RFID LOCALIZATION

Assoc. Prof. Dr. Holger Arthaber

Institute of Electrodynamics, Microwave and Circuit Engineering
TU Wien, Austria

holger.arthaber@tuwien.ac.at

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Interreg Austria-Czech Republic
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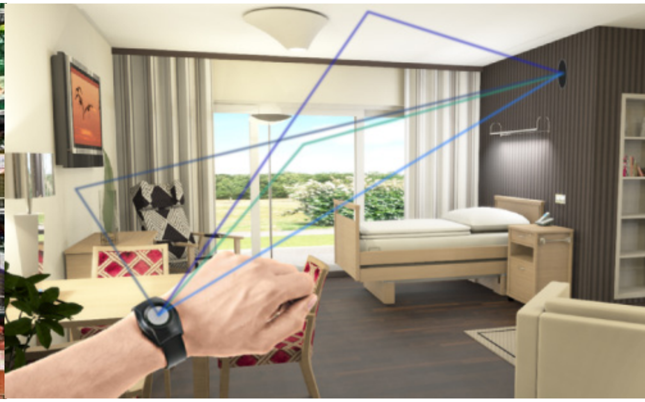

Objectives:
localization and navigation
activity sensing, controlling

Requirements:
accuracy (5 – 100 cm)
reliability (90 – 100%)

Challenges:
heterogeneous scenarios
(dense) multipath channels

Motivation – Application Example #1

- Potential **(future) applications** for RFID
  - **positioning** of massive tag populations
  - **activity recognition** (humans interacting with goods)
- Sales floor
  - recommender systems for “brick and mortar” stores
- Warehouses
  - Picking stations stations
- Requirements:
  - large read volumes (entire rooms); decimeter-range accuracies
  - reliability 50 % (activity recognition) … >99 % (inventory)

Images: SSI Schaefer, brighamyen.com

- **Traditional RFID applications** domains – **ranging** allows for:
- RFID gates
  - distance bounding, range gating → reduce false detects
  - movement direction detection
- Conveyor belts
  - sequencing of items on conveyor belt
  - **range gating** for parallel belts
- Requirements:
  - confined read volumes; 0.5 – 1 m accuracy; (typically) ~100 % reliability

Images: intermec

Motivation – Challenges in Localization

- **Accuracy**
  - simple solutions (e.g. field strength based) have limited accuracy
  - high precision requires dedicated localization hardware

- **Cost**
  - low cost solutions are inaccurate
  - dedicated localization hardware is expensive, requires batteries, problematic for high volume markets

- **Interoperability**
  - localization hardware with high accuracy is “proprietary”
  - existing tag populations can’t be used with proprietary systems

- **Use of existing tag-populations**
  - only change infrastructure but not the tag
    (there are billions of RFID tags in the field, waiting to be localized)

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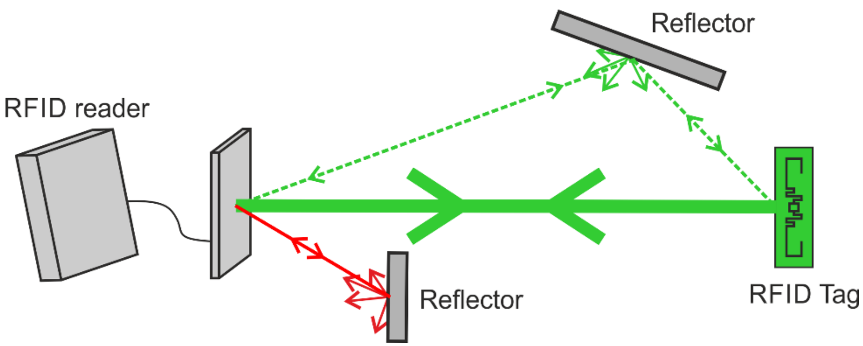
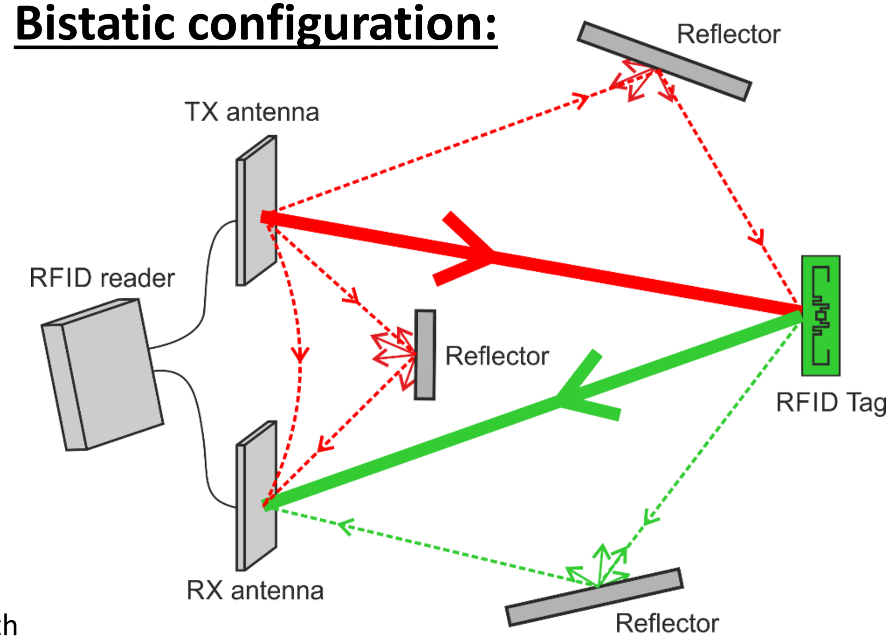
Monostatic configuration:



Bistatic configuration:



red ……. unmodulated signal from reader
green … signal with tag-modulation on it

line of sight path
other paths, e.g. via reflectors

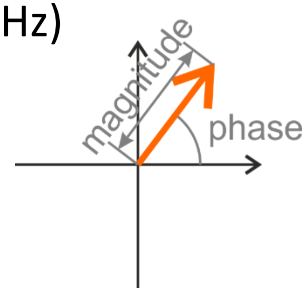
Problems:

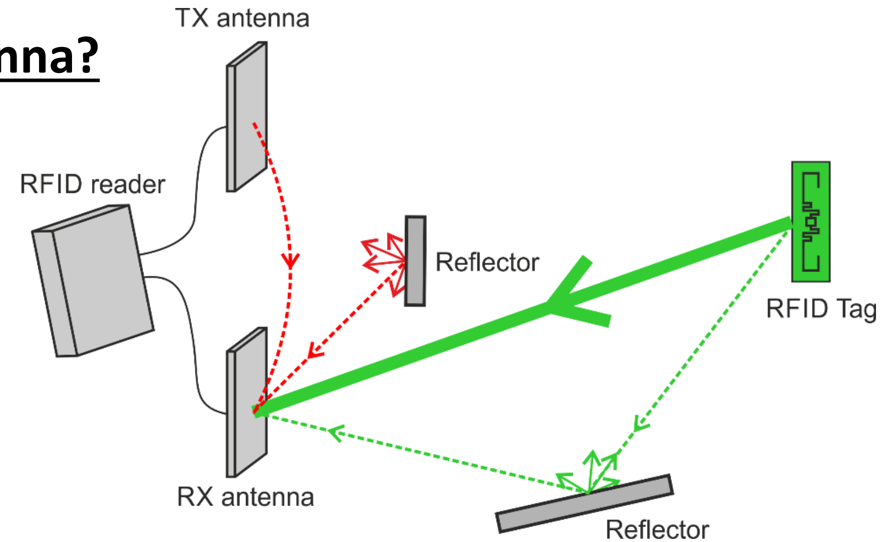
- „Multipath“: several ways/paths from antenna to tag
- „Reflectors“: introduce multipath and/or „blind“ the RFID reader
- „Dead spots“: no communication zones due to interference

The UHF RFID Radio Scenario – Signal Contributions

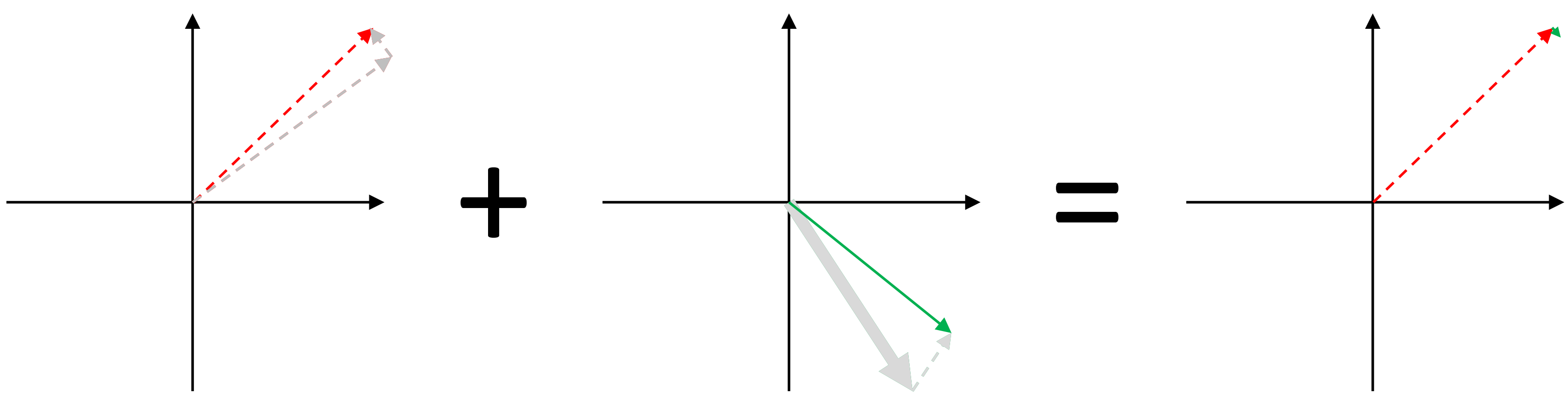
How does the signal look like at the RX-antenna?

