International Doctorate School in
Information and Communication Technologies

University of Modena and Reggio Emilia

Localization and Tracking for Indoor Environments

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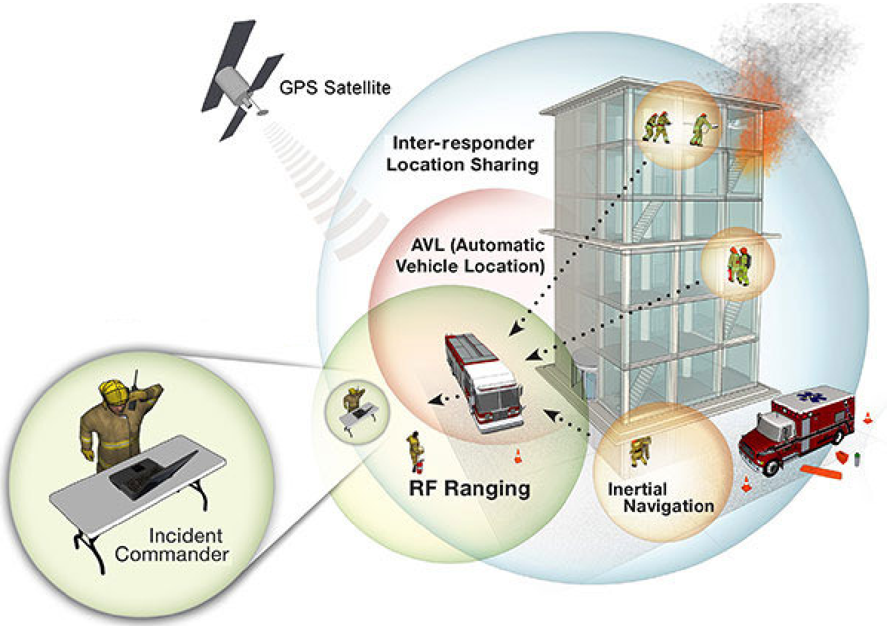
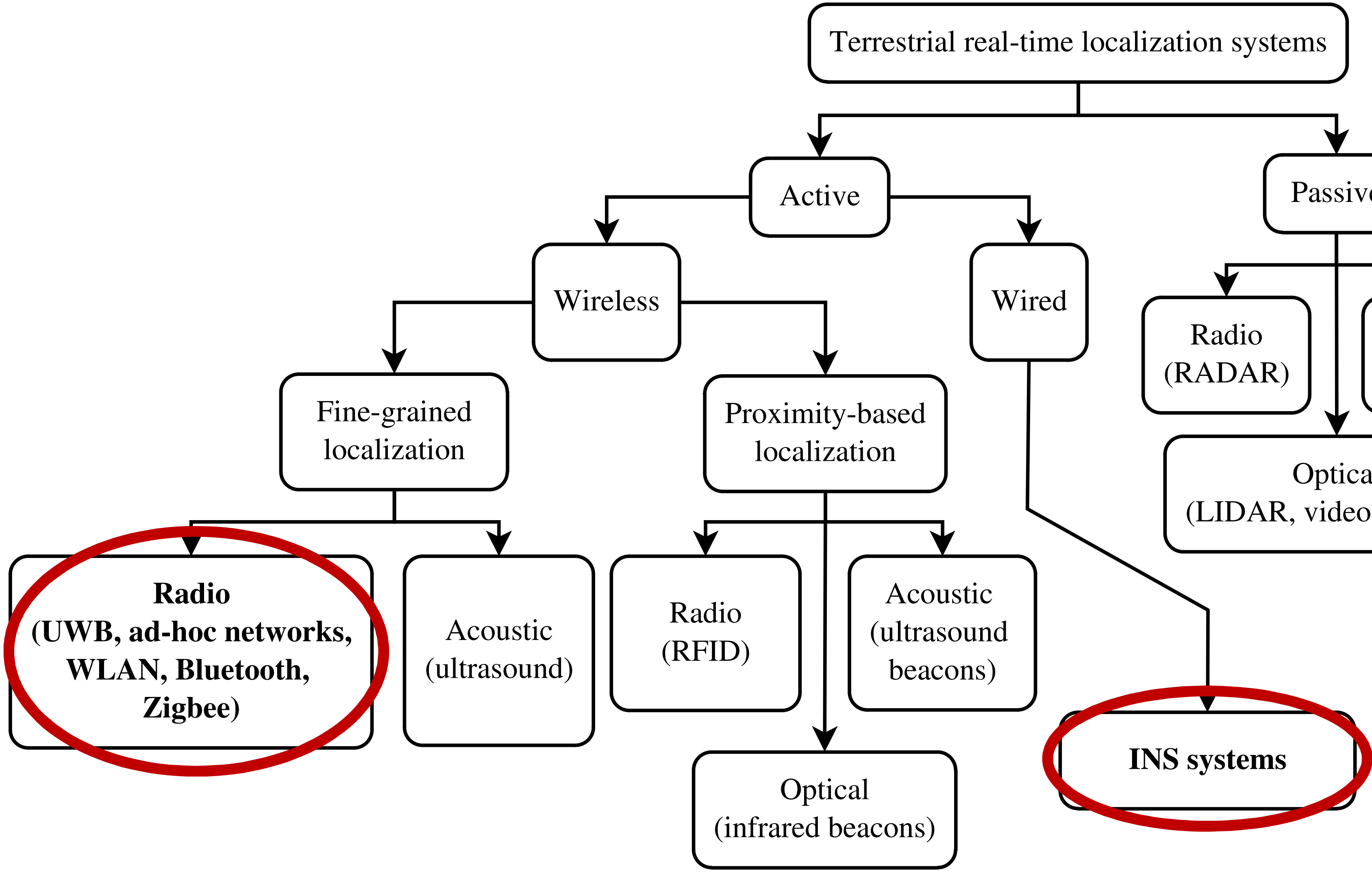
Outline of This Presentation

- Technologies and Techniques for Positioning
- **Modelling** based on Experimental Measurements:
  - UWB NLOS bias modelling
  - RSS measurements modelling
- **Localization** Algorithms:
  - Low-complexity Localization Algorithms
- **Navigation** Algorithms:
  - An INS for Low-Cost IMUs
  - Turbo Filtering
- Conclusions

