清華大學
Tsinghua University

From RF-based Sensing to RF Computing
– Unremitting Exploration about RF Signals

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Roadmap

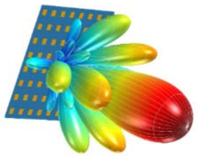
1. **RF-based Sensing**
    - **Vibration Sensing**
    - **Voice Recovery**
    - **Drone Detection**

2. **RF Computing**
    - **Analog Signal Processing**
    - **Inspiration and Concept**
    - **Future Directions**

Part 1: RF-based Sensing

Propagation of RF signals is jointly affected by the reflecting object(s), the environment, and the medium.

RF signals

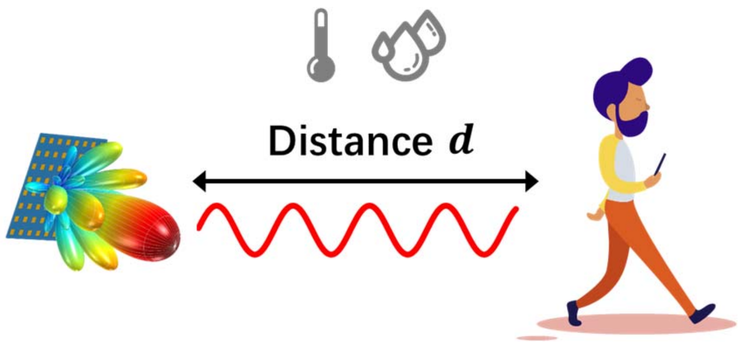


mmWave

WiFi

LoRa

RFID



Sensing Applications

Location/Orientation

Velocity/Motion/Micro-movement

Gesture/Posture/Activity ...

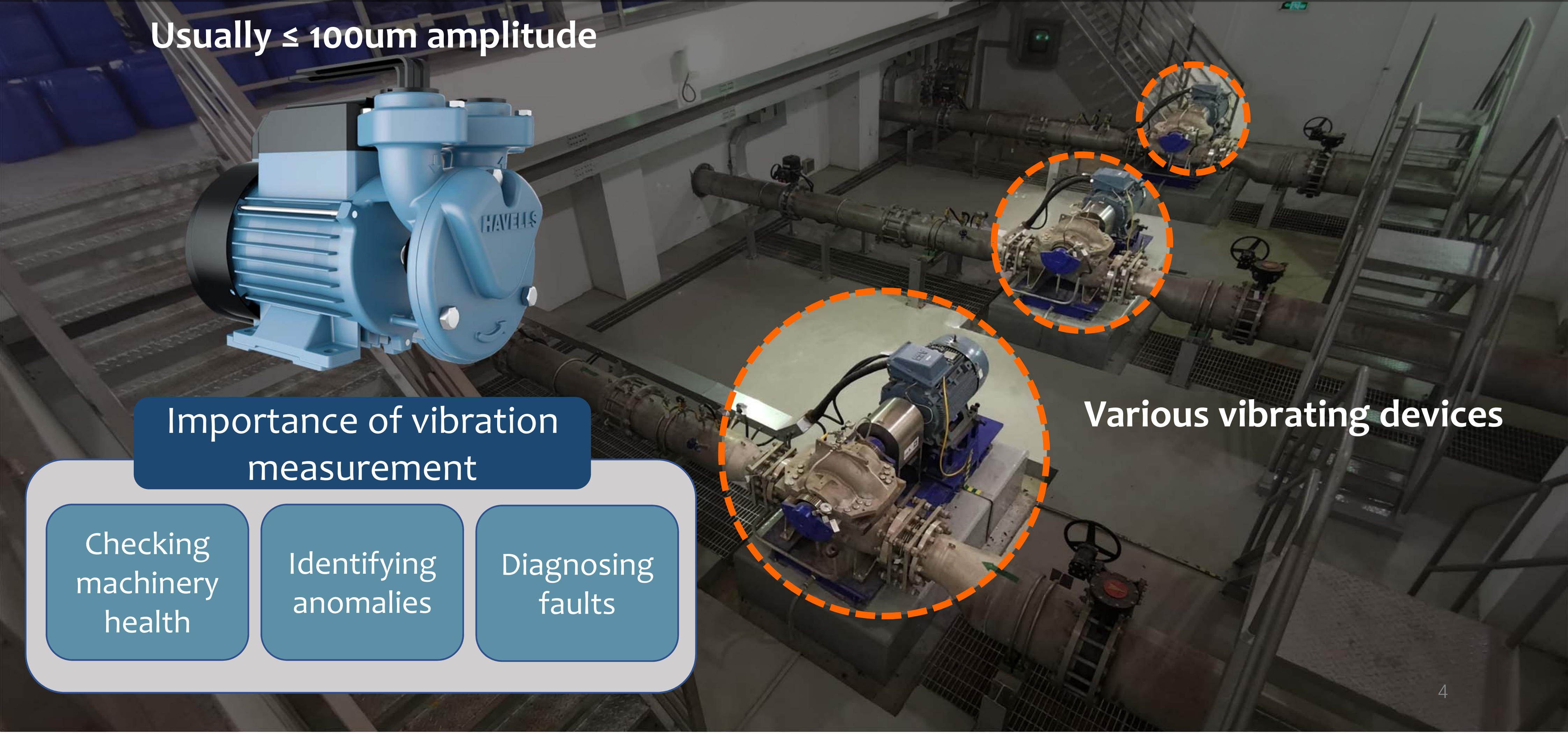
Biometric (Respiration/HBR/BP/Gait ...)

Temperature/Humidity

Material/Texture/Imaging ...

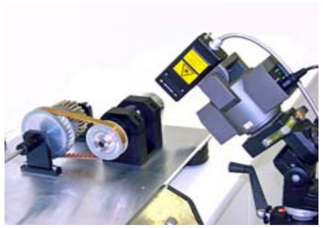
Channel condition

Background: Vibrations in Industry



Existing Measurement Approaches

Piezoelectric Accelerometer



Laser Vibrometer

Manual Inspection

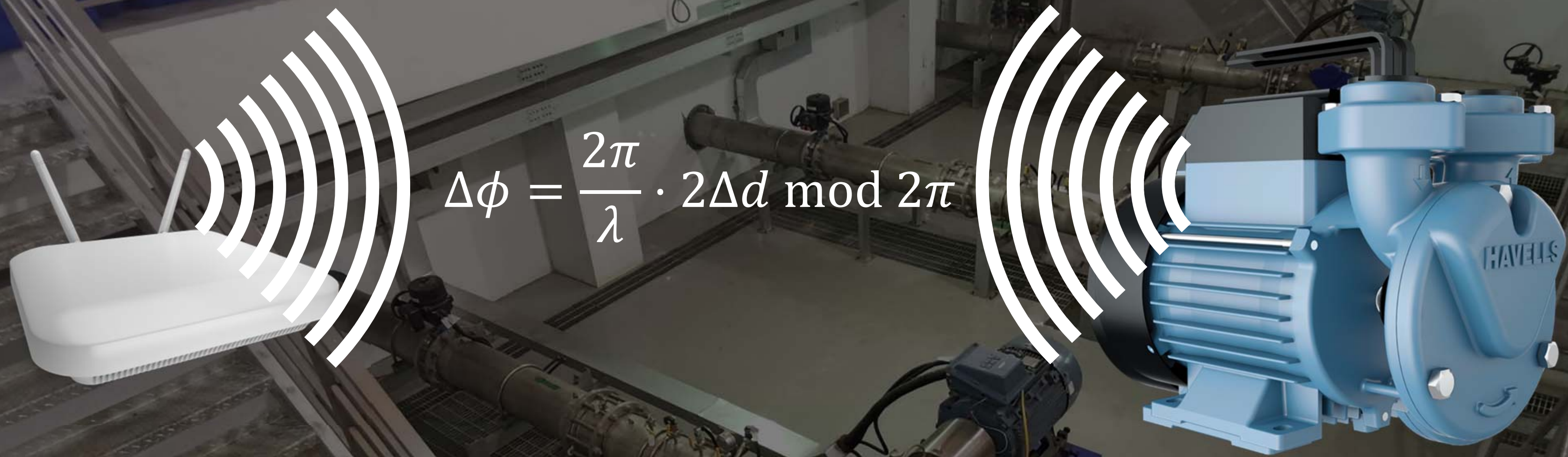
High Labor Cost / Not Real-time

Motivation: a new approach of vibration measurement!

- Non-intrusive Deployment
- High Accuracy
- Low Device Cost

Promising Solution: Wireless Sensing

Reflected signals carry the characteristics of vibration signals



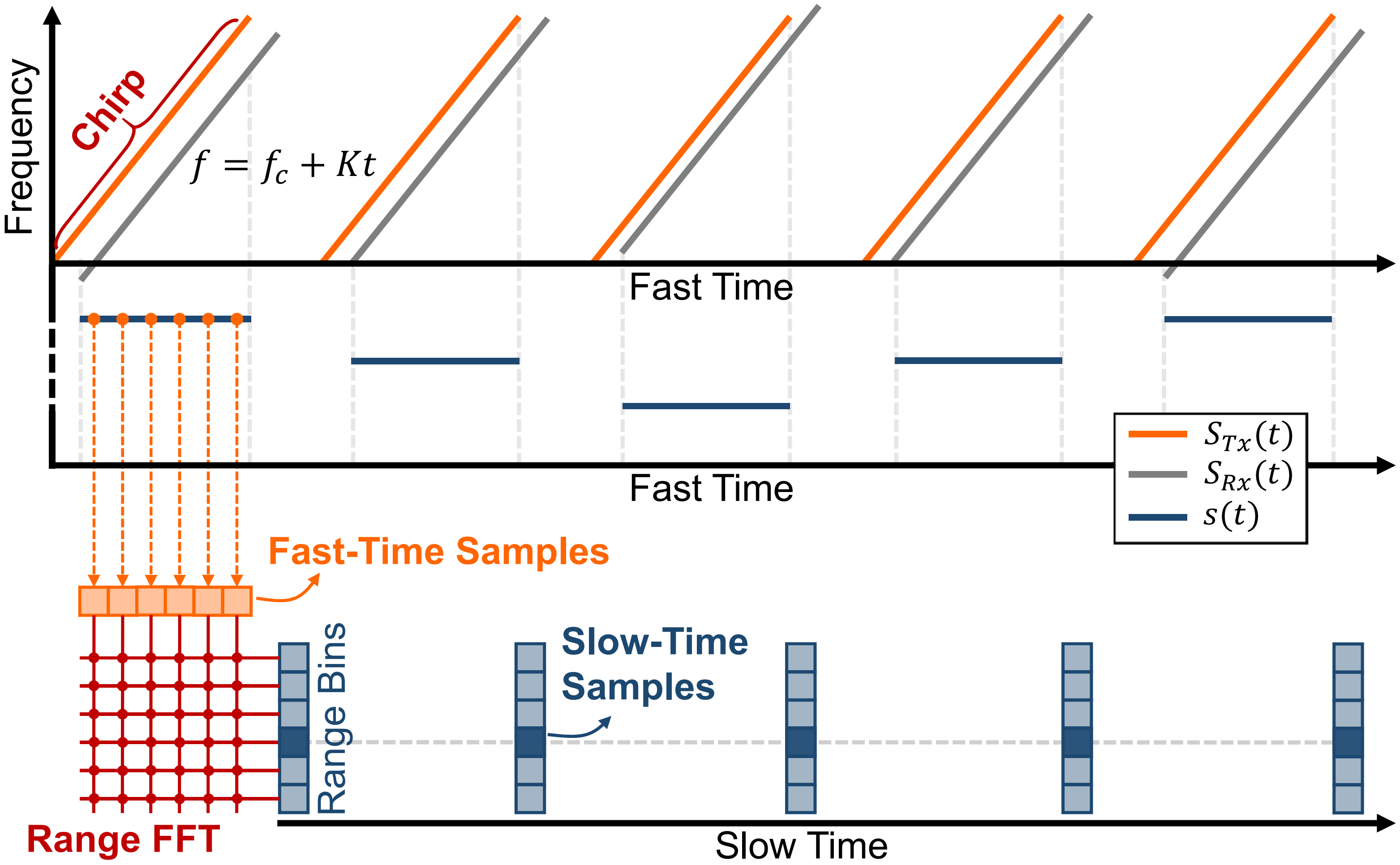
$$\Delta\phi = \frac{2\pi}{\lambda} \cdot 2\Delta d \bmod 2\pi$$

Existing works: WiFi, RFID, Acoustic…

Application Requirements

- μm-level Accuracy
- Complicated Reflections
- Multi-Target Monitoring

Preliminary: mmWave FMCW Signals



Raw mmWave signals

$$S_{Tx}(t) = e^{j(2\pi f_c t + \pi K t^2)}$$

$$S_{Rx}(t) = \alpha S_{Tx}\left(t - \frac{2R(t)}{c}\right)$$

Beat signal / IF signal

$$s(t) = \alpha e^{j4\pi(Kt + f_c)\frac{R(t)}{c}}$$

Vibration reflection signal

$$S(t) = \alpha e^{j4\pi f_c \frac{R(t)}{c}}$$

$$= \alpha e^{j4\pi \frac{R_0 + x(t)}{\lambda_c}}$$

Preliminary

Slow-time samples of vibration reflection signal

$$S(t) = \underbrace{\alpha}_{\text{Magnitude}} \underbrace{e^{j4\pi\frac{R_0+x(t)}{\lambda_c}}}_{\text{Phase}}$$

