Ultra-Wideband Beacons for Ranging and Navigation

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Ultra-wideband radio modules (UWB)

Low cost, low power nodes
Precision timing and ranging (around 15 ps resolution ~ 5 mm)

Communication

Ranging

- Digital keys
- Covid distance wearables

Real time locating systems

- Hospitals
- Industry, warehouse
- Mini drones

Tracking devices

- Apple Airtags, Samsung SmartTags+…

UWB Devices: ecosystem

Chip manufacturers

- Qorvo (formerly Decawave): DW1000, DW3000 series
- NXP: Trimension series
- Qualcomm: FastConnect 7900
- Microchip
- Apple: U1, U2 chips
- Samsung

Fira consortium

Positioning systems: RTLS

- Pozyx
- Ubisense
- Intranav
- Zebra
- ...

Qorvo DWM3001C


Posyx (anchor)

Ubisense

Technical details

Radio characteristics

- 500 MHz bandwidth pulses
- Centre frequency: 16 channels
  - 500 MHz (subGHz), 3.1-4.8 GHz (low); 6.0-10.6GHz (high band)
  - Qorvo modules: 6.5 GHZ (ch.5), 8 GHz (ch. 9)

- IEEE 802.15.4 standards

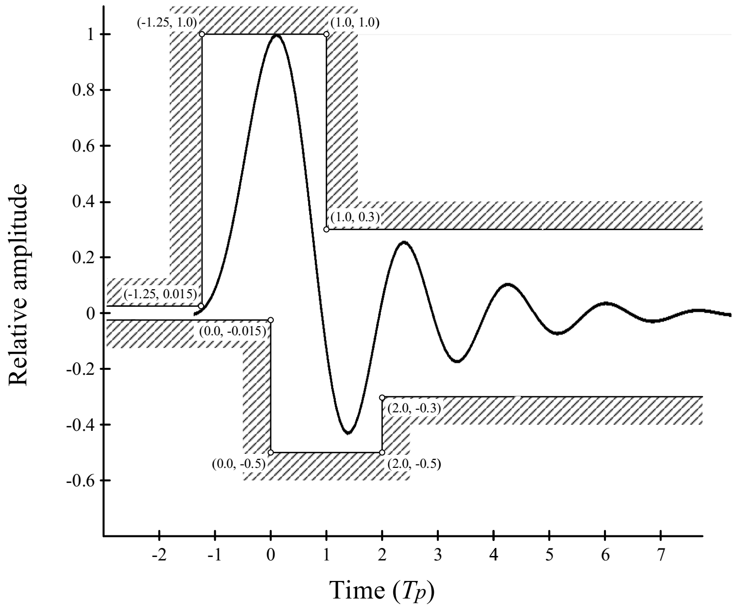


Figure 15-13a—Recommended time domain mask for the HRP UWB PHY pulse

from IEEE 802.15.4z

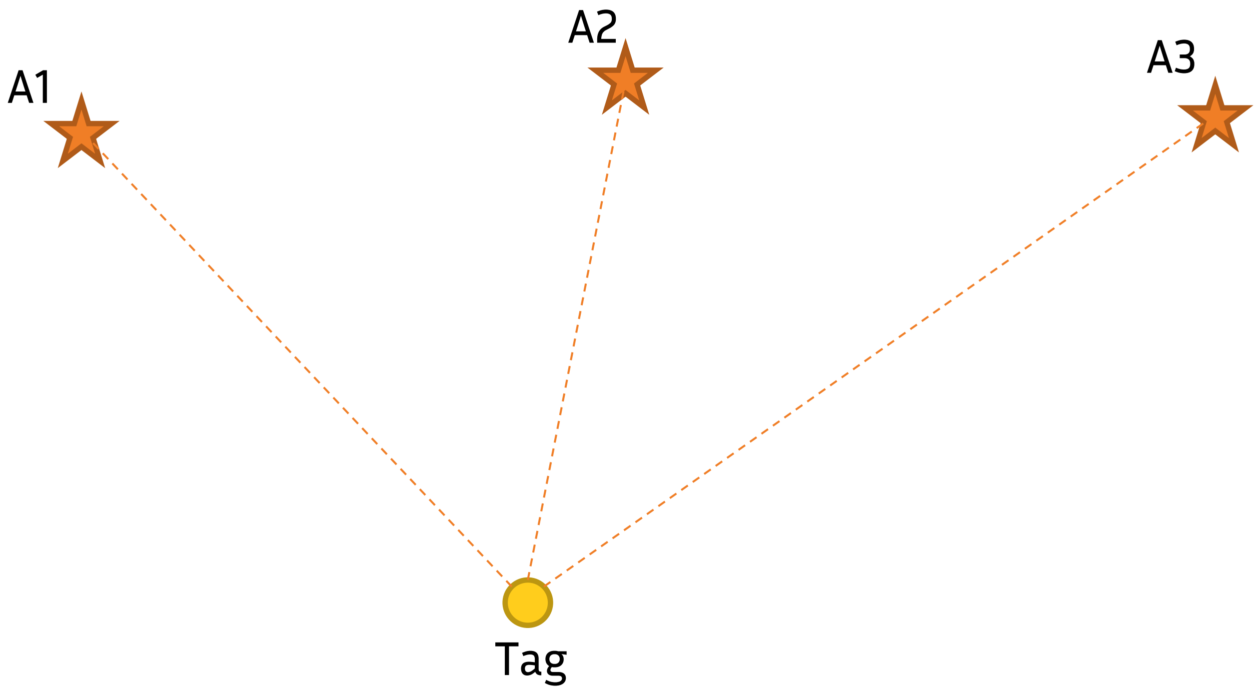
Frames / Packets

SYNC (preamble)	SFD start frame delimiter	PHY Header	PHY Payload

Preamble enables frame detection (by correlation)

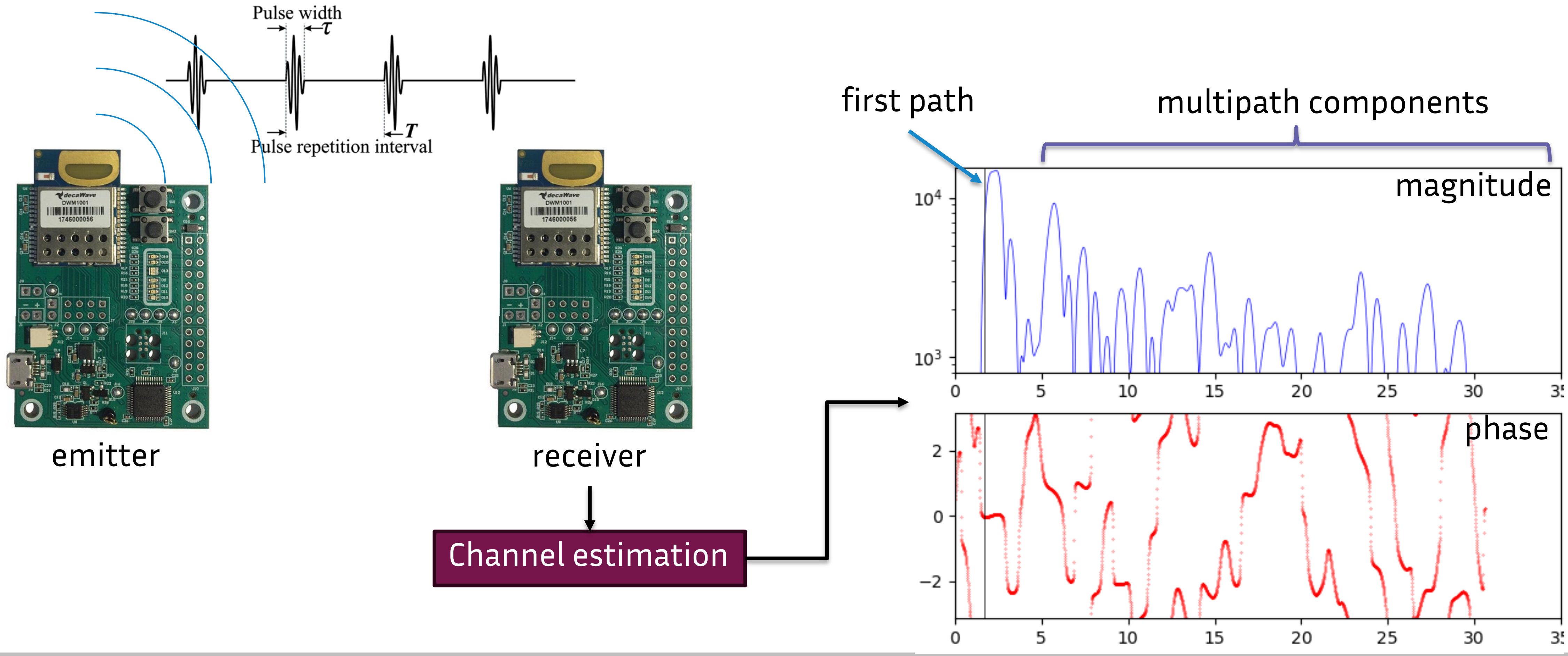
Positioning: Realtime locating system

- **Anchors**: fixed nodes, known position
- **Tags**: mobile nodes to be located