- Radio waves are described by
  - frequency (e.g. 868 MHz)
  - magnitude
  - phase





- RX antenna receives unmodulated TX signal and tag‘s modulated response



large signal (dominated by TX-RX-coupling) | very small signal, shown enlarged (dominated by line-of-sight path) | combined signal (tag response almost invisible)

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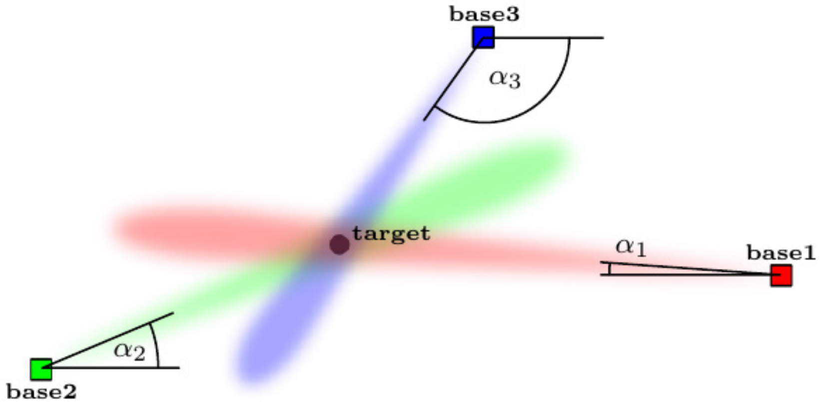
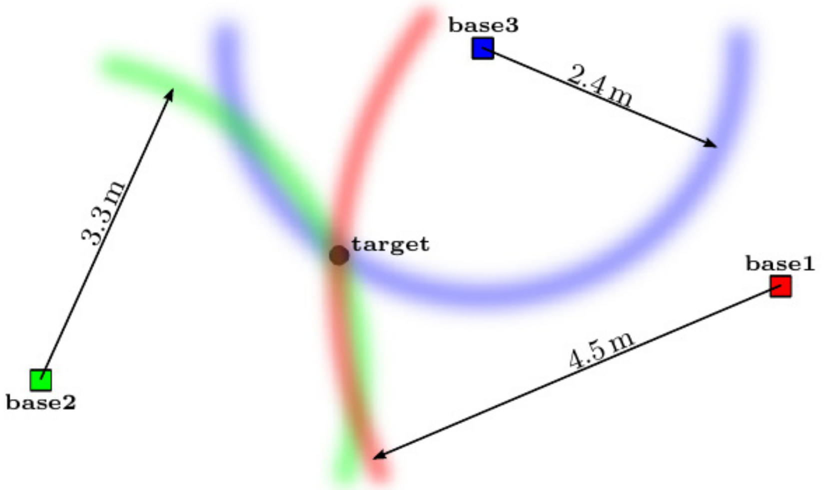
2D Positioning Methods

1) Angle based (Triangulation)
   - requires at least 2 RFID readers at exactly known positions and orientations



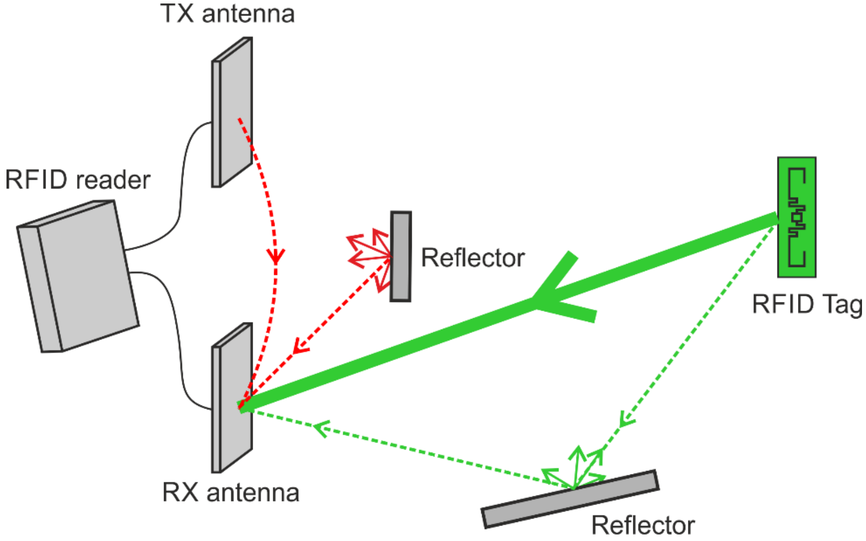
2) Distance based (Trilateration)
   - requires at least 2(3) RFID readers at exactly known positions



3) Combination of Angle + Distance
   - works with a single reader

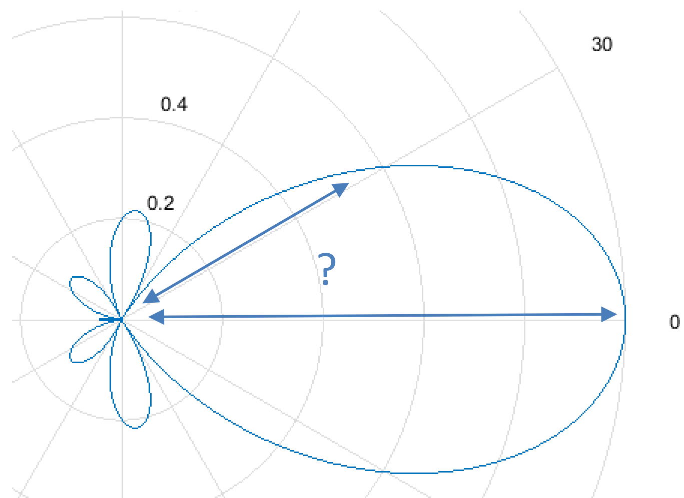
Received Signal Strength (RSSI)

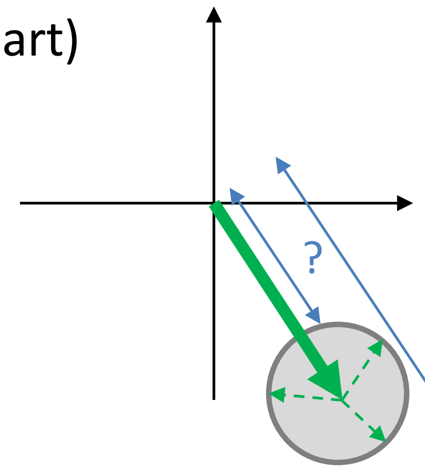
- Uses the received signal power
- Gives a distance estimate



Problems:

- Multipath results in inaccuracy
- Antenna pattern influence
- Tag‘s reflection is not constant
- Many RFID reader chipsets aren‘t capable of vector measurements (they either use real or imaginary part)





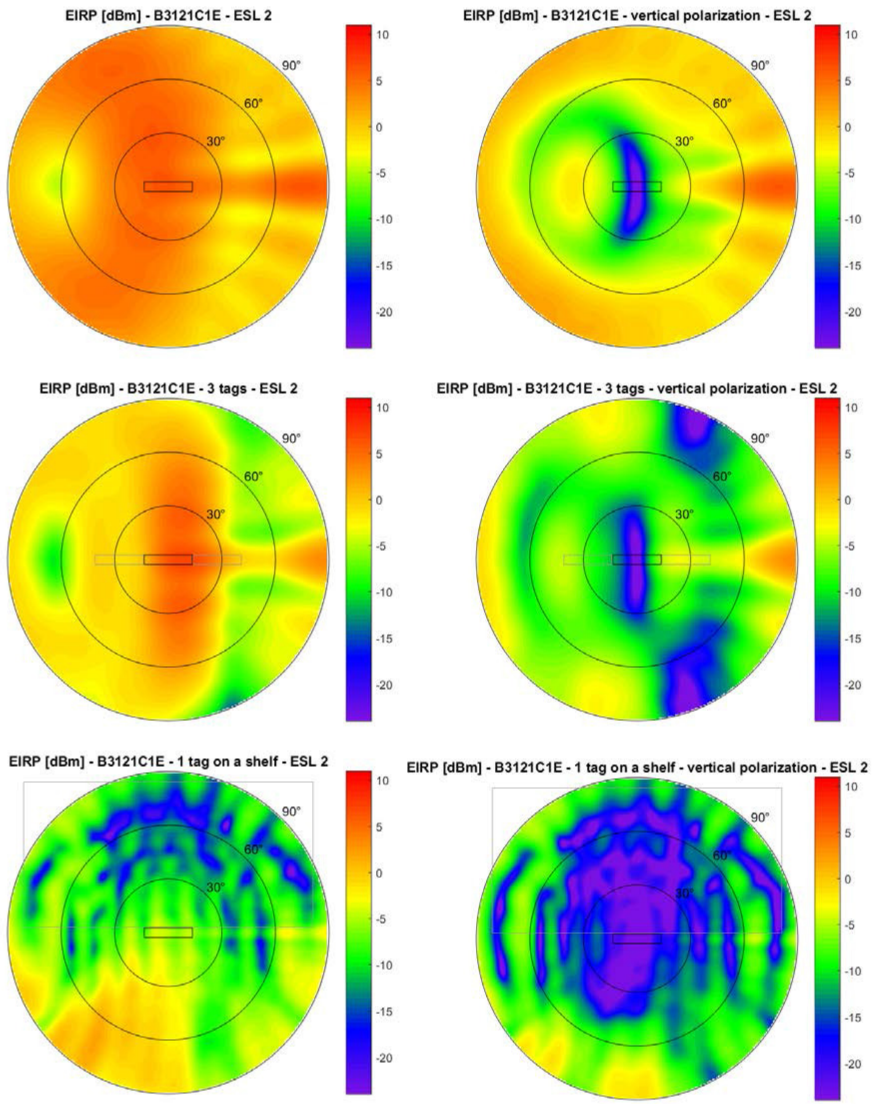
Antenna measurement example proofs the strong angular-dependency of RSSI ☹

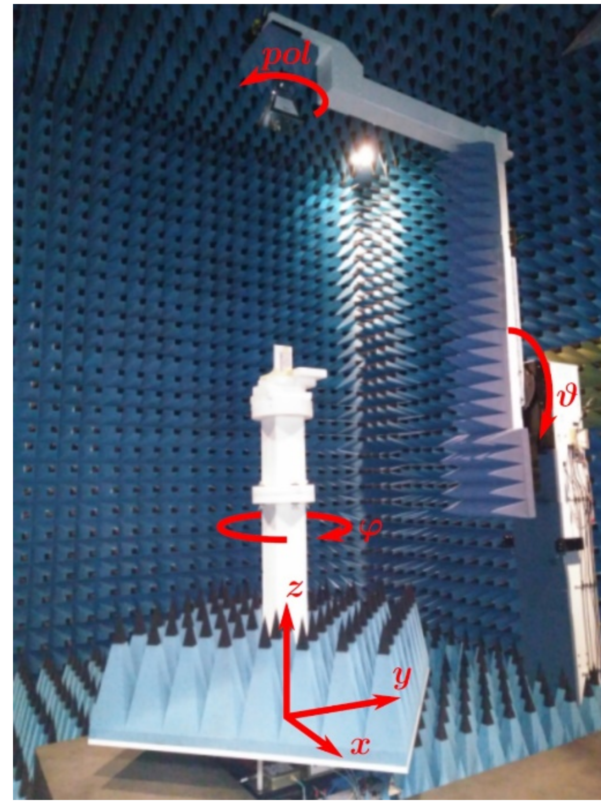
total power from tag power in one polarization