Technologies and Techniques for Positioning

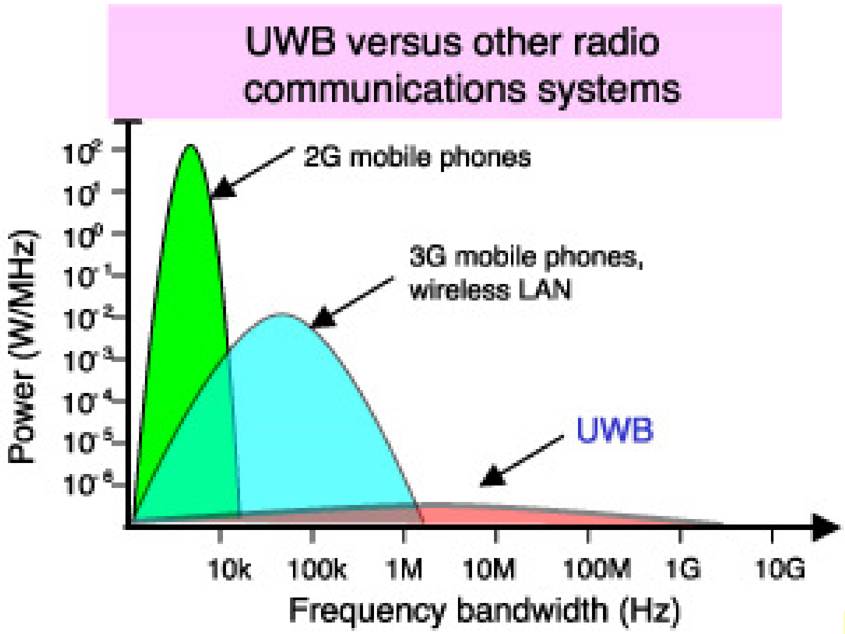


Technologies and Techniques for Positioning



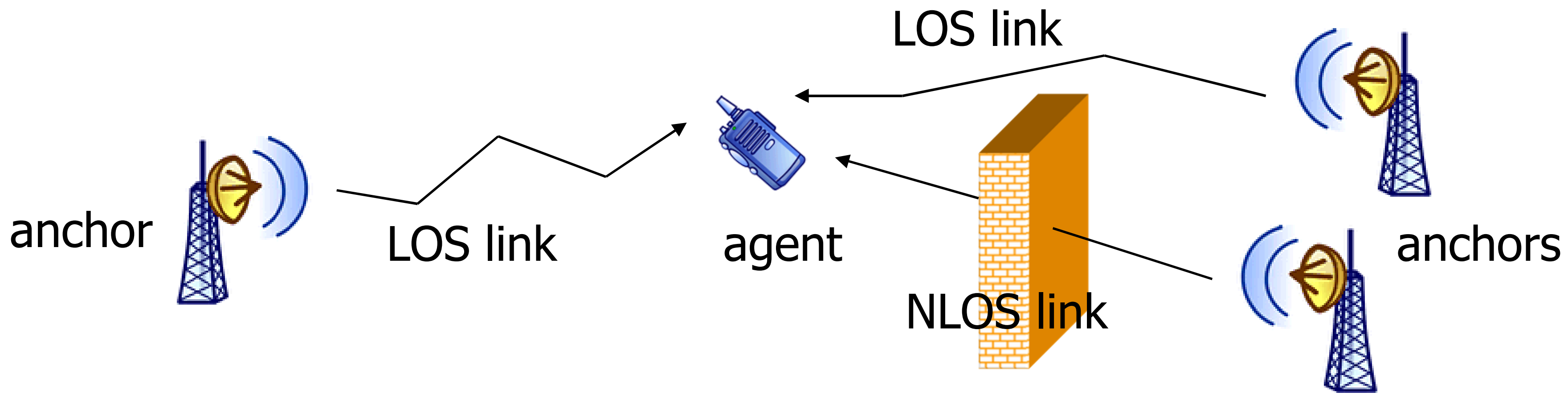
Modelling based on Experimental Measurements:

UWB NLOS bias modelling



UWB-based Localization and NLOS Bias

SCENARIO: indoor radiolocalization systems based on Time Of Arrival (TOA) measurements between radios with fixed, known positions (anchors) and a mobile station (agent):



PROBLEM:

- ❑ **Non Line Of Sight (NLOS)** propagation results in *biased* TOA estimation (obstructions slow down electromagnetic waves, so that the estimated TOA is larger than the true distance / speed of light).

APPROACH:

- ❑ A measurement campaign has been carried out to assess the correlation between NLOS bias and some features extracted from received signals.

Statistical Modelling of Signal Features

TOA model adopted: $\tau = d/c_0 + b + n$ → Gaussian noise r.v.

Real TX-RX distance

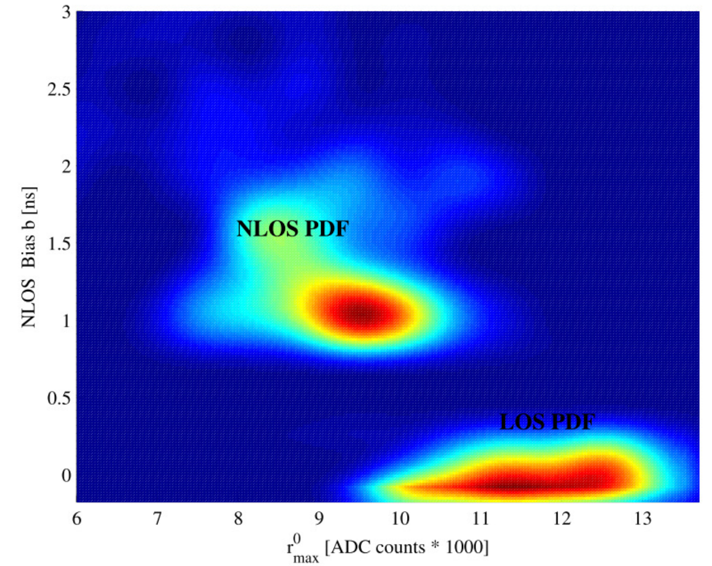
NLOS bias (r.v.)

APPROACH:

- For each measured link various features have been extracted: maximum signal amplitude, mean excess delay, rms delay spread, energy, rise time, kurtosis (the employed radios were able to store the received waveform).

RESULT:

- NLOS bias for TOA UWB waveforms is strongly correlated with some of the considered features; this can be exploited to *infer* and *mitigate* the bias!



Localization Algorithms

APPROACH:

- We have proposed **estimators** of the agent position which:
  - exploit the joint *multidimensional* pdf resulting from experimental acquisitions (histograms or multidimensional fitting polynomials have been used to represent this function);
  - exploit the TOA vectors from all available links.

