Decimeter Accurate, Long Range Non-Line-of-Sight RF Wireless Localization Solution for Public Safety Applications

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Motivation: Fast and Accurate Indoor Localization

- **Applications for Indoor Localization**
  - Public safety
    - Firefighter / first responder rescue operations
    - Emergency evacuation path planning / guidance
    - Medicine, equipment, patients, and staffs in hospitals
  - Customer Applications
    - Indoor navigation (airport, retail malls, museum, conference center, etc.)
  - Industrial Applications
    - Intelligent logistics by tracking robots, packages, and workers in warehouses

Image from http://scanonline.com/rtls/

Indoor Localization Technologies

- Inertial measurement unit (IMU) based
  - Accelerometer and gyroscope for 6 degree-of-freedom measurement
  - Susceptible to error integration
- Computer vision based
  - Simultaneous localization and mapping (SLAM)
  - Sensitive to light conditions
  - Computationally demanding
- Radio frequency (RF) based
  - Non-line-of-sight operable
  - Faster measurement time
  - Challenges to obtain long range, decimeter accuracy indoors
- Sensor fusion
  - IMU + CV + RF: fusion with adaptive filter

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Research Scope

- **New Indoor RF Localization Solutions**
  - Year1: RF-Echo with custom ASIC tag
  - Year2: iLPS for simultaneous communication and localization
  - Year3: Sound-RF hybrid solution

- **Application specific integrated circuit (ASIC) fabrication**
  - Year1: Low power active reflection tag ASIC
  - Year2 and 3: Low power processor for software-defined radio ASIC
    - Wireless communication (WiFi, Bluetooth, Zigbee, proprietary)
    - RF localization
    - Deep learning neural network processing for RF

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  - Covered Area 
  - Accuracy 
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- Ultra-wide Band (UWB, IEEE802.15.4a, Decawave)
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Requirements for Public Safety Apps

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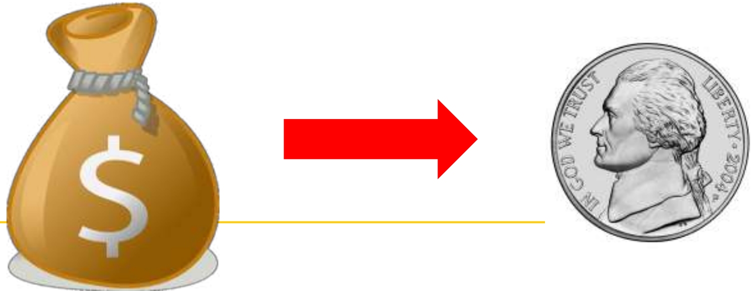
  - Milli-second refresh rate, tens of centimeter accuracy
- Ultra-low cost tags
  - To be ported on numerous IoT devices
  - Tracking of disposable tags



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  - Unobtrusive integration into IoT

Small

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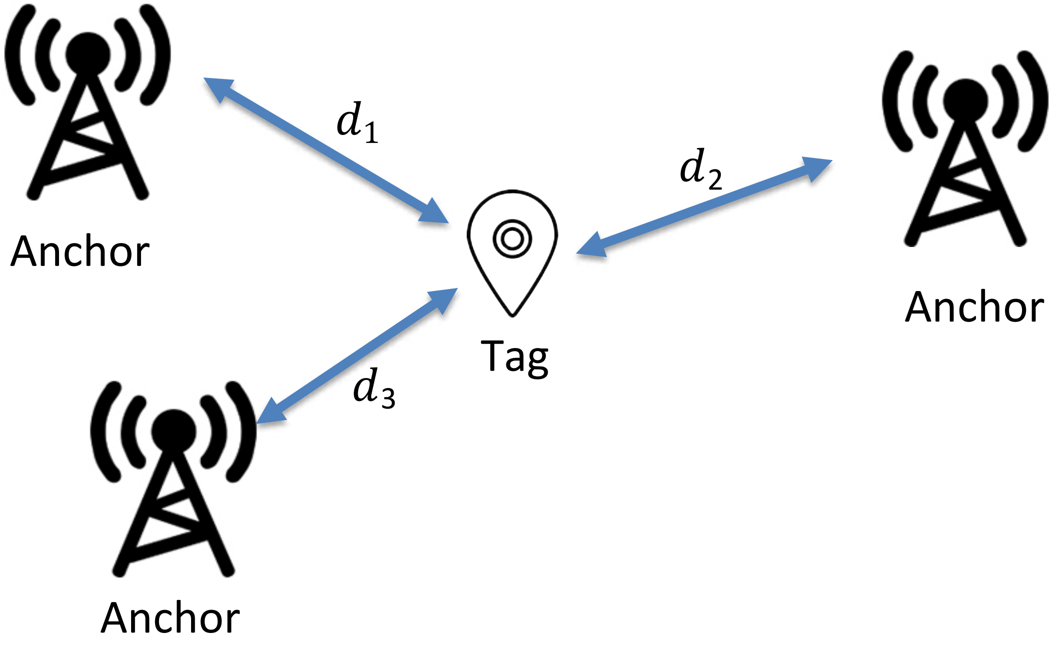
- Small form factor
  – Unobtrusive integration into IoT
- Low power consumption
  – Sustainable with a small coin-cell battery
  – No manual battery management

Small

Low-power

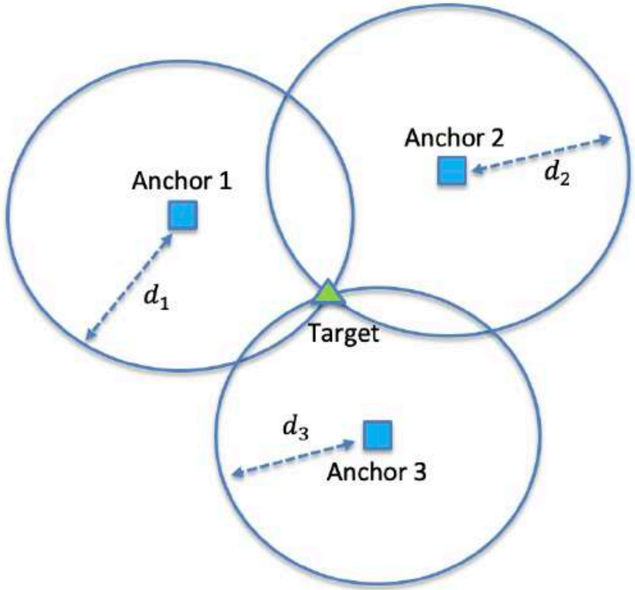
General RF Localization System

- Find the distance between anchors and tags

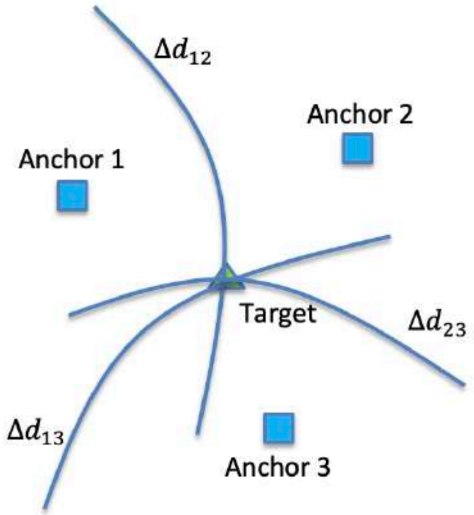


General RF Localization System

- Find the distance between anchors and tags
- Distance → Lateration
  - Time of Arrival (ToA), Time Difference of Arrival (TDoA)



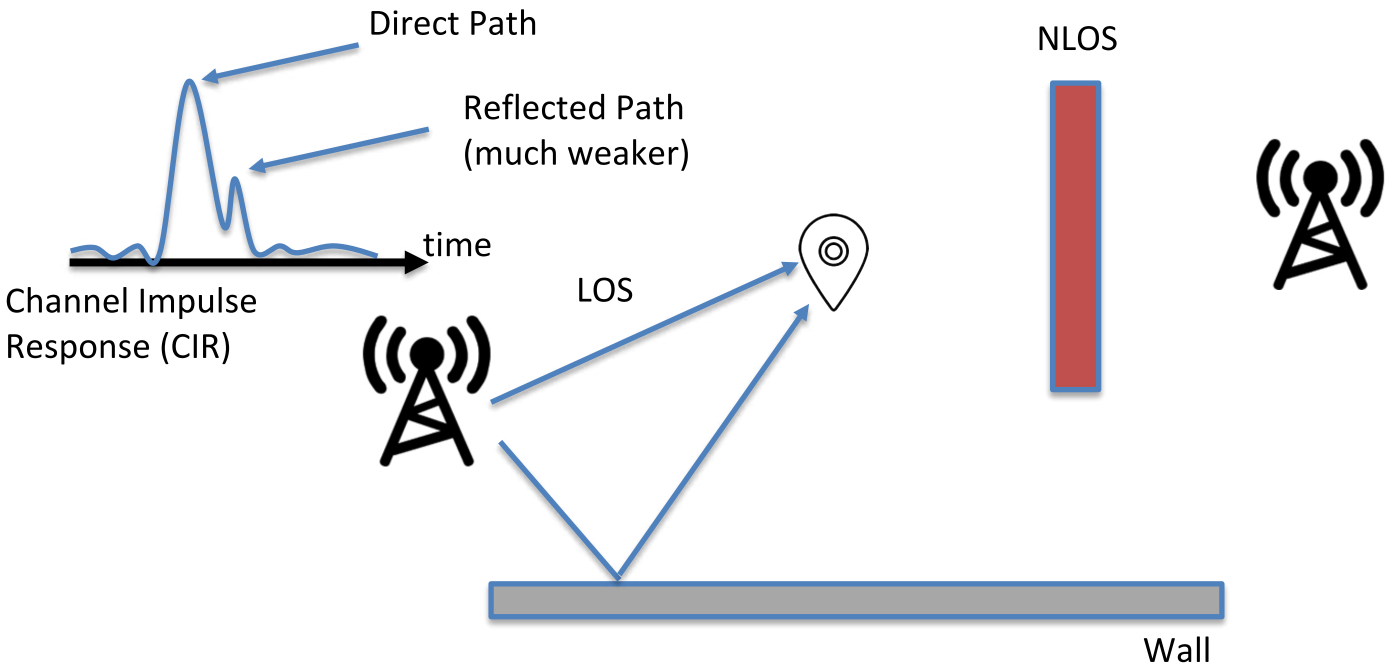
ToA (circle)



TDoA (hyperbola)

Why RF Indoor Localization is Difficult

- Multipath and Non-Line-of-Sight (NLOS)



