(Indoor) Localization of Sensors

Motivation

- Astonishing growth of wireless systems in last years
  - Wireless system used in large number of applications
- Wireless information access has become ubiquitous
- Gave rise to location-based services
  - Navigation systems, location-aware social networks, …
- High demand of location information
  - both in outdoor and indoor environments
  - Outdoor mostly solved with GPS or Galileo
  - Indoor localization is still an open issue

Types of location information

- *Physical* vs *Symbolic* location
  - Physical location: 2D or 3D coordinates referring to a map (e.g. latitude and longitude)
  - Symbolic location: natural language information (e.g. near the fridge, in the bedroom, etc.)
- *Absolute* vs *Relative* location
  - Absolute: uses a shared reference system
  - Relative: each object has its own frame of reference (e.g. proximity to an access point or position with respect to a destination)

Types of location information

- It is always possible to convert absolute location in relative location
- A relative location can be converted into an absolute one if:
  - The absolute position of the reference points is known
  - Multiple relative readings are available
  - ...but there's a need for a triangulation algorithm

Indoor localization systems

- Localization achieved by exchange of radio signals
- Three components :
  - Signal transmitter and receiver (HW)
  - Measuring unit (HW)
    - that uses received signals to make measurements of distances, angles etc. (also called ranging)
  - Localization algorithm (SW)
    - That uses the above information to determine the positioning of an object

Indoor localization systems

- Two main topologies:
  - *Remote positioning*: the unit to be localized is mobile and acts as transmitter. The measuring units (*anchors*) are fixed. A fixed location manager (may be an anchor) executes the localization algorithm
  - *Self-positioning*: the unit to be localized is mobile, makes the measurements and runs the localization algorithm
    - This unit receives the signal from fixed anchors (whose position is known) that are only transmitters
- Two derived topologies:
  - *Indirect remote positioning*: similar to self-positioning, but the mobile sends its location to a remote location manager
  - *Indirect self-positioning*: similar to remote positioning, but the location manager sends the position to the mobile

Measuring principles and positioning algorithm

Triangulation

- Lateration (*range-based*)
  - Time of Arrival (ToA)
  - Time Difference of Arrival (TDoA)
  - Received Signal Strength (RSS)
  - Roundtrip Time of Flight (RToF)
  - Received Signal Phase (RSP)
- Angulation
  - Angle of Arrival (AoA)

Scene analysis (fingerprinting)

- Probabilistic methods
- K-Nearest Neighbors (kNN)
- Neural Networks
- Radio Tomography

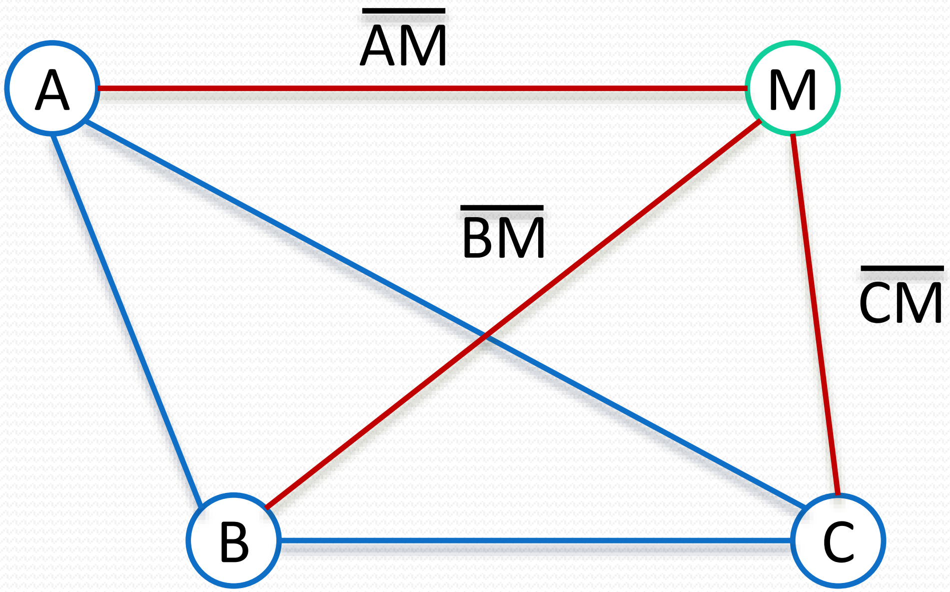
Proximity

- Radio Frequency Identifier (RFID)
- Passive Infrared (PIR)
- WSN Multihop proximity

Triangulation

- Uses geometric properties of triangles to estimate target location
- Two approaches:
  - *Lateration*: estimates position of an object based on its distance from reference points (also called *range-based localization*)
  - *Angulation*: estimates position based on the angles between the lines connecting the object and the reference points

Triangulation – Lateration

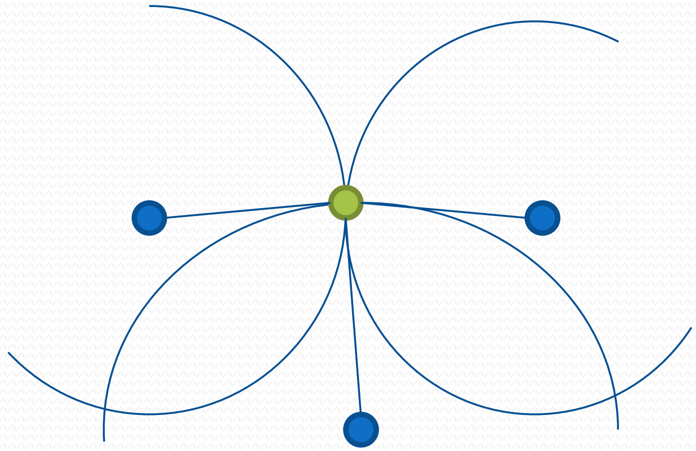


Time of Arrival (ToA)

- The distance between a measuring unit and a mobile target is directly proportional to propagation time
- How it works
  - The mobile target emits a radio signal at time t
  - The measuring unit receives the radio signal at time t'
  - The measuring unit estimates the distance as (t'-t)/p
    - Where p is the propagation speed of the signal
- Issues:
  - Requires tight synchronization of transmitter and receiver
  - The signal must encode the transmission time (t)

Time of Arrival (ToA)

- To compute the position of the mobile target in 2D are required at least 3 measurements from 3 different anchors
- The position can be computed with different methods:
  - Intersection of circles centered in the anchors



Time of Arrival (ToA)