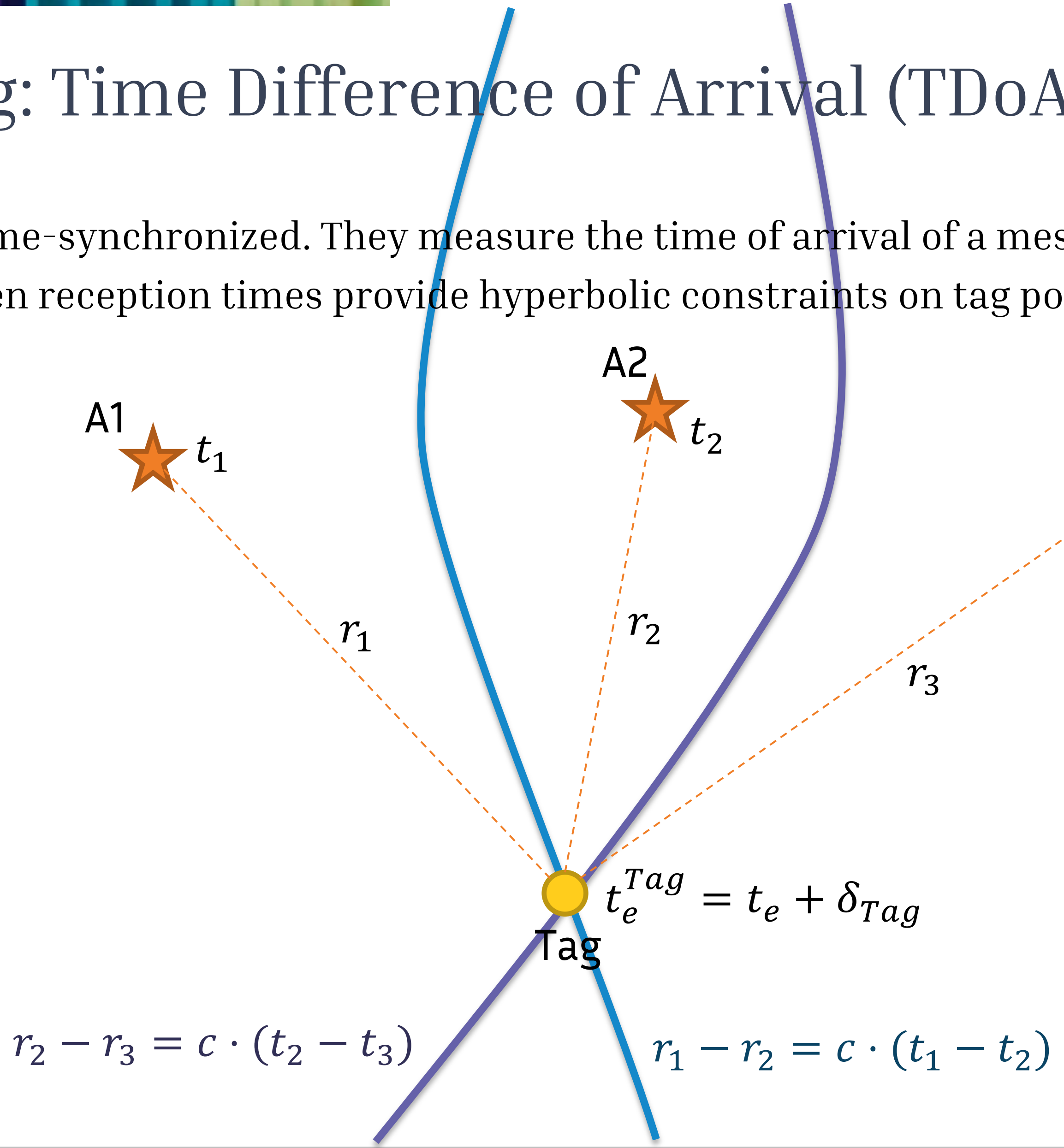
Time of arrival measurement

The receiver performs channel impulse response (CIR) estimation by correlation



Positioning: Time Difference of Arrival (TDoA)

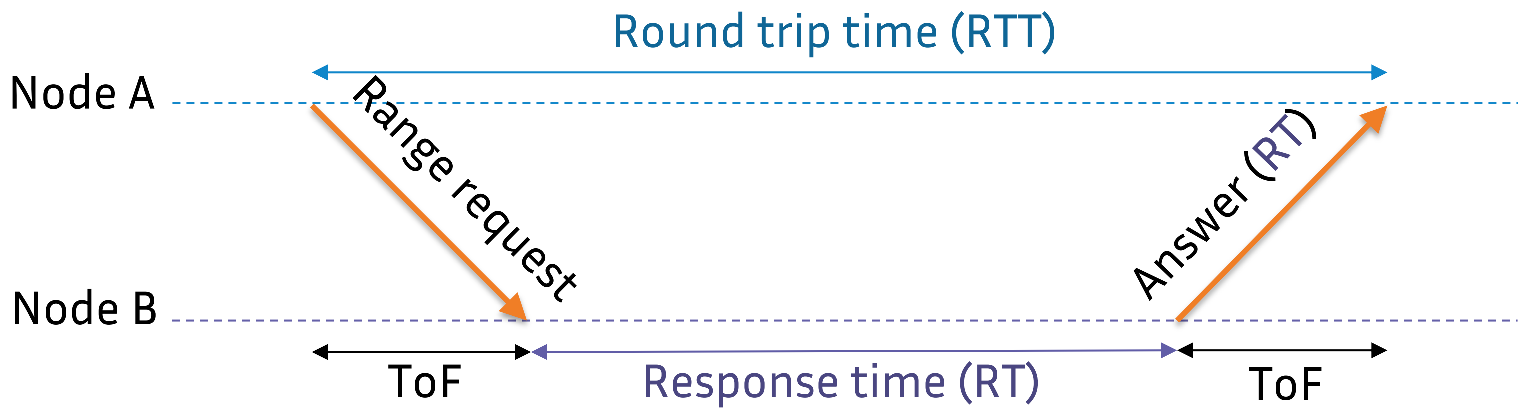
The anchors are time-synchronized. They measure the time of arrival of a message from the tag.
Differences between reception times provide hyperbolic constraints on tag position



Measuring distances: two-way ranging (TWR)

Range measurement between two nodes

Exchange of messages to compute the time-of-flight (ToF).



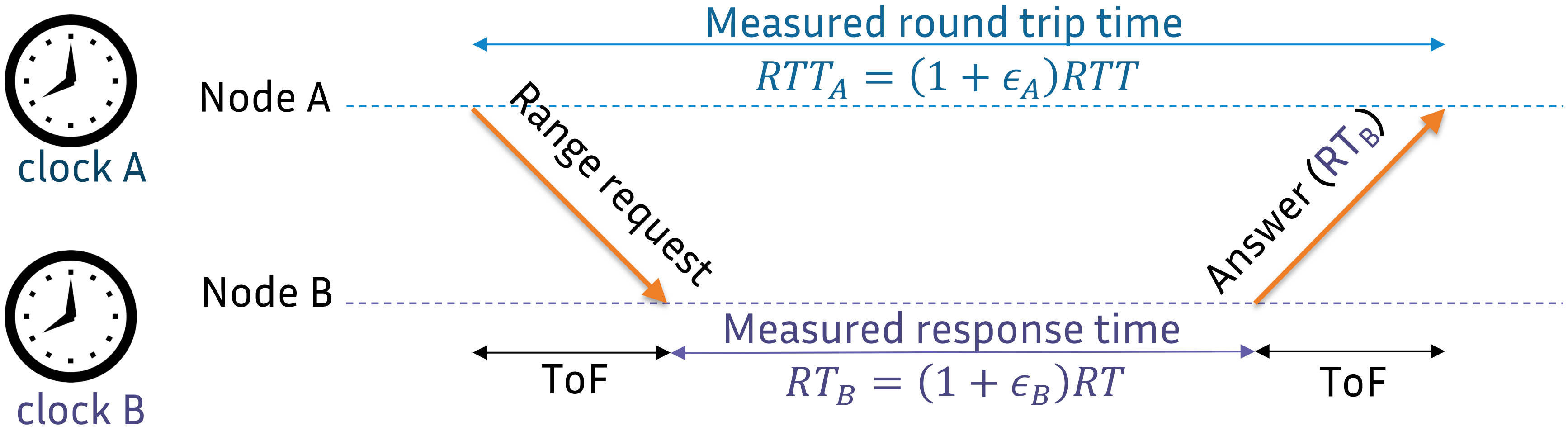
$$ToF = \frac{RTT - RT}{2}$$

More advanced schemes can be employed to compensate clock rate differences between nodes: carrier frequency offset estimation, 3 or 4 messages protocols.