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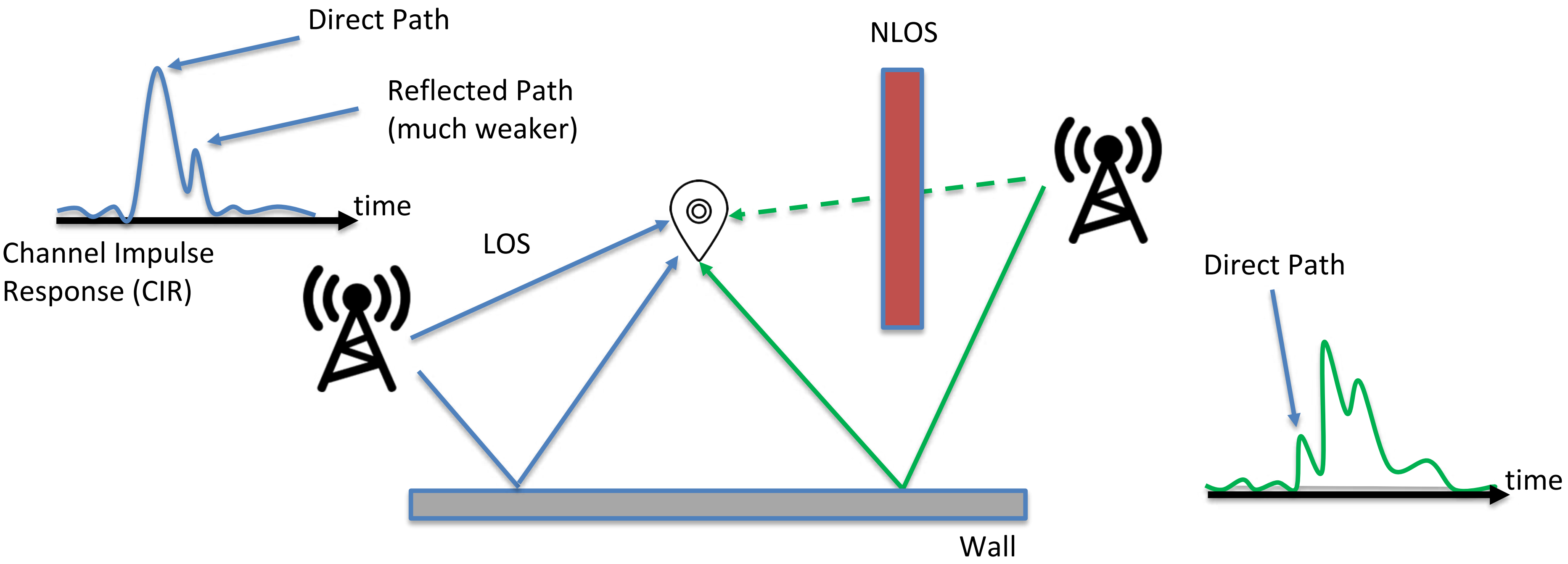

Time of Arrival (ToA) from Channel Impulse Response (CIR)

- Speed of light: c, Time of Arrival (ToA): τ
- Distance: $d = c\tau$ → 30cm with ToA of 1ns

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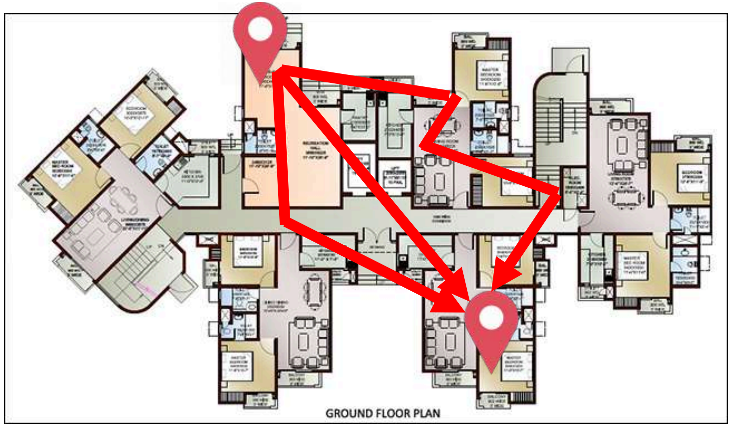

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- Speed of light: c, Time of Arrival (ToA): τ
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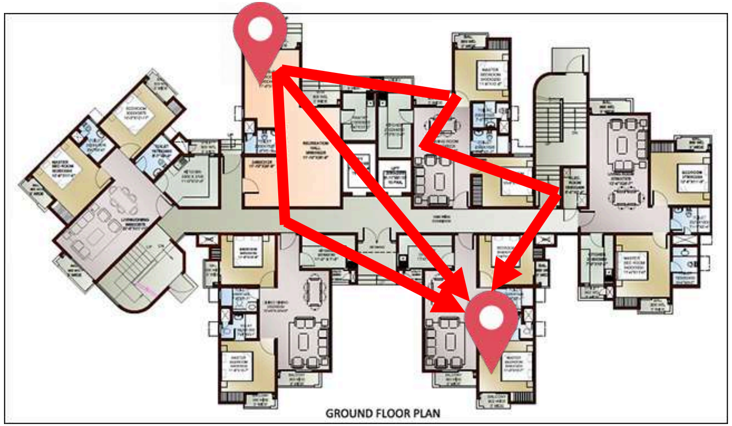
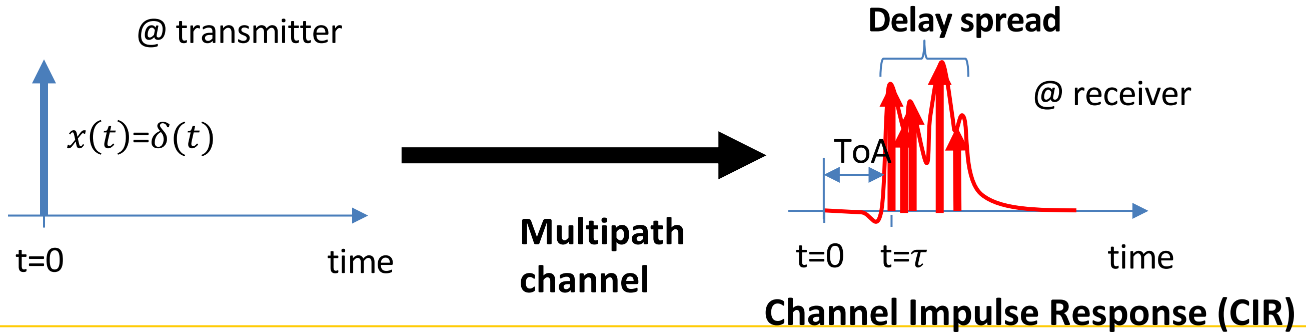
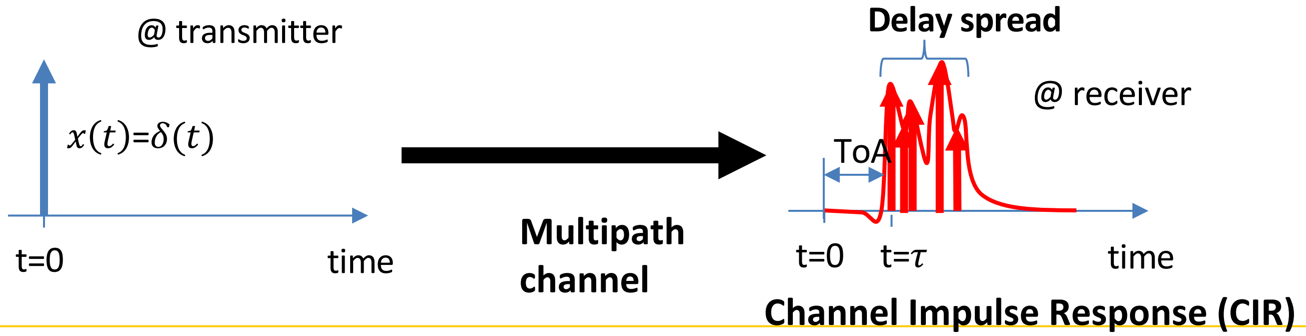
- Indoor channel is **multi-path** rich
- ToA or distance is estimated from channel impulse response (CIR)





TDoA Localization Challenges

- CIR estimation in multi-path indoor channels
  – Direct path can be much weaker than multipaths
- Time synchronization between transmitter and receiver
  – 1ns mismatch → 30cm error
- Limited bandwidth (80MHz) for ISM band operation → 3.75m resolution

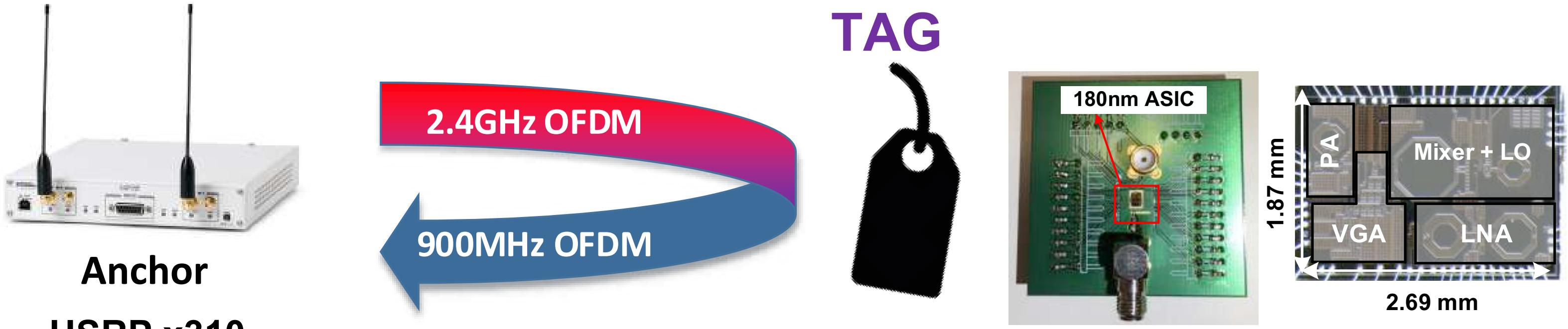


Proposed System: RF-Echo and iLPS

- **Decimeter-level (tens of centimeter)** ranging accuracy
- Large covered area: >**100m** distance
- GPS-like local positioning scheme
  - Indefinite number of tags localize themselves simultaneously
- **Reliable wireless communications** between anchors and tags
  - Localization and communication at the same time
- Deployable without heavy infrastructure investment

Overview: RF-Echo (Year1)

- RF-Echo Operating Principle:
  - Round-trip Time-of-Flight (RToF)
  - Introduce **active reflector tag with frequency conversion**
    - Full-duplex tag: **simultaneous TX and RX**
    - Increase ranging distance by **active signal amplification** at tag
    - Tag reflection has **different frequency from passive reflection**
    - All analog tag design: **deterministic echo processing delay**

