Localization Techniques

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Summary

- Motivations
- Localization basics
- Ranging (theoretical aspect and practical schemes)
- Position estimation
- Position tracking
- Case studies
- Advanced issues

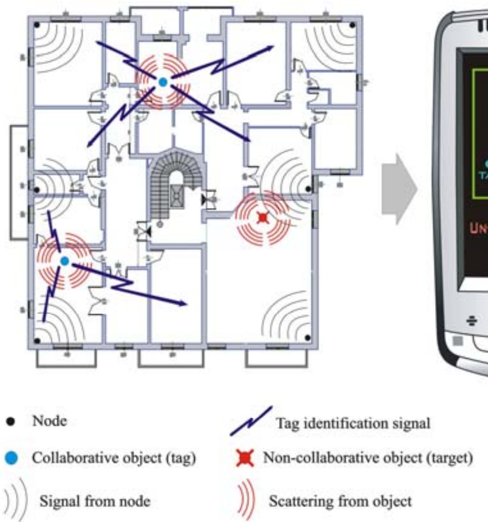
Why localization is important

- new context aware applications (e.g., real-time location systems, RTLS)
- new market opportunities ($6 Billion in 2017*)

* R. Das and P. Harrop "RFID Forecast, Players and Opportunities 2007-2017", 2007, http://www.idtechex.com.

Some examples:

- inventory/people tracking (RFID)
- surveillance/security
- wireless sensor networks (WSN)
- virtual immersive and augmented reality applications

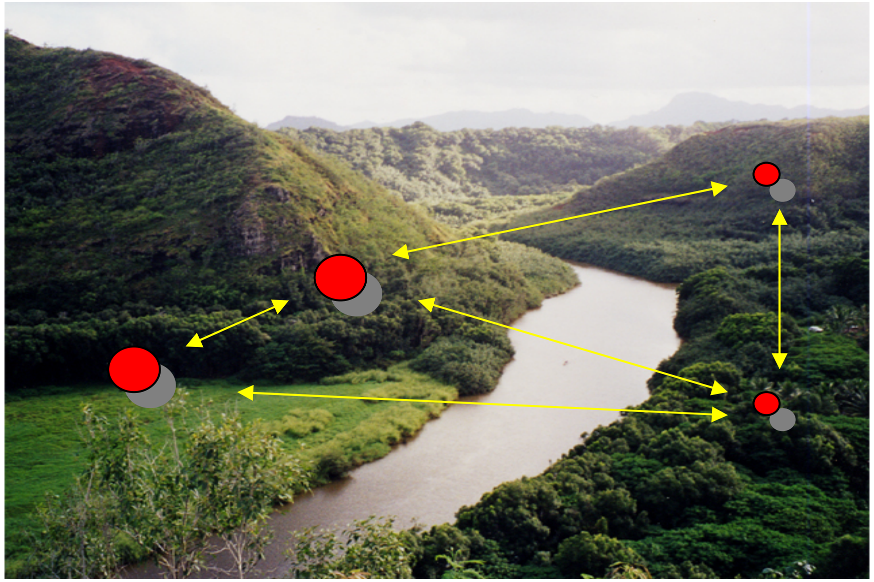


[VICOM Project
www.vicom-project.com]

In WSNs......

Sensed data without position and time information is often meaningless

For example, in habitat environments monitored sensed events must be ordered both in time and space to permit a correct interpretation.



In addition…

In many schemes proper time synchronization is required to achieve high ranging accuracies in positioning techniques

Positioning and time synchronization are also essential for basic mechanisms composing the WSN to work efficiently:

- *MAC scheduling algorithms can reduce packet collisions*
- *power-saving strategies (wake-up sleeping times)*
- *networking protocols to improve performance of routing algorithms (geo-routing)*
- *enabling interference avoidance techniques in future cognitive radios*

Needs

- high localization accuracy (<1m) in harsh environments (e.g., indoor)
- low device complexity (low cost, low size)
- standards (e.g., IEEE802.15.4a)

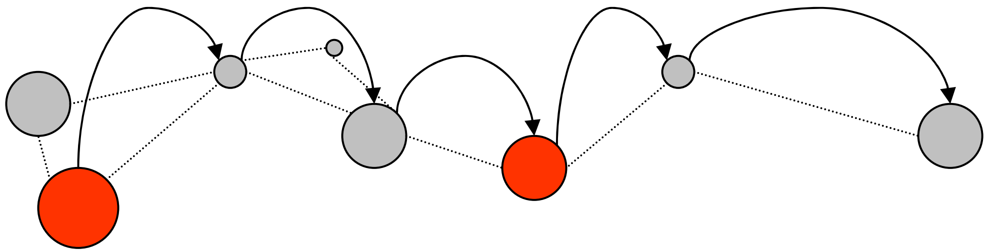
But in many cases:

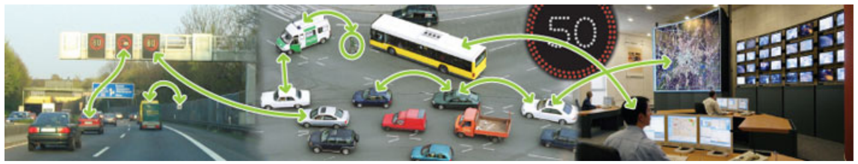
- nodes are GPS-denied (e.g., indoor, urban canyon)
- GPS is too expensive (e.g., WSN) and only a small fraction of nodes (anchors) have positioning information due to cost, size and power constraints
- higher accuracy than GPS is required
- no infrastructure available (anchor-free), only relative coordinates are estimated (ah hoc networks)

Localization basics

Localization Basics

The purpose of any localization algorithm is, given a set of measurements, to find the locations of target nodes with unknown positions.





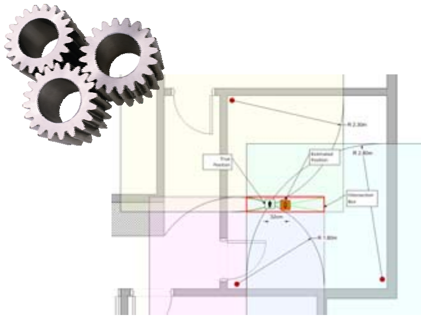
Localization occurs in two main steps:

1. Selected measurements are conducted between nodes
2. Measurements are combined to determine the locations of target nodes (*localization algorithm*).

Ingredients for localization-aware applications

Position-Based Applications

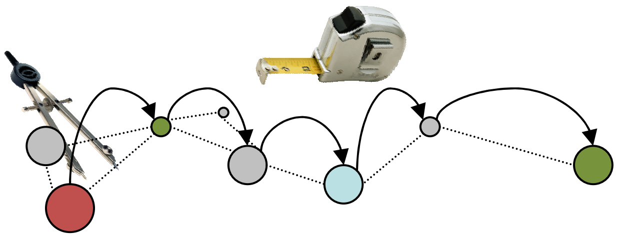
Robust
w/o memory
Range-, angle-, proximity-based
w/o cooperation



Algorithms

Error sources
Uncertainty

RSSI, ToA, TDoA, AoA, …



Technologies

Position estimation techniques classification (1/2)

•**Anchor-based** - Using GPS or using predefined coordinates, a subset of nodes in the network know their position a priori (these nodes are typically named *anchors* or *beacons*). Nodes with unknown positions (*targets*) use positioning information from anchors to determine their location.

Ranging between anchors and other nodes can be obtained by:
- direct interaction (*Single-Hop*),
- indirectly by means of intermediate nodes (*Multi-Hop*).

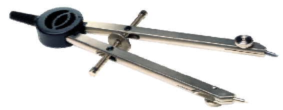
•**Anchor-free** - No nodes in the network have knowledge of their position a priori. Only relative coordinates can be found in such networks.

[R. Verdone, D. Dardari, G. Mazzini, and A. Conti, in *Wireless Sensor and Actuator Networks: technologies, analysis and design*. Elsevier, 2008]

Position estimation techniques classification (2/2)

•Range-based - Measurements provide distance information among nodes (*)

•Angle-based - Measurements provide angle information among nodes



•Range-free - Only connectivity information is used (*)

Other techniques

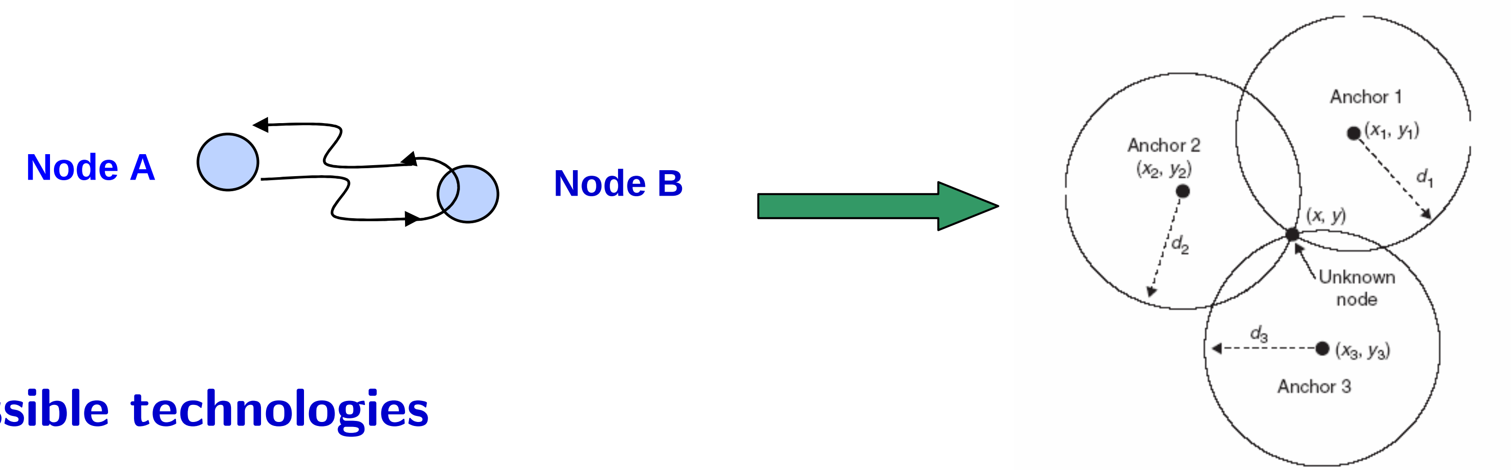
•Interferometric – (low complexity, problems with multipath) (*)
•Scene analysis – (e.g., based on receiver power "signature")
•Inertial – (error accumulation)
•DC magnetic tracker – (accurate but expensive and low range)
•Optical – (laser ranging systems, very accurate but expensive)

(*) suitable for typical WSN applications

Distance estimation:
Ranging

Distance Estimation: Ranging

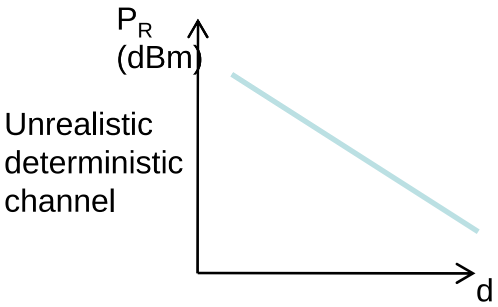
Ranging between two nodes is the technique employed by two nodes in the network to determine the physical distance between them.

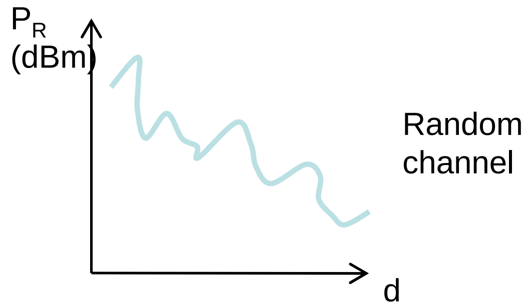


Possible technologies

- Received Signal Strength (RSS)
  - direct RSS-distance mapping
  - interferometric
- Time-Based
  - e.m. waves
  - ultrasound
- Near field (phase difference between the E & H fields in the near range) (*Q trace corporation*)

Ranging based on RSS measurements

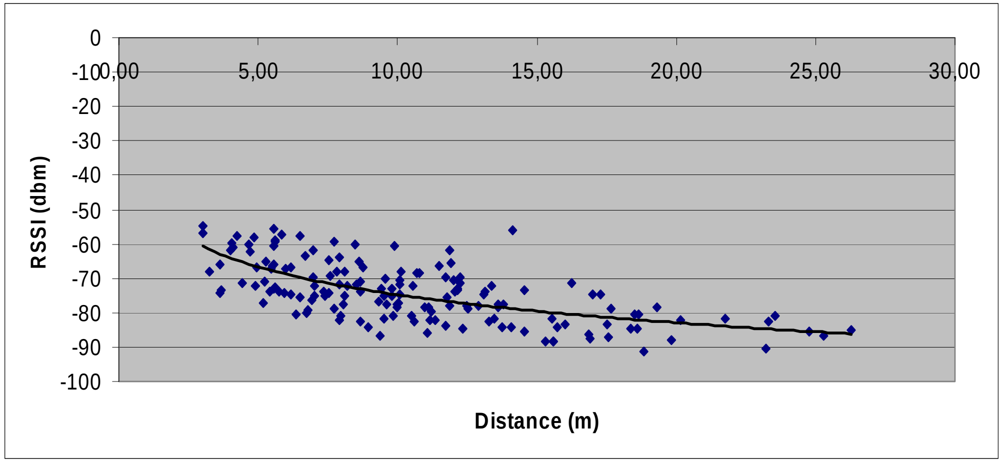




- Theoretical and empirical models are used to translate the difference between the transmitted signal strength and the RSS into a range estimate.
- Propagation effects (refraction, reflection, shadowing, and multipath) cause the attenuation to poorly correlate with distance

Inaccurate distance estimates

Time synch between nodes is not required



RSS ranging: theoretical bound

Received power v.s. distance model (in dBm):

$$P_r(d) = P_0 - 10\,\gamma \log_{10} d + S$$

P_0 received power (in dBm) at a reference distance of 1 meter
γ: path-loss exponent (typical values between 2 and 5)
S: Gaussian random variable with zero mean and standard deviation σ_{S} (shadowing spread). It accounts for large-scale random fluctuations (shadowing).

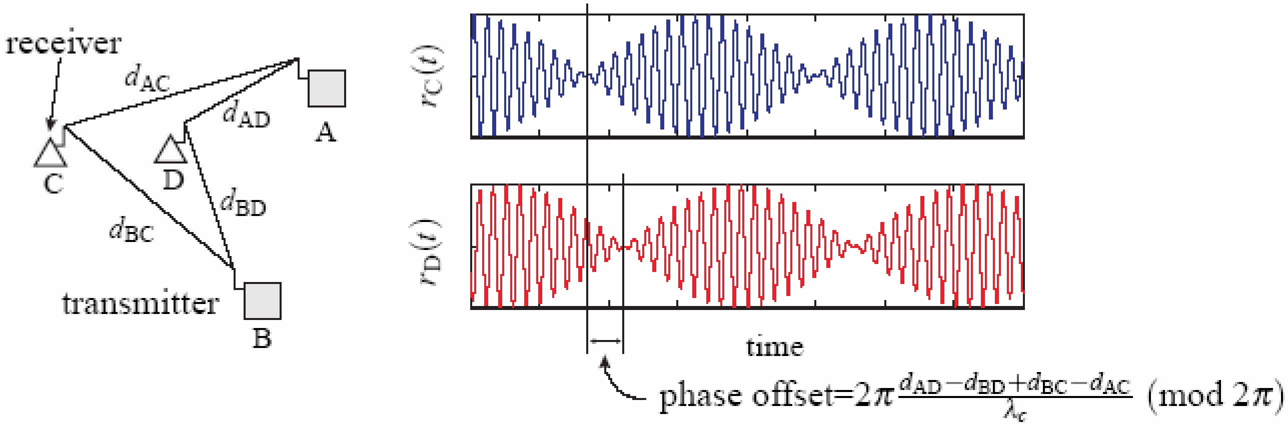
Cramer-Rao bound (CRB) for the distance estimation MSE

$$\mathrm{Var}\left(\hat{d}\right) \geq \left(\frac{\ln 10}{10} \frac{\sigma_{\mathrm{S}}}{\gamma}\, d\right)^2 .$$

- The MSE bound does not depend on signal structure
- RSS ranging does not require time synchronization between nodes
- No dedicated HW

Note: the CRB provides a minimum bound on the variance of any unbiased estimator.

Interferometric Ranging (1/2)



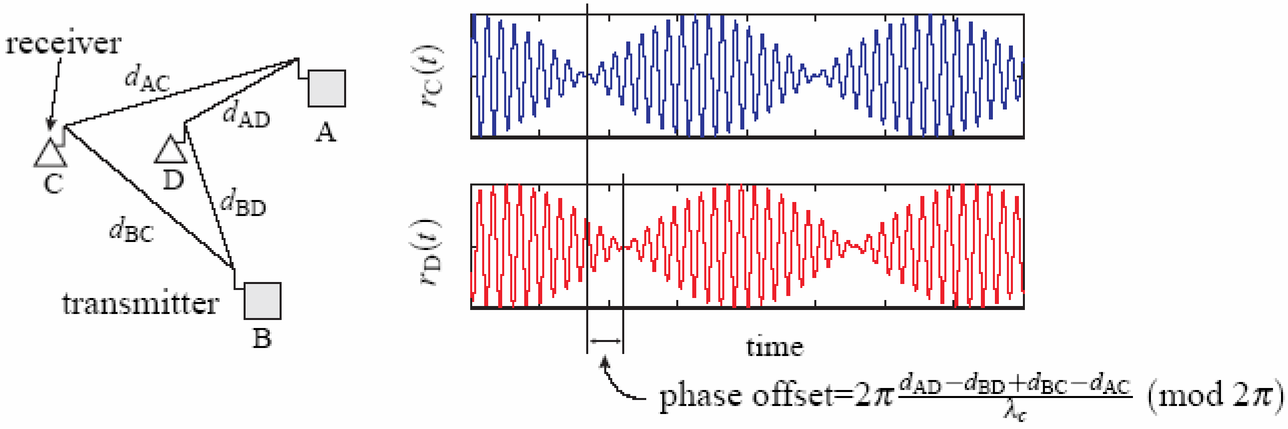
•Transmitters A and B transmit sinusoids at slightly different frequencies

•The envelope of the received composite signal, after band-pass filtering, will vary slowly over time.

•The phase offset of this envelope can be measured using cheap low-precision RF chips, and it contains information about the difference in distance of the two links.

M. Maroti, P. Völgyesi, S. Dora, B. Kusy, A. Nadas, A. Ledeczi, G. Balogh, and K. Molnar, "Radio interferometric geolocation," in *Proc. ACM Conference on Embedded Networked Sensor Systems*, San Diego, USA, Nov. 2005, pp. 1–12.

Interferometric Ranging (2/2)



•To solve the unknown initial phase of the two transmitted sinusoids (no time synch is present), a similar measurement is made by node D in a different location

•The difference in phase offset measured at the two receivers only depends on the four distances. Hence, given a number of phase-offset-difference measurements, the unknown locations of the two receivers can be inferred.

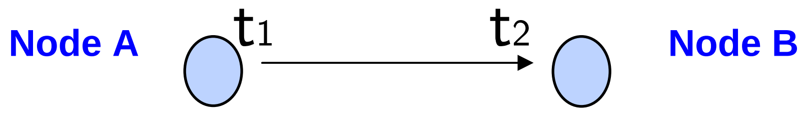
Comments:

- •Sub-meter precision can be achieved in outdoor environments with simple hardware
- •Problems with severe multi-path (e.g., indoor)
- •Infrastructure required.

Time-Based Ranging

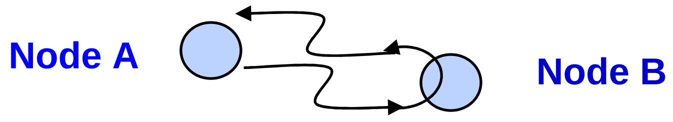
The distance information between a pair of nodes A and B (*ranging*) can be obtained using the measurement of the propagation delay or Time-of-Flight (ToF) $\tau_\mathrm{f} = d/c$, where d is the actual distance between A and B.