Measuring distances: two-way ranging (TWR)

Range measurement between two nodes

Effect of clock frequency offsets



$$\widehat{ToF} = \frac{RTT_A - RT_B}{2}$$

Time of flight error: $\widehat{ToF} - ToF = \cancel{\epsilon_A ToF} + \boxed{\frac{(\epsilon_A - \epsilon_B)}{2} RT}$

Example: d=3 m, ToF = 10 ns. RT = 100 µs. 20 ppm clock frequency offset

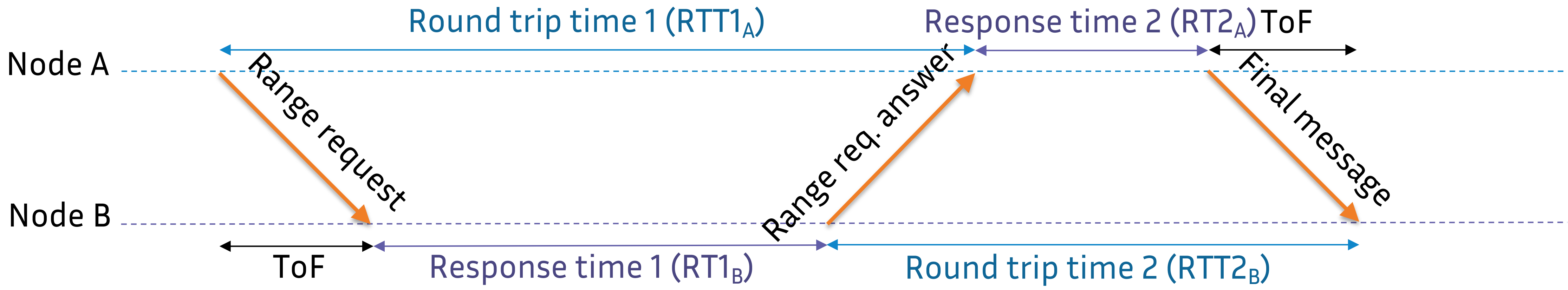
ToF error = 1 ns / 30 cm / 10%

To reduce ToF error
- Shorten RT
- Estimate and correct $\epsilon_A - \epsilon_B$

Measuring distances: double-sided two-way ranging (DS-TWR)

Range measurement between two nodes

Exchange of 3 messages to compute the time-of-flight (ToF) and correct for the clock frequency offset.



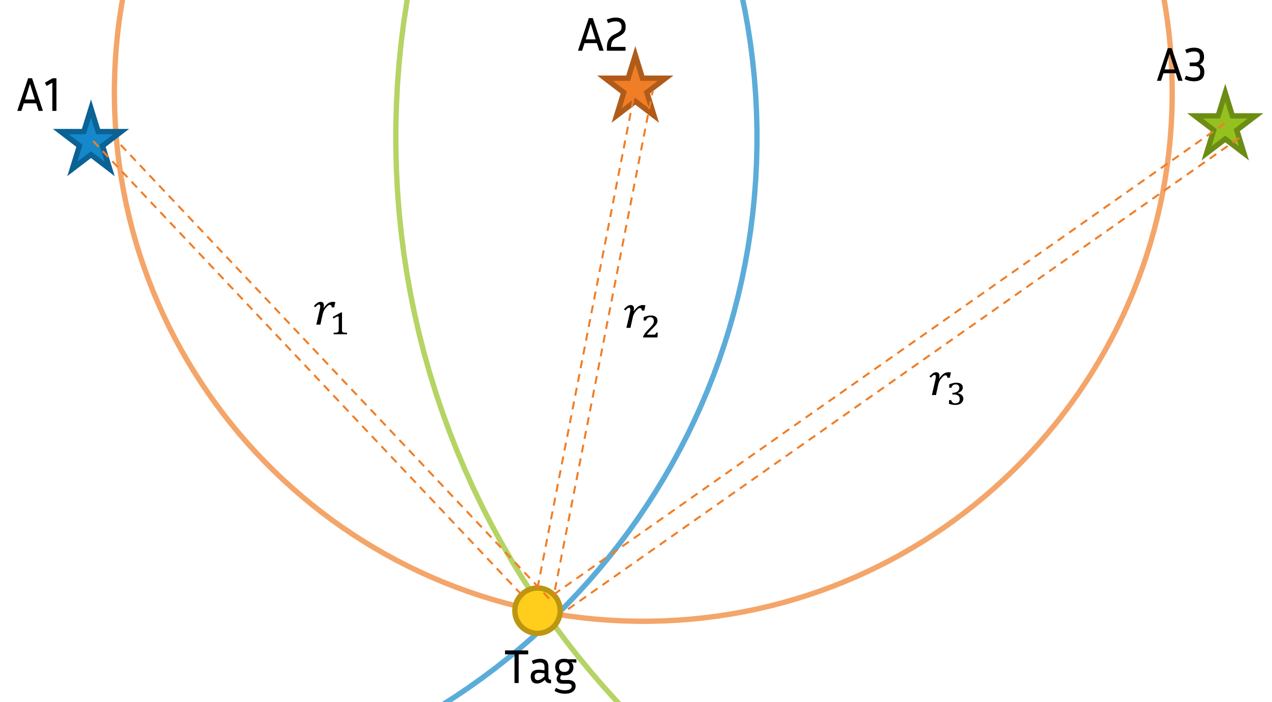
$$\widehat{ToF} = \frac{RTT1_A \cdot RTT2_B - RT1_B \cdot RT2_A}{2(RTT1_A + RT2_A)}$$

Residual clock frequency offset related error is $\epsilon_B \widehat{ToF}$. Useful protocol for long response times.
The receiver clock frequency offset ϵ_B is in the order of 10 to 100 ppm.

Positioning: Two-way ranging

The tag successively measure ranges with all neighboring anchors

Ranges provide spherical constraints on tag position



Better positioning precision than TDoA for a given number of anchors

UWB positioning comparison

	TDoA (anchors receive)	TDoA (anchors emit)	TWR
Needs anchors synchronization	yes	yes	
Ranging			yes
Position precision	lower	lower	better
Number of mobile nodes	Thousands	Unlimited	Tens to hundreds
Tag power consumption	lower	medium	higher
Position computed by	Infrastructure	Mobile node	Mobile node / Infrastructure

Measuring directions: Angle of arrival (AoA)

Use two/three antennas on a single receiver (or on synchronous receivers)

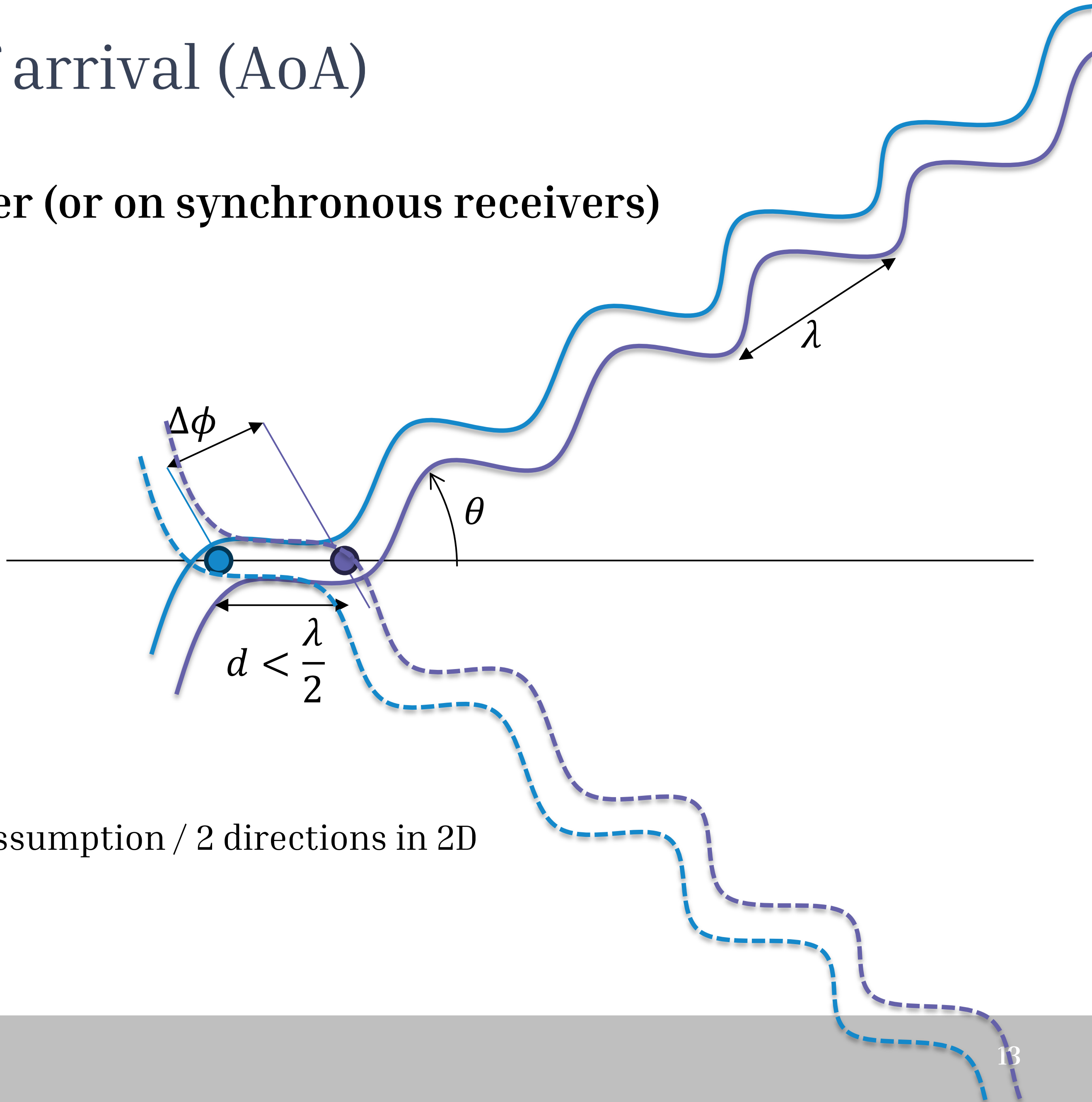
Long baseline between antennas :

