3D indoor positioning and navigation: theory, implementation and applications

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Summary

• Ranging
  – Ranging techniques
    • Received Signal Strength Indicator (RSSI), Angle Of Arrival (AOA), Time Of Arrival (TOA)
  – Ranging in Wireless Networks
    • Wi-Fi, GPS

• Positioning
  – Positioning techniques
    • TOA, TDOA
  – Positioning systems
    • GPS, Wi-Fi, RFID, UWB, Bluetooth
  – Positioning in distributed networks
    • Anchor-based and anchor-less protocols
  – Impact on routing and navigation

• The 3D case

• Overview on RSSI-based Positioning Algorithms for WPSs - A practical implementation at the DIET Department
Definitions

• **Ranging** is defined as the action of computing the distance of a target node from a reference node.

• **Node-centered positioning** is defined as the action of computing the positions of a set of target nodes with respect to a reference node.

• **Relative positioning** indicates the action of computing the position of a set of nodes with respect to a common system of coordinates.

• **Absolute** (or *geographical*) **positioning** indicates a special case of relative positioning when the coordinates associated to each node are unique worldwide.
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Ranging techniques

• **Time of Arrival (TOA)**
  the distance is estimated from the propagation delay between transmitter and receiver

• **Received Signal Strength Information (RSSI)**
  the distance is estimated based on the attenuation introduced by the propagation of the signal from transmitter to receiver

• **Angle of Arrival (AOA)**
  distances between terminals are estimated based on their relative angles
Let us assume a transmitted signal \( s(t) \) and the received signal \( r(t) \) is given by

\[
r(t) = h(t) \ast s(t) + n(t)
\]

where the channel impulse response is (assuming an ideal channel)

\[
h(t) = A(D) \delta(t - \tau(D))
\]

- **TOA** is tightly related to synchronization.
- **Synchronization** aims at compensating for delay between transmitted signal and template signal at the receiver.
- **Ranging based on TOA** needs to measure the component of such delay depending on propagation, excluding additional delays such as clock misalignments or processing time.
TOA Ranging theoretical limits

- The Cramer-Rao lower bound provides an estimation of achievable accuracy as a function of signal bandwidth and SNR:

\[ \sigma_{\hat{t}}^2 = \frac{N_0}{2\int_{-\infty}^{+\infty} (2\pi f)^2 |P(f)|^2 df} \]

- Larger signal bandwidth and higher SNR (i.e. transmitted power) lead to lower error in estimation of time of arrival, and thus to higher ranging accuracy.

- Both transmitted power and signal bandwidth are limited by regulation -> emission masks.
TOA Ranging theoretical limits

• Example: FCC UWB indoor emission mask
TOA Ranging theoretical limits

• Under this hypothesis, one can write:

\[
\sigma_{\hat{t}}^2 = \frac{N_0}{8 \frac{\pi^2}{3} 2G_0 B \left(f_H^2 + f_H f_L + f_L^2\right)}
\]

with:

\[B = 7.5 \text{ GHz}, \ f_H = 10.6 \text{ GHz}, \ f_L = 3.1 \text{ GHz},\]
\[2G_0 = 9.86 \cdot 10^{-24} \text{ Joule/Hz}, \text{ and } N_0 \approx 2 \cdot 10^{-20} \text{ W/Hz},\]

which leads to the average error in distance estimation:

\[c\sigma_{\hat{t}} = 2.44 \cdot 10^{-6} m\]
Example of TOA measurement procedure (1/2)

- TOA Ranging -

- Let us assume a correlation receiver:

- If one assumes \( s(t) = rect_T(t + T/2) \)

- The output will be:

- If synchronization is perfect, \( R_s(x) \) is sampled at \( x = T \) -> peak of the autocorrelation
- If synchronization is not perfect, \( R_s(x) \) is sampled at \( x \neq T \) -> lower value
- The symmetry of \( R_s(x) \) can be used for achieving synchronization
Early-late gate synchronizer:
It takes two samples of $R_s(x)$, shifted of $\pm \Delta$, and evaluates the quantity:

$$\Delta R = R_s(\xi - \delta) - R_s(\xi + \delta)$$

Case 1: Perfect synchronization: $x = T \rightarrow \Delta R = 0$

No action needed
Example of TOA measurement procedure (2/2)
- TOA Ranging -

• Early-late gate synchronizer:
  It takes two samples of \( R_s(x) \), shifted of \( \pm \Delta \), and evaluates the quantity:

\[
\Delta R = R_s(\xi - \delta) - R_s(\xi + \delta)
\]

