Ultra-wideband Backscatter Signaling for Zero-power Radio Identification and Positioning

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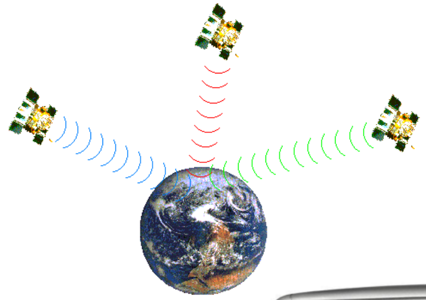
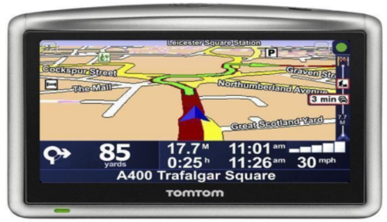
Summary

- Introduction
- “Zero-power” identification and localization
- The UWB backscatter principle
- Main challenges
- Architectures and processing schemes
- Experimental results: The SELECT and GRETA projects
- Non-regenerative relaying techniques for coverage extension
- Conclusions and perspectives

Introduction

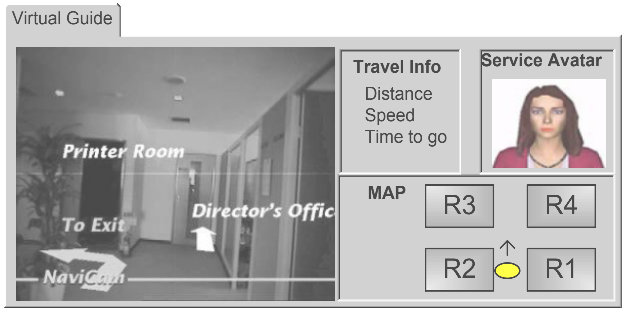
The **Global Positioning System (GPS)** is recognized to be the legacy system in outdoor environments





It is expected that in the near future we will witness a boom of **location-aware services for indoor scenarios** where people spend more than 70% of their lives.

Indoor real-time locating systems (RTLS) have been gaining relevance due to the widespread advances of devices and technologies and the necessity for *seamless solutions* in location-based services.

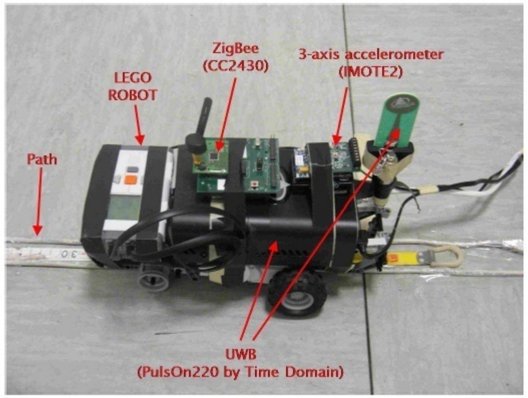


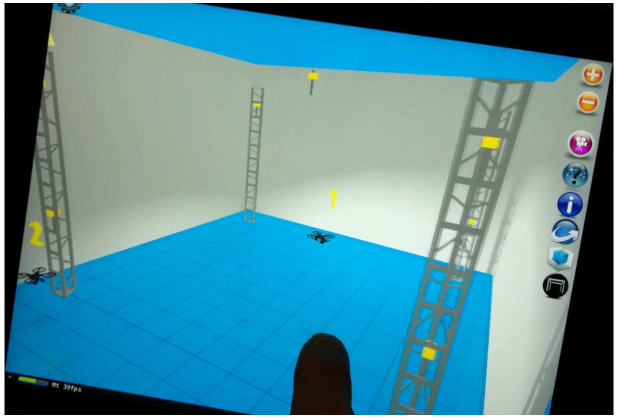
It is expected that the market opportunities for RTLS will be in the order of $10 billion yearly in 2024 [*IDTech2014*]

Indoor real-time locating systems

Indoor positioning is very challenging: multipath, non line-of-sight (NLOS) conditions, infrastructure deployment and cost constraints, ….

Several ad hoc solutions using a large variety of technologies: ultrasound (e.g., ActiveBat), WiFi, RFID, ultra-wideband (UWB), Bluetooth LE (e.g., iBeacon), NFC, 3GPP/LTE, signals-of-opportunity, inertial measurement units.



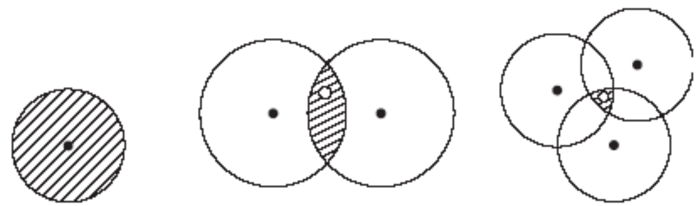


No legacy system available as in outdoor

Current (indoor) RTLS Technologies in Brief

Proximity

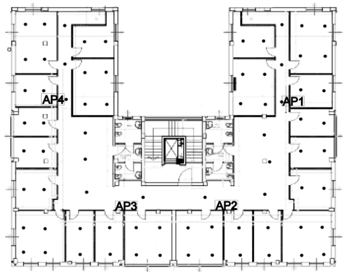
- Technologies: RFID tag, Bluetooth, ..
- Accuracy: very poor



(b) (c)

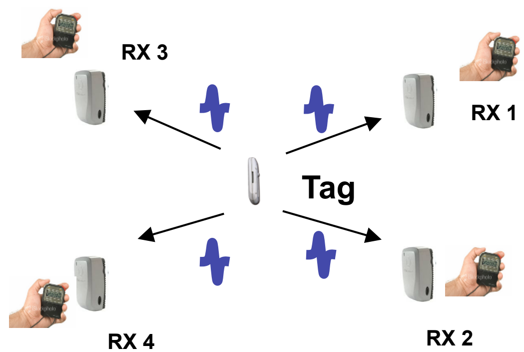
Fingerprinting

- Technologies: typically Wi-Fi
- Accuracy: poor



Geometric

- Technologies: Wi-Fi, Zigbee, UWB
- Techniques: Multi-lateration (TOA, TDOA, RSS), Triangulation (AOA)
- Accuracy: Potentially high depending on the technology (e.g., UWB)



Hybrid

- Technologies: combine inertial and magnetic sensors with previous technologies (e.g., WiFi)
- Accuracy: Potentially high depending on the technologies combination

[Ref.] D. Dardari, E. Falletti, M. Luise “Satellite and Terrestrial Radio Positioning Techniques - A Signal Processing Perspective”, Elsevier, 2011

Zero-power localization

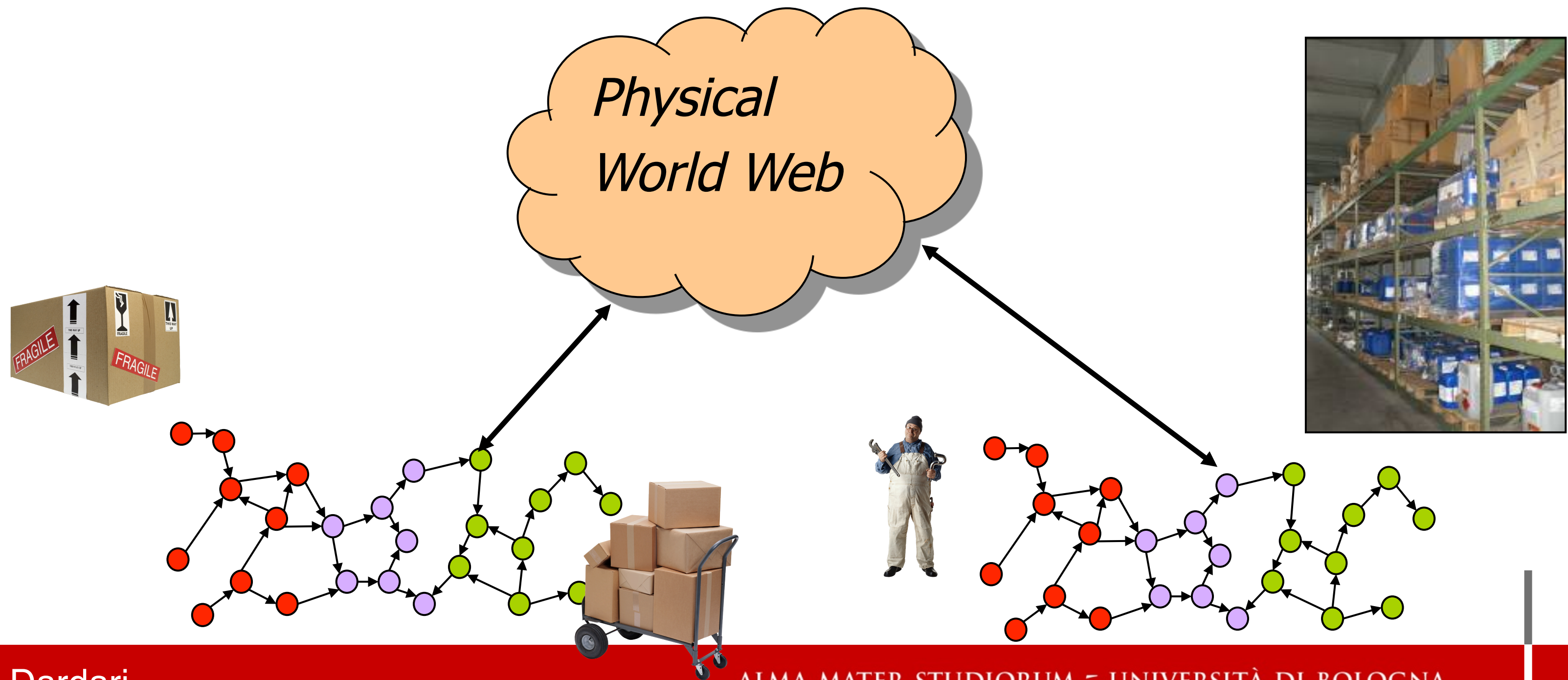
The vision: "Internet of Things"

"Enable the interaction between people and their personalised surroundings"

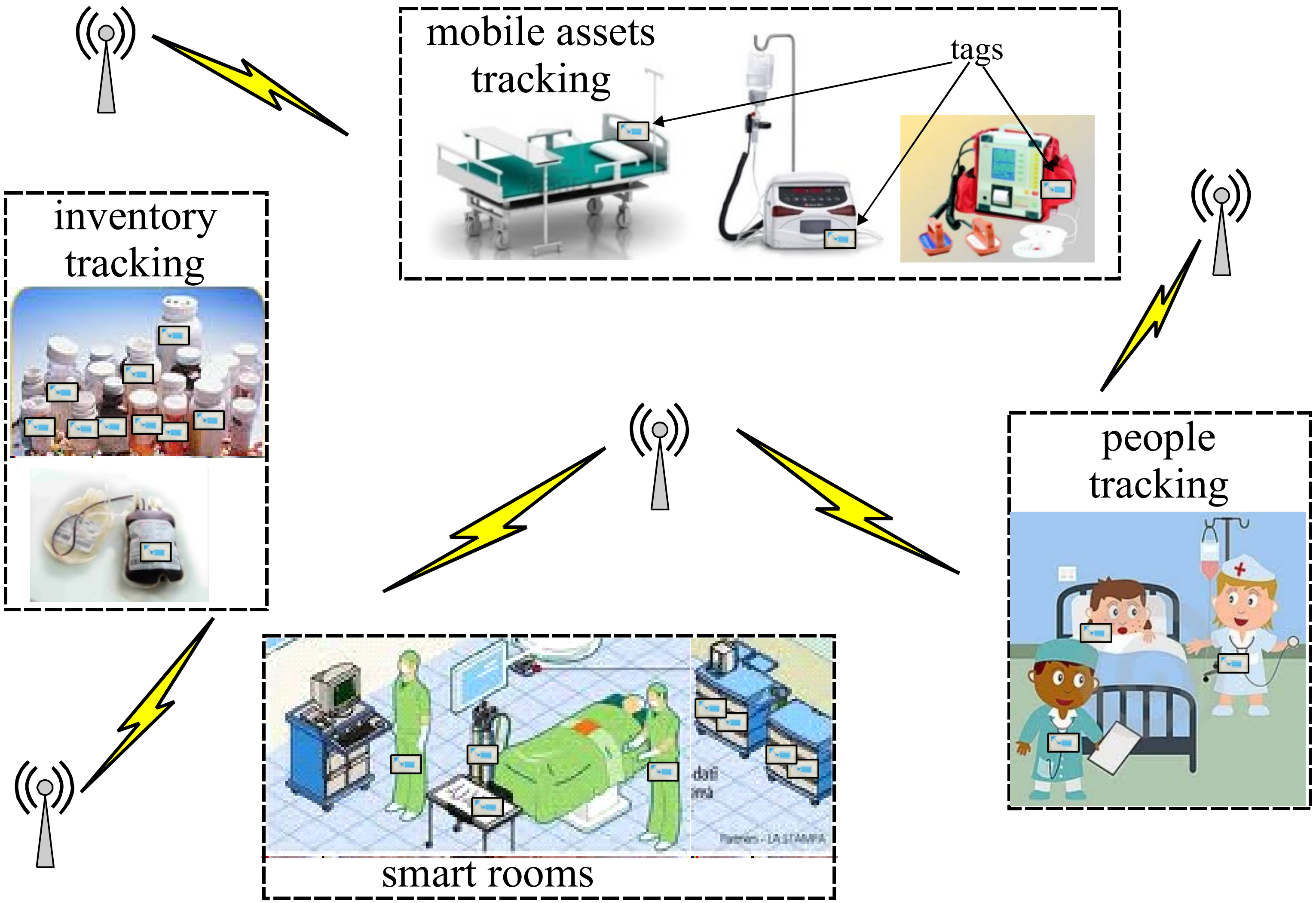
"Map" the physical world into the internet space (Physical World Web)

Expected >50 billion devices!

