Enabling IoT Self-Localization Using Ambient 5G Signals

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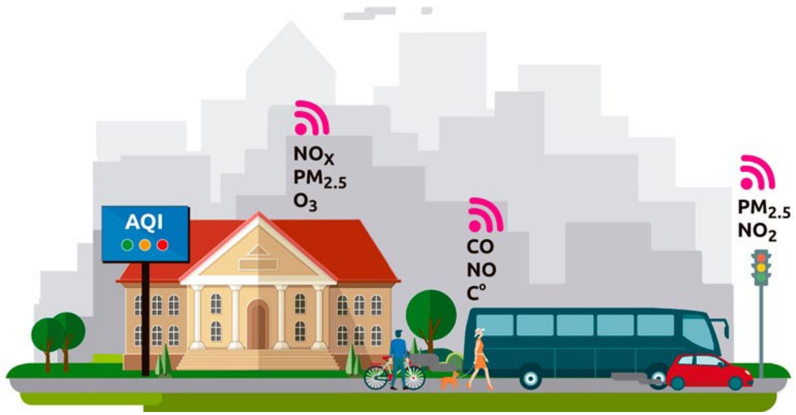
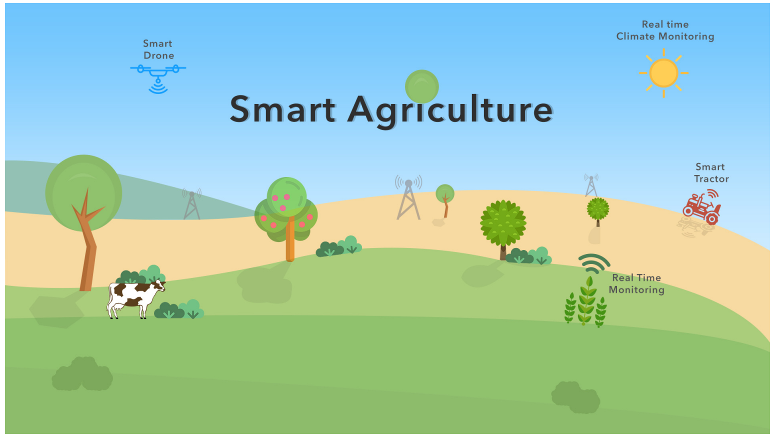
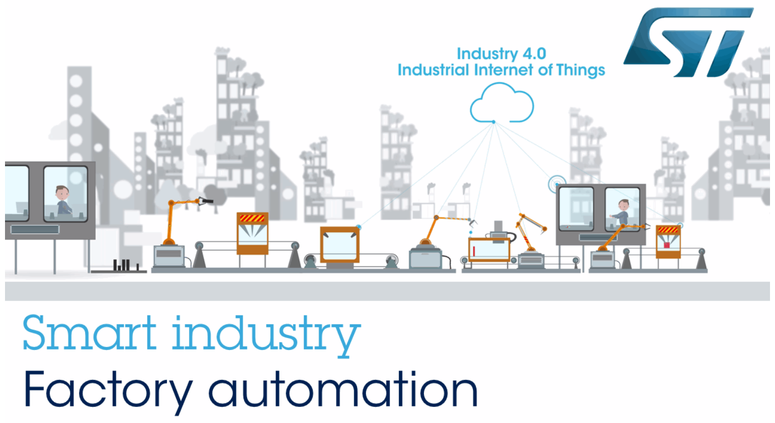
Number of Deployed IoT Devices to Explode



Smart City Monitoring



Data Driven Agriculture



Industry 4.0 Automation

Deployed IoT nodes projected to grow to 31 billion units by 2030

Localization and Tracking are essential primitives for multiple applications

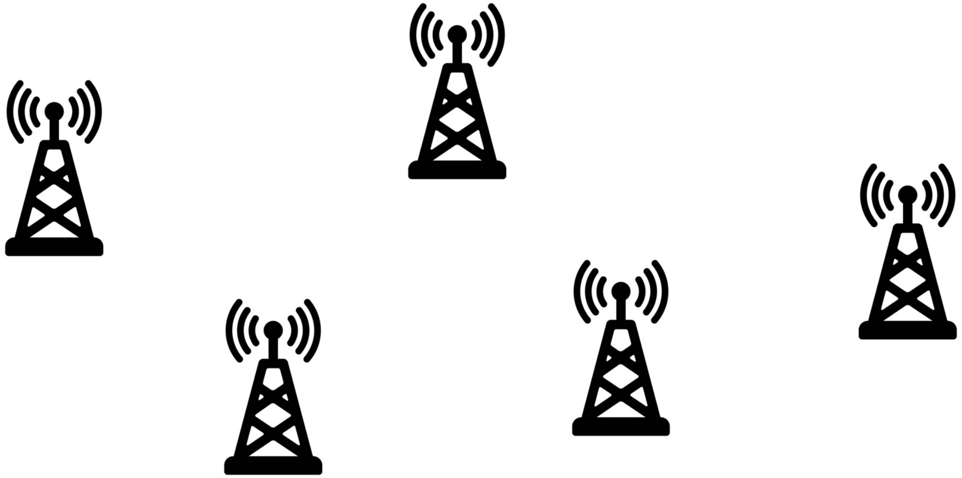
Related Work

GPS

- Power Hungry
- Extra Hardware Costs

Cellular Networks and IoT Base Stations

[WCNC’19, IPSN’21, IEEE J-SAC’22]



- Achieve very low resolution ~ 100s of meters
- Requires active base station participation for tight synchronization

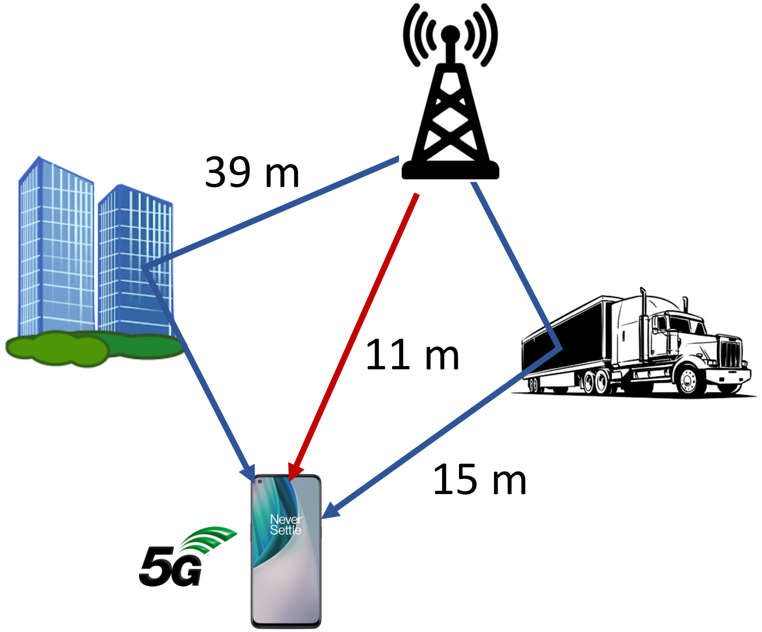
Can an IoT device accurately localize itself:

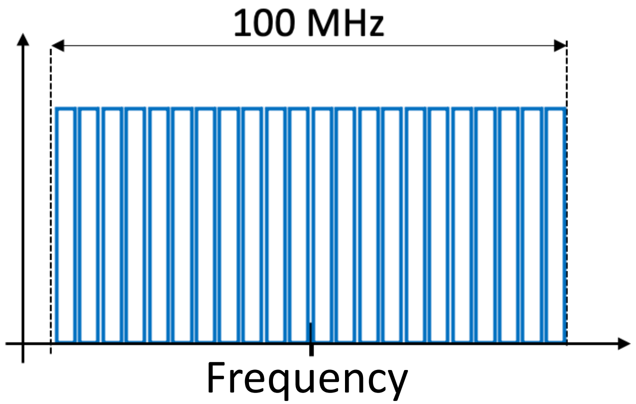
1. Simply by listening to ambient 5G cellular signals?
2. Without any coordination with the base stations?

Ambient Localization is very important for scalability

5G presents Unique Opportunity for Localization

1. Small Cell Architecture leads to very high density of 5G Base Stations
   - Gives large number of anchor points for improved accuracy
2. 5G packets can span up to 100 MHz bandwidth
   - The high bandwidth allows for high ToF resolution (3 meters for 100 MHz)