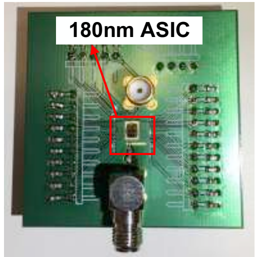


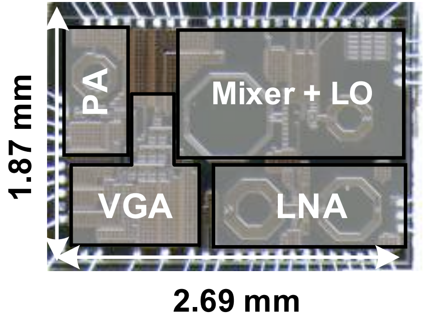
Anchor

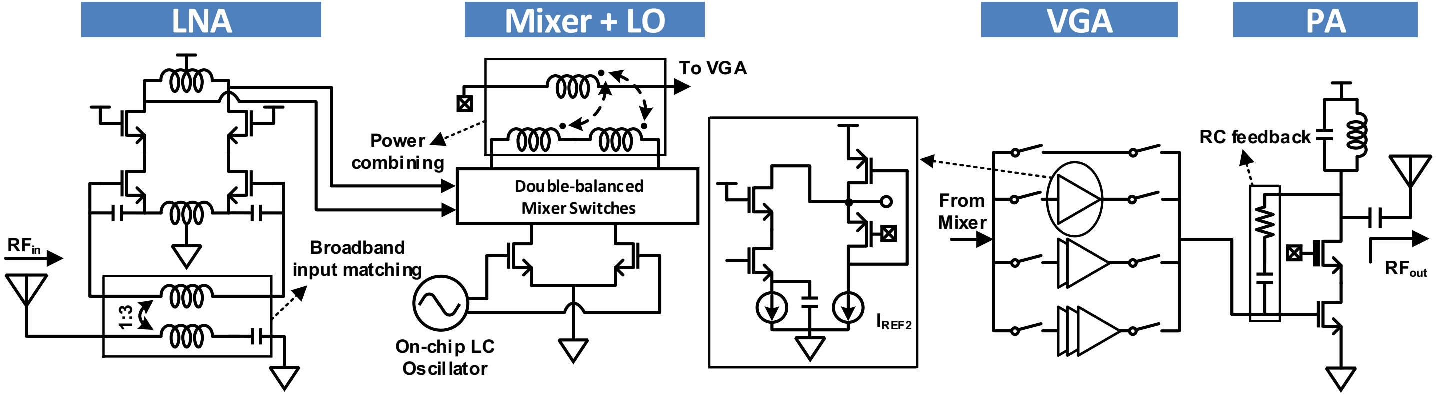
USRP x310

RF-Echo ASIC Tag

- Tag ASIC in TSMC 180 nm
- Low-cost simple tag design
  - Crystal-less, PLL-free
- Analog-only design
  - No digital signal processing circuitry
  - Deterministic delay

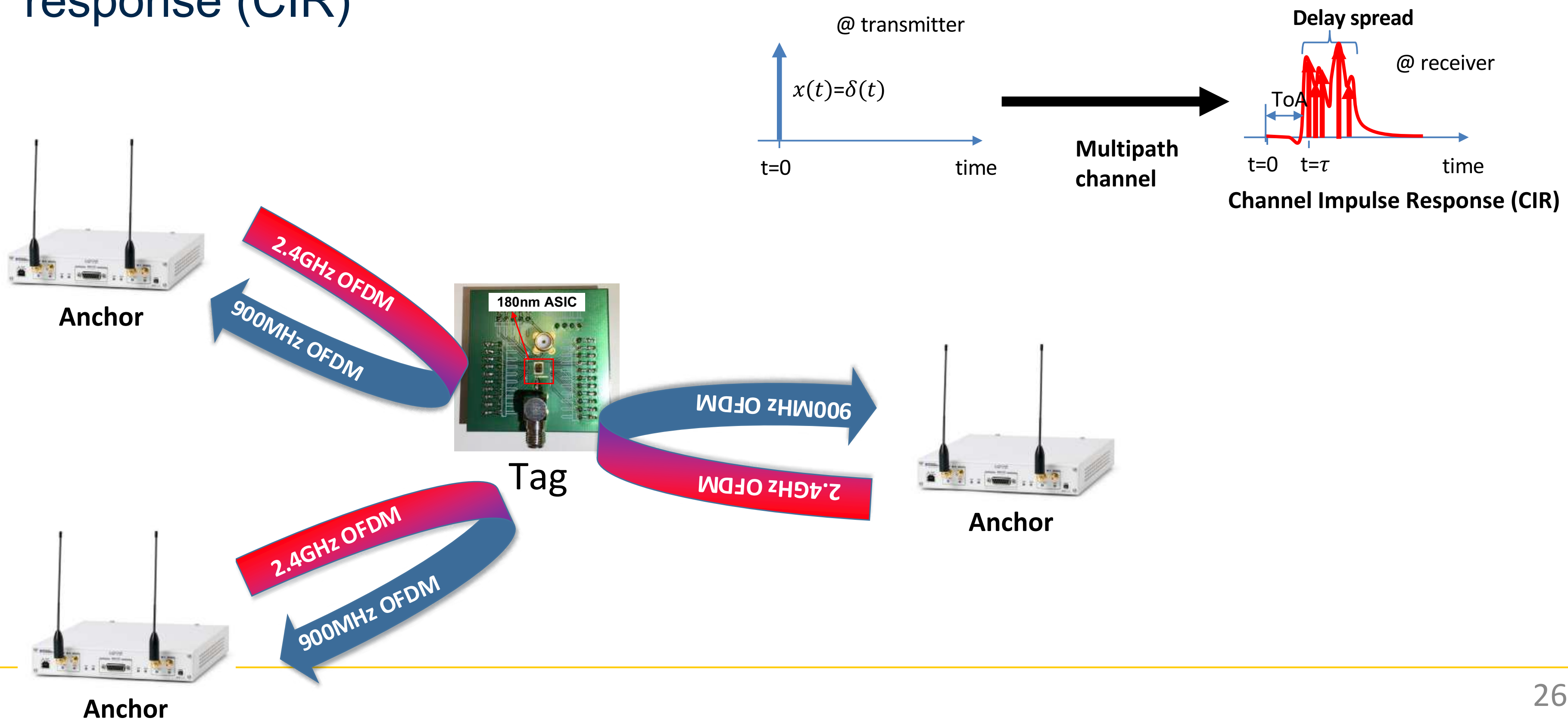






RF-Echo System

- Round-trip ToF or distance measurement by analyzing channel impulse response (CIR)



RF-Echo System Evaluation

System	Technology	LOS Accuracy	NLOS Accuracy	Testing Dimension	Tag Power	System Bandwidth	Signal Type	Time per Fix	Energy per Fix
WiTrack	FMCW ToF	31 cm (90%)	40 cm (90%)	LOS: 3-11 m NLOS: 6 x 5 m^2	No Tag	1.69 GHz	FMCW	> 2.5 ms	N/A
Harmonium	UWB TDoA	31 cm (90%)	42 cm (90%)	LOS/NLOS: 4.6 x 7.2 x 2.7 m^3	75 mW	3.5 GHz	Impulse	52 ms	3900 μJ
Ubicarse	SAR + Motion sensor	39 cm (median)	59 cm (median)	LOS/NLOS: 15 x 15 m^2	N/A	N/A	WiFi	100 ms	N/A
Tagoram	RFID SAR	12 cm (median)	N/A	LOS: 1 x 2 m^2	Passive	6 MHz (UHF)	UHF RFID	> 33 ms	N/A
Chronos	802.11 WiFi + Band-stiching	14.1 cm (median)	20.7 cm (median)	LOS/NLOS: 20 x 20 m^2	1.6 W	20 MHz x 35 ch.	OFDM	84 ms	1.34×10^5 μJ
RF-Echo	**ASIC Active reflection + Neural network**	**26 cm (90%)**	**46 cm (90%)**	**LOS: 7 x 90 m^2** **NLOS: 30 x 20 m^2**	**62.8 mW**	**80 MHz**	**OFDM**	**20 μs per sym.**	**18 μJ 10 sym.**

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- **New Indoor RF Localization Solutions**
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- **Application specific integrated circuit (ASIC) fabrication**
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  - Year2 and 3: Low power processor for software-defined radio ASIC
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    - RF localization
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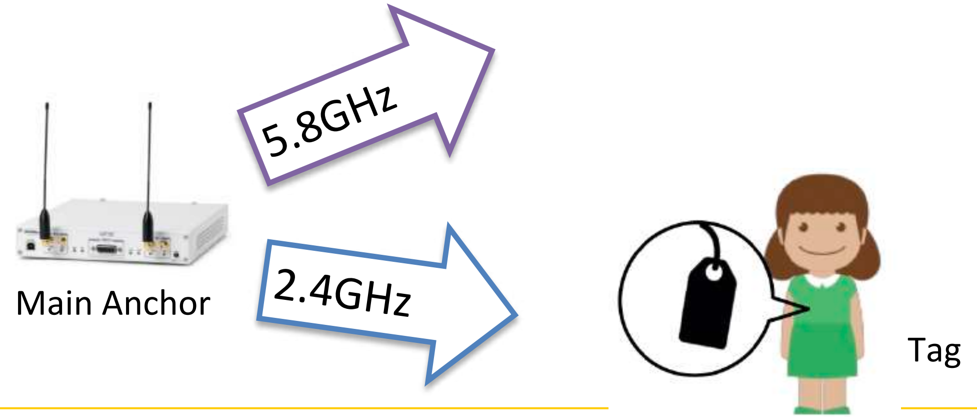
Overview: iLPS (Year2)

- iLPS: Indoor Local Positioning System
- Two kinds of anchors: Main anchor & Reflector anchor
  - Main anchor broadcasts OFDM signal at **2.4GHz** and **5.8GHz**