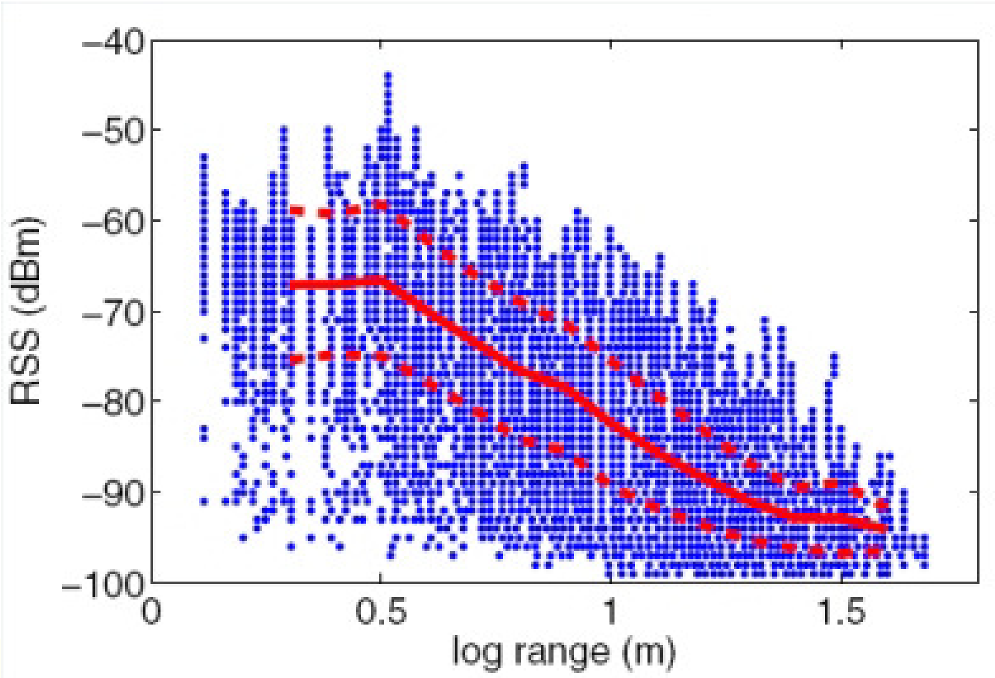
RESULTs:

- We have found that this approach, on the average, provides performance improvements in radio localization accuracy; however, it is difficult to *consistently* achieve such improvements.

- NLOS bias *detection* is more robust than NLOS bias *mitigation* in environments characterized by strong multipath propagation.

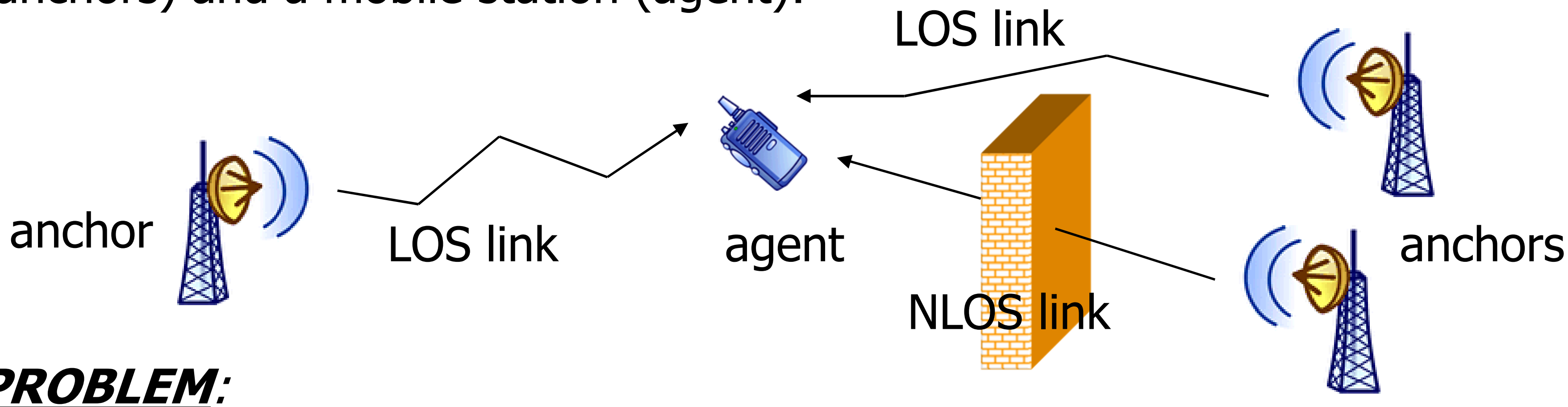
Modelling based on Experimental Measurements:

RSS measurements modelling



Localization with RSS Measurements

SCENARIO: indoor radiolocalization systems based on Received Signal Strength (RSS) measurements between radios with fixed, known positions (anchors) and a mobile station (agent):



PROBLEM:

- **Non Line Of Sight (NLOS)** propagation results in *biased* RSS estimation. In fact, obstructions introduce attenuation which is not accounted for by the traditionally-employed free-space propagation law; this strongly degrades localization accuracy.

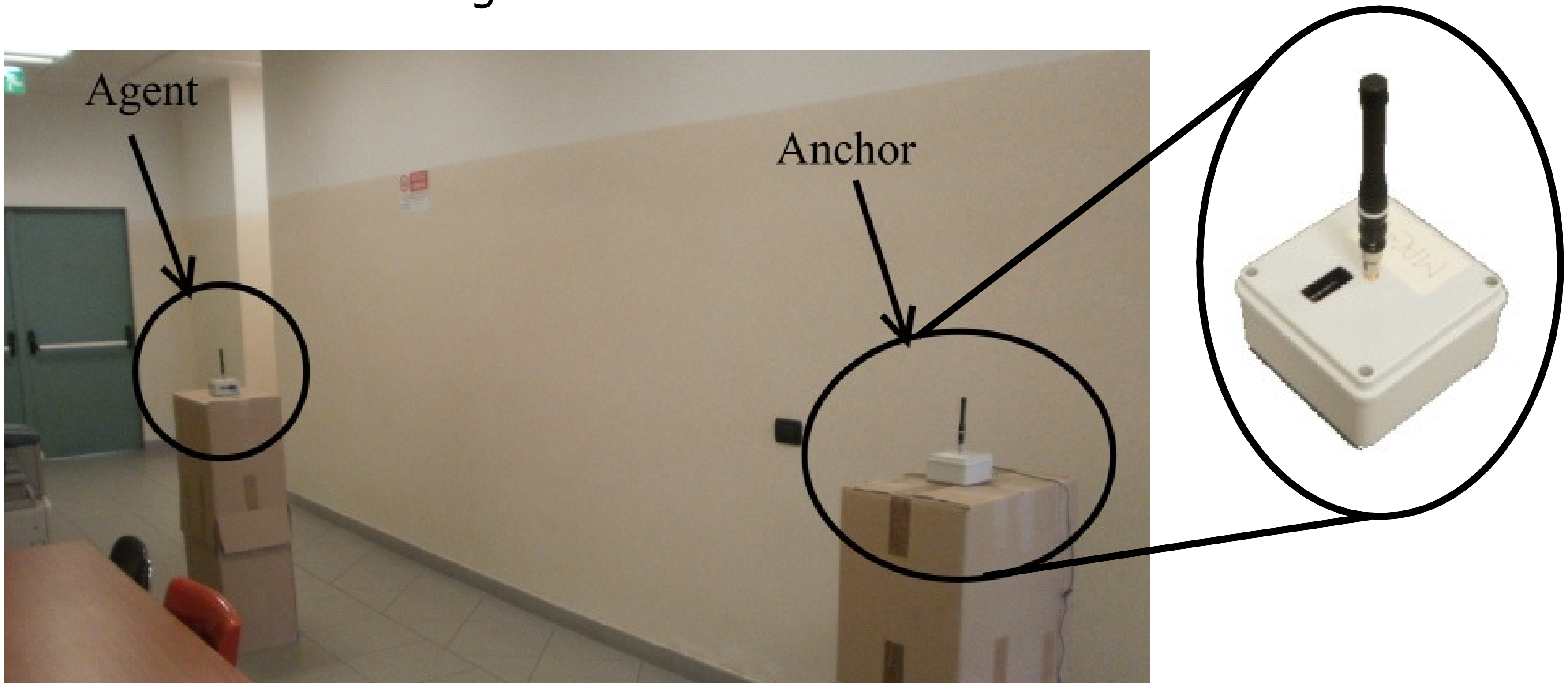
APPROACH:

- A measurement campaign has been carried out to 1) assess the attenuation in RSS due to indoor obstructions (mainly walls) and 2) develop a *map-aware* statistical model for RSS measurements.