- > Time difference of arrival (TDoA)

Short baseline (< half wavelength) :

- > Phase difference of arrival (PDoA)

$$\theta = \arccos(\frac{\phi\lambda}{2\pi d})$$



Ambiguity :

Two-antenna receiver : semi-cone in under far field assumption / 2 directions in 2D

3-antenna receiver : -> front/back ambiguity

UWB positioning and ranging: Sources of error

Random noise

- > Thermal & RF noise
- > Clock jitter and drift

Systematic biases

- > RF module, antenna calibration
- > Antenna pattern / robot body : pose dependent

filter

calibrate / estimate

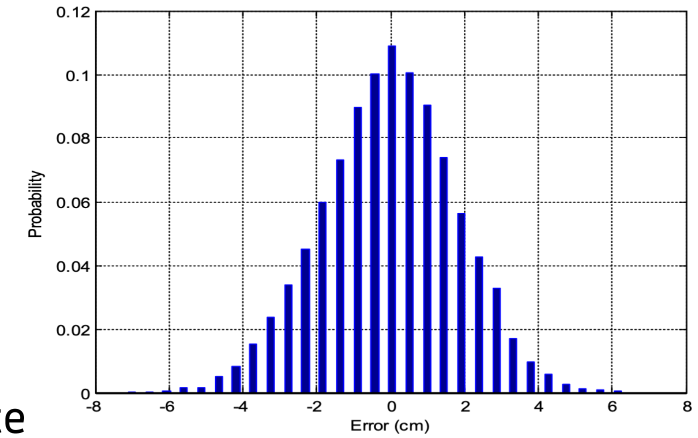
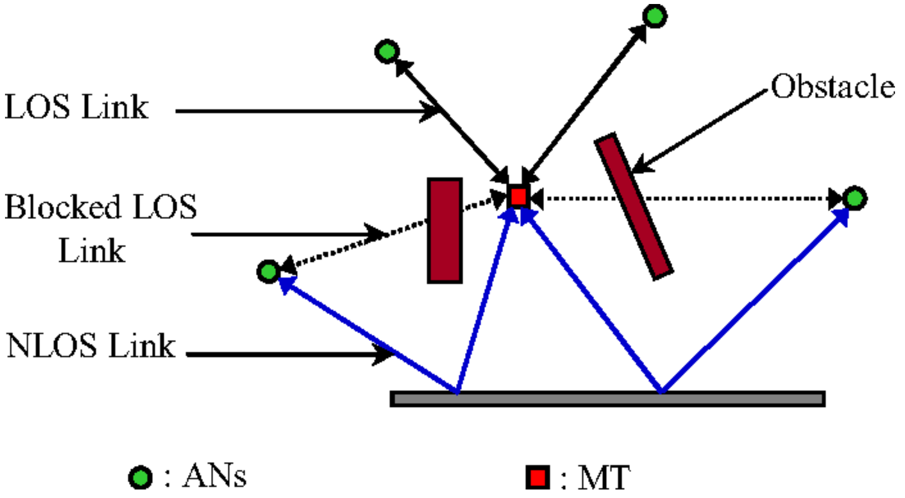


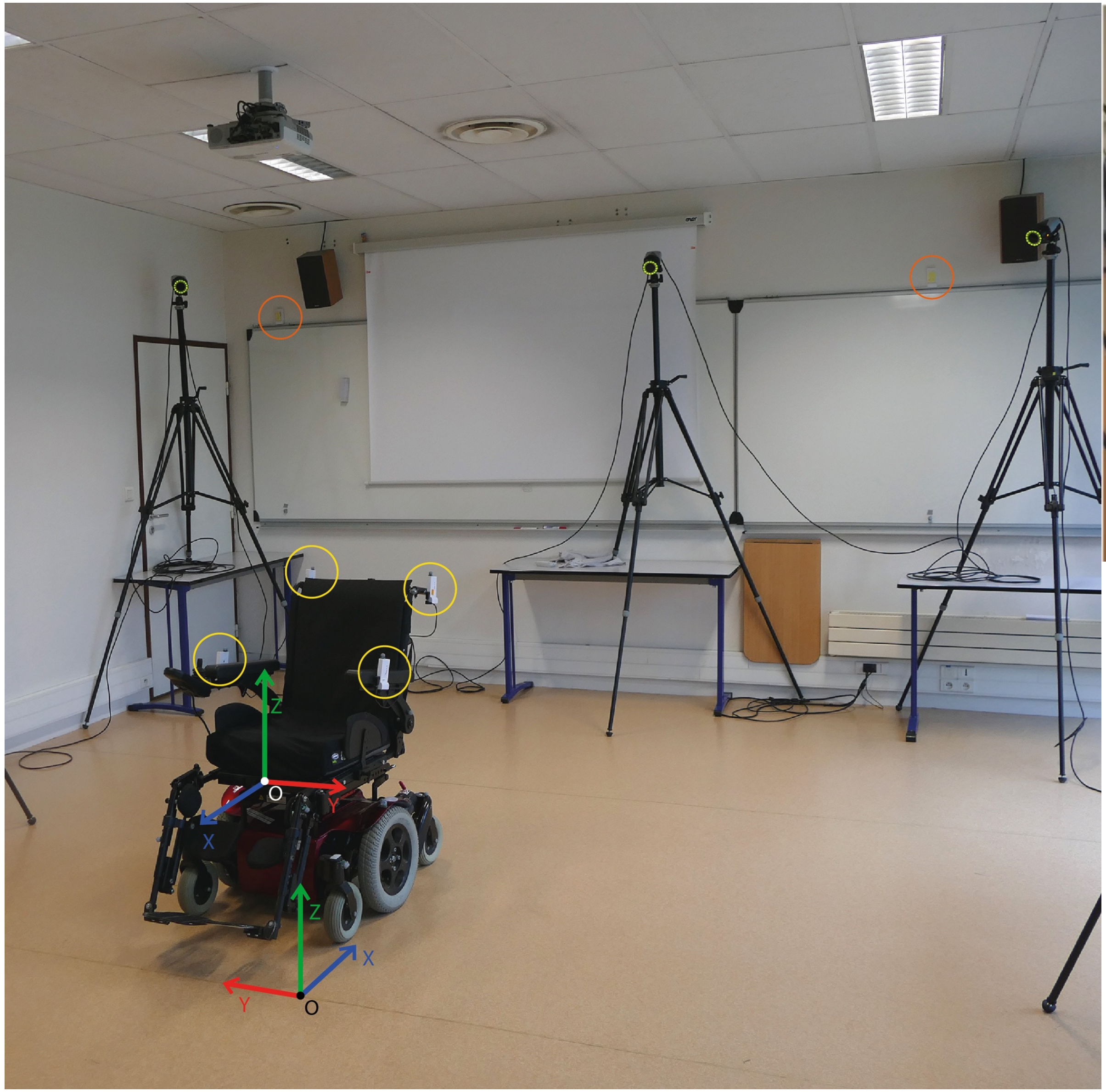
Figure 11: Typical probability distribution of Line of Sight 2-way ranging performance
From Qorvo DW1000 Datasheet