- **One-way Time-of Arrival (ToA) ranging**

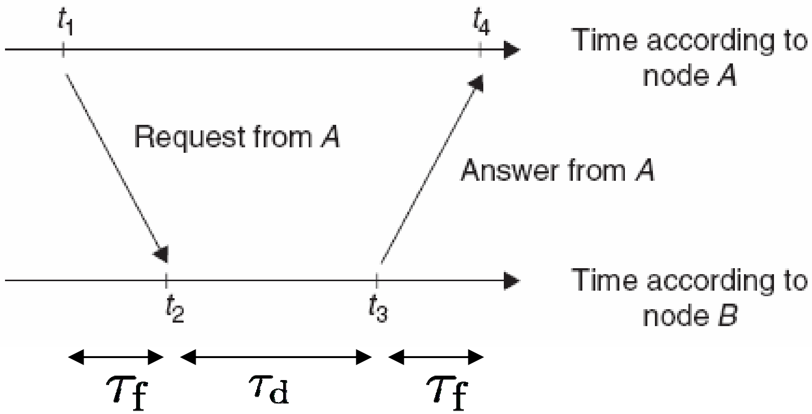


$$\hat{\tau}_\mathrm{f} = t_2 - t_1$$

- **Two-way ToA ranging**

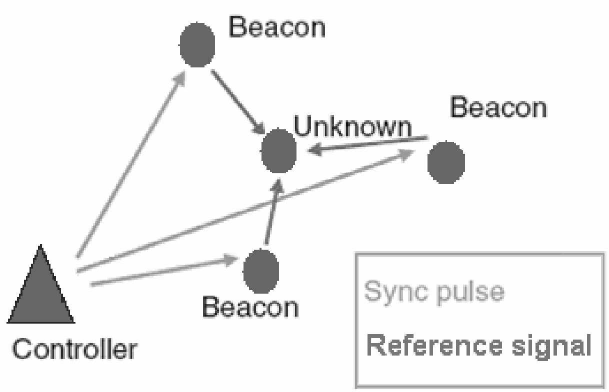


$$\hat{\tau}_\mathrm{f} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2}$$

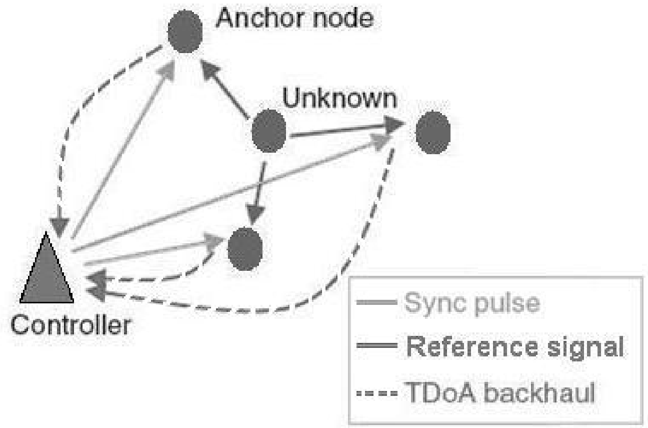


Time-Difference-of-Arrival (TDoA) (1/3)

TDoA scheme A

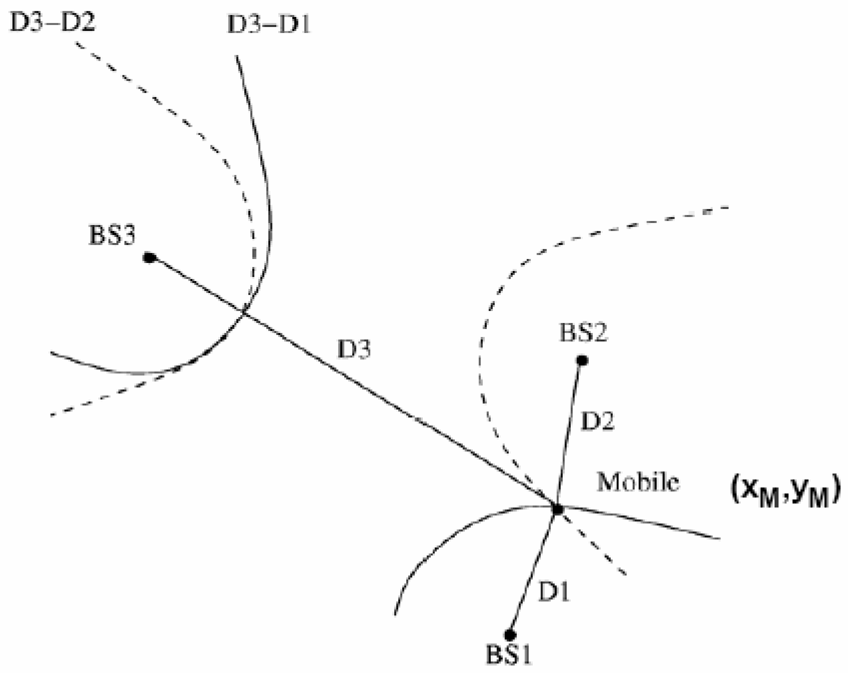


TDoA scheme B



Networks with infrastructure (anchor nodes) and accurate anchors synchronization (e.g., through cable connections) are required

Time-Difference-of-Arrival (TDoA) (2/3)

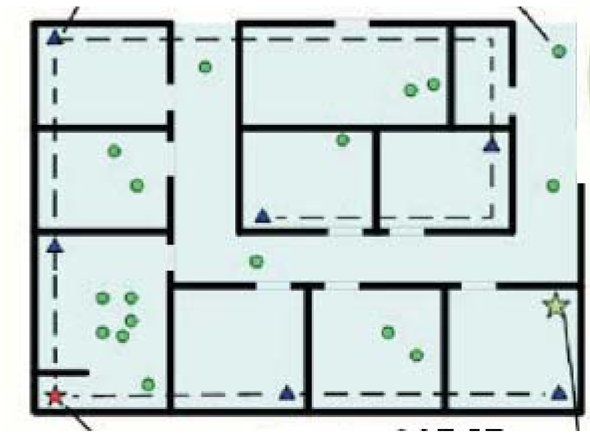


A typical approach uses a geometric interpretation to calculate the intersection of two or more hyperbolas: each sensor pair gives a hyperbola which represents the set of points at a constant range difference (time-difference) from two sensors

Time-Difference-of-Arrival (TDoA) (3/3)

Networks with infrastructure (anchor nodes) and accurate anchors synchronization (e.g., through cable connections) are required

TDoA scheme B suitable for extremely low complexity targets nodes (e.g., TAGs in UWB-RFID systems)



www.ubisense.net

All time-based ranging techniques require time-of-arrival (ToA) estimation of the received signal

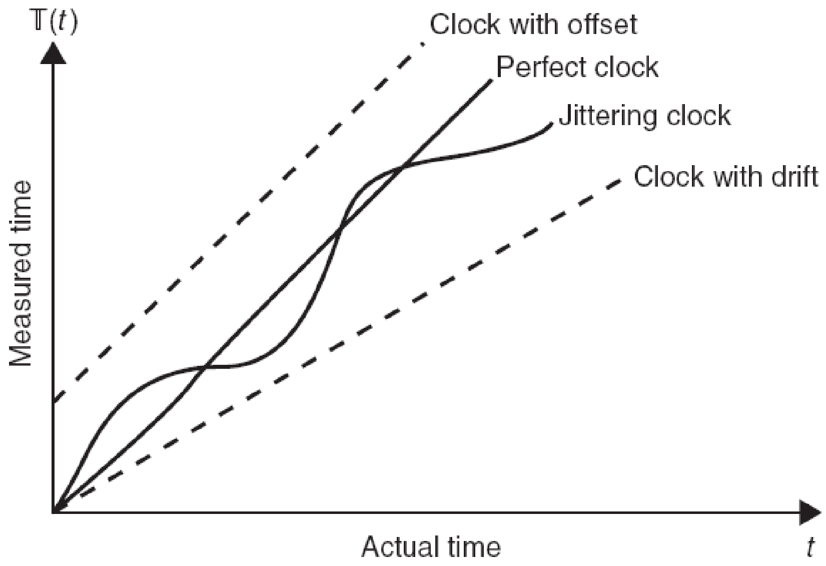
For example, $\tau_{\mathrm{f}} = 1$ ns means a distance $d \approx 30$ cm

$\Downarrow$

Hence, accurate ToA estimation
and time measurement are required!

Time Measurements (1/2)

Only an estimation $\hat{t} = \mathbb{T}(t)$ of the real time t can be obtained due to node local oscillator frequency drift



Reasonable model:

$$\boxed{\mathbb{T}(t) = (1 + \delta)t + \mu}$$

δ: *clock drift*
relative to the correct rate
μ: *clock offset.*

The rate of a perfect clock, $d\mathbb{T}(t)/dt$, would equal 1 (i.e., $\delta = 0$).

The clock performance is often expressed in terms of part-per-million (ppm) defined as the maximum number of extra (or missed) clock counts over a total of 10^6 counts, i.e., $\delta \cdot 10^6$.

Time Measurements (2/2)

Suppose that a node intends to generate a time delay of τ_{d} seconds, the effective generated delay $\hat{\tau_d}$ in the presence of a clock drift δ would be

$$\hat{\tau_d} = \frac{\tau_{\mathrm{d}}}{1+\delta}$$

In case a node has to measure a time interval of true duration $\tau = t_2 - t_1$ seconds, the corresponding estimated value $\hat{\tau}$ would be

$$\hat{\tau} = \mathbb{T}(t_2) - \mathbb{T}(t_1) = \tau\,(1+\delta)$$

In both cases there is no dependence on the clock offset μ.

One-Way ToA Ranging: effect of clock drifts

According to node A's local time, the packet is transmitted at time $t_1^{(A)} = \mathbb{T}_A(t_1)$ (included as a timestamp in the packet) and it is received at node B's local time $t_2^{(B)} = \mathbb{T}_B(t_2)$. Node B calculates the estimated propagation delay as

$$\hat{\tau}_{\mathrm{f}} = t_2^{(B)} - t_1^{(A)} = \tau_{\mathrm{f}} \cdot (1 + \delta_A) + t_2 \cdot (\delta_B - \delta_A) + \mu_B - \mu_A$$

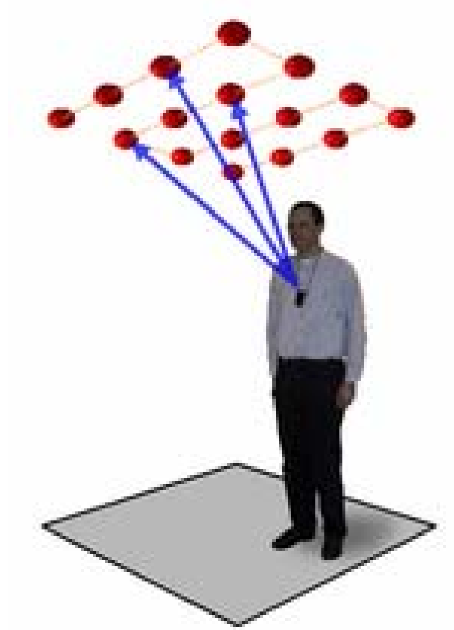
clock offsets may be in the order of us,
one-way raging tied to network synchronization

One-way ranging requires stringent network synchronization constraints which are often not feasible in low-cost systems.

Possible application of one-way ToA ranging

Ultrasound devices

•propagation speed of acoustic waves (≅340 m/s) is much lower than light-speed
•synchronization errors can be several orders of magnitude smaller than the typical propagation delay values
•high positioning accuracy (3 cm)



Ultrasound technology has several disadvantages

•Hybrid technology
•Propagation limited by walls (coverage)
•Effect of temperature and pressure (calibration)
•Power-hungry

Active Bat localization system

A. Harter, A. Hopper, P. Steggles, A. Ward and P. Webster "The anatomy of a Context-Aware Application", In Wireless Networks, Vol. 8, pp. 187-197, Feb. 2002.

Two-Way ToA Ranging: effect of clock drifts (1/2)

The effective response delay introduced by node B is $\tau_{\mathrm{d}}/(1+\delta_B)$, whereas the estimated RTT denoted by $\hat{\tau}_{\mathrm{RT}}$, according to node A's time scale, is

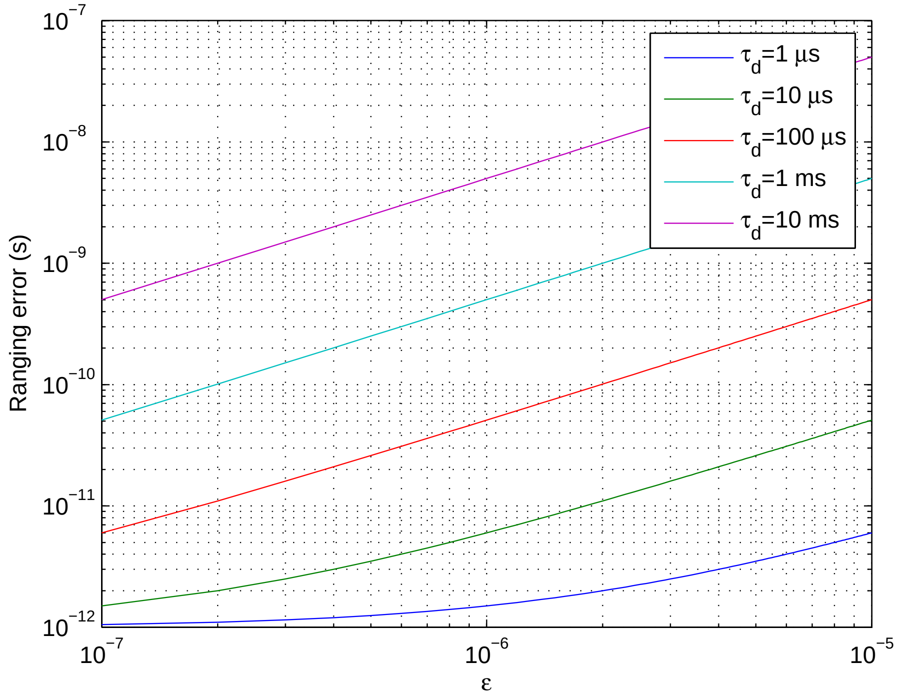
$$\hat{\tau}_{\mathrm{RT}} = 2\,\tau_{\mathrm{f}}(1+\delta_A) + \frac{\tau_{\mathrm{d}}(1+\delta_A)}{(1+\delta_B)}$$

In absence of other information, node A derives the estimation of the propagation time, $\hat{\tau}_{\mathrm{f}}$, by equating the previous equation with the supposed round-trip time $2\,\hat{\tau}_{\mathrm{f}} + \tau_{\mathrm{d}}$ leading to

$$\hat{\tau}_{\mathrm{f}} = \tau_{\mathrm{f}}\,(1+\delta_A) + \frac{\varepsilon\,\tau_{\mathrm{d}}}{2(1+\delta_A-\varepsilon)}$$

where $\varepsilon \triangleq \delta_A - \delta_B$.

Two-Way ToA Ranging: effect of clock drifts (2/2)



$\tau_{\mathrm{f}} = 100$ ns (about 30 meters), $\delta_A = 10^{-5}$ (10 ppm)

Low response delay must be ensured for high ranging accuracy

⇓

The ranging protocol must be implemented at PHY level

Remarks

Two-way ranging requires less stringent synchronization constraints compared to one-way ranging (relative clock drifts still affect ranging accuracy)

Suitable for networks without infrastructure (e.g., ad hoc networks)

Adopted in the IEEE 802.15.4a standard

Time-of-Arrival (ToA) estimation

Time-of-Arrival Estimation (ToA)

Problem statement in an ideal scenario

Consider the transmission of a single pulse *p(t)* in AWGN channel in the absence of other sources of error. The received signal is

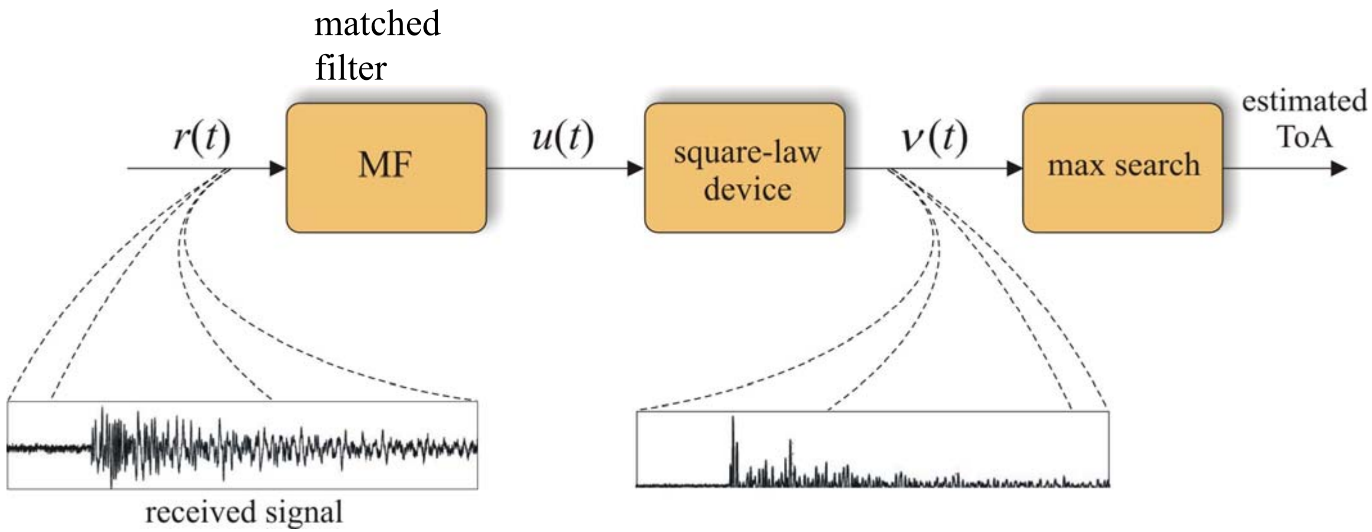
$$r(t) = \sqrt{E_{\mathrm{p}}}\, p(t-\tau) + n(t)$$

The problem is to obtain the best estimate for the ToA, τ, based on the received signal $r(t)$ observed over the interval $[0, T_{\mathrm{ob}})$.

$\Downarrow$

Classical non-linear parameter estimation problem

Maximum likelihood (ML) ToA estimator



The ML ToA estimator is asymptotically efficient in AWGN

Theoretical limits in AWGN

The estimation Mean Square Error (MSE) of any unbiased estimation $\hat{\tau}$ of τ can be bounded by the Cramer-Rao bound (CRB)

$$\mathrm{Var}(\hat{\tau}) = \mathbb{E}\left\{(\hat{\tau}-\tau)^2\right\} \geq \mathsf{CRB}$$

The CRB is given by

$$\mathsf{CRB} = \frac{N_0/2}{(2\,\pi)^2 E_{\mathrm{p}}\,\beta^2} = \frac{1}{8\,\pi^2\,\beta^2\,\mathsf{SNR}}$$

where
- $\mathsf{SNR} \triangleq E_{\mathrm{p}}/N_0$
- β^2 represents the second moment of the spectrum $P(f)$ of $p(t)$ defined by

$$\beta^2 \triangleq \frac{\int_{-\infty}^{\infty} f^2 |P(f)|^2\, df}{\int_{-\infty}^{\infty} |P(f)|^2\, df}$$

- β: *effective bandwidth*

Bound on ranging MSE

Lower bound on ranging MSE

$$\mathrm{Var}\left(\hat{d}\right) \geq \frac{c^2}{8\,\pi^2\,\beta^2\,\mathsf{SNR}}\,.$$

How to improve the accuracy?

Increase the SNR → towards very narrowband systems

To mitigate the effect of multipath in indoor environments, low frequency bands must be used → not practical for small size devices due to large antennas

Increase the bandwidth → towards ultra wideband (UWB) systems

Higher frequencies bands can be used. Multipath can be resolvable.
Technique chosen by the IEEE 802.15.4a standard

Ranging using UWB signals

Impulse Radio UWB (IR-UWB)

Base-band generation

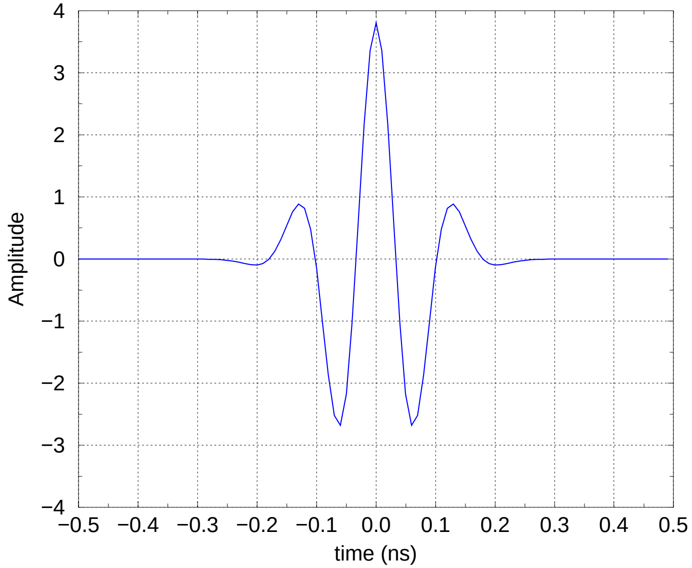
of the signal

•Low complexity (no RF and IF stages)

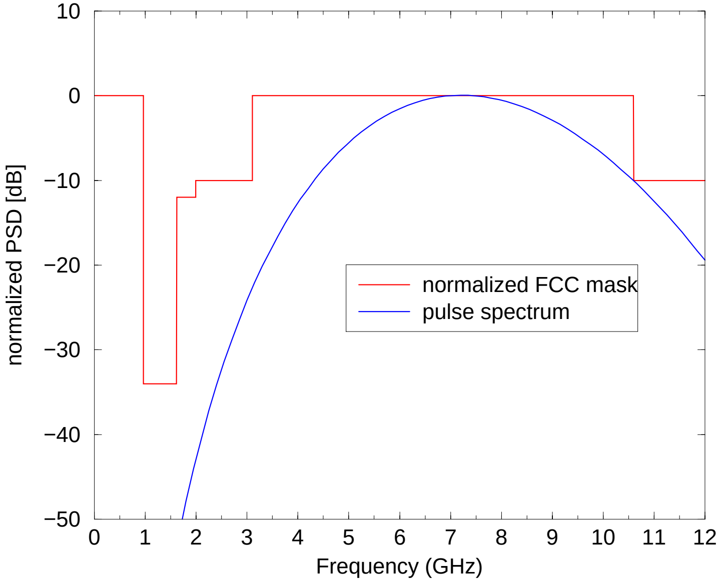
•Low consumption

Example of Gaussian

6th derivative monocycle



Spectrum



An improved bound: the Ziv-Zakai Lower Bound (1/2)

UWB systems are expected to operate at low SNR

CRB is not accurate at low and moderate SNR and/or when the observation time is short → improved bounds needed

⇩

The Ziv-Zakai bound (ZZB) can be applied to a wider range of SNRs and can also take the presence of ambiguities into account, but more complex than CRB for analytical evaluation

An improved bound: the Ziv-Zakai Lower Bound (2/2)

When τ is uniformly distributed in $[0, T_\mathrm{a})$, the ZZLB is

$$\mathsf{ZZB} = \frac{1}{T_\mathrm{a}} \int_0^{T_\mathrm{a}} z\,(T_\mathrm{a} - z)\, P_{\min}(z)\; dz$$

where $P_{\min}(\tau)$ is the error probability of the classical binary detection scheme with equally probable hypothesis:

$$\mathcal{H}_1 : \; r(t) \sim \mathbf{p}\{r(t)|\tau\}$$
$$\mathcal{H}_2 : \; r(t) \sim \mathbf{p}\{r(t)|\tau + z\}$$

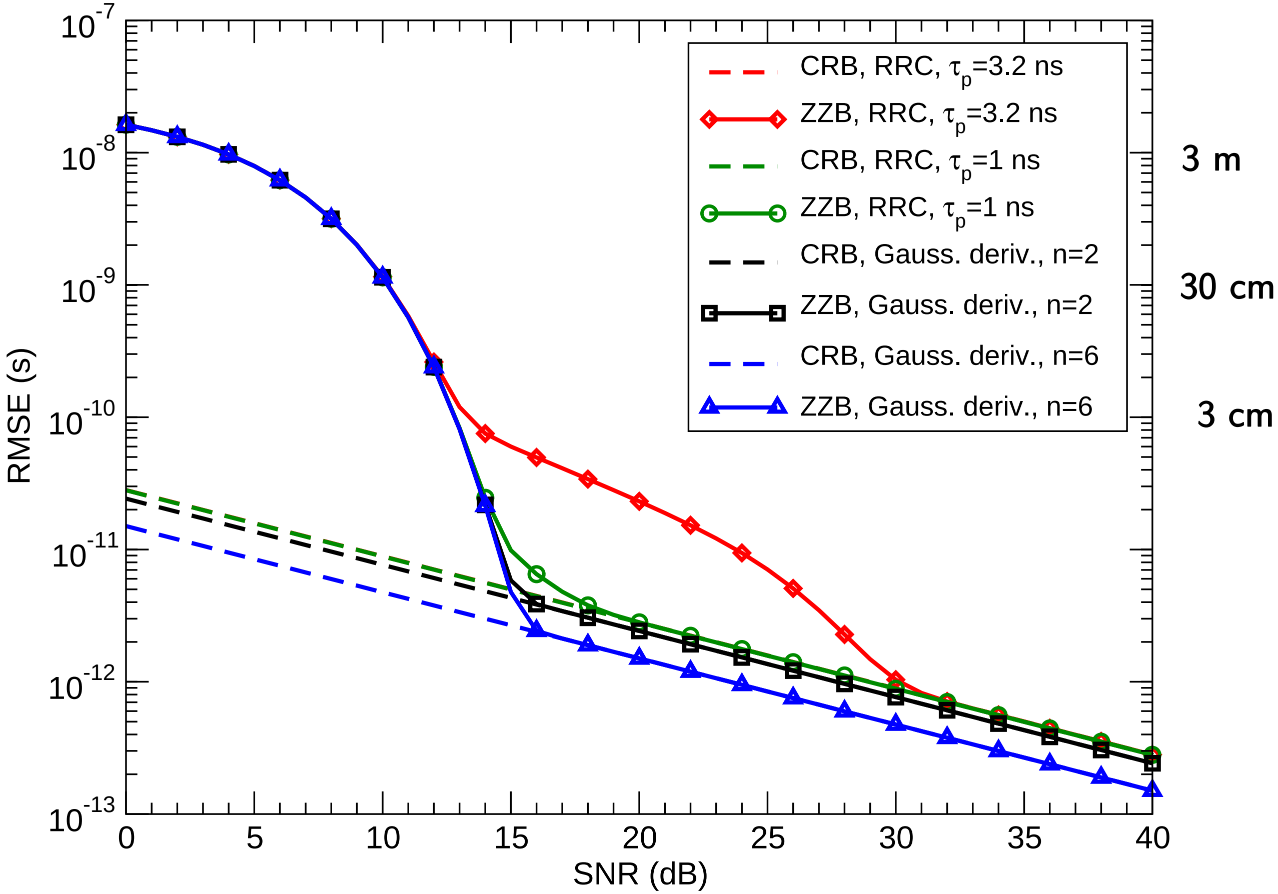
In AWGN the minimum attainable probability of error becomes

$$P_{\min}(z) = Q\left(\sqrt{\mathsf{SNR}\,(1 - \rho_\mathrm{p}(z))}\right)$$

where $Q(\cdot)$ is the Gaussian Q-function and $\rho_\mathrm{p}(z)$ is the autocorrelation function of $p(t)$.