RSS Measurement Campaign

- 169 MHz radios transmitting at +15dBm have been employed, so that the effect of signals propagating through multiple walls could be studied (up to 10 walls)

- The RSS has been acquired in many different positions inside the 2nd floor of the DII building:



A Novel RSS Model

- Based on experimental evidence, a *novel map-aware* statistical model for the acquired measurements has been developed:

RSS measurements

Trial agent position

$$f(\mathbf{z}|\tilde{\mathbf{p}}) = \prod_{i\in\mathcal{Z}} \mathcal{N}\Big(z_i; d_i(\tilde{\mathbf{p}}) + \mu_{b,0}^{\mathrm{RSS}} + \mu_{b,m}^{\mathrm{RSS}} N_o(\mathbf{p},\mathbf{p}_i^a)\Big)\, \mathrm{u}_{N_o},$$
$$\max\left\{\left(\sigma_{b,0}^{\mathrm{RSS}} - \sigma_{b,m}^{\mathrm{RSS}} N_o(\tilde{\mathbf{p}},\mathbf{p}_i^a)\right)^2, 0\right\} + \left(\sigma_{n,0}^{\mathrm{RSS}}\right)^2 (d_i(\tilde{\mathbf{p}})/d_0)^{2\beta_n^{\mathrm{RSS}}}\Big)$$

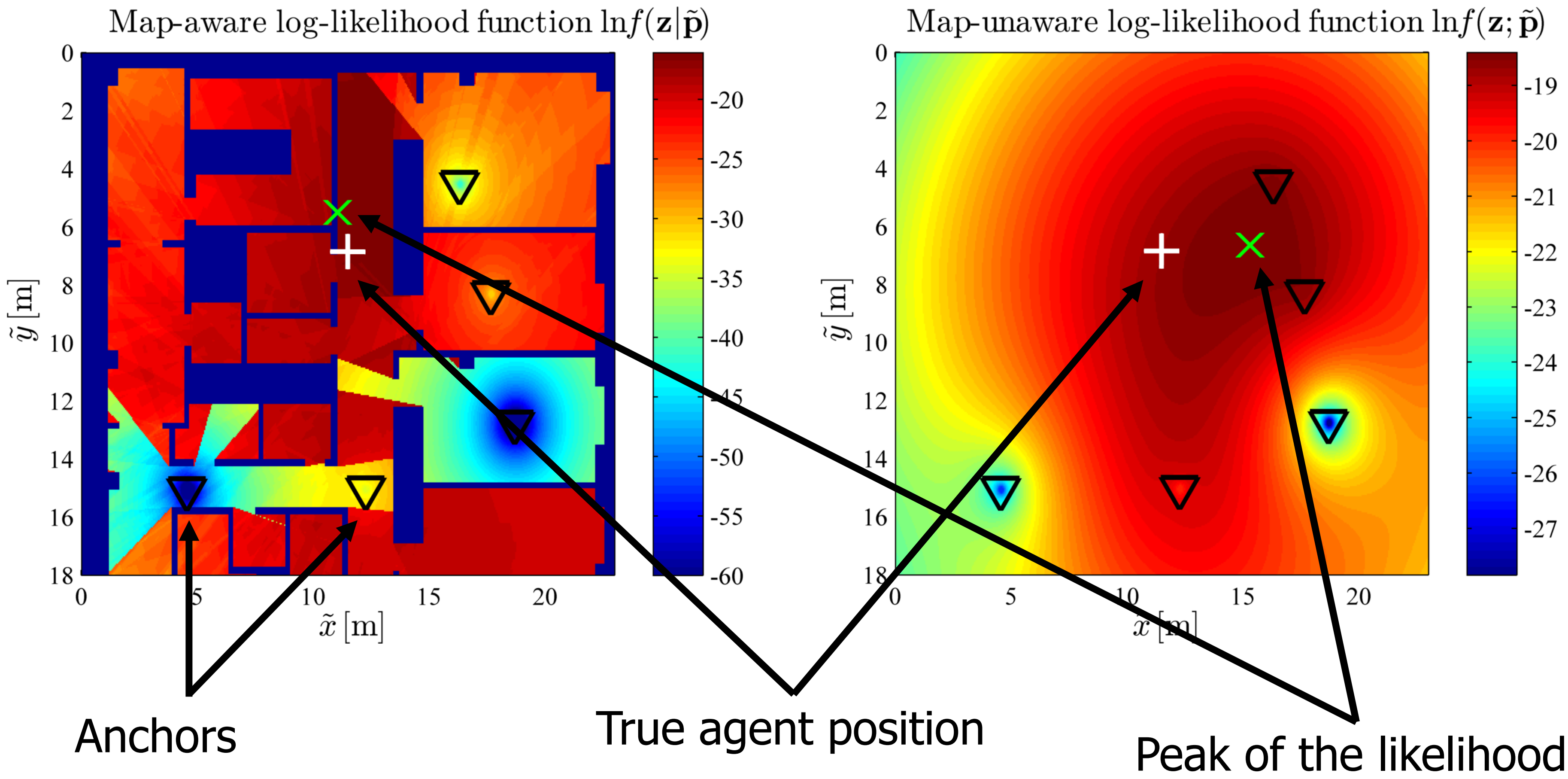
Model parameters…

Number of obstructions (map-awareness)

- Such a statistical model represents the likelihood of obtaining a certain set of RSS measurements for a given (trial) agent position; searching for the trial position which corresponds to the maximum value of the likelihood produces an *optimal estimate* (in ML sense) of the agent position