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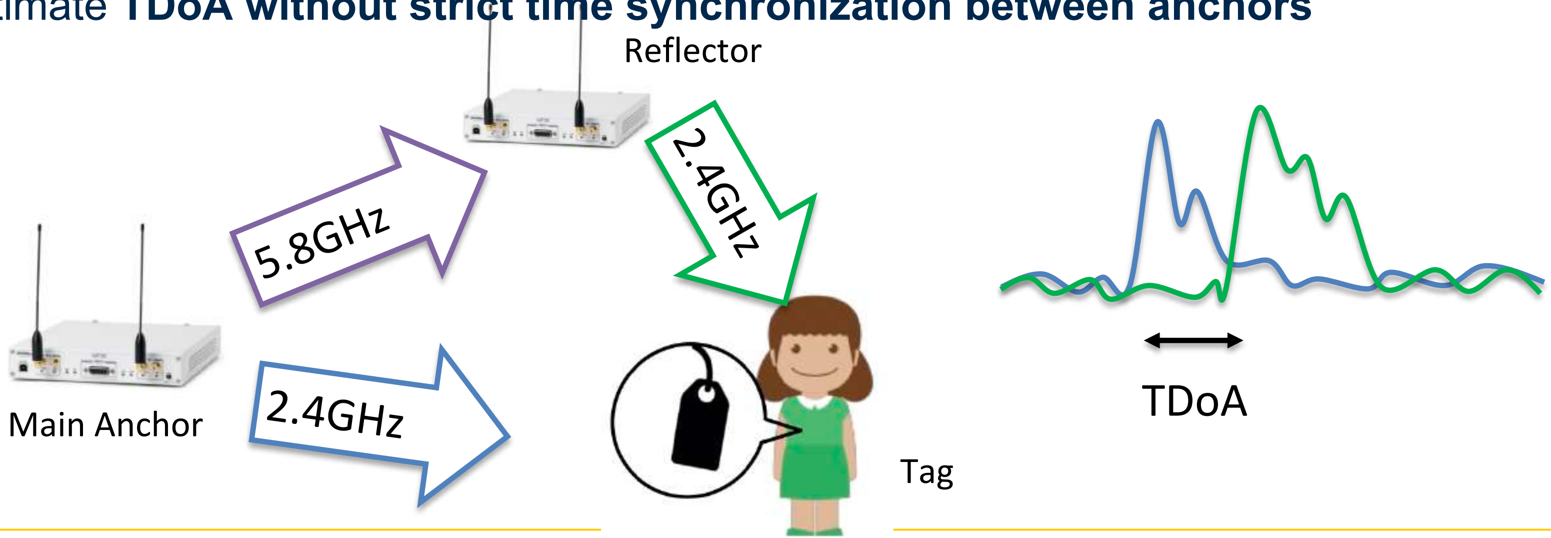
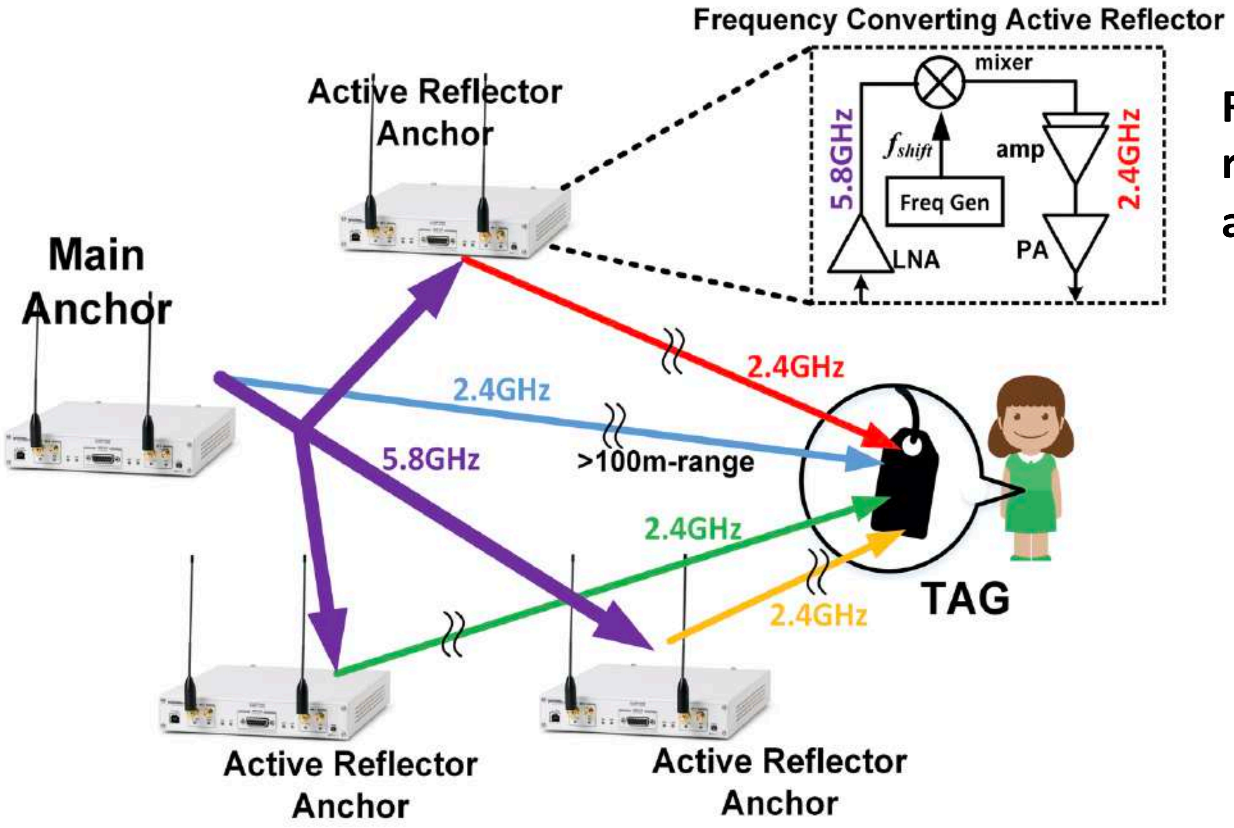
- Two kinds of anchors: Main anchor & Reflector anchor
  - Main anchor broadcasts OFDM signal at **2.4GHz** and **5.8GHz**
  - Reflector anchors reflects the signal at **5.8GHz** with signal amplification and frequency conversion to **2.4GHz**
  - Estimate **TDoA without strict time synchronization between anchors**



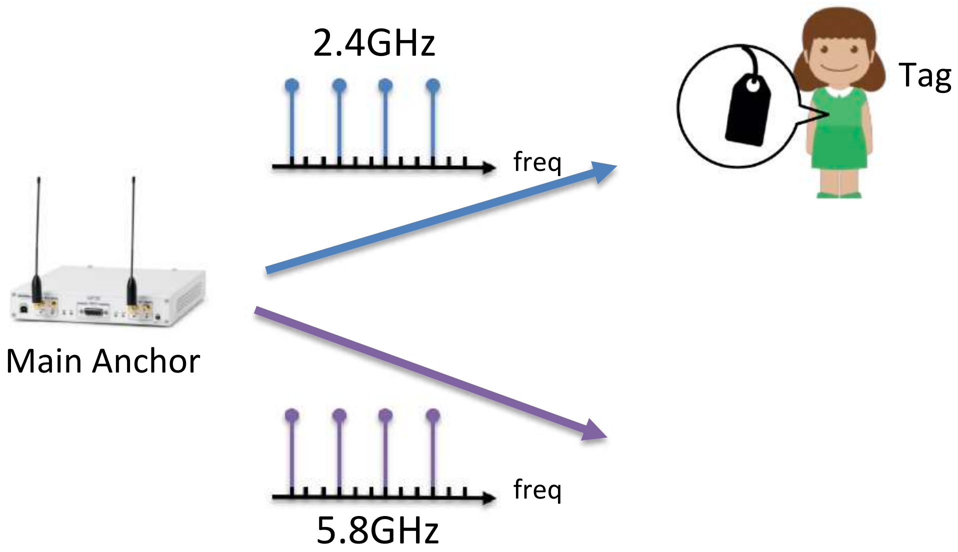
iLPS operation principle



Reflectors can be realized with all-analog processing

Inter-anchor Interference Avoidance

- **Orthogonal (OFDMA)** subcarrier allocation for different reflectors



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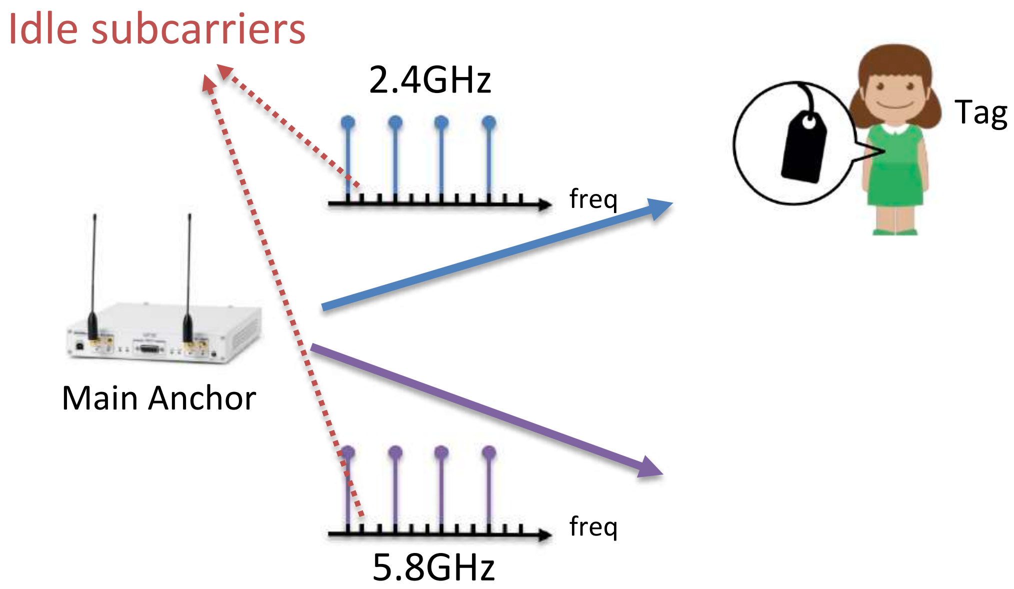

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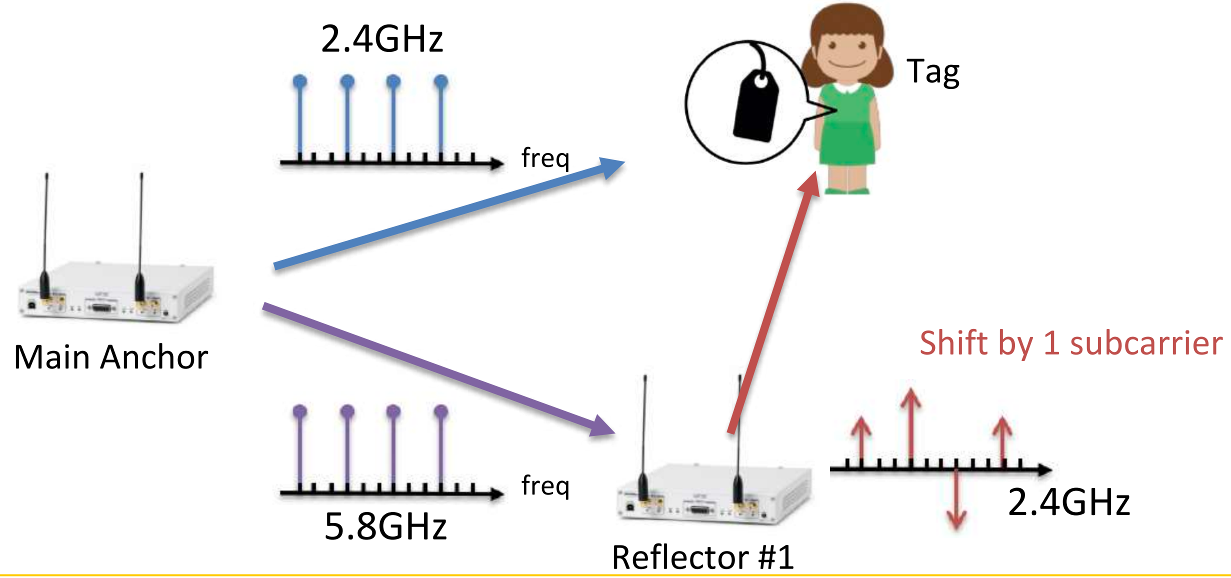