ToA estimation theoretical limits using UWB pulses

CRB and Ziv-Zakai Bound in AWGN (single path)

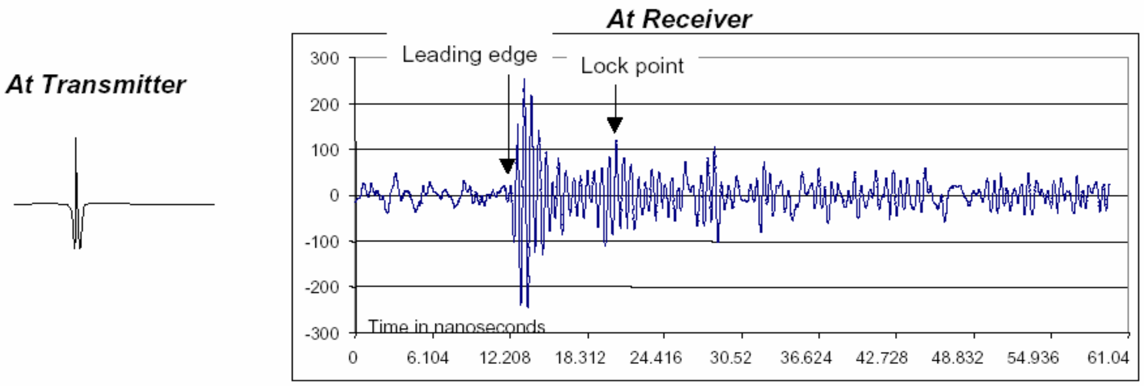


From D. Dardari, C.-C. Chong, and M. Z. Win, "Improved lower bounds on time-of-arrival estimation error in realistic UWB channels," in *IEEE International Conference on Ultra-Wideband, ICUWB 2006*, (Waltham, MA, USA), pp. 531–537, Sept. 2006.

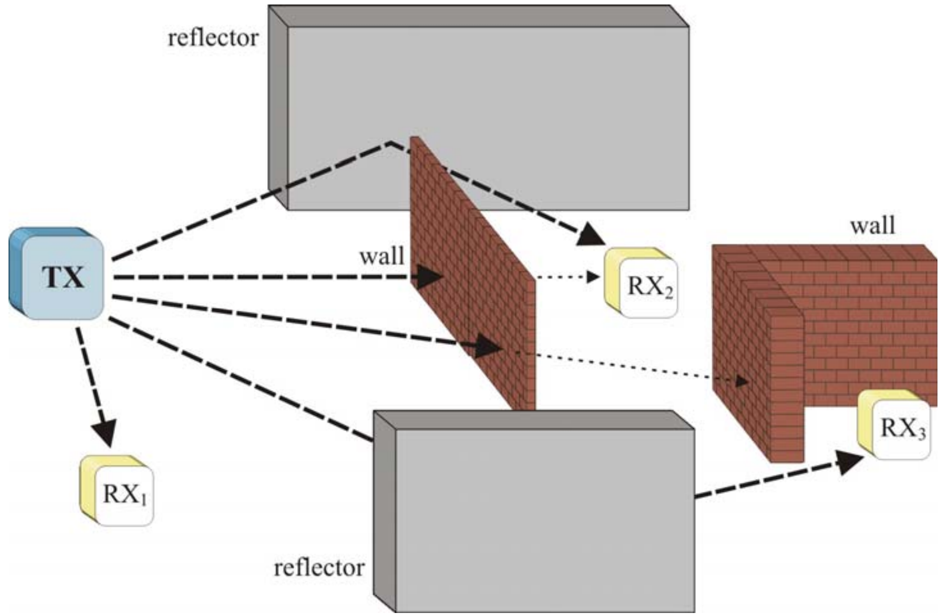
Main sources of error in ToA Ranging

Main issues in UWB ToA Estimation

Rich multipath
(ambiguities in first path detection)



Non Line-of-Sight (NLoS) conditions
- direct path blockage
- extra propagation delay due to different e.m. propagation speeds



Interference
(narrowband and wideband)

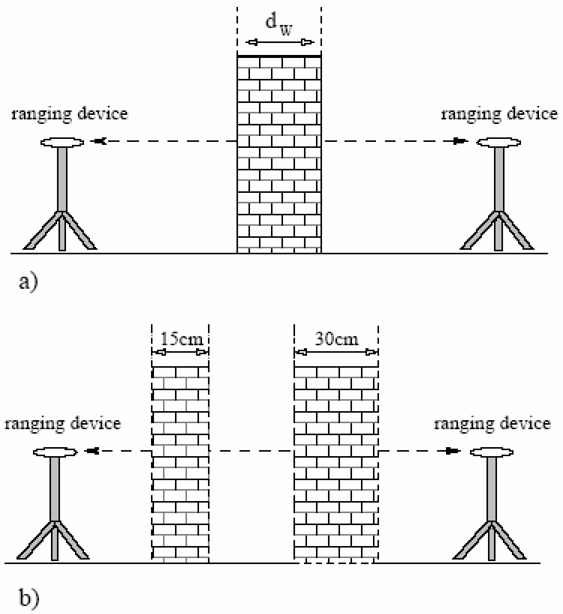
In addition:
- clock drift (time synch algorithms)
- design of low-complexity ToA estimators

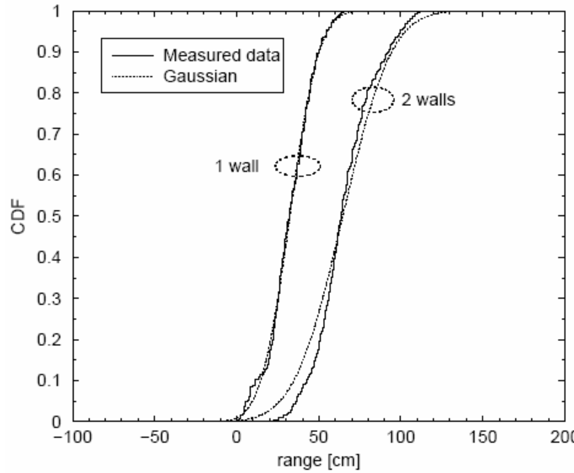
NLOS condition: extra propagation delay (1/2)

The extra delay $\Delta\tau$ introduced by a homogeneous material with thickness d_{W} is given by

$$\Delta\tau = \left(\sqrt{\epsilon_{\mathrm{r}}} - 1\right) \frac{d_{\mathrm{W}}}{c}$$

where ϵ_{r} is the relative electrical permittivity of the material.





Layout, d_{W} [cm]	mean bias [cm]	std dev [cm]
1 wall, 15.5	16.4	3.7
1 wall, 30	29.5	3.2
2 walls, 15.5+30	45.2	3

D. Dardari, A. Conti, J. Lien, and M. Z. Win, "The effect of cooperation in UWB based positioning systems using experimental data," *EURASIP Journal on Advances in Signal Processing, Special Issue on Cooperative Localization in Wireless Ad Hoc and Sensor Networks*, 2008.

NLOS condition: extra propagation delay (2/2)

Extra propagation delay effect leads to biased estimations, typically some nanoseconds

⇓

Ranging error on the order of 50 cm!

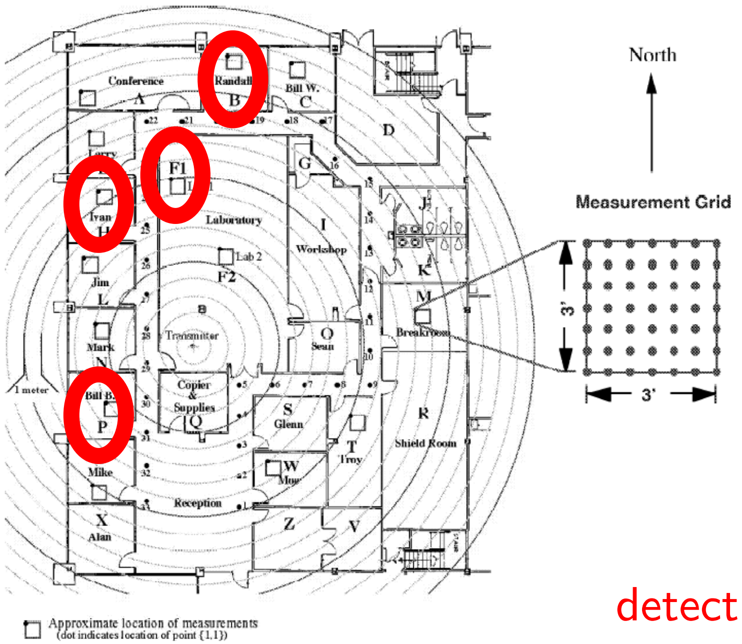
Possible solutions:

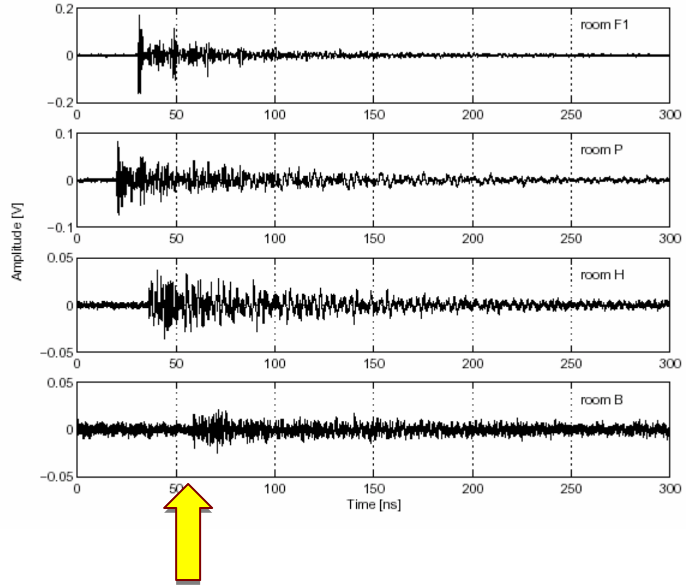
- larger number of anchor nodes
- knowledge of some a priori information (e.g., scenario layout)
- cooperation among nodes

ToA Estimation in Multipath Environments

$$p(t) \longrightarrow r(t) = \sqrt{E_\mathrm{p}} \sum_{l=1}^{L} \alpha_l \, p(t-\tau_l) + n(t)$$

In general, dense multipath is composed of tens or hundreds paths.
It may be difficult to recognize the first path, especially at low and medium SNRs





detection of first path may be challenging

Moe Z. Win, and Robert A. Scholtz, "Characterization of Ultra-Wide Bandwidth Wireless Indoor Channels: A Communication-Theoretic View", IEEE Journal On Selected Areas In Communications, Vol. 20, No. 9, December 2002

ToA Estimation in Multipath Environments

Received signal

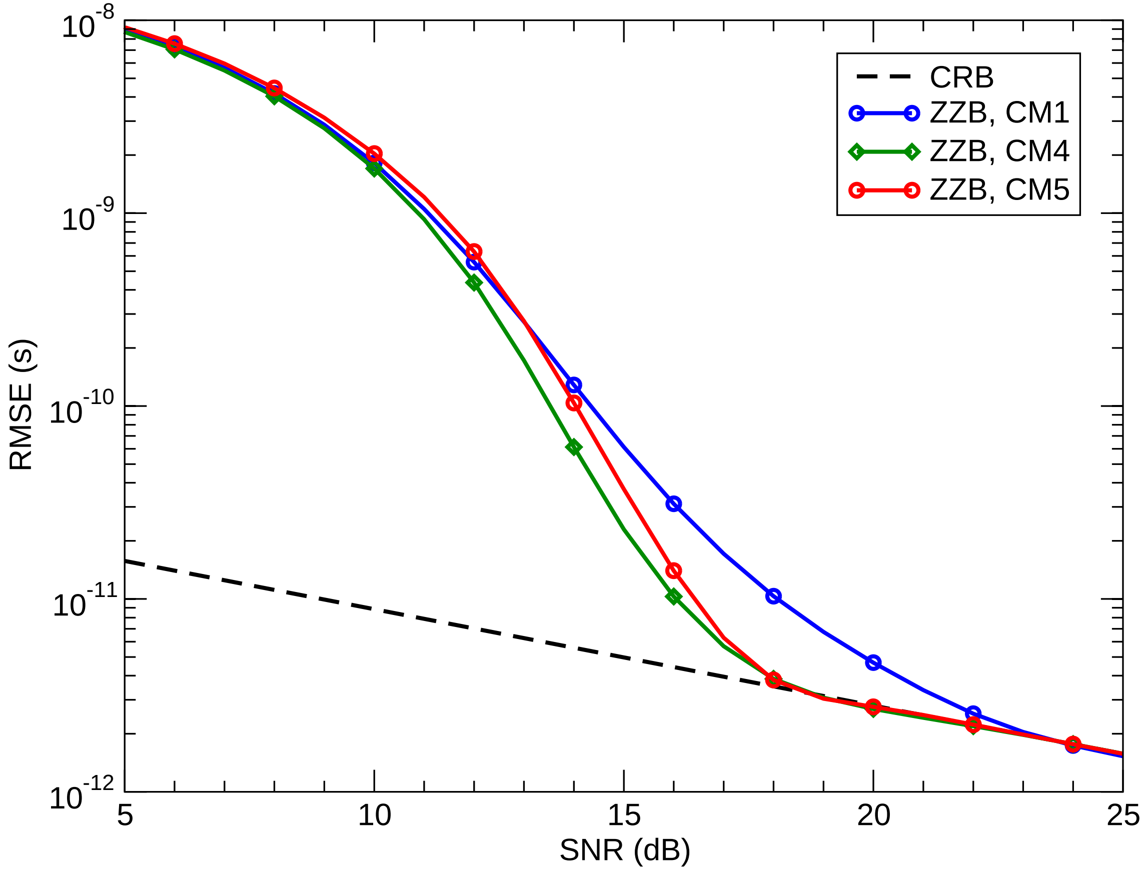
$$r(t) = \sqrt{E_{\mathrm{p}}} \sum_{l=1}^{L} \alpha_l \, p(t-\tau_l) + n(t)$$

Problem formulation

- we are interested in the estimation of the ToA, $\tau = \tau_1$, of the direct path by observing the received signal $r(t)$ within the observation interval $[0, T_{\mathrm{ob}})$;
- we consider τ to be uniformly distributed in the interval $[0, T_{\mathrm{a}})$, with $T_{\mathrm{a}} < T_{\mathrm{ob}}$;
- set of nuisance parameters $\mathcal{U} = \{\tau_2, \tau_3, \ldots, \tau_L, \alpha_1, \alpha_2, \ldots, \alpha_L\}$

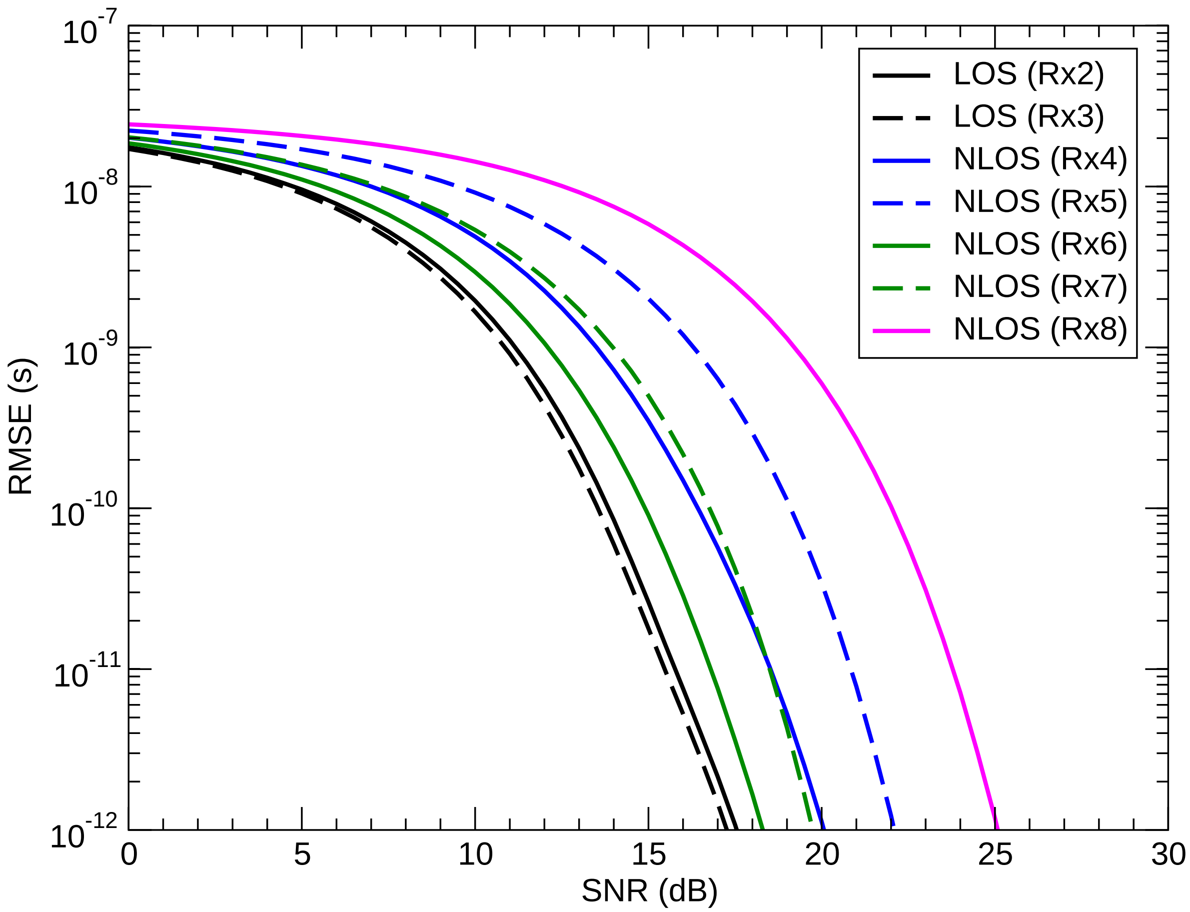
CRB and ZZB for ToA Estimation with Multipath

Using the IEEE802.15.4a channel model



D. Dardari, A. Conti, U. Ferner, A. Giorgetti, and M. Z. Win, "*Ranging with Ultrawide Bandwidth Signals in Multipath Environments*", Proc. of IEEE (Special Issue on UWB Technology & Emerging Applications), Summer 2008.

ZZB for ToA Estimation using Measured Data



D. Dardari, C.-C. Chong, and M. Z. Win, "Improved lower bounds on time-of-arrival estimation error in realistic UWB channels," in *IEEE International Conference on Ultra-Wideband, ICUWB 2006*, (Waltham, MA, USA), pp. 531–537, Sept. 2006.