RSS Map-aware vs Map-unaware Model

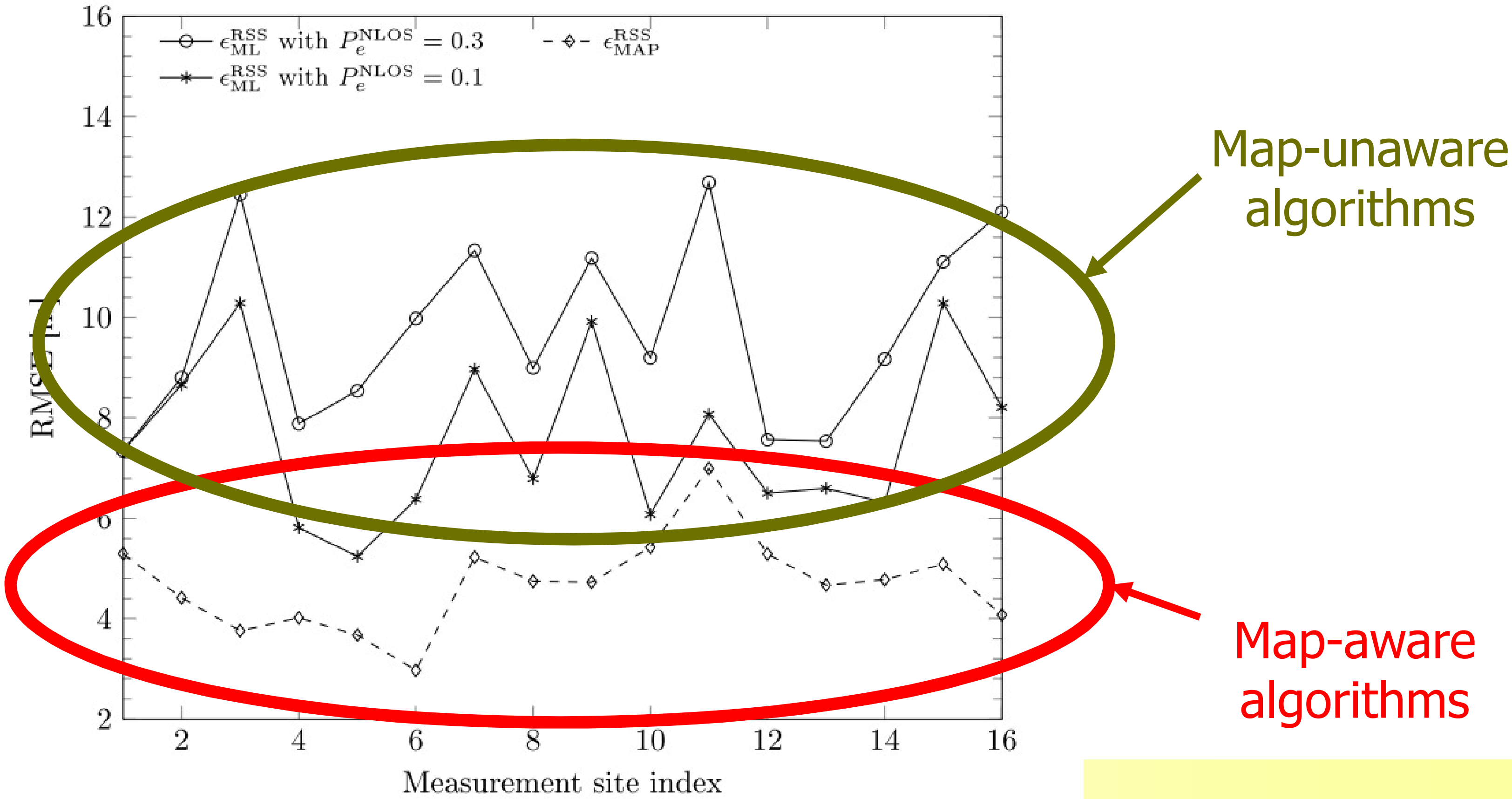
- In the same scenario a map-aware model and a map-unaware model lead to substantially different likelihoods:



RSS Map-aware & Map-unaware Accuracy

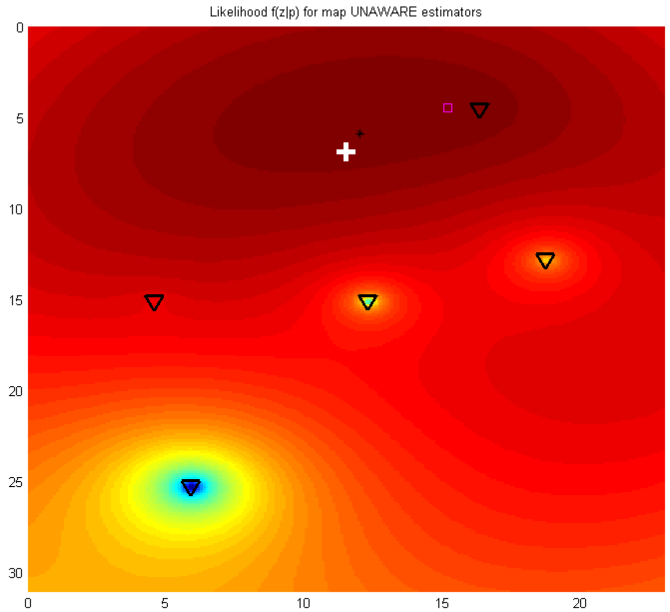
***RESULTS*:**

- A comparison between map-aware and map-unaware localization algorithms processing the RSS measurements stored in our experimental database shows that the former algorithms are, on the average, 64% more accurate (in terms of RMSE) than the latter ones:



Localization Algorithms:

Low-complexity Localization Algorithms



Algorithm Complexity as FLOPs

***PROBLEM*:**

- Map-aware modelling improves accuracy in localization systems but requires more complex estimators.

***APPROACH*:**

- Complexity of map-aware localization algorithms needs to be **quantified**. Complexity depends on a) type of estimator employed, b) models employed, c) implementation of the estimator and d) the required accuracy in computations.

- Computational complexity is **difficult to analyse** and quantify whenever non-linear algebra is involved (e.g., this occurs when the RSS statistical modelling described above is used).

- We decided to adopt a **mixed simulation/analytical approach** which allows to count the different types of floating-point operations (**FLOPs**): multiplications, divisions, square roots, etc. and weight them differently.