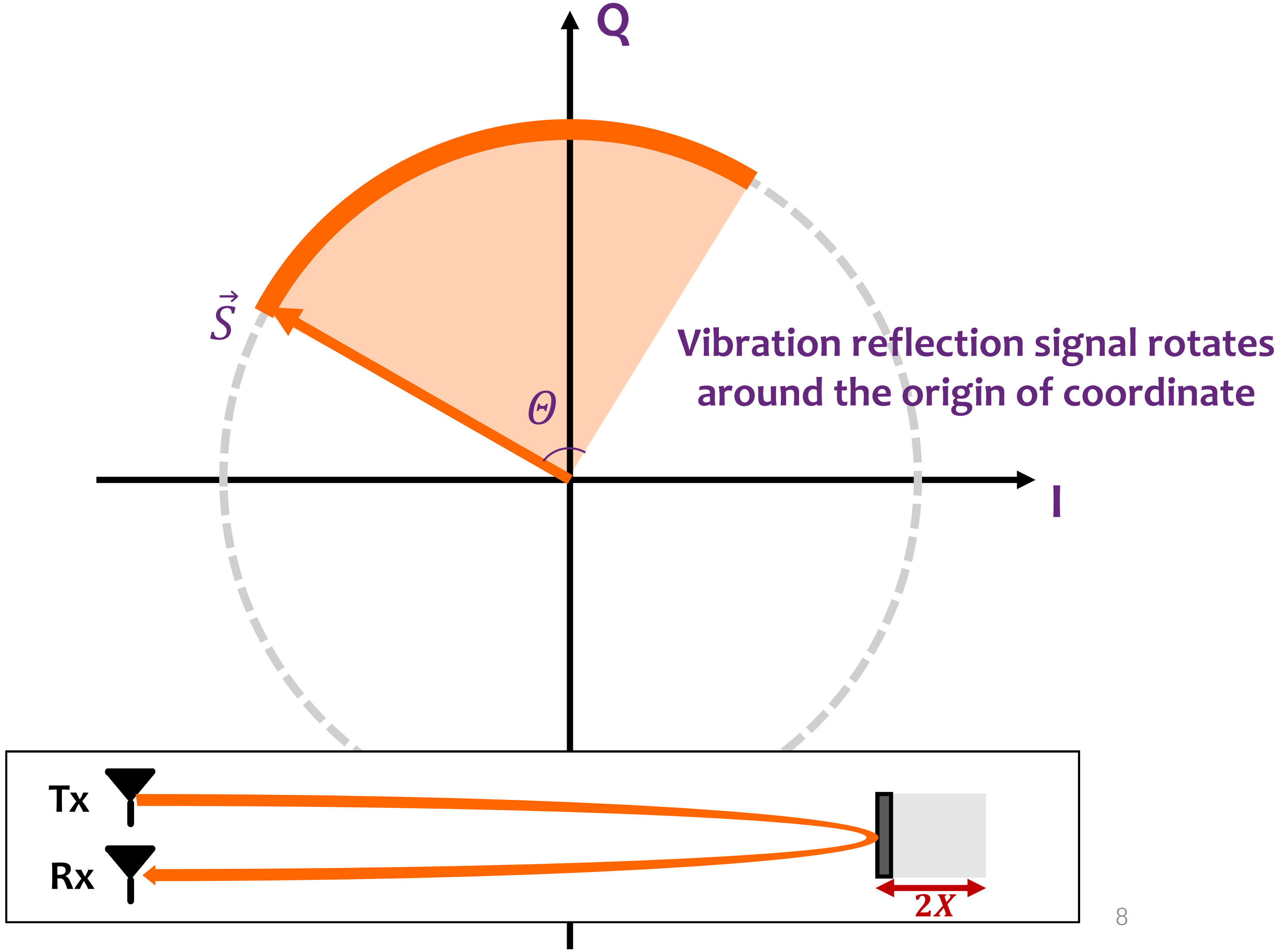
$$\theta(t) = 4\pi\frac{R_0+x(t)}{\lambda_c}$$

$$\Theta = 4\pi\frac{2X}{\lambda_c}$$

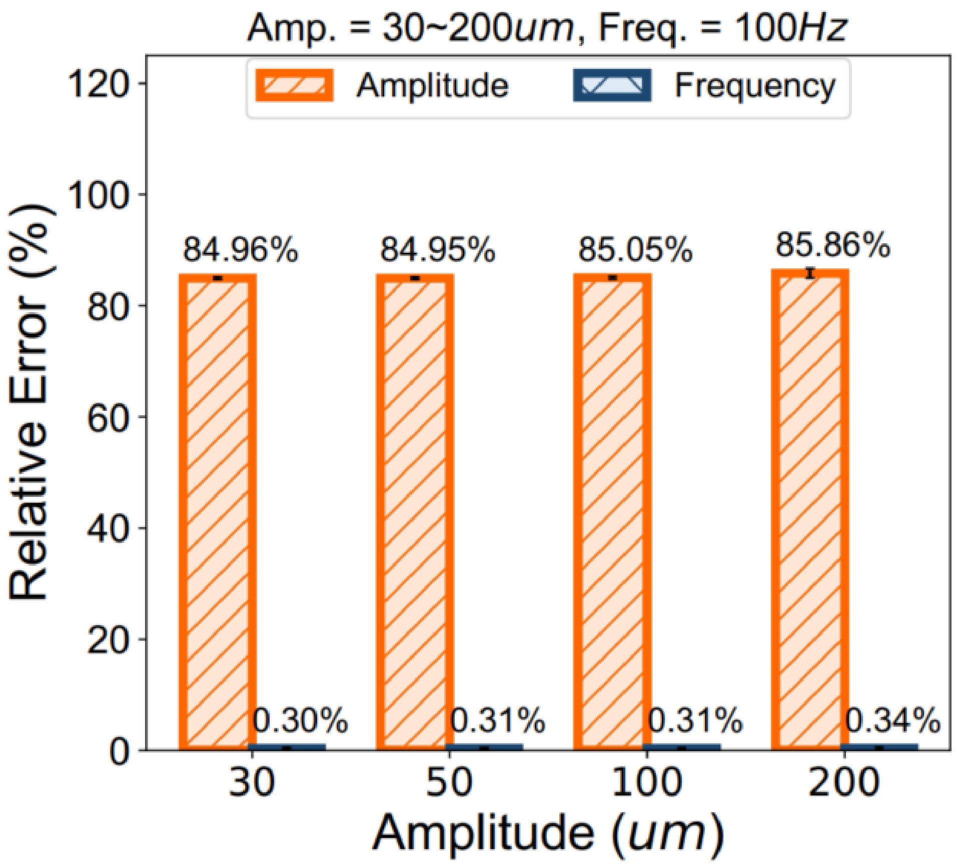
Signal strength:

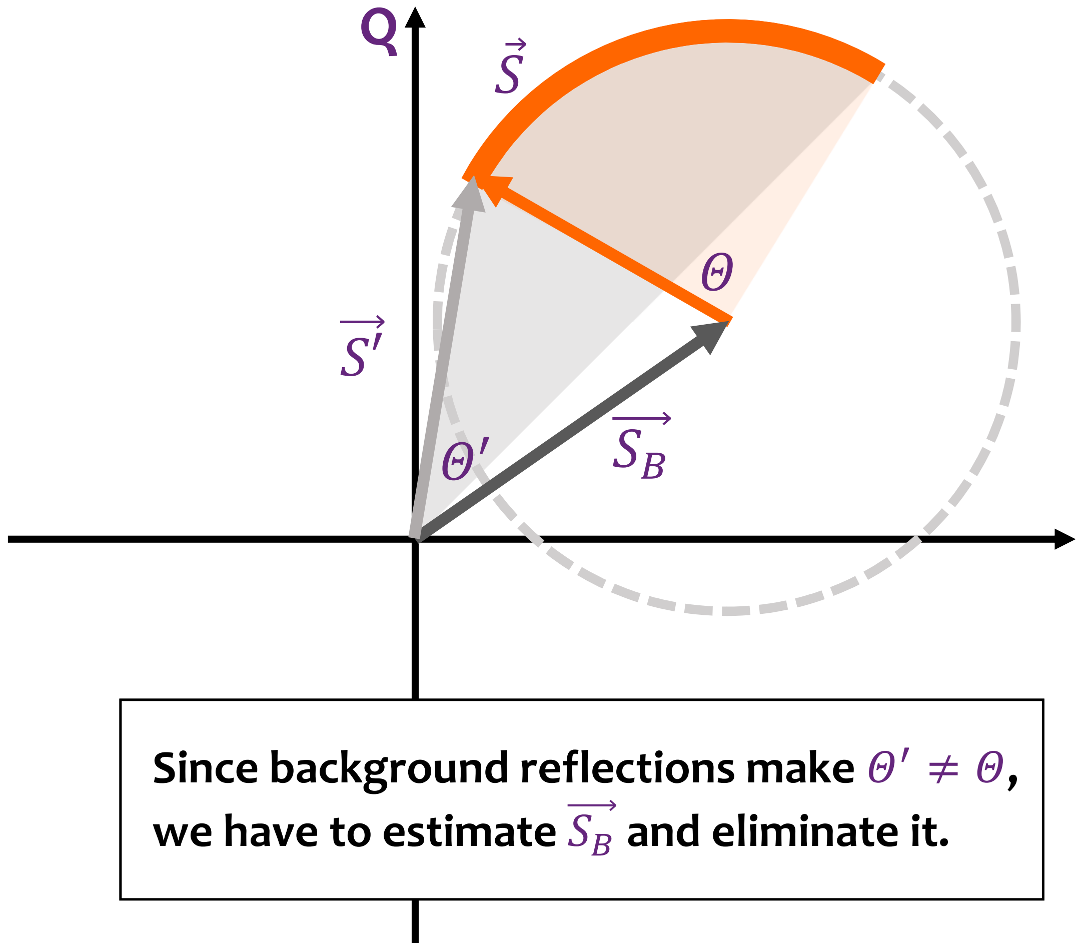
- Tx power, Tx antenna gain
- Target's radar cross sector (RCS)
- Measurement distance