ML ToA Estimator in Multipath Environments

When channel parameters are unknown, ToA estimation in multipath environments is closely related to channel estimation, where path amplitudes and ToA $\boldsymbol{\tau} = [\tau_1, \tau_2, \ldots, \tau_L]^T$ are jointly estimated using, for example, a ML approach

The ML estimate of $\boldsymbol{\tau}$ is $\hat{\boldsymbol{\tau}} = \arg\max_{\tilde{\boldsymbol{\tau}}} \{\boldsymbol{\chi}^H(\tilde{\boldsymbol{\tau}})\, \boldsymbol{R}^{-1}(\tilde{\boldsymbol{\tau}})\, \boldsymbol{\chi}(\tilde{\boldsymbol{\tau}})\}$, where $\mathbf{R}(\boldsymbol{\tau})$ is the autocorrelation matrix of $p(t)$ and

$$\boldsymbol{\chi}(\boldsymbol{\tau}) \triangleq \int_0^{T_{\rm ob}} r(t) \begin{bmatrix} p(t-\tau_1) \\ p(t-\tau_2) \\ \cdot \\ \cdot \\ \cdot \\ p(t-\tau_L) \end{bmatrix} dt$$

Implementation at Nyquist sampling rate or higher difficult with UWB
→ looking for sub-optimal schemes

ToA estimation in realistic environments

Results from: C. Falsi, D. Dardari, L. Mucchi, and M. Z. Win, “Time of arrival estimation for UWB localizers in realistic environments,” *EURASIP J. Appl. Signal Processing (Special Issue on Wireless Location Technologies and Applications)*, 2006.

Algorithms tested

Lower complexity

Simple thresholding, peak detection

Iterative cancellation techniques (to deal with paths overlapping)

Higher complexity

Decreasing SNR

Room	Algorithm	μ_ϵ [ns]	σ_ϵ [ns]	μ_ρ [cm]	σ_ρ [cm]
F1	Threshold and Search	−0.10	0.15	−3.0	5.7
	Single Search	−0.045	0.19	−1.3	5.7
	Search and Subtract	0.17	0.24	5.1	7.2
	Search Subtract and Readjust	0.42	0.20	12.6	5.6
P	Threshold and Search	−0.082	0.20	−2.46	5.6
	Single Search	−0.10	0.25	−3.0	7.5
	Search and Subtract	0.22	0.25	6.6	7.5
	Search Subtract and Readjust	0.24	0.24	7.2	7.2
H	Threshold and Search	−0.20	0.43	−5.6	12.9
	Single Search	−0.38	0.44	−11.4	13.2
	Search and Subtract	0.11	0.30	3.3	9.0
	Search Subtract and Readjust	0.086	0.34	2.6	10.2
B	Threshold and Search	−0.17	0.56	−5.1	16.8
	Single Search	−0.19	0.66	−5.7	19.8
	Search and Subtract	−0.11	0.40	−3.3	12.0
	Search Subtract and Readjust	0.013	0.45	0.39	13.5

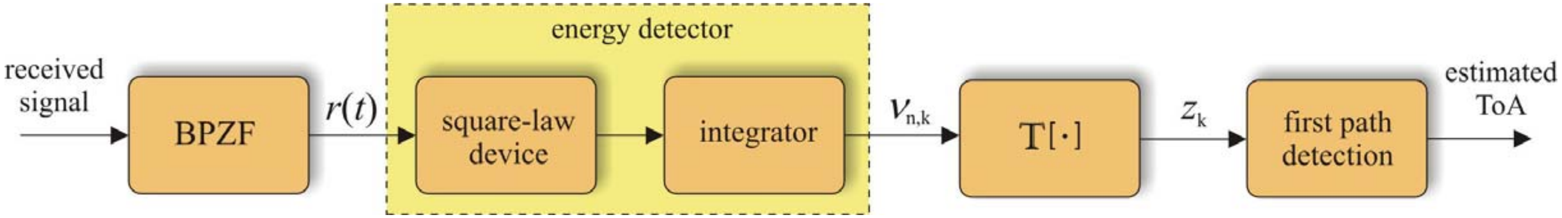
Main observations:

-There is no a large performance difference between simple and complex algorithms considered (especially at medium and large SNRs)

-Ranging resolutions on the order of 10 cm are achievable!

Low-complexity ToA Estimators

ToA estimators based on energy detection (ED) can operate at sub-Nyquist sampling rate → low complexity

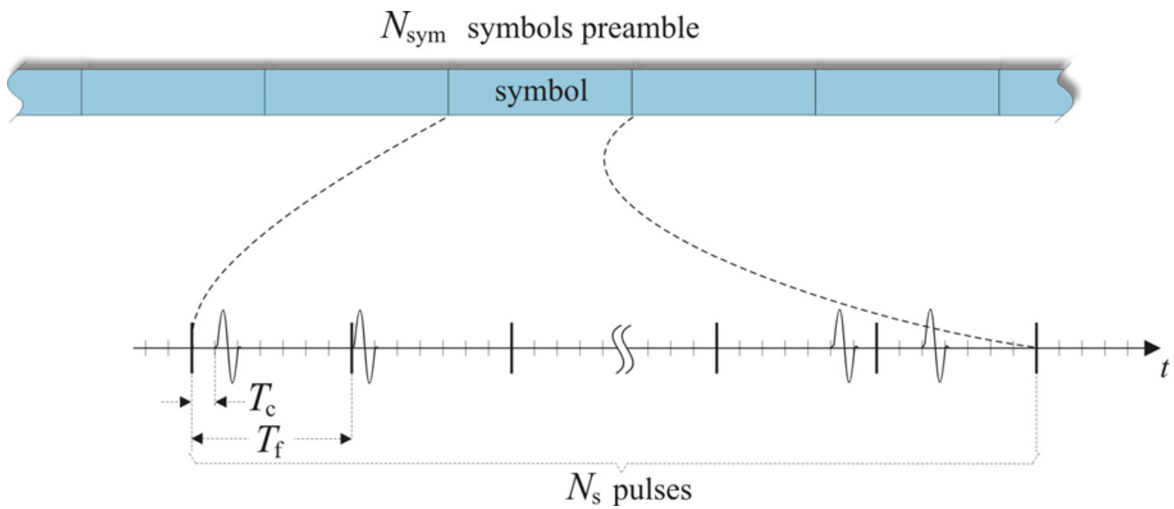


- T[.]: pre-processing filter
  - to improve the first path detection
  - to mitigate the effect of the interference

- First path detector: several algorithms can be adopted

The ToA resolution is bounded by the ED integration time

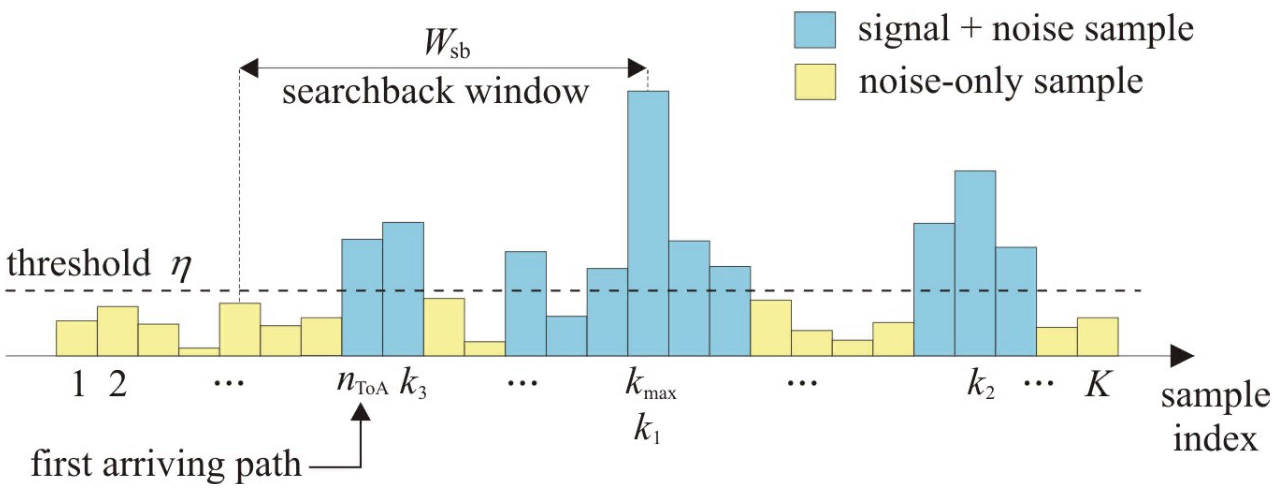
Example of ranging preamble structure



Each user has a different time-hopping sequence
to allow multi-user communication

ToA estimation algorithms

Collected energy vector



Possible algorithms

- Simple thresholding
- Peak-MAX
- Backward search
- ………

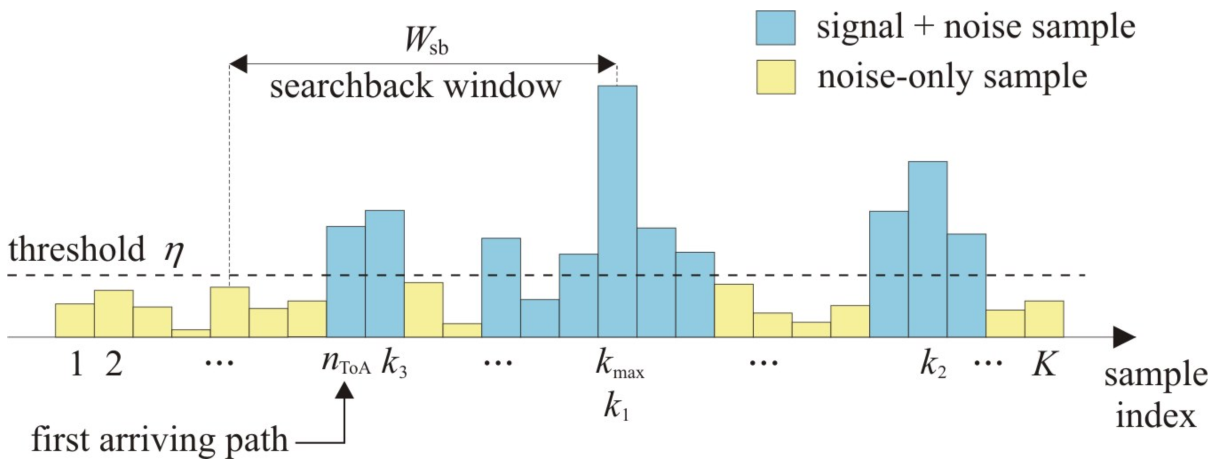
- D. Dardari, C.-C. Chong, and M. Z. Win, "Analysis of threshold-based ToA estimators in UWB channels," in European Signal Processing Conference, EUSIPCO 2006, Florence, ITALY, Sep. 2006.

- I. Guvenc and Z. Sahinoglu, "Threshold-based TOA estimation for impulse radio UWB systems," in Proc. IEEE Int. Conf. on Ultra-Wideband (ICU), Zurich, Switzerland, Sep 2005, pp. 420–425.

- S. Gezici, Z. Tian, G. B. Giannakis, H. Kobayashi, A. F. Molisch, H. V. Poor, and Z. Sahinoglu, "Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks," IEEE Signal Processing Mag., vol. 22, pp. 70–84, Jul. 2005.

Simple thresholding ToA estimation

Detect the time slot within the observation interval that contains the first path by comparing each element of $\{z_k\}$ to a fixed threshold η.
The first threshold crossing event is taken as the estimate of the ToA

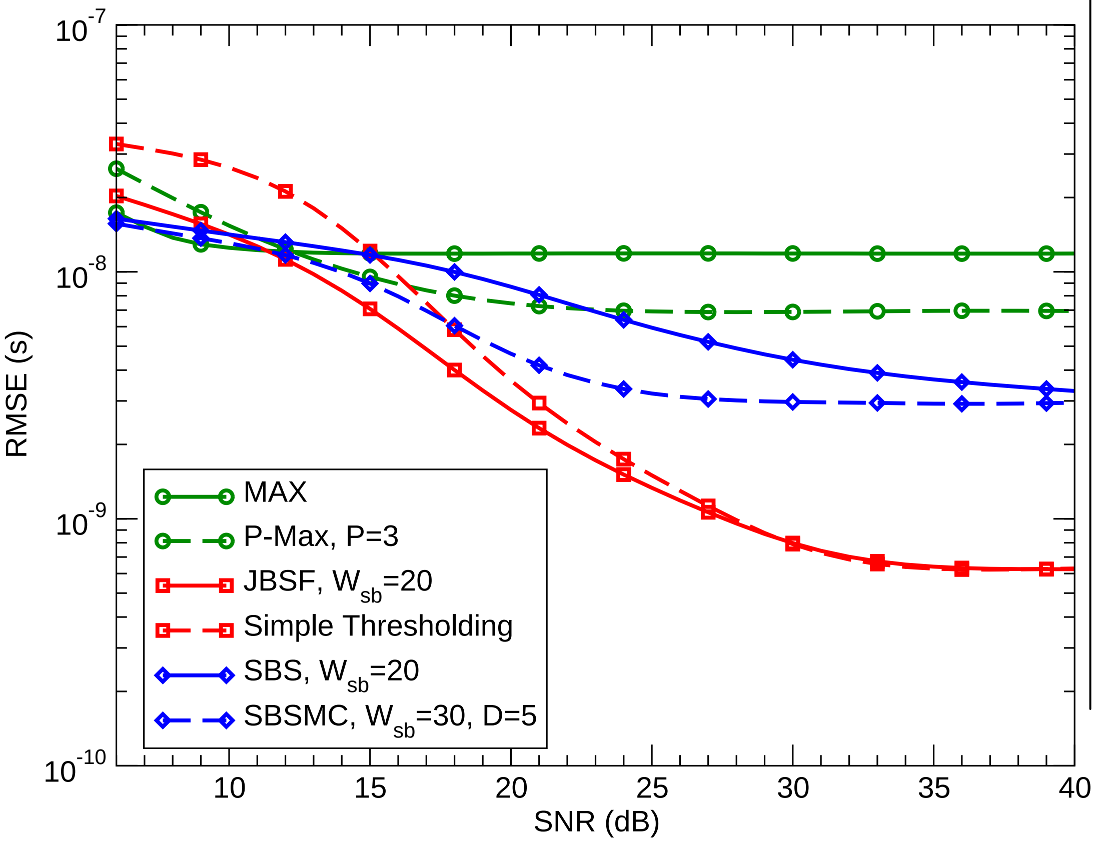


Decision vector

The optimum choice of η depends on channel statistics and SNR:

- Small $\eta \rightarrow$ high probability of early detection prior to the first path (early ToA estimation) due to noise and interference
- Large $\eta \rightarrow$ low probability of detecting the first path and a high probability of detecting an erroneous path (late ToA estimation) due to fading

Performance comparison between ToA est. techniques



Signal bandwidth 1.6 GHz
Center frequency 4 GHz
ED integration time 2 ns
Preamble length 400 pulses
Frame duration 120 ns
IEEE802.15.4a (CM4) channel model

Error floor $T_{\text{int}}/\sqrt{12}$

From: D. Dardari, A. Conti, U. Ferner, A. Giorgetti, and M. Z. Win, "*Ranging with Ultrawide Bandwidth Signals in Multipath Environments*", Proc. of IEEE (Special Issue on UWB Technology & Emerging Applications), Summer 2008.

Interference effects

UWB systems are expected to work in coexistence with other UWB and narrowband systems as an underlying technology

↓

Both wideband interference (WBI) and narrowband interference (NBI) can be present and degrade the ToA estimation

↓

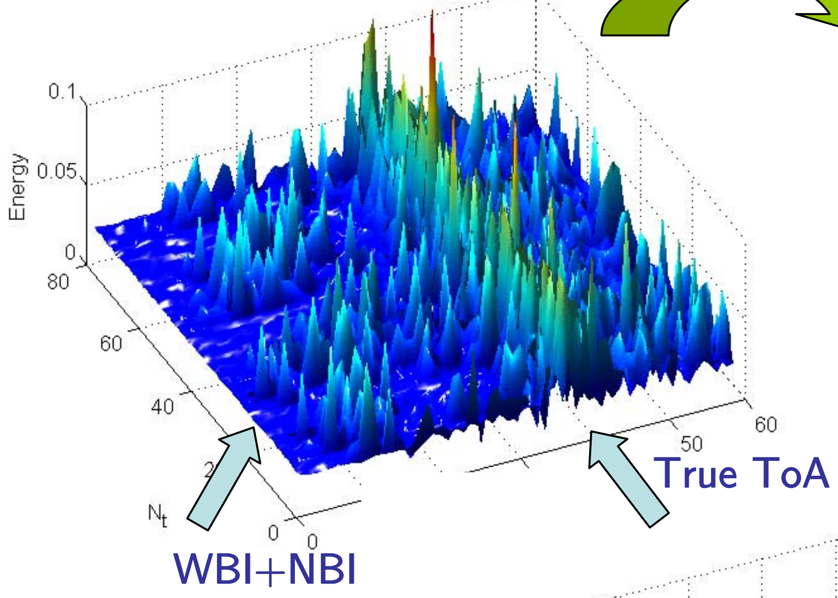
Either non-linear and linear 2D filtering techniques can be applied to mitigate the effect of the interference

- Z. Shainoglu and I. Guvenc, “Multiuser interference mitigation in noncoherent UWB ranging via nonlinear filtering,” EURASIP J. Wireless Communications and Networking, vol. 2006, pp. 1–10, 2006.

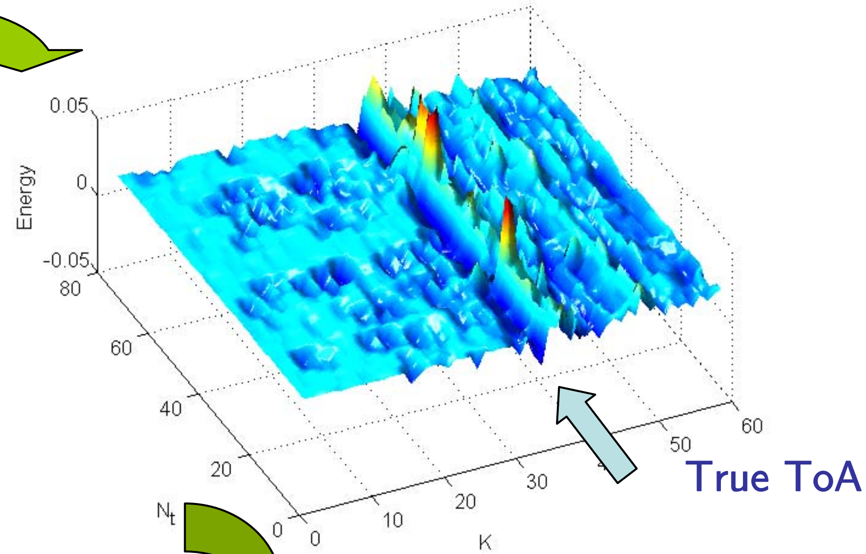
- D. Dardari, A. Giorgetti, and M. Z. Win, “Time-of-arrival estimation in the presence of narrow and wide bandwidth interference in UWB channels,” in IEEE International Conference on Ultra-Wideband, ICUWB 2007, Singapore, Sep. 2007.

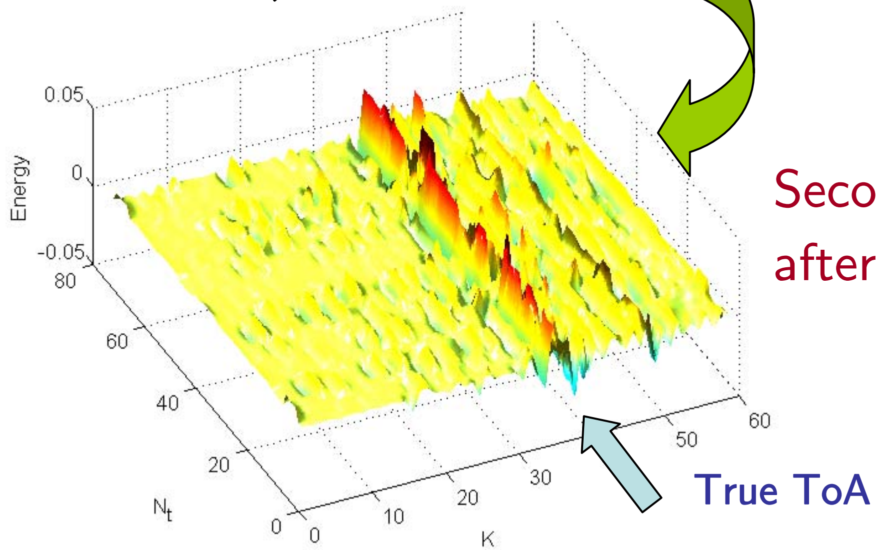
Energy matrix filtering examples

Before filtering



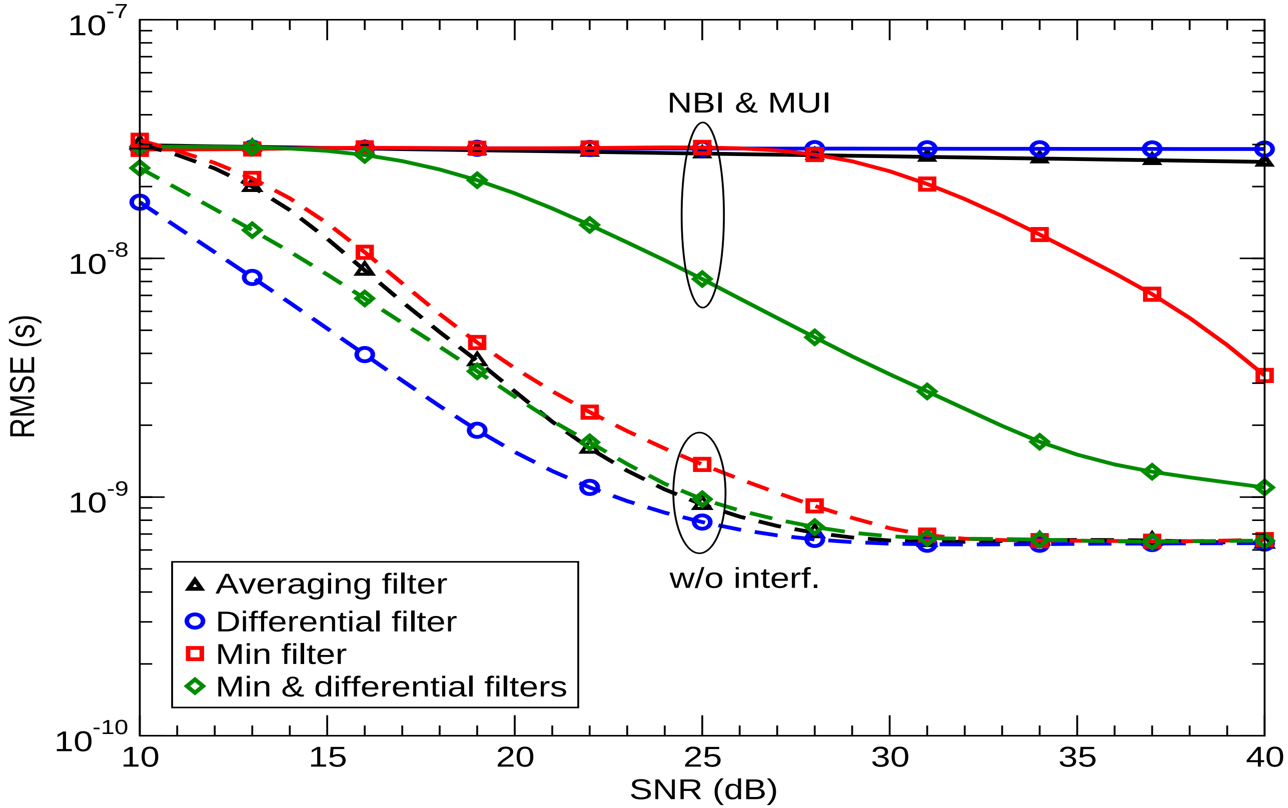
First step: after the *min* filter





Second step:
after the *differential* filter

Performance comparison between mitigation techniques



$N_{\mathrm{sym}} = 400$: preamble length.