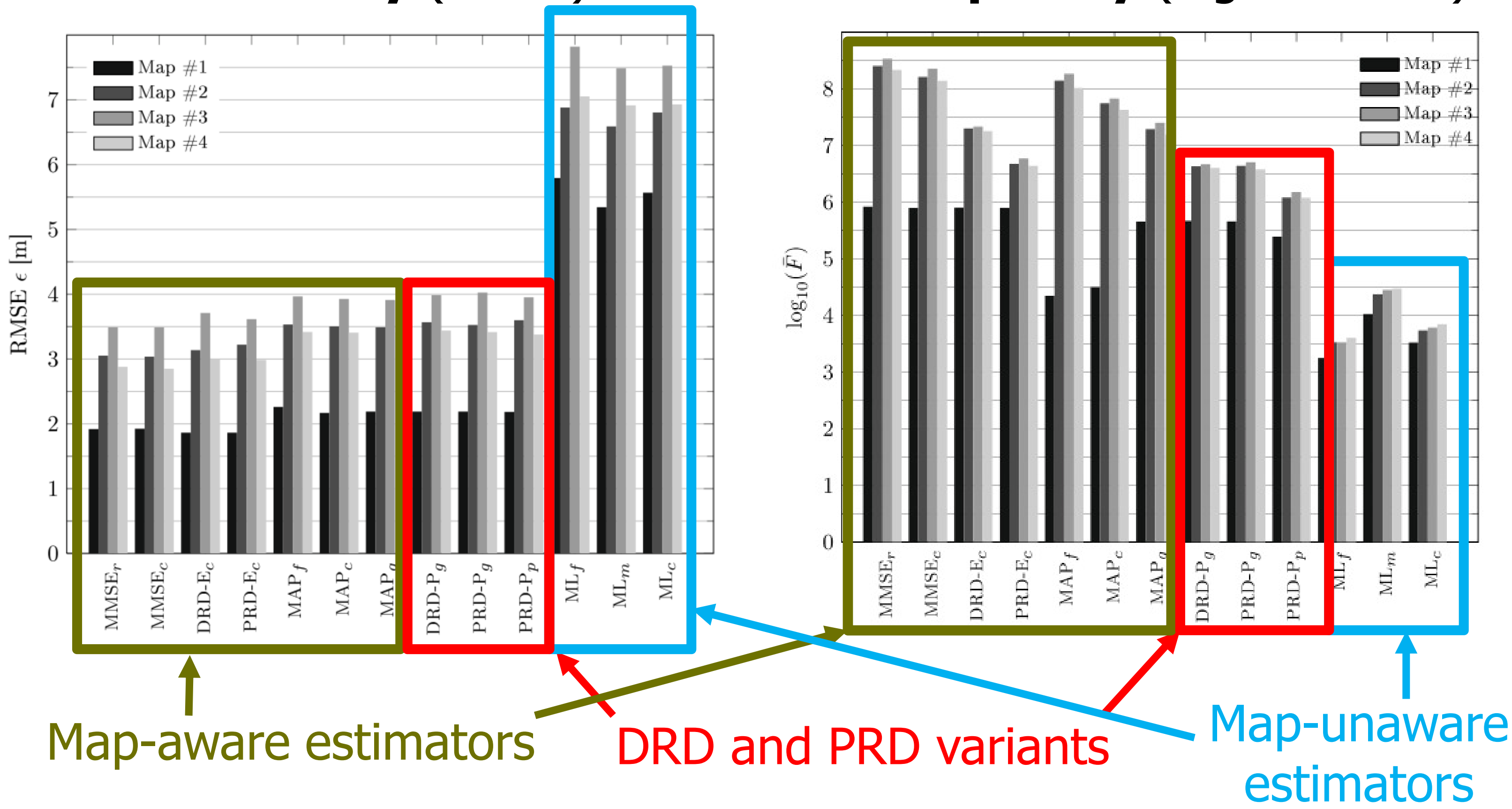
Novel Low-Complexity Localization Algorithms

- Based on our complexity results, two *novel* low-complexity localization algorithms have been developed:
  1. A **distance-reduced domain (DRD) estimator**: it is based on the fact that localization can be split in two phases: a) a raw (map-unaware) estimation reducing the search domain and a b) fine (map-aware) estimation.
  2. A **probability-reduced domain (PRD) estimator**: it is based on the fact that complexity can be reduced by: a) evaluating the likelihood in selected points of a given map and b) shrinking the search domain around the most-likely positions found in step a).

- In addition, for localization algorithms involving the search for minima in non-convex functions, several state-of-art direct-search optimizers have been tested: active-set, iterative grid search, iterative compass search.

RESULTS:

Accuracy (RMSE) **Complexity** (log10 FLOPS)



- DRD and PRD variants offer an accuracy close to that of map-aware algorithms but require a lower complexity (on the average 13 times smaller).

Navigation Algorithms:

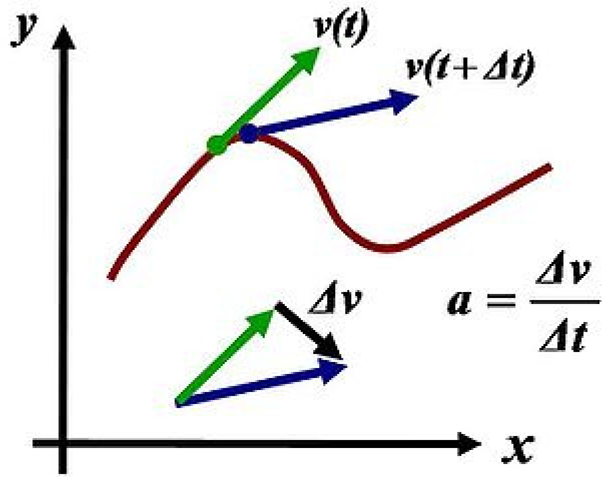
An INS for Low-Cost IMUs

Dead-Reckoning (INS) for Navigation

***CONTEXT*:**

- **Inertial measurements units (IMUs)** based on MEMS are low-cost sensors which can be used in **Inertial Navigation Systems (INS)** for indoor/outdoor pedestrian dead-reckoning.

- MEMS IMUs provide 3-axis acceleration and angular velocity measurements, which can be used to perform **dead-reckoning**, i.e., position estimation sequentially integrating estimated velocities and accelerations.



Error Mitigation for Map-unaware INSs

***PROBLEM*:**

- Outputs of low-cost IMUs' accelerometers and gyroscopes are affected by **several sources of errors** (random noise, time-variant biases, etc). Such measurements are continuously integrated in an INS, so that even small errors quickly affect the estimate of the agent position.

***SOLUTION*:**

- The INS was implemented in a real-time system using an **Extended Kalman Filter** (non-linear filtering technique).

- In our system model biases of the sensor are part of an hidden state and thus can be **tracked** together with the pedestrian position and dynamic state (orientation, velocity, acceleration, etc):

$$\mathbf{x}_k \triangleq \left[\mathbf{p}_k, \mathbf{v}_k, \mathbf{a}_k, q_k^{n\triangleright b}, \mathbf{a}_k^{b}, \boldsymbol{\omega}_k^{b,b\triangleright n}, \mathbf{b}_k^{a}, \mathbf{b}_k^{\omega}\right]^T$$

Dynamic state vector
Position
Velocity
Acceleration
Orientation
Body acceleration
Angular velocity
Acc. biases
Ang. velocity biases

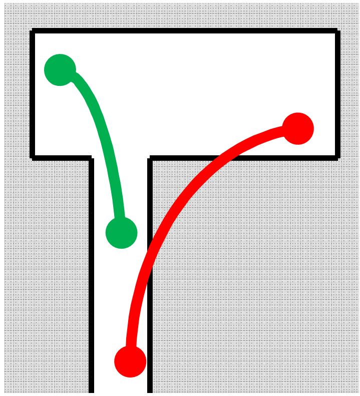
Map-awareness Reduces Drifting

***PROBLEM*:**

- Any INS based only on accelerometers/gyroscopes suffers from a slow **drift** between the true position and the INS-estimated one.