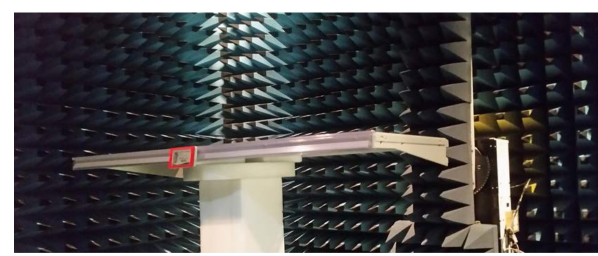
single tag in air

tag in between two other tags in air

single tag mounted on shelf

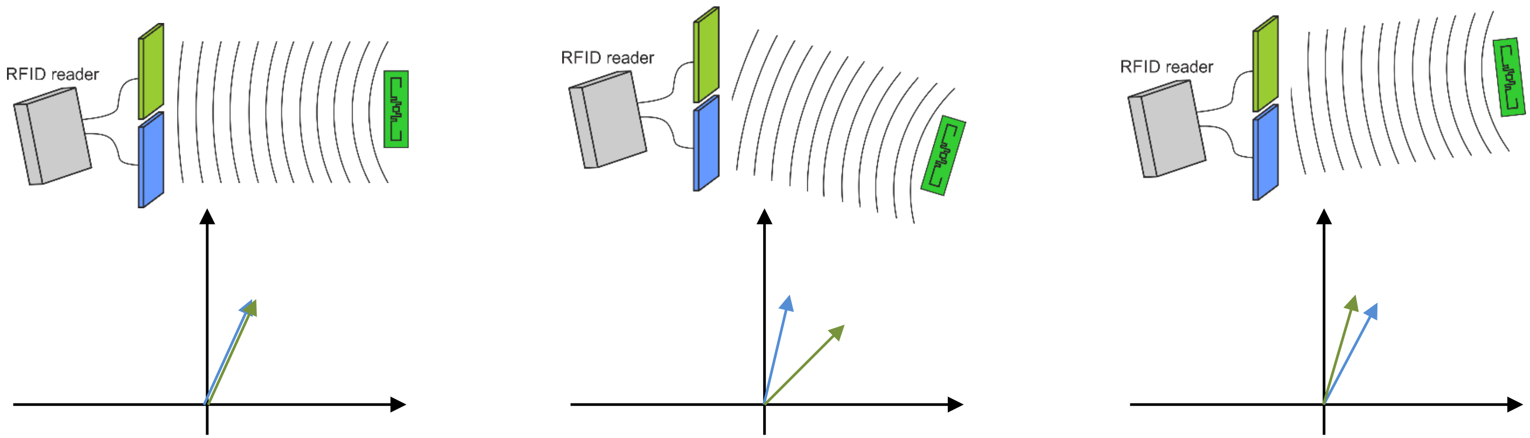






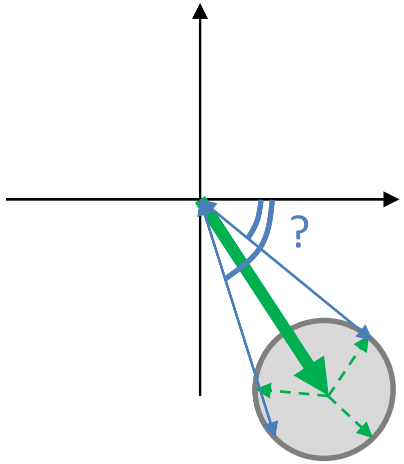
Angle of Arrival (AoA)

- Uses at least two antennas
- Phase difference of tag's signal gives an angle estimate



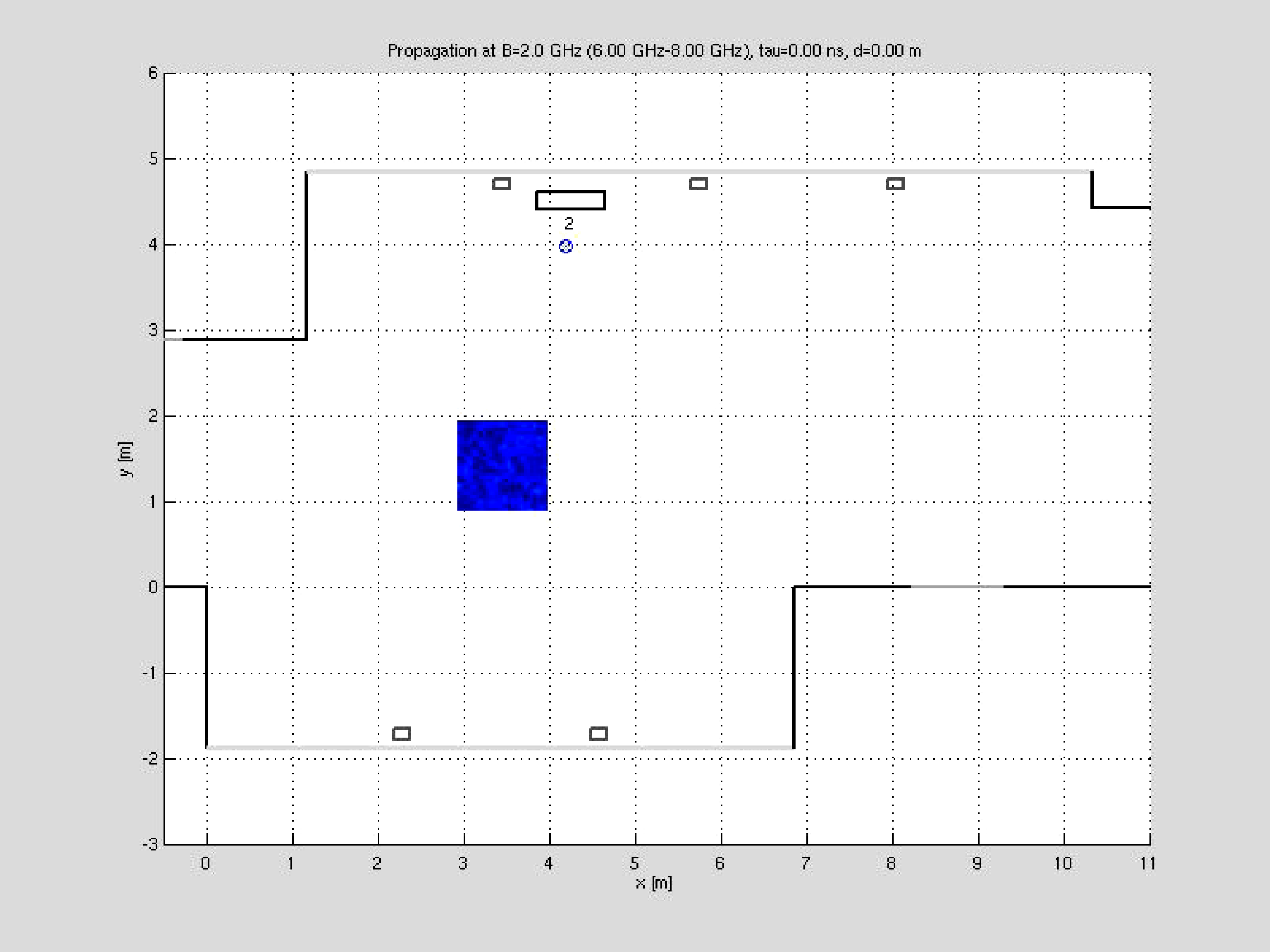
Problems:

- Multiple antennas needed
- Multipath will result in wrong power readings
- Many RFID readers aren't capable of vector measurements



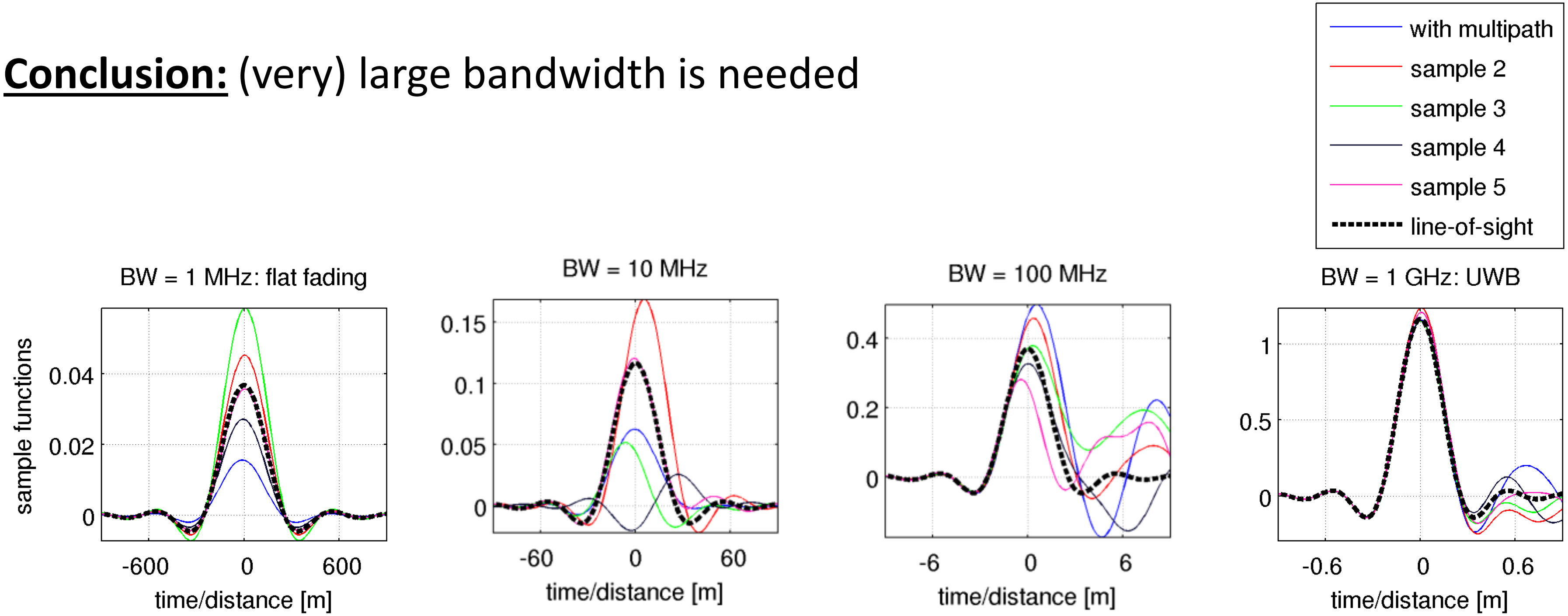
Time of Flight (ToF)