Translate to
ToF of paths

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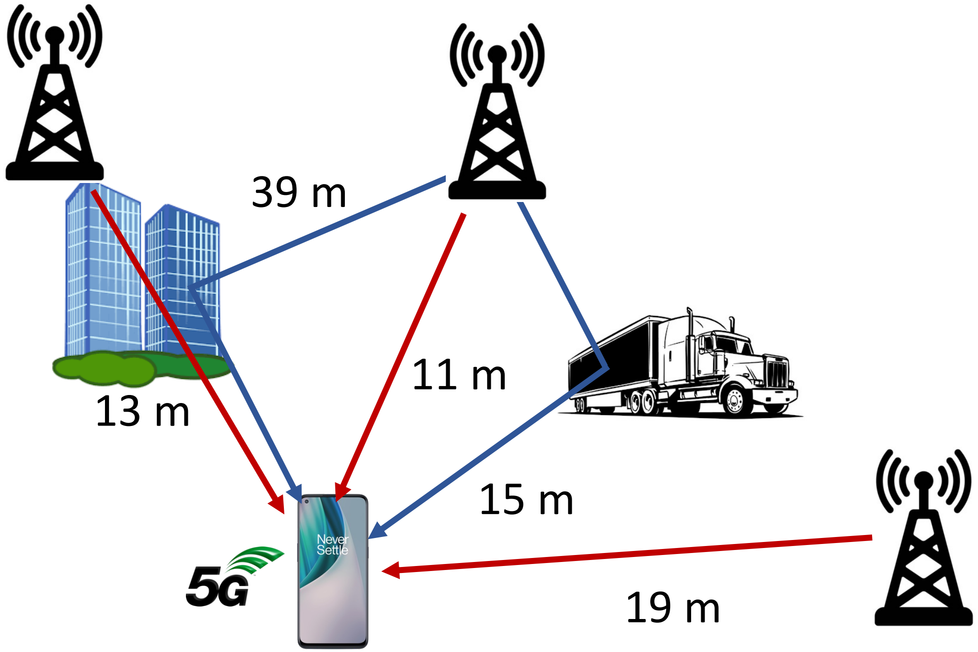
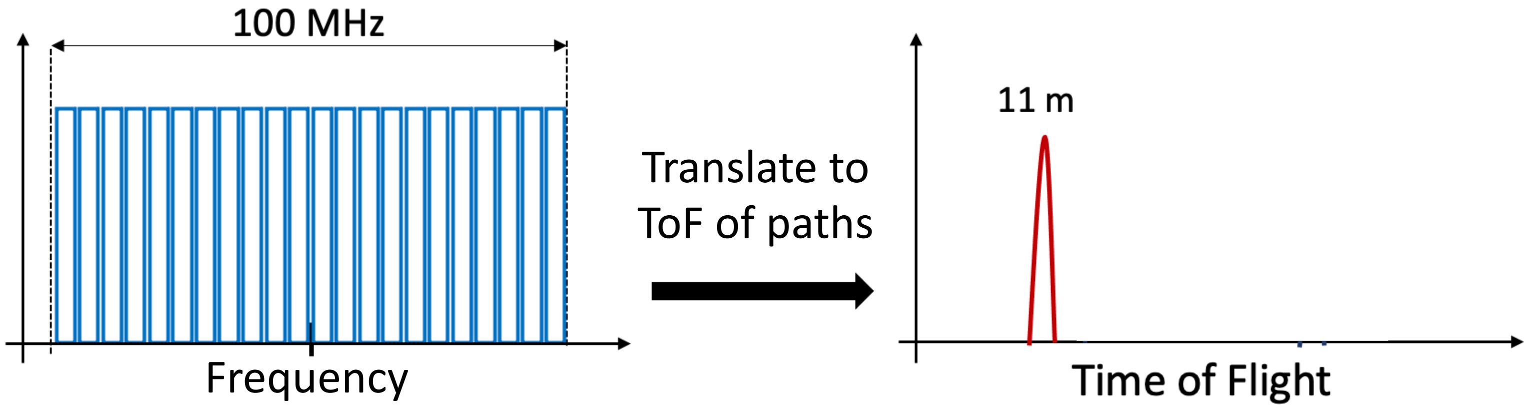
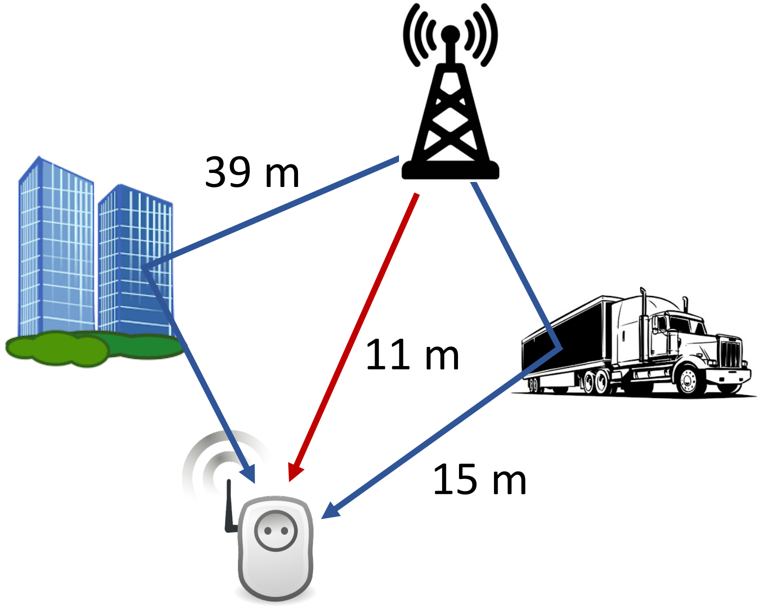


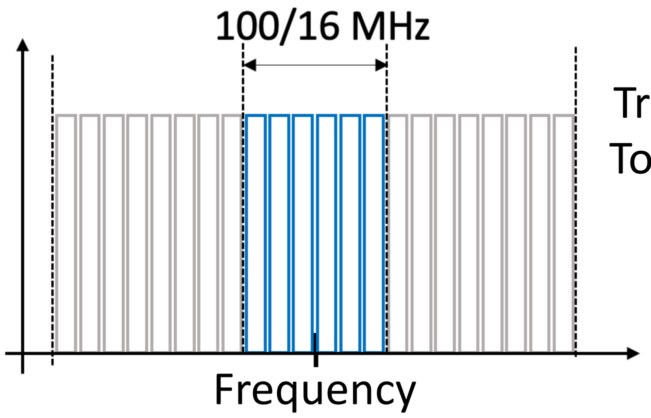


Ambient Localization on Low-Cost IoT Devices is Challenging!

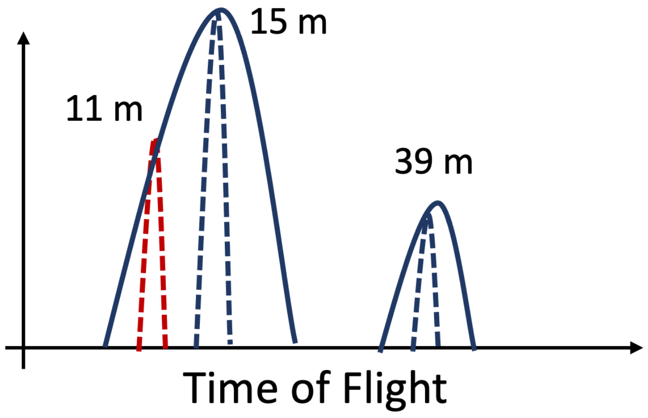
Challenge 1: Low-Cost IoT Devices cannot leverage Bandwidth

- Low Speed ADCs can only capture narrow bandwidth
- 16x smaller bandwidth





Translate to ToF of paths



Ambient Localization on Low-Cost IoT Devices is Challenging!

Challenge 1: Low-Cost IoT Devices cannot leverage Bandwidth

- Low Speed ADCs can only capture narrow bandwidth
- 16x smaller bandwidth → 16x lower ToF resolution

Challenge 2: Absolute ToF requires synchronization with BSs

- Synchronization Offsets between BS and IoT node corrupts ToF estimates
- 1-way measurements from ambient packets alone cannot correct for offsets

ISLA Overview

ISLA enables **I**oT **S**elf-**L**ocalization using **A**mbient Broadband 5G Signals

Capturing Large Bandwidth 5G Signals on Narrow Bandwidth IoT Device

$\xrightarrow{\text{Recovered ToF information}}$

Localization without coordination with Base Stations

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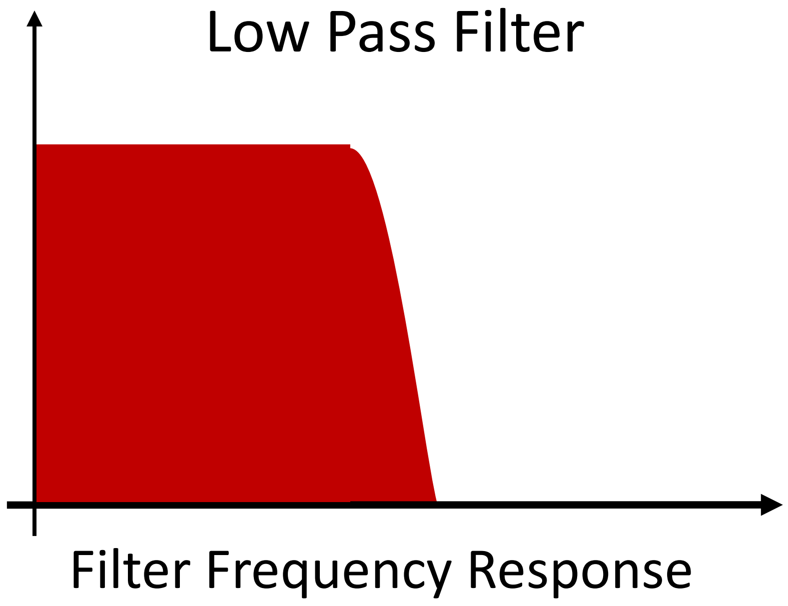
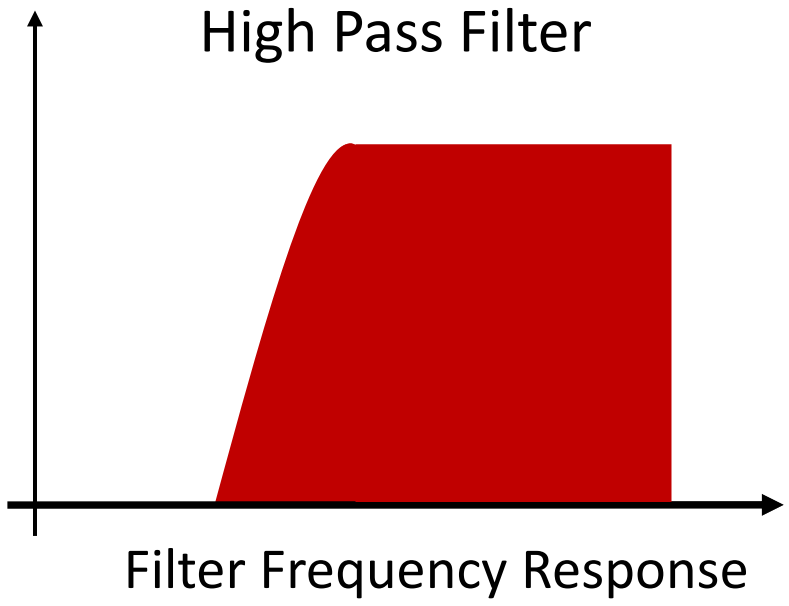
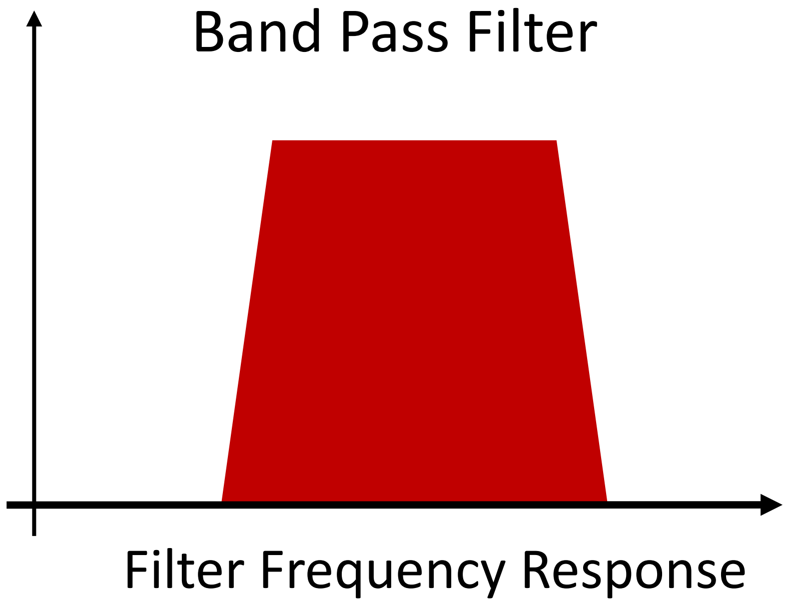
Capturing 5G Signals on Narrowband IoT Devices