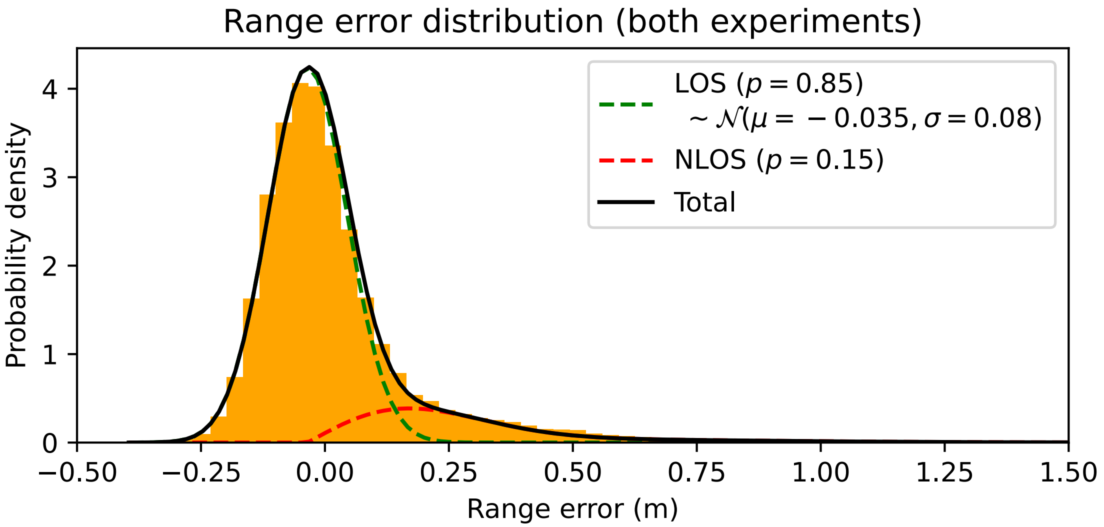
Spurious measurements

- > Multipath
- > Non line of sight (NLOS)

detect and reject / adapt



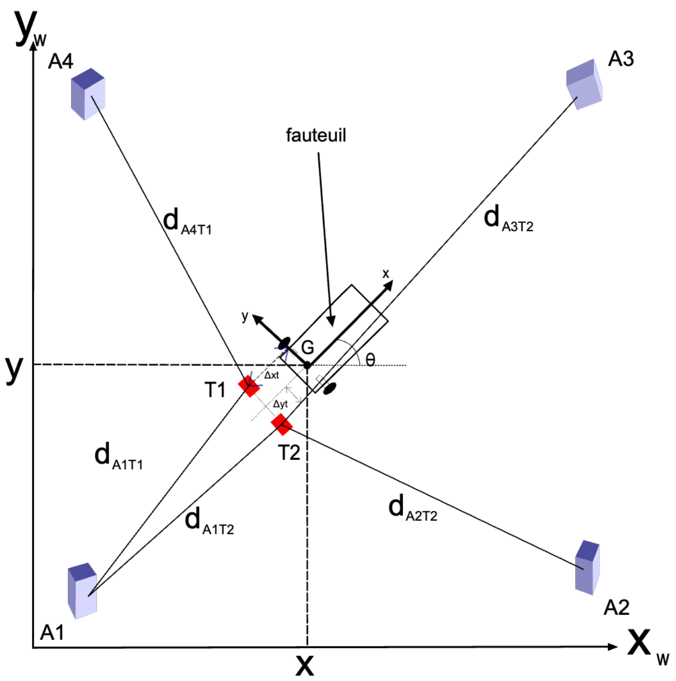

Z
O
Y
X
Z
X
Y
O

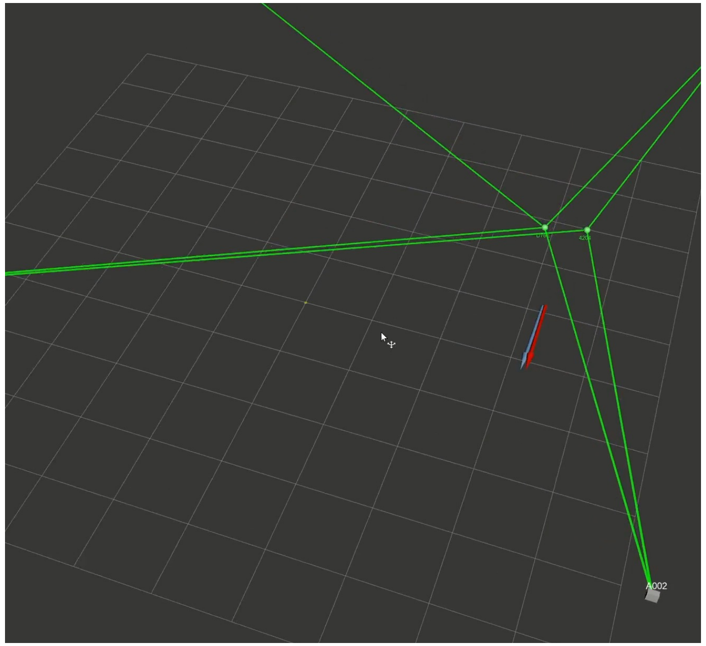

Range error distribution (both experiments)
Probability density
Range error (m)
LOS ($p = 0.85$)
$\sim \mathcal{N}(\mu = -0.035, \sigma = 0.08)$
NLOS ($p = 0.15$)
Total
0
1
2
3
4
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50

UWB: Power wheelchair indoor navigation

Ambrougerien project: Autonomous power wheelchair indoor navigation and induction recharge

- Use 2 tags on the wheelchair, 4 anchors in the room for indoor navigation (Merwane Bouri)
- Robust Iterated Extended Kalman Filter for pose estimation with **outliers exclusion**.