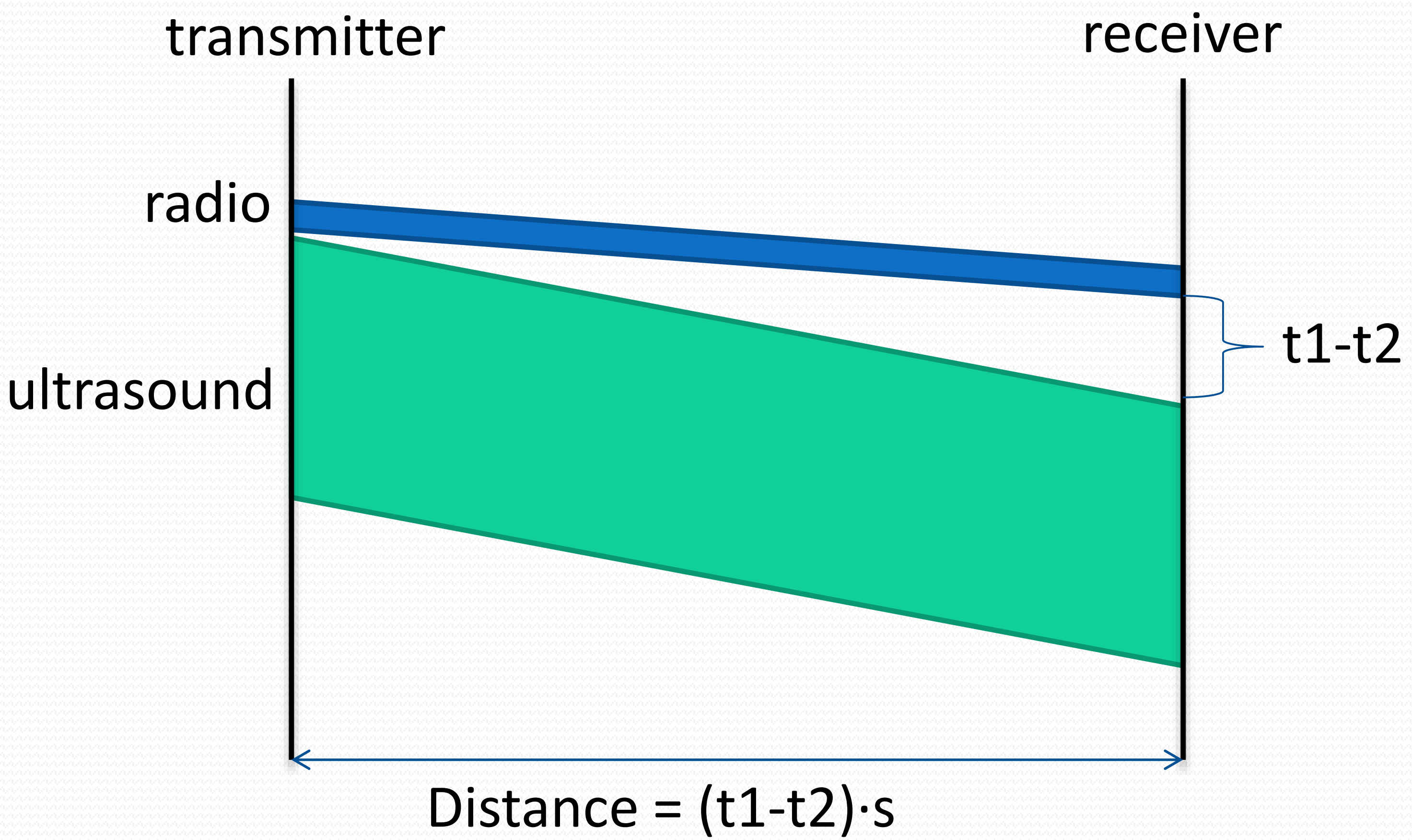
- Other positioning method:
  - Solving a non-linear optimization problem (least squares)
    - the unknown are t, the coordinates (x,y) of the mobile target
    - The coordinates of anchors $(x_1,y_1),\ldots,(x_n,y_n)$ are known
    - The time of arrival of the signal at the anchors $t_1,\ldots,t_n$ are known
    - c is the light speed

$$\min \sum_{i=1}^{n} \left| c \cdot (t_i - t) - \sqrt{(x_i - x)^2 + (y_i - y)^2} \right|$$

Time of Arrival (ToA)

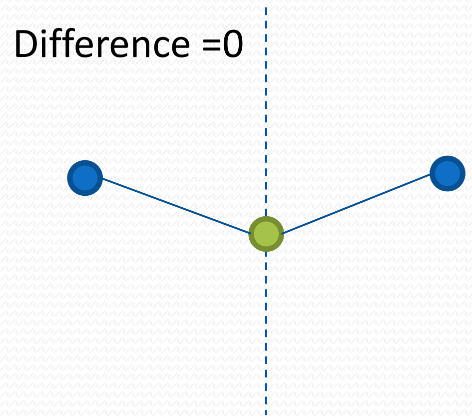
- In some applications, the ToA is implemented by using signals of different nature, e.g. radio and acoustic:
  - The radio signal is used to synchronize the measuring units
- The difference in time between the arrival of the two signals is (almost) proportional to the distance
  - Because the radio signal is order of magnitudes faster than the acoustic signal
- Some systems use ultrasound
  - Cricket motes, Active Bat, etc.

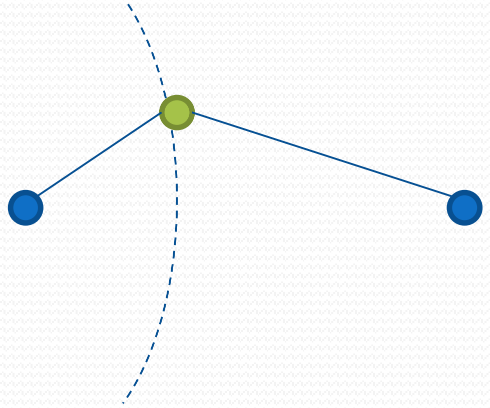
Time of Arrival (ToA)



Time Difference of Arrival (TDoA)

- Uses the difference between the arrival times at the measuring units (rater than the absolute time)
- For each TDOA measurement, the transmitter must lie in a hyperboloid with a constant range difference between any two measuring units
- For example, in 2D:



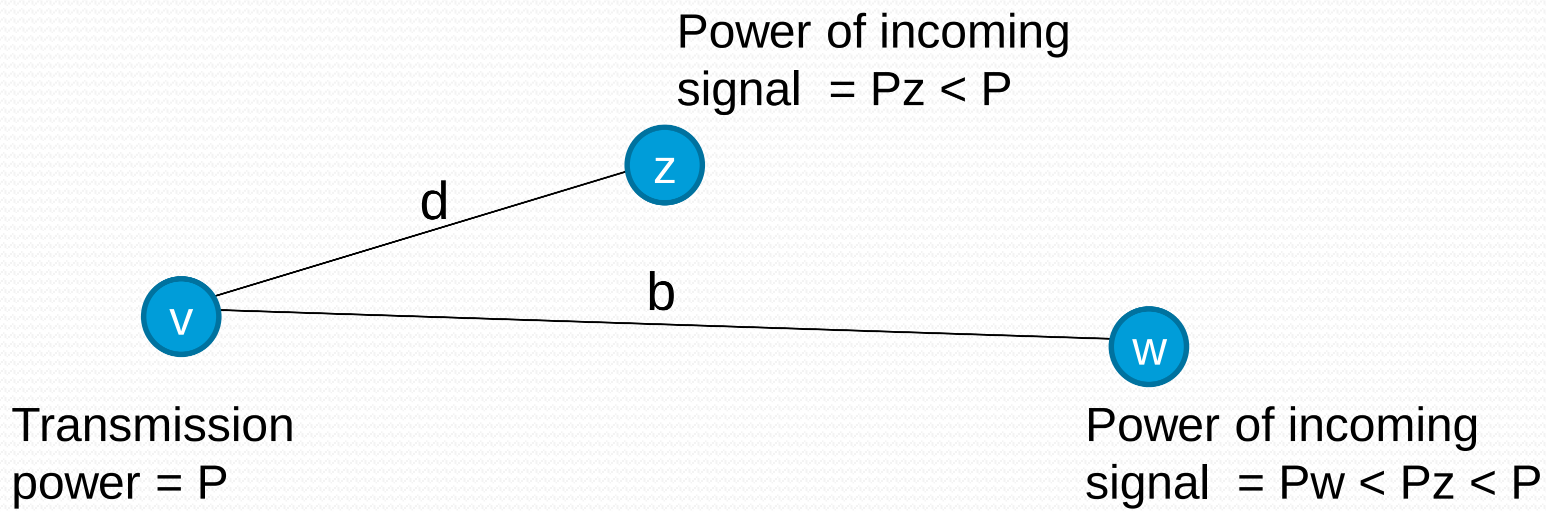


TOA and TDoA

- Both system work well if transmitter and measuring units are in Line Of Sight (LOS)
- If not, the signal is affected by multipath that affects time of arrival and angle

Received Signal Strength (RSS)

- Radio signal attenuates with distance
  - Power of the signal decays with an exponential rule
- There is a relationship between signal attenuation and distance



Received Signal Strength (RSS)

- Friis equation: estabilish a relationship between transmission power and distance between transmitter and receiver