Case 2: Imperfect synchronization: \( x = T \pm t \rightarrow \Delta R \neq 0 \)

The sampling time is adjusted in a loop depending on the value of \( \Delta R \), until \( \Delta R = 0 \) and \( t \) is estimated
Angle of Arrival
- Ranging techniques -

• Based on directional antennas (e.g.: linear arrays):

  - Two main measurement techniques:
    - *Phase interferometry*: the angle is estimated by phase differences in the signal received by antenna elements
    - *Beamforming*: the angle of arrival is estimated by moving the main beam of the array over the angular field of interest

![Diagram showing Angle of Arrival with directional antennas and phase interference calculations](image)
Angle of Arrival
- Ranging techniques -

- Drawbacks:
  - Highly coherent receiver (all channels must have the same effect on the received signal)
  - The cost of the receiver increases as the array size increases

The size should be reduced as much as possible

BUT

the number of elements required to obtain a given accuracy strongly depends on the radio environment
Angle of Arrival
- Ranging techniques -

• Angle measurements from two anchor nodes are required to determine a position in a 2-d environment:

\[
\begin{align*}
X_3 &= X_1 - \frac{1}{\tan(\alpha_1)} \left[ Y_1 - \frac{X_1 - X_2 - Y_1/\tan(\alpha_1) + Y_2/\tan(\alpha_2)}{1/\tan(\alpha_1) + 1/\tan(\alpha_2)} \right] \\
Y_3 &= \frac{X_1 - X_2 - Y_1/\tan(\alpha_1) + Y_2/\tan(\alpha_2)}{1/\tan(\alpha_1) + 1/\tan(\alpha_2)}
\end{align*}
\]

• No distance estimation is required
Received Signal Strength Indicator
- Ranging techniques -

• Alternative solution to Time of Arrival in order to estimate distance between terminals

  + Lower requirements in terms of synchronization and clock precision

  - Requires accurate estimation of channel behavior

  - Distance estimation extremely sensible to propagation fluctuations and moving obstacles
Example: RSSI estimation with WiFi
- RSSI Ranging -

- 2 tablet Samsung Galaxy Note 10.1
- 1 smartphone Samsung Galaxy S II Plus
- 2 router TP-Link dualband N750-WDR4300
Example: RSSI estimation with WiFi
- RSSI Ranging -

• Series of 100 measurements – Day 1

RSSI – series 1
Example: RSSI estimation with WiFi
- RSSI Ranging -

• Series of 100 measurements – Day 2

RSSI – series 2

dBm
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Code shift is used to estimate propagation time between transmitter and receiver:

\[ d_{TXRX} = c \cdot \Delta T_{prop} \]

Chip rate \( 1/T_c \) determines the ranging accuracy:

\[ \Delta d = c \cdot \delta = c \cdot \frac{T_c}{2} \]
Ranging in wireless networks
- Direct Sequence Ranging -

How to improve ranging accuracy?

Use \textit{carrier phase}

+ Accuracy is now related to the carrier frequency \( f_p \):

\[
\overline{\Delta d} \propto \frac{c}{f_p} = \lambda
\]

- Carrier locking is more difficult than code locking:
  1. Get code locking
  2. Start searching carrier locking
Ranging in wireless networks
- Example: GPS -

• Two codes:
  – C/A code: $T_c \approx 1 \text{ ms}$
  – P code: $T_c \approx 0.1 \text{ ms}$

\[
\Delta d = c \cdot \frac{T_c}{2} = 150 \text{ m}
\]

• Two carrier frequencies:
  – L1: $f_p \approx 1575 \text{ MHz}$
  – L2: $f_p \approx 1227 \text{ MHz}$

\[
\Delta d \propto \lambda_1 = 19 \text{ cm}
\]

Surveying GPS receivers now can reach centimeter accuracy

BUT

Cost: 40000 – 50000 dollars
When there is no common time reference ranging can be based on the evaluation of roundtrip time between transmitter and receiver:

\[ t_1 - t_0 = 2 \cdot \Delta t_{prop} + \Delta t_{sync} \]

\[ \Delta t_{prop} = \frac{t_1 - t_0 - \Delta t_{sync}}{2} \]

\[ d_{AB} = \frac{c}{\Delta t_{prop}} = \frac{2 \cdot c}{t_1 - t_0 - \Delta t_{sync}} \]