Vibrations in mmWave Signals



Challenge 1: Background Reflections

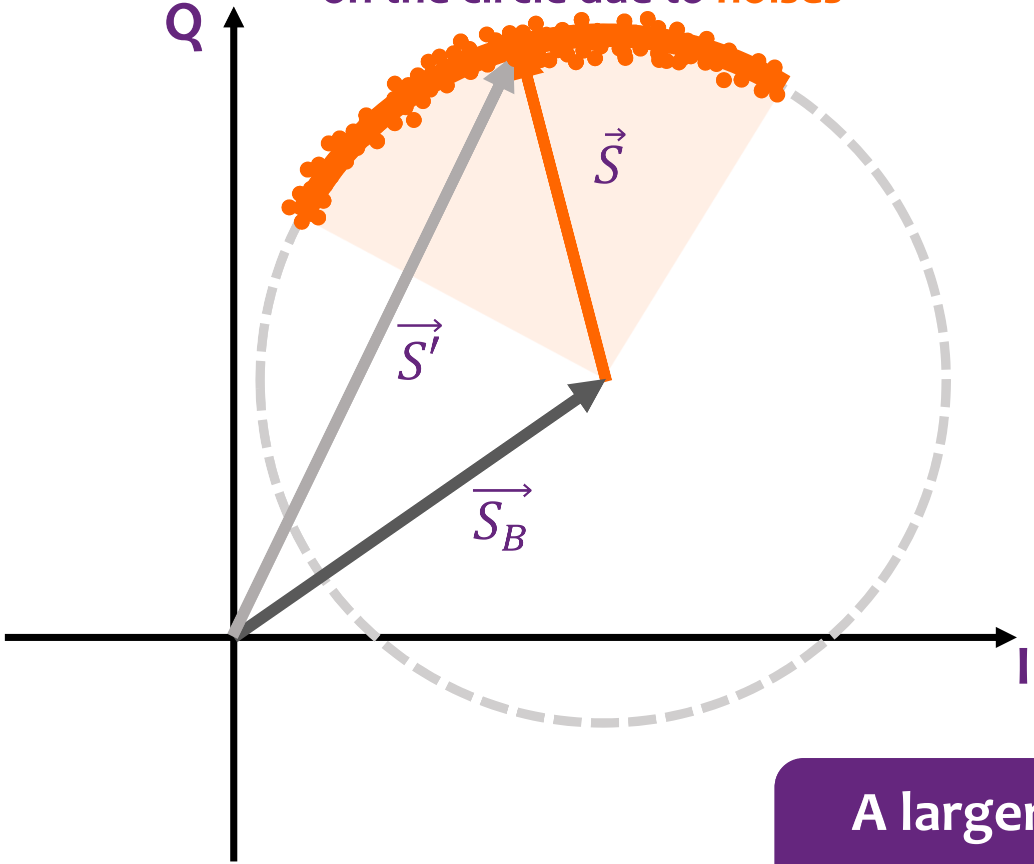




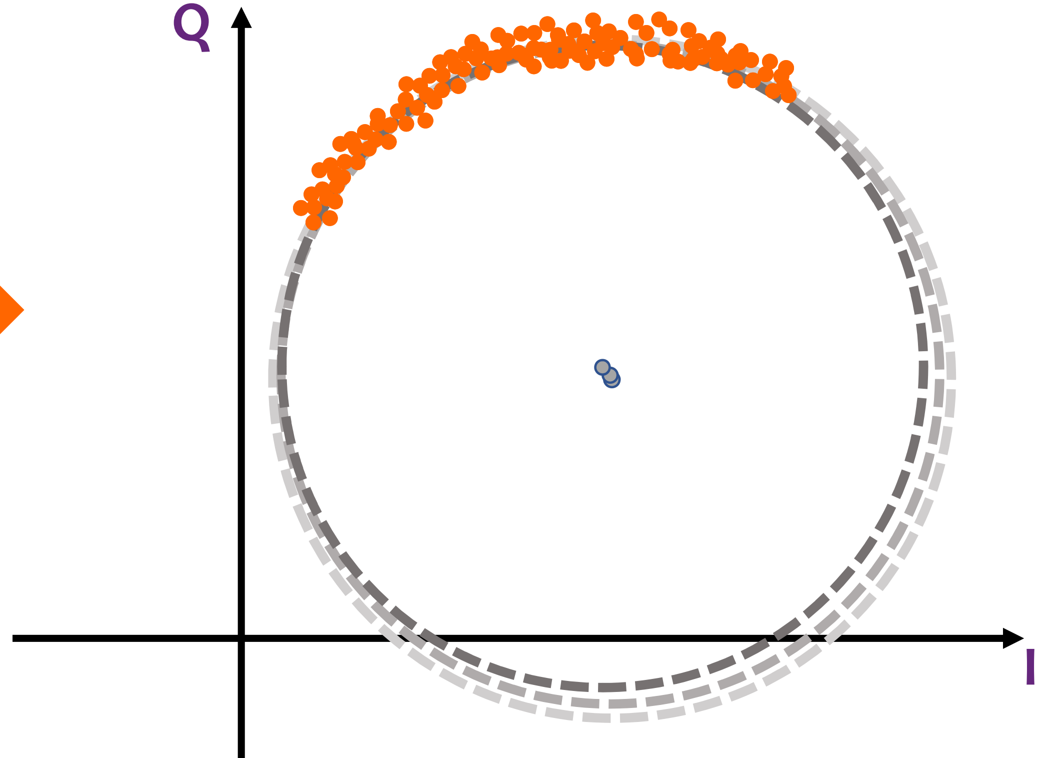
Since background reflections make $\Theta' \neq \Theta$, we have to estimate $\overrightarrow{S_B}$ and eliminate it.

Challenge 2: Limited Signal-to-Noise Ratio (SNR)

The samples don't necessarily fall on the circle due to noises



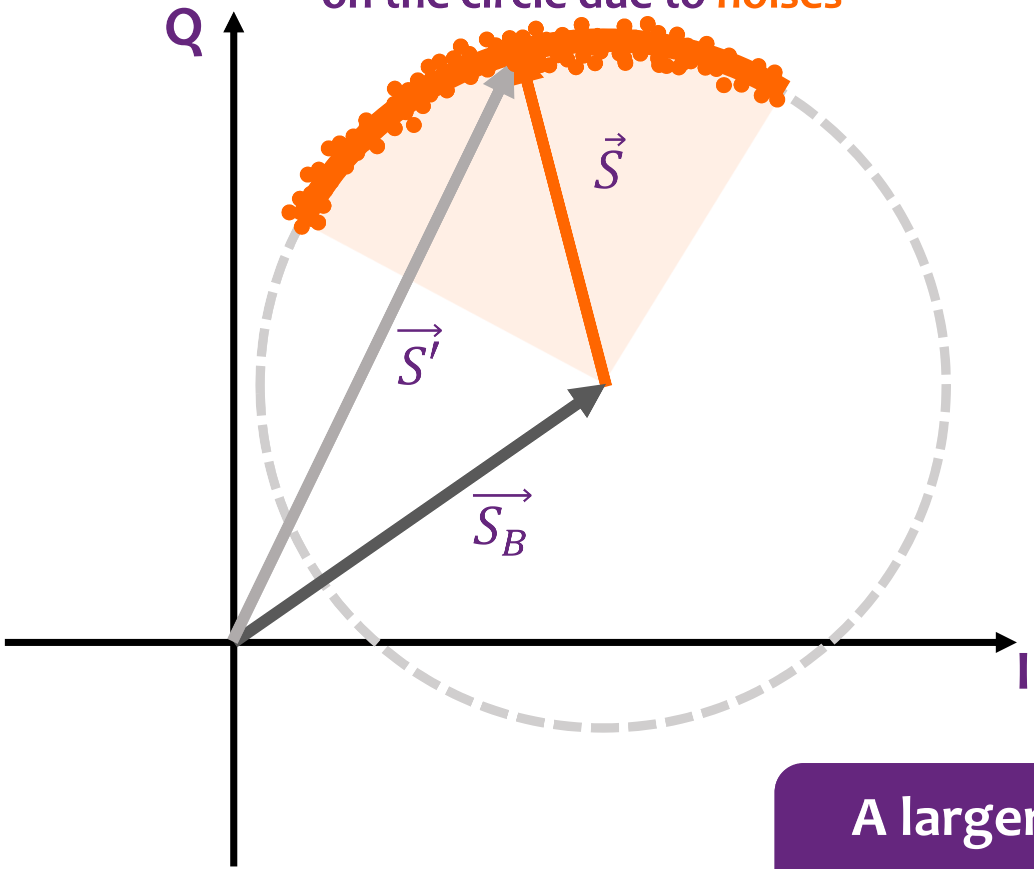
$\Theta \approx 108^\circ$ when $X = 300um$



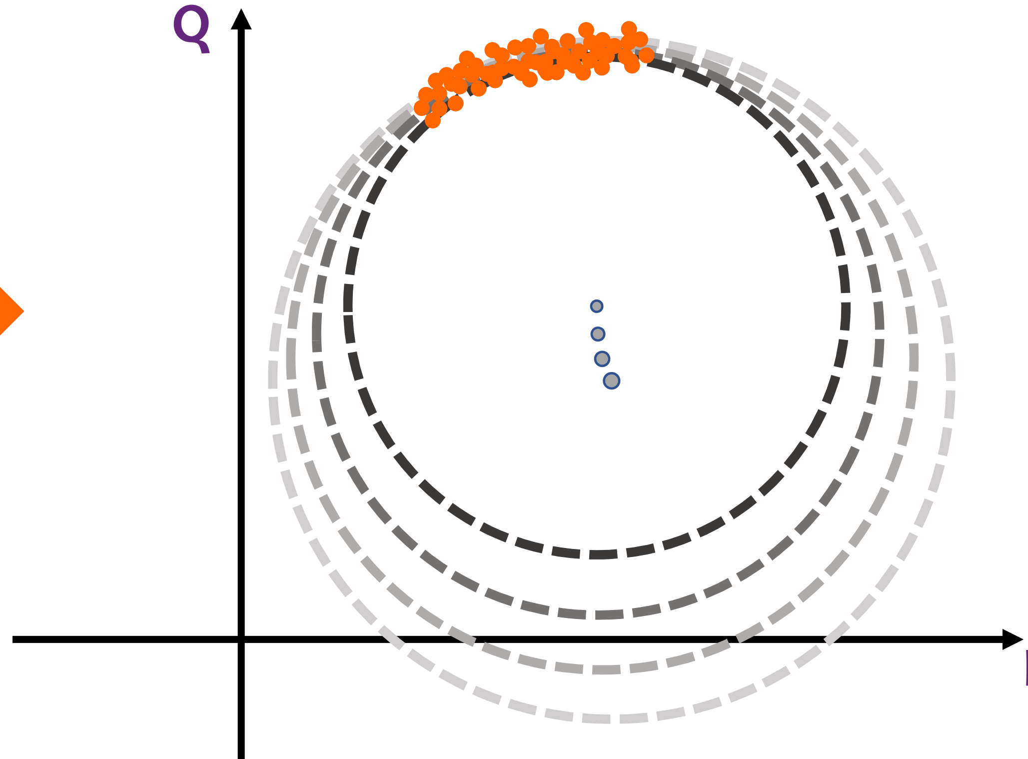
A larger arc controls the accuracy of the circle fitting

Challenge 2: Limited Signal-to-Noise Ratio (SNR)

The samples don't necessarily fall on the circle due to noises



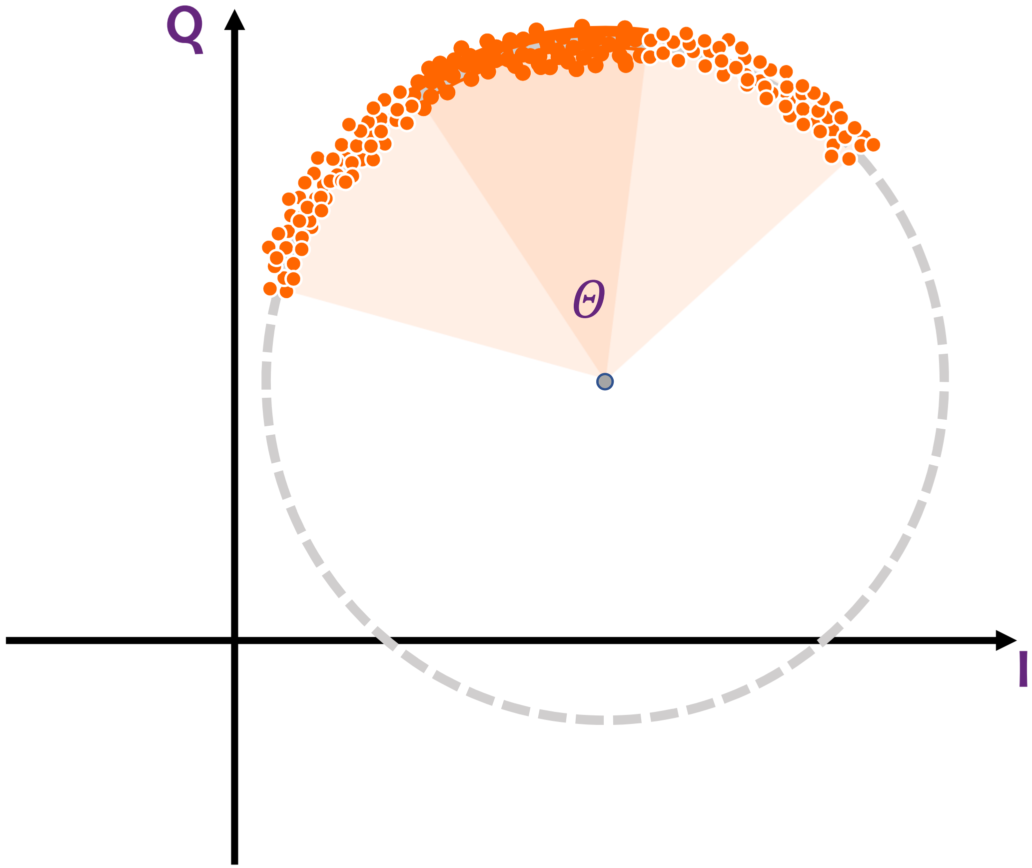
$\Theta \approx 36^{\circ}$ when $X = 100um$



A larger arc controls the accuracy of the circle fitting

A smaller arc induces the fitting ambiguity

Intuition: Improving Accuracy by Extending the Signal arc



The central angle Θ is determined by:

- Chirp start frequency f_c
- Vibration amplitude X

$$\Theta = \frac{8\pi f_c X}{c}$$

Multi-Signal Consolidation (MSC) Model

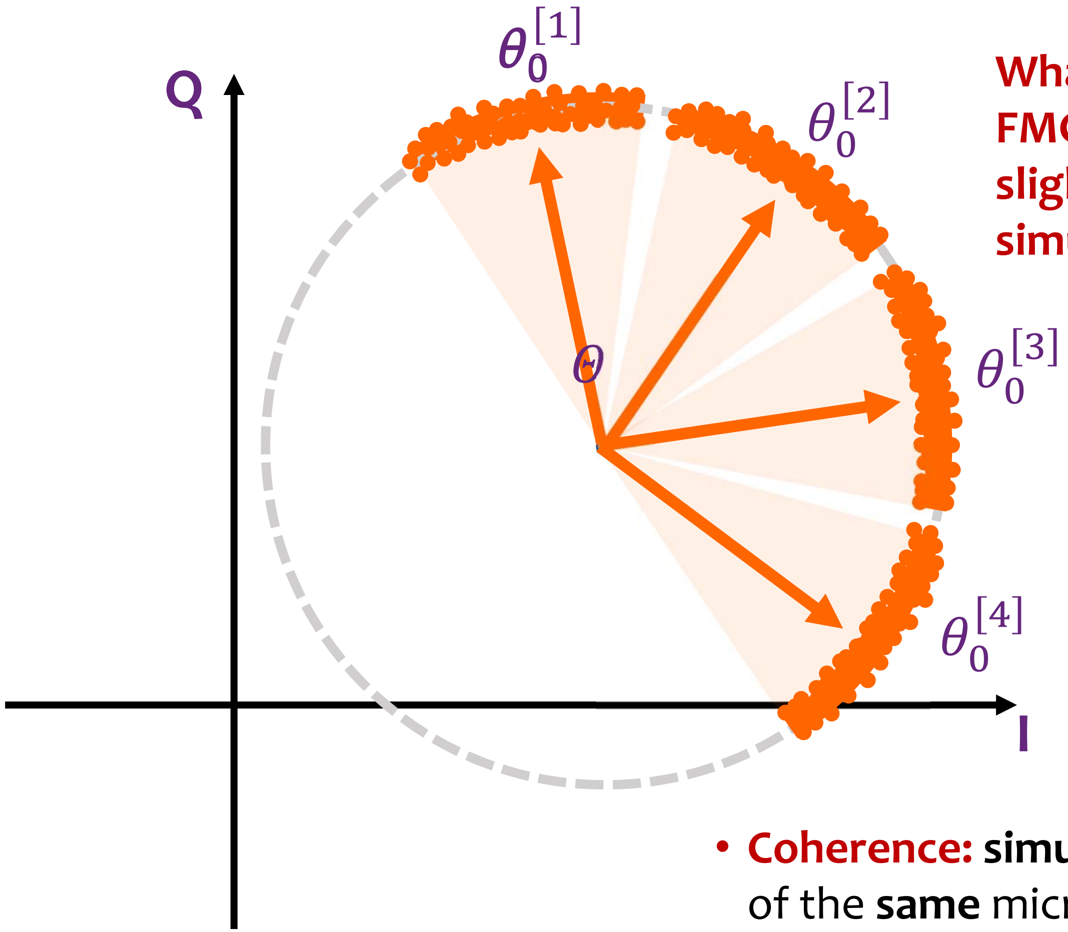
Since we cannot guarantee **a large vibration amplitude** X, we can only count on the **chirp start frequency** f_c.

Phase model:

$$\theta(t) = \underbrace{\frac{4\pi f_c R_0}{c}}_{\theta_0 = \frac{4\pi f_c R_0}{c}} + \underbrace{\frac{4\pi f_c x(t)}{c}}_{\Theta = \frac{8\pi f_c X}{c}}$$

$\because R_0 \gg X$

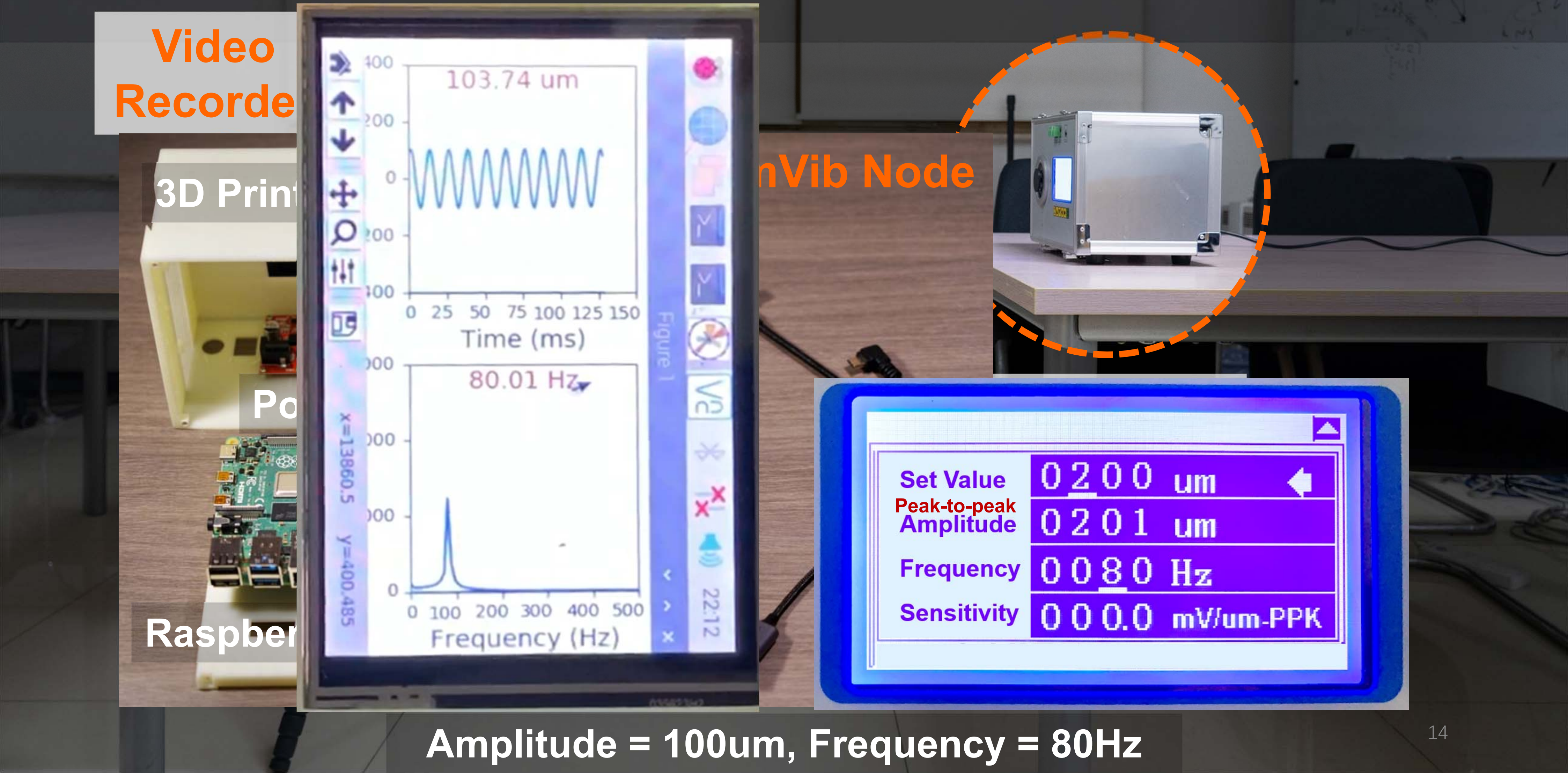
$\therefore$ a slight change of f_c will significantly change θ_0 rather than Θ



What if we send multiple FMCW chirp signals with slightly different f_cs simultaneously?

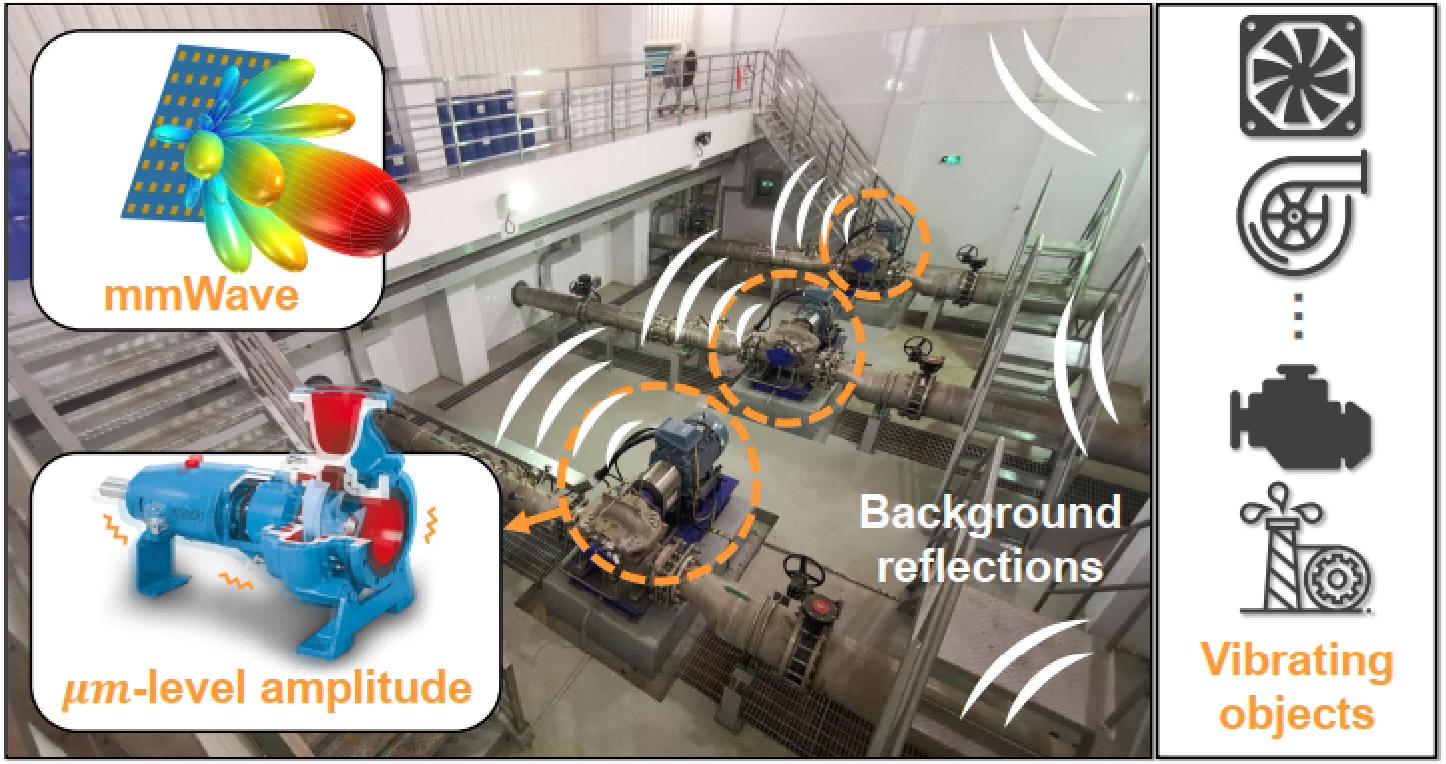
- **Coherence: simultaneous** observations of the **same** micro-motion
- **Diversity: different** starting frequency

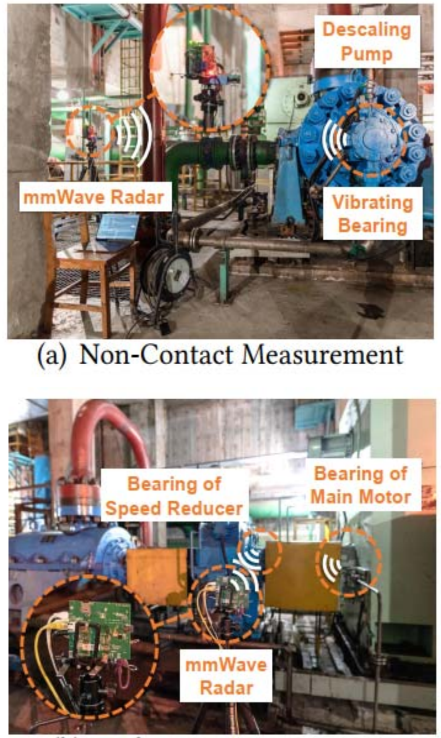
Demo



Amplitude = 100um, Frequency = 80Hz

mmVib: Micrometer-Level Vibration Measurement with mmWave Radar @MobiCom' 20





(a) Non-Contact Measurement

(b) Multi-Spot Measurement

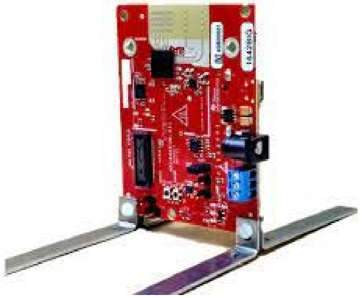
mmVib achieves the 3.4um median amplitude error when measuring the 100um-amplitude vibration.

Real-world deployment in a steel plant.

What have we learned from mmVib?