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi)^2 d^n}$$

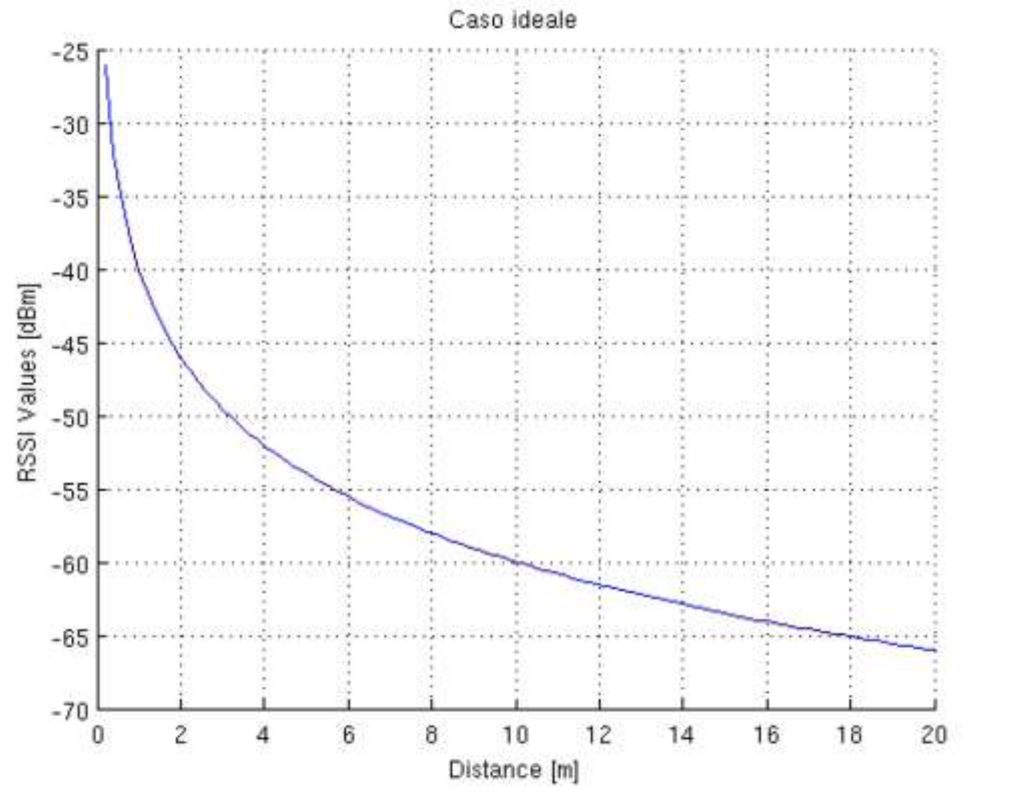
- P_T e P_R: signal power at transmitter and receiver (in Watt)
- G_T e G_R: antennas gain (at transmitter and receiver)
- λ: wave length
- d: distance between the transmitter and receiver
- n: path loss (usually between 2 and 4)

Received Signal Strength (RSS)

- Signal attenuation depends on the environment.
- There are many models that relate distance with transmission and received power.
- Converting Watt in dBm:
  - $P[dBm]=10 \log_{10} (10^3 P[W])$
- and combining with Friis equation we obtain:
  - $RSS = -(10\, n \log_{10} d - A)$
- where
  - A is attenuation of the signal at a reference distance (typically 1 m)
  - n is the path loss (typically in the range [2,4])

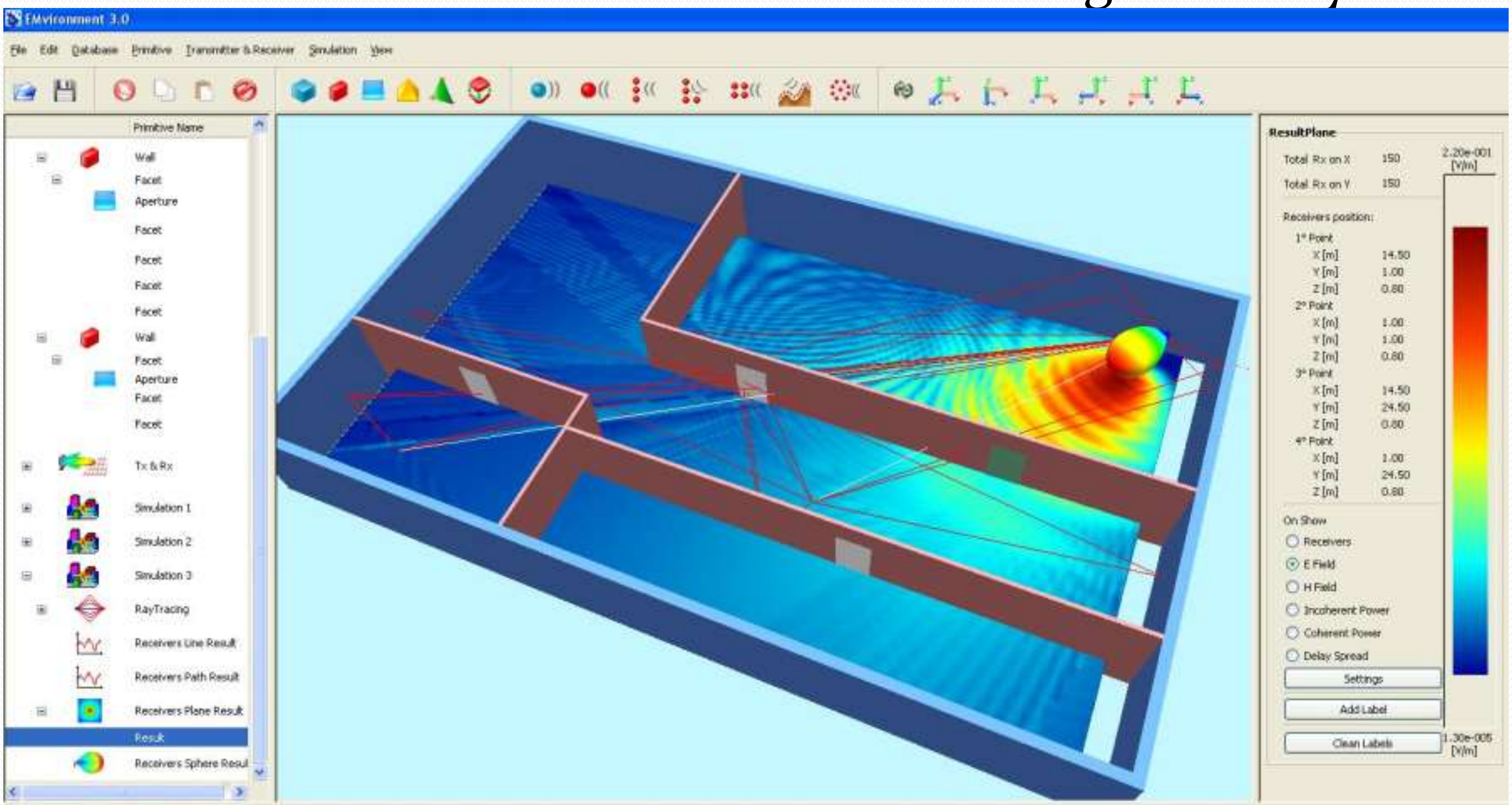
Received Signal Strength (RSS)

- Power vs distance



Received Signal Strength (RSS)