Requires coordination between transmitter and receiver.
Ranging in distributed networks

• Issues:
  – The estimation is influenced by clock relative drifts between the two terminals:
    \[
    \Delta t_{\text{sync}A} \neq \Delta t_{\text{sync}B}
    \]

  Relative clock rates must be estimated by localizers

  – A small time value \((D_{t_{\text{prop}}})\) is obtained as the difference of two larger time values \((t_1 - t_0, D_{t_{\text{sync}}})\)

More elaborated ranging schemes avoid this problem
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Positioning techniques

Distance information provided by ranging can be used by a node $N_i$ in order to retrieve its own position, related to a set of reference nodes $\{N_1, \ldots, N_k\}$. This can be done by applying a positioning technique, such as:

– **Spherical positioning**: the position of node $N_i$ is determined as the intersection of spheres centered in the reference nodes

– **Hyperbolic positioning**: the position of node $N_i$ is determined as the intersection of spheres centered in the reference nodes

These techniques provide the same solution if distance measurements are not affected by noise
Spherical positioning
- Positioning techniques -

• Given a target node \( N_i \), the distance \( D_{ji} \) between the generic reference node \( N_j \) and \( N_i \) determines a sphere of radius centered in \( N_j \) and passing in \( N_i \).

• Since the intersection of four spheres defines a single point in a tridimensional space, at least four reference nodes are required to compute the position of the node, solving the system of equations:

\[
\begin{align*}
\sqrt{(X_1 - X_i)^2 + (Y_1 - Y_i)^2 + (Z_1 - Z_i)^2} = & D_{1i} \\
\sqrt{(X_2 - X_i)^2 + (Y_2 - Y_i)^2 + (Z_2 - Z_i)^2} = & D_{2i} \\
\sqrt{(X_3 - X_i)^2 + (Y_3 - Y_i)^2 + (Z_3 - Z_i)^2} = & D_{3i} \\
\sqrt{(X_k - X_i)^2 + (Y_k - Y_i)^2 + (Z_k - Z_i)^2} = & D_{ki}
\end{align*}
\]

with \( k \geq 4 \)
Spherical positioning
- Positioning techniques -

- In a bidimensional space, three reference nodes are enough:

\[
\begin{align*}
\sqrt{(X_1 - X_i)^2 + (Y_1 - Y_i)^2} \\
\sqrt{(X_2 - X_i)^2 + (Y_2 - Y_i)^2} \\
\vdots \\
\sqrt{(X_k - X_i)^2 + (Y_k - Y_i)^2}
\end{align*}
\]

\[
\begin{cases}
D_{1i} \\
D_{2i} \\
\vdots \\
D_{ki}
\end{cases}
\]

with \(k \geq 3\)

The solution is thus given by the intersection of three circles in the plane:
Hyperbolic positioning
- Positioning techniques -

• Spherical positioning can be used only when a common time reference is available to \( N_i \) and all reference nodes \( \{N_1,\ldots,N_k\} \).

• Hyperbolic positioning only requires a common time reference to be available between the reference nodes, and compensates for an unknown delay \( \delta \) between the common time reference and the time reference of target node \( N_i \) by working in time differences:

\[
D_{ni} - D_{(n-1)i} = c\left(\tau_{ni} + \delta\right) - c\left(\tau_{(n-1)i} + \delta\right) = c\left(\tau_{ni} - \tau_{(n-1)i}\right)
\]

• In conditions of perfect distance measurements, hyperbolic positioning leads to the same result of spherical positioning

• It can be shown however that ranging errors have a stronger effect on hyperbolic positioning
Hyperbolic positioning
- Positioning techniques -