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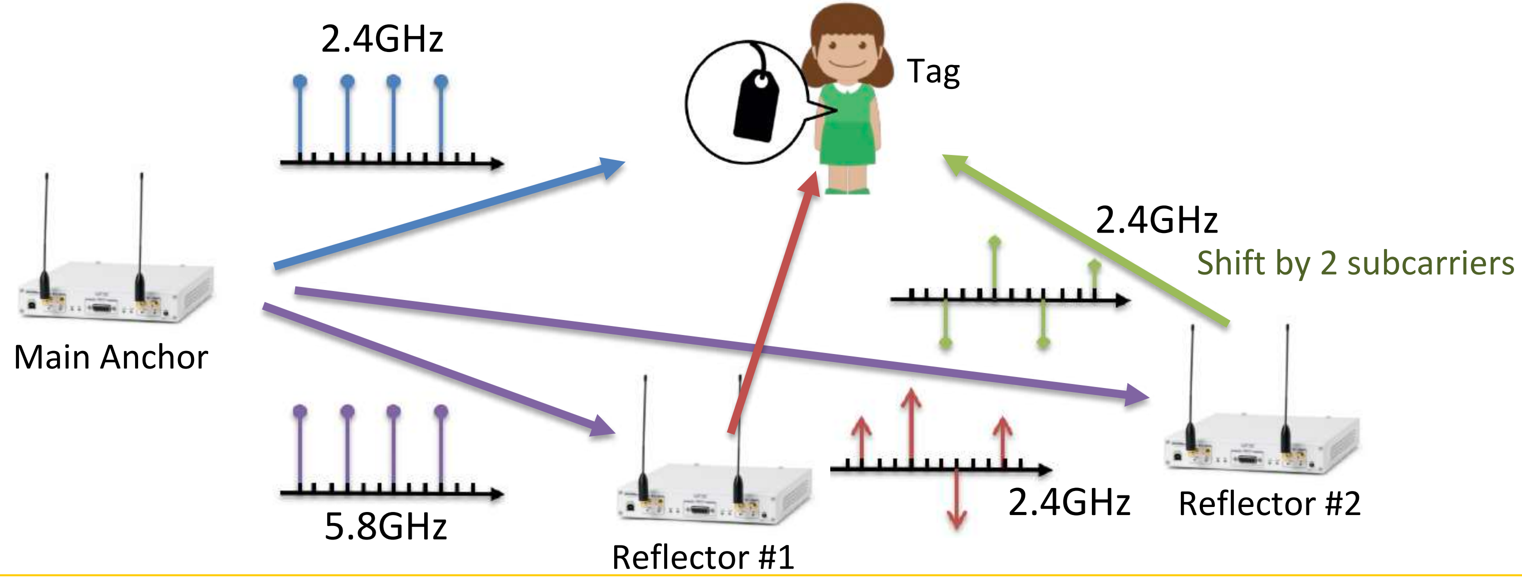

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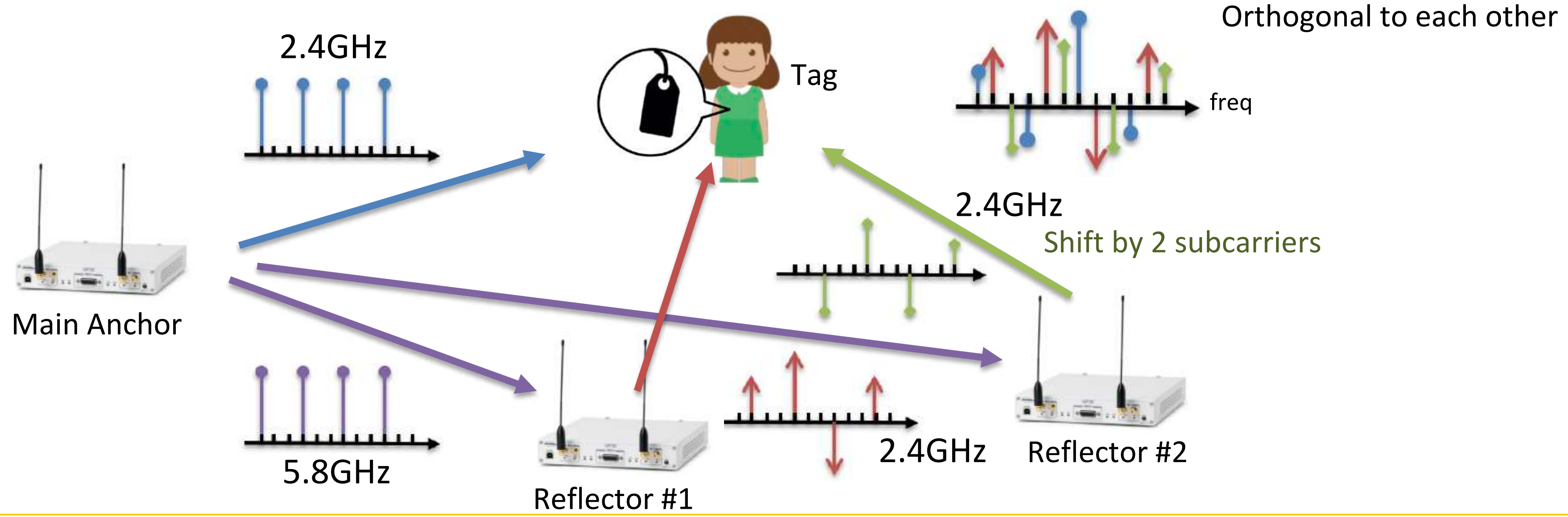
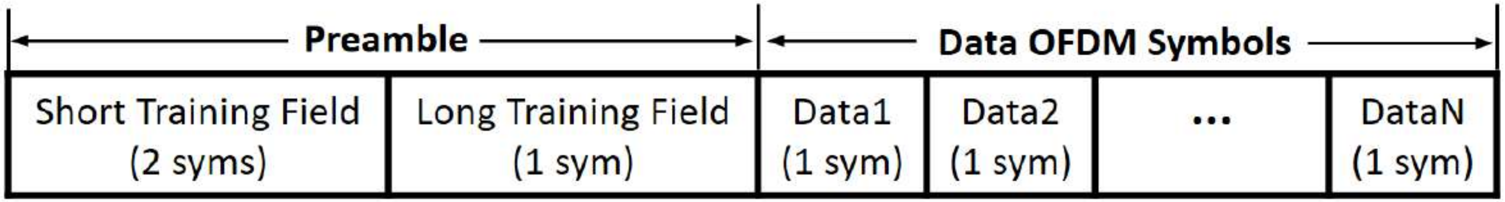


iLPS Communication

- Packet structure based on IEEE802.11a/g/n WiFi
  - STF for packet detection, LTF for CIR estimation
  - Data symbols contain anchor coordinate information and other general data



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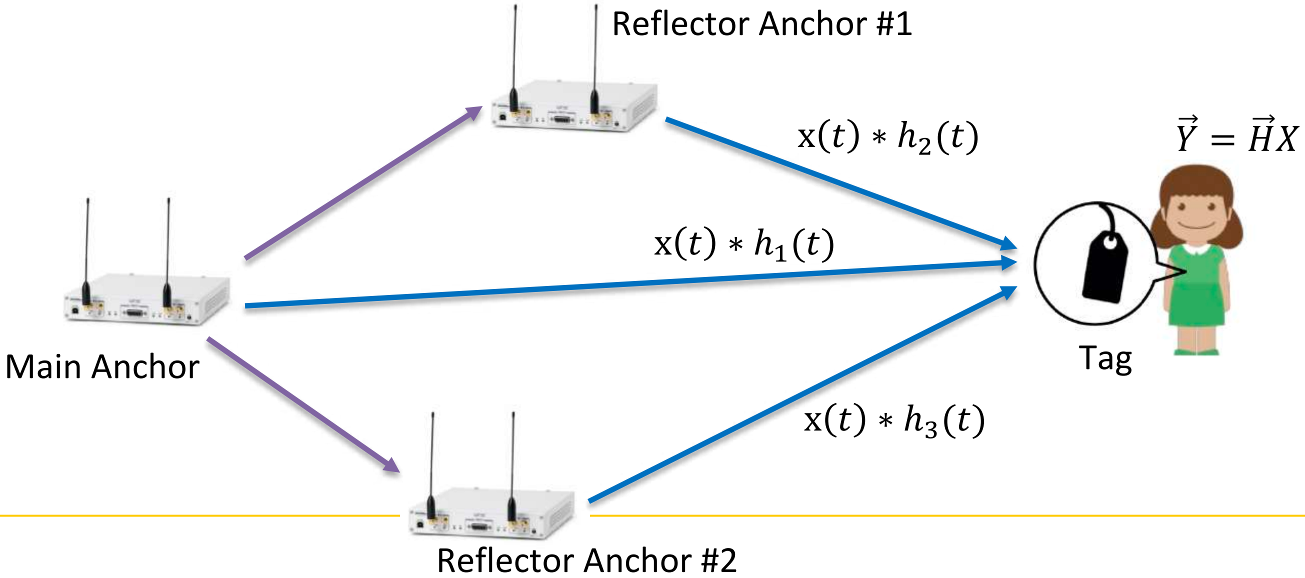
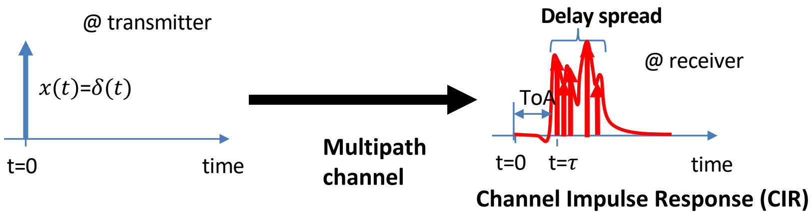
- **Distributed MISO system with frequency diversity**
  - Improves communication reliability



iLPS TDoA Estimation Accuracy

- Ranging accuracy vs Signal bandwidth

$$Distance\ resolution \propto \frac{1}{BW}$$



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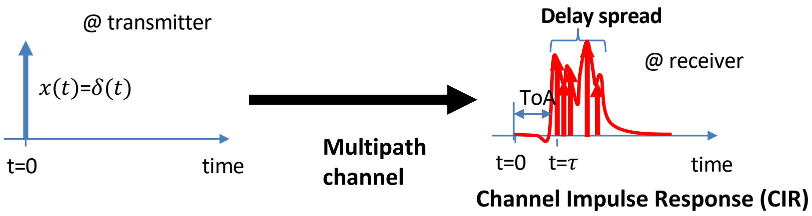