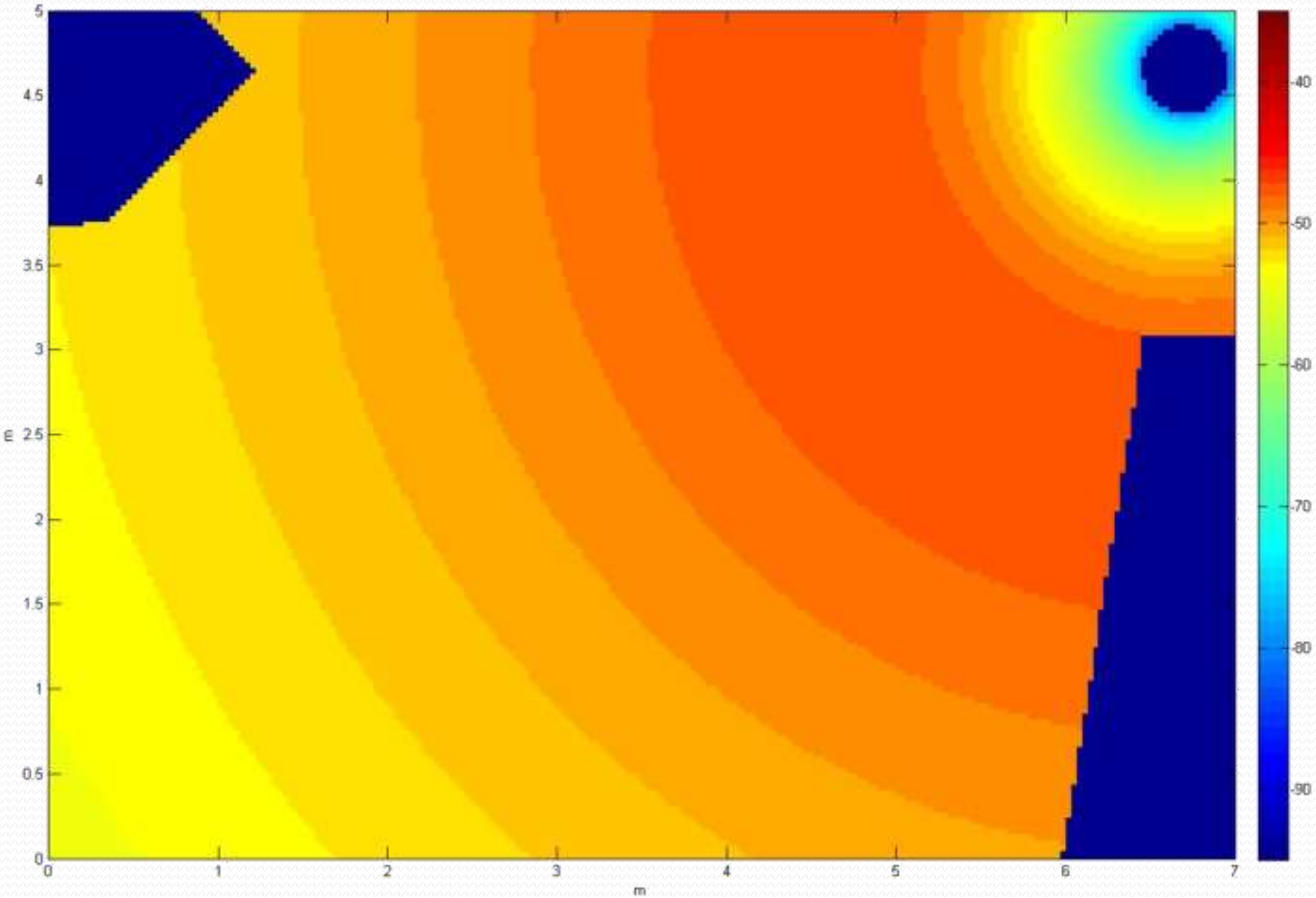
- In indoor environments the RSS worsens significantly



Triangulation - lateration

Received Signal Strength (RSS)