A potentially huge number of possible applications



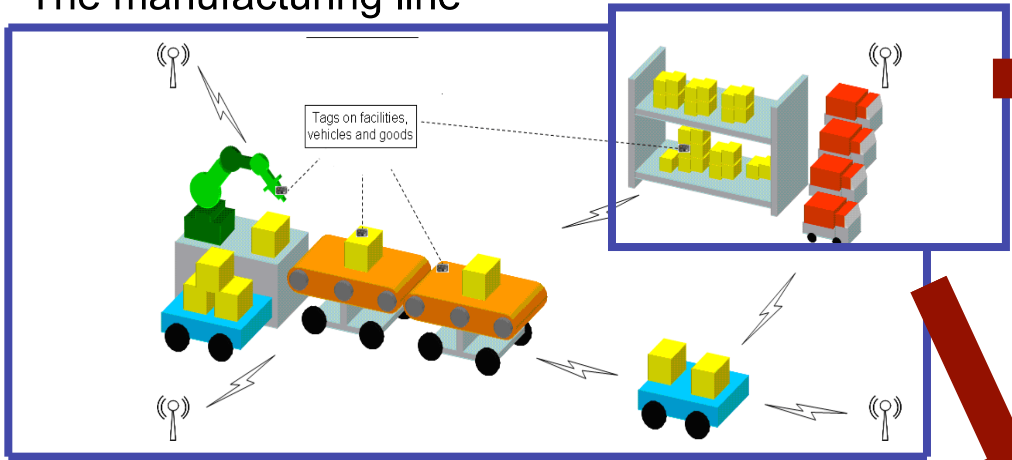
Internet of Things: Applications



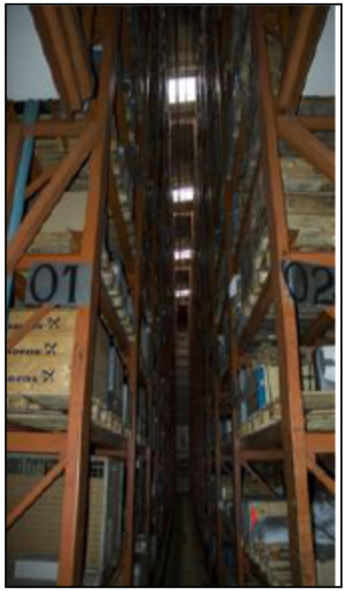
Internet of Things: Applications

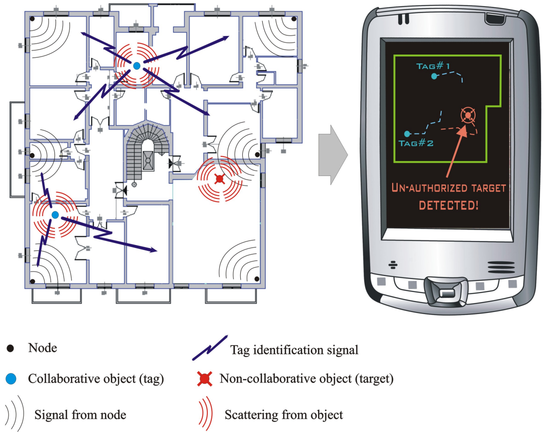
The manufacturing line

The warehouse

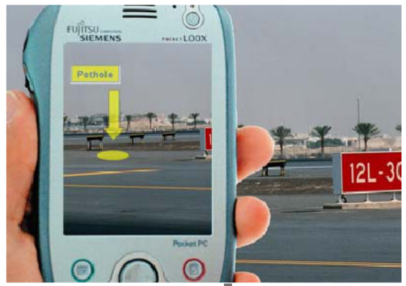


The warehouse





Augmented reality



Internet of Things: Technology requirements

Devices embedded to objects

- *Extremely low cost*
- *Energy autonomous (energy harvesting, low consumption)*
- *Eco-compatible (disposable)*
- *Sub-meter localizable*
- *Sensing capability*

Convergence of Radio Frequency IDentification (RFID) and Real-time Locating Systems (RTLS)

(>6 billions new market opportunities in 2022*)

Zero-power communication and localization

(*) IDTechEx "Real Time Locating Systems 2012-2022" www.IDTechEx.com/RTLS
P. Harrop and R. Das, "Wireless Sensor Networks 2011-2021: The new market for Ubiquitous Sensor Networks (USN)", www.IDTechEx.com
P. Harrop and R. Das, "Energy Harvesting and Storage for Electronic Devices 2011-2021", www.IDTechEx.com

Current Object Identification Technologies in Brief

Barcode / QR code

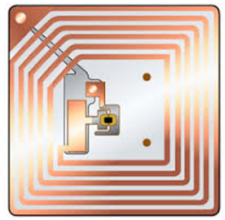
- Tags on paper
- Optical reading

Radiofrequency Identification (RFID)

- Wireless interrogation signal through a reader
- Different technologies and bands (LF/HF: inductive, UHF: e.m.)

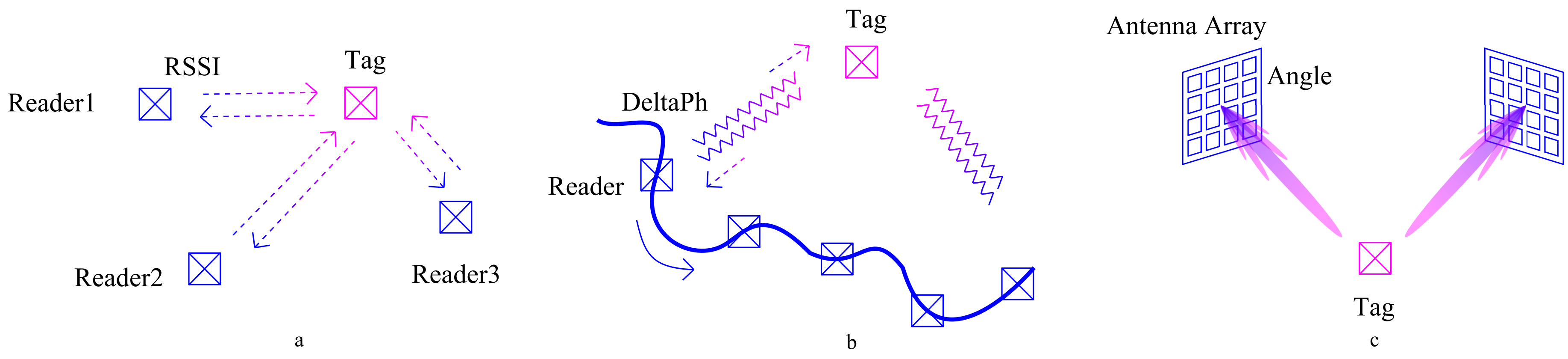
Tag technology

- *Active:* RF transmitter + battery
- *Semi-passive:* backscatter modulation, battery only for control operations



- *Passive:* backscatter modulation, no battery, energy scavenging only for control operations
  - Chipless: completely passive devices, no energy required

Positioning using standard UHF RFID



a) Received signal strength indicator (RSSI)
b) Phase variation
c) Angle-of-arrival (AOA) estimation

RFID and RTLS Convergence

- Current RTLS make use of active tags (battery)

For example, in the field of UWB solutions:

  – Standards: IEEE 802.15.4a, IEEE 802.15.4f, ..
  – Proprietary solutions: Timedomain, Ubisense, etc.

→ Not suitable for energy harvesting tags

- Passive or semi-passive RFID solutions are particularly attractive due to their low energy consumption

→ But current RFID solutions do not offer high-definition localization capability

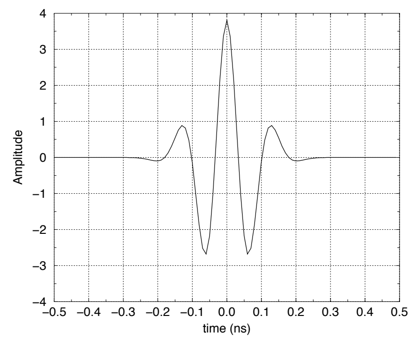
↓

RFID and RTLS convergence → Technology shift needed

Ultra-wide bandwidth (UWB) backscatter signalling

Why Ultra-Wideband (UWB) for RFID?

Expected advantages using UWB

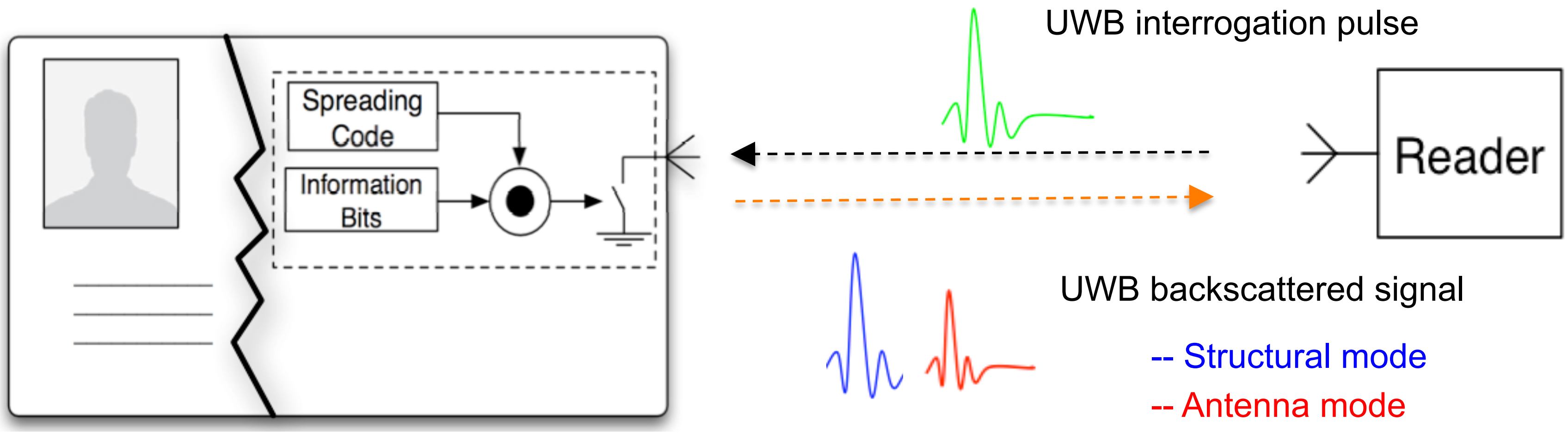


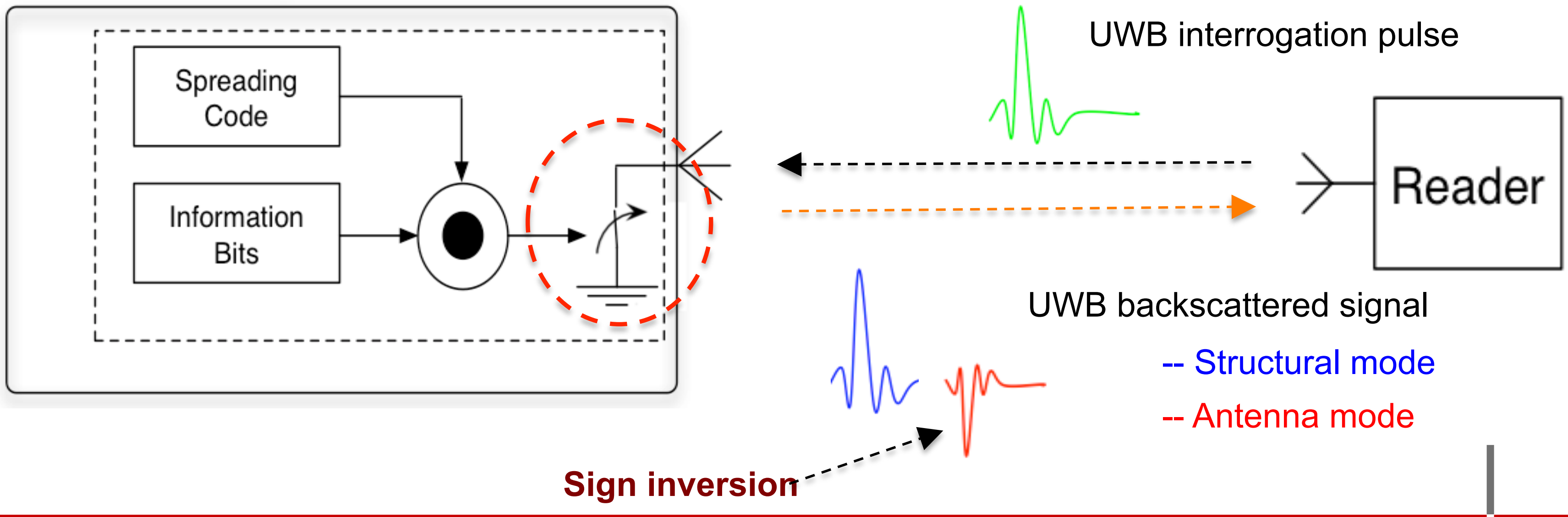
- Coverage (multipath can be exploited advantageously)
- Multiuser capability (large number of Tags/area unit)
- Security (low probability of detection)
- Robustness to interference
- Small antennas
- Low transmitted power levels (less than 1mW vs more than 1W)
- Accurate ranging → Tag localization
- Possibility to combine tagged and untagged object detection and tracking (wireless sensor radar) by exploiting similarities with backscatter modulation

But also some disadvantages

- Spectrum emission mask and coexistence constraints
  - Transmitted power less than 1mW (vs 2-4W UHF RFID), no sufficient power from RF to energize the tag at distances of interest (>1m), poor link budget
- New technology
- Higher frequency

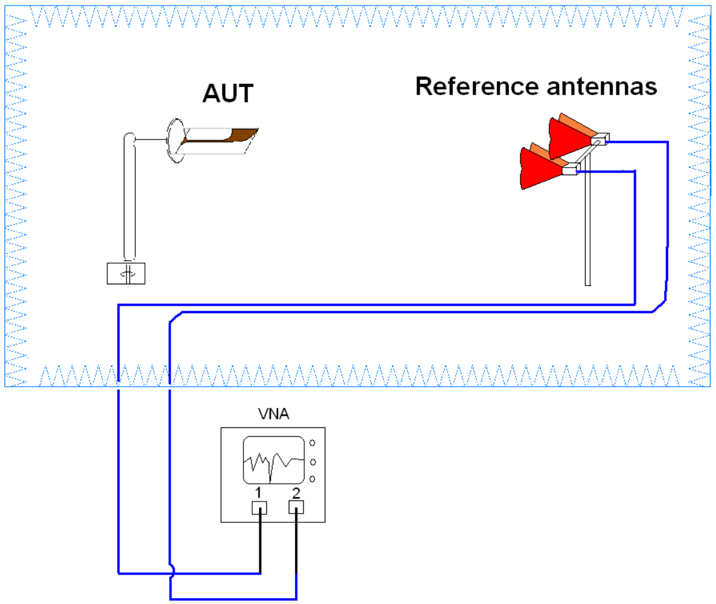
The UWB Backscatter communication principle

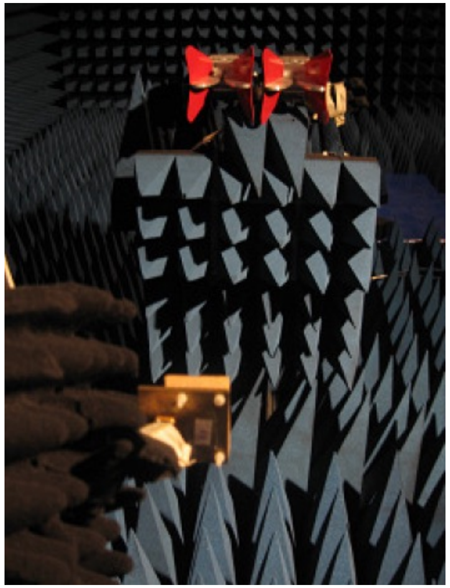




Experimental Round-trip Channel Characterization (1/2)

Antenna under test (AUT): Balanced Antipodal Vivaldi (BAV) antenna on its E-plane realized on strip-line technology on dielectric substrate with $\varepsilon_r = 2.33$. Its overall dimensions are 160 × 100 × 3.048 mm^3.