Performance of the threshold-based estimator with different 2D filtering techniques in the presence of both NBI, $\mathsf{INR} = 35\,\mathrm{dB}$, and WBI, $\mathsf{SIR} = -15\,\mathrm{dB}$.

From D. Dardari, A. Giorgetti, and M. Z. Win, "Time-of-arrival estimation in the presence of narrow and wide bandwidth interference in UWB channels," in IEEE International Conference on Ultra-Wideband, ICUWB 2007, Singapore, Sep. 2007.

Ranging in the IEEE802.15.4a standard

- Two-way ToA ranging
- Adoption of ternary sequences (ideal autocorrelation function)
- Both coherent and non coherent estimation

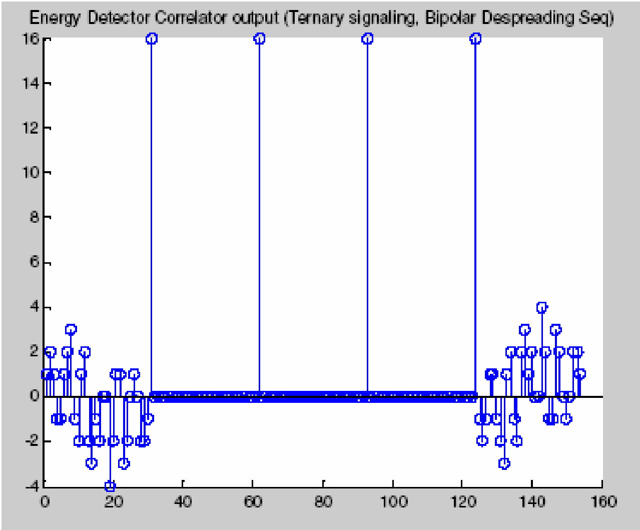
IEEE 802.15.4a packet structure

Preamble	Start of frame delimiter, SFD	PHY header	Data field
[16,64,1024,4096] symbols	[8,64] symbols		

Example of one the 8 possible length-31 ternary sequence

[-000+0-0+++0+-000+-000+-+++00-+0-00]

Autocorrelation function



Position estimation

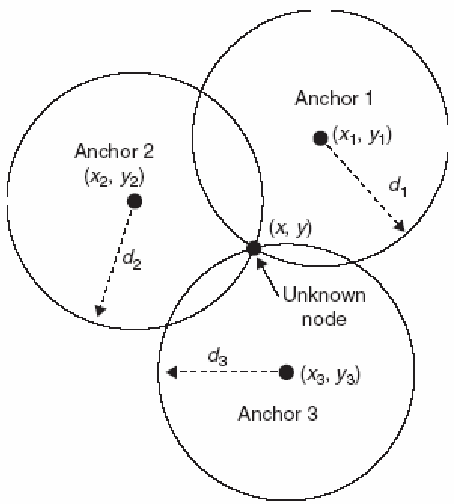
Position Estimation

- **Single-hop**
- **Multi-hop**
- **Range-free**
- **Anchor-free**

Single-hop Localization

Problem statement

Consider the problem of determining the position (x,y) of an unknown node by using distance estimates d_i between the unknown node and a set of N anchor nodes (beacons) placed at known coordinates (x_i, y_i), with i 1, 2, . . . N . These estimates can be obtained, for example, through ToA or RSS measurements.



Multilateration

With ideal distance estimate the intersection of the circles corresponds to the position of the target node.

$$\begin{cases} (x_1 - x)^2 + (y_1 - y)^2 = \hat{d}_1^2 \\ \qquad \vdots \\ (x_N - x)^2 + (y_N - y)^2 = \hat{d}_N^2 \, . \end{cases}$$

The effect of ranging errors

In the presence of distance estimation error we have

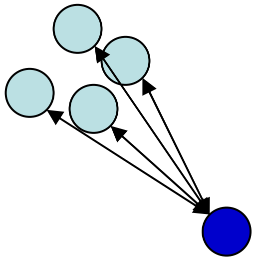
$$\hat{d}_i = d_i + \epsilon_i$$

where ϵ_i represents the estimation error.

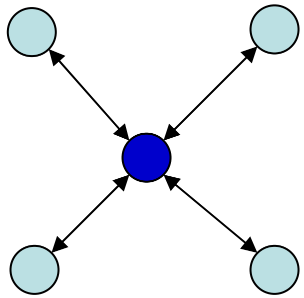
The estimation error is usually modeled as a Gaussian r.v. with standard deviation function of the true distance *d*

$$\sigma^2 = \sigma_0^2 \cdot d^\alpha$$

The effect of ranging errors



(?) worse than



The localization accuracy is influenced by:

- The geometry of the beacons with respect to the target
- The quality of the range measurements

The position error bound (PEB)

It is the CRB of the position estimation MSE

$$\mathrm{PEB} = \sqrt{\frac{\sum_{i=1}^{n_\mathrm{B}} A_i}{\left(\sum_{i=1}^{n_\mathrm{B}} A_i c_i^2\right)\left(\sum_{i=1}^{n_\mathrm{B}} A_i s_i^2\right) - \left(\sum_{i=1}^{n_\mathrm{B}} A_i c_i s_i\right)^2}}$$

with $A_i = A(\boldsymbol{\beta}^{(i)}, d_i)$, $c_i = \cos\theta_i$, and $s_i = \sin\theta_i$

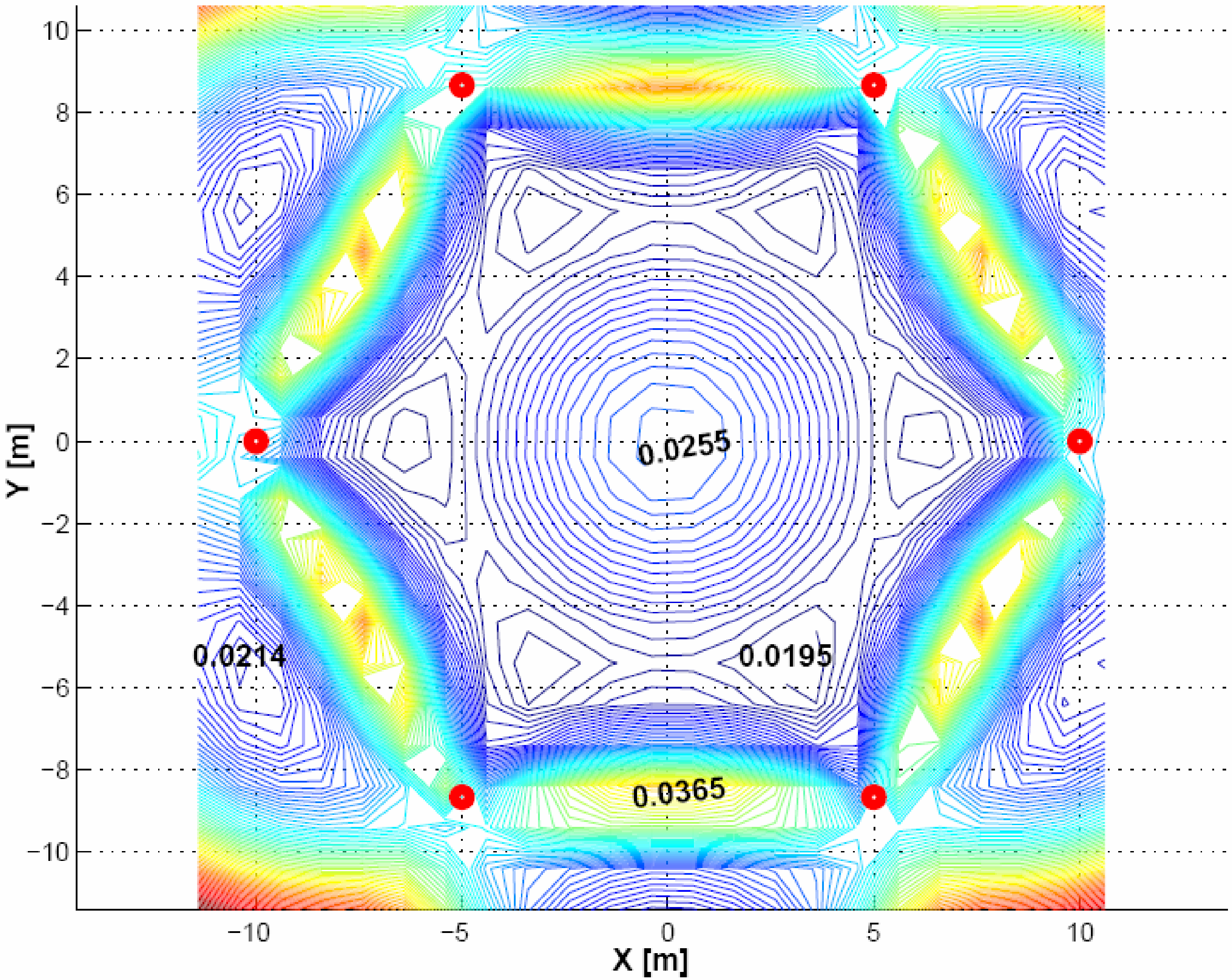
Quality of the measurement

Sensor geometry

It is a generalization of the geometric dilution of precision (GDOP).

D. Jourdan, D. Dardari, and M. Z. Win, "Position error bound for UWB localization in dense cluttered environments," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 44, no. 2, pp. 1–16, Apr. 2008.

Example



Contour map of PEB when 6 LOS beacons are placed at the vertices of a polygon with $d = 10m$

Practical position estimators

The target position estimate can be obtained using the ML approach, which is asymptotically efficient (i.e., for large SNR approaches the CRB).

Unfortunately, its solution poses several problems due to the presence of local maxima in the likelihood function and the need for good ranging error statistical models.

Sub-optimal estimators

A simple linear least square (LS) position estimator

$$\begin{cases} (x_1 - x)^2 + (y_1 - y)^2 = \hat{d}_1^2 \\ \quad\vdots \\ (x_N - x)^2 + (y_N - y)^2 = \hat{d}_N^2 \,. \end{cases}$$

the system of equations can be linearized by subtracting the last equation from the first N-1 equations which creates a proper system of linear equations

$$\mathbf{A} \cdot \mathbf{p} = \mathbf{b}\,, \qquad \mathbf{p} = [x\,y]^T$$

Using the linear LS method:

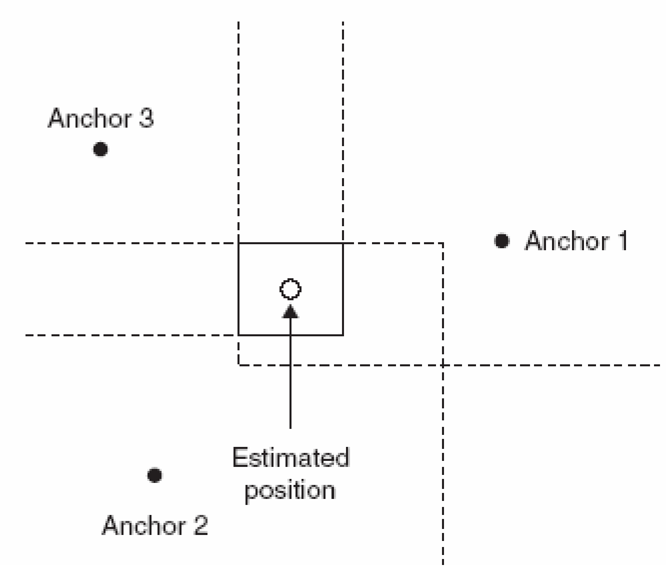
$$\boxed{\hat{\mathbf{p}}^{(\mathrm{LS})} = (\mathbf{A}^T\,\mathbf{A})^{-1}\mathbf{A}^T\,\mathbf{b}\,,}$$

$$\mathbf{A} \triangleq \begin{bmatrix} 2(x_1 - x_N) & 2(y_1 - y_N) \\ \vdots & \vdots \\ 2(x_{N-1} - x_N) & 2(y_{N-1} - y_N) \end{bmatrix} \qquad \mathbf{b} \triangleq \begin{bmatrix} x_1^2 - x_N^2 + y_1^2 - y_N^2 + \hat{d}_N^2 - \hat{d}_1^2 \\ \vdots \\ x_{N-1}^2 - x_N^2 + y_{N-1}^2 - y_N^2 + \hat{d}_N^2 - \hat{d}_{N-1}^2 \end{bmatrix}.$$

- Some performance loss is present
- Particular attention has to be paid in selecting the anchor node associated to the last equation
- Matrix inversion is required.

A low complexity estimator: Min-Max

A much simpler method, presented as a part of the *N*-hop multi-lateration algorithm by *Savvides et al. (2002)* is *Min-Max* .
The idea is to construct a bounding box starting from each known position (*xi,yi*) and distance measurement *di*. (approximates beacon ranges to squares)

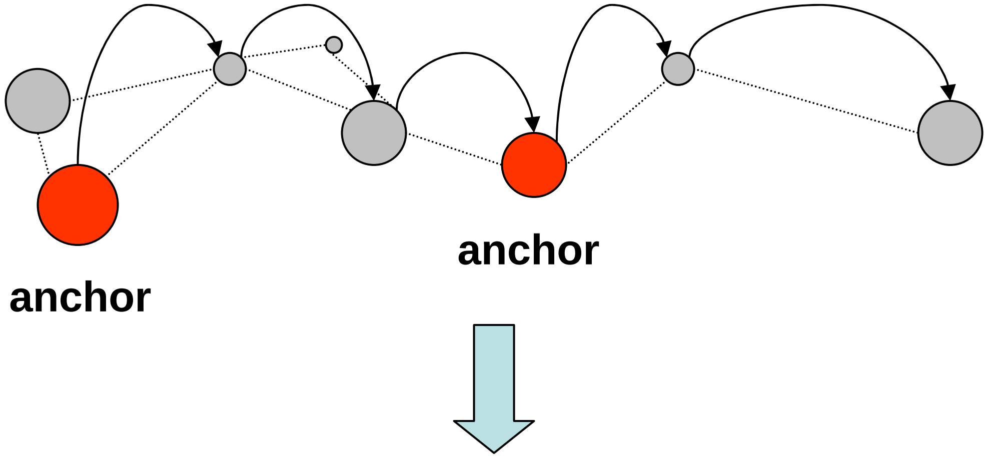


The estimated position is obtained as the centre of the intersection of these bounding boxes computed by taking the maximum of all coordinate minimums and the minimum of all maximums:

$$[\max_i(x_i - d_i), \max_i(y_i - d_i)] \times [\min_i(x_i + d_i), \min_i(y_i + d_i)]$$

Multi-hop localization

In many cases a node has to estimate its position without a direct interaction with anchor nodes and a cooperation between nodes is needed in a multi-hop fashion



Design of anchor-based distributed and cooperative localization algorithms that can cope with unreliable range measurements

Multi-hop localization

Most of multi-hop cooperative algorithms have a common 3-phase structure

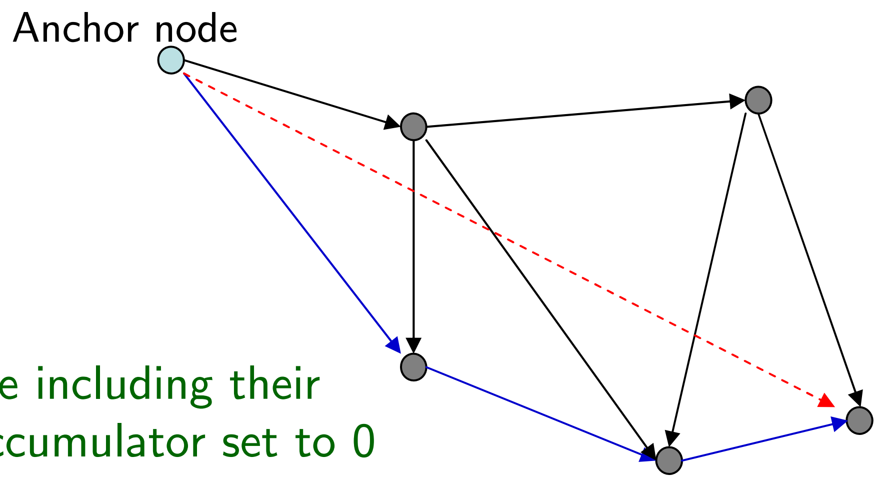
•*Phase 1* Determine the distances between unknowns and anchor nodes.

•*Phase 2* Derive for each node a position from its anchor distances (using, for example, multilateration or Min-Max algorithms).

•*Phase 3* Refine the node positions using information about the distance to, and positions of, neighbouring nodes.

N-Hop multilateration (Savvides, 2002)

The distance to the anchors is simply determined by adding the ranges encountered at each hop during the network flood.



- The anchors send a beacon message including their identity, position and path length accumulator set to 0
- Each receiving node adds the measured range from the previous node to the path length field and broadcasts the new message to the other nodes
- If multiple messages about the same anchor are received, the node keeps and forwards only the one containing the minimum value of path length.

A. Savvides, H. Park, M. Srivastava, *The bits and flops of the n-hop multilateration primitive for node localization problems*, First ACM Workshop on Wireless Sensor Networks and Application (WSNA), pp112-121, Atlanta GA, September 2002.

N-Hop multilateration

- Fully distributed algorithm
- Low complexity
- Range errors accumulate over multiple hops
- The cumulative error becomes significant in the presence of large networks with few anchors or poor ranging hardware

DV-hop multilateration (Niculescu & Nath, 2001)

The DV-hop algorithm is similar to the N-hop multilateration.

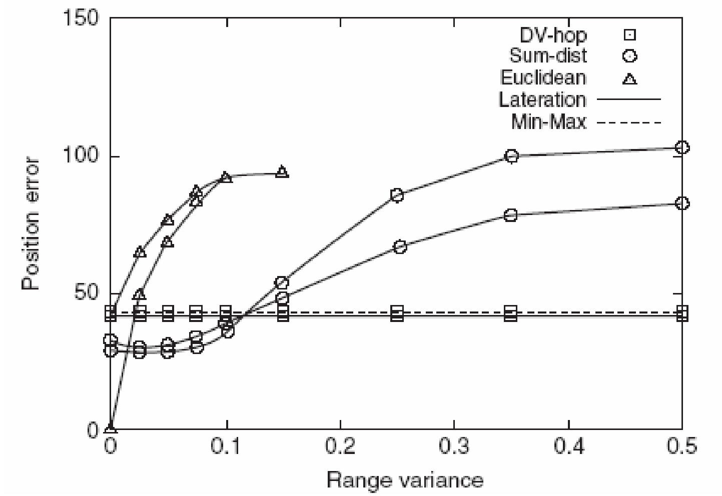
Here, the distance information is expressed in terms of number of hops to every anchor node.

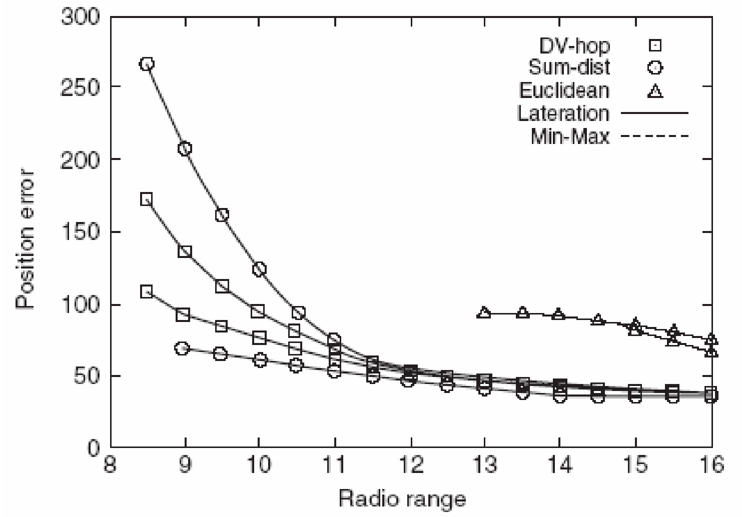
To enable the conversion from number of hops and physical distance, anchor nodes evaluate the average single-hop distance, *dhop*, starting from the hop count information and known position of all other anchors inside the network

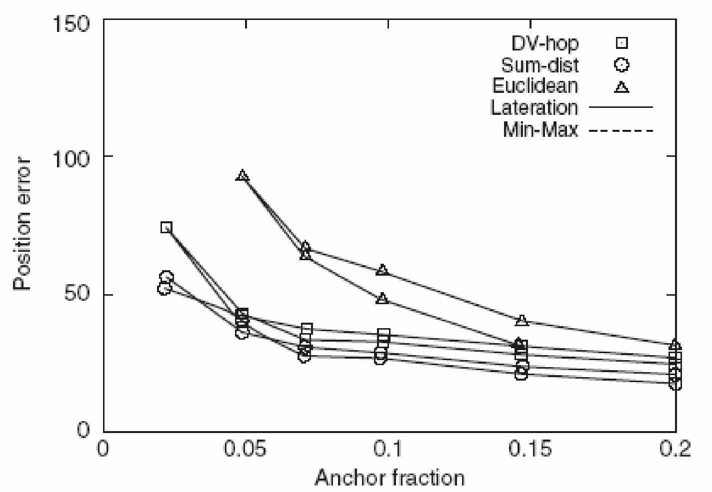
$$d_{\text{hop}_i} = \frac{\sum_j \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\sum_j h_{i,j}}$$

where (x_j, y_j) and $h_{i,j}$ are, respectively, the position of the jth anchor node and the distance, in hops, from anchor i to anchor j.