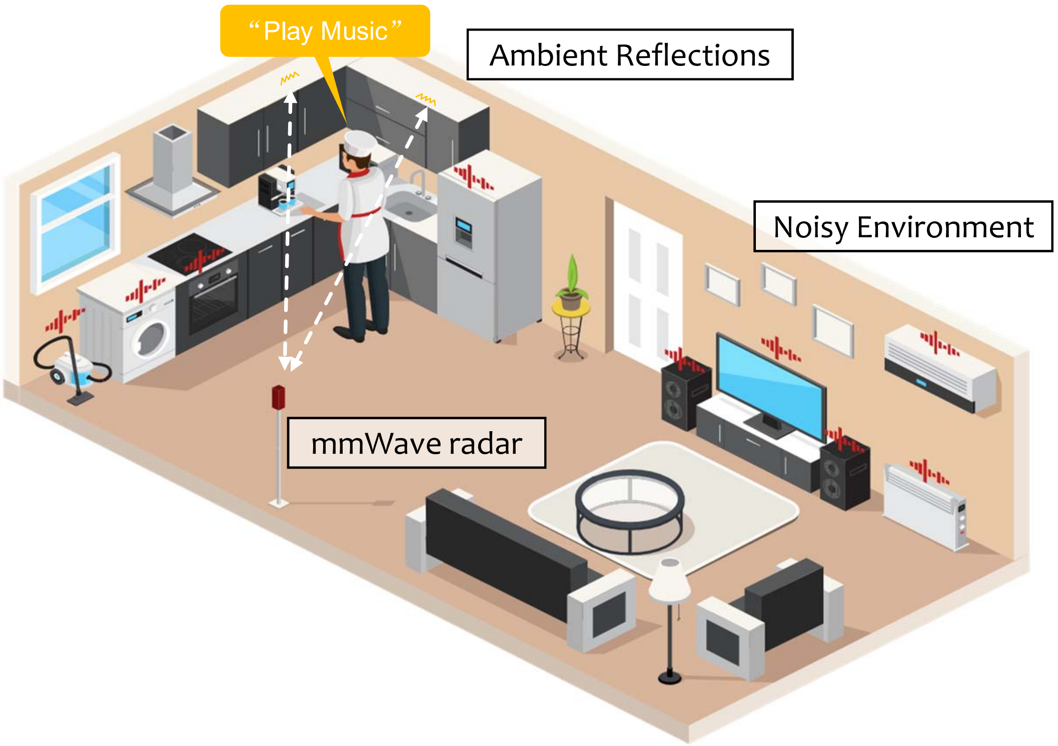
Don't always eat whatever is ready.
Reshaping the signals enhances the sensing capacity.

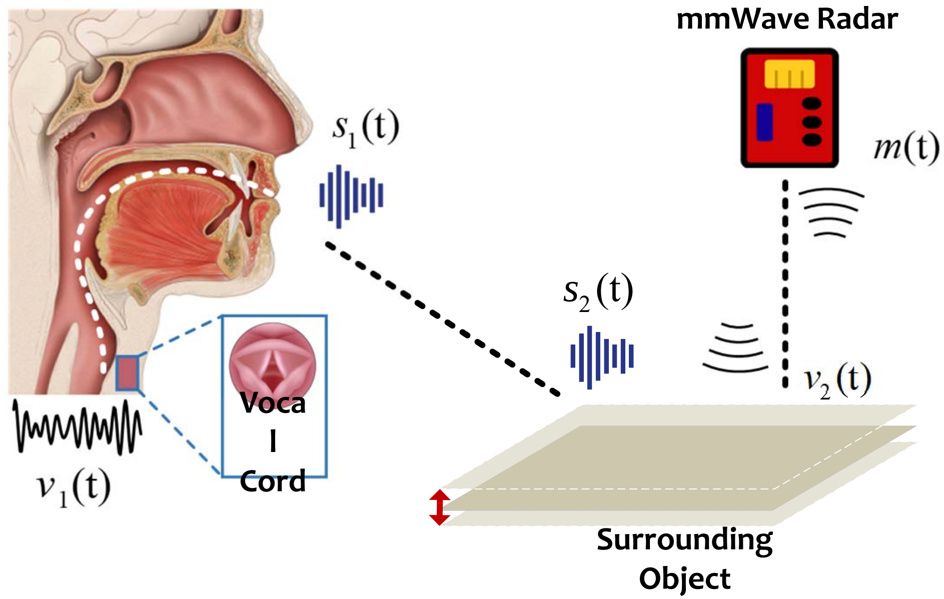
The Potential of mmWave Sensing in Voice Recognition



Waveear (MobiSys'19)
VocalPrint (SenSys'20)
Wavoice (SenSys'21)
RadioMic (IoTJ 2022)

AmbiEar: mmWave Based Voice Recognition in NLoS Scenarios @UbiComp' 22

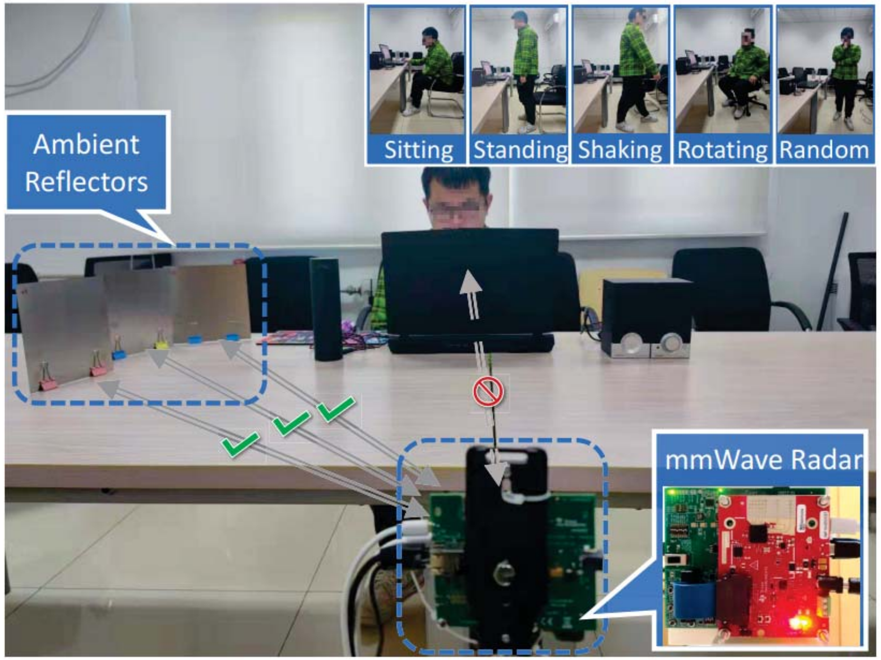




Application Scenarios

Theoretical Model

Implementation and Performance



3.2 × performance gain

Scene	Method	Word Error Rate		
		LoS	NLoS	Agg.
Meeting Room	AmbiEar	15.01%	16.19%	15.60%
	WaveEar	5.44%	95.92%	50.68%
Dormitory	AmbiEar	15.19%	16.58%	15.88%
	WaveEar	5.44%	96.37%	50.91%

Implementation

Overall Performance

What have we learned from AmbiEar?

The environment where the signal propagates can be exploited as a component of the sensing procedure.

MicNest: Long-Range Instant Acoustic Localization of Drones in Precise Landing

@SenSys' 22 (Best Paper Runner-up)

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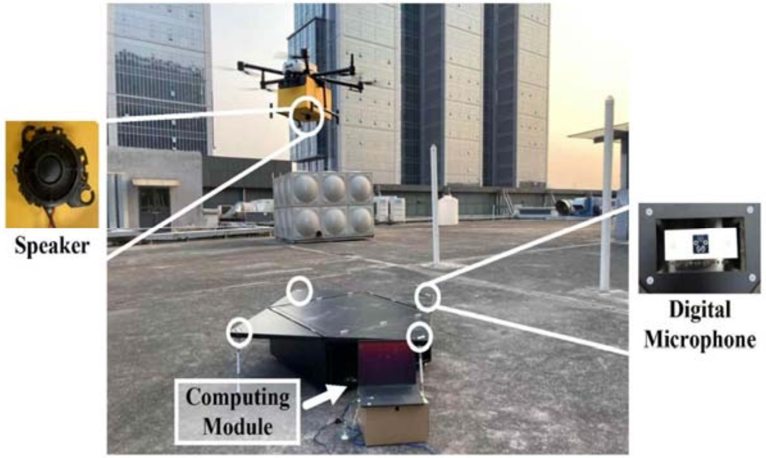
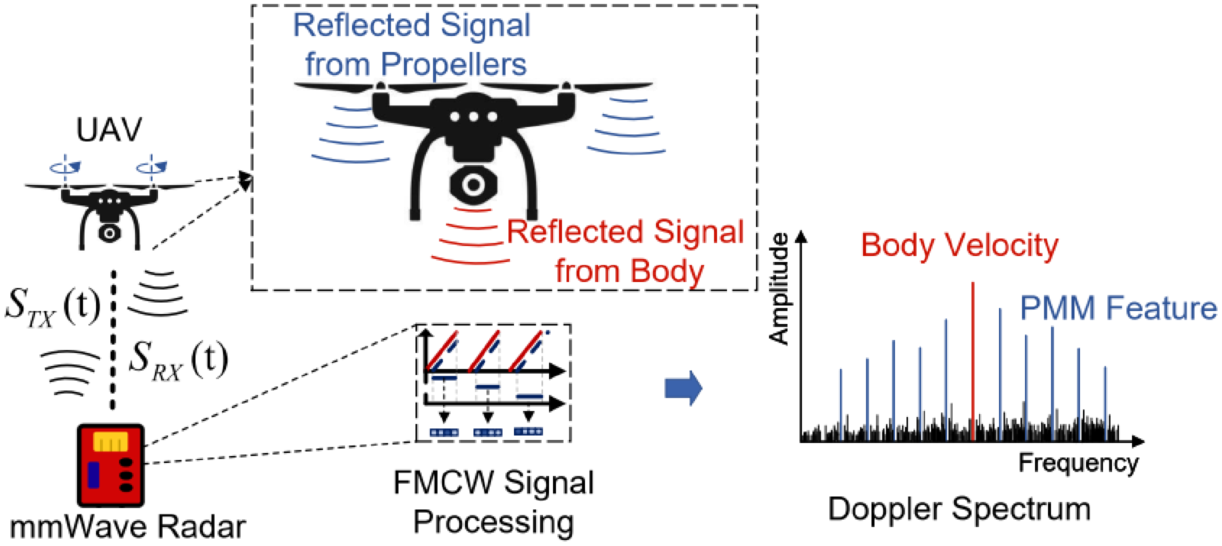
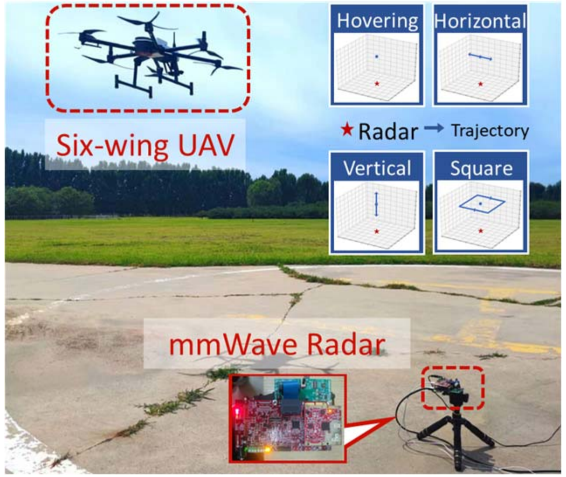


mmHawkeye: Passive UAV Detection with a COTS mmWave Radar @SECON' 23

Insight: **Capturing the periodic micro-motion (PMM) features of the reflected signal, distinguishing the UAV from other objects, and realizing the simultaneous tracking and recognition of the UAV.**





Results: Average detection accuracy of **95.8%** and a relative range error of **0.9%** at a detection range up to **80m**.

Summary of Part 1

Physical side: RF signals interact with the physical world. The principles of such interactions become the theoretical foundation of RF-based sensing.

Cyber side: RF signals are computable. When they carry information from the physical world, the feature space of the signals can be exploited for designing various sensing approaches.

A GOOD sensing solution depends on both sides:

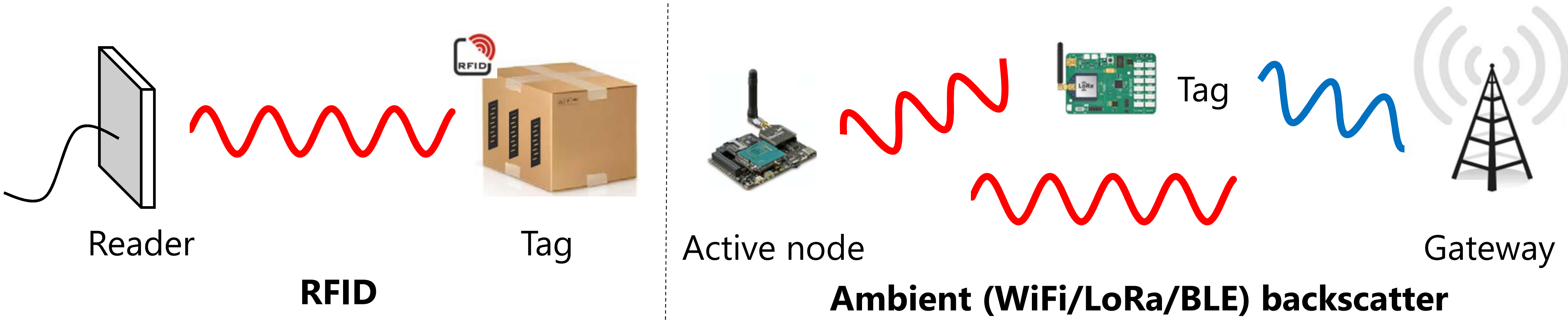
The accuracy and comprehensiveness of understanding of the physical side;

The extent to which we exploit in the cyber side.