***SOLUTION*:**

- Map-awareness may remove such a drift, thanks to the constraints that the map puts on the agent movements.



- Similarly to radio localization algorithms, map-awareness introduces strong **non-linearities** in the filtering algorithms, forcing a transition from semi-linear (EKF) to non-linear (e.g., PF) tracking algorithms.

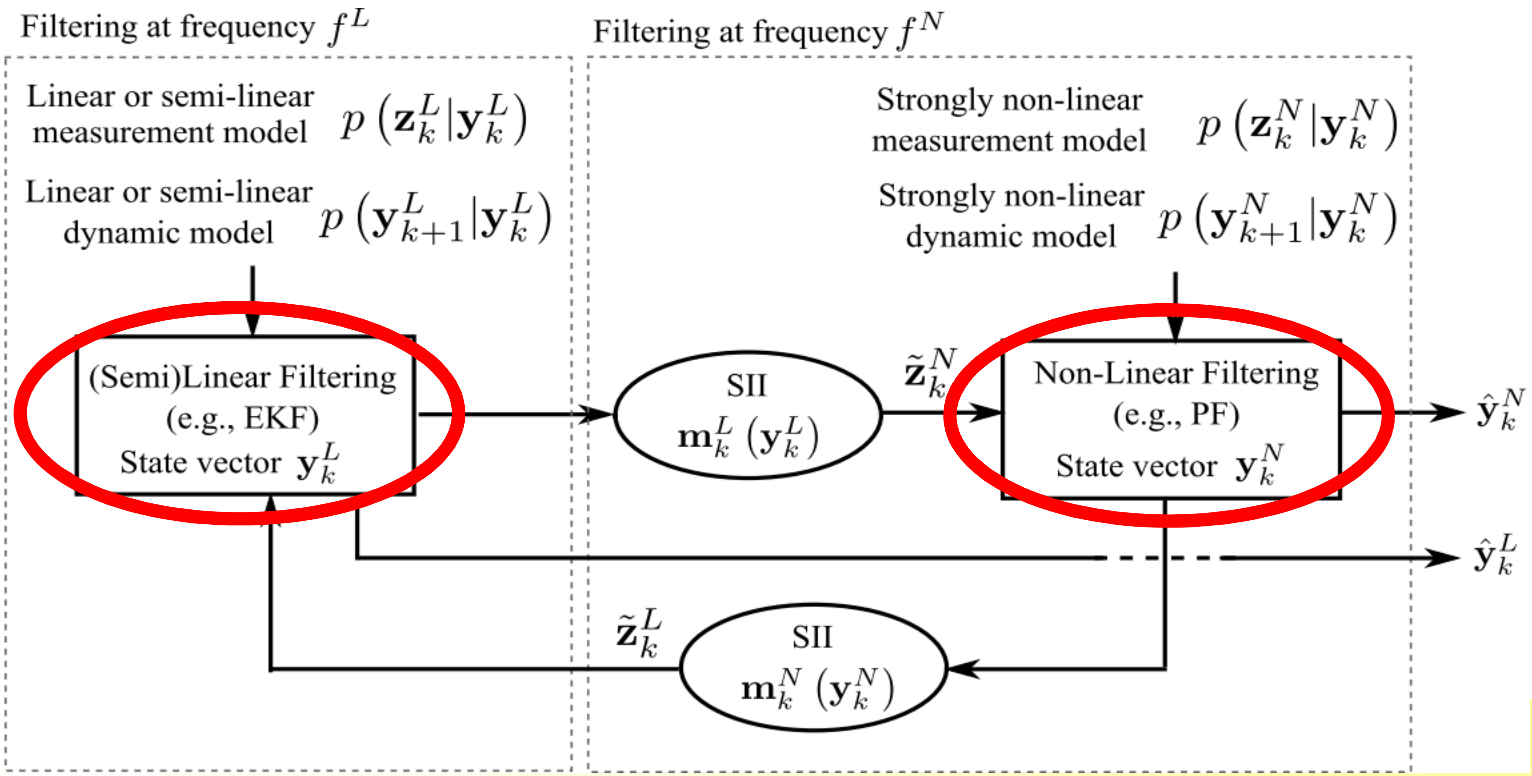
A Novel Filtering Technique for Non-Linear Systems

***PROBLEM*:**

- Traditional non-linear filtering techniques (PF, RBPF, UKF, etc) have a computational complexity which is **prohibitive** for large state vectors (in our case, dimensionality = 25)

***APPROACH*:**

- Turbo-like filtering:

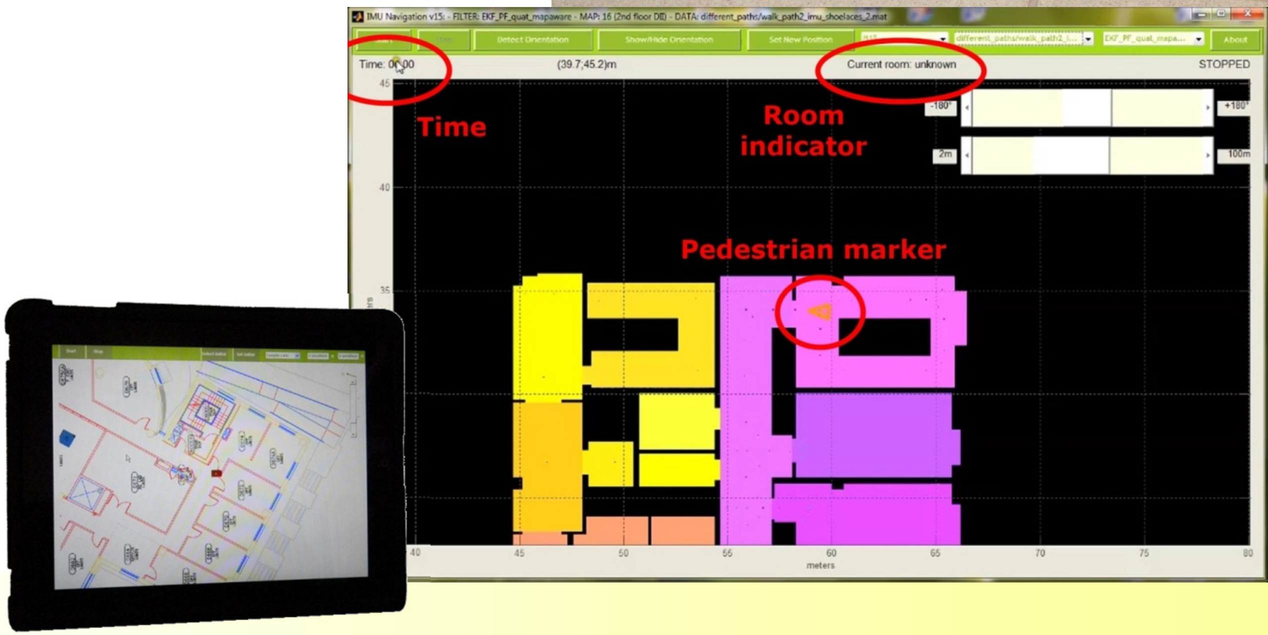


Map-aware INS with Turbo Filtering

RESULTs:

- Turbo-like filtering has been employed to track a pedestrian equipped with a foot-mounted IMU.