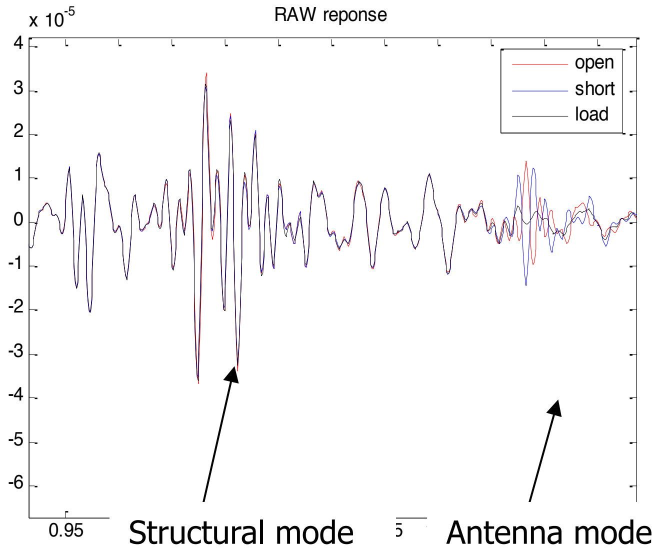


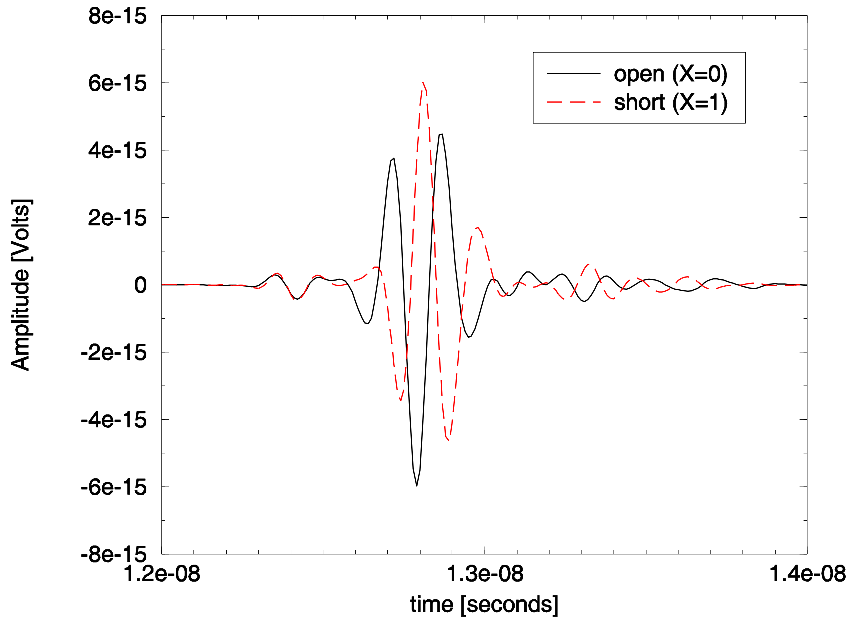


Measurements have been performed in frequency domain with a vector network analyzer in the 2-10 GHz band by steps of 5 MHz (ENSTA-ParisTech Labs).

Experimental Round-trip Channel Characterization (2/2)

Example of measured backscattered signal at reference distance d_{ref} = 1.44 m for different antenna load conditions (open-short).





BAV antenna in the direction of maximum radiation (only antenna mode shown, delay line present)

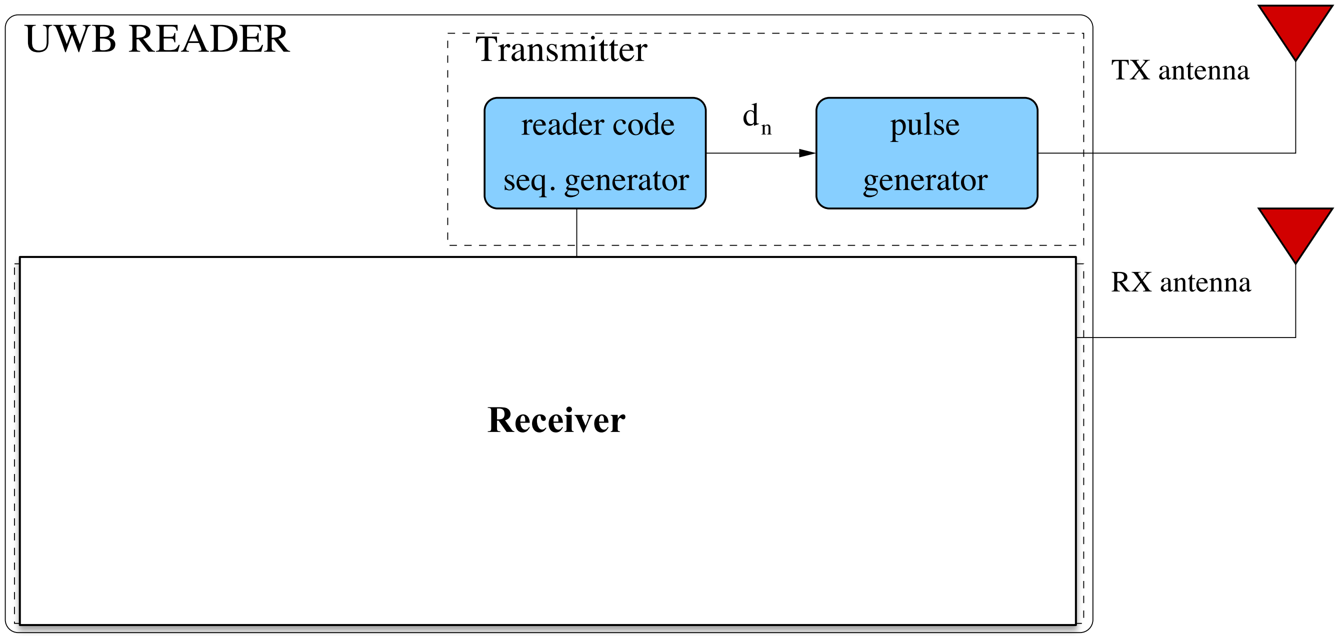
The cross-correlation between the 2 measured waveforms is $\rho = -0.98$ which confirms a good pulse symmetry between the two load conditions. → 2-PAM scheme possible

Main challenges

- Reflected signals coming from surrounding objects (*clutter*) and antenna structural mode are in general dominant → *Need for efficient signal structure and processing schemes to mitigate the effect of clutter*
- Multi-tag – Multi-reader → *Code division multiple access*
- Poor link budget → *High number of pulses per bit, relaying techniques*
- Ranging capability → *Signal round trip time estimation*
- Synchronization → *Wake-up signals*
- Clock drift → *Robust code acquisition schemes*

Architectures and signal processing schemes

Reader architecture: TX section

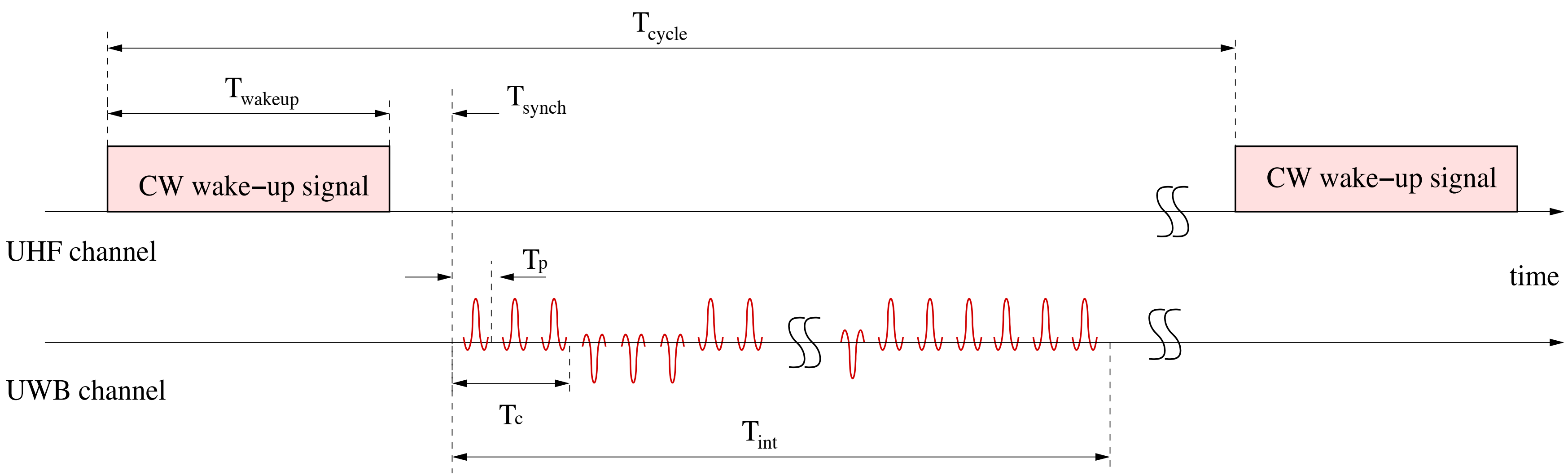


$\{d_n\}$: reader's code

D. Dardari et al. "Ultrawide bandwidth RFID: The next generation?" Proceedings of the IEEE, Sep 2010 - Special Issue on RFID - A Unique Radio Innovation for the 21st Century.

Interrogation cycle

- Tags are in sleeping state to save energy
- They are woken-up through a CW UHF signal
- Tags then reflect back the incoming UWB signals with modulation



UWB Interrogation signal

$$s_{\mathrm{reader}}(t) = \sum_{m=0}^{N_{\mathrm{r}}-1} s(t - mN_{\mathrm{c}}T_{\mathrm{c}})$$

N_r symbols

$$s(t) = \sum_{n=0}^{N_{\mathrm{c}}-1} d_n \, g(t - nT_{\mathrm{c}})$$

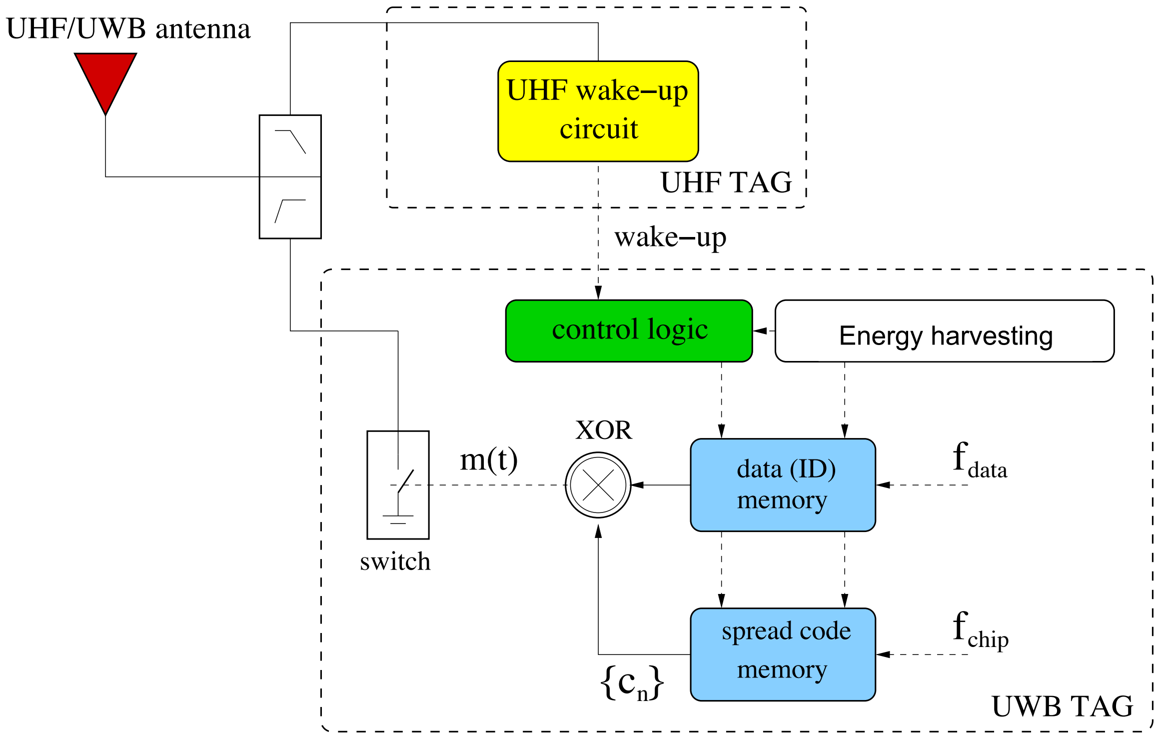
N_c chips per symbol

$$g(t) = \sum_{i=0}^{N_{\mathrm{pc}}-1} p(t - iT_{\mathrm{p}})$$

N_{pc} pulses per chip

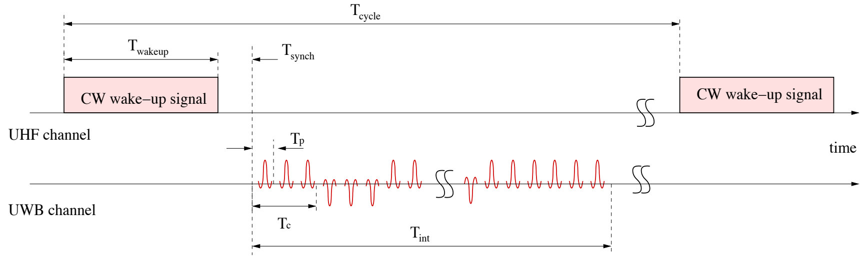
- T_p: Pulse repetition period (PRP). Chosen so that all backscattered signals are received before the transmission of the successive pulse.

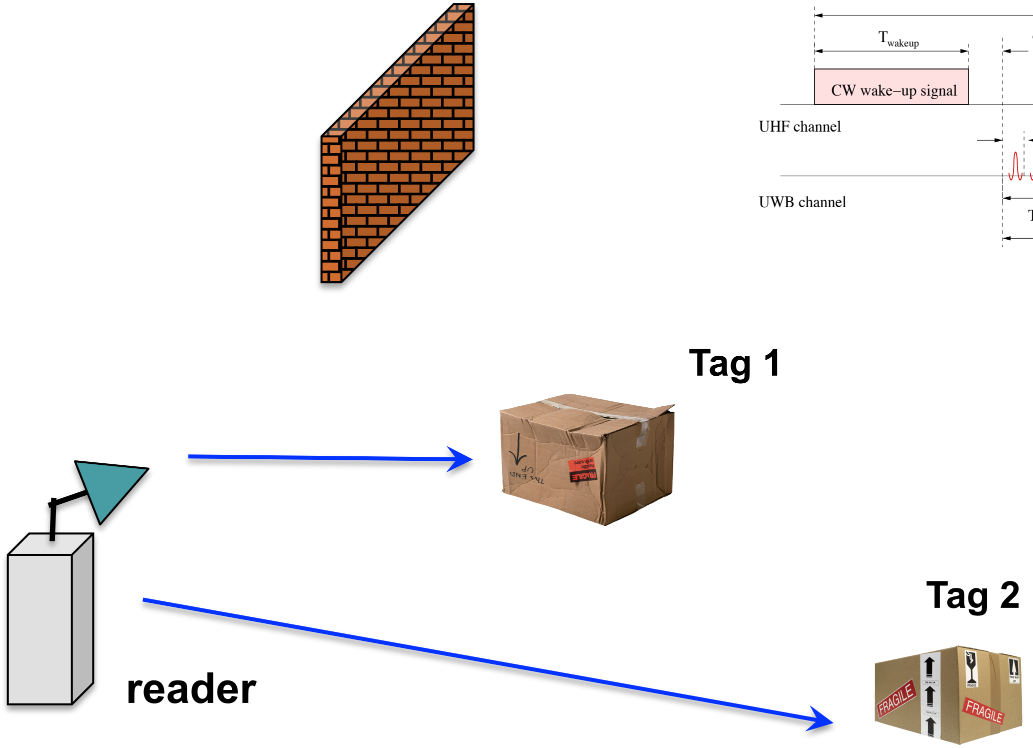
Tag architecture



❖ After the UHF wake-up signal, the Tag is switched on and changes continuously its reflection property according to the sign of code symbols $\{c_n\}$ (every T_c seconds) and data symbols $\{b_n\}$ (every $T_s=T_c*N_s$ seconds)

Tag-Reader passive communication (1/4)