Part 2: RF Computing

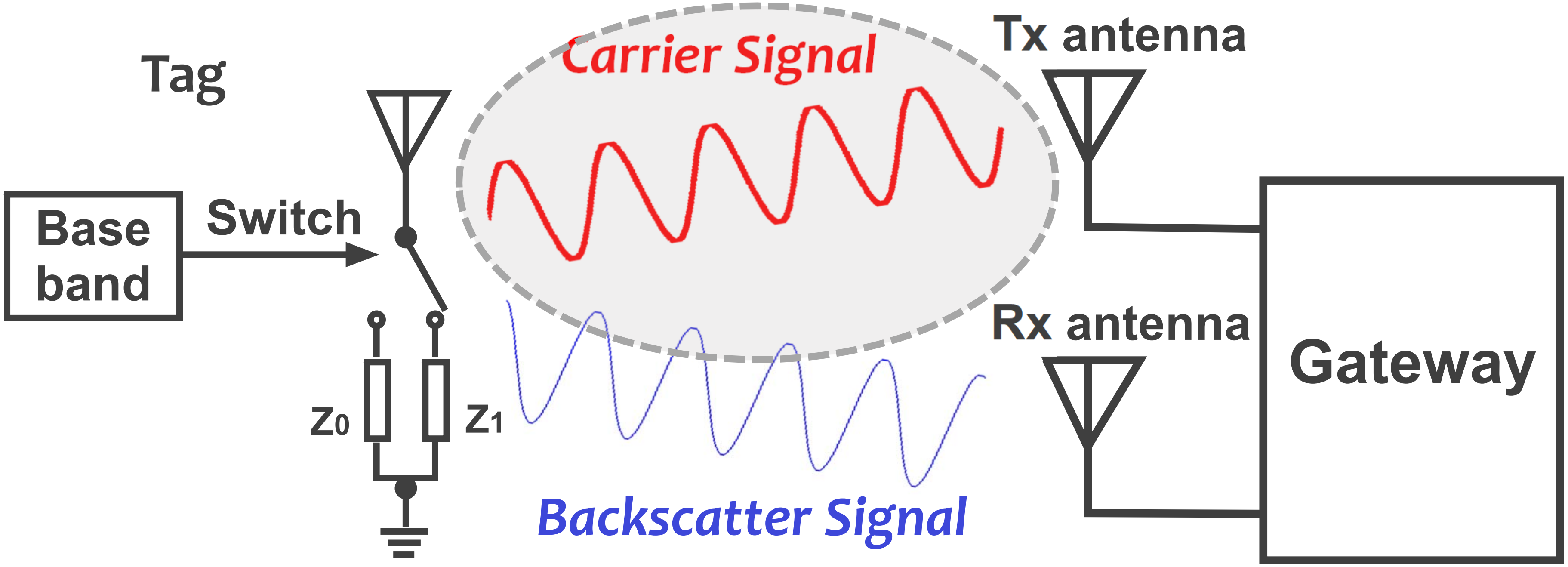
2-1 Analog Signal Processing in Backscatter

Backscatter



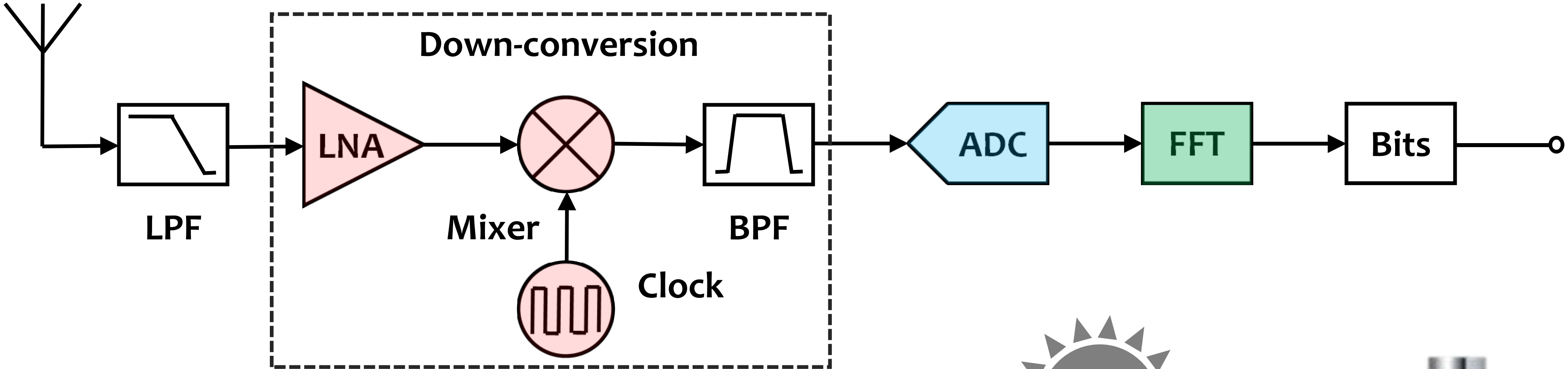
- **A tag is powered by the excitation source and modulates the backscattered signals.**
- **The excitation source is a commercial reader (RFID) or an ambient RF transmitter (Ambient Backscatter).**

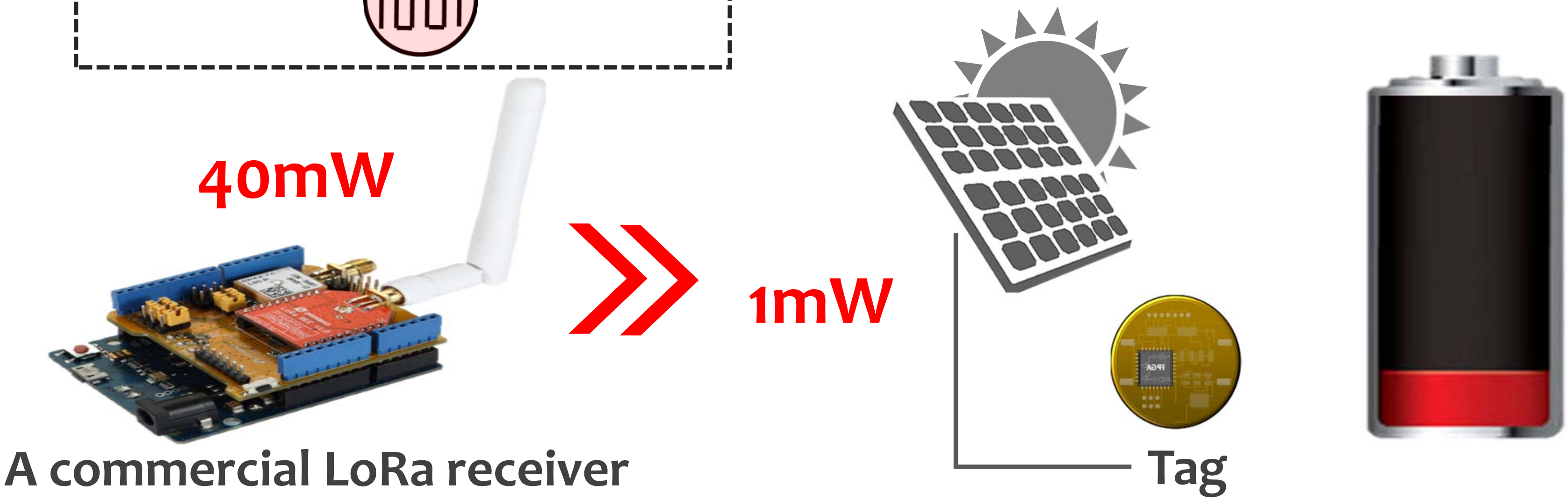
Bottleneck



The demodulation ability is missing on the downlink.

Challenge: High Power Consumption of an Active Demodulator

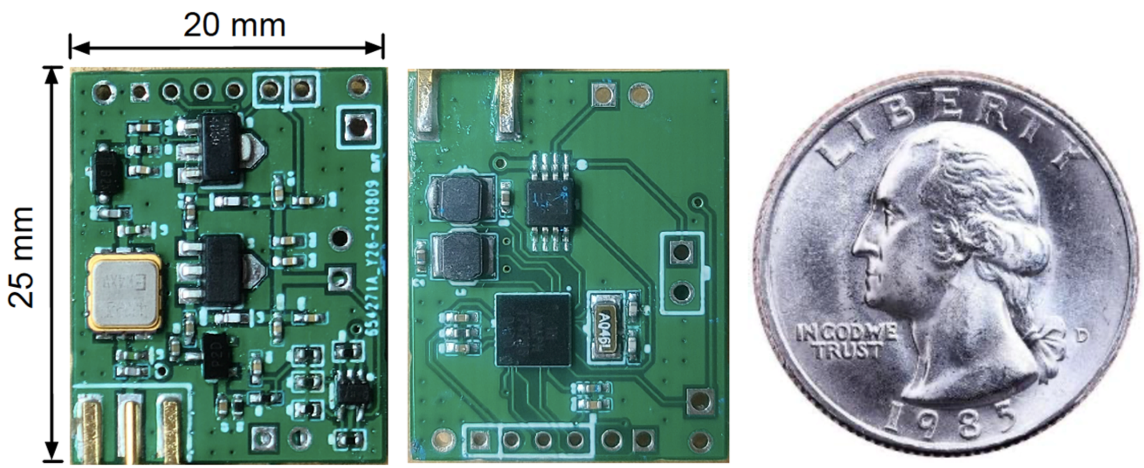




Can we enable a low-power demodulator for long-range LoRa backscatter systems?

Saiyan: Low-power LoRa Demodulator @NSDI' 22

- The first-of-its-kind low-power LoRa demodulator
  - Power consumption of 369.4uW
  - Demodulation range of 180m

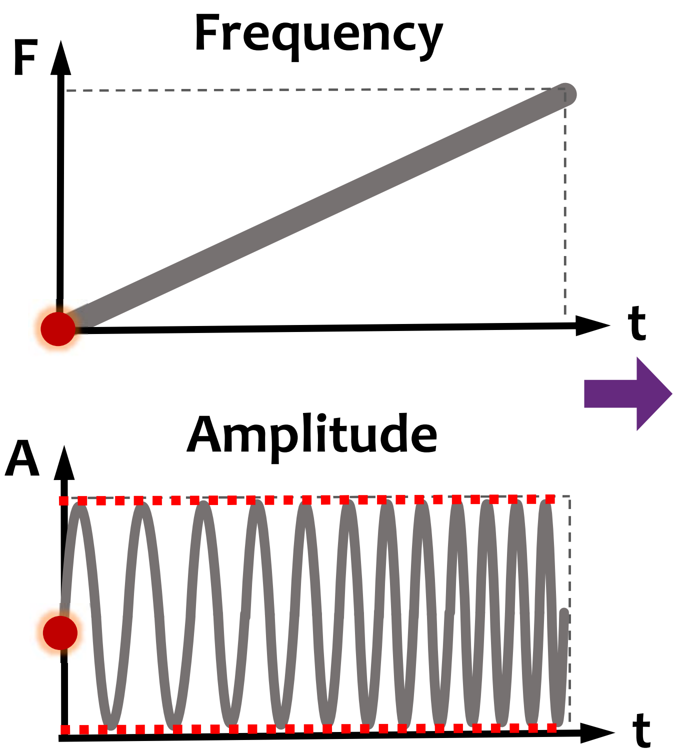


(a) Front (b) Back (c) Quarter

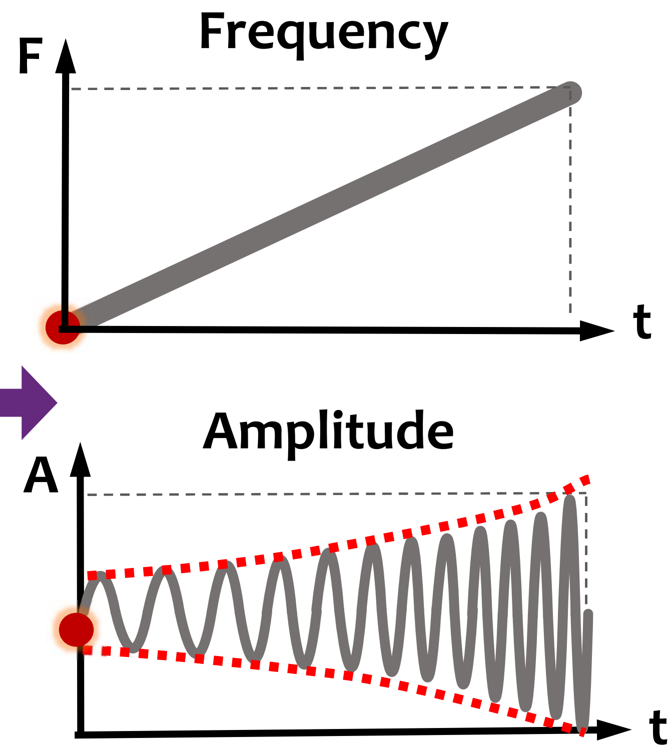
Open-sourced: Code and hardware schematics can be found at: https://github.com/ZangJac/Saiyan

Key Observation

Insight: The FM signal can be converted to FM and AM signal after differential operation!