Performance comparison







From: Langendoen & Reijers, 2003

Best algorithm depends on:

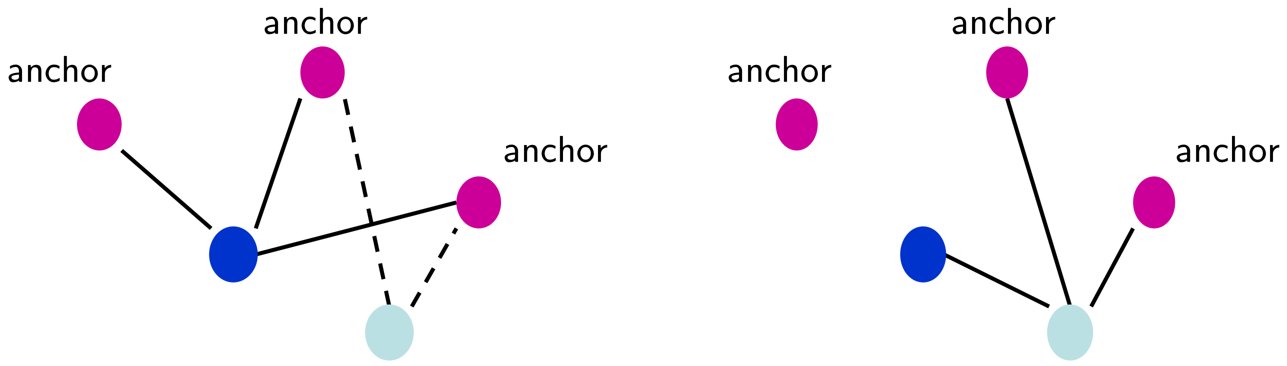
- error in range measurement (range variance)
- connectivity
- network topology
- node capabilities

For example, DV-hop good for very bad or none range measurements

Iterative distributed localization

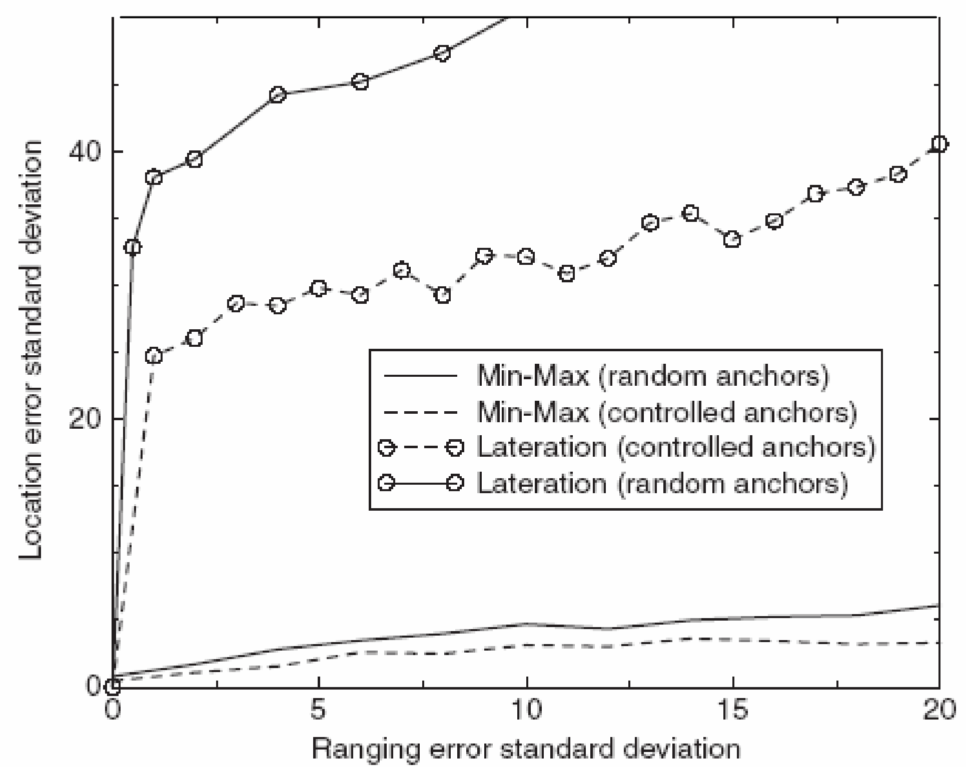
Nodes surrounding anchor nodes cooperatively establish position estimates that are successively propagated to more distant nodes, allowing them to estimate their position without direct anchor node visibility *(Savarese, Rabaey & Beutel, 2001).*

At each iteration step, once a node with unknown position (x,y) bears N nodes with known or estimated positions, it would be able to estimate its position starting from the measured distances d_i and known positions (x_i,y_i) if N 3.



Step *n* Step *n+1*

Performance

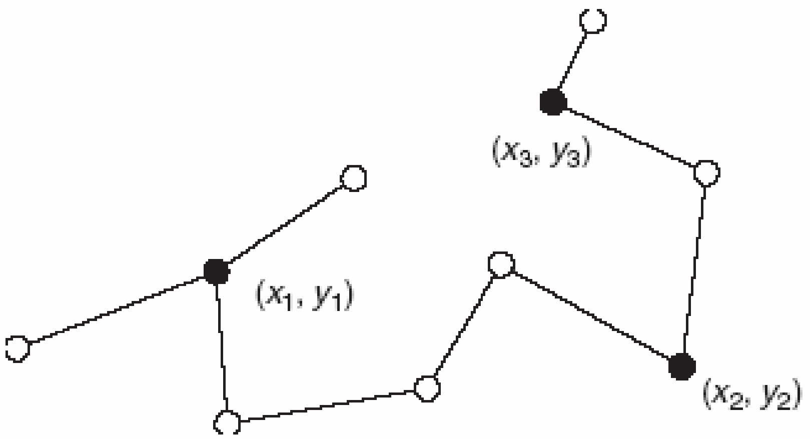


- Multi-lateration gives the better precision only if the range measurement is very accurate
- Anchor placement affects the performance

Range-free localization (1/2)

Problem statement

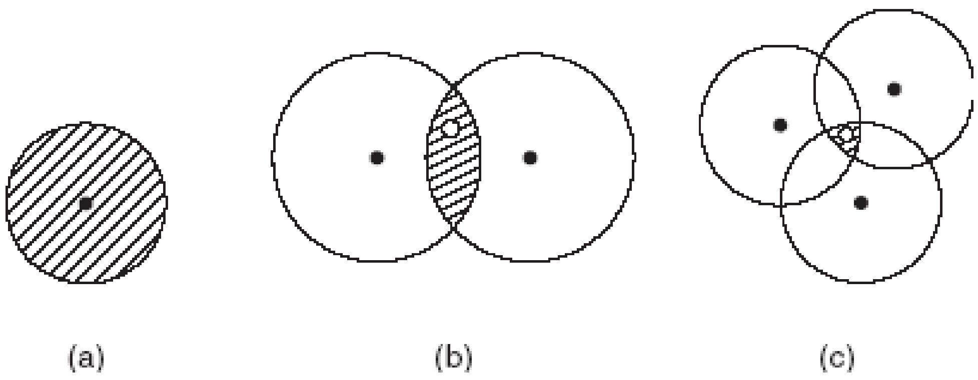
m anchor nodes are present with coordinates **b**= $(x_1, y_1, x_2, y_2, \ldots, x_m, y_m)$ and the positions **x**=$(x_{m+1}, y_{m+1}, \ldots\ldots, x_n, y_n)$ of the remainder *n*-*m* nodes are unknown. The problem is to find **x** such that the proximity constraints are satisfied.



The radio connectivity model, which considers a circle with a fixed radius r_0, is the simplest way to model the proximity constraint.

Range-free localization (2/2)

As the number of constraints increases, the feasible region of solutions for x, given by the intersection of individual constraints, becomes smaller.



The work in *Doherty, Pister & Ghaoui, 2001* presents a centralized methodology to solve this problem as a linear or semi-definite program. It is shown that the position estimation error can be dramatically reduced as the network connectivity increases.

Note that the DV-hop scheme is actually a range-free positioning algorithm since distance estimation between unknown and anchor nodes is performed by hop counting.

Anchor-free localization (1/2)

Problem statement

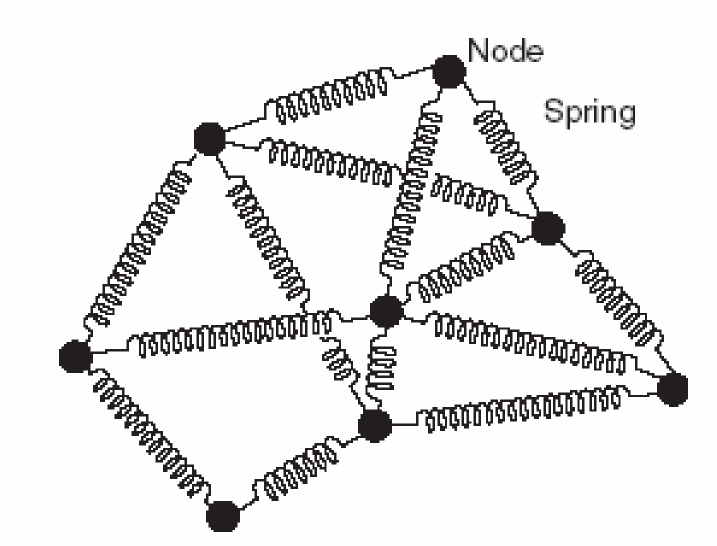
given a set of nodes with unknown position and range measurements among neighbours' nodes, determine the (relative) position coordinates of every node in the network.

⇓

NP-hard problem
Distributed algorithms are appreciated

Anchor-free localization (2/2)

Anchor-free localization is analogous to find the resting point of masses (representing the nodes) connected by springs (with length proportional to distance measurements) *(Patwari, Ash, Kyperountas, Hero, Moses & Correal, 2005).* Springs exert forces on the nodes which move until stabilization.

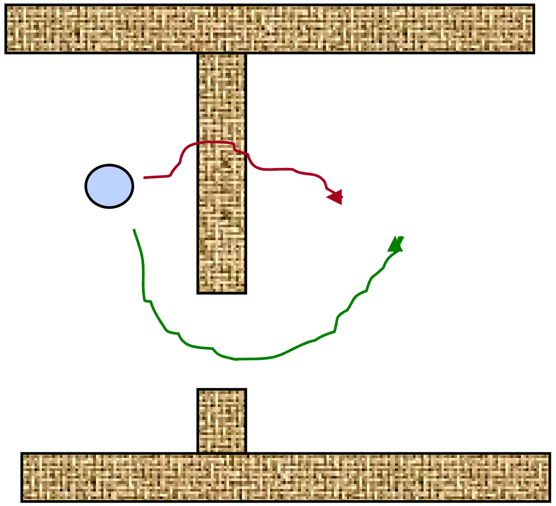


The equilibrium point of masses represents a minimum-energy localization estimate.

Position tracking

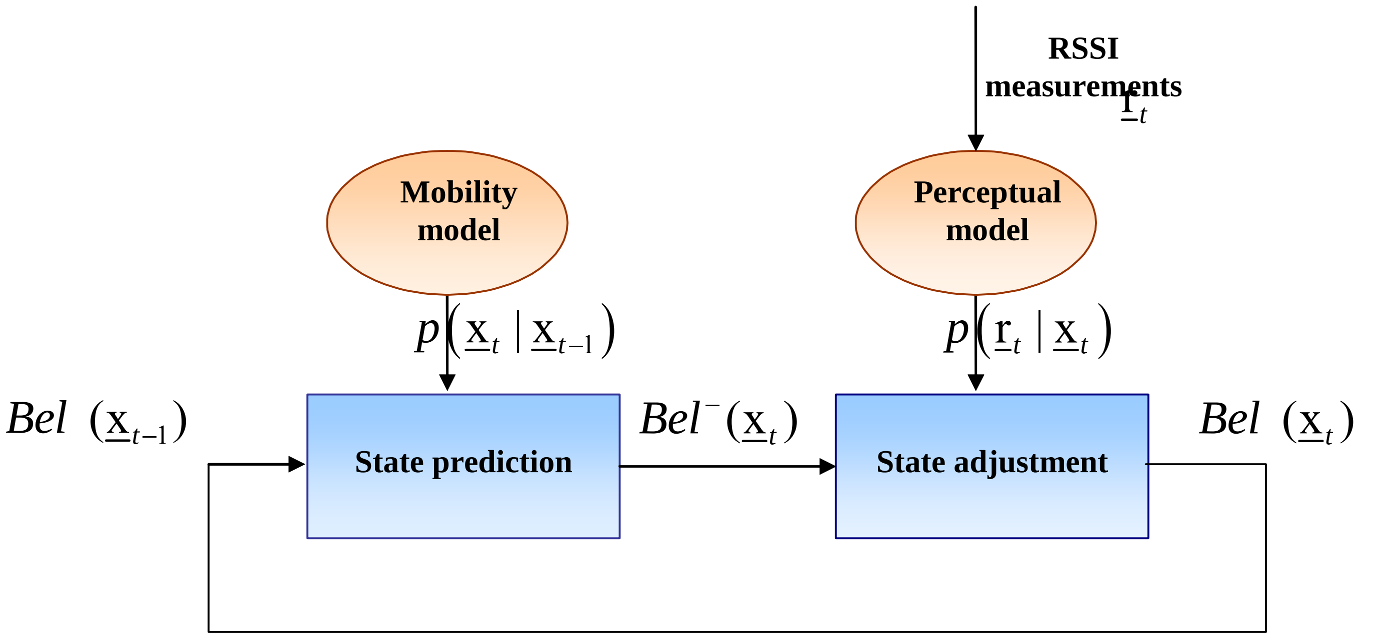
Position tracking

Given the actual and previous estimated positions, besides forbidden location configurations (e.g., inside buildings), there are also forbidden time configurations, for example the node cannot suddenly move from one room to another one.



Position tracking algorithms, in addition to range measurements, take into account the system memory as well as a node mobility model to achieve better position estimation accuracy.

Example: Bayesian Filters



$$Bel(\underline{x}_t) = p(\underline{x}_t \mid \underline{r}_1, \underline{r}_2, \ldots, \underline{r}_t)$$

Posteriori prob. density conditioned on all sensor data available at time *t*

Filter update equations

$$Bel^{-}(\underline{x}_t) = \sum_{\underline{x}_{t-1}} p(\underline{x}_t \mid \underline{x}_{t-1}) Bel(\underline{x}_{t-1})$$

$$Bel(\underline{x}_t) = \frac{p(\underline{r}_t \mid \underline{x}_t)}{p(\underline{r}_t)} Bel^{-}(\underline{x}_t)$$

$$\underline{x}_t = (x_t, y_t)$$

System state (target position) at time *t*

Case studies

Case studies

Case study 1

UWB-based indoor localization platform

Purposes:

- to test techniques to mitigate the extra delay propagation effects
- to test cooperative algorithms

D. Dardari, A. Conti, J. Lien, and M. Z. Win, "The effect of cooperation in UWB based positioning systems using experimental data," *EURASIP Journal on Advances in Signal Processing, Special Issue on Cooperative Localization in Wireless Ad Hoc and Sensor Networks*, 2008.

Case study 2

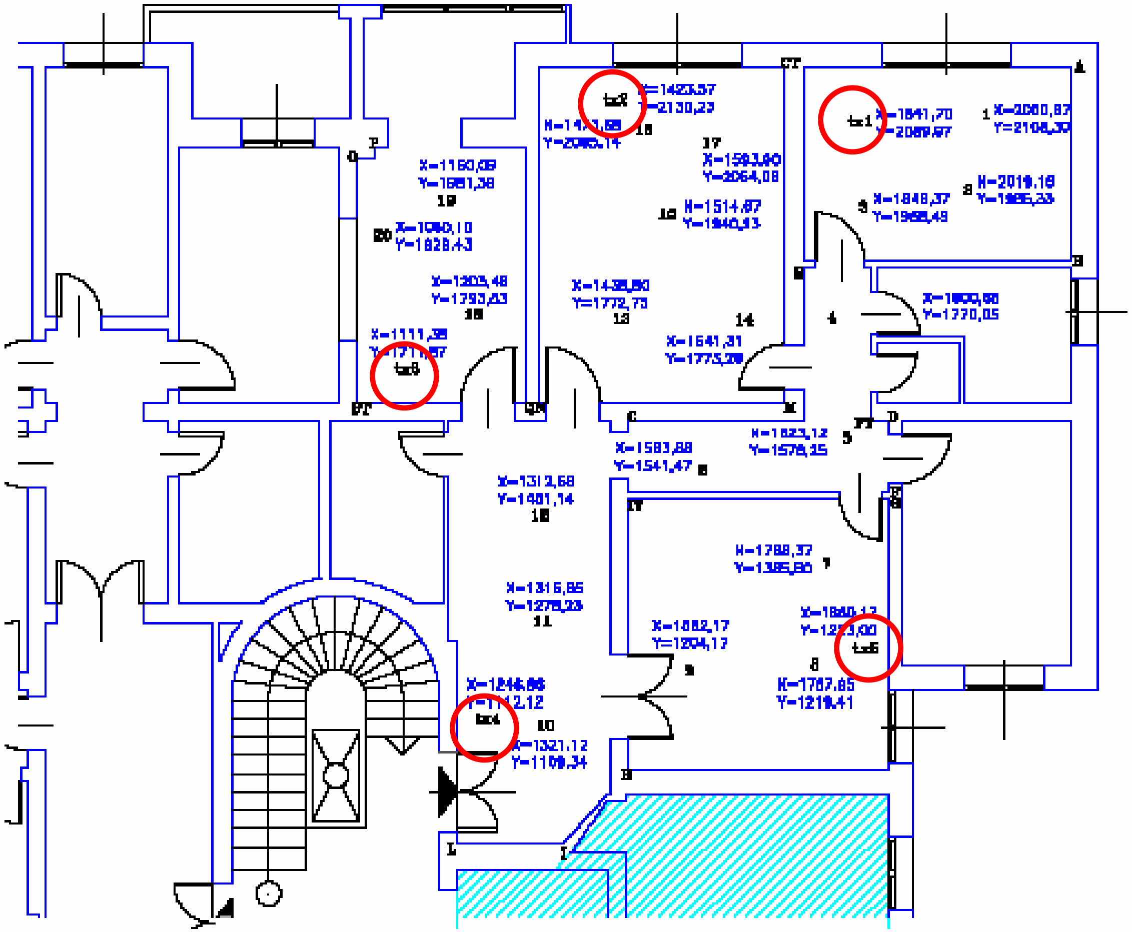
WSN-based indoor localization platform (VICOM Project)

Purposes:

- to test different RSS-based positioning and tracking techniques
- to test advanced context aware applications

T. Pavani, G. Costa, M. Mazzotti, D. Dardari, and A. Conti, "Experimental results on indoor localization technique through wireless sensors network," in *Proc. IEEE Vehicular Tech. Conf. (VTC 2006-Spring)*, (Melbourne, AUSTRALIA), May 2006.