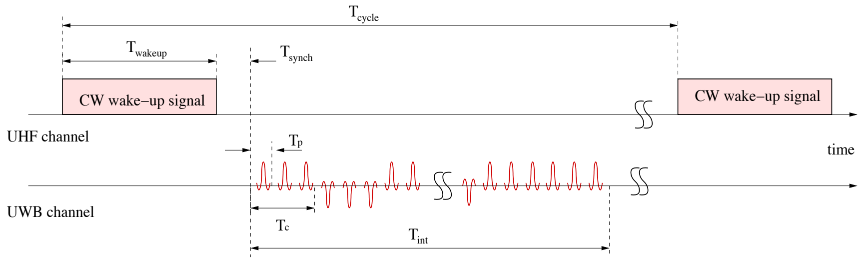


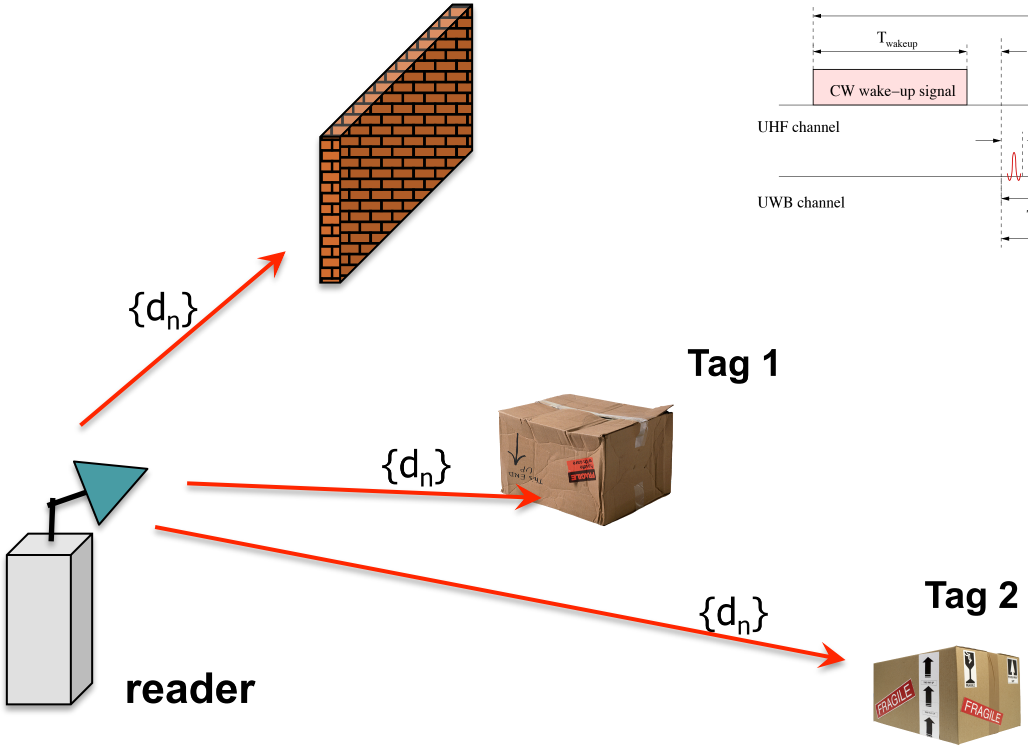


UHF wakeup

- Tags are in sleeping state to save energy
- They are woken-up through a CW UHF signal

Tag-Reader passive communication (2/4)





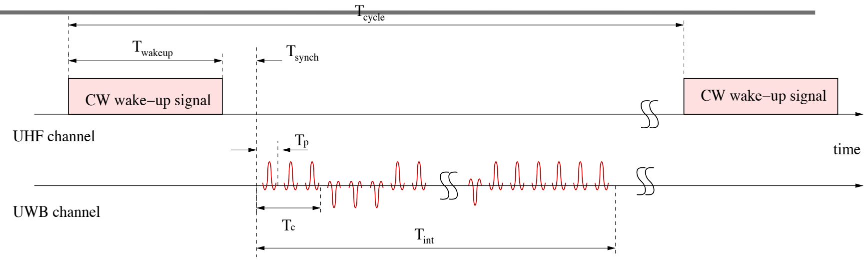
UHF wakeup

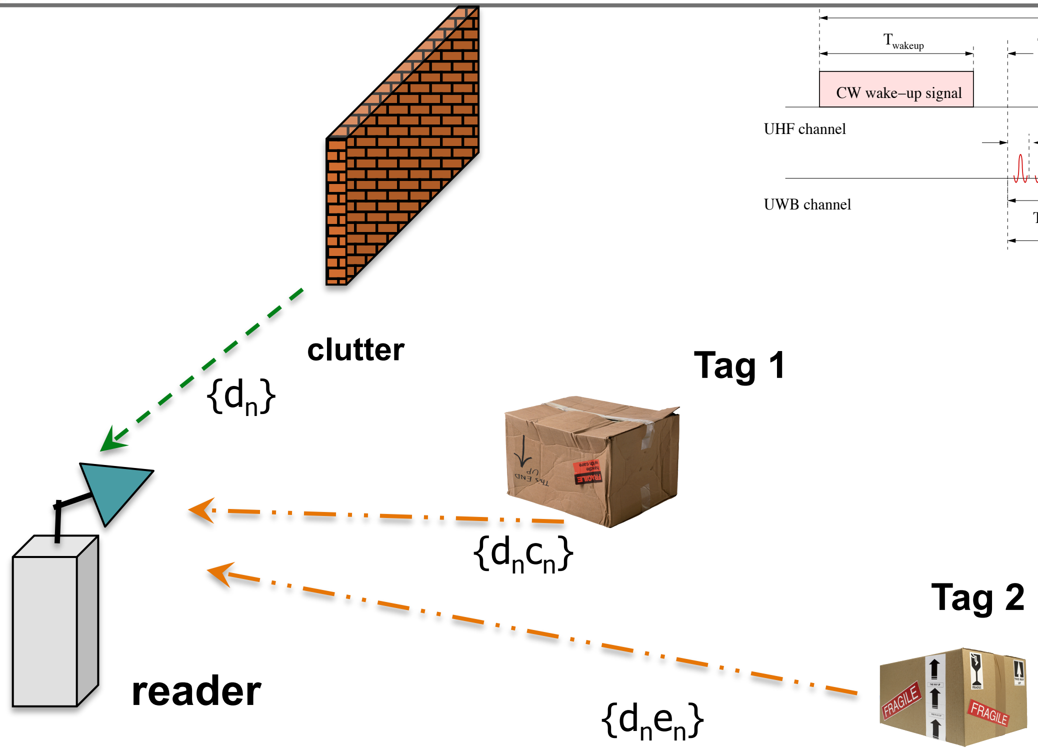
UWB interrogation

$\{d_n\}$: reader's code

- Readers transmit a coded UWB interrogation signal

Tag-Reader passive communication (3/4)





UHF wakeup

UWB interrogation

UWB backscattered signal (tags)

Clutter

- Tags then reflect back the incoming UWB signals with modulation
- Signal backscattered by tag results to be spread by the combined code $\{d_n\ c_n\}$
- Signal backscattered by the environment (clutter) results to be spread by code $\{d_n\}$

$\{d_n\}$: reader's code
$\{c_n\}$: TAG 1 code

$\{e_n\}$: TAG 2 code

Tag-Reader passive communication (4/4)

Signal received by the reader

$$r_{\text{reader}}(t) = \sum_{k=1}^{N_{\text{tag}}} \left[\left(s_{\text{reader}}(t) \otimes h^{(k)}(t) \right) \cdot m^{(k)}(t) \right] \otimes h^{(k)}(t) \; + s_{\text{reader}}(t) \otimes h^{(\text{C})}(t) + n(t)$$

Interrogation signal

Reader to *k*th tag channel impulse response

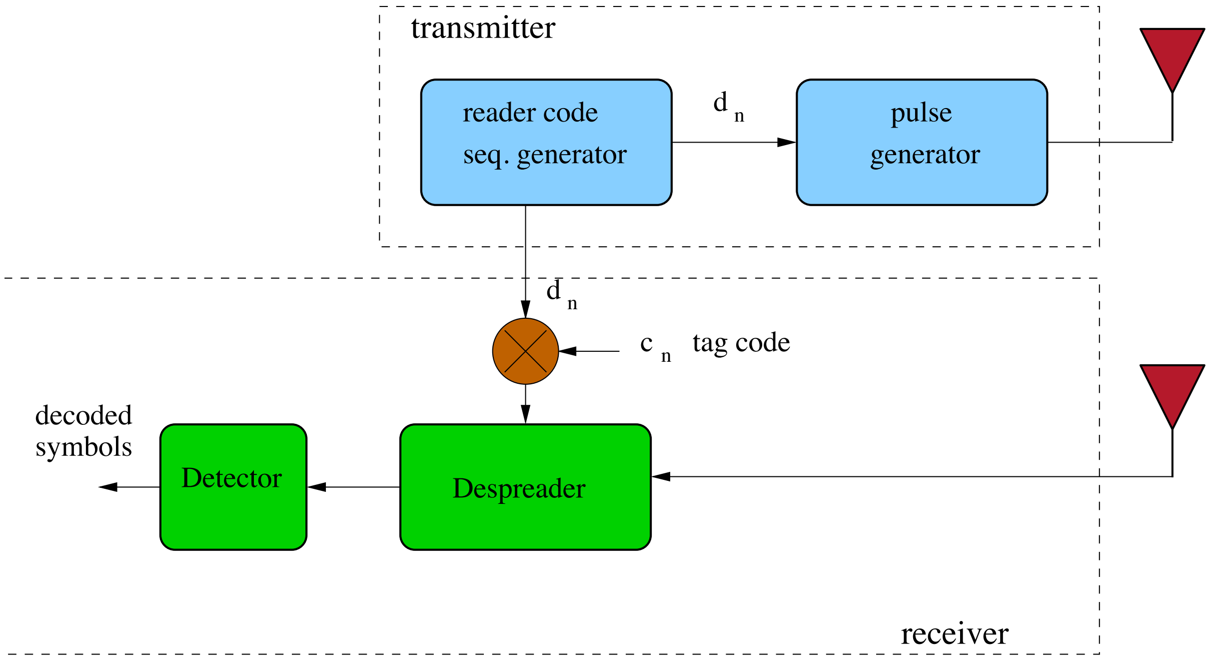
Tag's switch status

Clutter channel impulse response

Receiver noise

- Multi-tag interference + clock drift + clutter + multipath+ noise
- Doubly convoluted channel → Poor link budget

Reader architecture: RX section



TX antenna

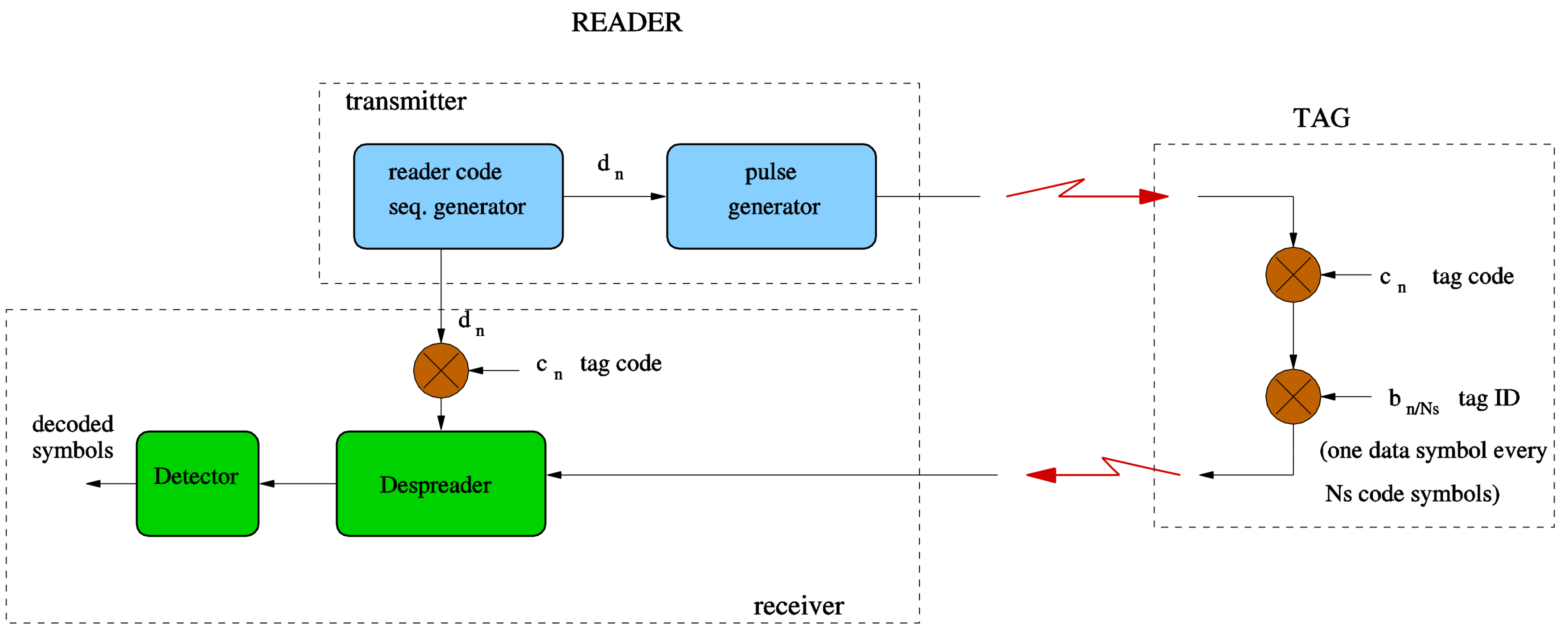
RX antenna

$\{d_n\}$: reader's code

$\{c_n\}$: Tag's code

- At the receiver the signal is de-spread using the composite sequence $\{d_n c_n\}$ which identifies the couple reader-Tag

Equivalent scheme of the backscattering link



- If the Tag code has zero mean → the clutter is removed after the de-spreader (if slow-varying)
- Multiple readers can access the same tag using different codes provided that they have good-cross correlation properties (e.g., Gold codes)

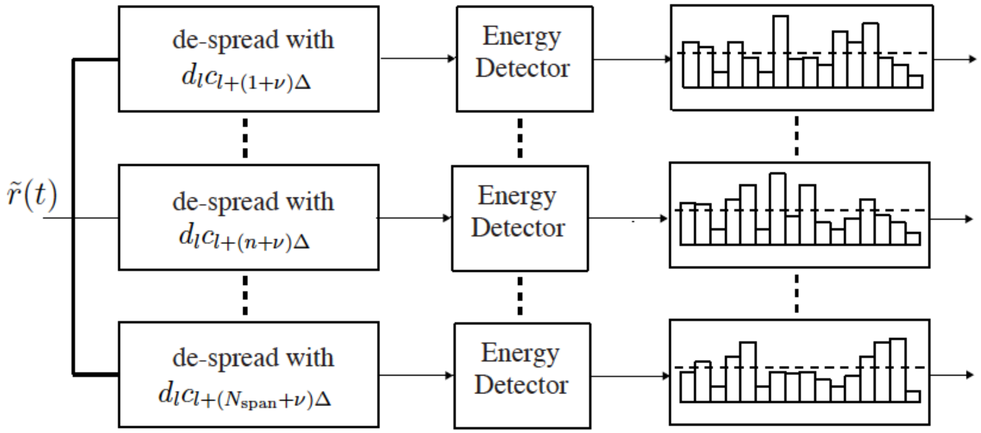
Receiver signal processing

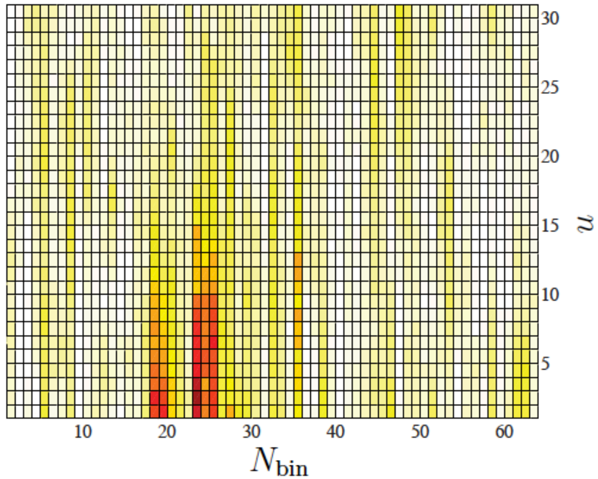
Tag Detection

- Available RF front-end constraints
- Estimation of the two-way channel has high complexity
- Code acquisition might be very slow