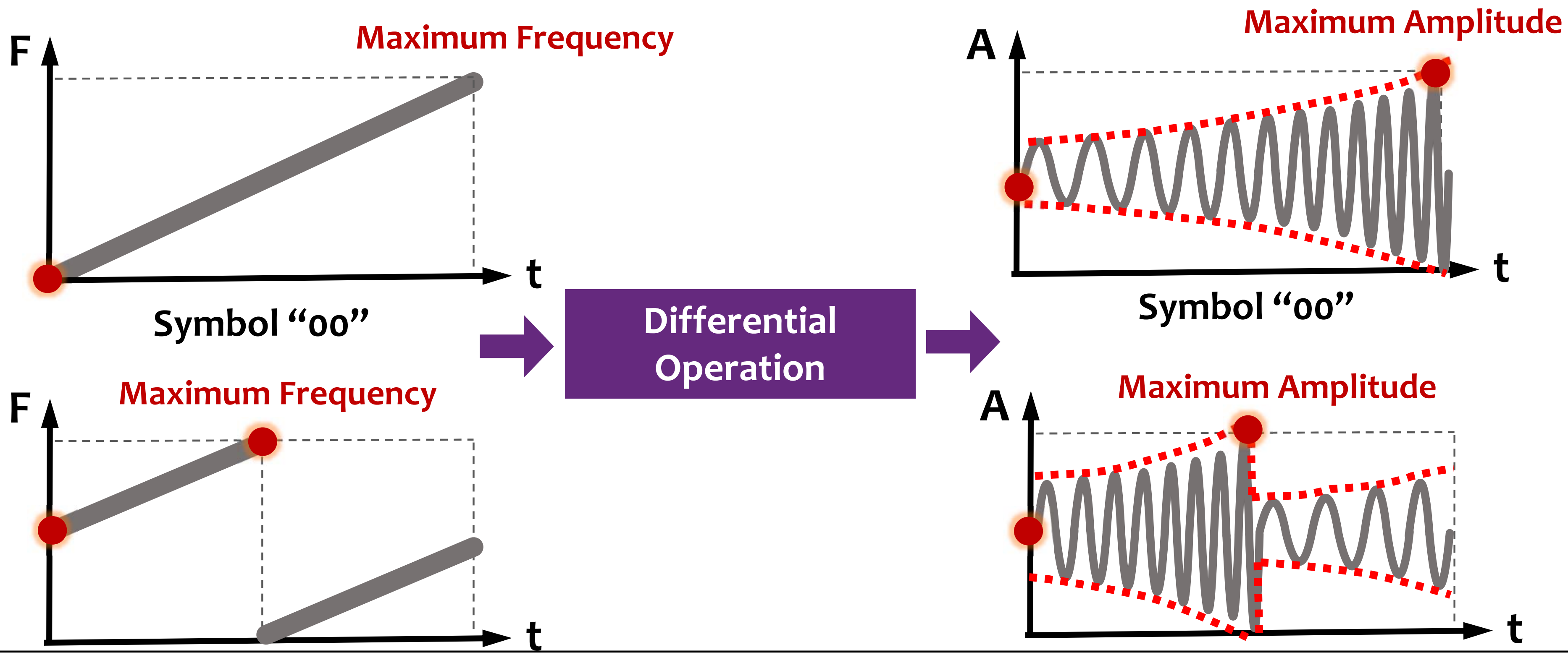
Differentiation Operation



$$s(t) = Asin(2\pi f(t)t)$$
$$f(t) = F_0 + kt$$

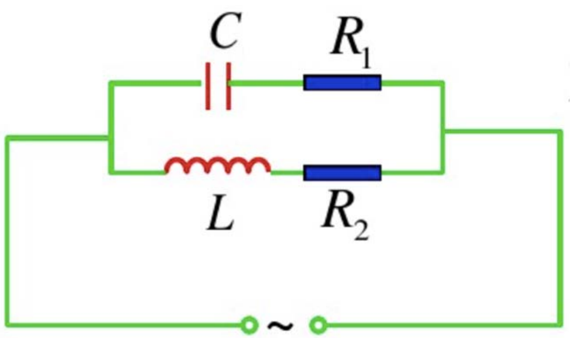
$$s'(t) = \frac{ds(t)}{dt} = Acos(2\pi f(t)t)[2\pi \frac{df(t)}{dt} t + 2\pi f(t)]$$
$$= \underbrace{2\pi A(F_0 + 2kt)}_{Amplitude} cos(2\pi f(t)t)$$

Key Observation

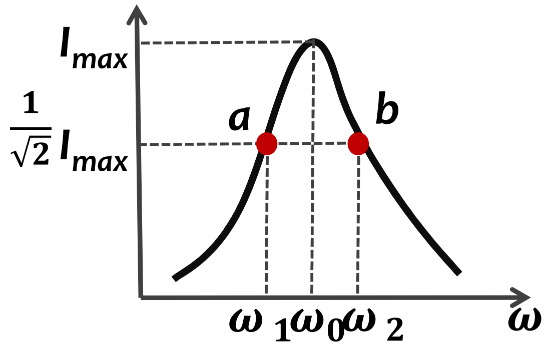


Our idea: Chirp signals can be decoded by identifying the position of the highest amplitude of the AM signal

Frequency-amplitude Transformation



Differential Circuit



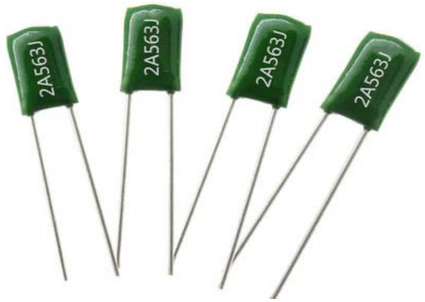
Upper bound capacitance

$$C = \frac{1}{Q\,\omega_0 R} = \frac{\Delta\omega}{\omega_0^2 R} = \frac{500KHz}{(433MHz)^2 * 50}$$

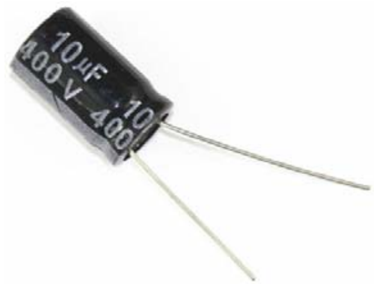
$$= 5.2 * 10^{-14} pF$$

5pF

100pF



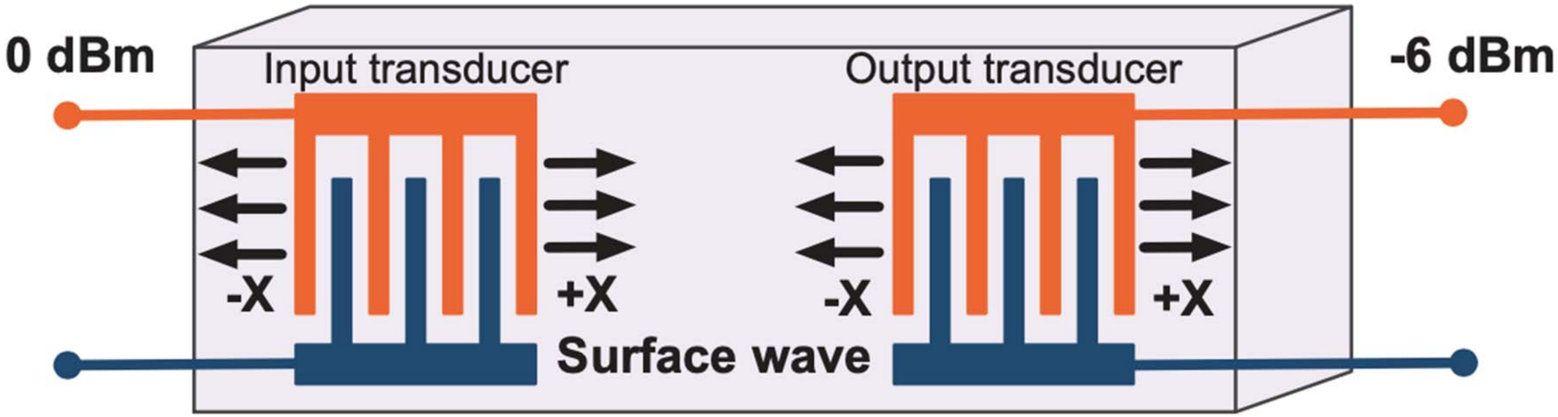
1000pF



0.1uF

Very difficult!

Surface Acoustic Wave (SAW) Filter

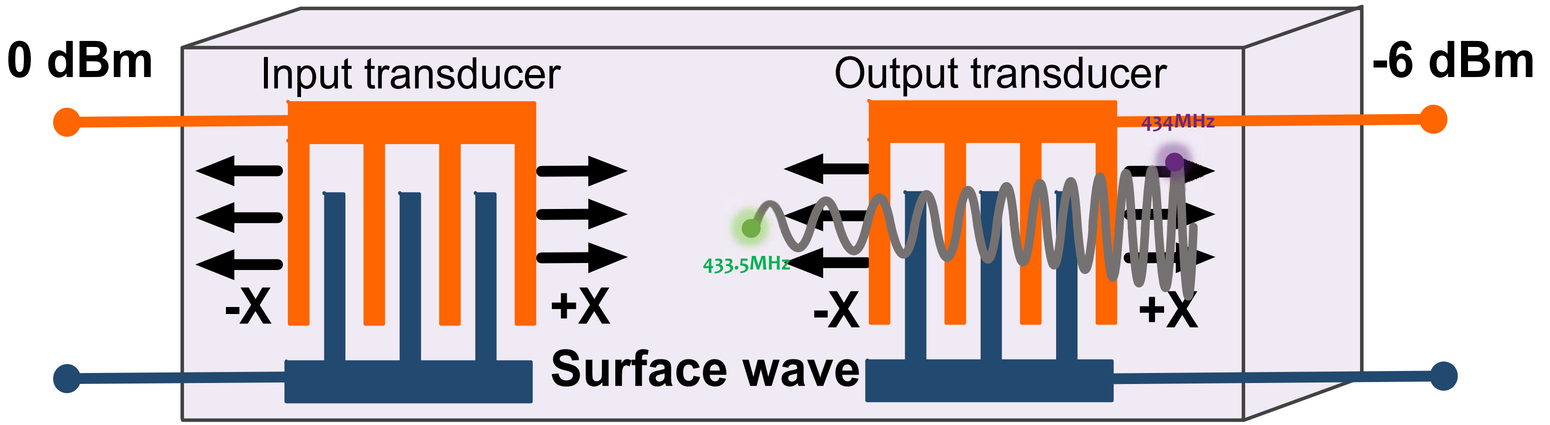


Passive SAW (Surface Acoustic Wave) Filter

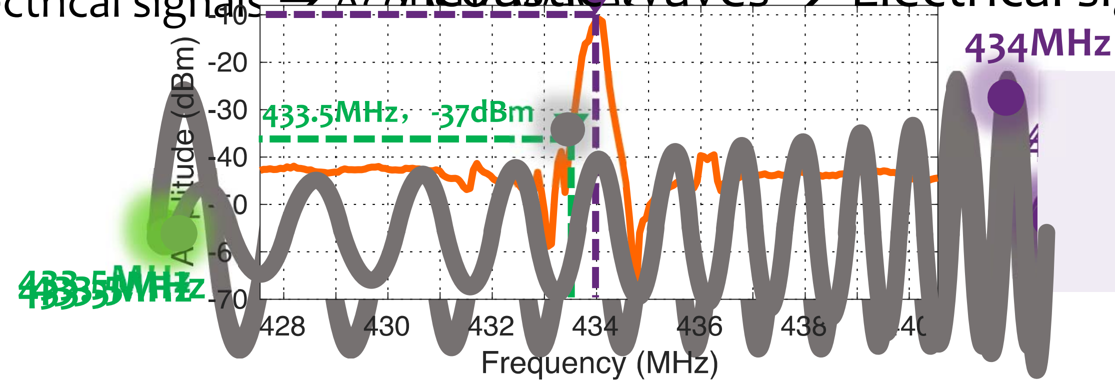
When energy consumption becomes a prioritized factor…

