is:
  - AoD: the receiving device can calculate its own position in space using angles from multiple beacons and their positions
  - When in AoA: the receiving device tracks arrival angles for individual objects
- All kinds of combinations are possible. When measuring RSSI / distance data, we'll get even more possibilities.
- Expected accuracy can be around a half meter.

# Theoretical Example Applications (from my own life)

- Problem 1: Dude, where’s my car? (lost in a parking building) (AoA)
  - Take a connection to the car
  - Ask the car to send a narrowband tone
  - IQ-sample the received tone using antenna array
  - Feed the IQ-data to a direction of arrival algorithm to get an angle estimate
  - Get the car
- Problem 2: Find my way out of a shopping mall (AoD)
  - Open mobile phone app with a map of the shopping mall
  - Listen to the multiple fixed-position beacons installed in the mall
  - IQ-sample the beacons coming from the known locations
  - Calculate my own position using the angle estimates and beacon device positions
  - Escape and celebrate freedom

# Challenges in RTLS



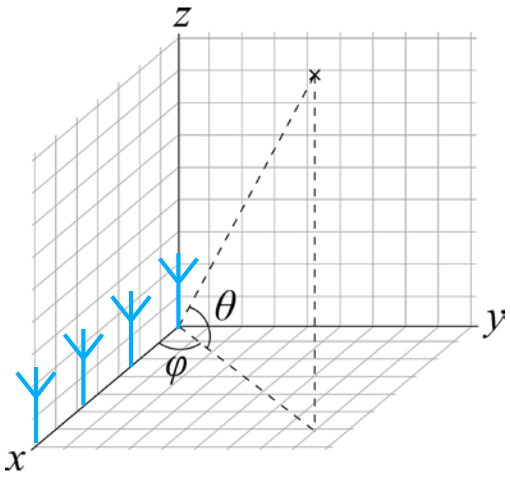
- How to calculate angle estimates based on the sampled data
- Multipath
  - Two signals are coherent if one is a delayed and scaled version of the other
  - When indoors, there can be several reflections, i.e. the receiving device sees coherent reflections of the original incident signal coming in from several other angles
- Polarization
  - Cannot control orientation of the mobile device
- Signal noise, clock jitter, signal propagation delays, switching timings, etc.
  - Errors in the signals affect accuracy of the estimates
- RAM / CPU performance in an embedded device
  - Some data needs to be buffered for the calculations
  - Estimation algorithms are CPU intensive
- Antenna array size limitations

# Some Comparative Technologies

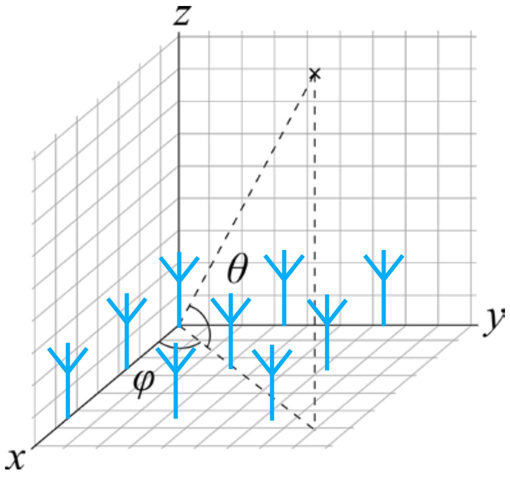
- RSSI (Received Signal Strength Indicator)
  - Measure strength of the received signal to get distance approximation
  - Trilaterate position based on multiple distance measurements from different points
  - Requires only one antenna per device
  - Usually not very accurate indoors
- ToA/ToF (Time of Arrival / Time of Flight), TDoA (Time Difference of Arrival)
  - Measure travel-time and trilaterate
  - In ToA, all devices are time-synchronized. In TDoA only receiving stations are time-synchronized.
  - Requires only one antenna per device
  - Requirement for very high time resolution / clocks
- Solutions for these technologies already exist for Bluetooth from several manufacturers. Only phase-based technologies (AoA/AoD) have a specification by the Bluetooth SIG.