- Given a target node \( N_i \) its position in a tridimensional space is determined as the intersection of hyperboloids in space, as described by the following equations:

\[
\begin{align*}
\sqrt{\left( X_2 - X_i \right)^2 + \left( Y_2 - Y_i \right)^2 + \left( Z_2 - Z_i \right)^2} - \sqrt{\left( X_1 - X_i \right)^2 + \left( Y_1 - Y_i \right)^2 + \left( Z_1 - Z_i \right)^2} \\
\sqrt{\left( X_3 - X_i \right)^2 + \left( Y_3 - Y_i \right)^2 + \left( Z_3 - Z_i \right)^2} - \sqrt{\left( X_2 - X_i \right)^2 + \left( Y_2 - Y_i \right)^2 + \left( Z_2 - Z_i \right)^2} \\
\vdots \\
\sqrt{\left( X_k - X_i \right)^2 + \left( Y_k - Y_i \right)^2 + \left( Z_k - Z_i \right)^2} - \sqrt{\left( X_{k-1} - X_i \right)^2 + \left( Y_{k-1} - Y_i \right)^2 + \left( Z_{k-1} - Z_i \right)^2}
\end{align*}
\]

\[
\begin{align*}
&= \begin{pmatrix} D_{2i} - D_{1i} \\
& D_{3i} - D_{2i} \\
& \vdots \\
& D_{ki} - D_{(k-1)i} \end{pmatrix}
\end{align*}
\]

with \( k \geq 4 \)
In a bidimensional space, one has:

\[
\frac{\sqrt{(X_2 - X_i)^2 + (Y_2 - Y_i)^2} - \sqrt{(X_1 - X_i)^2 + (Y_1 - Y_i)^2}}{\sqrt{(X_3 - X_i)^2 + (Y_3 - Y_i)^2} - \sqrt{(X_2 - X_i)^2 + (Y_2 - Y_i)^2}} \ldots \frac{\sqrt{(X_k - X_i)^2 + (Y_k - Y_i)^2} - \sqrt{(X_{k-1} - X_i)^2 + (Y_{k-1} - Y_i)^2}}{D_{2i} - D_{1i} \ldots D_{ki} - D_{(k-1)i}} \]

The solution is thus given by the intersection of two hyperboles in the plane:

\[
\begin{align*}
\sqrt{(X_2 - X_i)^2 + (Y_2 - Y_i)^2} - \sqrt{(X_1 - X_i)^2 + (Y_1 - Y_i)^2} \\
\sqrt{(X_3 - X_i)^2 + (Y_3 - Y_i)^2} - \sqrt{(X_2 - X_i)^2 + (Y_2 - Y_i)^2} \\
\ldots \\
\sqrt{(X_k - X_i)^2 + (Y_k - Y_i)^2} - \sqrt{(X_{k-1} - X_i)^2 + (Y_{k-1} - Y_i)^2}
\end{align*}
\]
Effect of ranging errors
- Positioning techniques -

- In presence of ranging errors analytical solutions provided by spherical and hyperbolic positions may not exist:
  - Position must be derived by means of minimization methods (e.g. Least Square Errors)
  - Error in position estimation can be reduced by increasing the number of observations

![Diagram showing the effect of ranging errors on position estimation](image)
Effect of ranging errors
- Positioning techniques -

- Example: 10 nodes in an area 50x50 m²:

  Step 0: generate the set of nodes in random positions
  Step 1: choose a target node and a set of k reference nodes
  Step 2: perform spherical positioning

![Graph showing position estimation](image)

Case A: TOA error variance $\sigma^2 = 0$
Effect of ranging errors
- Positioning techniques -

- Example: 10 nodes in an area 50x50 m²:

Step 0: generate the set of nodes in random positions
Step 1: choose a target node and a set of k reference nodes
Step 2: perform spherical positioning

Case B: TOA error variance \( \sigma^2 = 5 \)
Effect of ranging errors
- Positioning techniques -

Positioning error increases with ranging error

But can be reduced with redundant measurements
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Position systems

• Global Positioning System
  – 21 satellites
  – At least 4 visible from any point on earth
  – Distance estimation: Time of Arrival based on Direct Sequence signals
  – Position estimation: 4 distance measurements are used:
    • 3 measurements to determine approximate position
    • 1 additional measurement to estimate the rate between local and system clock and compensate for it:
Position systems

• **Spot On**
  – Dedicated hardware, composed of RF tags
  – Based on RSSI
  – Each tag estimates distance based on the reception of beacons
  – A prediction model of RSSI as a function of distance is adopted
  – Cost effective, but requires accurate calibration of each tag due to HW inaccuracies
Position systems