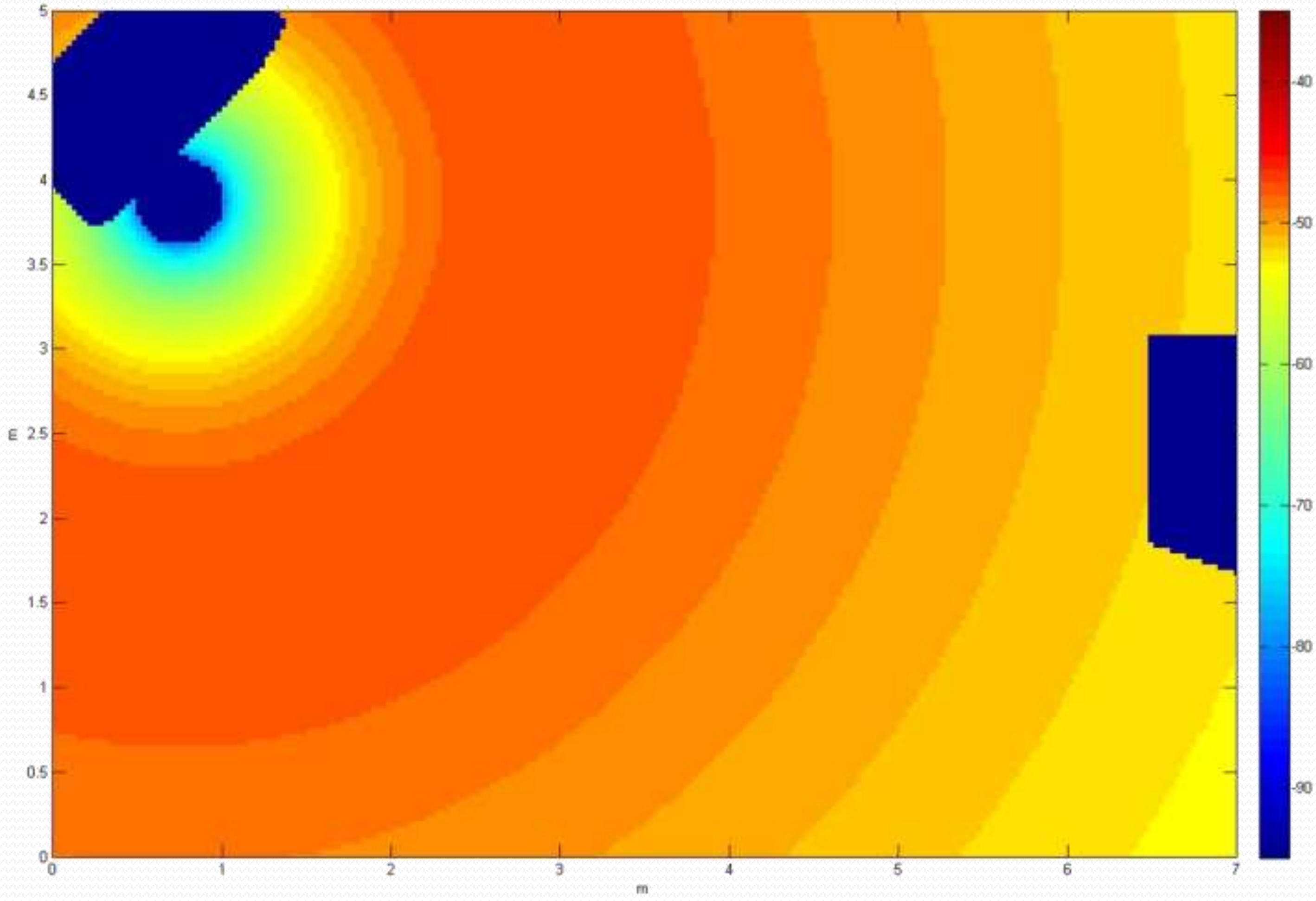
- Ideal situatio



courtesy of F.Potortì, A.Corucci, P.Nepa, P.Barsocchi, A.Buffi

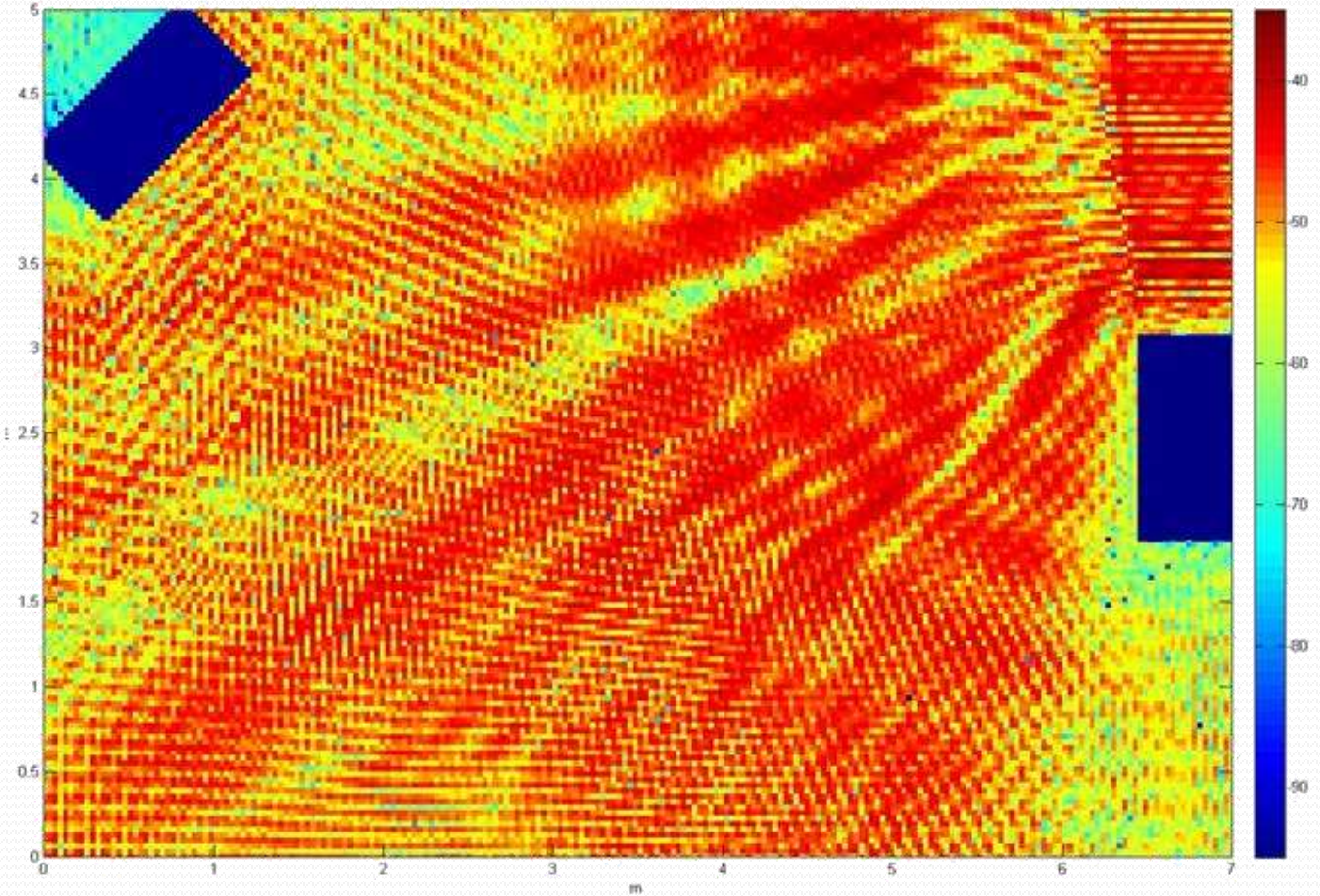
Received Signal Strength (RSS)

- Ideal situation:



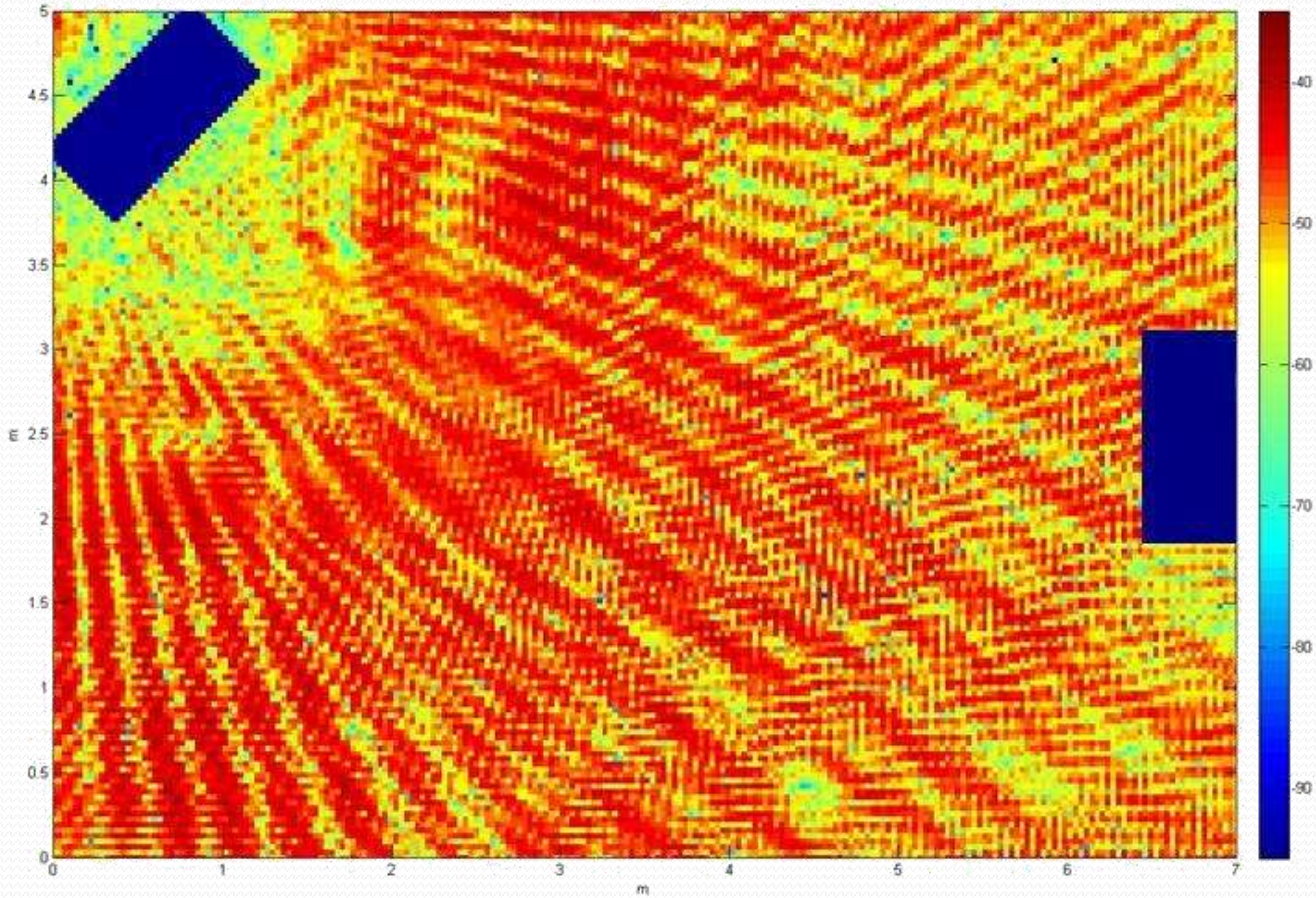
Received Signal Strength (RSS)

- Realistic situation
  - 3° order reflections



Received Signal Strength (RSS)