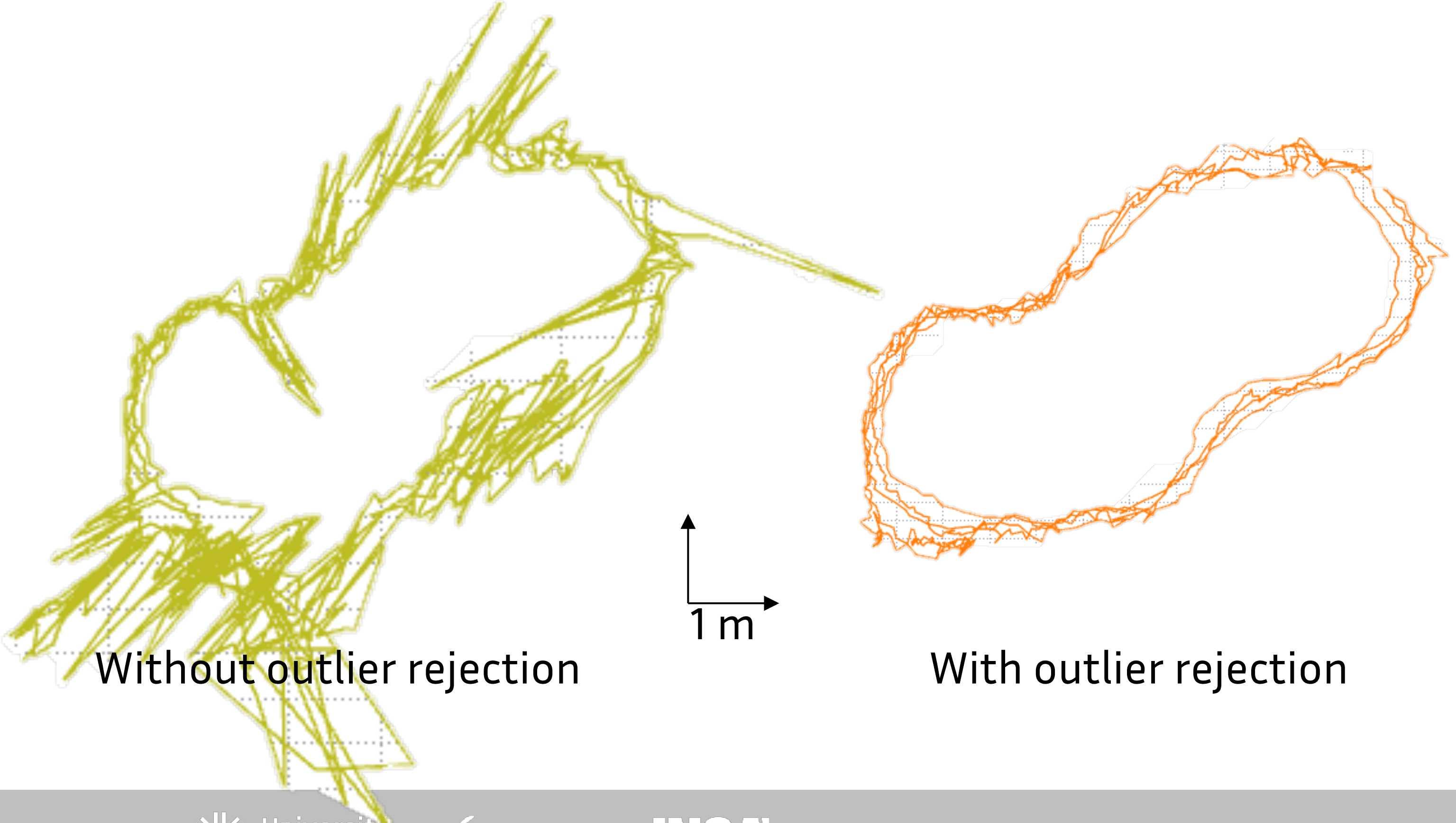




UWB: Power wheelchair indoor navigation

Outlier rejection impact on estimated position

2 tags on wheelchair, 4 anchors. 2021 summer bootcamp @ Insa

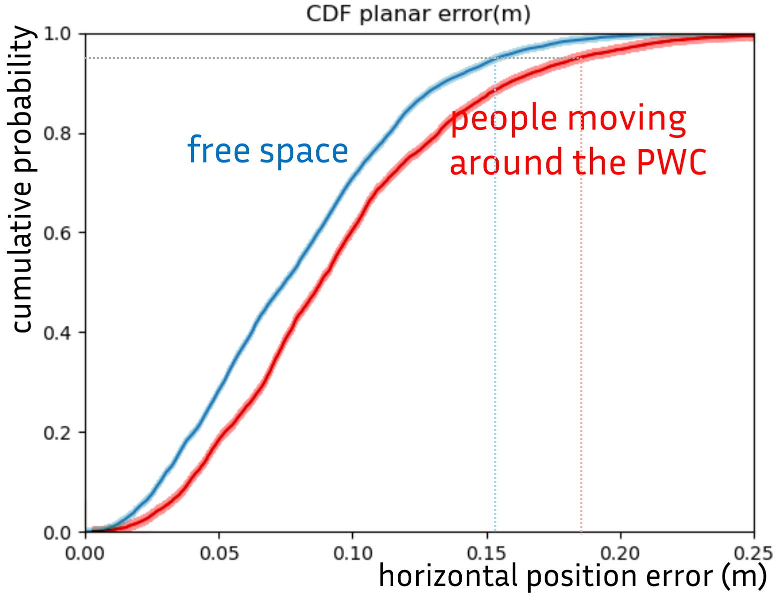


UWB: Power wheelchair indoor navigation

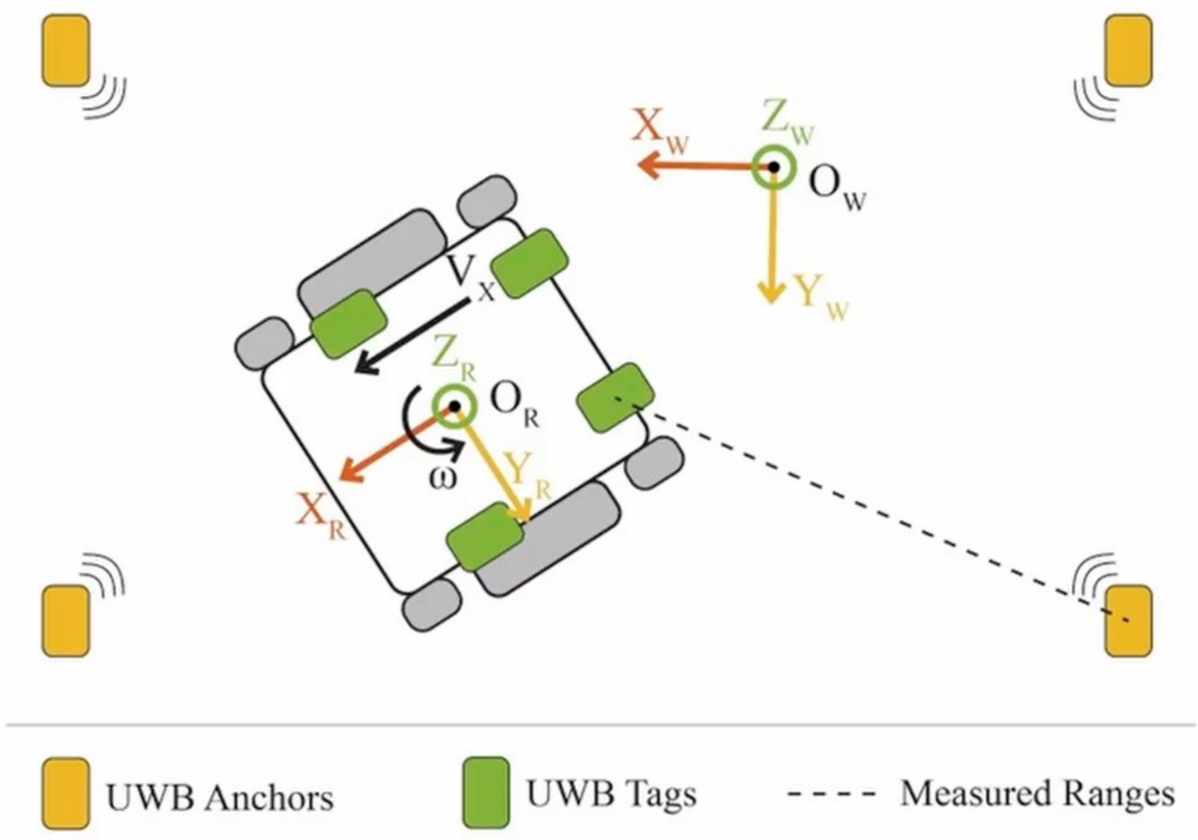
2022 IH2A summer bootcamp (Insa sports hall)

Autonomous navigation demo.

Positioning accuracy tests (4 tags on PWC, 4 anchors). Better than 18.5 cm horiz. (95%) with people moving around.



UWB: Interval methods for localization (Théo Le Terrier)