- **RADAR**
  - Wi-Fi based positioning
  - Exploits *fingerprinting* of the target area: a set of positions is decided a priori, and RSSI received by all Base Stations from a terminal disposed in each position is recorded
  - When the position of a station must be evaluated, the system searches for the most probable combination of received power values at the base-stations and determines the closest position
  - Errors in average positioning in the order of 3 - 4 meters
Position systems

• UWB Sapphire tags from Zebra
  – Designed for in-building positioning (typically hospitals)
  – TOA for ranging measurements
  – TDOA (hyperbolic) positioning
  – Requires installation of ceiling-mounted receivers, which are cabled for maintaining a common time reference
  – Calibration is performed at system set-up by means of a tag at known location
  – Position accuracy: better than 30 cm
Position systems

• RFID / Bluetooth LE / iBeacons
  – Based on the concept of proximity
  – The position of the user is associated to the position of the closest infrastructure element
  – Accuracy is determined by the combination of radio coverage and density of infrastructure element:
    • Lower coverage -> higher accuracy
    • High density required to provide reasonable area coverage
  – Simple to implement, not necessarily cost effective
  – A system based on this concept using RFID was implemented temporarily in the first floor of San Pietro in Vincoli in December 2012
Position systems

• SPinV experiment
  – 26 passive RFID readers
  – 130 active RFID tags
  – Mixed wired-wireless architecture
Position systems

• SPinV experiment
  – Integration with smartphone web-app
  – Positioning and navigation
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**The Picoradio approach:**

- Based on GPS-enabled **anchor nodes**
- **Full connectivity**: triangulation from anchor nodes

- **Partial connectivity**: *cooperative ranging*, divided in two phases:
  - **Start-up**
  - **Maintenance**
A GPS-enabled protocol
- Distributed positioning algorithms -

• **Start-up:** two alternatives
  1. **Assumption Based Coordinates (ABC):**
     • Each terminal (including anchor nodes) performs its own triangulation at local level considering itself in position (0,0) and broadcasts the results through the network
     • When a terminal receives localization information generated by an anchor node it rotates its own coordinate system
  2. **Triangulation via Extended Range and Redundant Association of Intermediate Nodes (TERRAIN):**
     • Only anchor nodes start broadcasting localization information
     • Not GPS-enabled terminals wait for localization information from 4 different anchor nodes.

• **Maintenance:** periodical triangulation to manage with terminal mobility
A GPS-enabled protocol
- Distributed positioning algorithms -
• **Self-Positioning Algorithm:**
  – No anchor nodes
  – Each terminal starts its own topology discovery
  – A criterion must be given to establish which coordinate system will be adopted in the network:
    • MAC address
    • Speed (the lower, the better)
    • Reliability (Available power)
    • ....
Local coordinate system (1/2)

- Three steps performed by each terminal $i$:
  1. Detect its set of one-hop neighbours $K_i$;
  2. Evaluate the set of distances from its neighbors $D_i$;
  3. Send $D_i$ and $K_i$ to all one-hop neighbors;
Local coordinate system (2/2)

- In a 2-D environment, 3 terminals are required to form a coordinate system:
  - \( i \) selects a couple of terminals \((p,q)\) in \( K_i \) such that:
    - \( p \) and \( q \) are not co-linear with \( l \)
    - \( p \text{ in } K_q \) (or \( q \text{ in } K_p \))
  - Based on \( p \)'s and \( q \)'s position, \( i \) will be able to evaluate the position of a \textbf{subset} of terminals in \( K_i \) (yellow terminals), called \textbf{Local View Set} (LVS)
  - Remaining terminals are not positioned in \( i \)'s system (blue terminals)
Network coordinate system (1/2)

- After Phase 1, terminals use different coordinate system
- Phase 2 deals with this topic, by forcing terminals to rotate and/or mirror their coordinate systems until only one remains
  - Conditions for $i$ and $k$ to harmonize their coordinate systems:
    1. $i$ in $LVS_k$ and $k$ in $LVS_i$;
    2. $j \neq i,k$ such that: $j$ in $LVS_i$ and $j$ in $LVS_k$
Harmonization of two different coordinate systems may require:
- Rotating
- Mirroring

In order to understand if mirroring is required, the common neighbor is used:
Algorithm definition
- Open issues -

• Algorithm convergence is a serious issue with or without anchor nodes

• In real world we must take into account
  – Ranging errors
  – Communication failures
  – Mobility