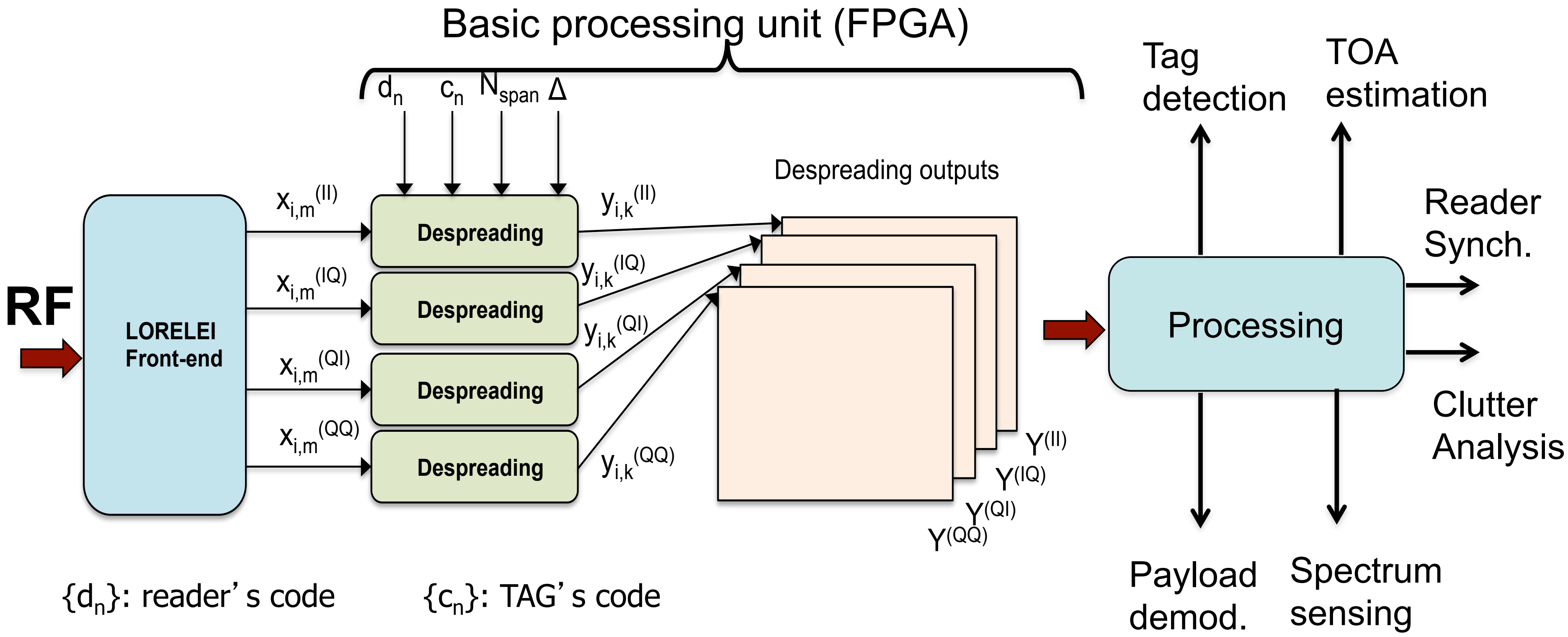
Parallel partial coherent receiver (low complexity)

To counteract the presence of clock drift and synchronization uncertainties, for each finger output de-spreading is performed with the composite sequences given by $\{d_n\}$ and N_{span} shifted versions of Δ PRPs of the intended useful tag code $\{c_n\}$



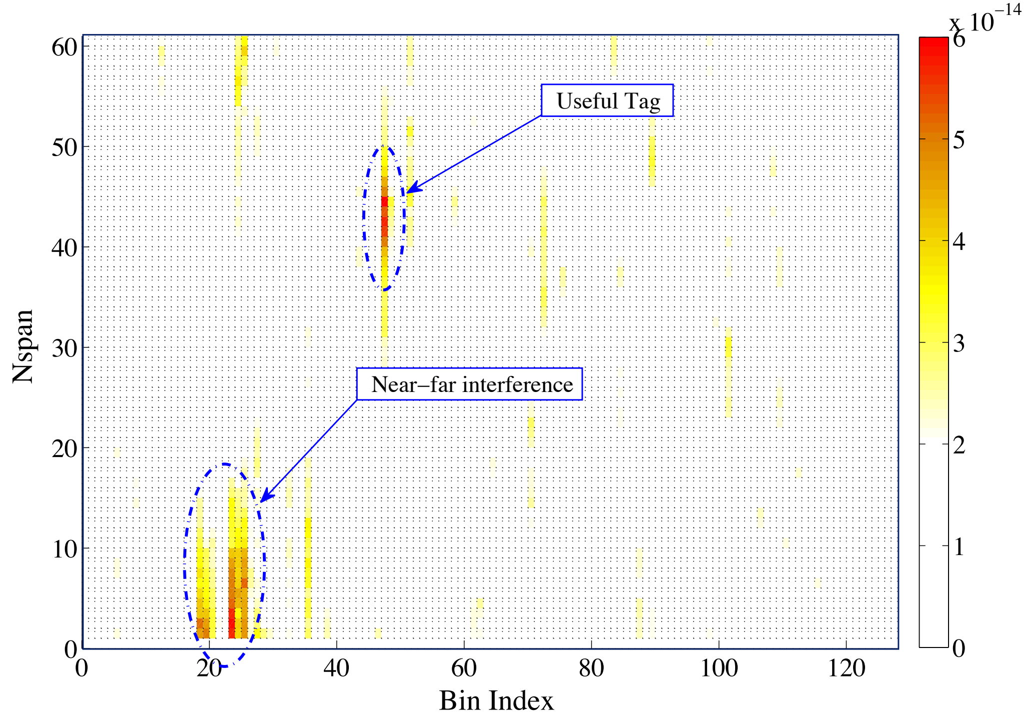


Receiver: signal processing



- Signal backscattered by tag results to be spread by the combined code $\{d_n\ c_n\}$
- Signal backscattered by the environment (clutter) results to be spread by code $\{d_n\}$
- Signal coming from other readers results to be spread by readers' code
- To acquire potential tag code offsets (caused by wake-up offset and clock drift), multiple despreadings are performed in parallel for a set N_{span} of possible offsets

Example of Energy Matrix for tag detection



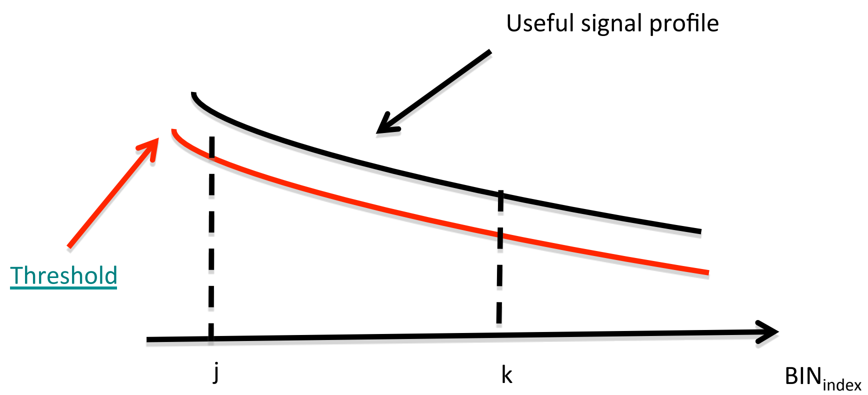
Comparison of each bin with a threshold → threshold design to minimize the false alarms and maximize the tag detection probability

Near-far effects!

Near-Far Effect

- **Near-far effects** cannot be mitigated by power control schemes as the tag is a passive device

→ Bin-dependent threshold for robust tag detection and TOA estimation in the presence of near-far effects.

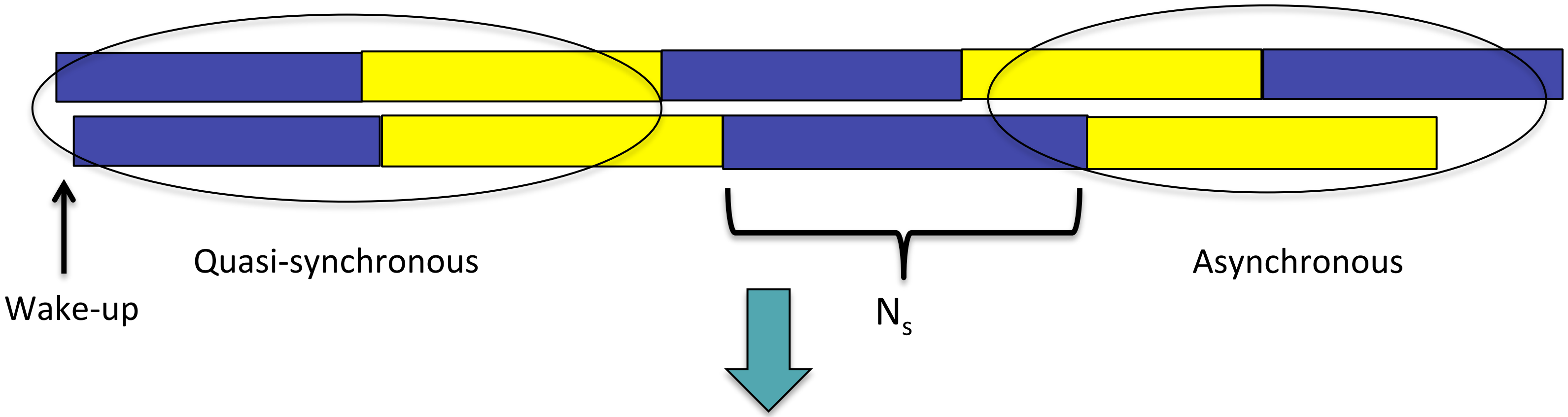


Constant false alarm receiver (CFAR) → bin-dependent threshold design criterium

Spreading code design issues

Requirements to be fulfilled by the spreading code:

- *Large number of available codewords*
- *Clutter removal capability (i.e. zero mean codes)*
- *Multi-Tag interference suppression/mitigation*
- *Robustness to strong tag's clock drifts (i.e. zero correlation zone or chip duplication)*
- *Different working conditions: quasi-synchronous just after the wake-up, then completely asynchronous due to the strong clock drift.*



To fulfill the previous requirements, **Orthogonal Gold codes** have been chosen, as they maintain good cross-correlation properties in both synchronous and asynchronous conditions.

Experimental results:

The GRETA and SELECT projects

The Italian GRETA project

GREen TAgs and sensors with ultra-wide-band identification and localization capabilities

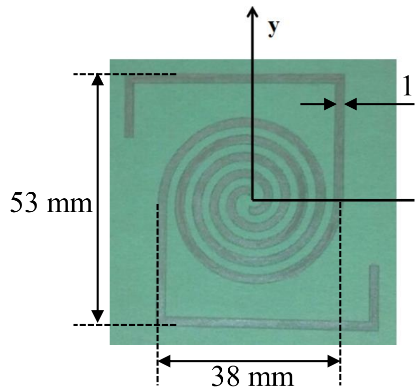
Main objectives for tag design:

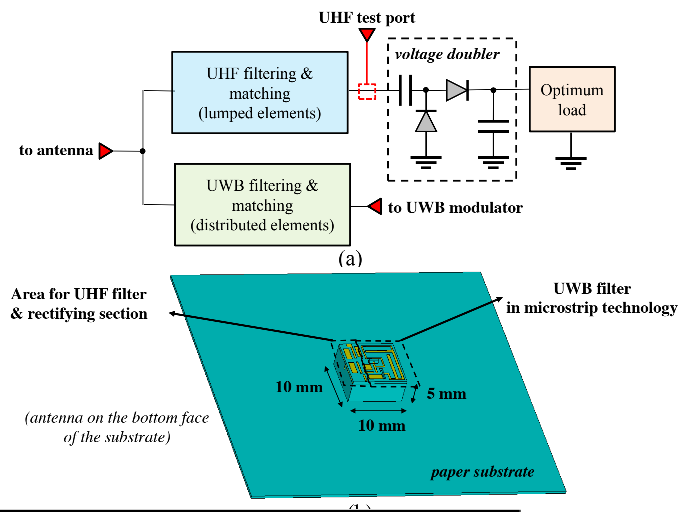
- localizable with sub-meter precision even in indoor scenarios or in presence of obstacles;
- small-sized (with an area in the order of a few square centimeters) and lightweight (without cumbersome batteries);
- eco-compatible (made with recyclable materials as paper);
- energy-autonomous;
- easy integrable in goods, clothes and packages;
- low-cost to permit the pervasive diffusion of tags in the environment;
- capable of sensing physical quantities.

Tag subsystems (GRETA)

On paper UWB/UHF Antenna design and rectifiers

Loaded with the UWB and UHF backscatter modulator and the energy-harvesting block

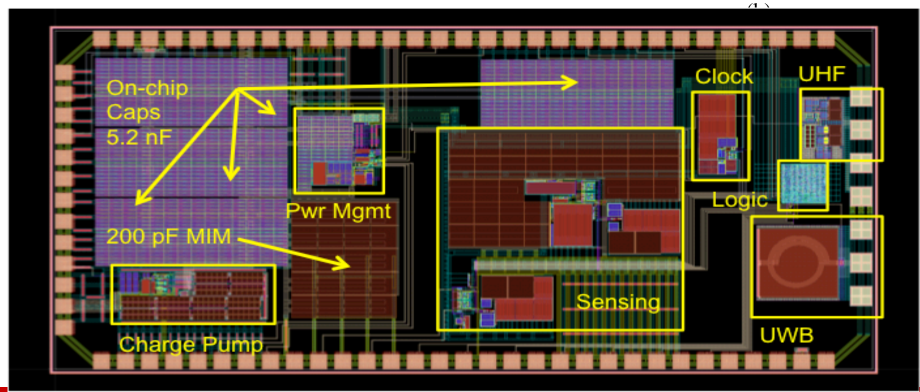




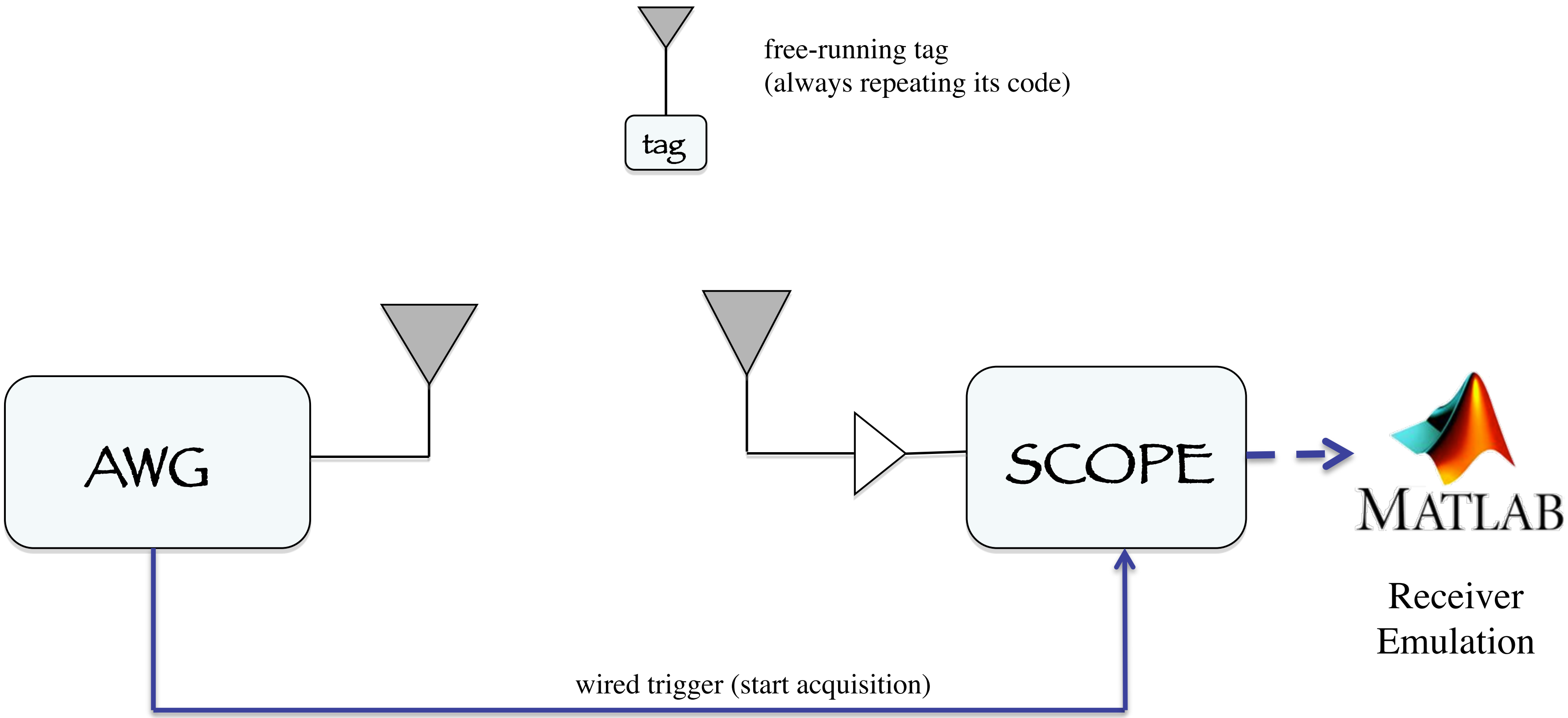
The "GRETA" chip

Layout of the custom chip under test developed at Univ. Bologna containing:

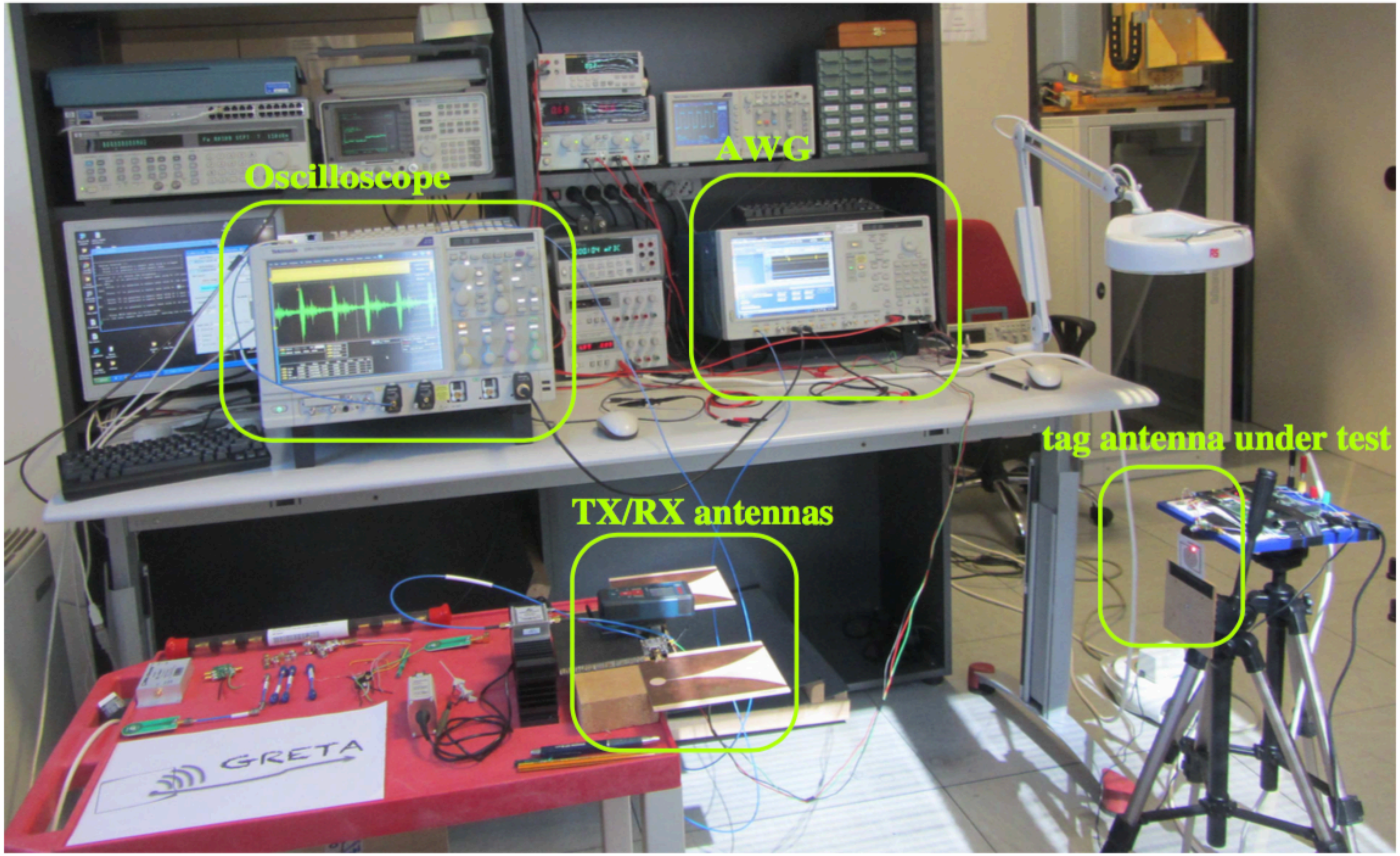
- UWB backscatter modulator,
- energy harvesting unit at UHF,
- power management unit,
- control logic.



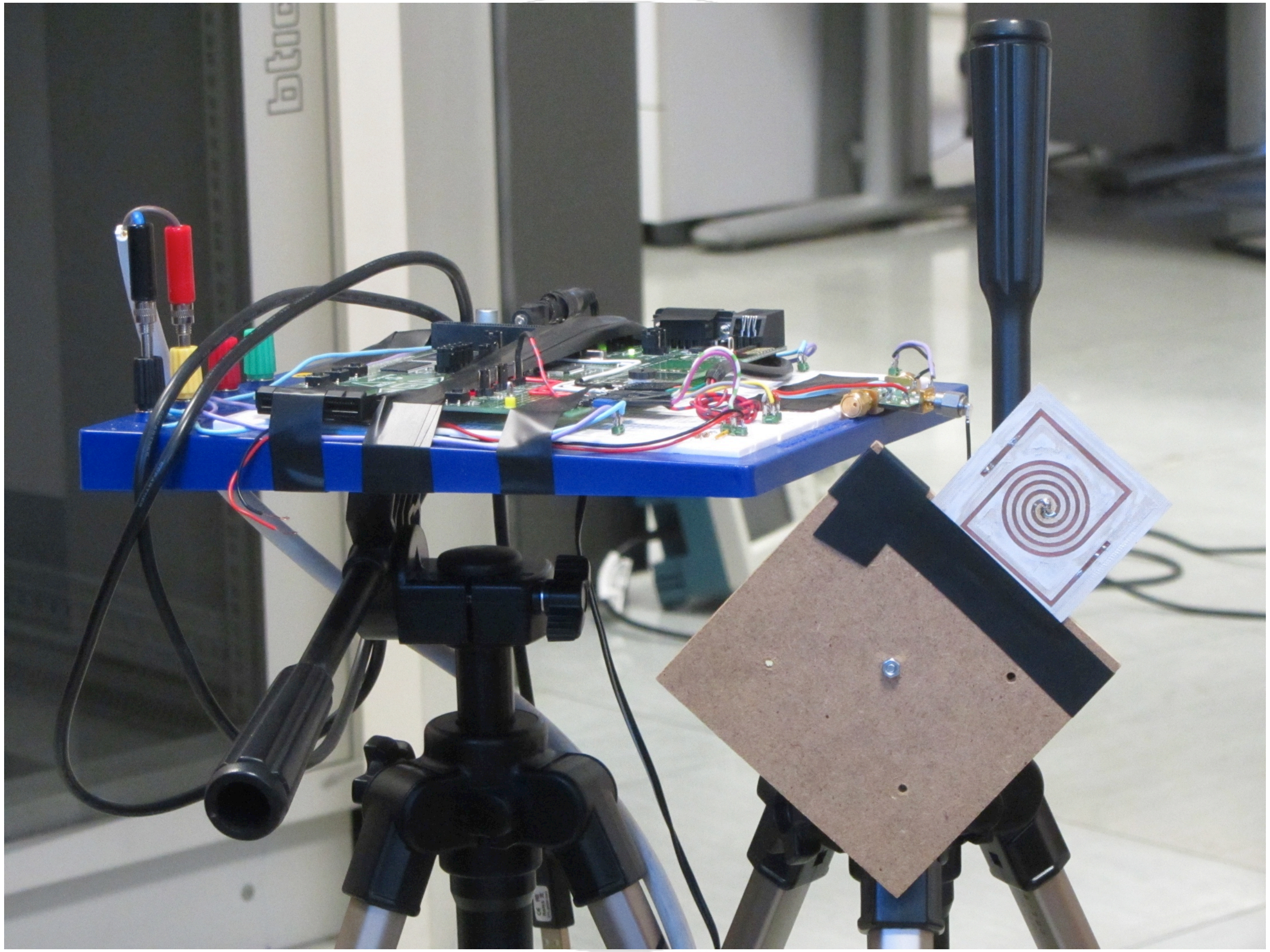
Laboratory tests



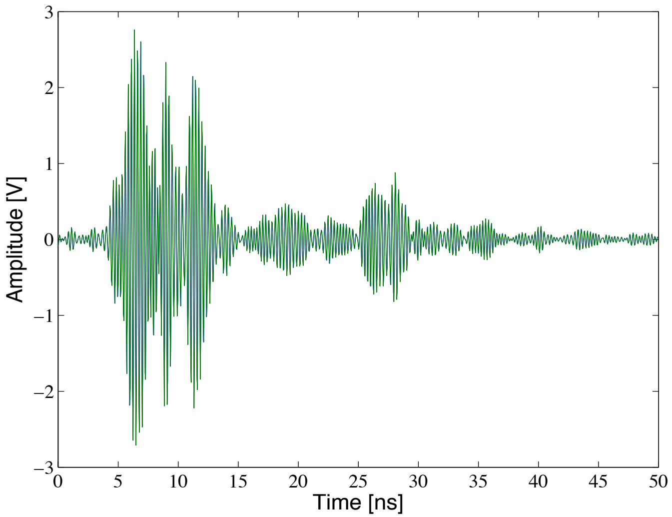
Laboratory tests



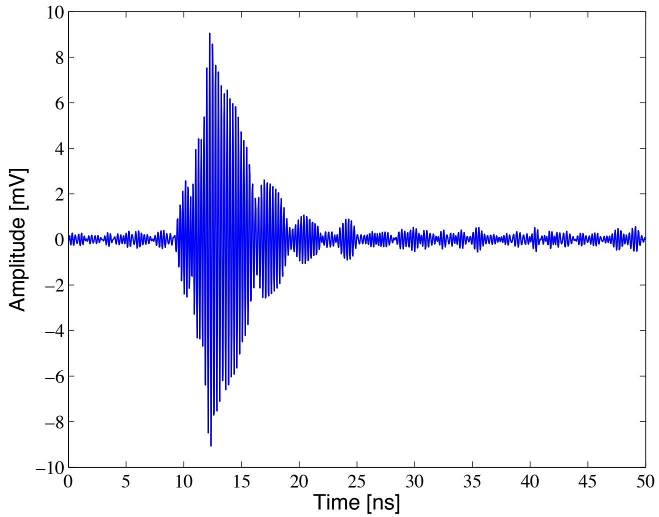
The UWB "tag"



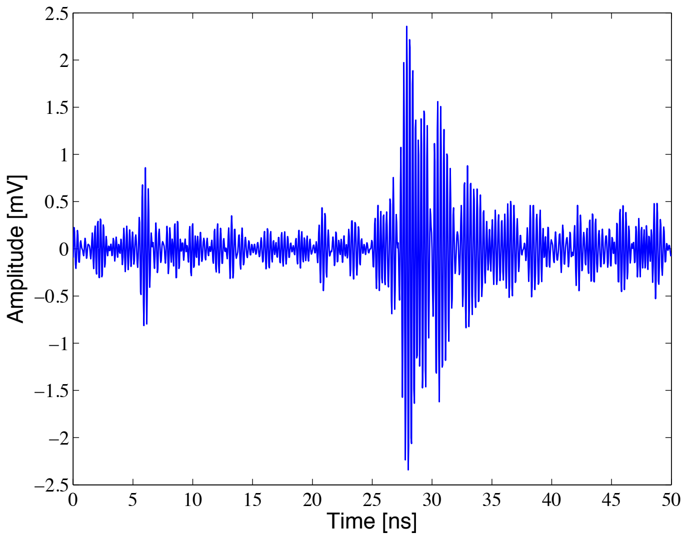
Measured waveforms



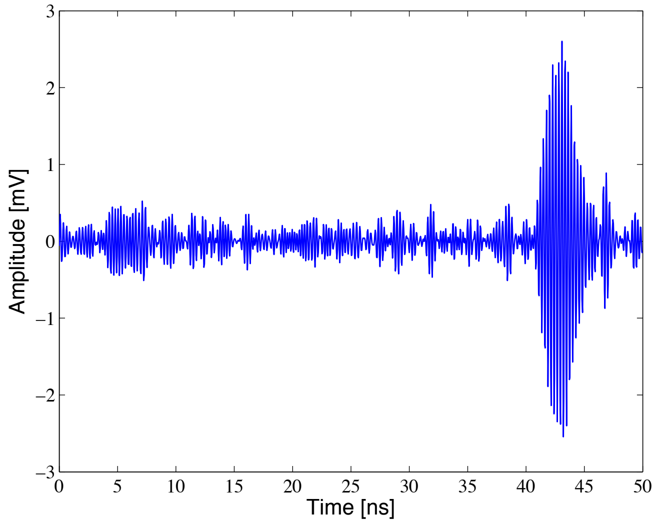
RX signal
(oscilloscope)