- An experiment:
  - transmission of an ultra-short pulse in an indoor environment
  - signal reflections lead to multipath propagation



- Influence of bandwidth:
  - time/range resolution changes vastly
- Impact of multipath propagation onto ToF ranging:
  - ultra-wideband (> 500 MHz): line-of-sight signal is clearly seen
  - 10 – 100 MHz: signal distortions and fading
  - narrowband (≤ 1 MHz): flat fading (only)

Conclusion: (very) large bandwidth is needed



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Use of Multiple Antennas – Performance Comparison

Three reader configurations with **2 reader positions** are compared.
Each reader has:

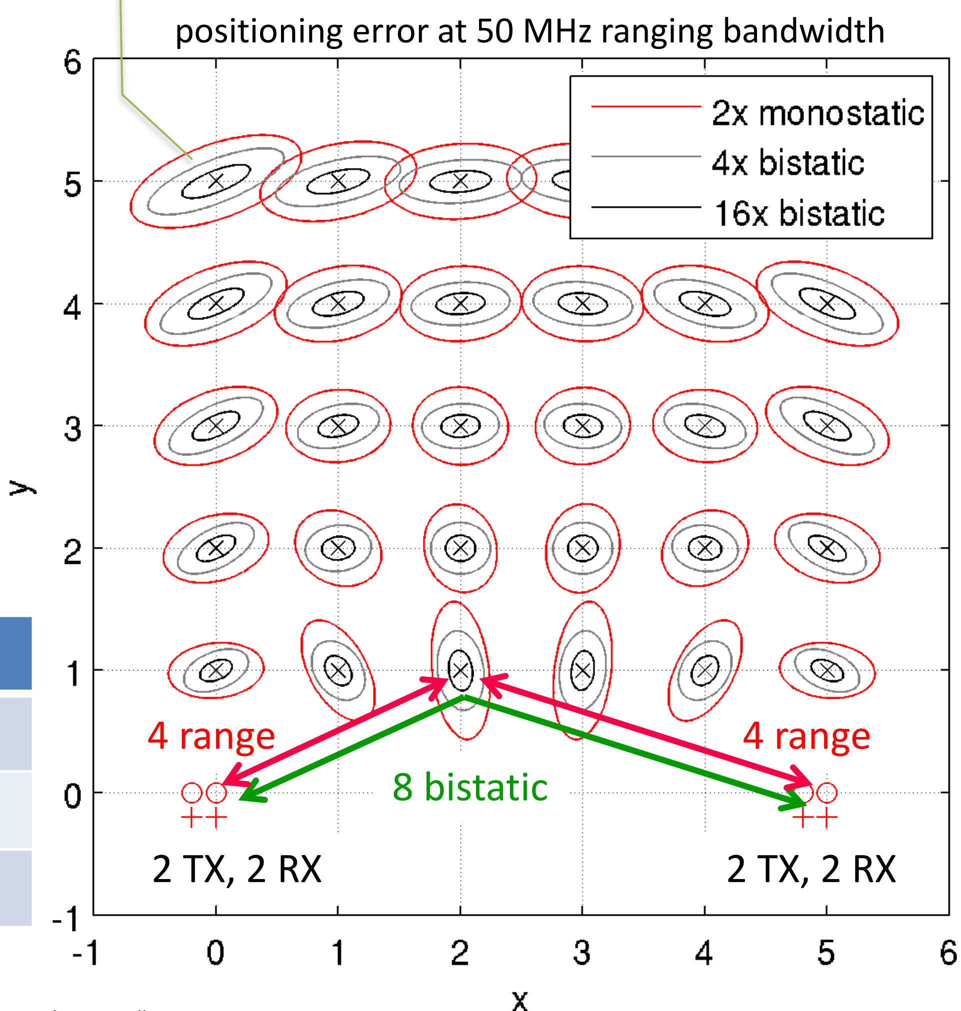
1) – combined TX/RX antenna
   ➔ **2 range** measurements

2) – separated TX/RX antennas
   ➔ **2 range** + **2 bistatic** meas.

3) – 2 pairs of separated TX/RX ant.
   ➔ **2 x 4 independent range** plus **8 independent bistatic** meas.

	95% error	99% error
2 x monostatic	34 cm	38 cm
4 x bistatic	26 cm	30 cm
16 x bistatic	13 cm	15 cm

Error ellipses: 95% of measurements are inside



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Conclusions

- **Simple methods (e.g. RSSI, AoA) lack accuracy** due to
  - antenna patterns (of reader and tag)
  - nonlinear backscatter behavior
  - different tag-ICs behave different
  - multipath propagation

- **Time of flight is the method of choice**
  - high bandwidth needed → impossible for narrowband UHF RFID?
  - the more bandwidth, the better the multipath resolution
  - Independent on antenna pattern/orientation, chip manufacturer…

- Use of **multiple antennas improve performance**
  - can extend a 1D-localization method to 2D/3D
  - improves accuracy with increasing antenna count

- All methods always provide a **statistical and not an exact solution**
  - For time of flight, the used bandwidth controls the accuracy
    50 MHz seems sufficient for typical UHF RFID applications

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ToF UHF RFID Ranging Principle – Basic Concept

Recap – Goals from part I:

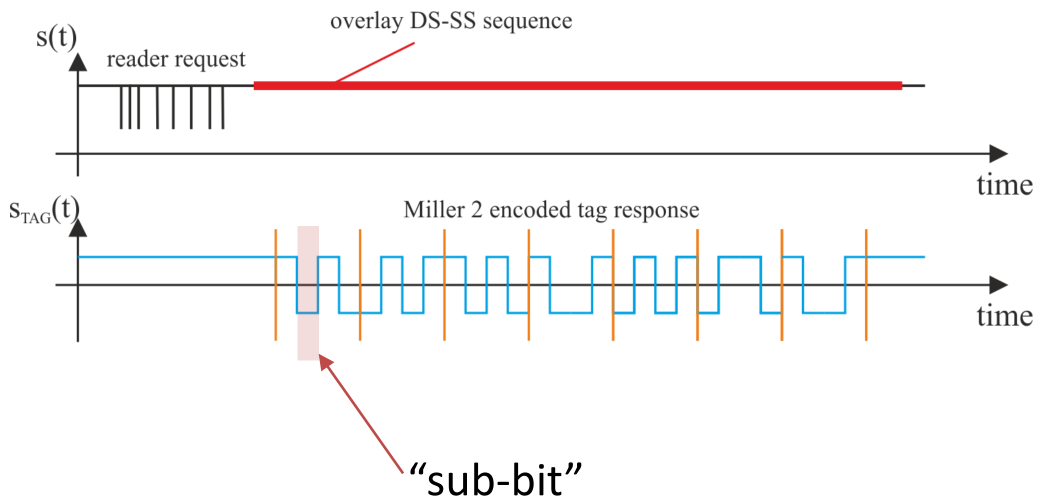
- Time of flight (ToF) based ranging
- Bandwidth ≥ 50 MHz
- Interoperable with standard EPC Gen2 tags
- Independent on tag chip manufacturer, antenna, label construction…

Solution:

- Superimpose a ranging sequence during tag to reader communication
- Keep the ranging sequence's power so small that it
  - does not influence the EPC-communication (→ interoperability with legacy RFID systems)
  - does not generate too much out of band content (→ limit interference for co-existence)
- Find a method to distinguish the "echo" from the tag's antenna from others

Working principle

- UHF EPC RFID is based on backscatter communication
- Tag must be powered by the interrogator (CW signal during tag→reader comm.)
- A superimposed spread-spectrum signal (e.g. DS-SS sequence) onto the CW signal will be reflected back by the tag to the reader
- The tag has two modulation states, both will reflect CW + DSSS slightly different



ToF UHF RFID Ranging Principle – Basic Concept

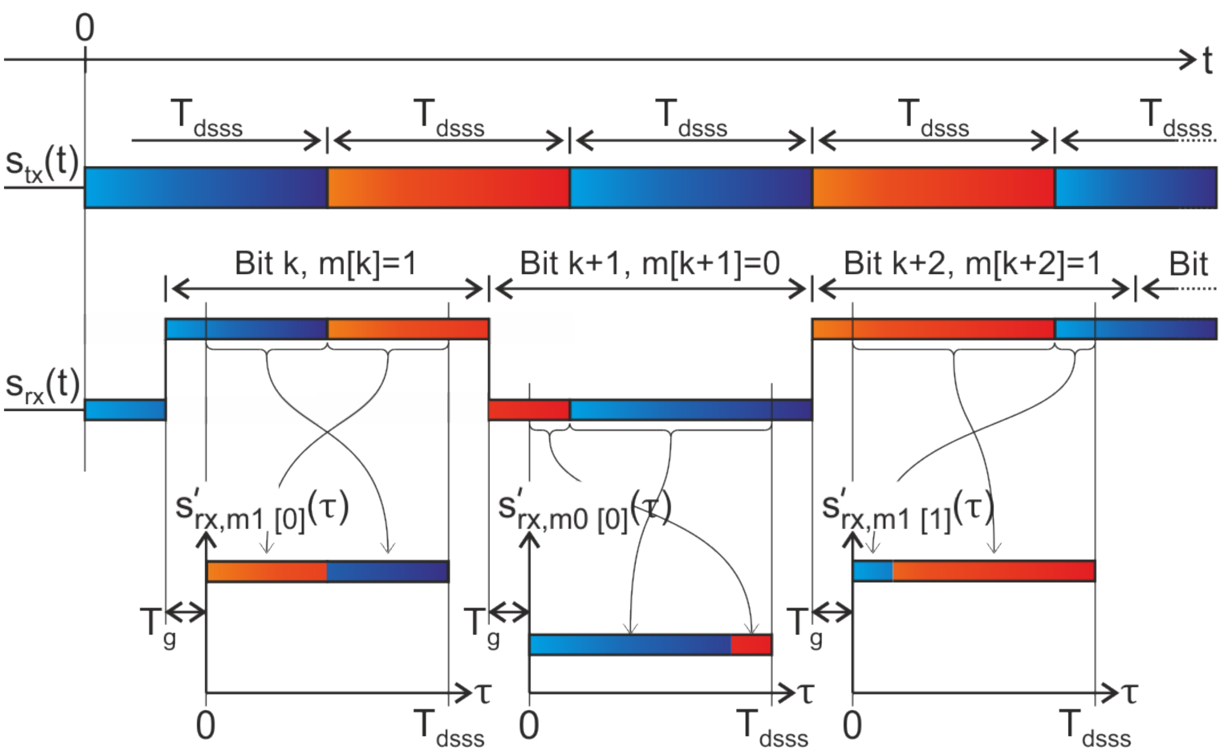
To ease up the math, we target at **one period of the DSSS sequence per “sub-bit”**:

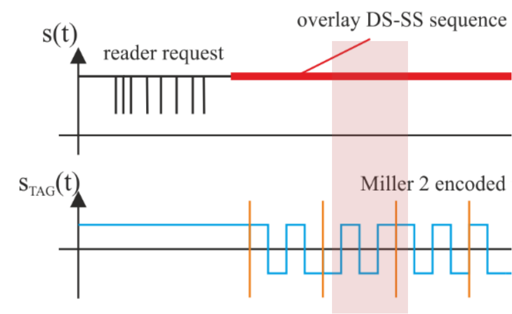
- Selected **BLF = 40 kHz, Miller-coding**
  - UHF RFID frequency tolerance is ± 4 % for this rate
  - the length of a single information bit is at least 48 µs, 96 µs, or 192 µs (depending on Miller-coding’s parameter M = 2, 4, or 8)
  - encoded information bits consists of 4, 8, or 16 “sub-bits” each
  - “sub-bit” length is independent on M and ≥ 12.02 µs

- Assuming a minimum **guard time of 1 µs** requires a DSSS period of ≤ 11.02 µs

- One of many possible DSSS sequences is:
  - **25 MHz chip rate, M-sequence with 255 chips length** → 10.2 µs length

- As DSSS period T_{DSSS} fits into a “sub-bit”, we can extract a complete period each
- **No need for synchronization** between DSSS and tag communication
- Use of **cyclic rotation for realigning the asynchronous sequence**
- Note: depending on the “sub-bit” modulation state “0” or “1” the reflected signal experiences a slightly different impulse response by the tag



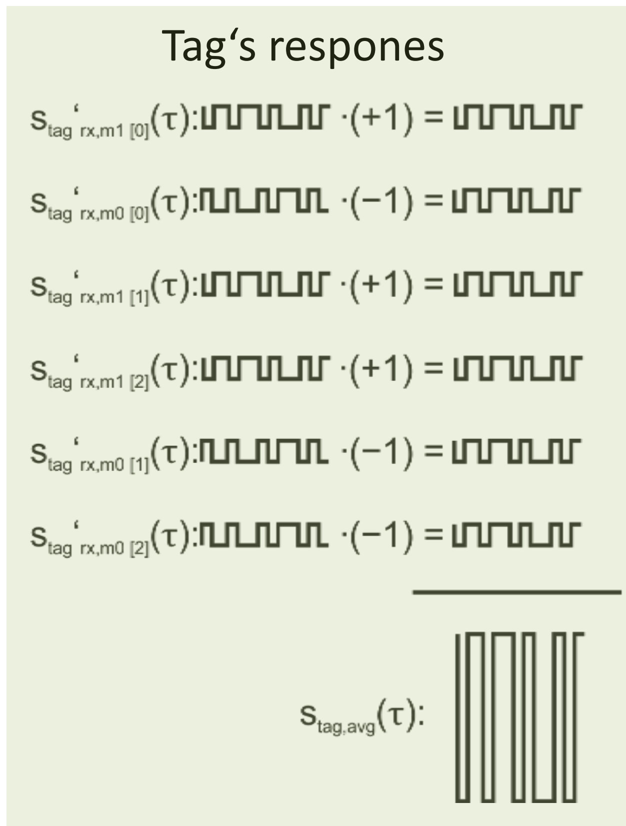


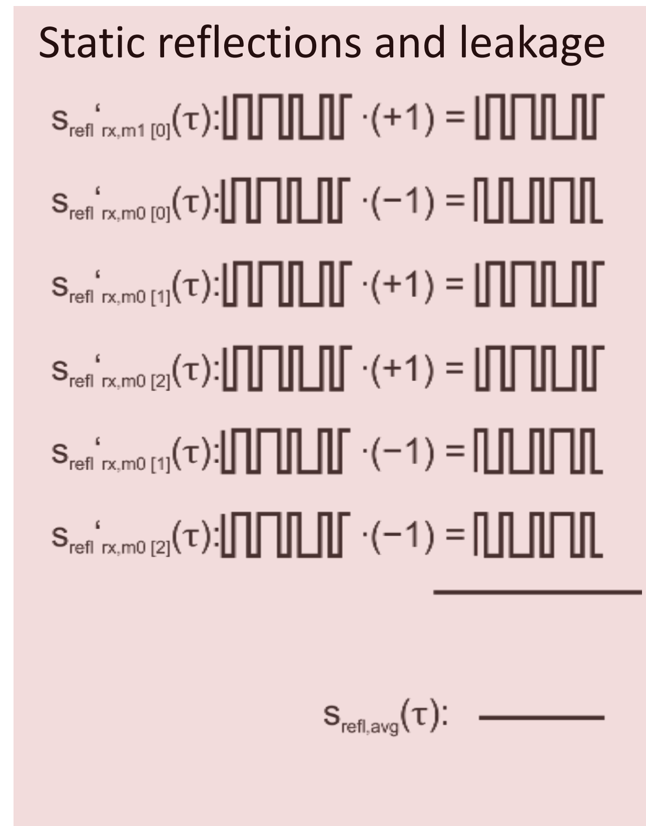
- The reader now performs a „**coherent set averaging**“ over all recorded echoes of the DSSS sequence

$$s_{avg}(\tau) = \frac{1}{K_0}\sum_{k=1}^{K_o} s'_{rx,m_0[y]}(\tau) - \frac{1}{K_1}\sum_{k=1}^{K_1} s'_{rx,m_1[y]}(\tau)$$

- This eliminates static echoes end emphasizes the echo of the tag of interest

$s'_{rx} = s_{tag}' + s_{refl}'$





ToF UHF RFID Ranging Principle – Basic Concept

- Finally, we obtain the **echo of the transmitted DSSS sequence**
  - Delayed by the time of flight (interrogator to tag to interrogator)
  - SNR can be controlled by the number of averages
    → use of M = 8 and/or reads of many data bits from the tag are preferable

- The final averaged **echo signal depends on**
  - the transmitted DSSS sequence s_{tx}, cyclically convolved with
  - the total impulse response h_{all} of tx- and rx-antenna, downlink- and uplink-path, cyclically convolved with
  - the delta-impulse response of the tag $h_{tag}^{\Delta}(\tau) = \frac{1}{2}[h_{tag}^{0}(\tau) - h_{tag}^{1}(\tau)]$
  - the number of averaged sub-bits K, and
  - the thermal/receiver noise n

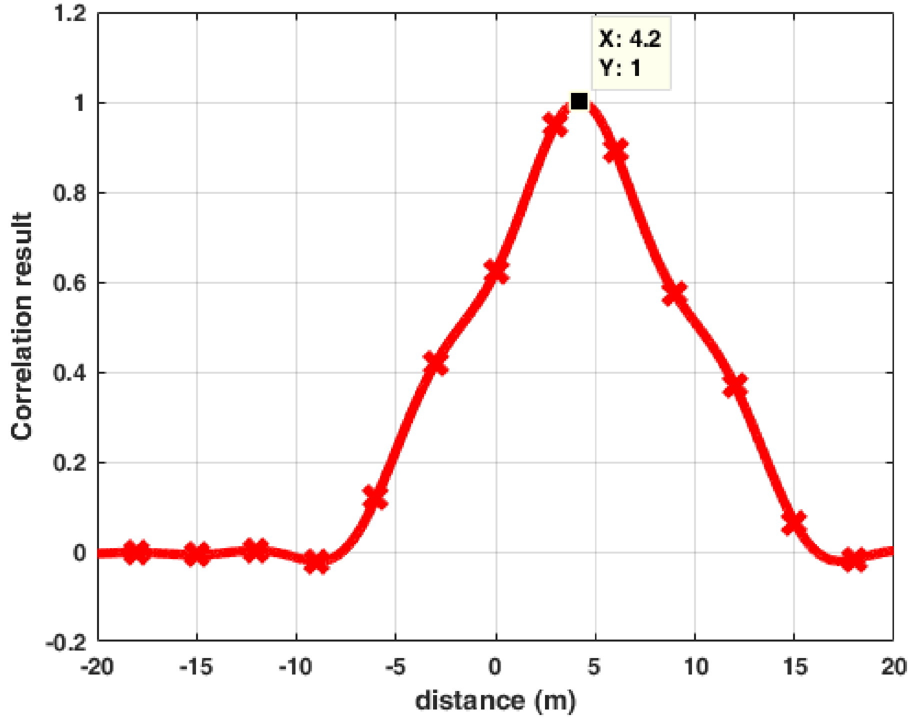
$$s'_{avg}(\tau) = \left(s_{tx} \otimes h_{all} \otimes h_{tag}^{\Delta}\right)(\tau) + \frac{1}{\sqrt{K}} n(\tau)$$

<u>The method is described in detail in:</u> H. Arthaber, T. Faseth, F. Galler, "Spread-Spectrum Based Ranging of Passive UHF EPC RFID Tags," *IEEE Communications Letters*, vol. 19, no. 10, pp. 1734–1737, Oct. 2015, doi: 10.1109/LCOMM.2015.2469664

ToF UHF RFID Ranging Principle – Basic Concept

- The result of **coherent averaging gives the echoed DSSS sequence**
- It can be **correlated with TX-signal to determine the flight time**
- Peak-search is the most simple approach

- Using cyclic oversampling (640 x) gives higher resolution
  - Length of single chip in air = 12 m (no oversampling)
  - Length of a single sample after oversampling = 1.87 cm