Robustness is a key point in algorithm definition and testing phases
Example: SPA robustness to network connectivity

Area size: 80 m  Number of terminals: 10

Percentage of terminals sharing the same coordinate system

Transmission Range (m)  Percentage of positioned terminals
Example: SPA robustness to ranging errors

Area size: 80 m  Number of terminals: 10

Average percentage positioning error

Maximum Ranging Error (m)
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Impact of positioning accuracy on routing

• Simulation assumptions
• 25 Nodes
• No mobility
• 150 x 150 m²
• Mixed LOS/NLOS propagation conditions
  – An NLOS link affects both range and ranging accuracy
• Energy consumption (Tx/Rx/Idle) and ranging error models derived from literature
• Varying connectivity scenarios, depending on % of NLOS links
Positioned nodes

Abrupt decrease in positioning performance
Positioning errors

Positioning Error(%) = \(|Real\ distance - Estimated\ distance|\) / Real\ distance

Error undefined (not enough positioned nodes)
Throughput & Energy

- Throughput vs. Probability of NLOS links
- Energy per packet (J) vs. Probability of NLOS links
Impact of positioning refresh interval

![Graph showing the impact of positioning refresh interval on energy per packet (J)].

The graph illustrates the relationship between the positioning refresh interval (s) and the energy per packet (J). As the refresh interval increases, the energy per packet decreases, indicating a possible energy efficiency improvement.
From positioning to tracking

• Positioning is a required step to get a first fix on the position of the user
• Tracking is the natural next step
• Rather than evaluating from scratch the position on each update, tracking may leverage on previous estimates
• The problem becomes a status update one, and can be addressed with approaches based on filtering:
  – Kalman filter
  – Particle filter
• Both share the possibility of defining the status in a flexible way
From positioning to tracking

- Status can be defined based on the estimate obtained by a single technology, or by many different inputs:
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The 3D case

• 3D may be a nice addition to outdoor position visualization, but is usually not crucial to have a satisfactory user experience

• Indoor positioning calls for specific solutions to handle 3D in positioning and visualization of position

• The extension from 2D to 3D is straightforward from a theoretical point of view

• In the real world however the third dimension is often harder to address properly:
  – The disposition of the infrastructure is typically optimized for 2D positioning and tracking
  – The same error may have dramatically different effects when it happens to be in the vertical dimension
The 3D case

- Example: impact of Geometric Dilution of Precision

Case a): 3D uniform reference point disposition

Case b): Ceiling reference point disposition
The 3D case

- User mobility tracking and navigation becomes a harder problem as well.
- Most technologies available for user tracking do not currently provide the same level of performance on the vertical dimension.
- Examples:
  - Wi-Fi, due to AP typical deployment patterns.
  - Inertial sensors / MEMS, due to difficulties in compensating drifts due to vertical movement.
- 3D tracking is also made more difficult by the need for additional coverage by the positioning infrastructure for passages between floors (e.g. stairs, elevators).
- Even simple floor detection can be a significant issue.
The 3D case

- Visualization also requires dedicated tools in order to provide a clear, usable 3D representation of indoor environments.
- Multi-floor scenarios representation in particular may become chaotic if not properly designed.
- An example of a 3D representation tool will be given at the end of the seminar.
Summary

• Ranging
  – Ranging techniques
    • Received Signal Strength Indicator (RSSI), Angle Of Arrival (AOA), Time Of Arrival (TOA)
  – Ranging in Wireless Networks
    • Wi-Fi, GPS

• Positioning
  – Positioning techniques
    • TOA, TDOA
  – Positioning systems
    • GPS, Wi-Fi, RFID, UWB, Bluetooth
  – Positioning in distributed networks
    • Anchor-based and anchor-less protocols
  – Impact on routing and navigation

• The 3D case

• RSSI-based Positioning Algorithms for WPSs
  – RSSI-based WPSs: Fingerprinting vs Propagation Channel Modeling
  – Fingerprinting-based positioning algorithms
  – A practical implementation at the DIET Department
Fingerprinting approach for Positioning

- The Fingerprinting technique aims at localizing a WiFi device by using a prebuilt radio map of the WiFi coverage over the area of interest.