- This resulted in a prototype of indoor localization system for pedestrians with sub-meter accuracy.

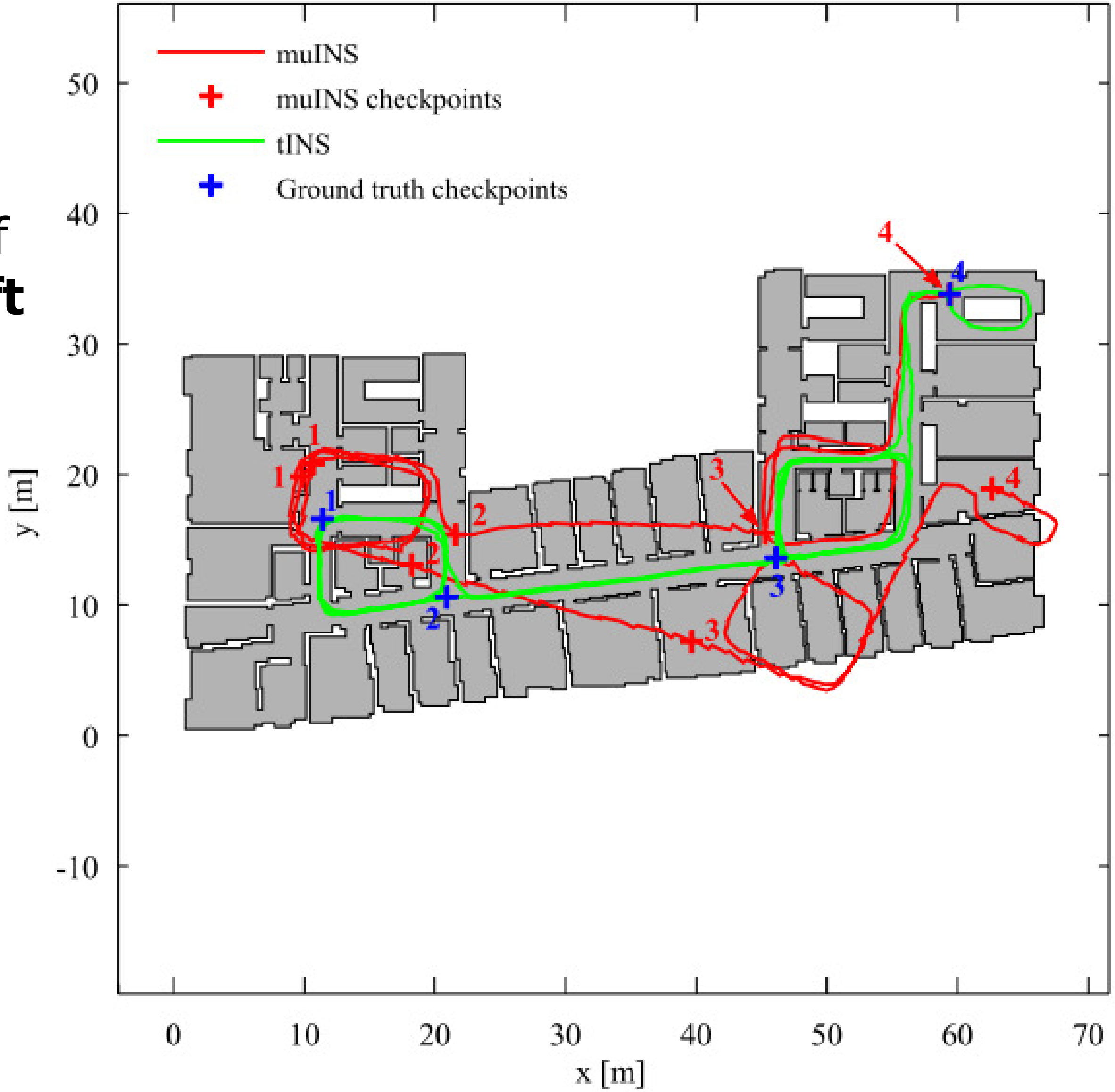


Map-aware INS with Turbo Filtering: Results

RESULTs:

- The map-aware INS employing turbo-filtering is capable of **correcting the drift** that substantially affects a map-unaware INS.

- The computational complexity of the map-aware INS is roughly **1.5 times** the complexity of map-unaware INS.



Thanks for your attention.

Questions?

Publications

Journal Publications (published & submitted)

1. **Montorsi, F.**; Vitetta, G. M.; "On the Performance Limits of Pilot-Based Estimation of Bandlimited Frequency-Selective Communication Channels," *IEEE Transactions on Communications*, vol. 59, no. 11, Nov. 2011;
2. **Montorsi, F.**; Pancaldi, F.; Vitetta, G. M.; "Statistical Characterization and Mitigation of NLOS Bias in UWB Localization Systems," *Advances in Electronics and Telecommunications*, pp. 11-17, Issue no. 4, ISSN 2081-8580;
3. **Montorsi, F.**; Mazuelas S.; Vitetta, G.; Win M. Z.; "On the Performance Limits of Map-Aware Localization," Accepted for publication in *IEEE Transactions on Information Theory*
4. **Montorsi, F.**; Pancaldi, F.; Vitetta, G.; "Map-Aware Models for Indoor Wireless Localization Systems: An Experimental Study," Submitted to *IEEE Transactions on Wireless Communications*
5. **Montorsi, F.**; Pancaldi, F.; Vitetta, G.; "Reduced-Complexity Algorithms for Indoor Map-Aware Localization Systems," Submitted to *IEEE Transactions on Wireless Communications*

Conference Publications (published)

1. **Montorsi, F.**; Pancaldi, F.; Vitetta, G. M.; "Statistical characterization and mitigation of NLOS errors in UWB localization systems," *IEEE International Conference on Ultra-Wideband*, pp. 86-90, 14-16 Sept. 2011;
2. **Montorsi, F.**; Mazuelas S.; Vitetta, G.; Win M. Z.; "On the Impact of A Priori Information on Localization Accuracy and Complexity," Accepted for publication in *IEEE International Conference on Communications 2013*
3. **Montorsi, F.**; Pancaldi, F.; Vitetta, G.; "Map-Aware RSS Localization Models and Algorithms Based on Experimental Data," Accepted for publication in *IEEE International Conference on Communications 2013*
4. **Montorsi, F.**; Pancaldi, F.; Vitetta, G.; "Design and Implementation of an Inertial Navigation System for Pedestrians Based on a Low-Cost MEMS IMU," Accepted for publication in *IEEE International Conference on Communications 2013 - Workshop on Advances in Network Localization and Navigation*

More details at http://www.commlab.unimo.it/projects/indoor-positioning/