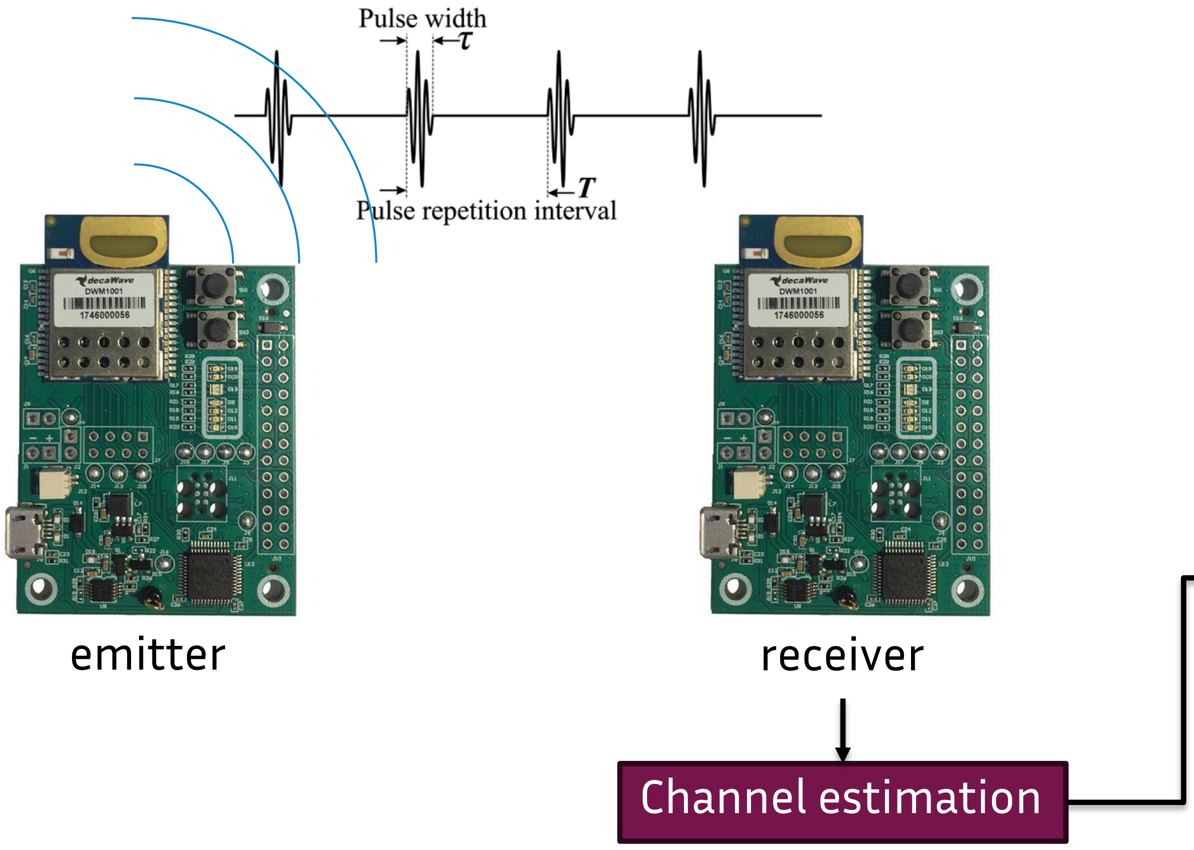


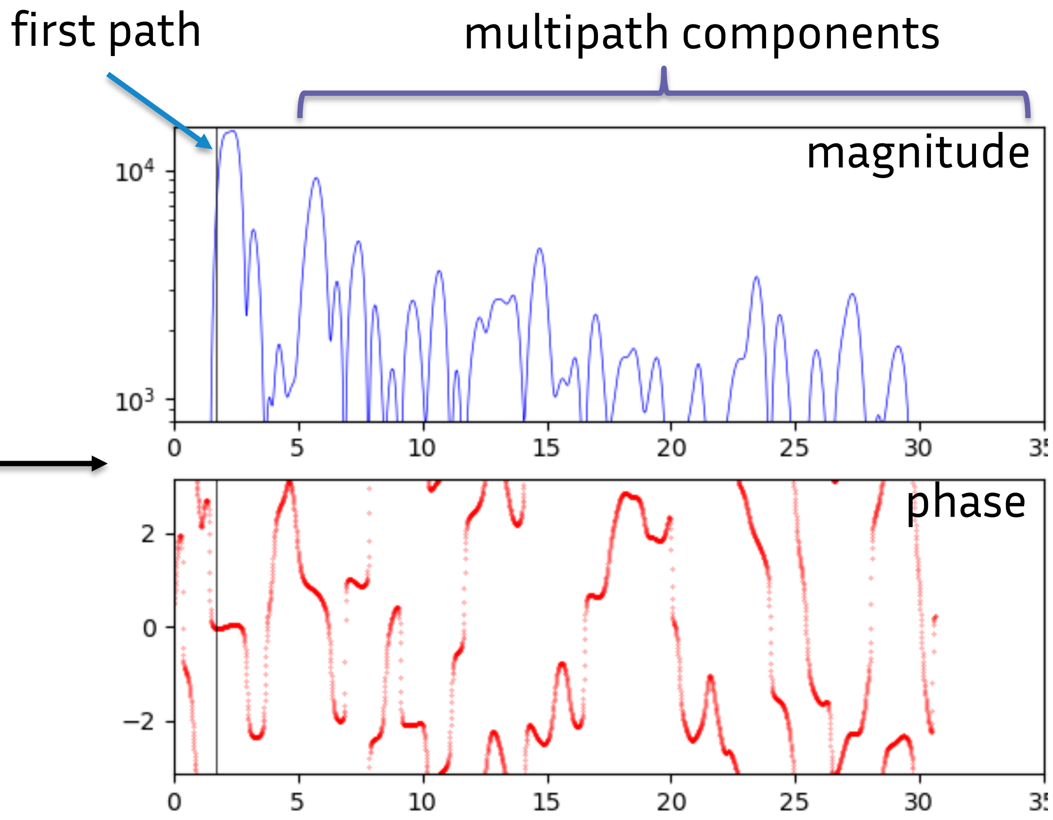
We provide an interval-based method for indoor robot localization, using Ultra-Wideband (UWB) sensors.

RSIVIA algorithm is used w.r.t. UWB constraints to compute outer subpavings of the robot pose. Evolution constraints over a horizon are used to contract uncertainty domains computed from these subpavings.

Channel impulse response estimation

The receiver performs channel impulse response (CIR) estimation by correlation





Playing with the estimated Channel Impulse Response

High rate / low power positioning

- All anchors emit in the time of a single message. Receive once and analyze the CIR for TDoA
  - *Großwindhager et al. (2019), SnapLoc: An Ultra-Fast UWB-Based Indoor Localization System for an Unlimited Number of Tags*

Single antenna angle of arrival estimation

- With learning and ad hoc antenna or local perturbation from the robot body
  - *Ledergerber, A. et D'Andrea, R. (2019), "Ultra-Wideband Angle of Arrival Estimation Based on Angle-Dependent Antenna Transfer Function."*

Radar-like moving objects tracking

  - *Ledergerber, A. et D'Andrea, R. (2020), "A Multi-Static Radar Network with Ultra-Wideband Radio-Equipped Devices",*

Use multipath components for enhanced localization

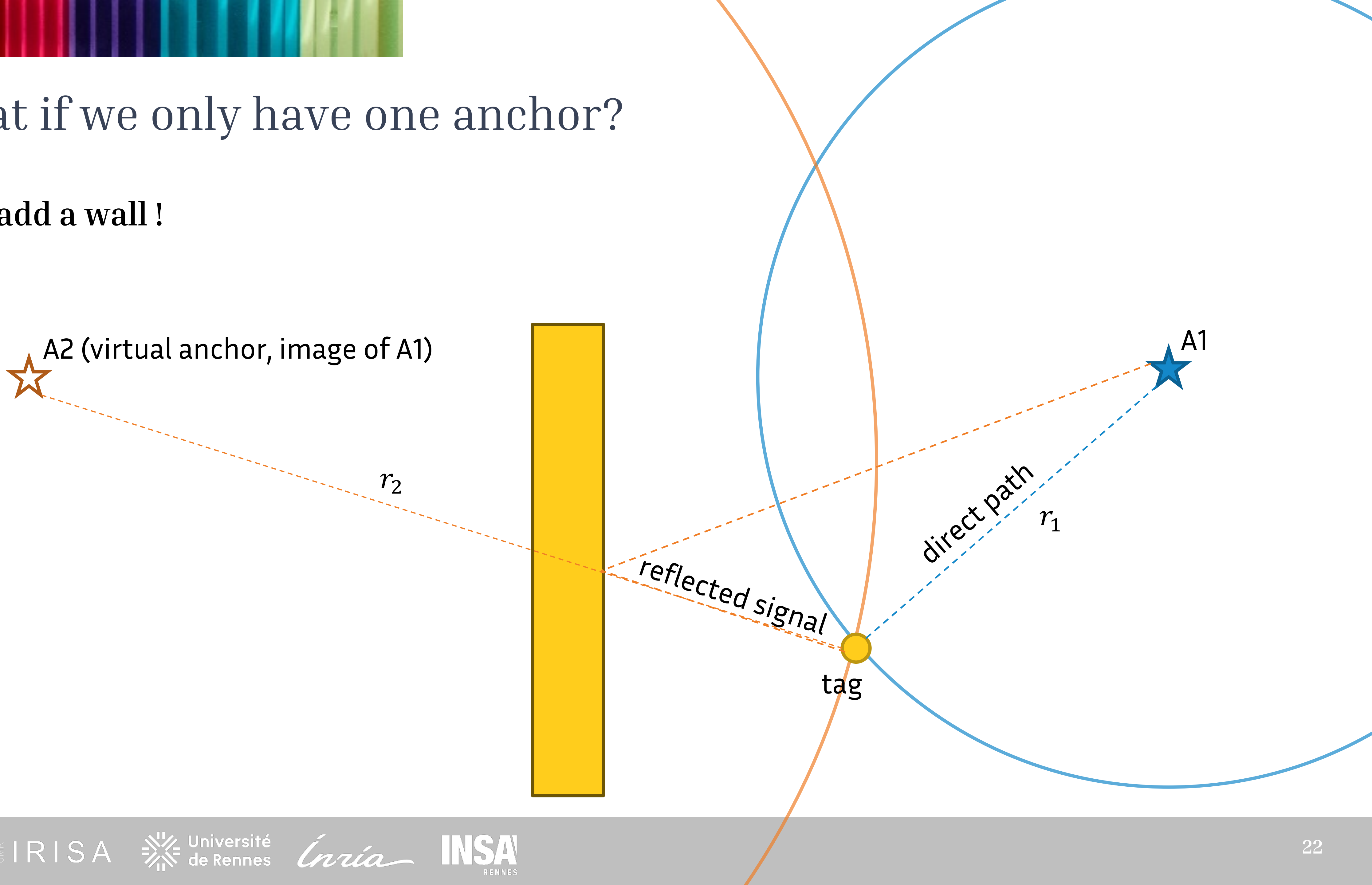
- Learning or geometric approaches with virtual anchor images

Range falsification

- Shorten of lengthen the measured range by jamming with another UWB emitter to alter the first path detection
  - *Poturalski, M. et al. (2010), "The cicada attack : degradation and denial of service in IR ranging"*

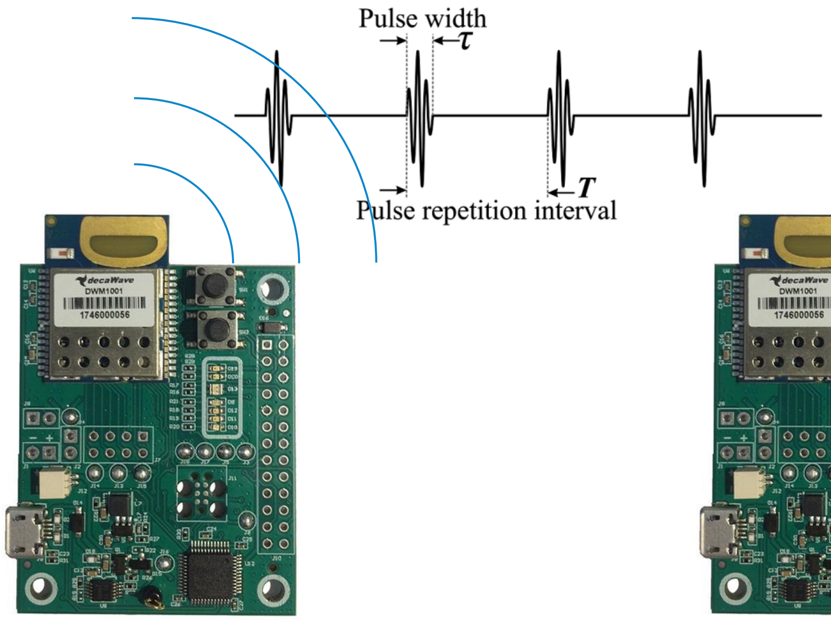
What if we only have one anchor?