Leverage MEMS Acoustic Resonators to design new RF Filters

Traditional RF Filters

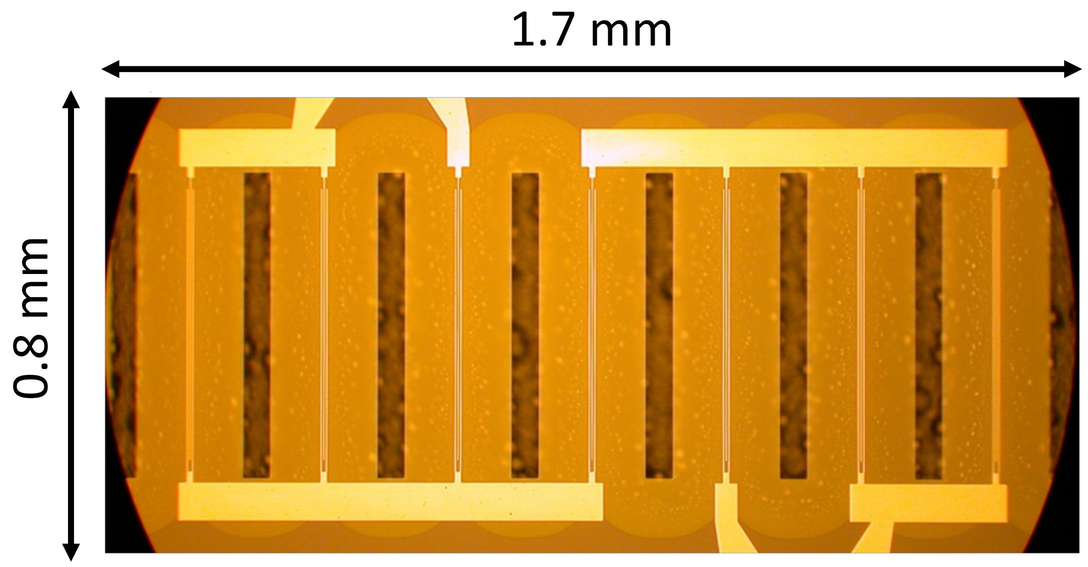




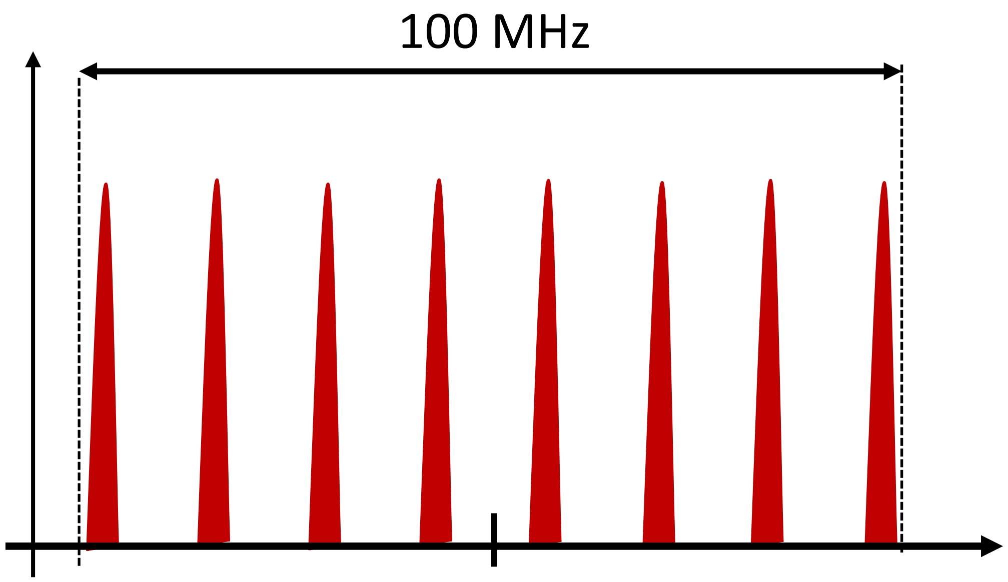


Capturing 5G Signals on Narrowband IoT Devices

Leverage MEMS Acoustic Resonators to design new RF Spike-Train Filters



Filter under microscope
[NSDI'21, IEEE J-MEMS'18]

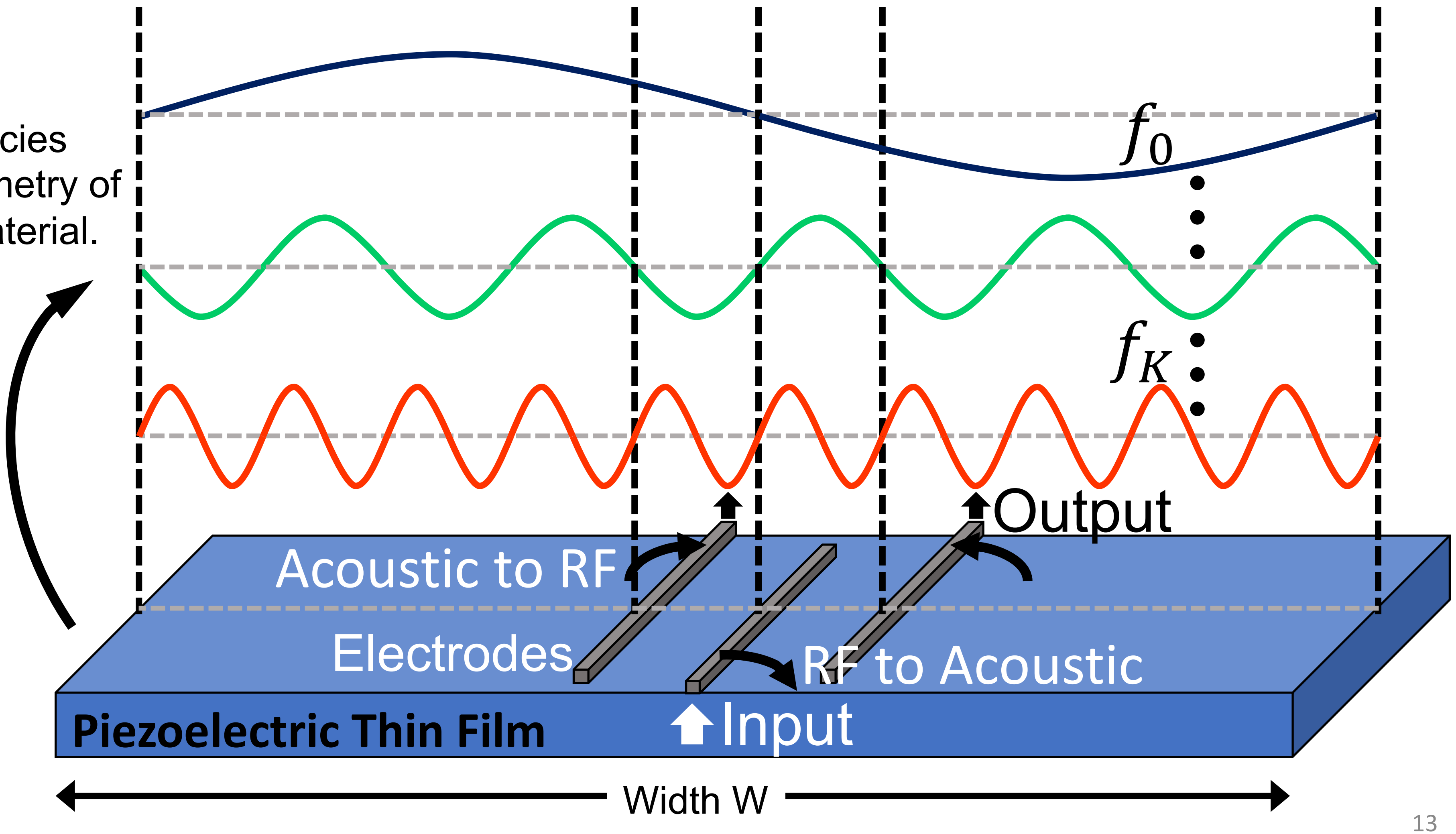


Filter Frequency Response

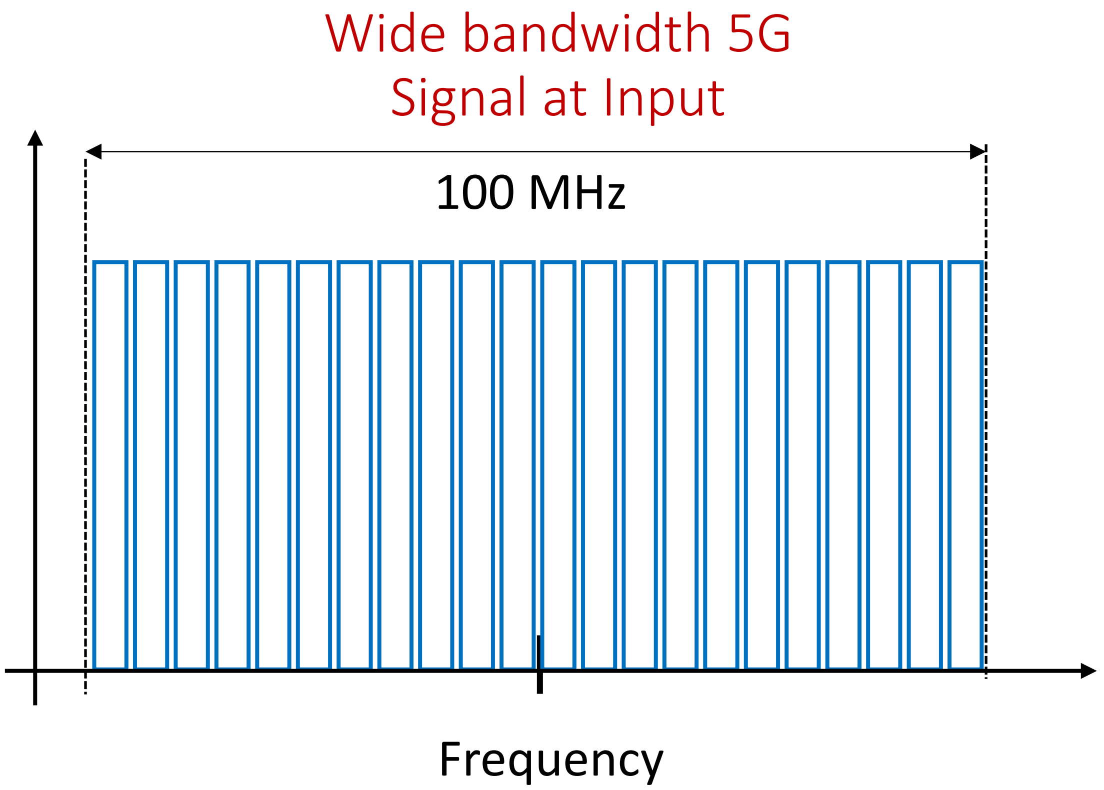
Spike-Train Filter Created by MEMS Acoustic Resonators