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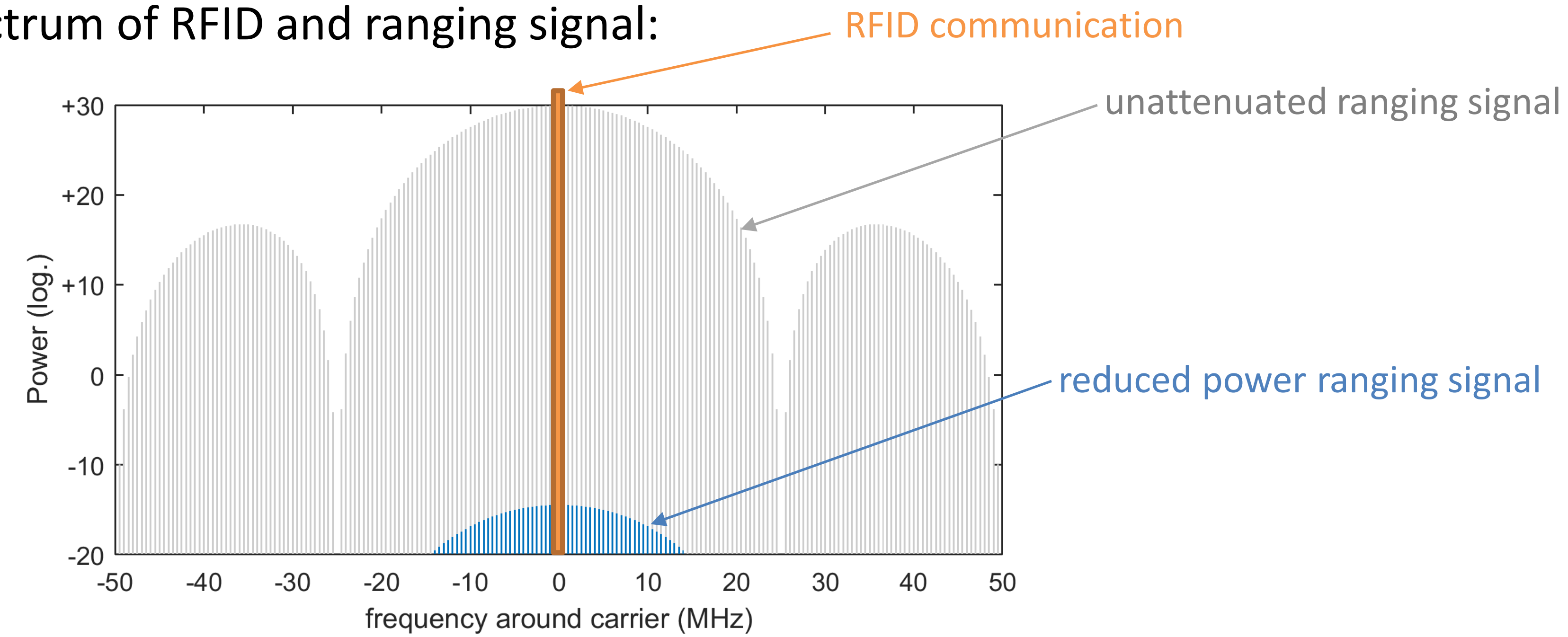
How does the ranging signal look like?

- Spectrum of RFID and ranging signal:



- Without any changes, the signal violates EPC standard and radio standards
  ➔ an extremely low power ranging signal must be used
  ➔ this reduces signal to noise ratio → expect noisy distance measurements

- **Requirement #1:**
  EPC Class 1 Gen 2 specifies a spectral mask for the interrogator

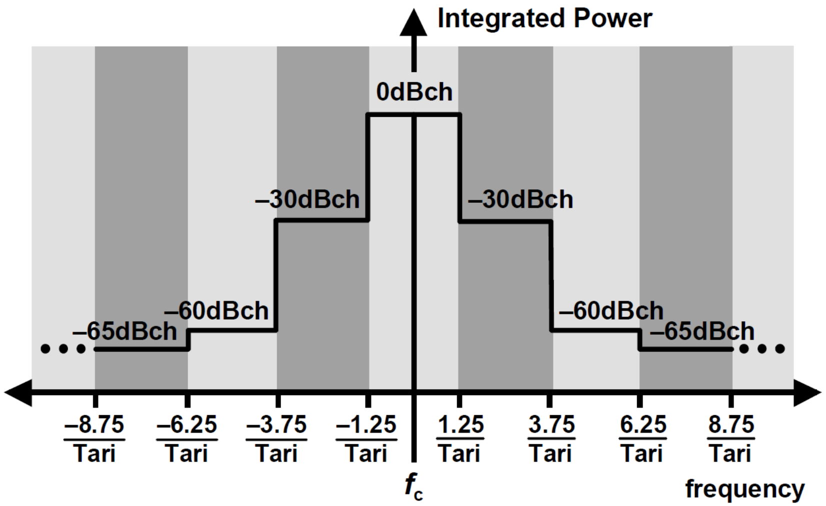
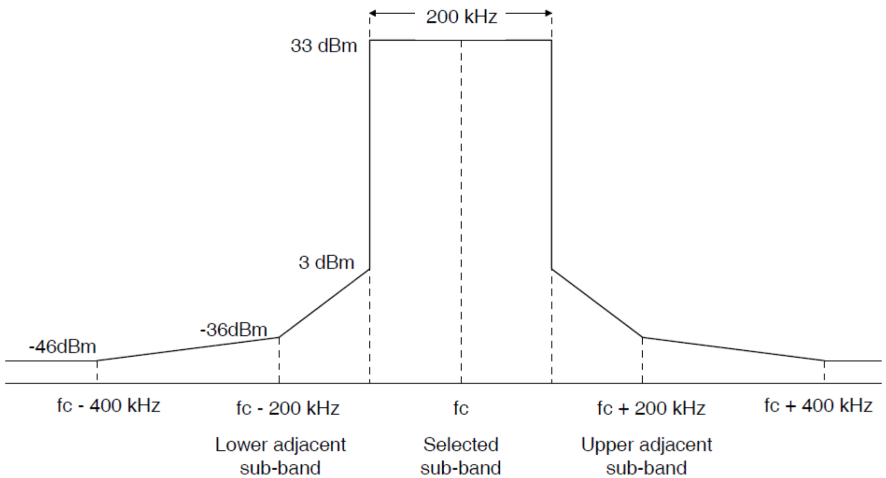


Figure 6.7 – Transmit mask for dense-Interrogator environments

- **Requirement #2:**
  ETSI EN 302 208-1 Mask, Lower Band

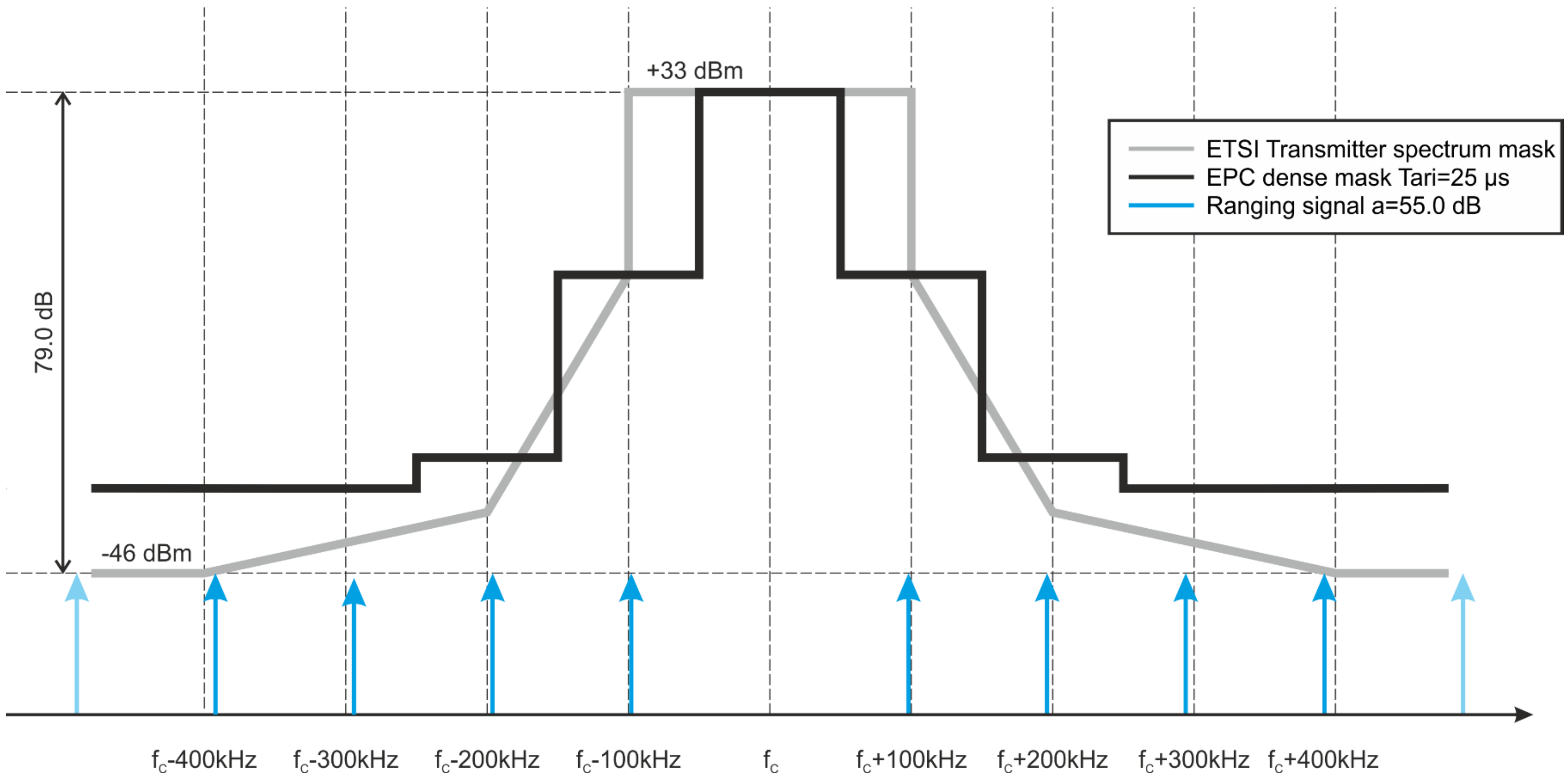


NOTE: Where fc is the centre frequency of the carrier transmitted by the interrogator applicable over the frequency range fc ±500 kHz.