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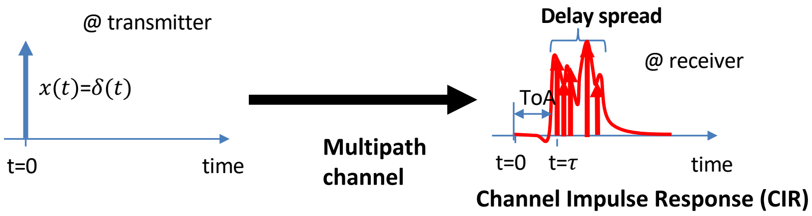

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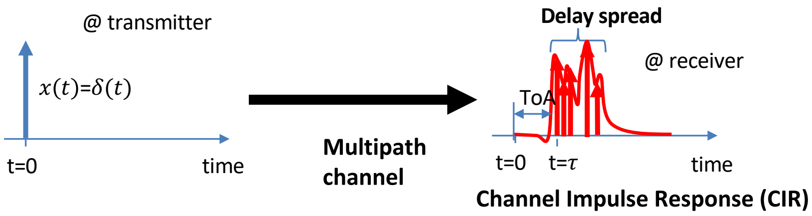

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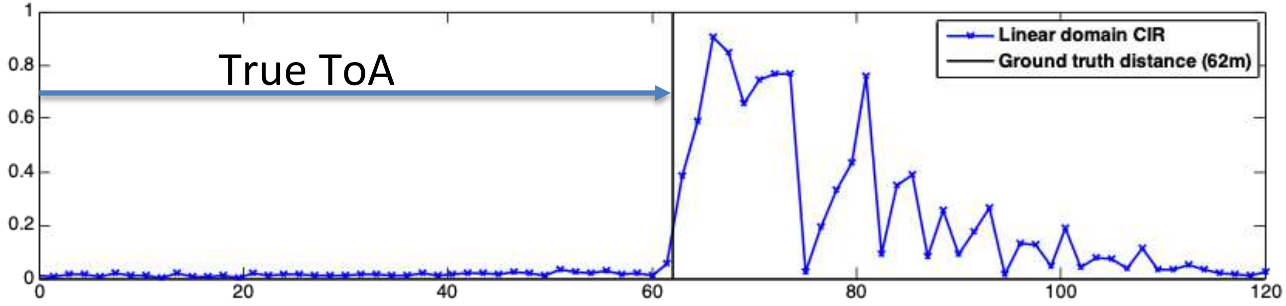
Machine learning based accuracy enhancement

Neural Network Based ToA Estimation

- How do we estimate ToA from coarsely measured (BW limited) CIR?



Neural Network Based ToA Estimation

- CIR pattern recognition via neural networks
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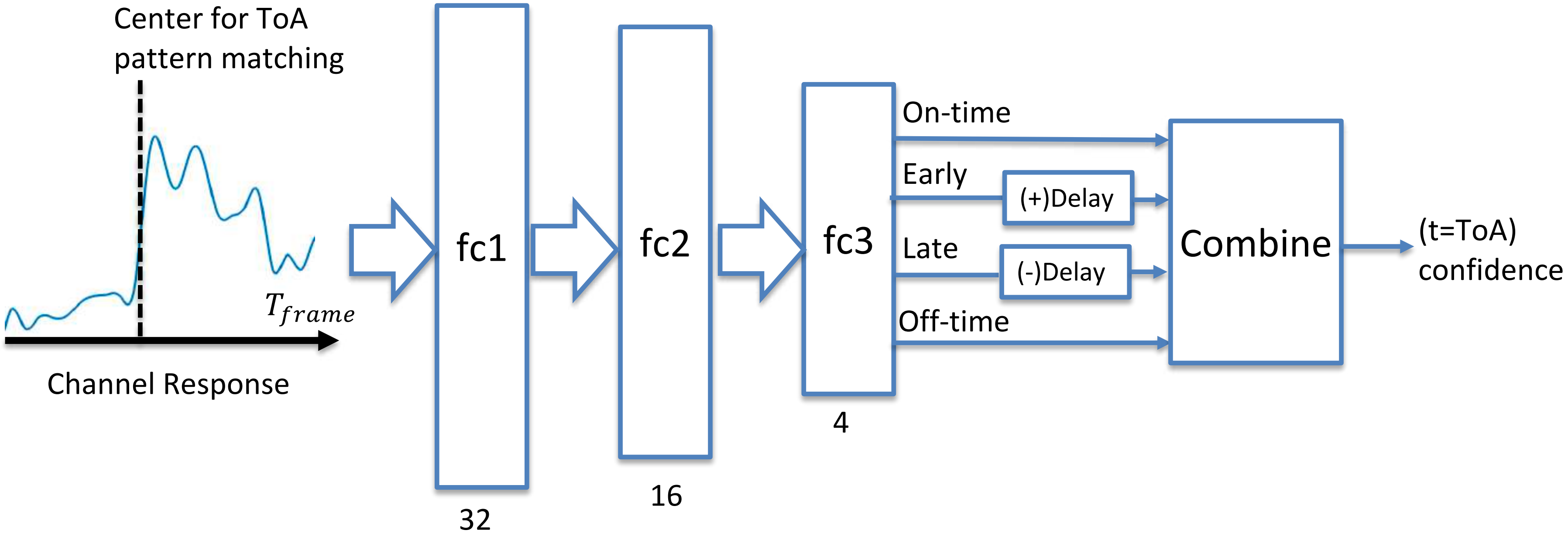
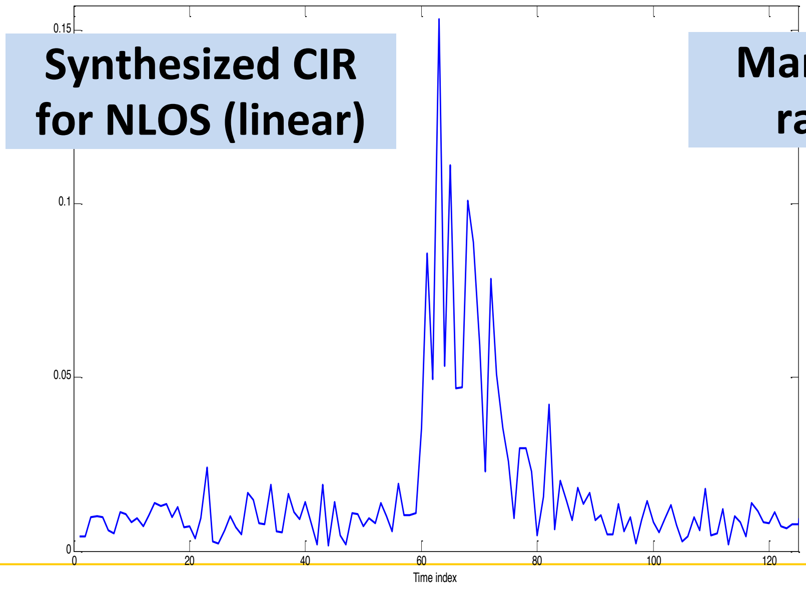
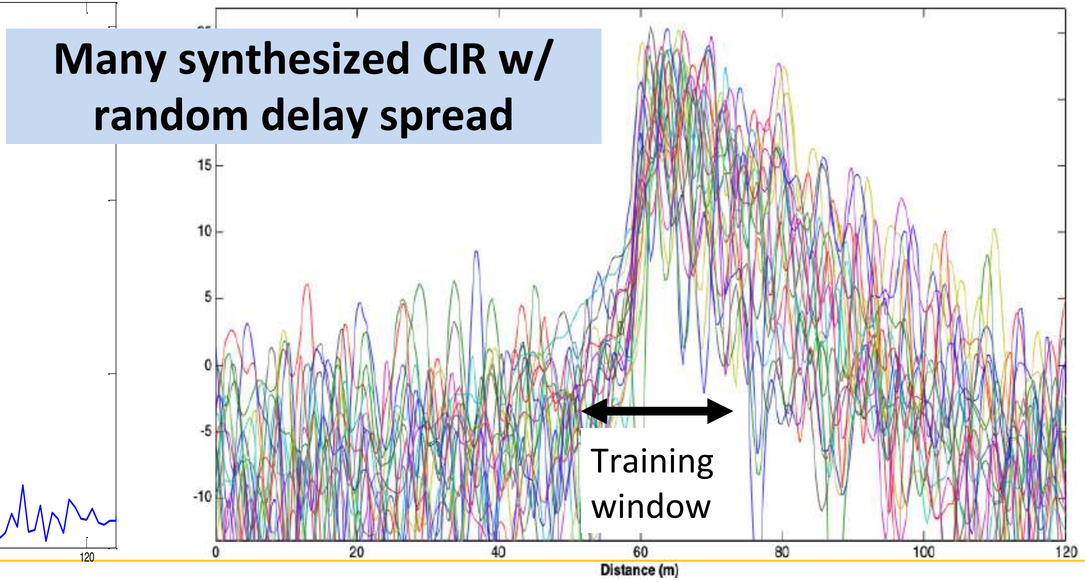


Neural Network Based ToA Estimation

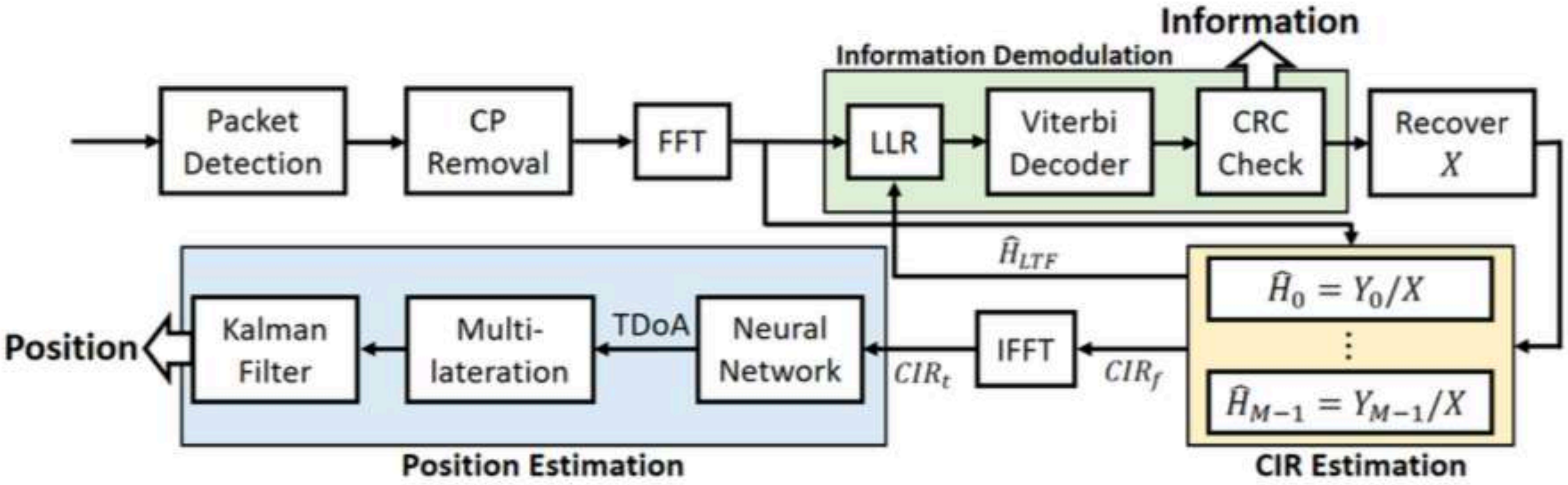
- CIR pattern recognition via neural networks
  - Train neural network to learn the shape around the first path
- Training set generated in Matlab simulation
  - No need of collecting real-world data before deploying tags