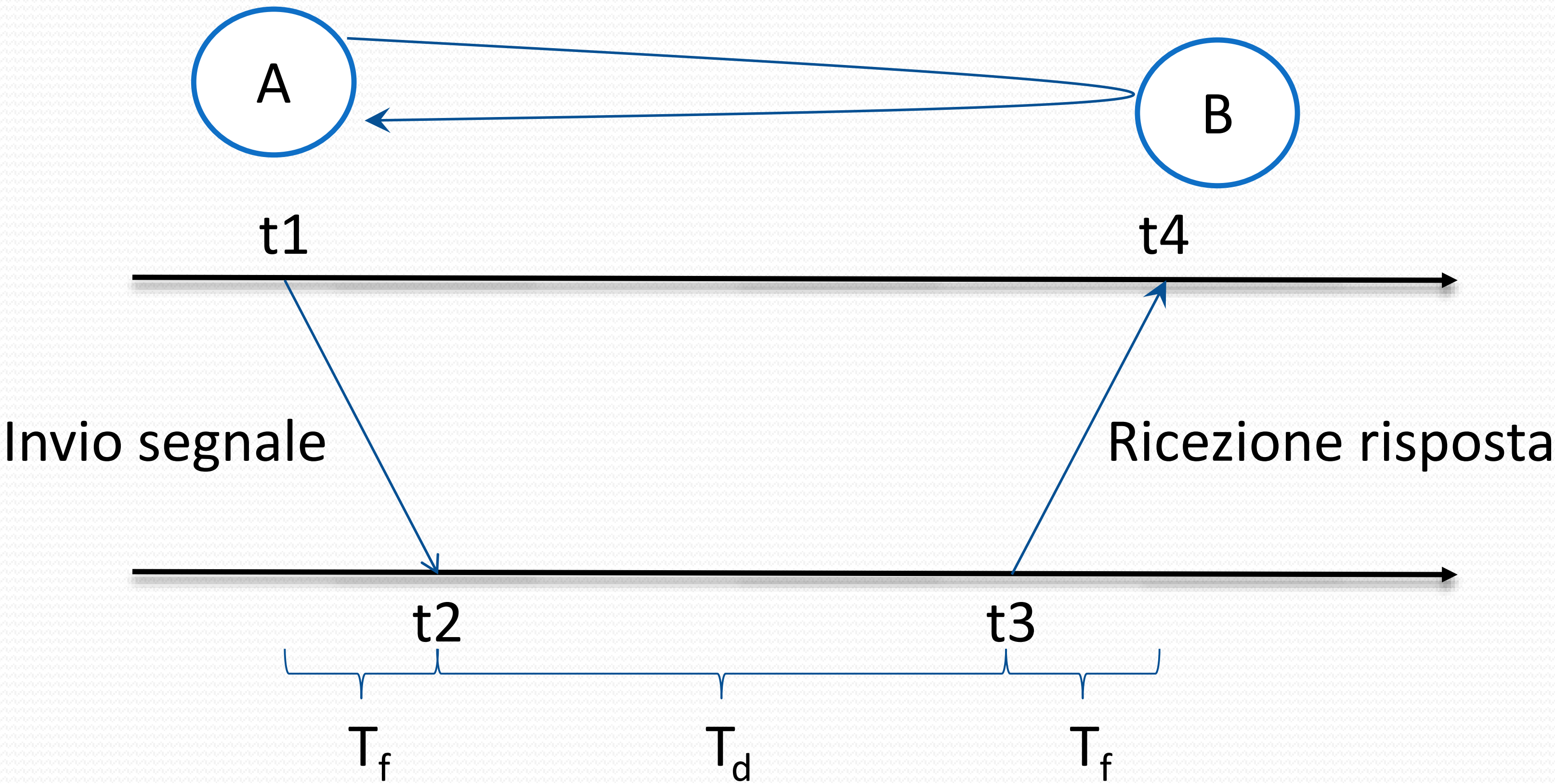
- Realistic situation
  - 3° order reflections



Roundtrip Time of Flight (RToF)

- The transmitter and the measuring unit are the same
- The device to be localized is only a transponder
  - receives the signal and sends it back
- The measuring unit measures the difference between the time of transmission t_1 and the time of reception t_2
  - distance = $c^*(t_1 - t_2)/2$
- Reduces the need of synchronization with respect to ToA
  - At small ranges, the processing time of the transponder and measuring unit are not negligible and must be estimated accurately

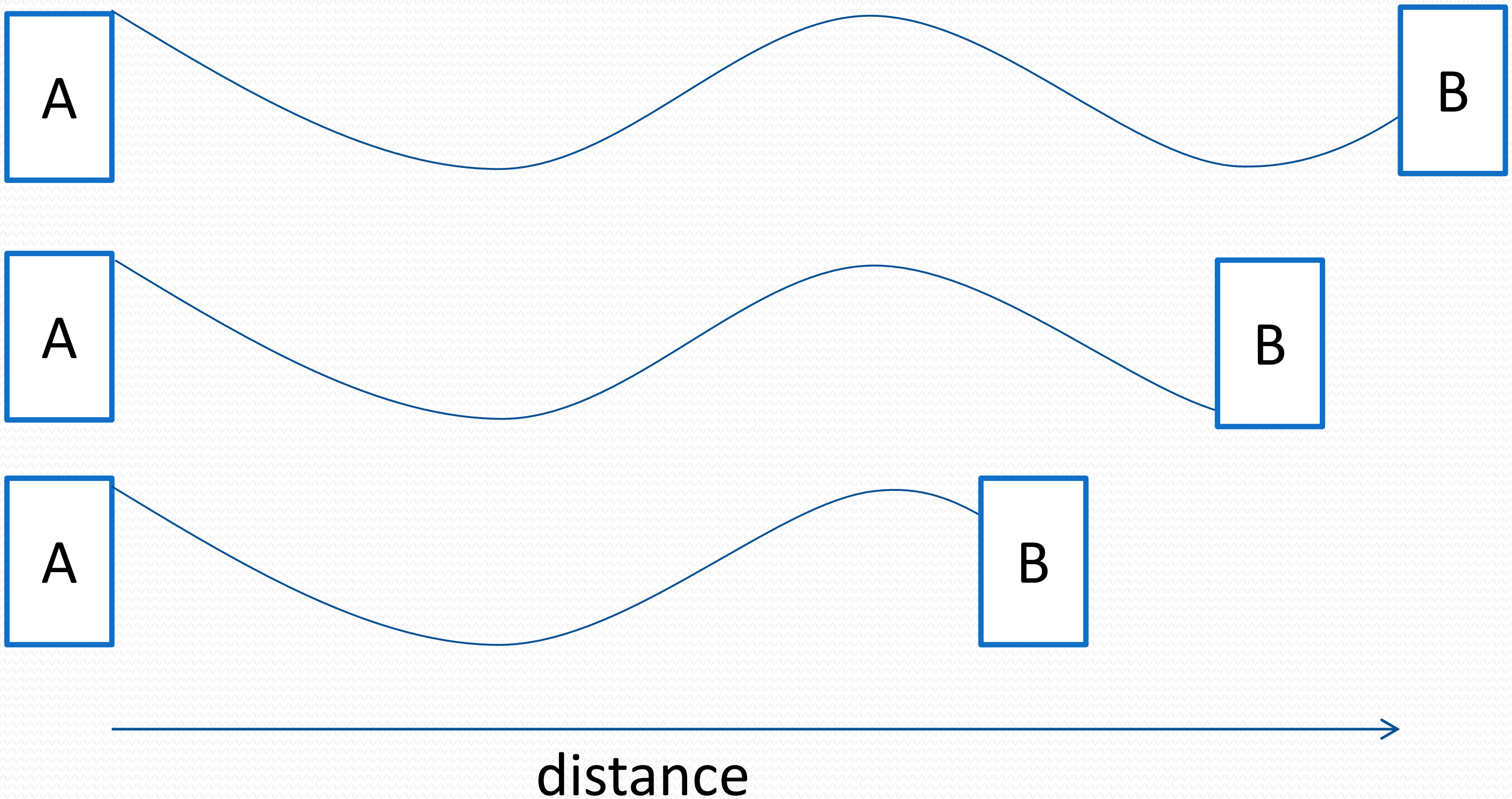
Roundtrip Time of Flight (RToF)



$$d = c\,\tfrac{1}{2}\left(\left(t_2 - t_1\right) + \left(t_4 - t_3\right)\right)$$

Received Signal Phase (RSP)