Figure 5: Spectrum mask for modulated signals in the lower band

Spectral Compliance – Spectral Mask Requirements

- DSSS sequence must have much lower power level than CW signal



- Same powerlevel, a = 0 dB → violation of all spectral masks
- Attenuated by a = 41.0 dB → fulfilling EPC mask, sufficient for FCC
- Attenuated by a = 55.0 dB → fulfilling EPC + ETSI mask (FCC anyway)

Definition Spurious emissions

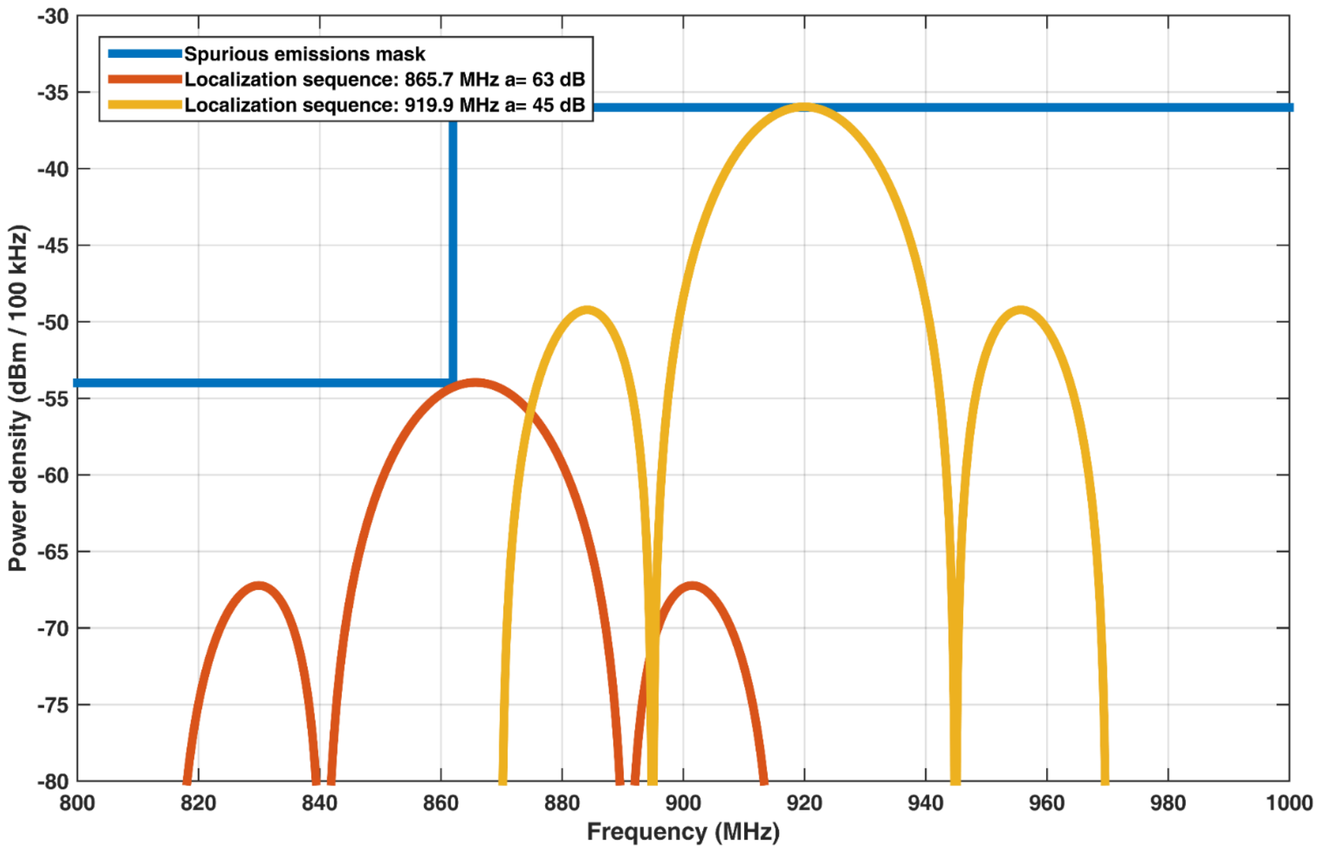
- ETSI: *"Spurious emissions are emissions at frequencies other than those of the wanted carrier frequency and its sidebands associated with normal test modulation."*
- ITU: *"Emission on a frequency, or frequencies, which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products but exclude out-of-band emissions."*

➔ In a strict sense, the definitions for spurious do not apply for the superimposed DSSS signal (it's an intended signal and must fulfil the spectral mask only)

➔ Even regulatory bodies abstain from a clear yes or no

Spectral Compliance – Spurious Emissions

- How to stay on the „safe“ side?
  ➔ Further reduction of DSSS power, to fulfill requirements
- a = –45 dB and a = –63 dB required for the ETSI high and low band, resp.
- Recommended approach for 868 MHz operation:
  CW-powering at 868 MHz, ranging at 915 MHz (as typical tags are broadband)



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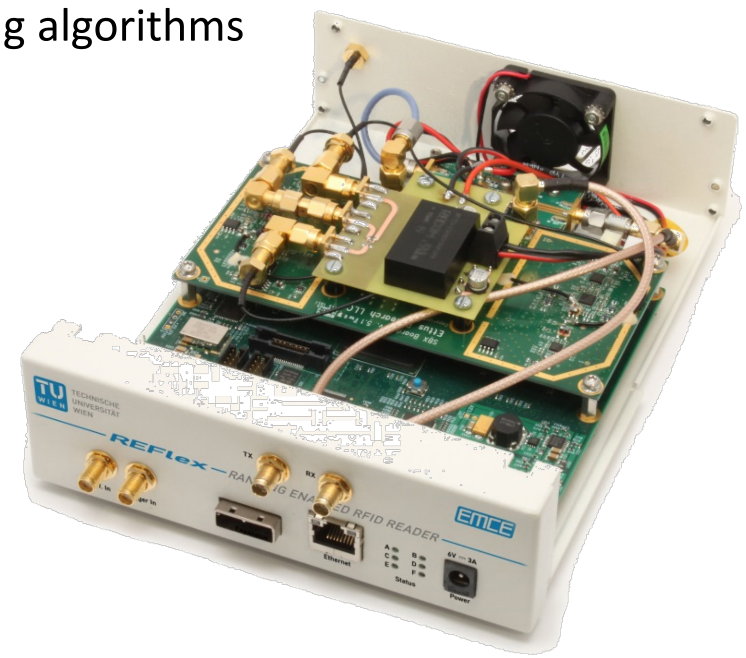
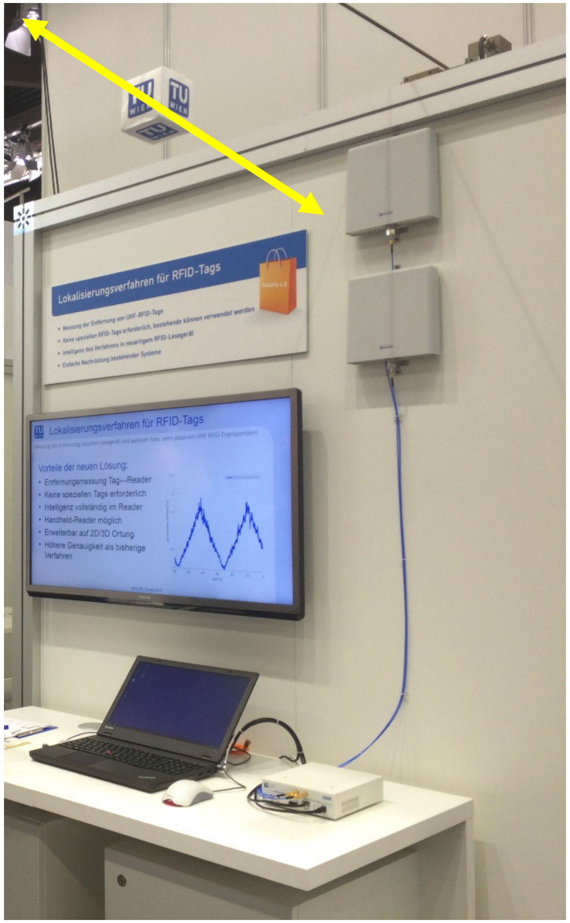
- UHF RFID communication requires real-time operation as replies must be sent within some microseconds → use of RF-measurement not possible

➔ **Ranging enabled RFID reader needed:**

- EPC compliant 868/915 MHz reader
- Real-time positioning of standard UHF EPC tags
- FPGA implementation
- Research platform:
  - RF-frontend not yet optimized
  - Positioning algorithms

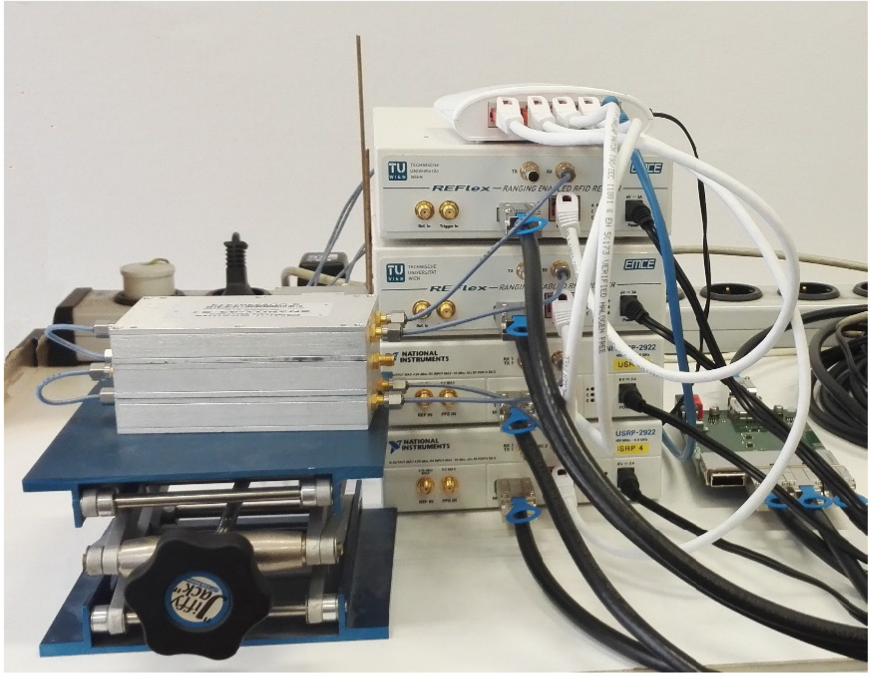




SPS IPC Drives 2015, Nuremberg

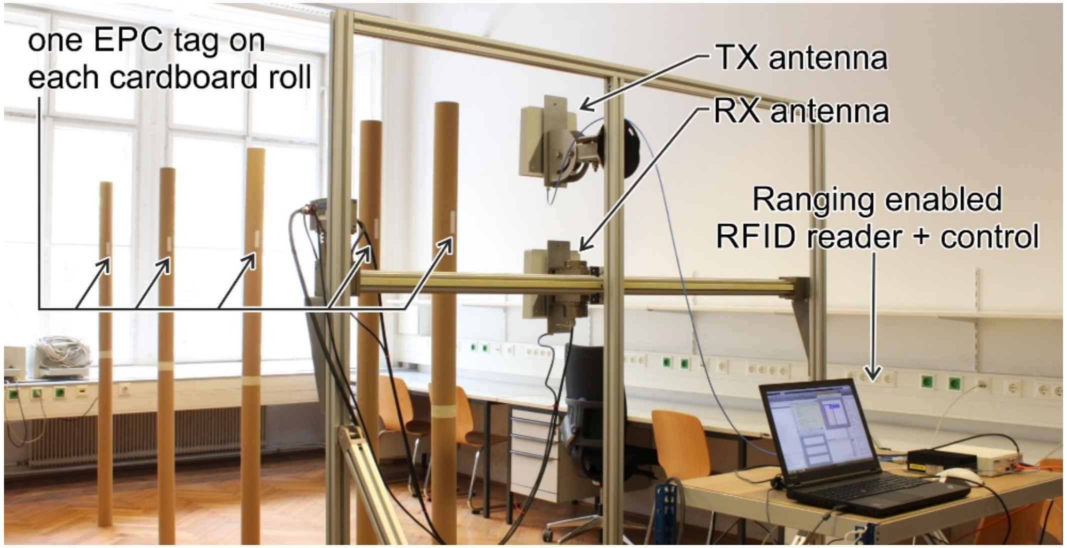
Measurement Results – Dedicated SDR Hardware, MIMO Ext.