# Direction of Arrival Theory

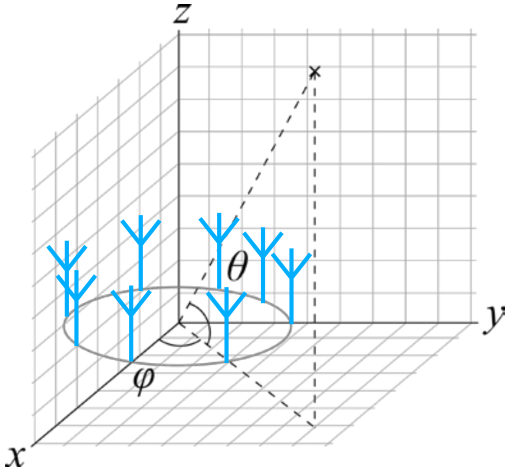
# Antenna Arrays




ULA – Linear array




URA – Rectangular array




UCA – circular array

- Antenna arrays play a significant role in Direction of Arrival (DoA) systems
- Arrays are commonly divided into separate categories and have different properties and performance
- The most common ones are
  - Uniform Linear Array – ULA
  - Uniform Rectangular Array – URA
  - Uniform Circular Array – UCA
- Azimuth vs elevation angle
- Algorithms often require certain properties from the array geometry to work properly
- Designing a proper antenna array is not a copy-paste process

# Direction of Arrival Theory 1/5

- Problem definition: Estimate arrival angle of an emitted (narrowband) signal arriving at the receiving array
- Given a data set of IQ-samples for each antenna in the array. Let the data vector be x
  - Assume the signals to be phase shifted and scaled sinusoidal (narrowband) signals

$$x(t) = a(\theta)s(t) + n(t)$$

  - Where *a* is a mathematical model of the antenna array, the so-called array steering vector
  - The term *s* is the incoming signal and *n* a noise term
- We can calculate the so-called sample covariance matrix $R_{xx}$ by calculating

$$R_{xx} \approx \frac{1}{N} \sum_{t=1}^{N} x(t) x^H(t)$$

- The sample covariance matrix will be used as input for the estimator algorithm

# Direction of Arrival Theory 2/5

- Let's consider the so-called conventional (Bartlett) beamformer to solve the problem of DoA
- Idea for a uniform linear array
  - Formulate steering vector *a* for the ULA

$$a(\theta) = [1, e^{j2\pi dsin(\theta)/\lambda}, ..., e^{j2\pi(m-1)dsin(\theta)/\lambda}]$$

  - Calculate the so-called spatial spectrum using the steering vector *a* and covariance matrix $R_{xx}$

$$P(\theta) = \frac{a^H(\theta)R_{xx}a(\theta)}{a^H(\theta)a(\theta)}$$

- While this approach is quite simple, it's resolution could be better

# Direction of Arrival Theory 3/5

- One type of estimator algorithm is the so-called subspace based estimator, and a popular algorithm in  that category is called MUSIC
- The idea is to perform eigendecomposition on $R_{xx}$ (the covariance matrix):