- Assumes the transmitter sends a pure sinusoidal signal

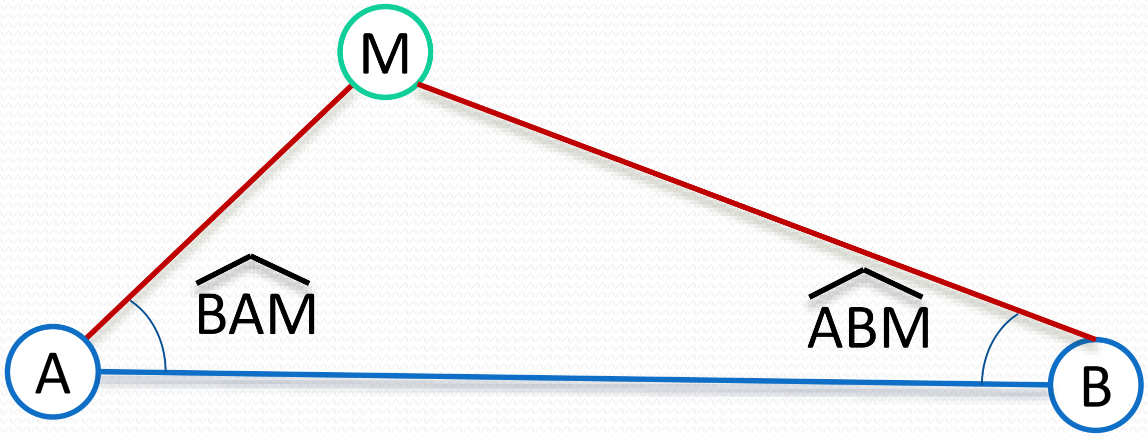


Received Signal Phase (RSP)

- Based on the received phase of the signal, the measurement unit estimates the distance
  - This holds within a wave length
- Once distance is known it uses the same triangulation algorithm as ToA
- For distances larger than a wave-length it does not work
- Requires LOS between transmitter and receiver

Angle of Arrival (AoA)

- Target location obtained by the intersection of several pairs of angle direction lines
- 2D: Requires at least two reference points and the respective angle measurements
- 3D: Requires at least three reference points and the respective angle measurements



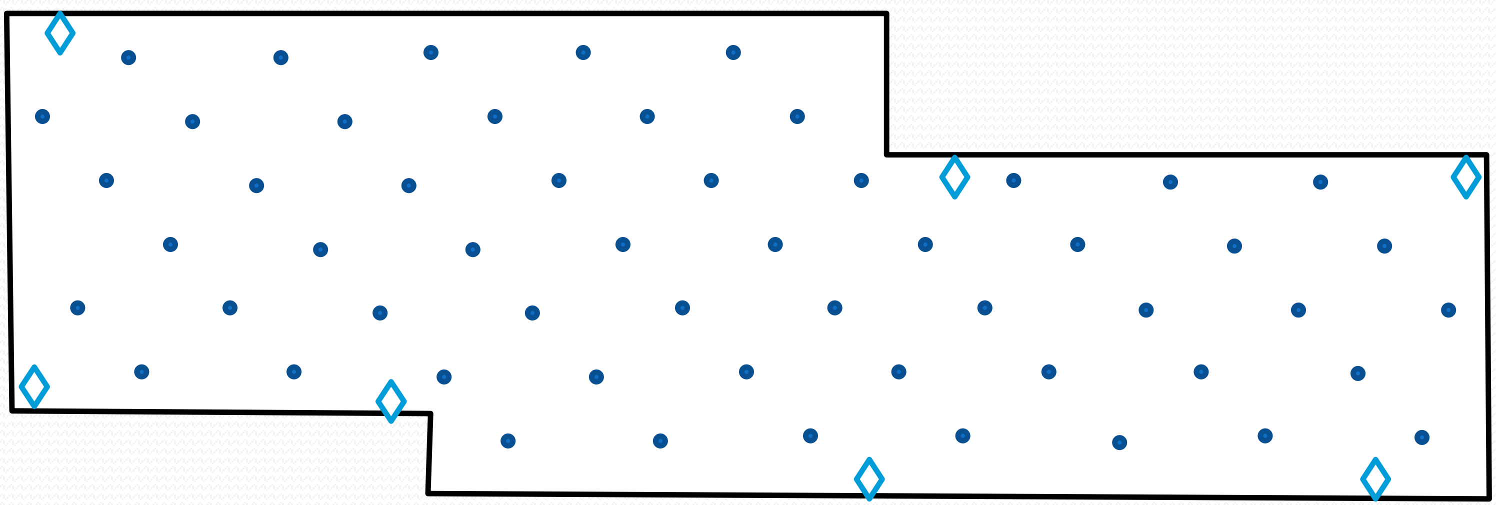
Triangulation - angulation

Angle of Arrival (AoA)

- Requires directional antennas
  - Usually not available in sensors
  - More expensive and larger
  - Often implemented as arrays of antennas
- Angle measurement should be very accurate
  - Again multipath and reflection affect the measurements

Scene analysis

- Exploits maps of RSSs measurements with respect to a set of anchors
- Measurements usually in a grid of points
  - For each point *i* in the map, is defined a tuple of RSS measurements R_i



Scene analysis

- At runtime, the position of a target is determined by measuring the RSS of the target with respect to the anchors
  - This produces a new tuple *R* of RSSs
  - R is compared against all the tuples R_i
  - The position of the mobile target is approximated with the position of the point (or points) whose tuple is most similar to *R*
- To find the suitable points can be used either probabilistic methods, neural networks of KNN

kNN

- Let $R=\langle r_1,\ldots,r_n\rangle$; $R_i=\langle r_{i,1},\ldots,r_{i,n}\rangle$;
- Find k points for which the least mean square:

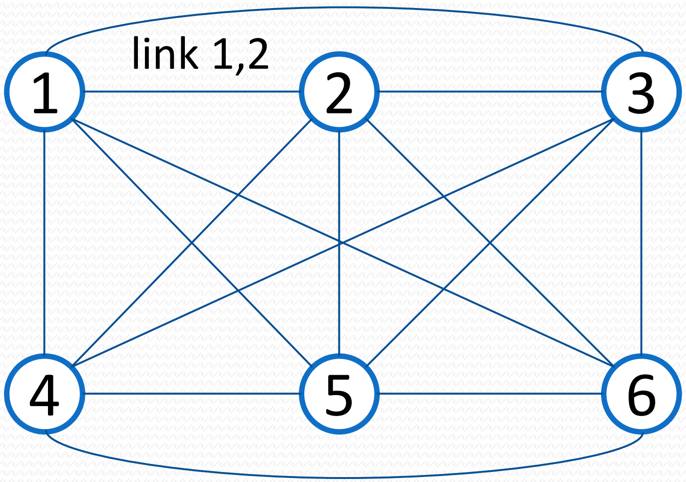
$$\sqrt{\tfrac{1}{n}\left(\left(r_1-r_{i2}\right)^2+\ldots\left(r_n-r_{in}\right)^2\right)}$$

- is minimum
- The position of the target can be estimated as the average position (center of mass,...) among these k points

Radio Tomography

- A recent technique
- Exploits a grid of anchors usually deployed at the sides of a room
- The anchors exchange beacons with each other
- If a target cuts the line of sight this results in a significant change in the RSS along a link
  - …but not so easy, a target also affects other links due to multipath

Radio Tomography



1	RSS(1,2), …, RSS(1,6), time
…	…
6	RSS(6,1), …, RSS(6,5), time

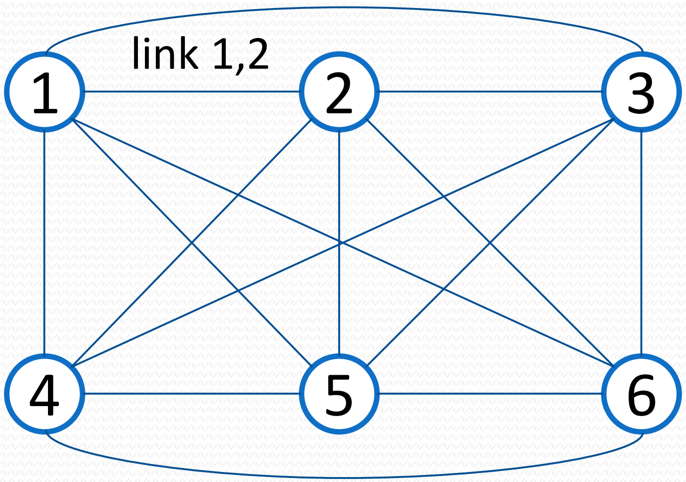
RSS of each link (6·5/2 columns)