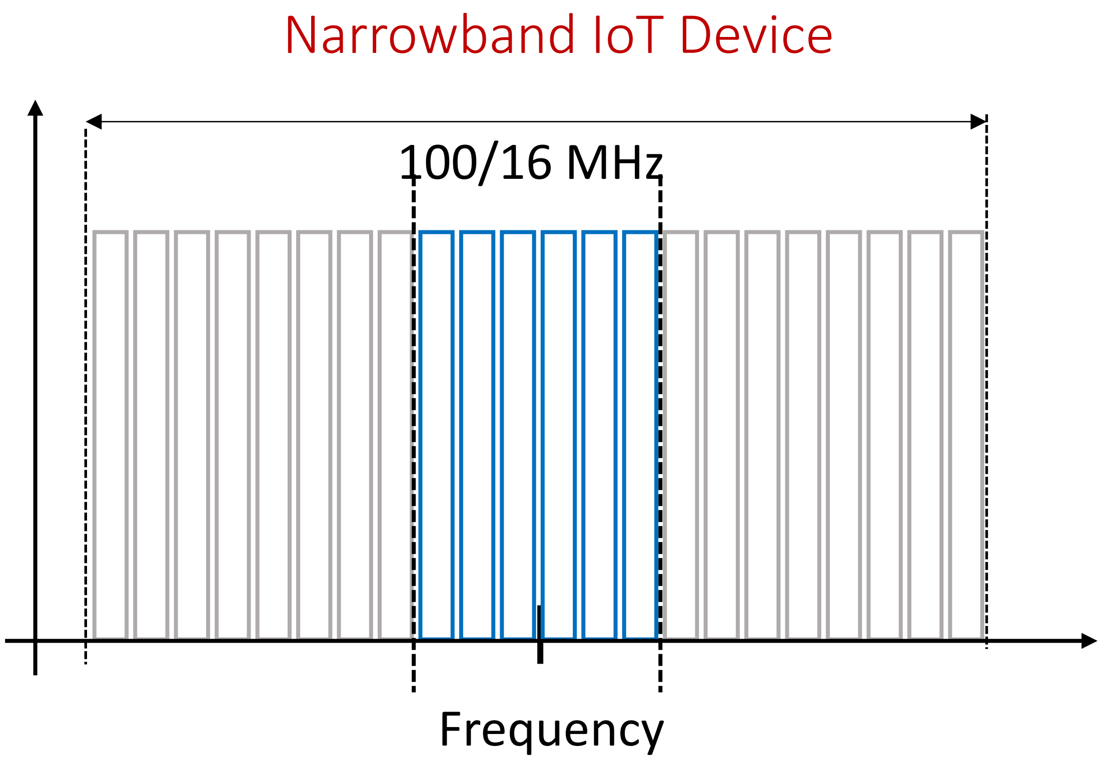
MEMS: Micro-Electro-Mechanical Systems

Resonance frequencies determined by geometry of the piezoelectric material.

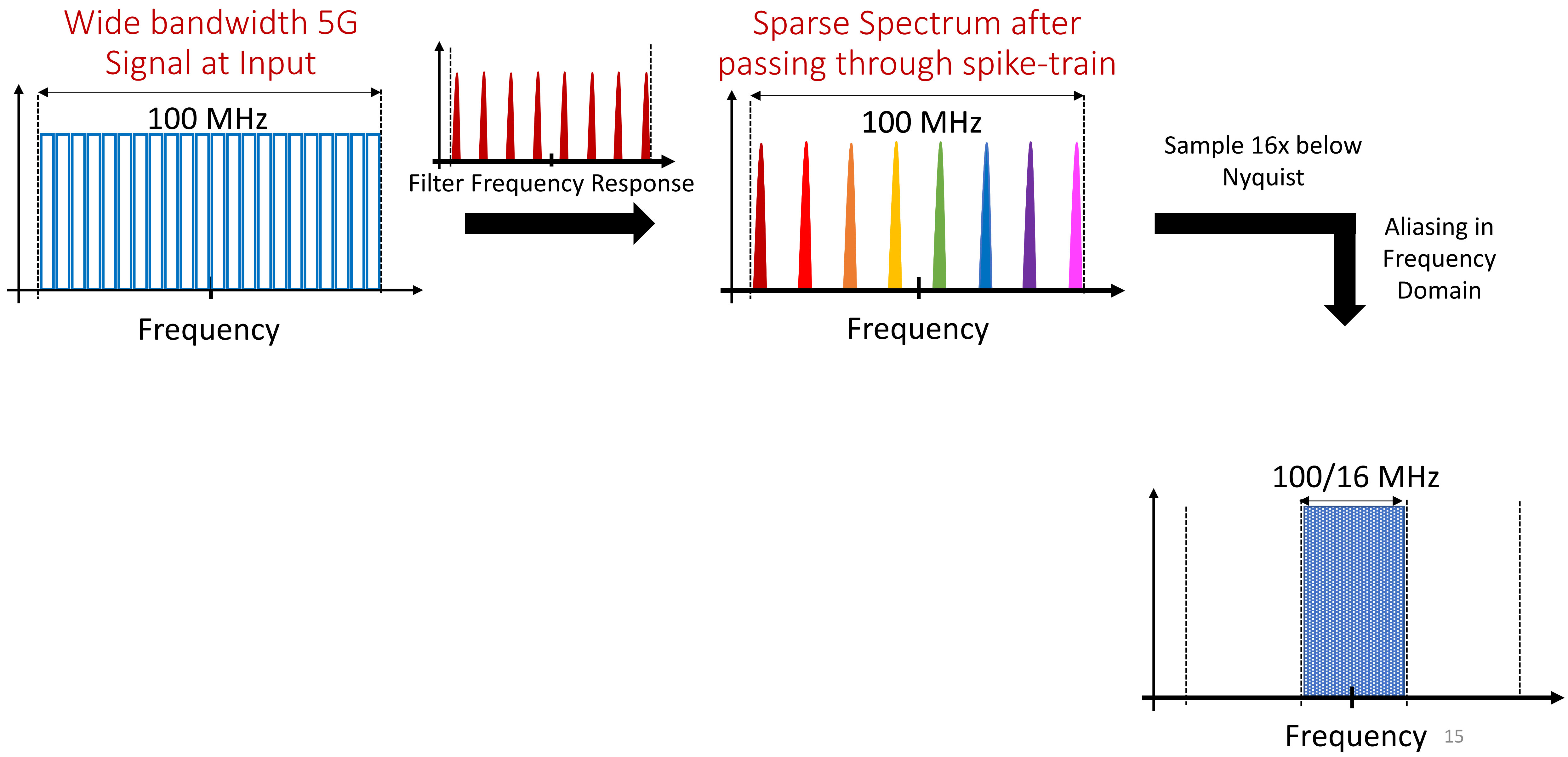


Capturing 5G Signals on Narrowband IoT Devices



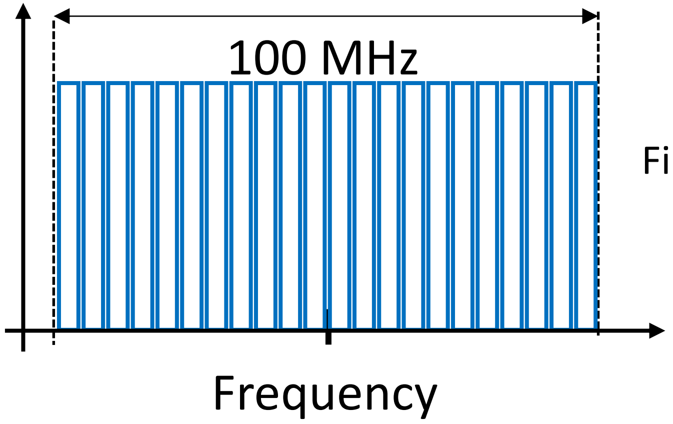


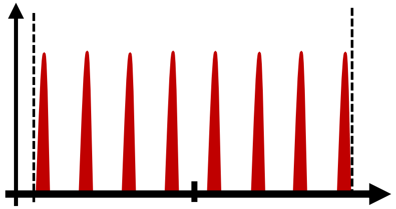
Capturing 5G Signals on Narrowband IoT Devices