Let's add a wall !



Can we hear the echo?

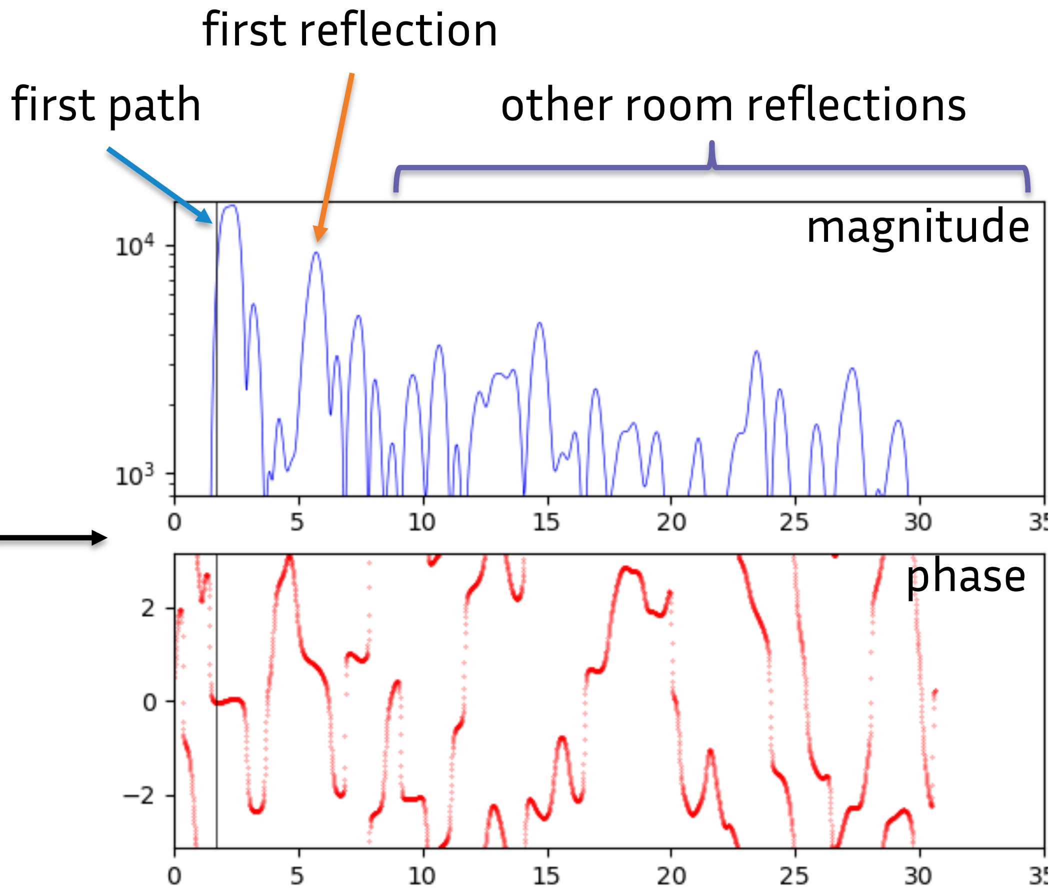
Look for multipath components in the estimated CIR

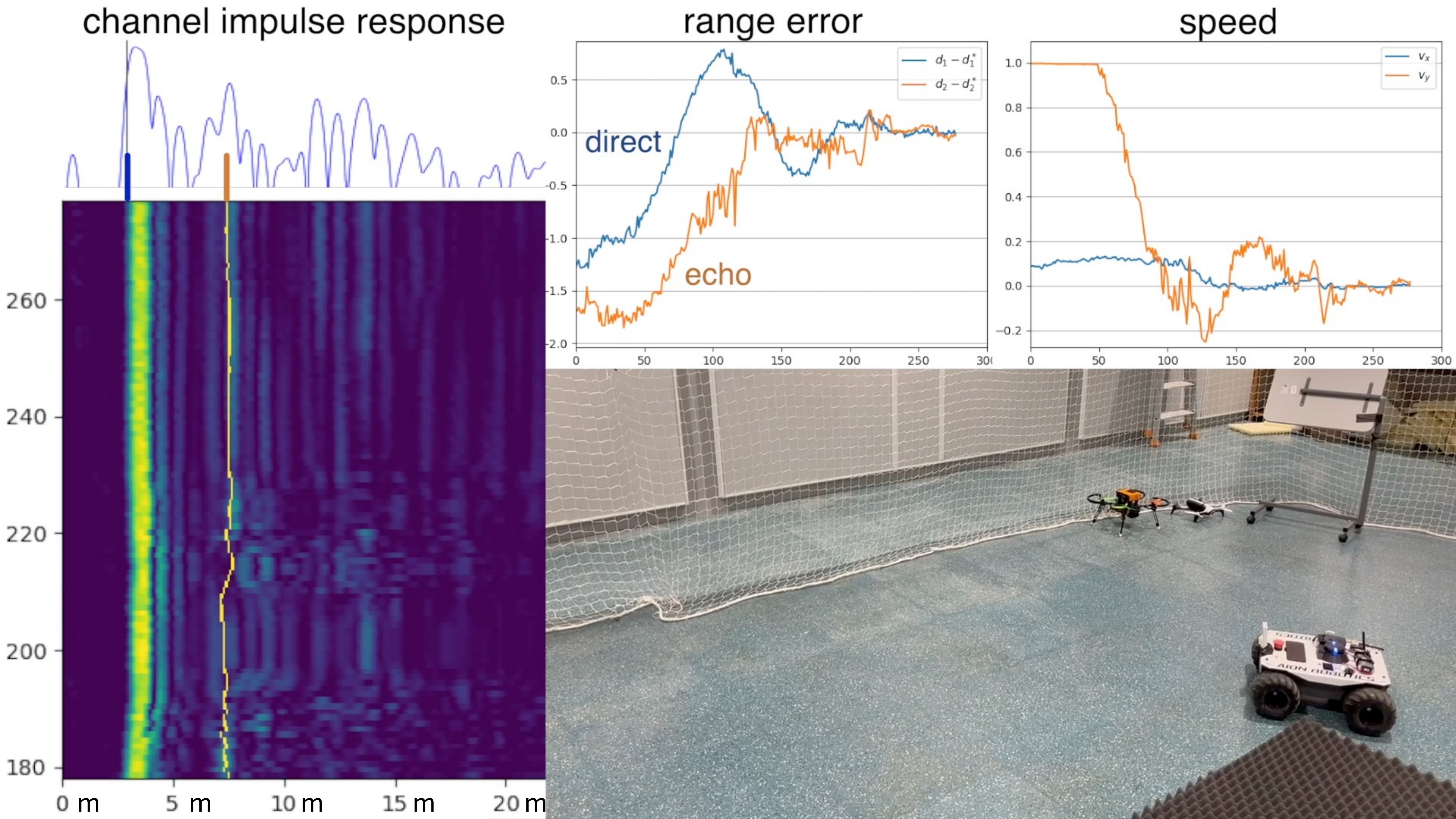


emitter

receiver

Channel estimation




channel impulse response
range error
speed
direct
echo
$d_1 - d_1^*$
$d_2 - d_2^*$
v_x
v_y
0 m
5 m
10 m
15 m
20 m
180
200
220
240
260

Working with Qorvo DWM1001

Module with DW1000 UWB transceiver, nRF52832 Bluetooth µC, motion sensor and antenna.

Using the stock RTLS firmware

- Tags, anchors. Network organization and synchronization.
- Up to 10 Hz measurement / positioning rate for tags
- 150 Hz max system rate (nb tags x measurement rate)
- Two-way ranging
- Tags only interrogate 4 anchors (in the best expected geometrical configuration)
- "IoT style" communication (needs a Raspberry Pi server)

Custom firmware

- Implement other positioning schemes/protocols (TDoA, ranging between nodes…)
- High rate measurements
- Access to Channel Impulse Response estimate
- Higher speed communication (6.81 Mbps)

DWM1001 Module

DWM1001 Dev board

UWB beacons for robotics

Low cost, easy to deploy realtime localization

- Good for teaching too…

Expect decimeter level position accuracy in good conditions (LoS)

- Use module and antenna calibration to improve accuracy
- Erroneous measurements (multipath, NLoS) have to be filtered out in cluttered environments

Use off the shelf Qorvo firmware for basic use

- Only distances to 4 anchors measured at a time
- Computed position is an average of le last 3 epochs
- Limited to 10 Hz

Need to use or develop custom firmware for more advanced use

- Various measurements protocols / rates
- Access to CIR estimation


Thank you