(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 \( \frac{t' - t}{p} \).
  - 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 $(x_1,y_1),..., (x_n,y_n)$ are known
    - The time of arrival of the signal at the anchors $t_1,...,t_n$ are known
  - $c$ is the light speed

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

\[\text{Distance} = (t_1 - t_2) \cdot s\]
Time Difference of Arrival (TDoA)

- Uses the difference between the arrival times at the measuring units (rather 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:

\[
\text{Difference} = 0
\]
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

Transmission power = $P$

Power of incoming signal = $P_w < P_z < P$

![Diagram](Diagram.png)
Friis equation: establish a relationship between transmission power and distance between transmitter and receiver

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

- \( P_T \) and \( P_R \): signal power at transmitter and receiver (in Watt)
- \( G_T \) and \( G_R \): antennas gain (at transmitter and receiver)
- \( \lambda \): 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:
  - \( P[\text{dBm}] = 10 \log_{10} (10^3 P[W]) \)
- and combining with Friis equation we obtain:
  - \( \text{RSS} = - (10 n \log_{10} d - A) \)
- 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
Received Signal Strength (RSS)

- Ideal situation

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

Triangulation - lateration

Received Signal Strength (RSS)
Received Signal Strength (RSS)

- Realistic situation
- $3^\circ$ order reflections
Received Signal Strength (RSS)

- Realistic situation
- $3^\circ$ 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 $= \frac{c(t_1 - t_2)}{2}$
- 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 (RTToF)

\[ d = c \frac{1}{2} \left( (t_2 - t_1) + (t_4 - t_3) \right) \]
Triangulation - lateration

Received Signal Phase (RSP)

- Assumes the transmitter sends a pure sinusoidal signal.
Based on the received phase of the signal, the measurement unit estimates the distance:
  - This holds within a wavelength.

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
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:

$$\sqrt{\frac{1}{n} \left( (r_1 - r_{i_2})^2 + \ldots (r_n - r_{i,n})^2 \right)}$$

- 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

Sliding table: time

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

RSS of each link (6·5/2 columns)

$\sigma_{1,2}$

$\sigma_{5,6}$
Radio Tomography

Each pixel is dependent on the crossing links (link 2,4 and link 3,4)

Uses $\sigma_{1,2}$, ..., $\sigma_{5,6}$ and $E_{\text{RSS}}$ 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 vary?
  - 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