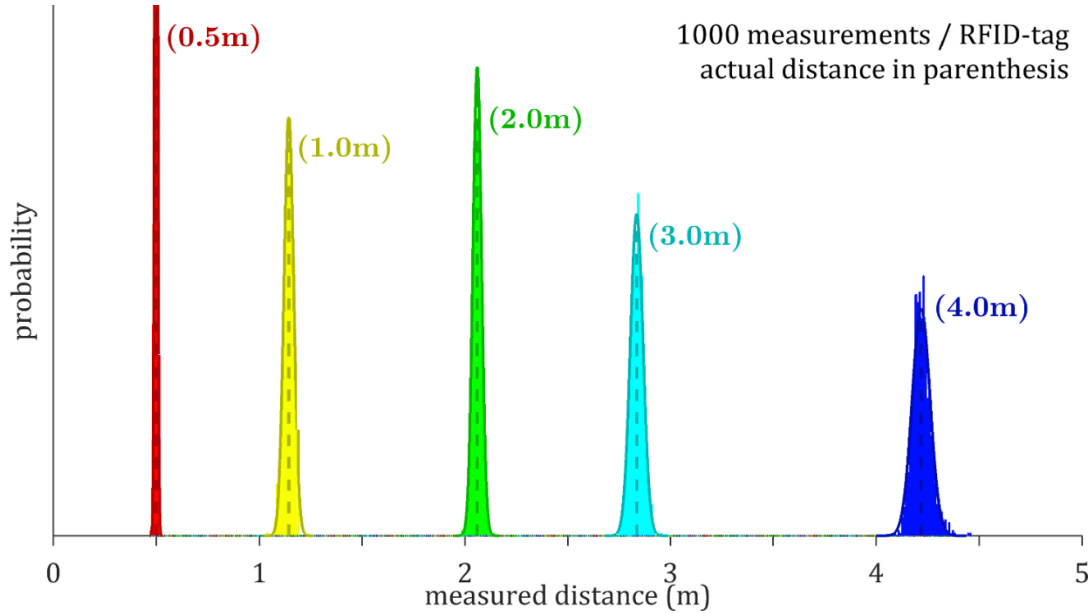
- **SDR-based hardware** supports MIMO configurations
- RF- and baseband-**coherent operation** of multiple SDRs
- Synchronization several Gbit-links
- **MATLAB class** to communicate with an arbitrary number of units
- Mixed UHF / 2.4 GHz operation
- Synchronous ranging with different ranging sequences
- Ranging between different SDRs possible



Measurement results – 1D, Fixed Tag Positions

- NXP UCODE 7 tags
- 5 tags in different distances

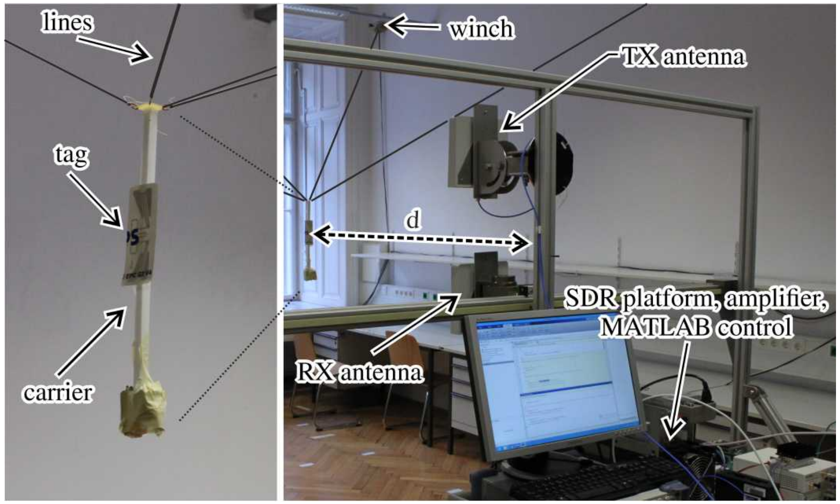


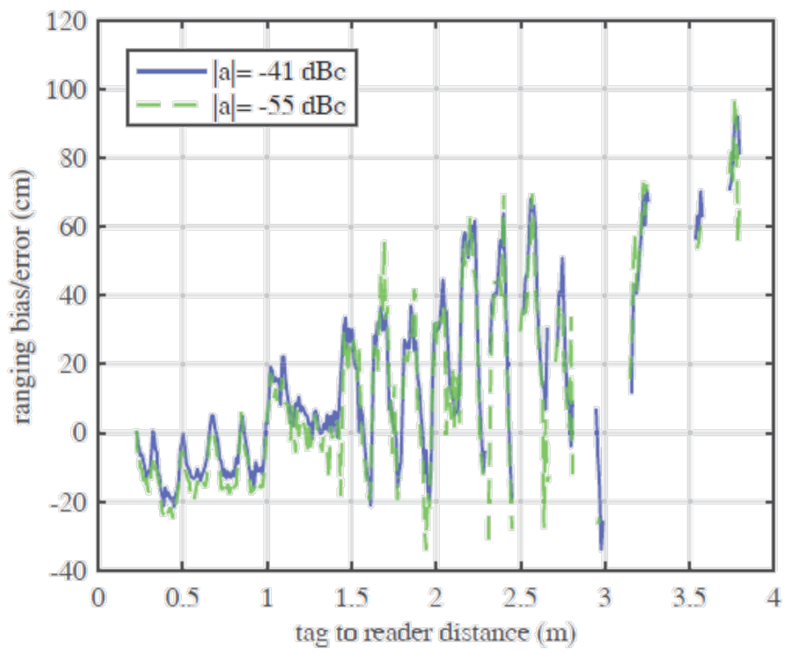


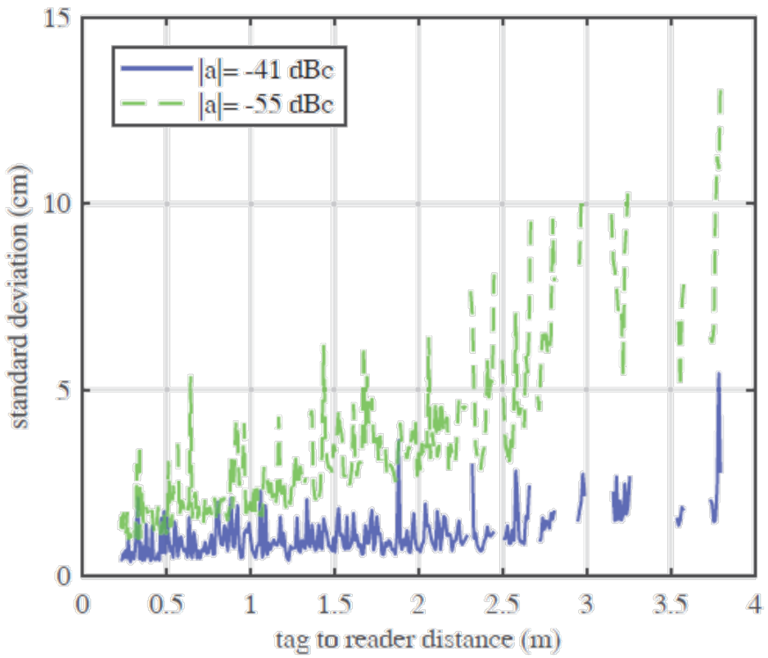
$\hat{\mu}$/m	95% of values
(0.5)	± 1.2 cm
1.14	± 4.8 cm
2.06	± 4.2 cm
2.84	± 6.2 cm
4.22	± 8.8 cm

Measurement results – 1D, Distance Sweep

- One NXP UCODE 7 tag on positioner
- DSSS power:
  - a = –41 dBc EPC mask
  - a = –55 dBc EPC+ETSI mask
- Ranging error < 35 cm within 1.5 m







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Summary

- Basic concepts and applications of localization introduced
  - received signal strength (RSSI)
  - angle of arrival (AoA)
  - time of flight (ToF)
- RSSI and AoA prone to inaccuracy, very sensitive on multipath
- Precise localization of UHF RFID tags difficult if the following is required
  - low cost
  - interoperability with existing tags
  - interoperability with users of neighboring frequencies (interference)
- ToF-based UHF RFID localization is possible
- Basic concept explained
- Spectral requirements can be fulfilled
- Measurement results are very promising

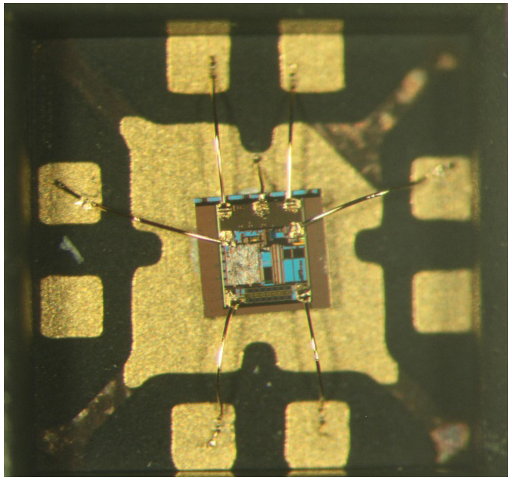
Outlook

Industrial aspects:

- Localization concept patent has been granted in AT and US (EU is pending)
- ISO standard developed, currently in DIS-stage (close to approval/publication)
- Method has been licensed to reader manufacturer

Academic aspects:

- Extension of the concept to 2.4 GHz
- Custom tag has been produced by NXP (EPC compliant with add. 2.4 GHz ports)
- MIMO based ranging
- Measurement system to measure delta-RCS in mag/phase (for delta impulse response)
- Space-saving dual frequency antenna design



Thank You For Your Attention!