Capturing 5G Signals on Narrowband IoT Devices

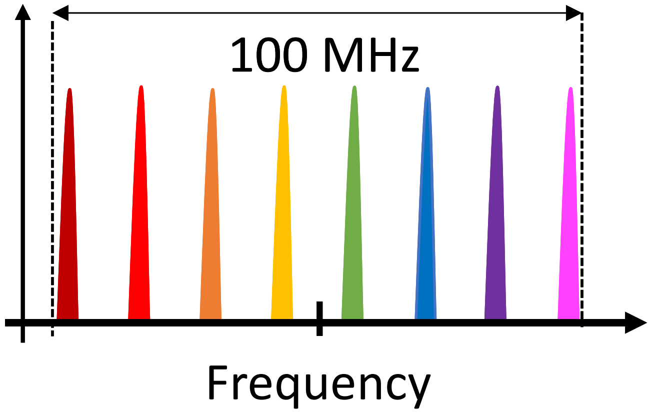
Wide bandwidth 5G Signal at Input





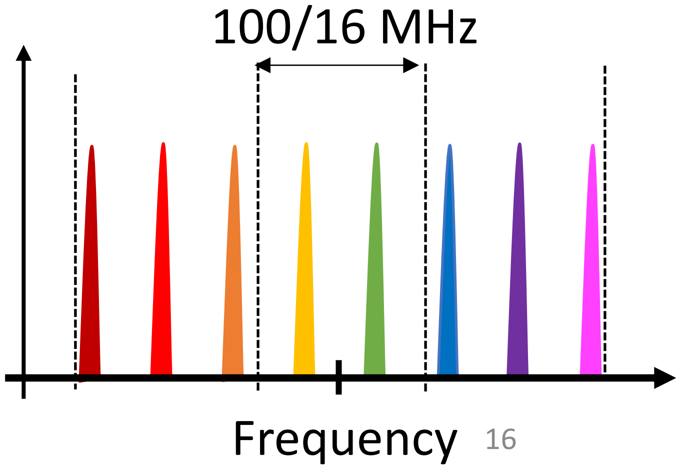
Filter Frequency Response

Sparse Spectrum after passing through spike-train

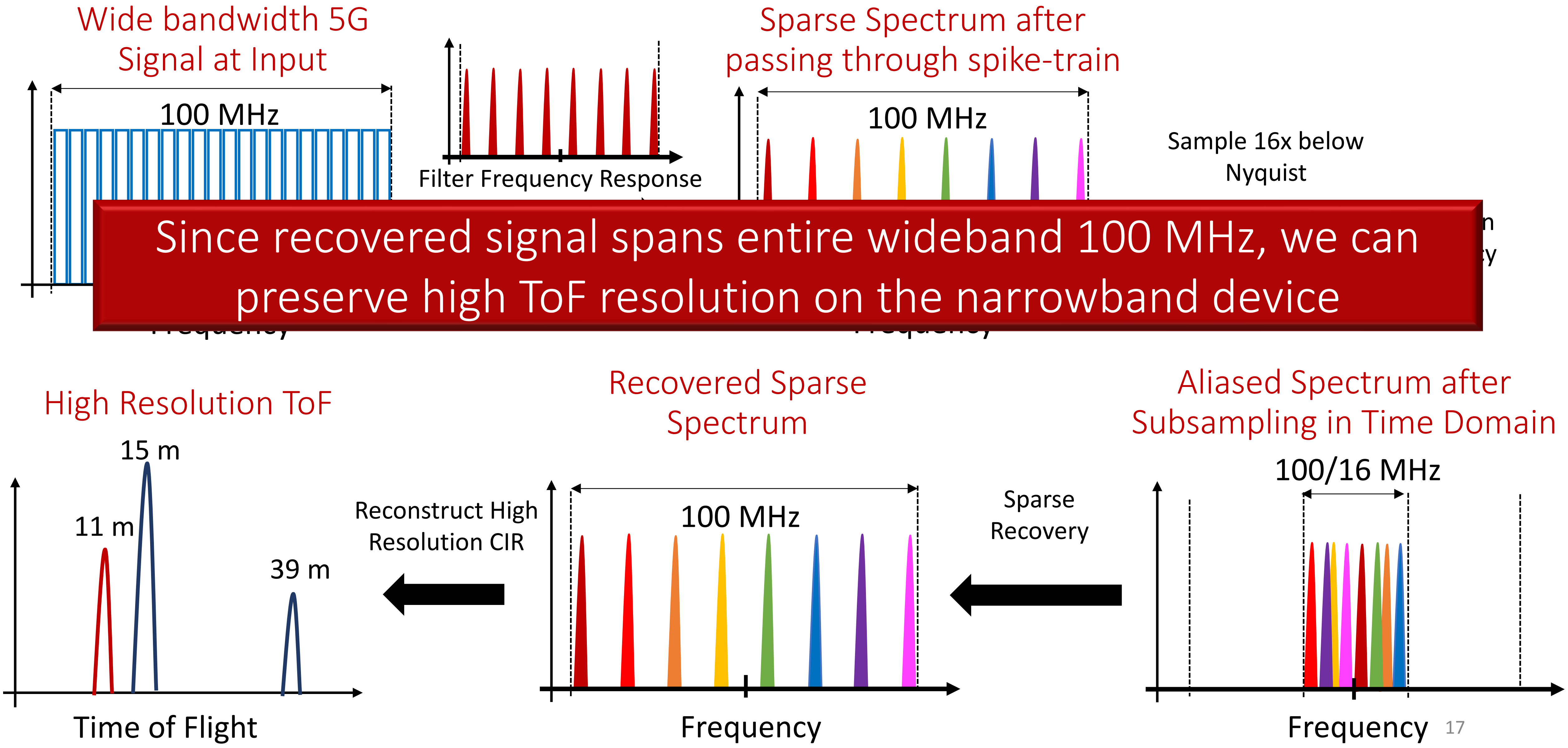


Sample 16x below Nyquist

Aliasing in Frequency Domain

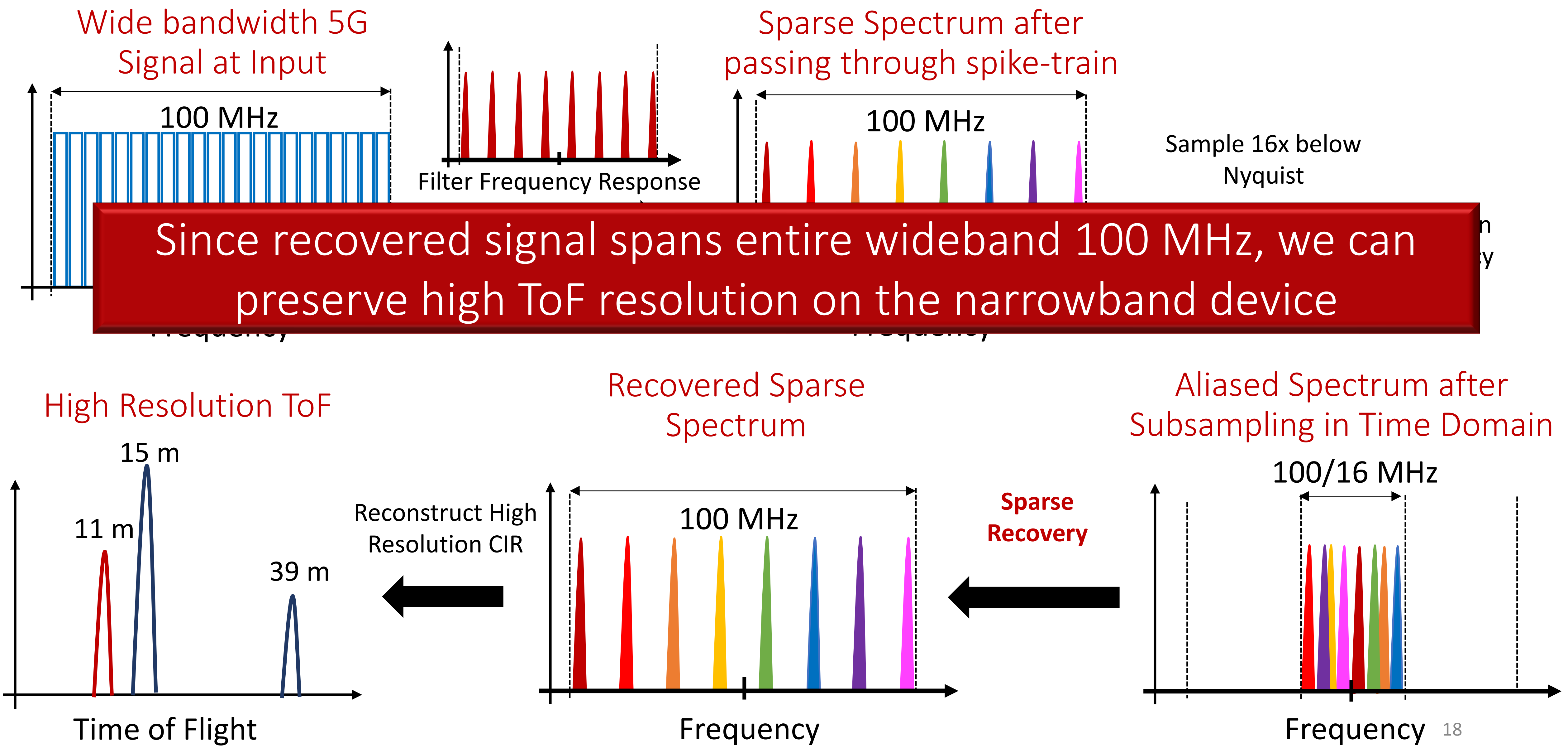


Capturing 5G Signals on Narrowband IoT Devices

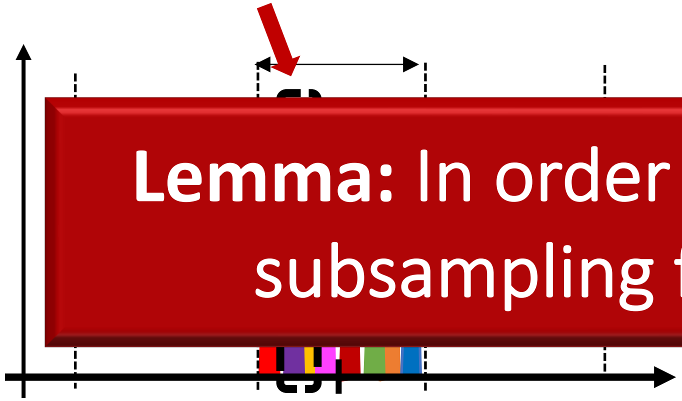


Since recovered signal spans entire wideband 100 MHz, we can preserve high ToF resolution on the narrowband device

Capturing 5G Signals on Narrowband IoT Devices

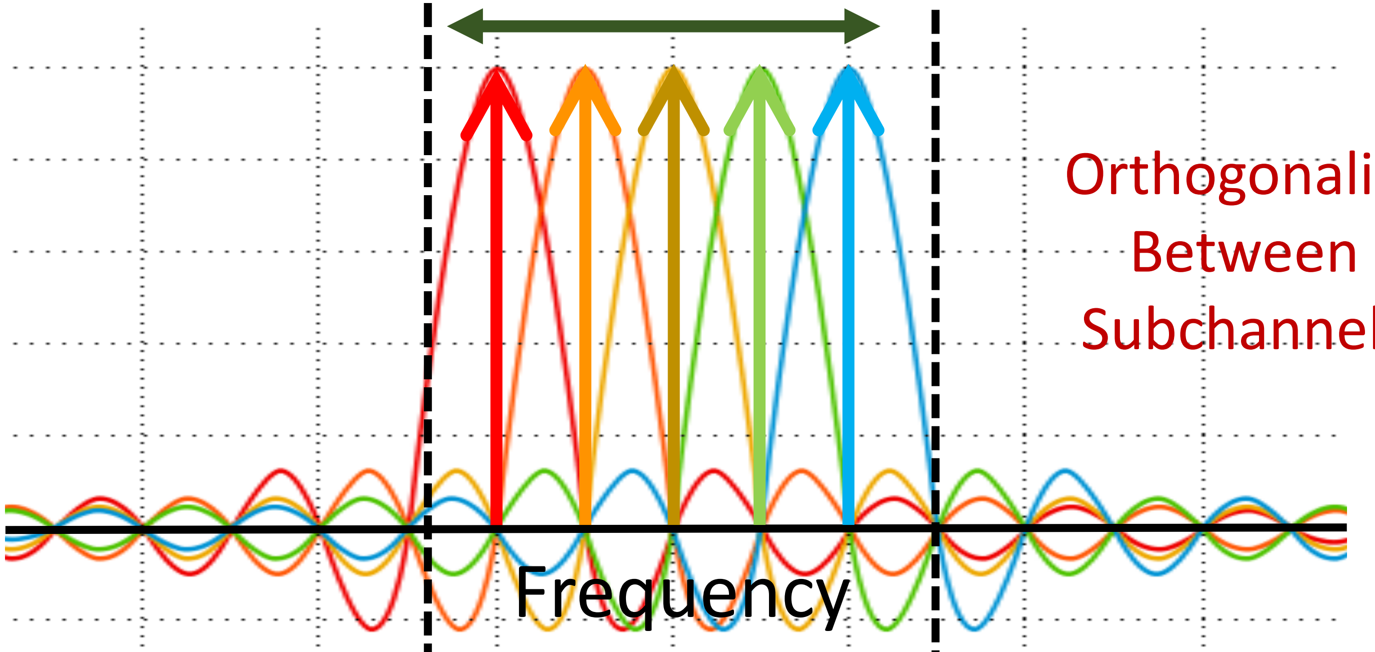


Recovering Original Spectrum from Aliased Spectrum is non-trivial!