Tag
@ 50cm



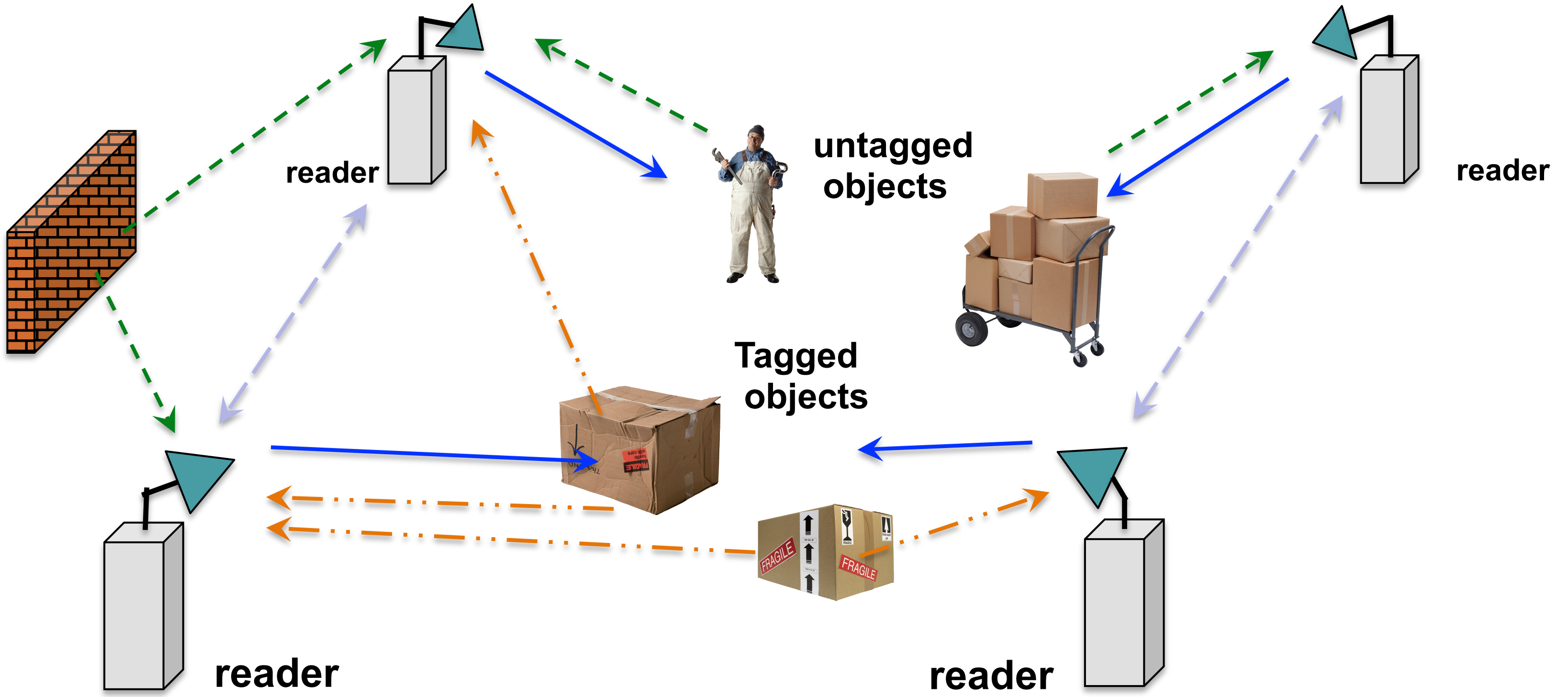
Tag
@ 300cm



Tag
@ 500cm

The EU Project SELECT

Detection and tracking of tagged and untagged objects through the processing of UWB backscattered signals



Integration of RFID, Localization (RTLS) and Wireless Sensor Radar (WSR) technologies

Tagget and untagged objects tracking

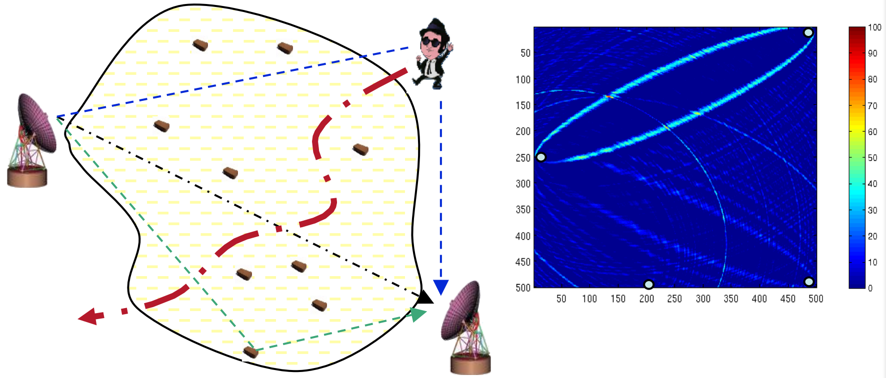
Starting from the processing of the interrogation signals backscattered by the environment:

Localize and track **tagged objects** through proper combination of TOA estimates

Reliable tag detection up to 5-6 meters (with detection rate >90% and false alarm <10^{-2}) in realistic LOS environments;

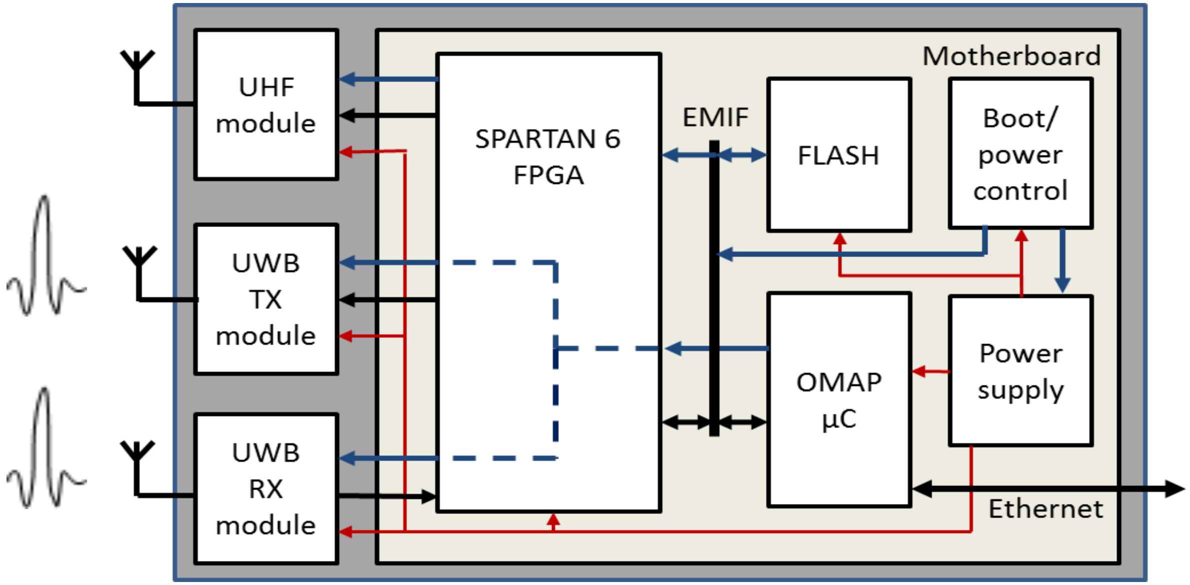
Ranging errors between tag and readers down to 30cm in realistic LOS environments up to 5-6 meters

Track **untagged moving objects** through proper analysis of clutter variations (*wireless sensor radar*)



Theoretical feasibility with accuracy <1m and 75% cell coverage with object speed up to 3m/s (simulations) with update rates>1Hz

Reader hardware architecture



RF analog front end:

- RF pulses generation and reception

FPGA:

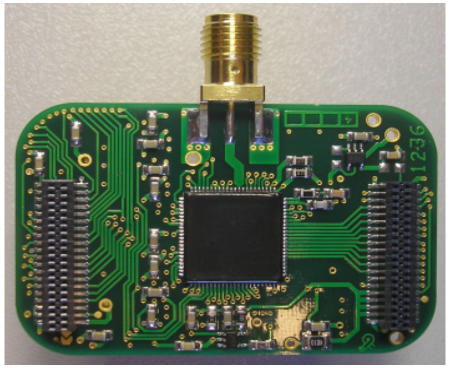
- Applies time-critical digital baseband signal processing algorithms

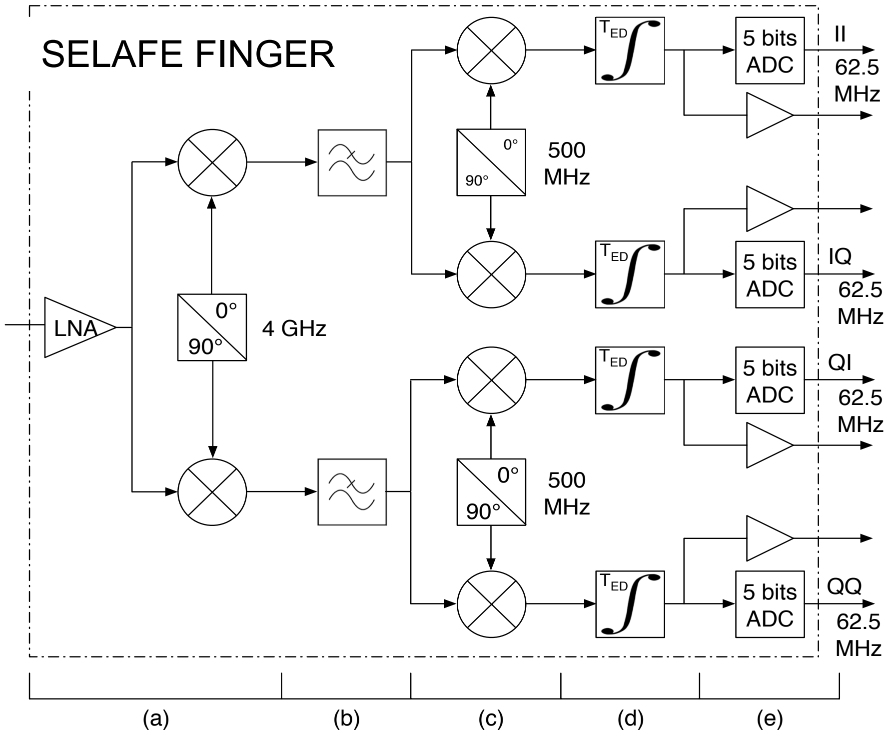
Microprocessor:

- Performs low-rate complex computations and asynchronous tasks

Reader Analog Front End

SELAFE board/chip (CEA-LETI)

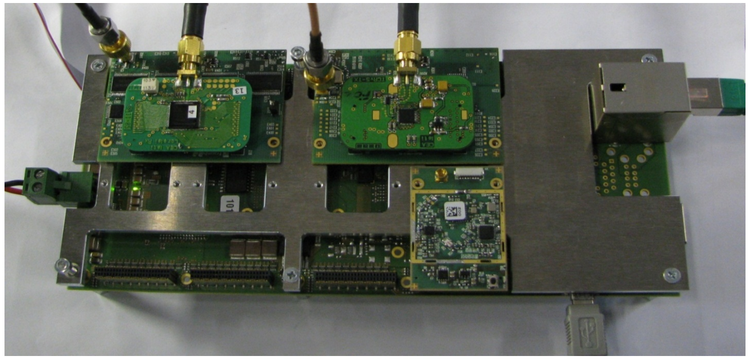




- Double-quadrature receiver
- Integration of the pulse inside a 2 ns window performed at the baseband (pseudo-energy)
- 8 "fingers" (integrators working at each symbol time)
- For each finger, 4 outputs are available

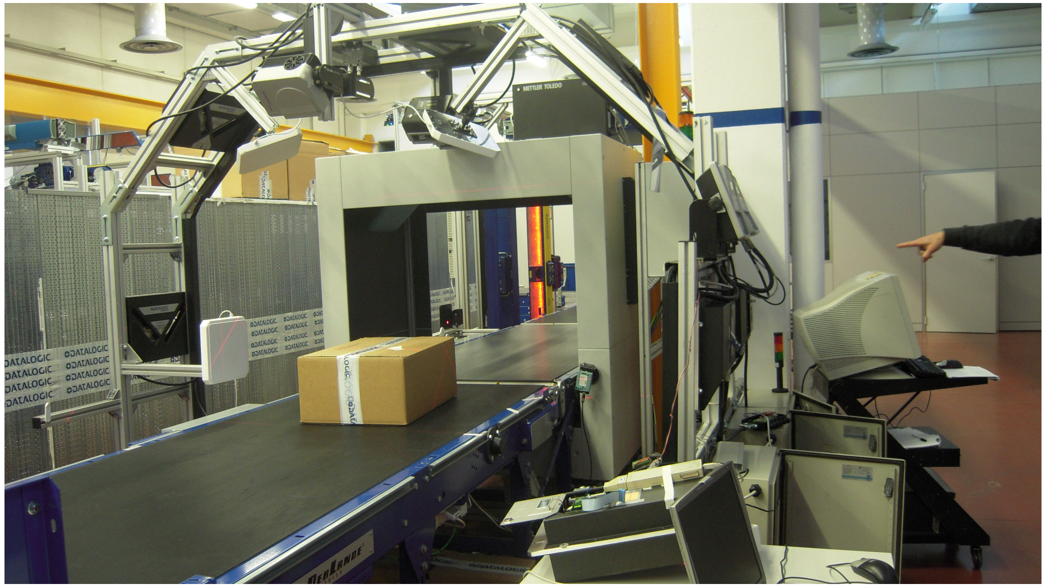
Main characteristics of the SELECT system

- Center frequency: 4.5 GHz – Bandwidth: about 1 GHz
- Reliable tag detection up to 5 meters (with detection rate >90% and false alarm <10^{-2}) in realistic LOS environments
- 30 cm precision ranging
- Up to 10 Hz refresh rate

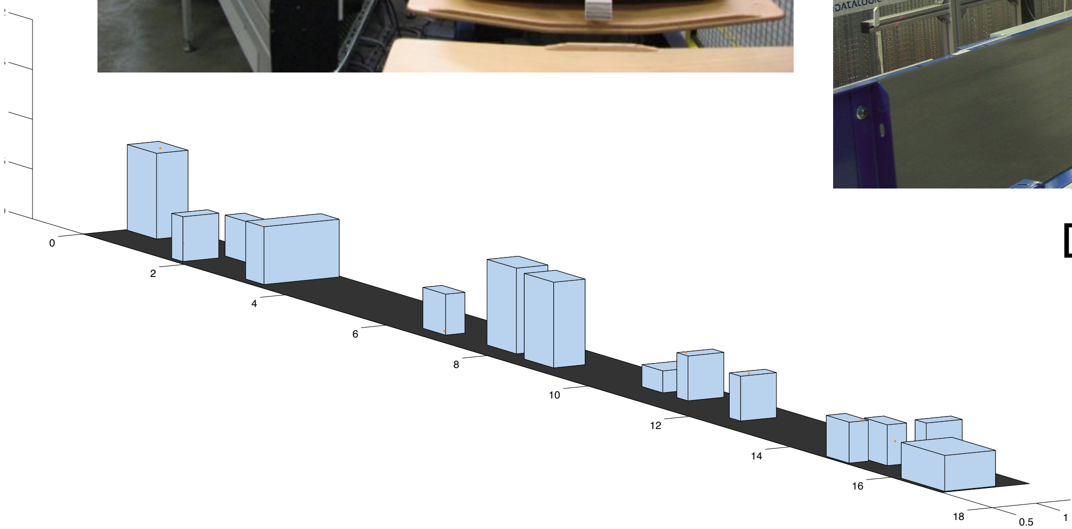


- Parallel detection of multiple tags (limited by HW capabilities)
- System capabilities proven for baggage sorting scenario on a conveyor belt (up to 2.8 m/s)