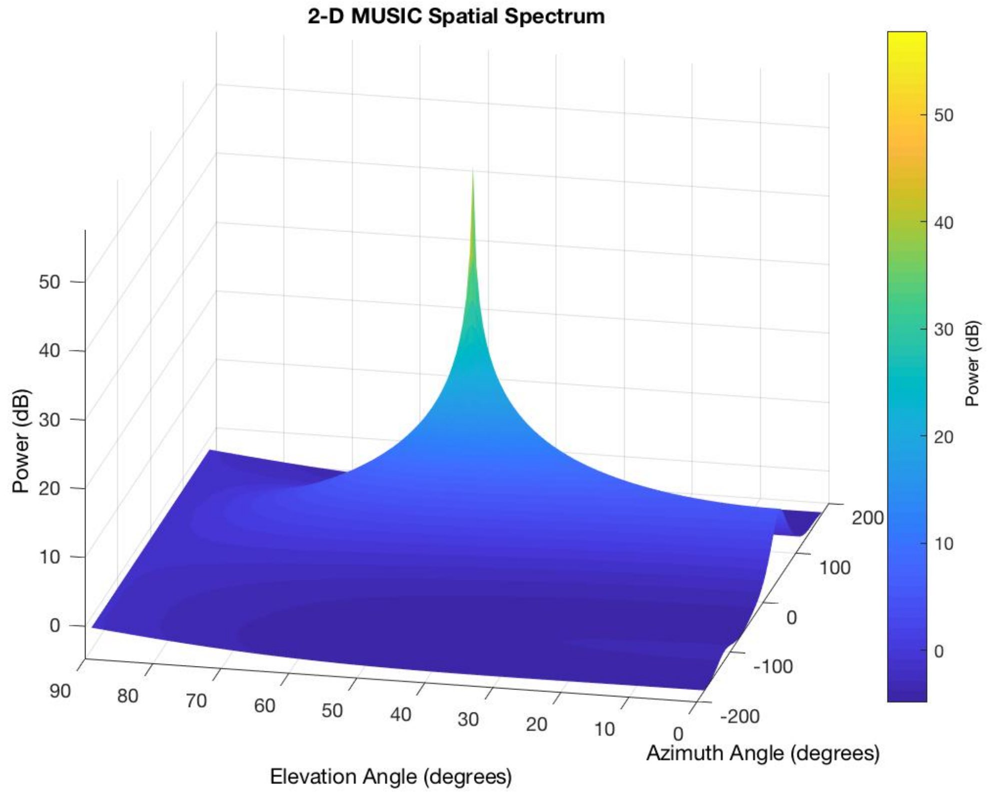
$$R_{xx} = VAV^{-1}$$

- Where $A$ is a diagonal matrix containing eigenvalues and $V$ contains the corresponding eigenvectors of $R_{xx}$
- With the help of $V$ we compute the so-called pseudo spectrum:

$$P(\theta) = \frac{1}{a^H(\theta)VV^H a(\theta)}$$

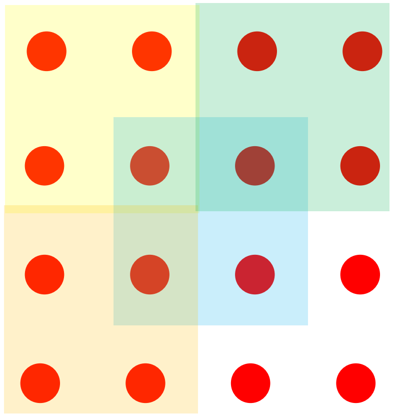
- Where $a$ is the steering vector of the antenna array
- The last step is to find the largest peak of the pseudospectrum, which corresponds to the angle of arrival

# Direction of Arrival Theory 4/5




- Example of a 2-dimensional pseudo spectrum, where the sender is located at azimuth = 50 and elevation = 45

# Direction of Arrival Theory 5/5



- Coherent signals are problematic and confuse the estimator algorithm
  - Pseudo spectrum shows peaks at incorrect angles
  - Solution: multipath "filtering," aka spatial smoothing
- Calculate subarray average of the covariance matrix
- In the 2 dimensional case, spatial smoothing is defined:

$$\overline{R} = \frac{1}{M_s N_s} \sum_{m=1}^{M_s} \sum_{n=1}^{N_s} R_{mn}$$

- This will reduce the size of covariance matrix but "separate" the coherent signals

# Summary

- Bluetooth Angle of Arrival and Angle of Departure are new emerging technologies that can be used for tracking assets as well as for indoor positioning / way finding
- A phase-based direction finding system requires an antenna array, RF switch / multi-channel ADC and processing power to run the algorithms
- Proper antenna array and algorithm design is essential for an RTLS system
- Good performing DoA algorithms are often not computationally cheap
- Other comparative technologies include RSSI based locationing systems and Time of Arrival

# Thank you!

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