- It involves two stages:
  1. **Offline Stage**: creation of the radio map (database) by collecting the RSSI readings from available surrounding WiFi Access Points (APs) within the area of interest in particular known and selected positions (Reference Points – RPs).
  2. **Online Stage**: device position estimation by comparing the online RSSI readings of the device with the offline RPs observations (fingerprints), forming the database. Several methods for position estimation:
     - Nearest Neighbor (NN)
     - K-Nearest Neighbors (KNN)
     - Weighted KNN (WKNN)
     - Enhanced WKNN (EWKNN)
     - Statistical Methods using Bayesian theory and kernel functions
     - Compressive Sensing

- Note that Fingerprinting does not need info on the APs position but it requires manual efforts for the database creation and management.
- Moreover, it requires a sensible plan regarding the number of RPs and their distribution in the area.
Fingerprinting approach for Positioning
Indoor Propagation Channel Modeling

• Fingerprinting of an indoor venue can be expensive and time consuming. For this reason, another approach could be to using an indoor propagation model, in order to create the radio map and estimate RSSI values in the area.

• This approach can be less accurate than fingerprinting, if the propagation model does not take into account the dynamic and unpredictable nature of the indoor radio channel (shadowing, multipath, device orientation, and so on) but it is computationally simpler (no need of offline phase).

• The major constraint is that it requires info on the APs position but no RPs definition is needed in the area.

• Several models have been deployed for indoor propagation analysis. They can be divided in two different classes:
  1. **Statistical (Empirical) Models**: the signal propagation and its parameters are evaluated within generic areas in a statistical scenario.
  2. **Deterministic Models**: they use information on the particular area of interest.
Multi-Wall (MW) Model

- The Multi-Wall (MW) model is a quite known empirical indoor propagation model. Its definition comes from the One-Slope (OS) model that assumes a linear dependence between the path loss and the logarithmic distance between the transmitter and the receiver.

\[ L_{OS}(d) = l_0 + 10\gamma \log(d) \quad (dB) \]

- MW adds a further attenuation term, due to the presence of walls and doors:

\[ L(d) = L_{OS}(d) + M_w \quad (dB) \]

- where

\[ M_w = l_c + \sum_{i=1}^{l} k_{wi}l_i + \sum_{n=1}^{N_d} X_n l_d + \sum_{n=1}^{N_{fd}} \lambda_n l_{fd} \quad (dB) \]

<table>
<thead>
<tr>
<th>( l_c )</th>
<th>Constant (least square fitting procedure from measurements)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_{wi} )</td>
<td># of walls crossed by the signal of type i</td>
</tr>
<tr>
<td>( l_i )</td>
<td>Attenuation introduced by walls of type i (least square fitting procedure)</td>
</tr>
<tr>
<td>( X_n, \lambda_n )</td>
<td>Binary variables indicating if doors are open or closed</td>
</tr>
<tr>
<td>( N_d, N_{fd} )</td>
<td># of doors and fire proof doors crossed by the signal</td>
</tr>
</tbody>
</table>
Fingerprinting vs Propagation Model

Comparison between optimal MW classic model (continuous line) and measurements (dots) – office environment

Comparison between optimal MW classic model (continuous line) and measurements (dots) – classroom environment
Preliminary experimental results @ DIET

Access Point 1

Access Point 2
Fingerprinting-based positioning algorithms: EWKNN

- The KNN algorithm selects and combine the nearest K neighbors (RPs fingerprints) around a device to determine its position.

- Using a fixed number (K) of fingerprints may decrease positioning accuracy: if K is not changed during the positioning process, sometimes, RPs far from the device might be included in the KNN algorithm. Therefore, eliminating some RPs before applying the positioning algorithm is often necessary.

- Furthermore, by computing proper weights, the WKNN algorithm can provide improved accuracy. However, WKNN with a fixed number of RPs cannot always achieve the required accuracy, for the same reason as simple KNN.

- EWKNN introduce simple filtering procedures in order to select the optimal number of RPs depending on the situation, improving the position accuracy of the WPS.
The EWKNN algorithm

The device receives RSSIs from the APs, compares them with the RPs fingerprints and calculate $D_i$ for each RP$_i$

$$D_i = \sum_{j=1}^{N} |A_j - R_{i,j}|, \quad i = 1, 2, 3, ..., L \quad (1)$$

where $A_j$ is the RSSI from the $j^{th}$ AP, $R_{i,j}$ is the RSSI of the $j^{th}$ AP at the $i^{th}$ RP stored in the database. $N$ is the number of APs, $L$ is the number of RPs.