Test bed: *Baggage sortation in airports*



Datalogic sortation plant



See the Video

Non-regenerative relaying techniques for coverage extension

Relaying techniques for coverage extension

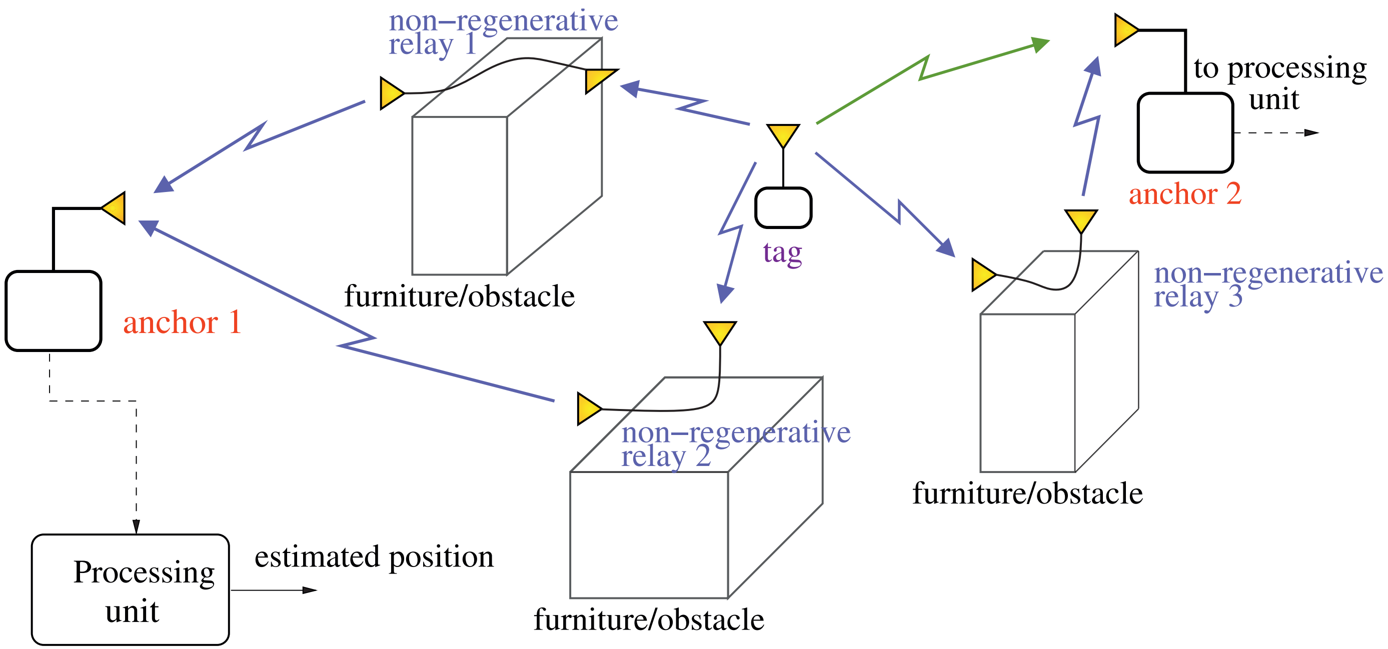
Regenerative relays (detection & forward): unfortunately the complexity is comparable to that of the readers

The idea is to add low complexity **active (amplify&forward) or passive (just forward) non-regenerative UWB relays** to create ***virtual anchors*** (readers) and reduce the necessity of large infrastructure (large number of readers)

Non-regenerative relays lead to simpler and cheaper implementation with respect to regenerative relays

Non-regenerative ***passive* relays** (also referred to *cold repeaters*), in which no signal amplification is present, are of particular interest

Localization system employing UWB non-regenerative relays



N_A anchors and N_R relays with (known) positions

Main advantages of non-regenerative relays

Advantages

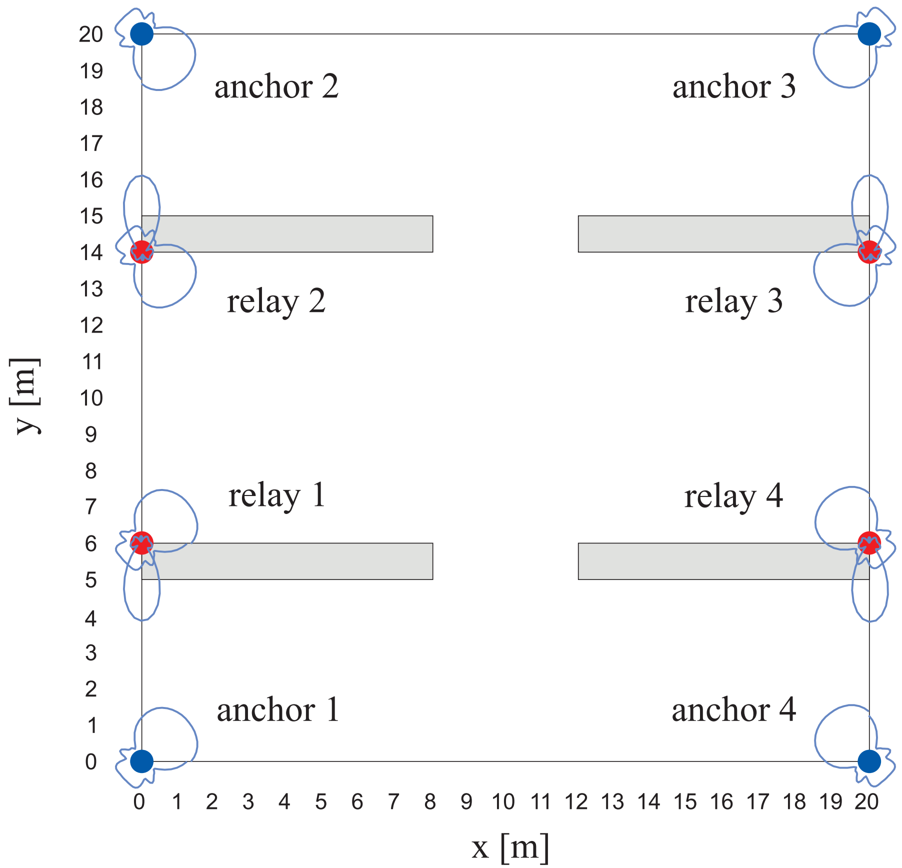
- Extremely low cost
- Absence of power supply requirement (in case of passive relays)
- No tight synchronization issues
- Bi-directionality and transparency to signals format
  - The same network could be used to localize *active tags* (e.g., existing UWB RTLS systems), or to localize *passive tags* based on backscatter modulation
- Easy deployment

Main issue

- Signals arriving to the reader directly from the tags or after being relayed need some signal processing techniques to solve ambiguities

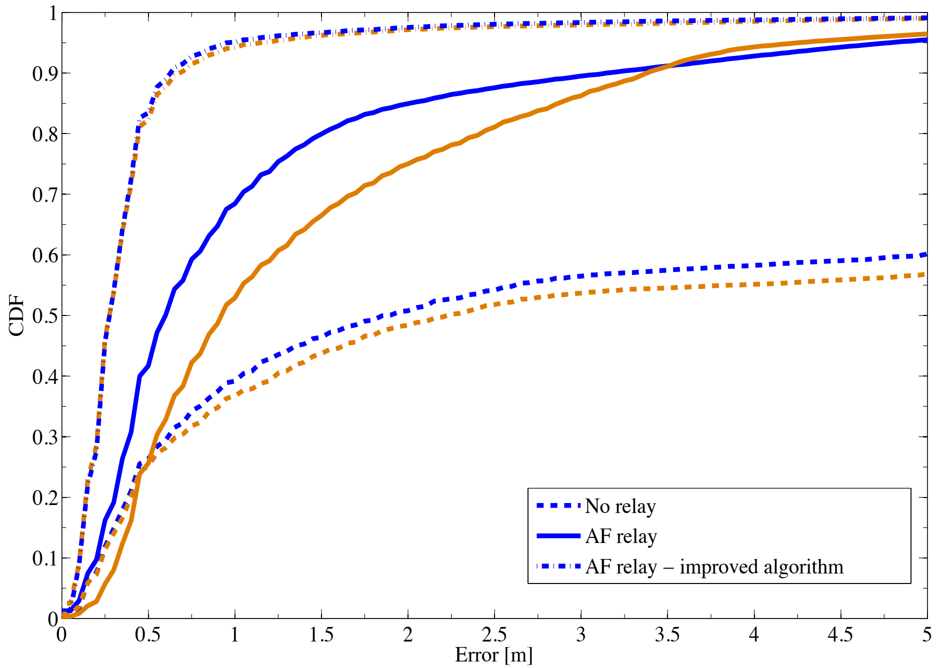
Case study: scenario

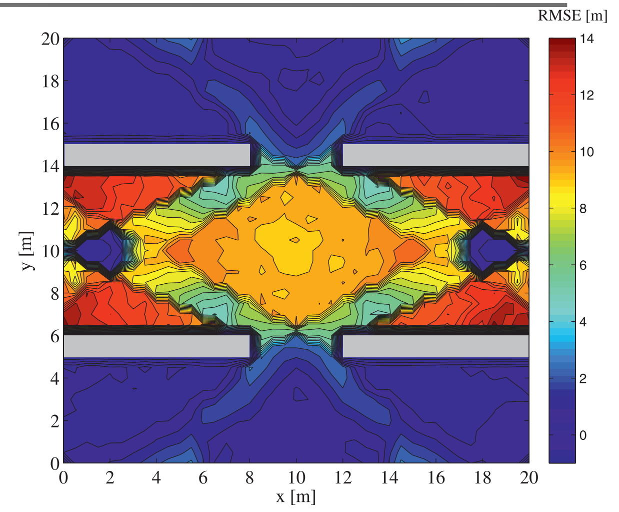
20x20 m² area with 4 completely blocking obstacles, 4 anchor nodes, 4 non-regenerative relays

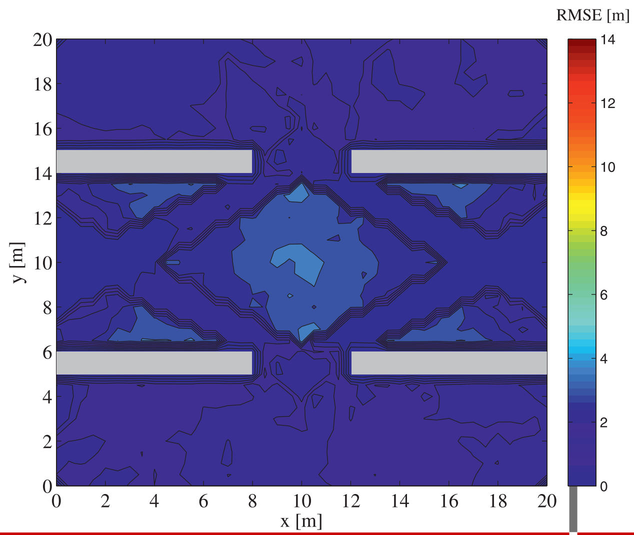


Simulation parameters
FCC-compliant transmission
3.2-4.7 GHz band
Receiver noise figure F=4dB
Antenna gains of 5 dBi and 8 dBi

Case study: simulation results







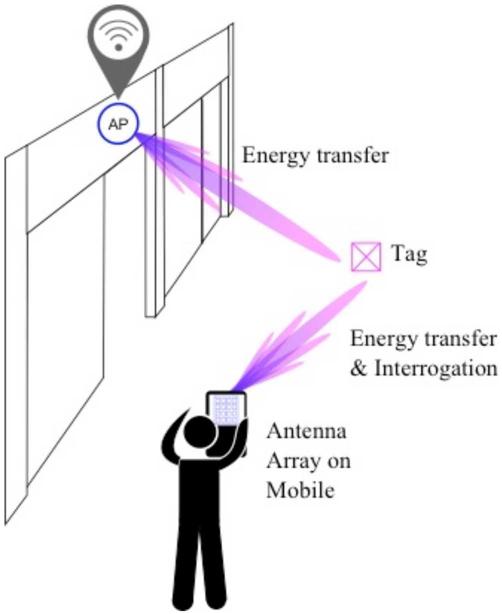
Example of localization error when adopting non-regenerative AF relays with 20dB gain (CDF plot) and with JF relays (RMSE contour map)

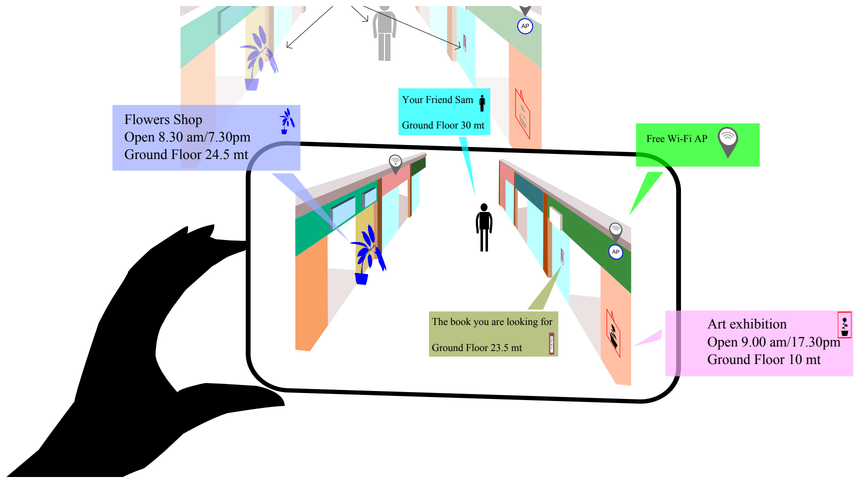
Concluding remarks

- UWB RFID based on backscatter signalling is a promising solution to integrate RFID, RTLS and energy harvesting capabilities for IoT applications
- Several issues addressed in recent research activities
- Some solutions proposed:
  - Robust coded signalling
  - Realization of innovative low-cost UWB-UHF RFID tags providing sensing, communication, high-accuracy localization/tracking
  - Non-regenerative relays to improve localization coverage with low complexity HW

What next?

Perspectives





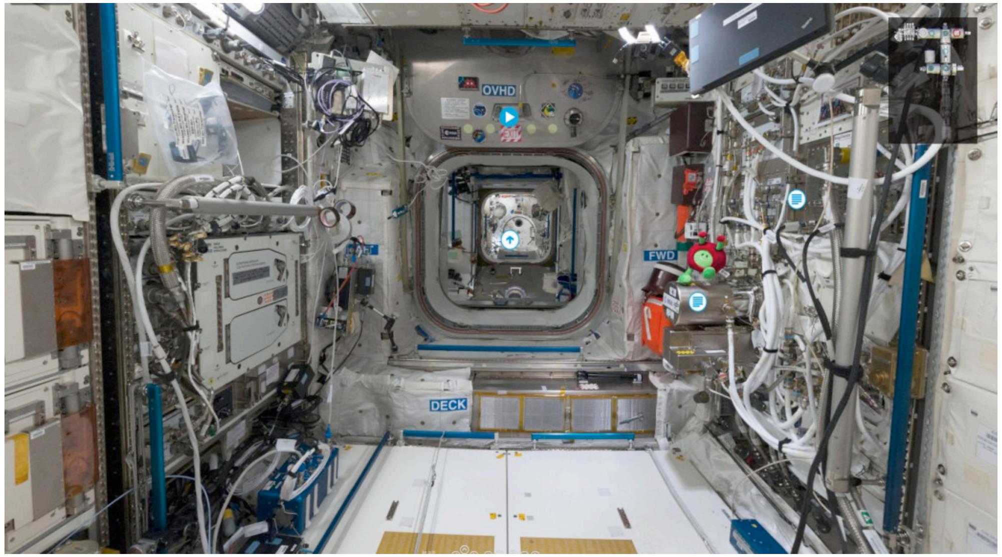
RFID/RTLS integration in smartphones:

- Millimeter wave massive antenna arrays
- Efficient energy transfer mechanisms to energize passive/active tags
- Single node localization

D. Dardari, et al. “The future of Ultra-Wideband localization in RFID,” in 2016 IEEE International Conference on RFID, Orlando, USA, May 2016

Perspectives: “*Lost in Space*”

LOST Project, European Space Agency, (2016-2017):
University of Bologna, Université catholique de Louvain



“Indoor” localization of objects inside the International Space Station

Main requirements: 1cm localization accuracy, passive tags, harsh environment
self-configurable network, long reading range (>10m)

→ **UWB backscattering**

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FP7 SELECT European project: http://www.selectwireless.eu

GRETA Project www.greentags.eu

EURASIP RFID 2015 Special Session: „GRETA Architecture" - http://www.eurasip-rfid.org/?page_id=195

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