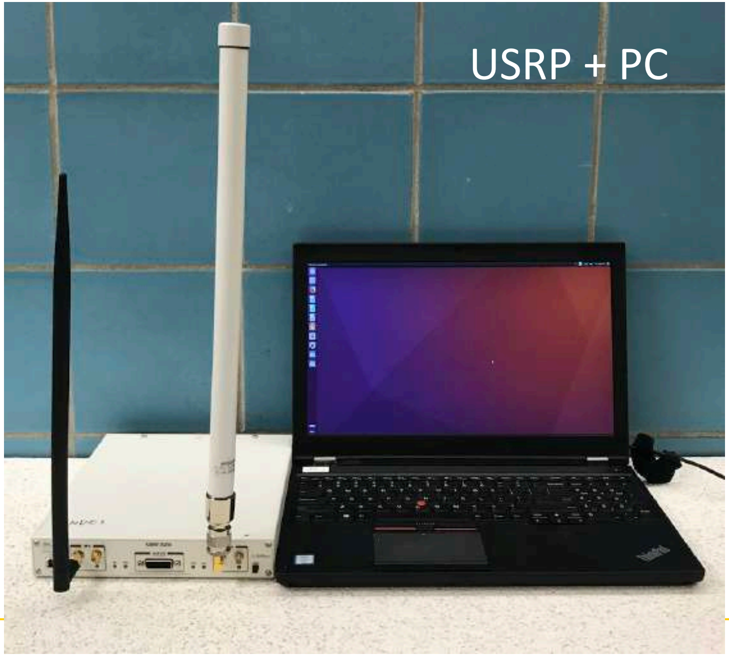
Baseband Signal Processing at Tags

- Tag implementation on USRP Software Defined Radio (SDR)
- Similar to WiFi 802.11 a/g/n
- Tag only requires a receiver for localization (similar to GPS receiver)



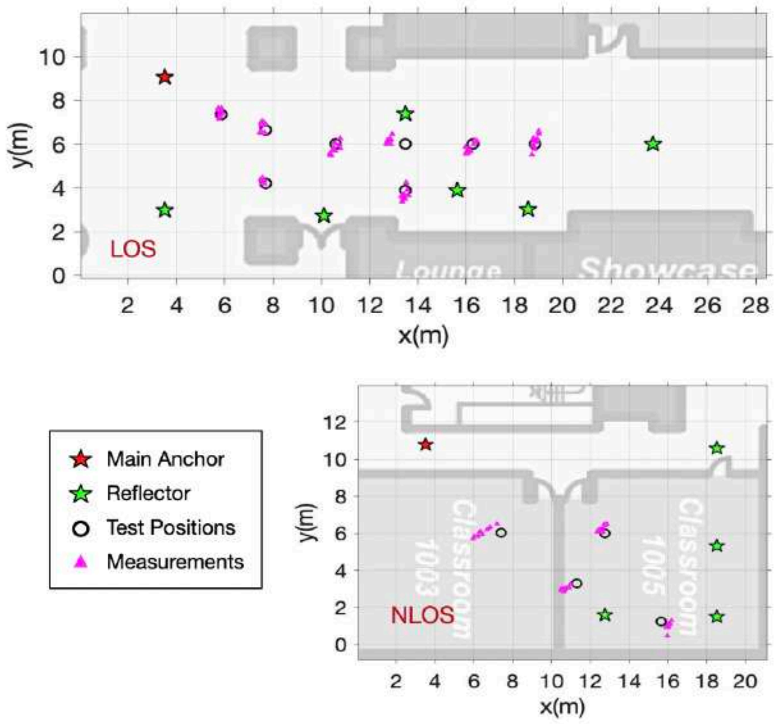
iLPS System Evaluation

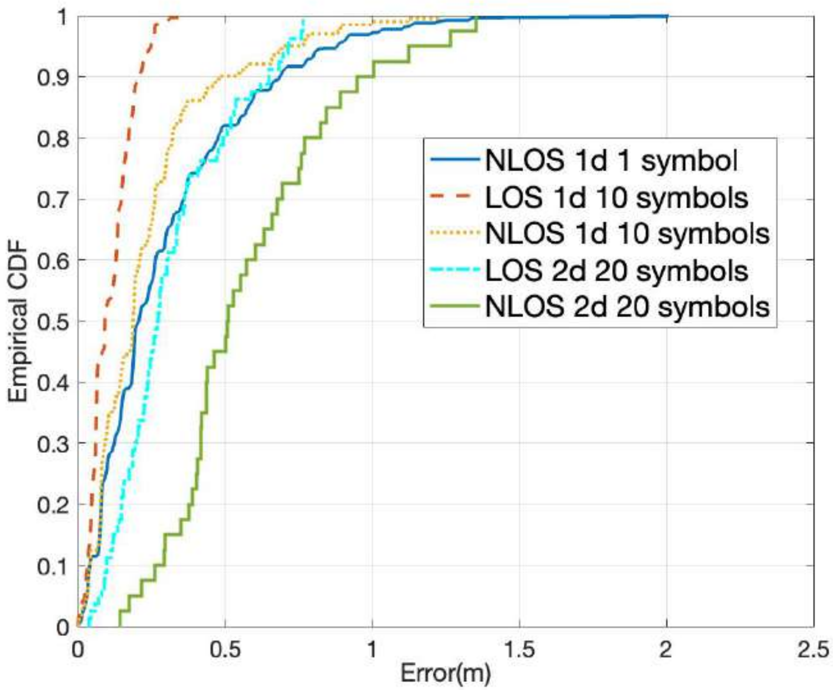
- Experiment environment and testing setup
- Main anchor, reflector and tags all implemented using USRP X310 SDR



iLPS System Evaluation

- 2D localization in University of Michigan EECS building





Comparison Table

System	Technology	LOS Accuracy	NLOS Accuracy	Testing Dimension	System Bandwidth	Latency for K tags Local.	Simultaneous Communication & Localization
WiTrack 2.0	FMCW+TDMA (ToA)	15.9 cm (median	16.1 cm (median)	LOS: 5 x 7 m^2 NLOS: 6 x 5 m^2	1.79GHz	10s (K < 5)	No
Harmonium	UWB+TDMA (TDOA)	31 cm (90%)	42 cm (90%)	LOS/NLOS: 4.6 x 7.2 x 2.7 m^3	3.5GHz	K x 52ms	No
WASP	OFDM+TDMA (ToA)	50 cm (85%)	50 cm (65%)	LOS: 10m NLOS: 15 x 15 m^2	125MHz	K x 2.5ms	Yes No diversity gain
Chronos	OFDM+TDMA (Band-stiching ToA)	14.7 cm (median)	20.7 cm (median)	LOS/NLOS: 20x 20 m^2	20MHz x 35 overlapped	3 x 84ms	Possible, Not demonstrated
RF-Echo	OFDM+TDMA (ToA)	26 cm (90%)	46 cm (90%)	LOS: 7 x 90 m^2 NLOS: 30 x 20 m^2	80MHz x 2	K x 200µs	No
iLPS	**OFDMA (TDoA)**	**20 cm (90%)**	**50 cm (90%)**	**LOS: 15-105m** **NLOS: 20 x 12 m^2**	**80MHz x 2**	**84µs**	**Yes** **MISO diversity gain**

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WASP	OFDM+TDMA (ToA)	50 cm (85%)	50 cm (65%)	LOS: 10m NLOS: 15 x 15 m^2	125MHz	K x 2.5ms	Yes No diversity gain
Chronos	OFDM+TDMA (Band-stiching ToA)	14.7 cm (median)	20.7 cm (median)	LOS/NLOS: 20x 20 m^2	20MHz x 35 overlapped	3 x 84ms	Possible, Not demonstrated
RF-Echo	OFDM+TDMA (ToA)	26 cm (90%)	46 cm (90%)	LOS: 7 x 90 m^2 NLOS: 30 x 20 m^2	80MHz x 2	K x 200µs	No
iLPS	**OFDMA (TDoA)**	**20 cm (90%)**	**50 cm (90%)**	**LOS: 15-105m** **NLOS: 20 x 12 m^2**	**80MHz x 2**	**84µs**	**Yes** **MISO diversity gain**

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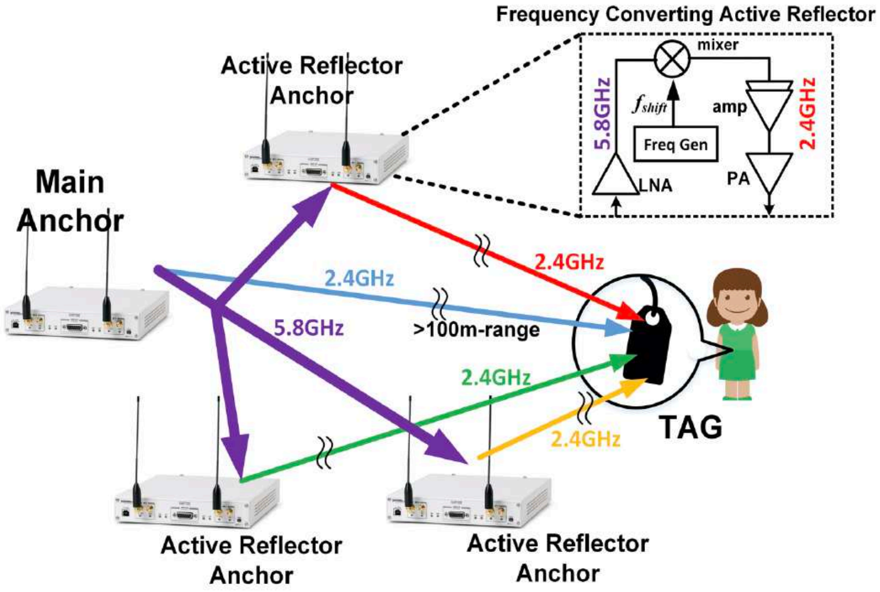
Summary of iLPS