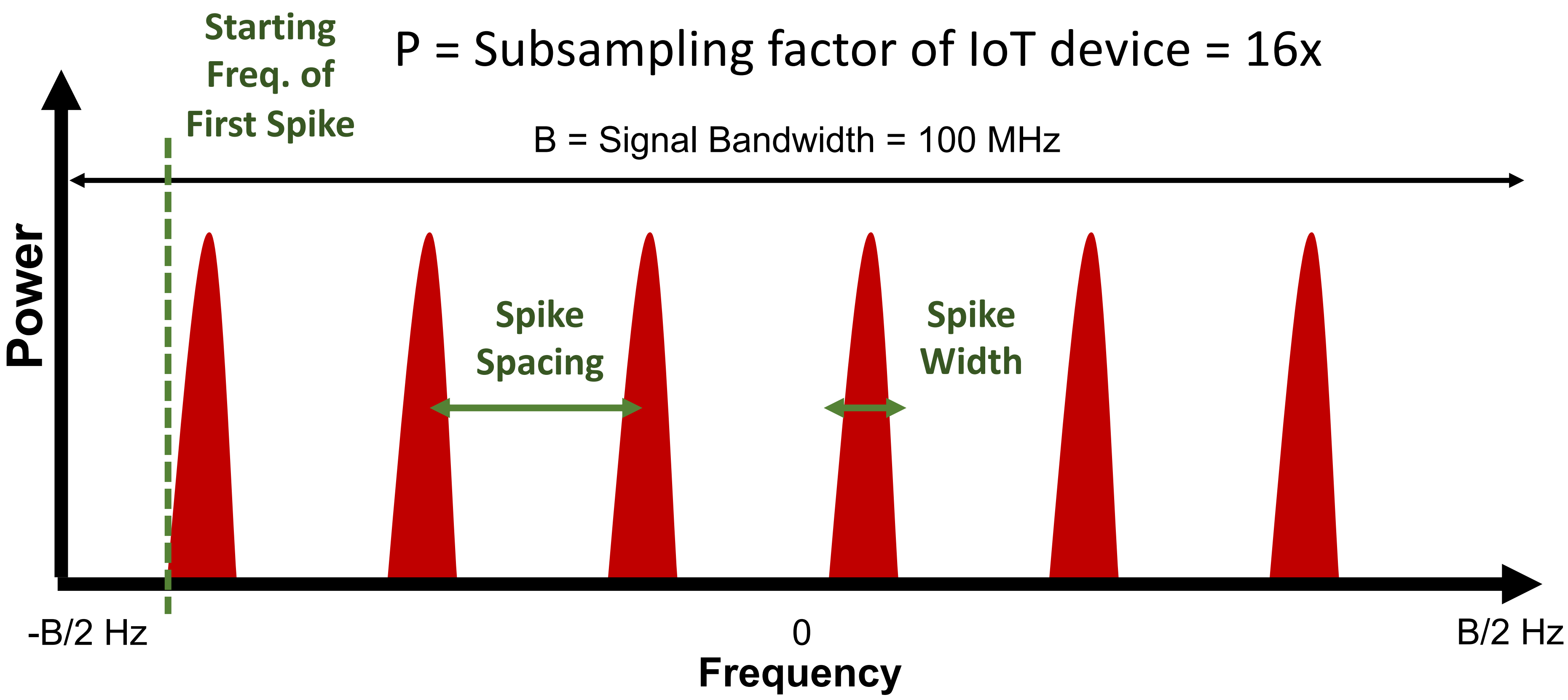
- Subcarriers may collide upon aliasing

Lemma: In order to recover the ToF information from OFDM packet, subsampling factor P has to divide number of subchannels N



How to resolve collisions without co-prime subsampling?

Solution: Design MEMS filter shape as a function of subsampling rate and signal bandwidth, to retrieve uncorrupted channel measurements



MEMS Parameters:

- Spacing between Spikes
- Width of Spikes
- Starting frequency of first Spike

ISLA Overview

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Recovered ToF information

Localization without coordination with Base Stations

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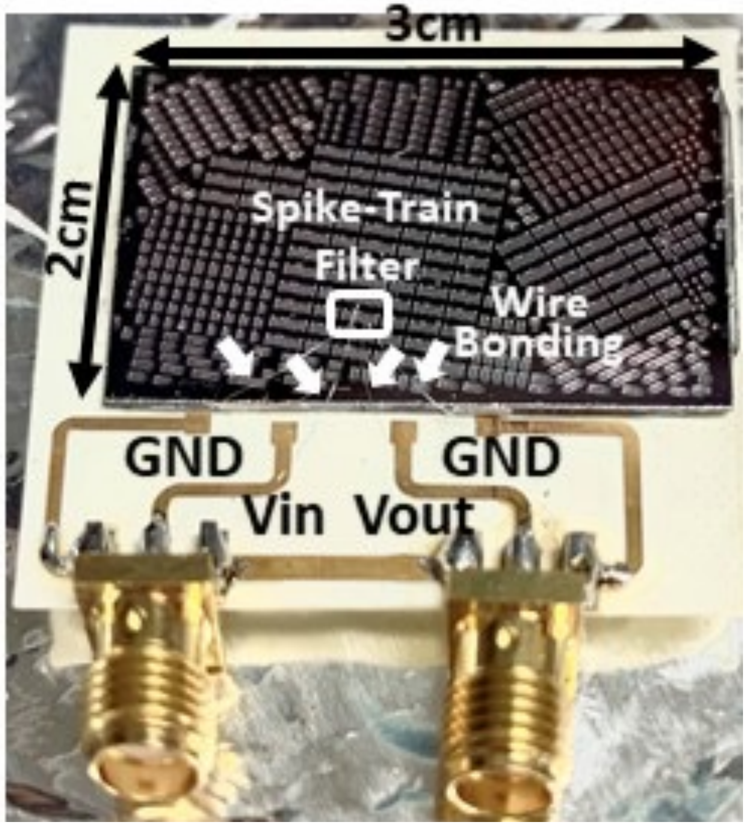
Recovered ToF information →

Localization without coordination with Base Stations

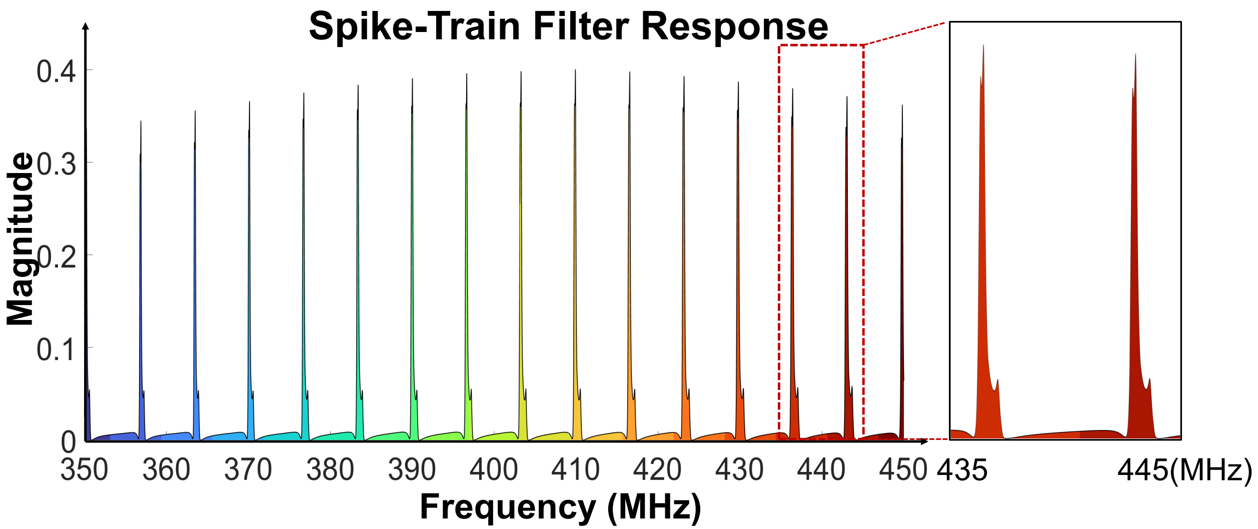
↓

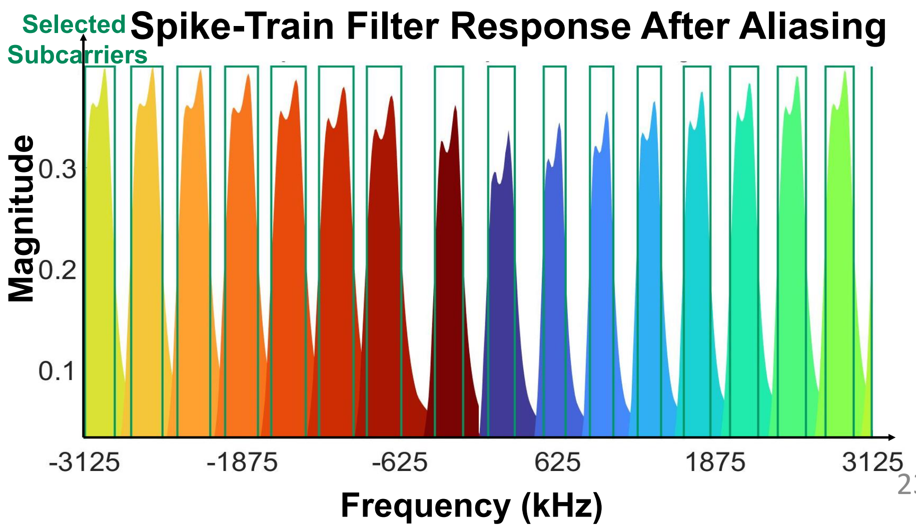
Leverage 2 antennas to convert ToF localization to differential ToF