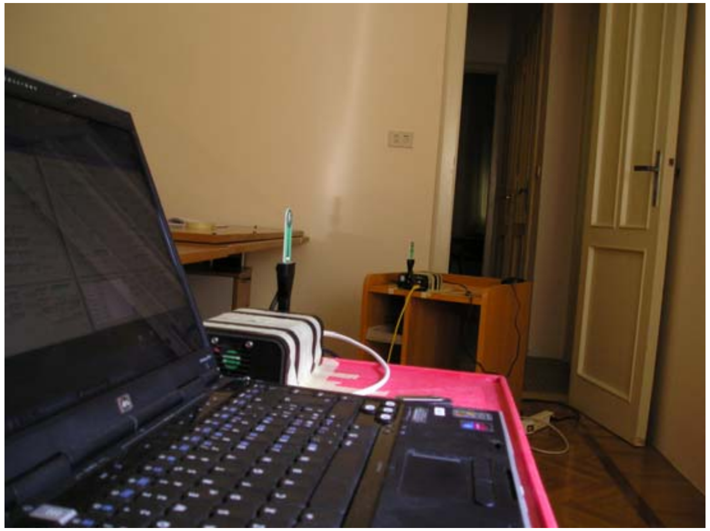
Case study 1: the scenario considered

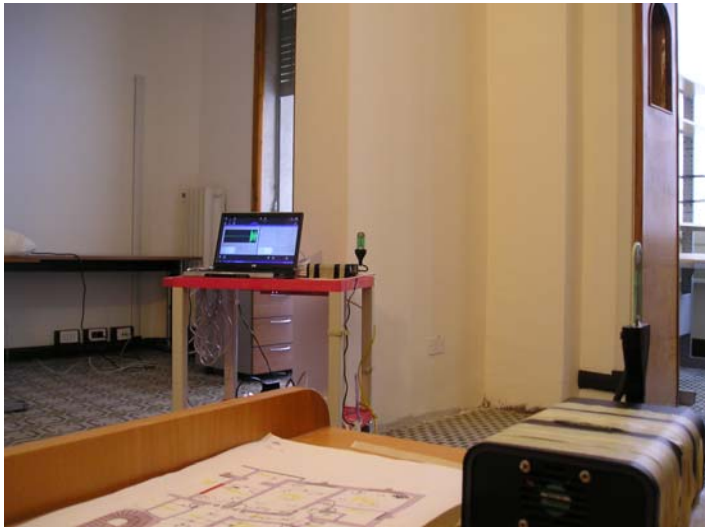


The measurement environment at the WiLAB, University of Bologna, Italy. Coordinates are expressed in centimeters

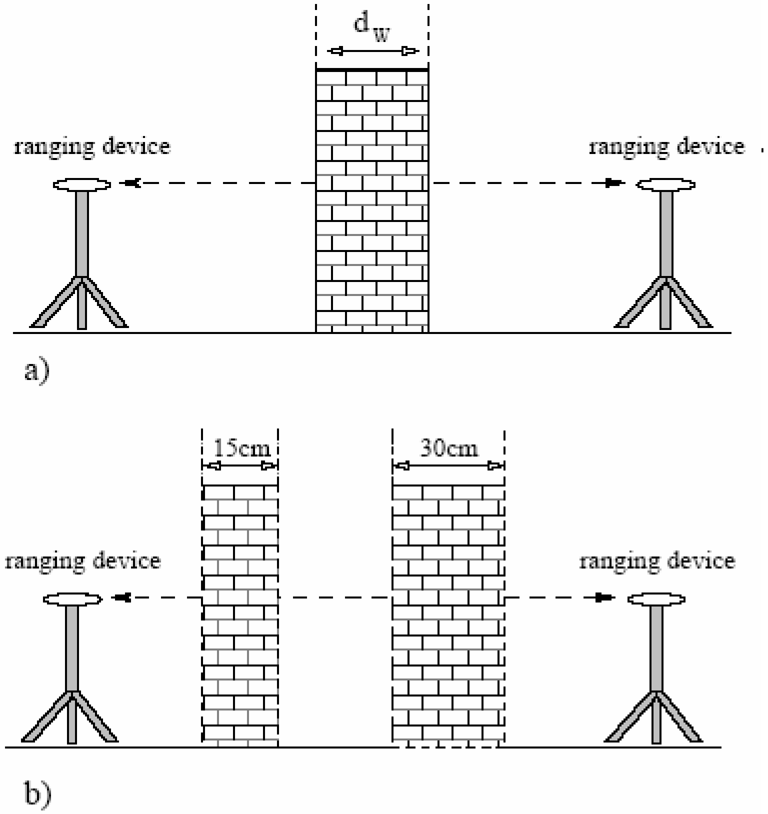
The UWB ranging equipment

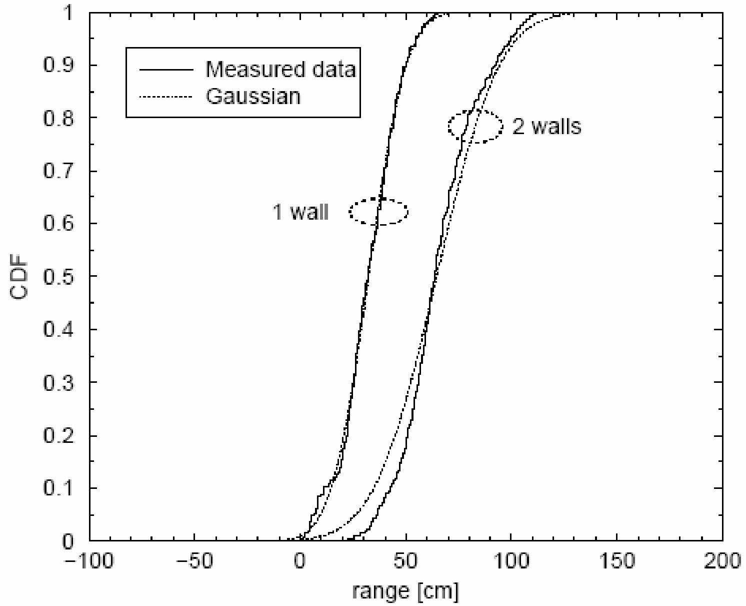
- $N = 5$ fixed UWB beacons (tx1-5) was deployed to localize one or more UWB targets.
- Each ranging device, placed 88 cm above the ground, consisted of one Time-Domain PulseOn 210 UWB radio operating in the 3.2-7.4 GHz 10dB RF bandwidth.
- These commercial radios are equipped to perform ranging by estimating the ToA of the first path using a thresholding technique
- A grid of 20 possible target positions (numbered 1-20) defined the points from which range (distance) measurements were taken at 76 cm height. For each target position, 1, 500 range measurements were collected from each beacon.





Extra delay propagation characterization (1/2)





Layout, d_W [cm]	mean bias [cm]	std dev [cm]
1 wall, 15.5	16.4	3.7
1 wall, 30	29.5	3.2
2 walls, 15.5+30	45.2	3

D. Dardari, A. Conti, J. Lien, and M. Z. Win, "The effect of cooperation in UWB based positioning systems using experimental data," *EURASIP Journal on Advances in Signal Processing, Special Issue on Cooperative Localization in Wireless Ad Hoc and Sensor Networks*, 2008.

Extra delay propagation characterization (2/2)

Wall Extra Delay (WED) model

$$b_i = E_i \cdot c$$

$$E_i = \sum_{k=1}^{N_e^{(i)}} W_k^{(i)} \cdot \Delta_k \, ,$$

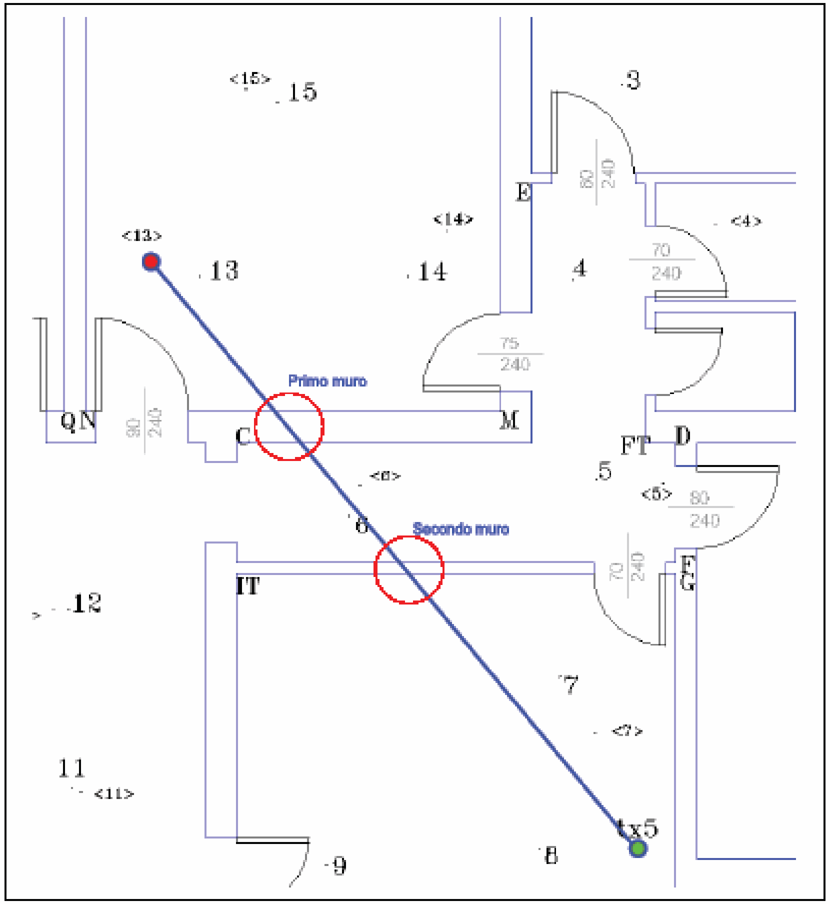
- E_i is the total time delay caused by NLOS conditions
- W_k is the number of walls introducing the same extra delay value Δ_k (i.e. the number of walls of the same material and thickness)
- N_e is the number of different extra delay values.

It can be adopted to correct range measurements once the environment layout is known

Extra propagation delay mitigation

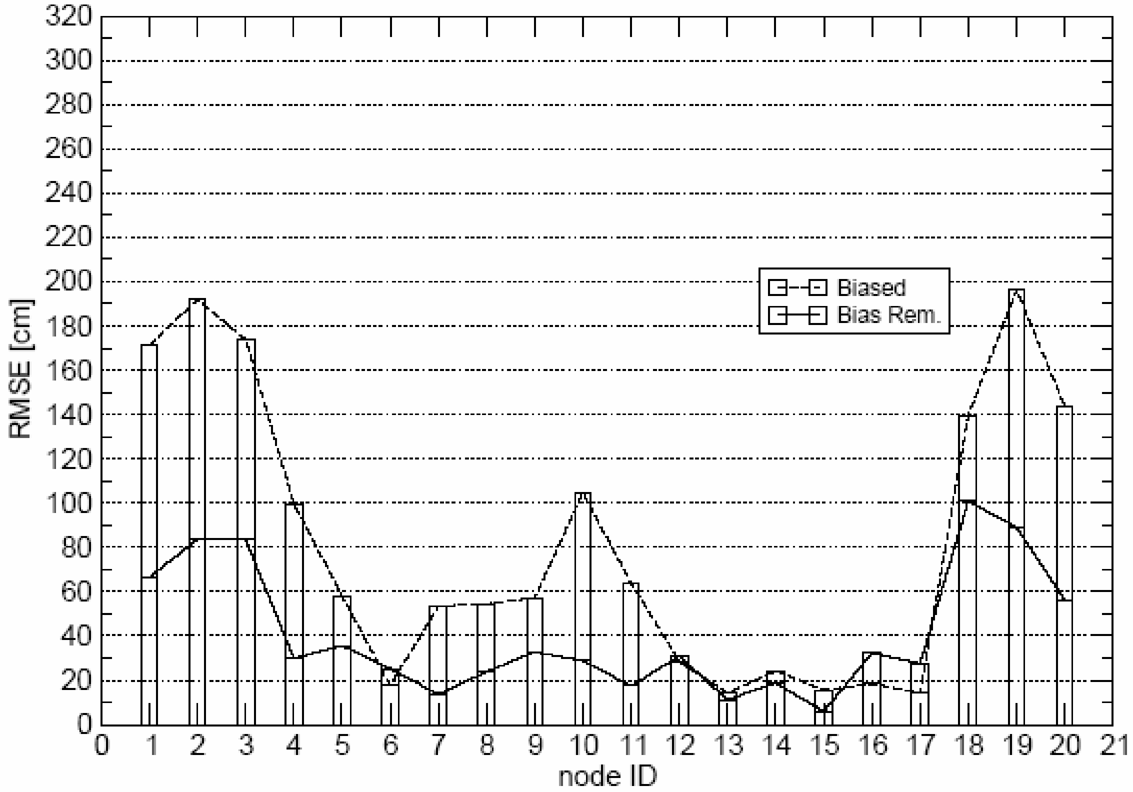
- LS positioning algorithm with 5 beacons

- A two-step LS positioning algorithm incorporating the WED model is introduced to correct the range measurements in NLOS conditions when the layout of the environment is known.



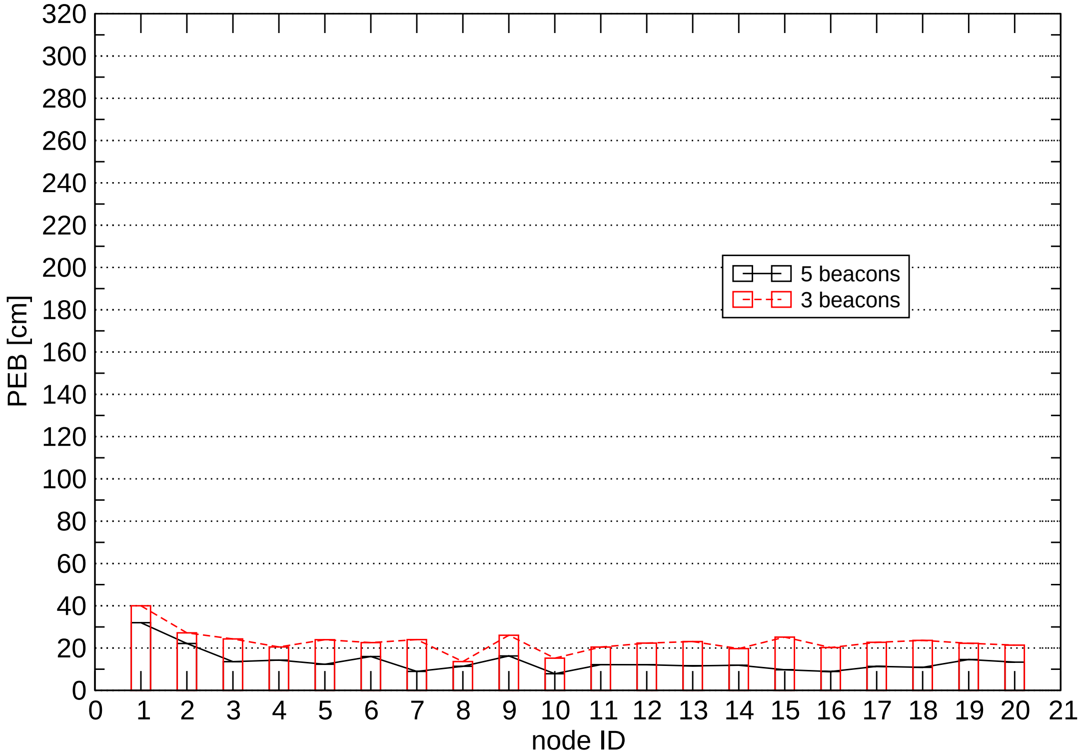
D. Dardari, A. Conti, J. Lien, and M. Z. Win, "The effect of cooperation in UWB based positioning systems using experimental data," *EURASIP Journal on Advances in Signal Processing, Special Issue on Cooperative Localization in Wireless Ad Hoc and Sensor Networks*, 2008, in publication.

Position estimation RMSE



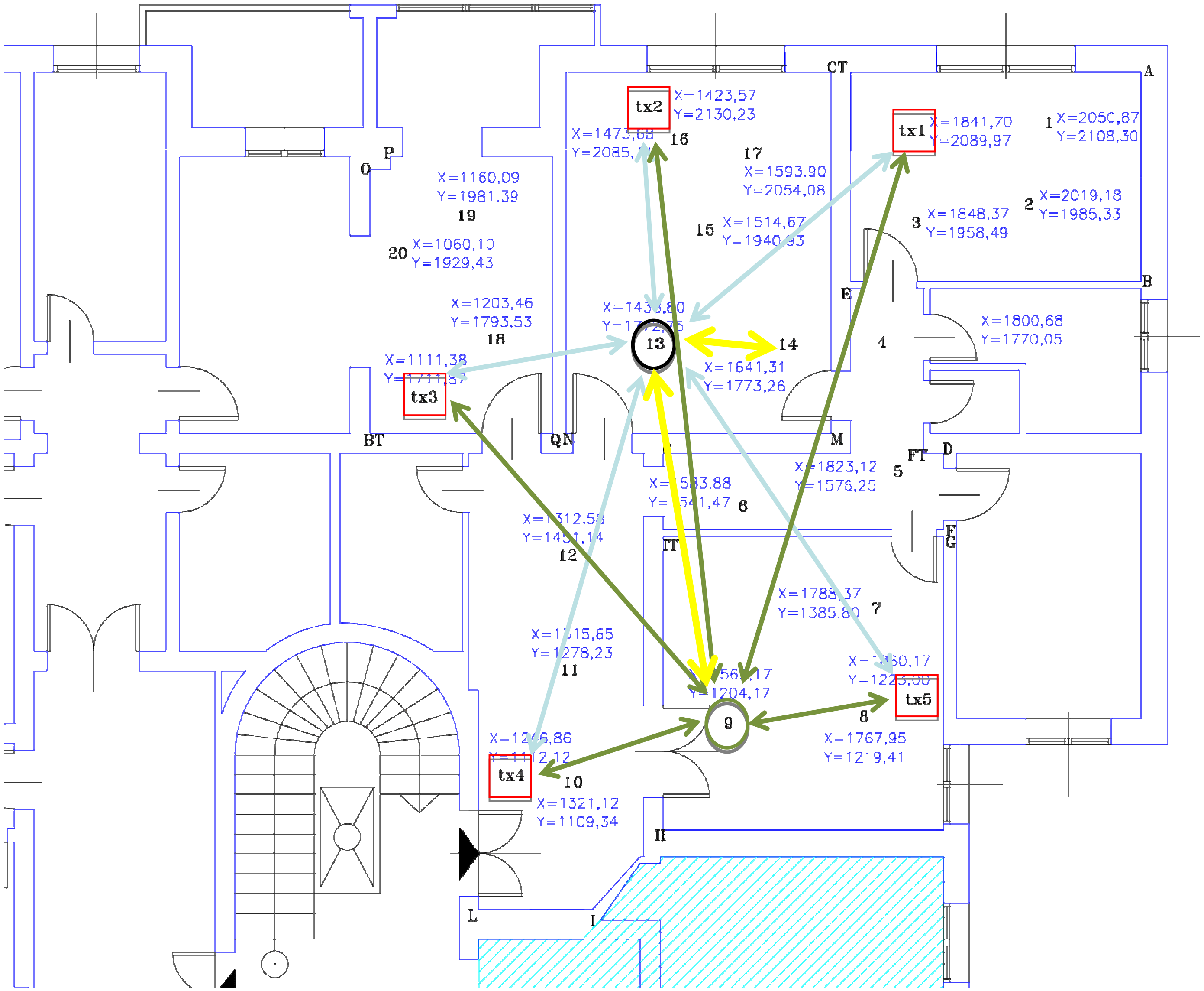
RMSE as a function of target position in the absence and presence of priori information (i.e. with bias and after removing bias, respectively). N = 5 beacons are considered.

Position estimation theoretical bound



PEB as a function of target position with 3 and 5 beacons

Set up for Cooperative Localization



The effect of cooperation

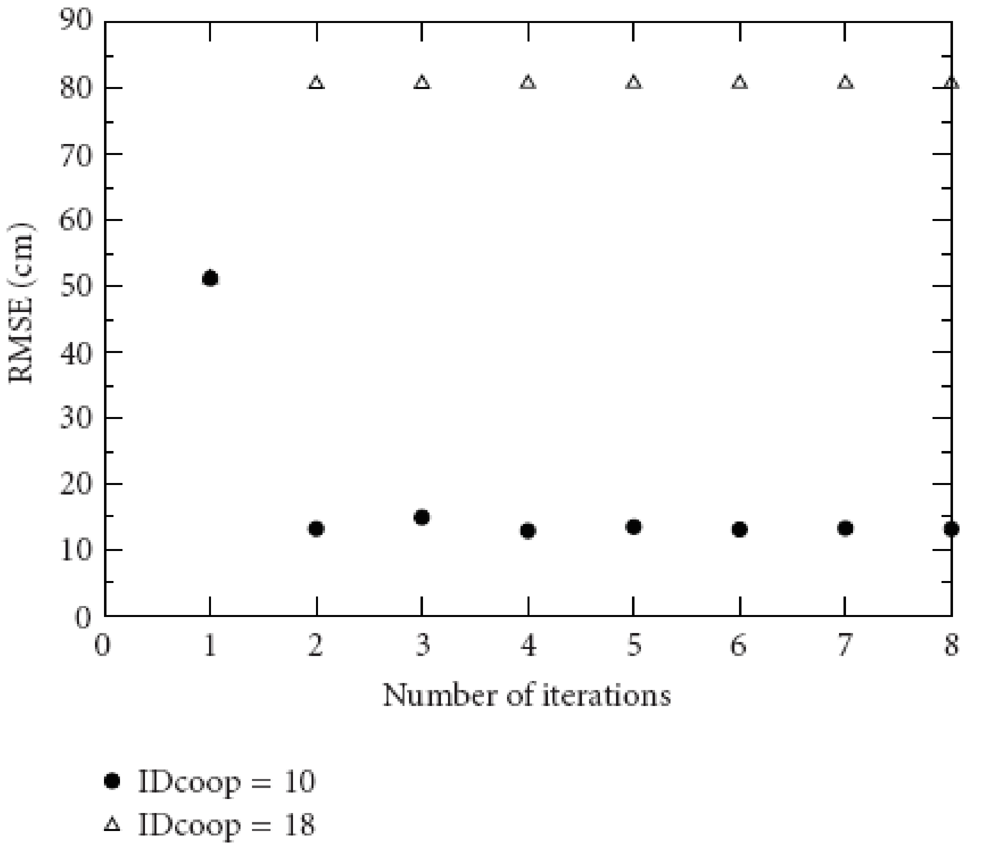


Figure 8: RMSE as a function of number of iterations when target 1, located in position 8, cooperates with target 2, in position 10 or 18. $N = 3$ (tx1,tx3,tx5) beacons are considered. Tx5 is taken as reference for the LS algorithm.

Case Study 2: WSN-based localization platform

The VICOM Project

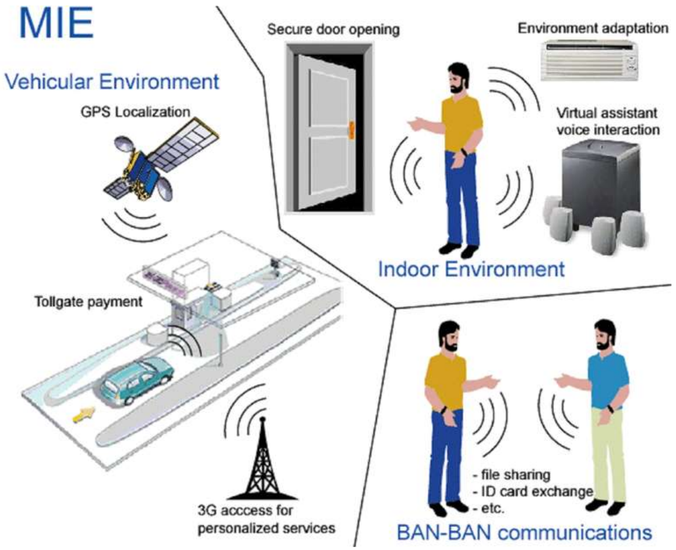
Virtual

Virtual Immersive Communication (VICOM) is an Italian FIRB project, funded by the MIUR (about 12MEuro), started in November 2002 and ended in 2006. Project partners include 16 Italian universities.

-Basic research
-Applied research using current technology (two demonstrators developed)

The VICOM Project

The aim of the Virtual Immersive Communications (VICOM) project is to study and develop techniques, protocols and applications for the Virtual Immersive Telepresence (VIT). The realization and the evaluation of two demonstrators is an integral part of the project.