Sliding table: time

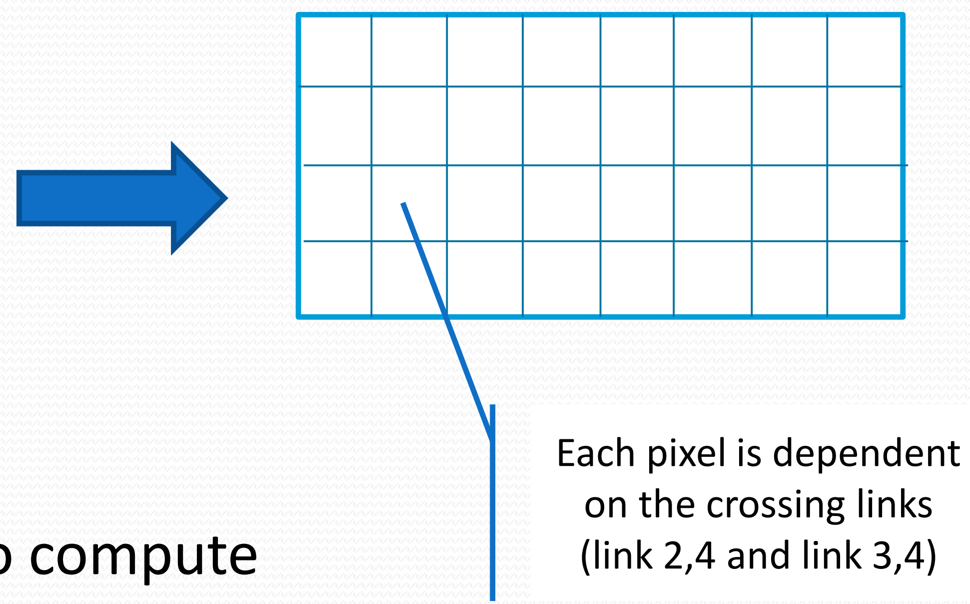
$\sigma_{1,2}$ $\sigma_{5,6}$

Let E_{RSS} be the average of the RSS on the links when there is no target

Radio Tomography



Variance-based Radio Tomography Image (VRTI)



Uses $\sigma_{1,2}$, …, $\sigma_{5,6}$ and E_{RSS} to compute VRTI (solves an optimization problem)

Radio Tomography

- See the animation
  - 25 sensors
  - Acquisition rate: 0.11 seconds

WSN multihop proximity

- Also called *Range-Free* localization: estimate position of objects based on connectivity information
- Cost-Effective: No special hardware for ranging
- Topology based (hop counting) techniques
  - Already discussed in the previous section
- Low precision

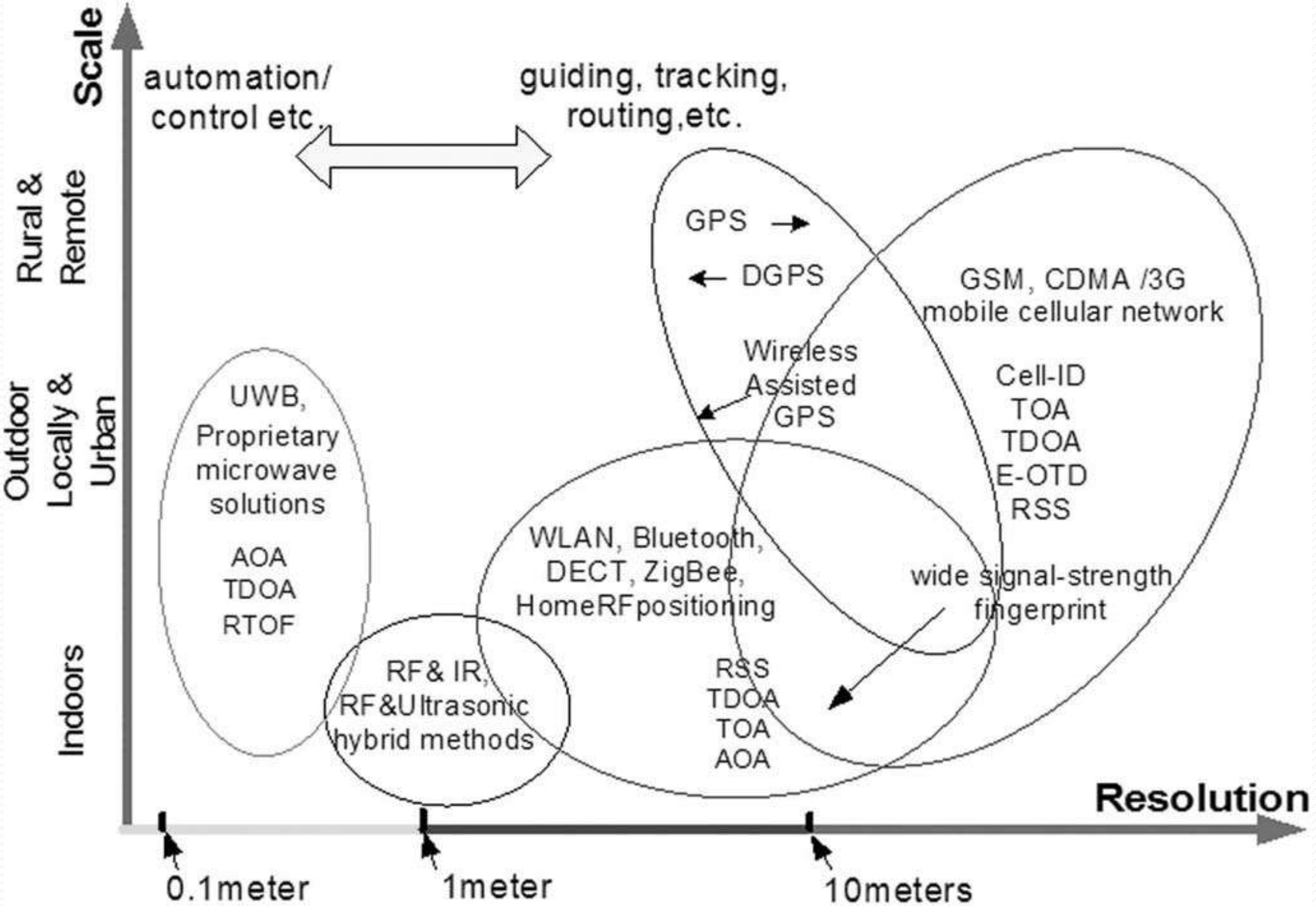
Performance metrics

- Accuracy (location error)
  - Usually measured as mean distance error between real position and estimated position of the target
- Precision
  - Measures the self-consistency of the system
  - In different trials, how does the accuracy varies?
  - Measured with the distribution of the localization accuracy

Performance metrics

- Complexity
  - Hardware but also communications and algorithms
- Robustness
  - To noisy signals, failure of anchors, non LOS
- Scalability
  - Coverage v.s. positioning performance
- Cost

Summary


Scale
automation/
control etc.
guiding, tracking,
routing,etc.
Rural &
Remote
Outdoor
Locally &
Urban
Indoors
GPS
DGPS
GSM, CDMA /3G
mobile cellular network
Wireless
Assisted
GPS
Cell-ID
TOA
TDOA
E-OTD
RSS
UWB,
Proprietary
microwave
solutions
AOA
TDOA
RTOF
WLAN, Bluetooth,
DECT, ZigBee,
HomeRFpositioning
wide signal-strength
fingerprint
RF& IR,
RF&Ultrasonic
hybrid methods
RSS
TDOA
TOA
AOA
Resolution
0.1meter
1meter
10meters