Spike-Train Filter

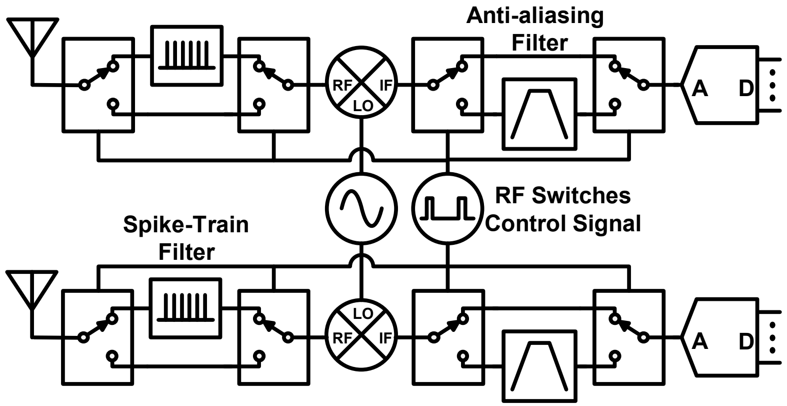


Fabricated MEMS Spike-Train Filter

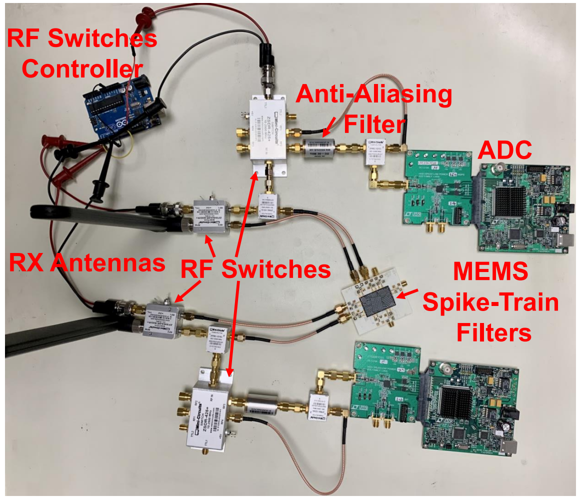




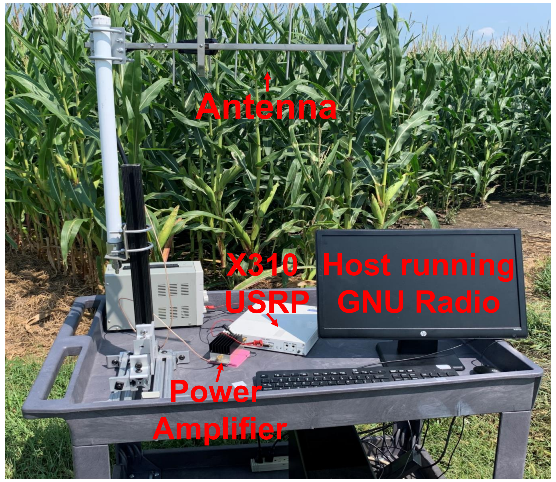
ISLA Evaluation



(a) Circuit Diagram

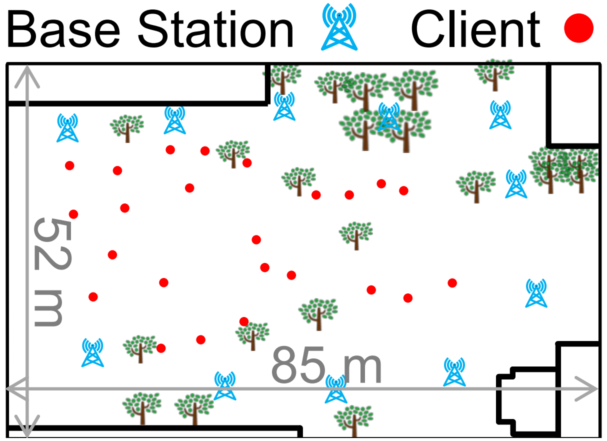


(b) Prototype Circuit

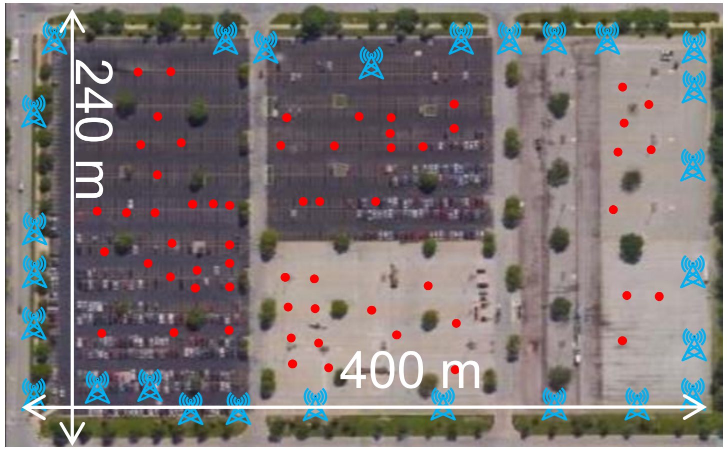


(c) Prototype Base Station in Experimental Testbed

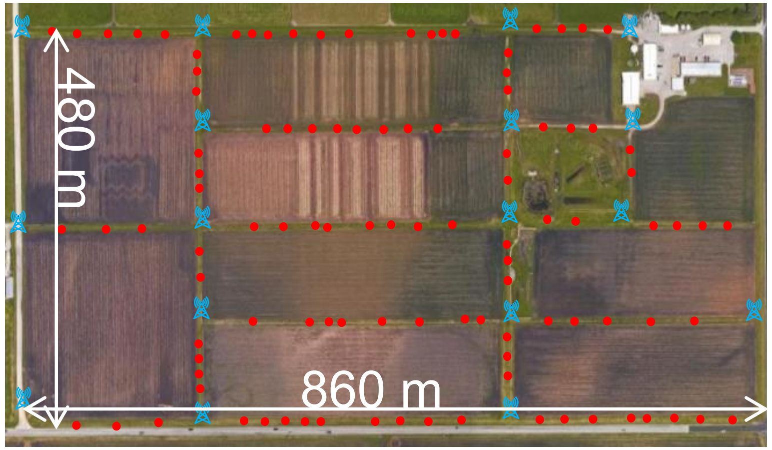
Testbeds



(a) Campus Testbed Surrounded by Buildings

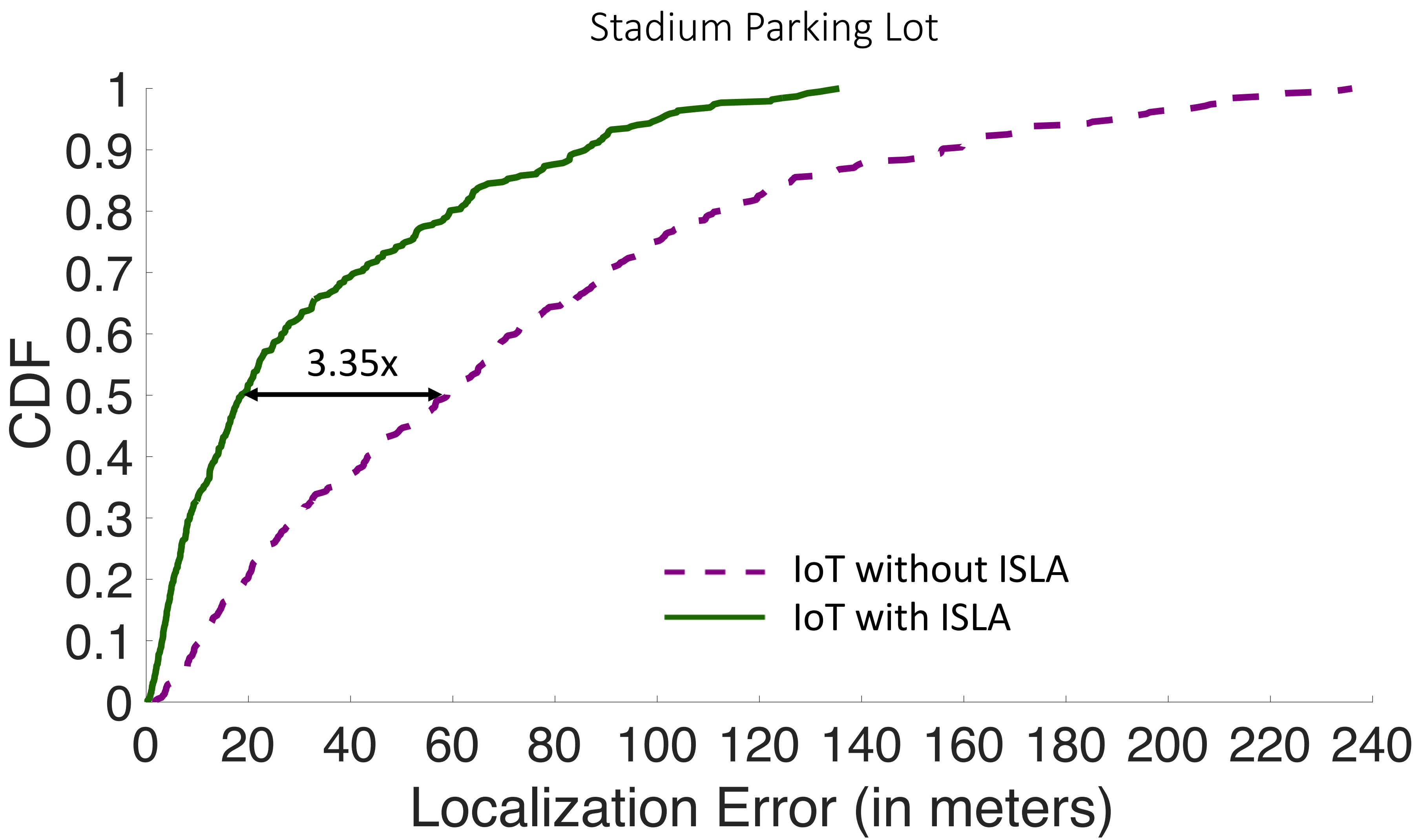


(b) Stadium Parking Lot

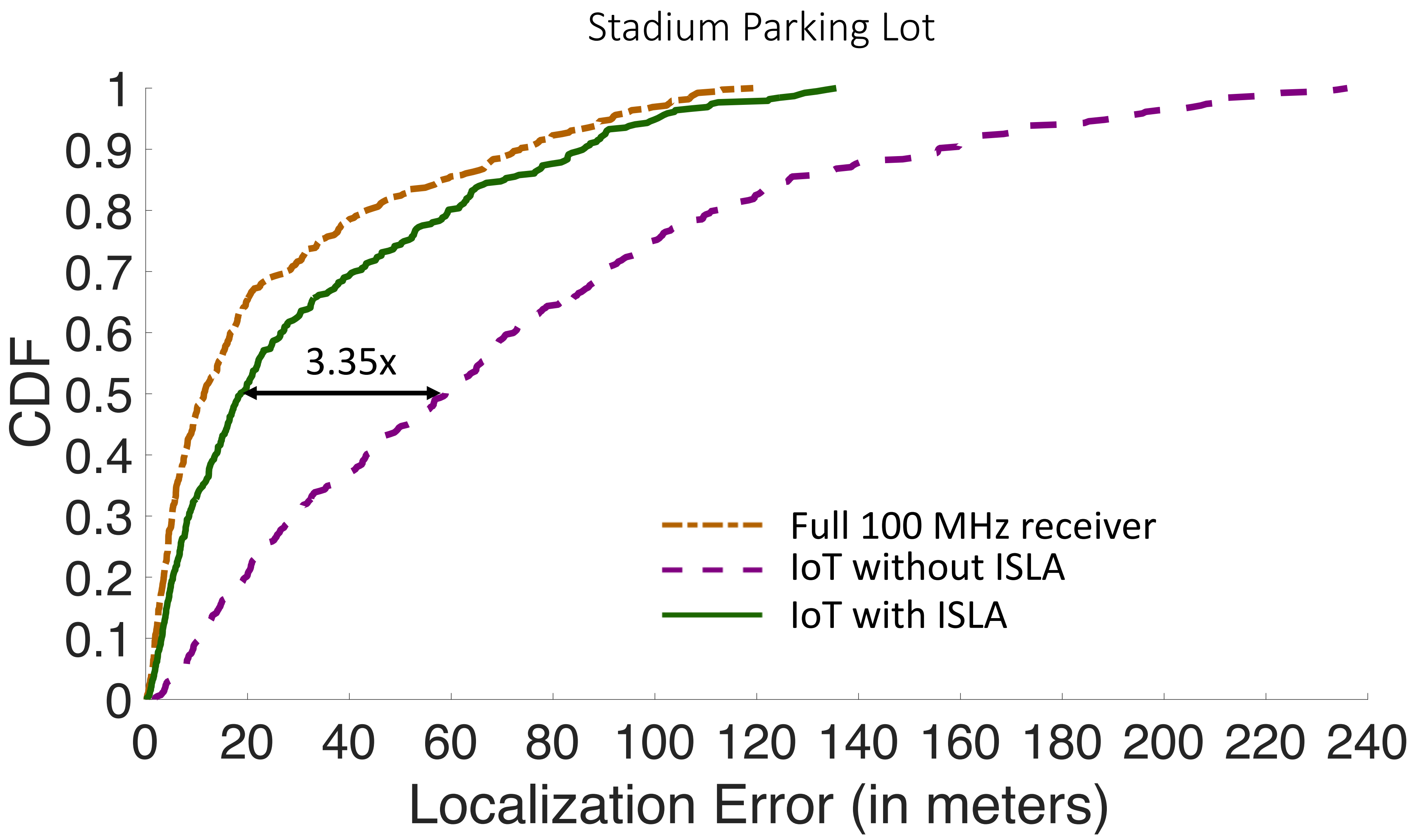


(c) Agricultural Farm

Leveraging Different Amounts of Spectrum



Leveraging Different Amounts of Spectrum



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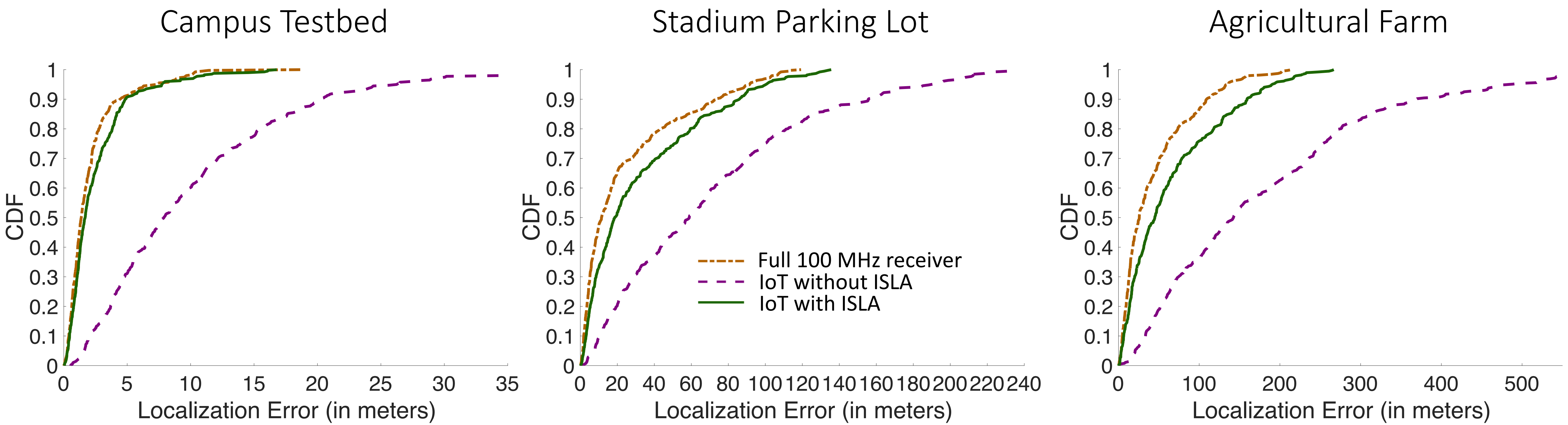