1. **I RPs filtering**: after sorting the $D_i$ in ascending order ($D_1$ will be the minimum), and denoting with $R_T$ a properly chosen threshold, RPs whose $D_i$ is larger than the threshold are removed from the list of useful RPs.

2. **II RPs filtering**: let be $G$ the number of remaining RPs after the I filtering and $S_i$ the difference between $D_1$ and the remaining $D_i$; after evaluating $E(S)$ as in (2), the RPs having a larger $S_i$ than $E(S)$ are removed from the list.

$$E(S) = \frac{(S_2 + S_3 + ... + S_G)}{G - 1} \quad (2)$$

The position of the device is estimated as shown in (3), where $L$($R_P_j$) denotes the location of RP$_j$

$$P = \frac{\frac{1}{D_1}L(R_P_1) + \frac{1}{D_2}L(R_P_2) + ... + \frac{1}{D_K}L(R_P_K)}{\frac{1}{D_1} + \frac{1}{D_2} + \frac{1}{D_3} + ... + \frac{1}{D_K}}, \quad (3)$$
EWKNN: experimental results

**TABLE 1. Positioning error of each algorithm.**

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Positioning error</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN</td>
<td>5.7126 m</td>
</tr>
<tr>
<td>KNN</td>
<td>4.0473 m</td>
</tr>
<tr>
<td>WKNN</td>
<td>2.8661 m</td>
</tr>
<tr>
<td>EWKNN</td>
<td>2.1077 m</td>
</tr>
</tbody>
</table>
Inertial sensors, maps, mobility models

- The past few years have seen mobile phones being equipped with inertial sensors (such as accelerometers and gyroscopes) and a magnetometer.
- Together, these sensors can provide useful information about the motion of the user that can augment WiFi based positioning.
- If the device is held in a steady position, the sensors can reliably detect user motion and improve position estimates. Addition of map constraints may help alleviate some of the fundamental limitations associated with a sensor-based tracking.
Inertial Sensors

• Sensors such as accelerometer, gyroscope and magnetometer can be used to determine device relative motion. For example, in the absence of motion, the accelerometer reading is constant (corresponding to gravity).

• However, the use of this kind of sensors is different from that in inertial navigation systems (INS) on planes. These sensors are of much lower quality and techniques such as double integration of acceleration data to get relative motion will be inaccurate.

• An alternate approach is to derive pedestrian odometry from two components:
  1. Distance estimate obtained from step count. The step count can be obtained from the accelerometer and combined with a step length model to estimate relative distance traveled.
  2. Heading estimate obtained by combining a 3D orientation estimate from the accelerometer, gyroscope and compass.

  Sensor odometry alone is generally insufficient for positioning.
Maps

- Map constraints provide additional information on the position.
- The following information can be derived from a map:
  - Certain areas of the map are not feasible for the location (for example, the area within a large solid column or wall).
  - Certain paths on the map are not possible for the (for example, movement across walls).
  - Some parts of the map may be more likely to be frequented by users (corridor areas).
  - Furthermore, the map can be used to predict a better model of WiFi signals, mitigating the need for fingerprinting.
  - Map constraints can also be used correct slow accumulating errors and drifts in sensor estimates.
Particle Filtering

- It is important to incorporate all available information pertaining to the location of the device.
- Given its representative flexibility, particle filter is more capable of incorporating various available sources of information, compared to various derivatives of Kalman filters.

Algorithm 1: Particle filter with $m$ particles

1. Select a collection of $m$ particles to represent the initial cloud, from a priori distribution.
2. For each estimation interval:
   3. - For each particle:
      4. * Propagate the particle using the mobility model and other indirect information (mobility model using sensors, map, etc.)
      5. * Calculate an importance weight associated with particle from the direct measurements (WiFi measurements, GNSS, etc.)
   6. - End for
   7. - Resample $m$ times from the propagated particle pool, according to the importance weights.
   8. - Report the mean or centroid of the particle cloud as the position estimate.
9. End for
WiFi + Inertial Sensors: experimental results

Cumulative distribution of positioning accuracy in a typical office building with 14 access points

Performance Comparison: a) WiFi + Maps and b) WiFi + Maps + Sensors


 References

References