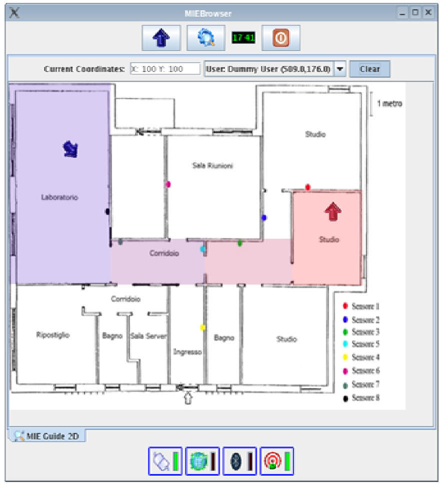


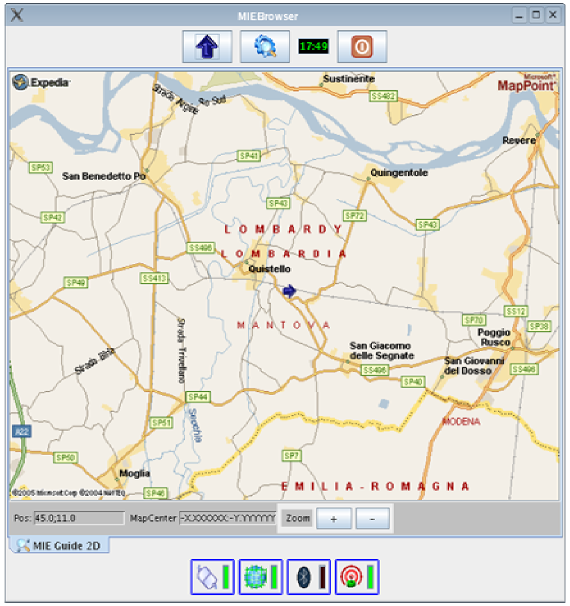
Typical applications of Intelligent Environment try to create an "*intelligent space*" in which the user is "immersed" maximizing the efficiency in performing his tasks.

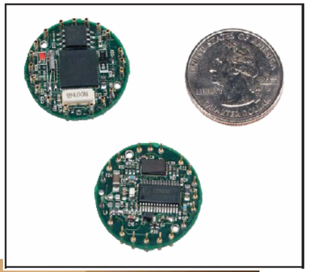
To provide the "immersivity" we assume that the user has a wireless mobile reconfigurable device with virtual assistant functionality ("Digital me").

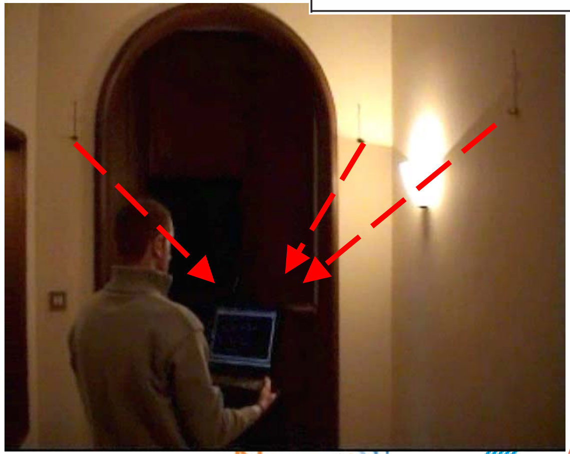
Demonstrator development activity at WiLAB

- Wireless sensor network (WSN) based localization platform set-up
- Localization algorithms design & test
- User applications:
  - 2D multiuser guide
  - Audio/video conference
  - Messaging
  - Ambient server





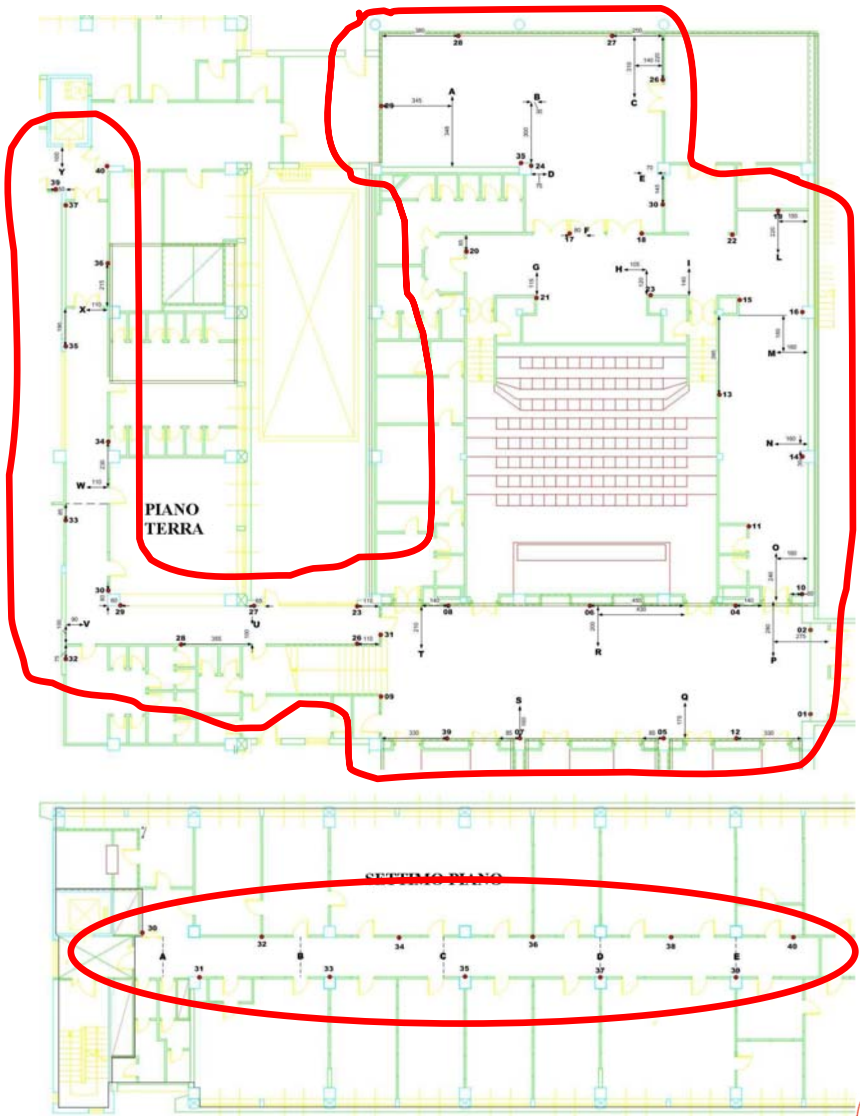




WSN-based localization platform

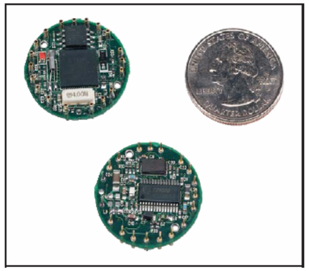
Field trial at Ministero delle Comunicazioni – Roma

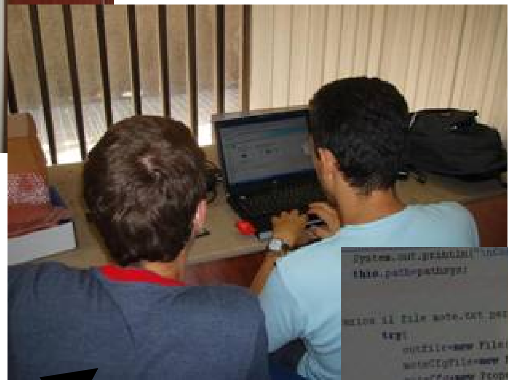
- Planning, deployment and test of sensors (Crossbow Mica2dot)
- Measurement campaign in some test-points:
  - Precise evaluation of the radio channel characteristics
  - Creation of a data-base for future off-line algorithms test and optimization
- Real-time test of the localization algorithms based on RSS measurements

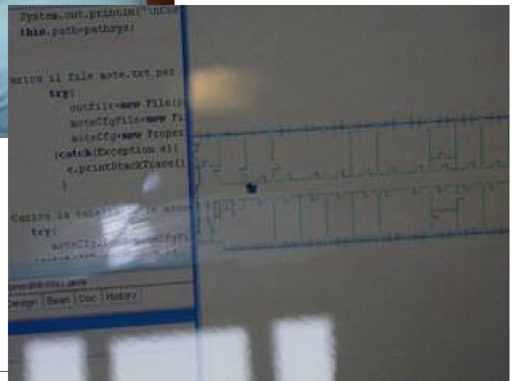


Platform set-up

Anchor nodes deployment

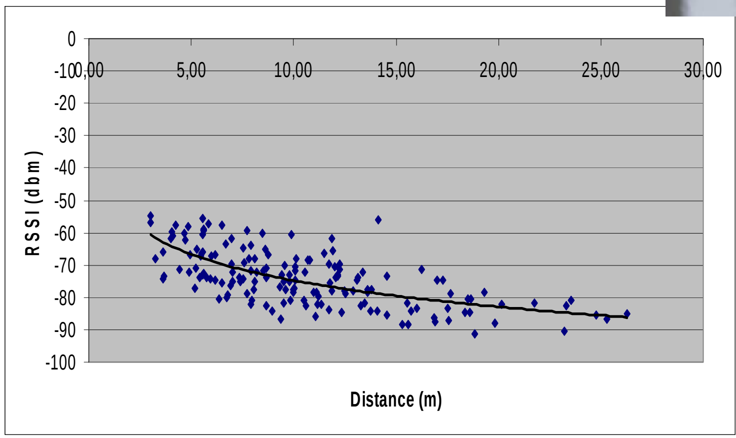


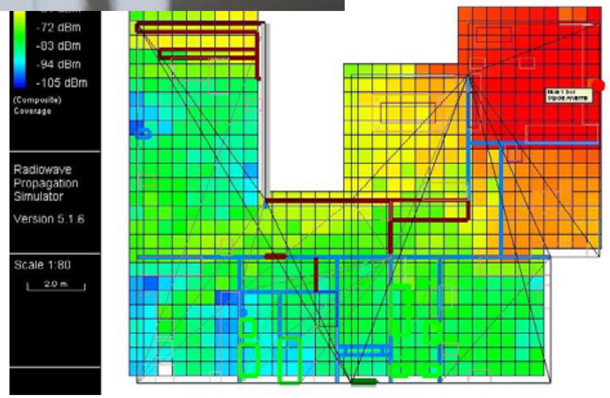




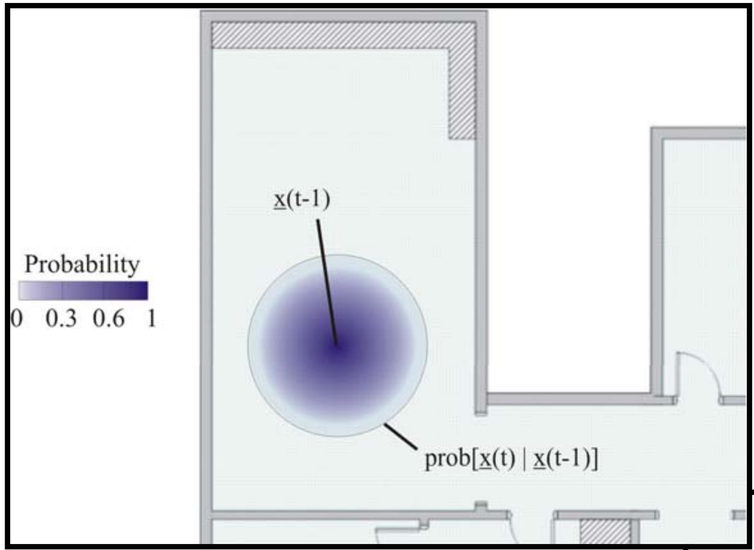
System configuration

Localization test and data collection



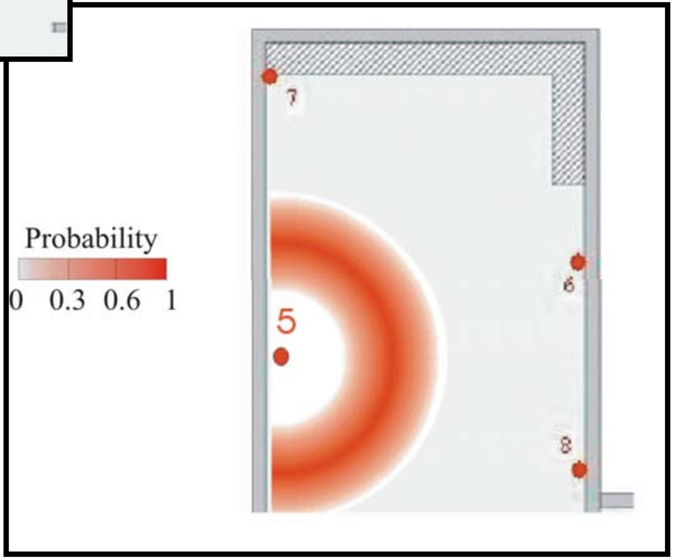


Mobility and perception models

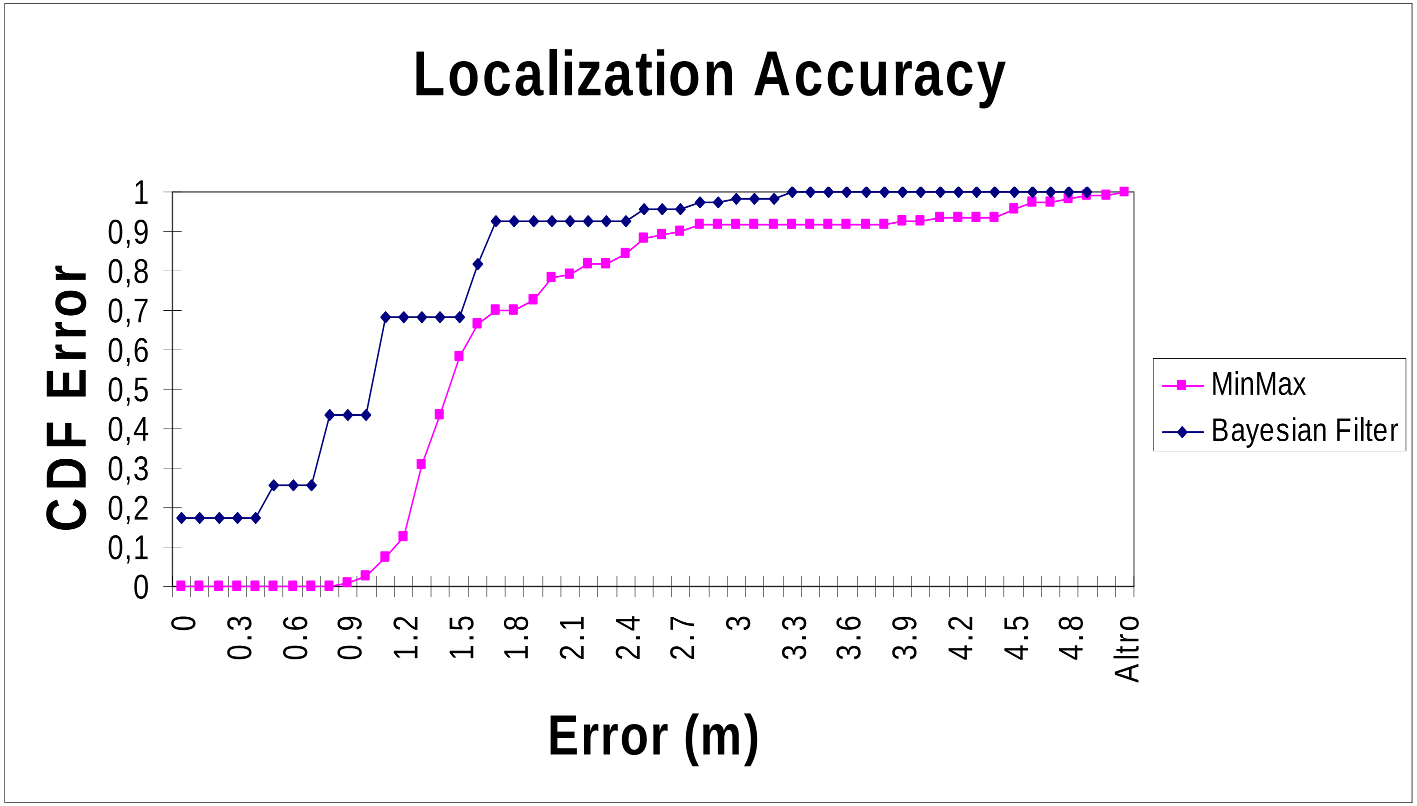


Mobility model

Perception model

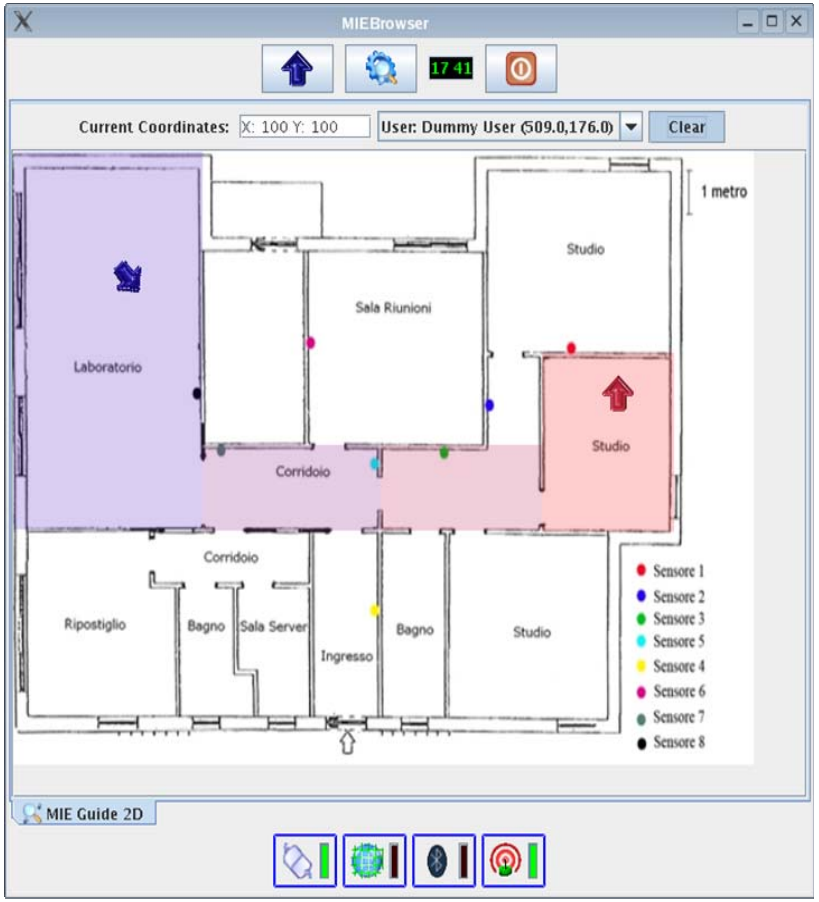


Algorithms comparison: Min-Max vs. Bayesian Filter



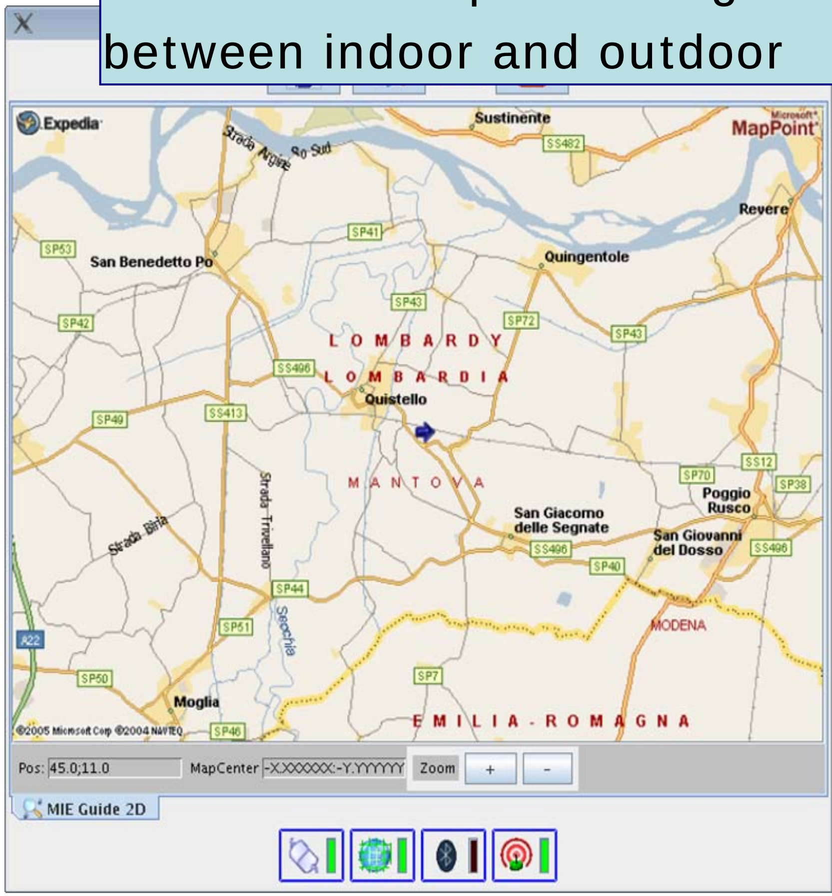
Results: *precision 1-2 meters, accuracy >90% can be achieved*

Example of application developed



Main capabilities:
- multiuser support
- orientation
- pathfinding
- automatic map switching

between indoor and outdoor



Indoor/outdoor multiuser

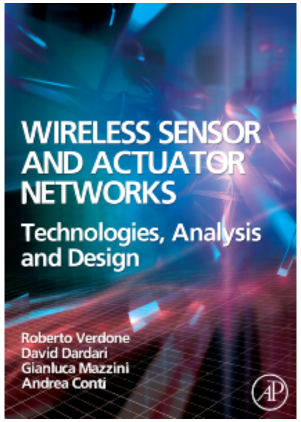
2D guide

Important “hot” topics

- Cooperative localization
- Secure ranging & localization
- Robust ranging
- Cognitive ranging & localization
- Distributed localization algorithms
- Fundamental performance limits of multi-hop and anchor-free positioning in the presence of unreliable measurements
- Definition of reference scenarios
- Interference mitigation
- ....

Some recent books and special issues

R. Verdone, D. Dardari, G. Mazzini, A. Conti
Wireless Sensors and Actuator Networks: Technologies, Analysis and Design, Elsevier, 2008



-EURASIP Journal on Advances in Signal Processing*, Special Issue on Cooperative Localization in Wireless Ad Hoc and Sensor Networks*, 2008.
Guest editors: D. Dardari, D. Jourdan, C-C. Chong, L. Mucchi

- Proc. of IEEE - *Special Issue on UWB Technology & Emerging Applications* -, Summer 2008.
Guest editors: A. Molisch, J. Zhang, M. Win, D. Dardari, W. Weisbeck

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