- **Decimeter** ranging accuracy
- Large covered area: **105m** LOS distance
- **GPS-like local positioning** scheme
  - Able to localize infinite number of tags simultaneously
- **Reliable wireless communications** between anchors and tags
- Deployable without heavy infrastructure investment



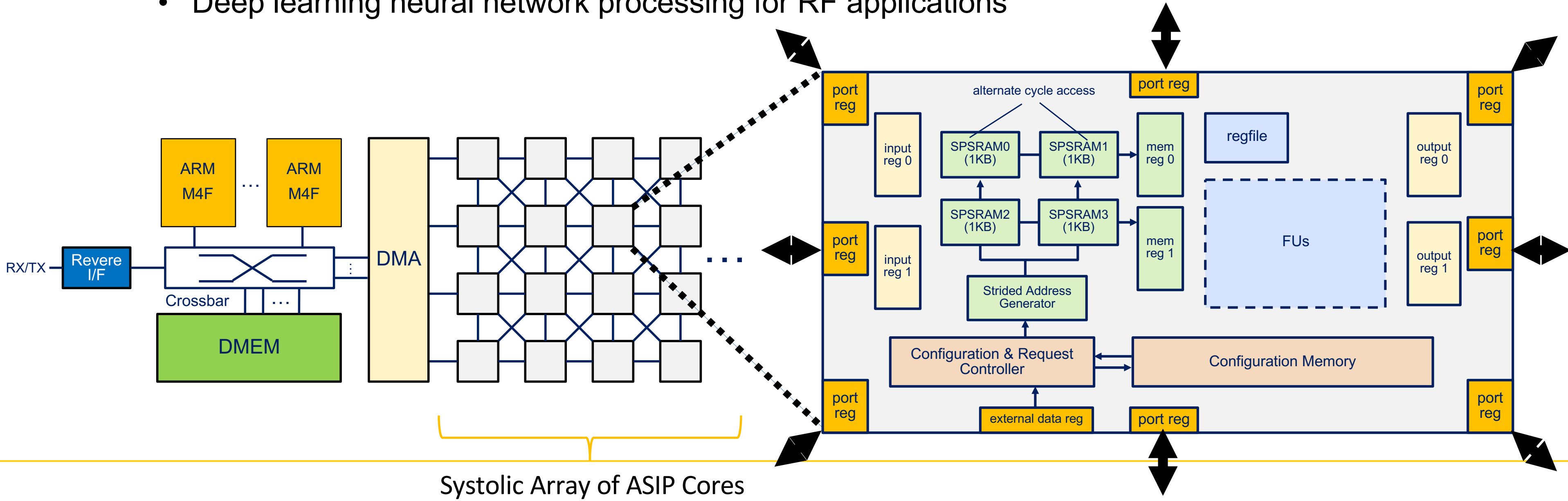
Research Scope

- **New Indoor RF Localization Solutions**
  - Year1: RF-Echo with custom ASIC tag
  - Year2: iLPS for simultaneous communication and localization
  - Year3: Sound-RF hybrid solution

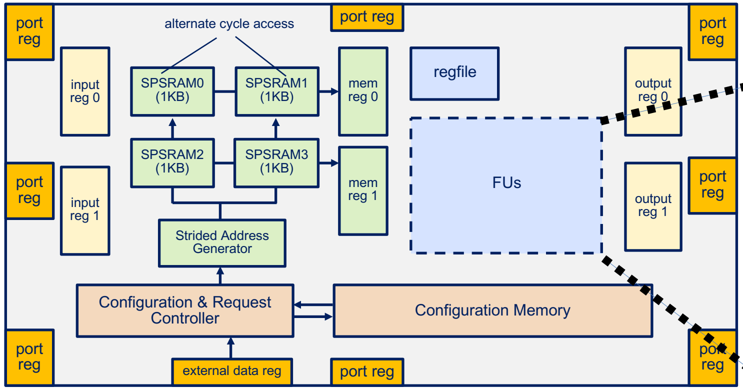
- **Application specific integrated circuit (ASIC) fabrication**
  - Year1: Low power active reflection tag ASIC
  - Year2 and 3: Low power processor for software-defined radio ASIC
    - Wireless communication (WiFi, Bluetooth, Zigbee, proprietary)
    - RF localization
    - Deep learning neural network processing for RF

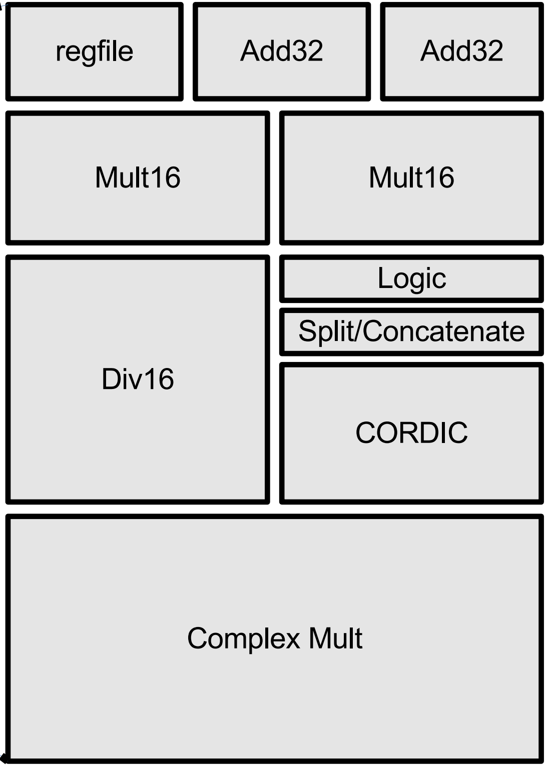
SDR Processor Architecture

- Systolic array of ASIP cores + Arm cores
  - Systolic array of application specific instruction set processor (ASIP)
  - Custom instruction set architecture designed for RF localization and communication
    - Wireless communication (WiFi, Bluetooth, Zigbee, proprietary)
    - RF localization
    - Deep learning neural network processing for RF applications



SDR Processor Core Functional Unites

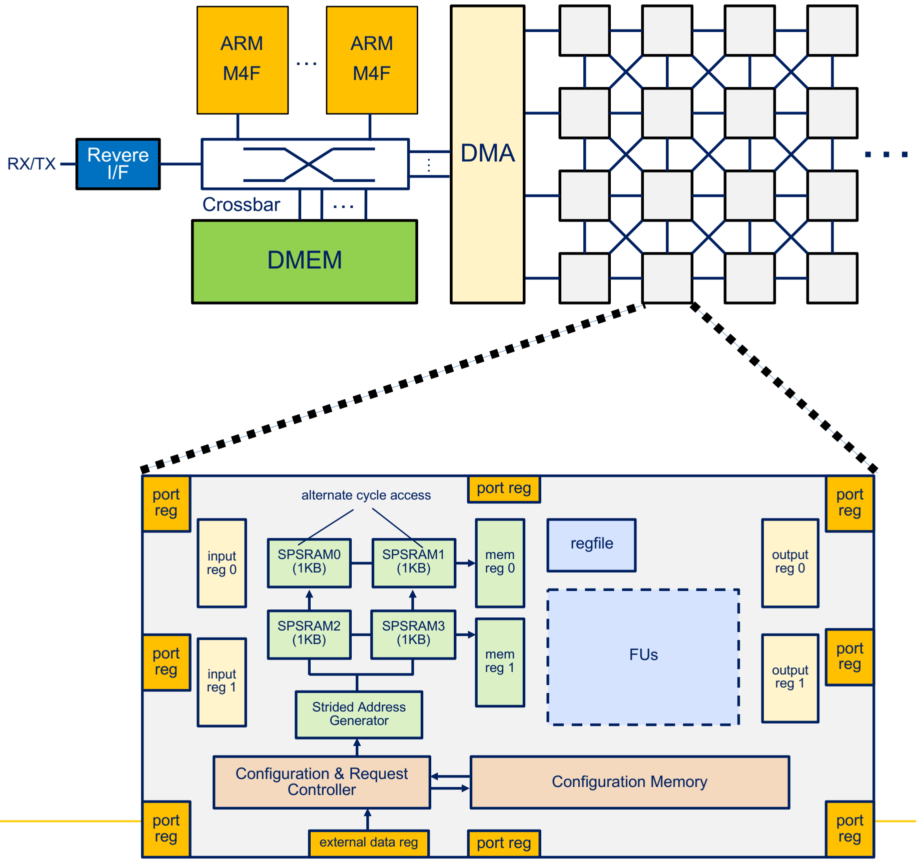




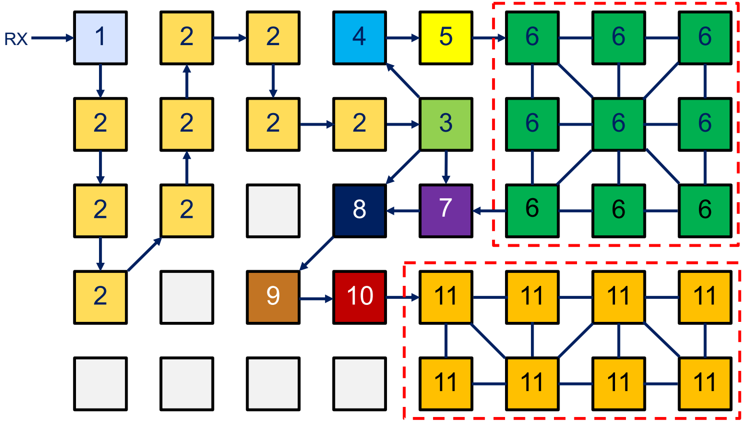
- 8-entry register file, 2r1w
- 2x 32-bit adders, can be configured as 4x 16-bit adders (2 complex adders)
- 2x 16-bit multipliers
- 1x 16-bit divider
- Logic module for AND/OR/XOR/CMP operations
- 1x 16-bit CORDIC
- 1x 16-bit Complex Multiplier
- 1 splitter and 1 concatenator for converting between complex and real values
- All computational FUs are followed by a shifter for pseudo-floating point

Algorithm Mapping on SDR Processor

Systolic Array of ASIP Cores



- iLPS localization processing mapping onto SDR



1. Auto-correlation packet detection
2. FFT (1024 point)
3 & 4. Channel estimation and equalization (complex multiplication)
5. QAM demapping LLR
6. Soft-input Viterbi
… 11. Neural network

Target Performance

Processor	Area (mm^2)	Clock Freq. (GHz)	Performance (GOPs)	Power (W)
Arm Quad-core A72 cluster	3.72	1.6	51.2	1.268
Proposed 256-core SDR Processor	**4.12**	**3.2**	**3277**	**~ 2.0**

Proposed SDR processor achieves ~30x higher efficiency compared to commercial low power mobile processor for wireless applications

Conclusion

- **New Indoor RF Localization Solutions**
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Thank you !

UNIVERSITY OF MICHIGAN

#PSCR2019

Get your hands on the tech!

Demos Open

BACK TOMORROW

8:00 AM