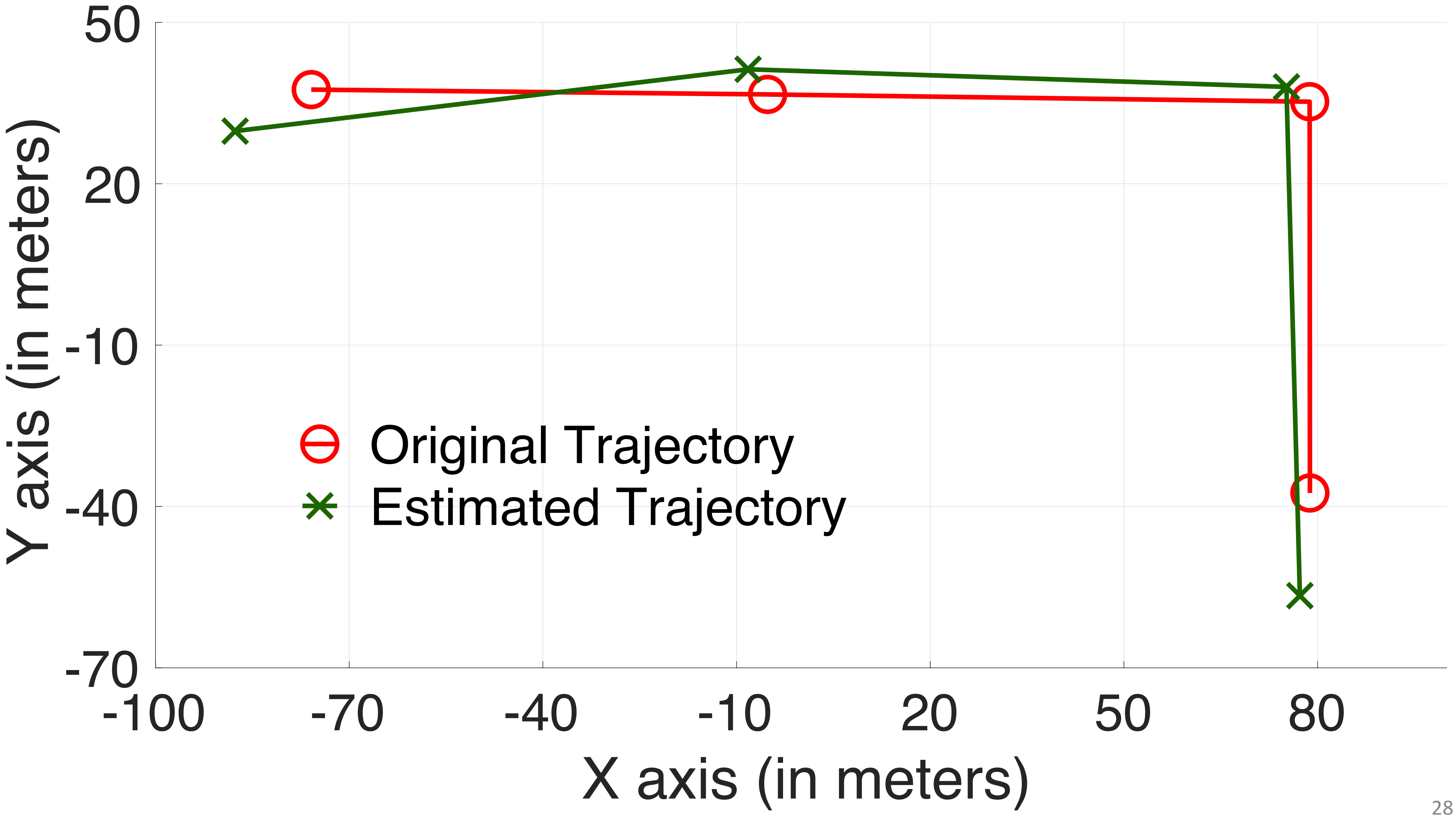
ISLA achieves 1.58 meters median accuracy

ISLA achieves 17.6 meters median accuracy

ISLA achieves 37.8 meters median accuracy

ISLA achieves performance close to a full 100 MHz receiver despite using 16x lower sampling rate

Application : Tracking Objects



Takeaways

- ISLA enables IoT nodes to self-localize themselves accurately using ambient 5G signals without requiring any coordination
- ISLA enables narrowband devices to sense wideband channel, thus achieving performance close to broadband receivers despite sampling 16x slower
- MEMS spike train filters can be leveraged to enhance performance in different RF tasks by stretching effective bandwidth of the device

Thank You!

I am on the job market this year! :)

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