Surface Acoustic Wave (SAW) Filter

Passive SAW Filter

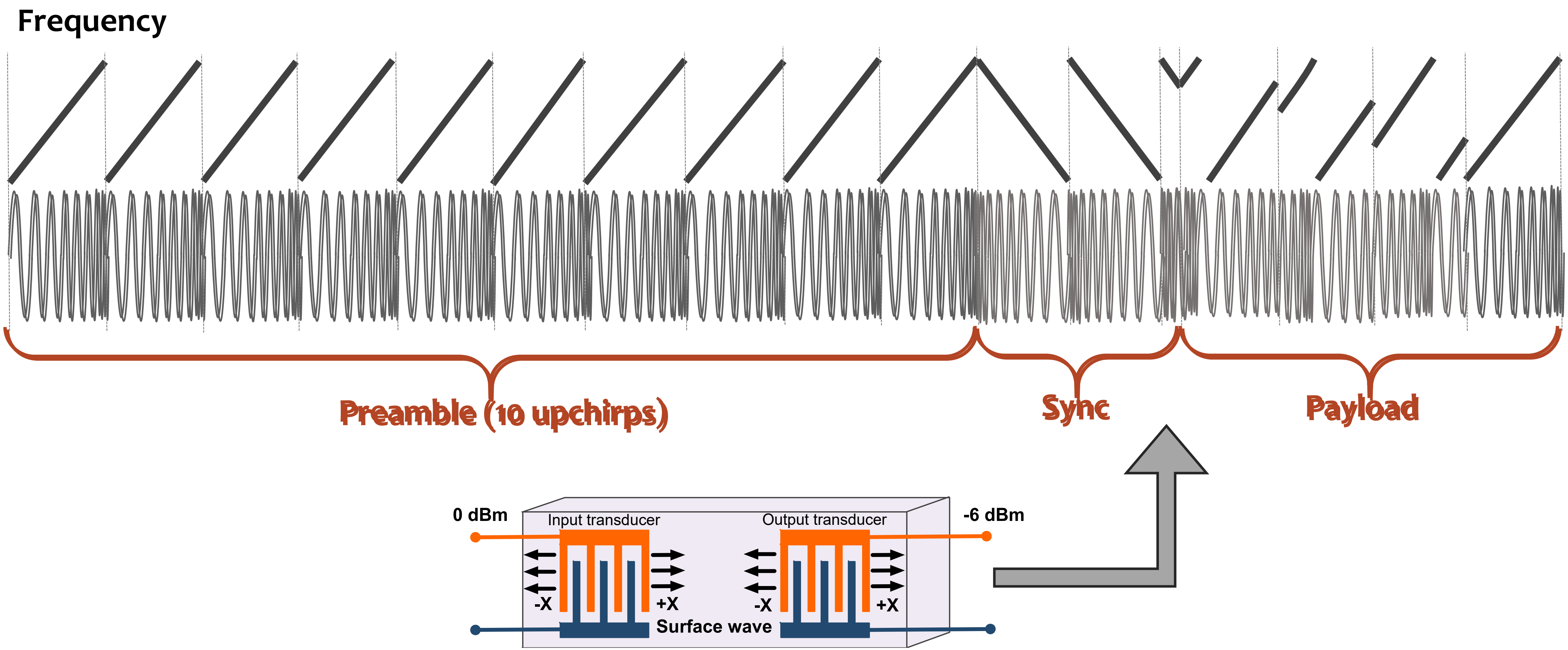


Electrical signals → Acoustic Waves → Electrical signals

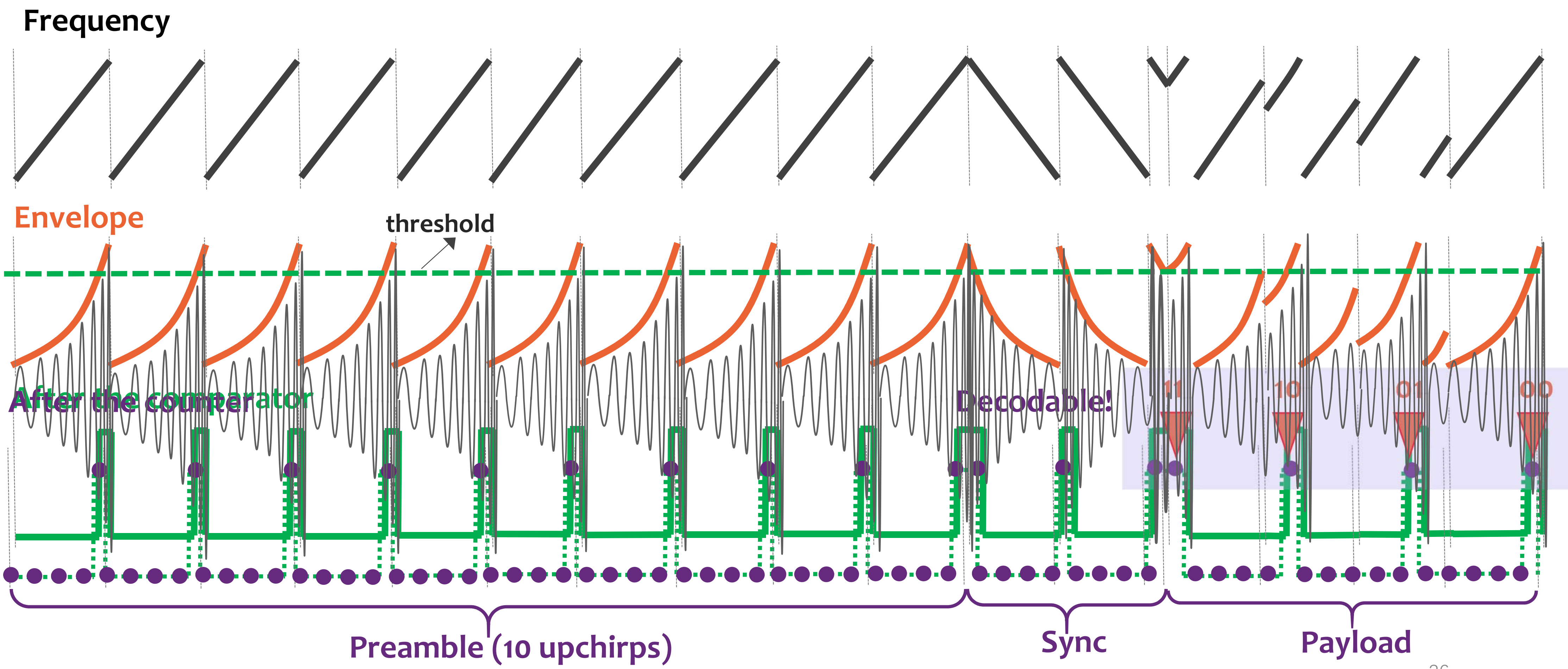


Sharp amplitude-frequency response

Saiyan Design

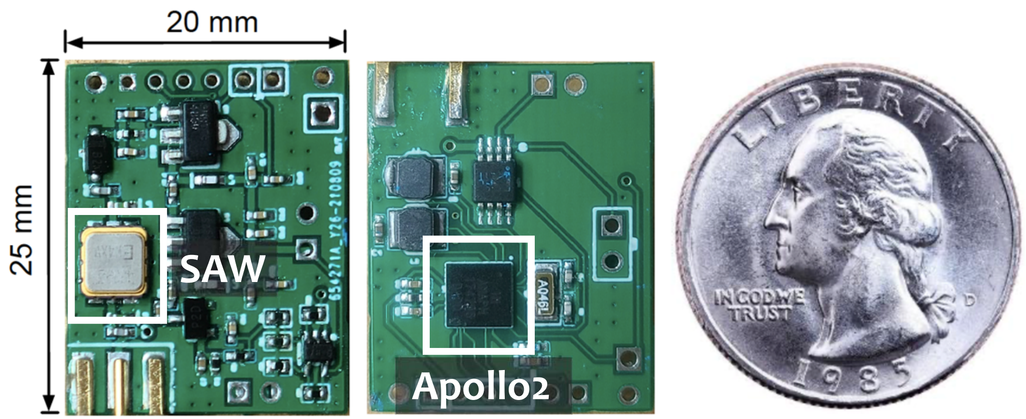


Saiyan Design



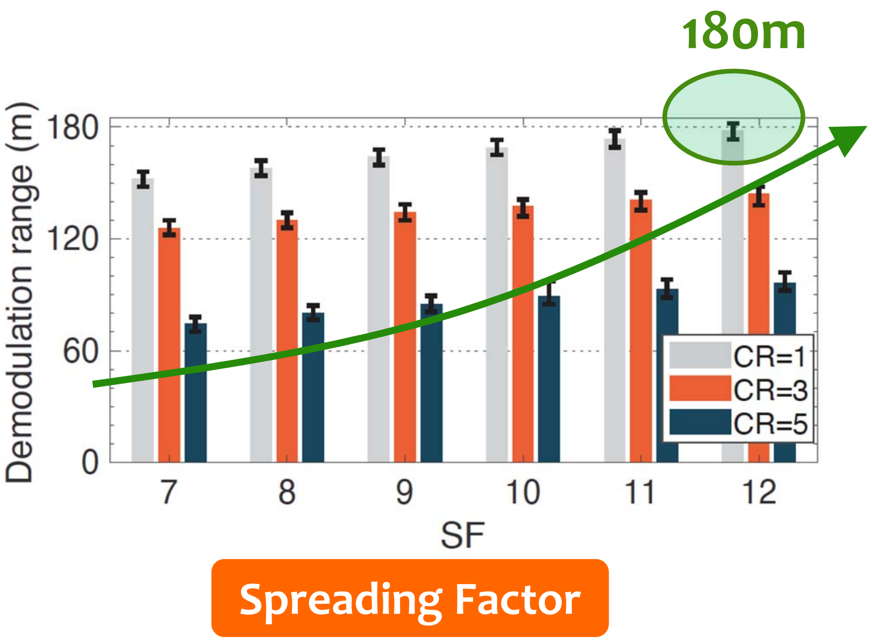
Implementation

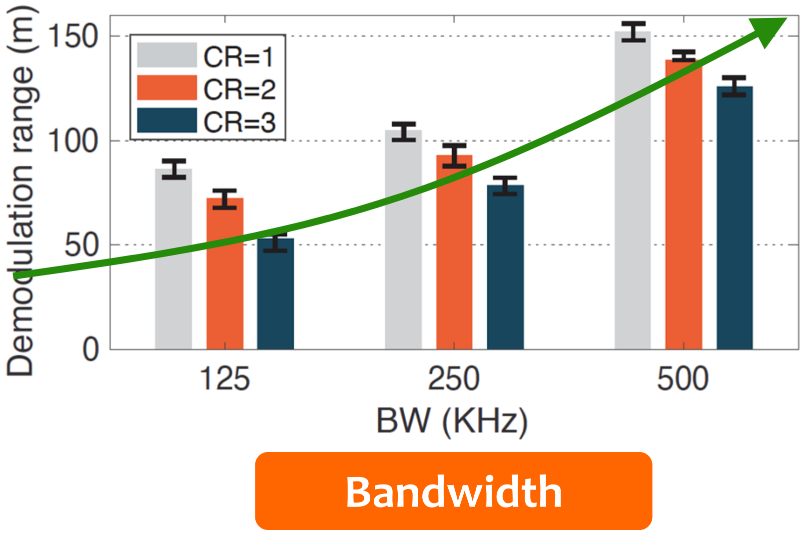
- Backscatter Tag
  - ➢ 25mm * 20mm two-layer PCB
  - ➢ Passive SAW chip B39431B3790Z810
  - ➢ Ultra-low power Apollo2 (10 μA/MHz) MCU
- Plug-and-play
- Power management: palm-sized photovoltaic panel + DC/DC converter LTC3105



(a) Front (b) Back (c) Quarter

Demodulation Range





- The maximum demodulation range can be up to 180m.
- The demodulation range grows with the increasing SF and BW.

Power Consumption & System Cost

Component	SAW Filter	LNA	OSC Clock	Envelope Detector	Comparator	MCU	Total
Energy (μW)	0	248.5	86.8	0	14.45	19.6	369.4
Cost ($)	3.87	4.15	1.25	1.20	1.26	15.43	27.2

Passive

Low-power

The power and cost can be reduced sharply after ASIC fabrication.

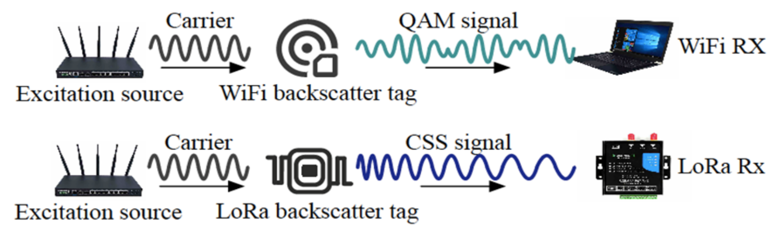
Insights

What we are most concerned in designing a demodulator is the energy consumption, rather than the precision or the speed of calculation.

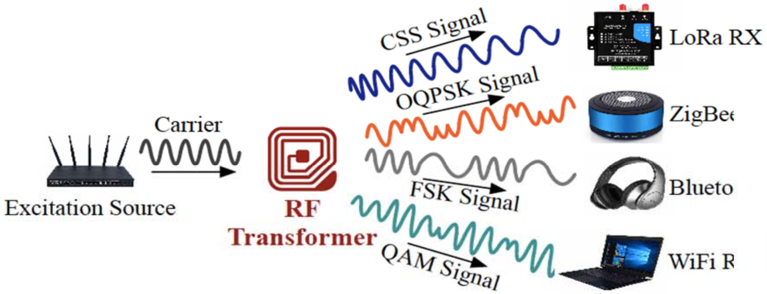
Passive analog devices can work as the equivalent replacement of the active digital component in many computational tasks.

RF-Transformer: A Unified Backscatter Radio Hardware Abstraction

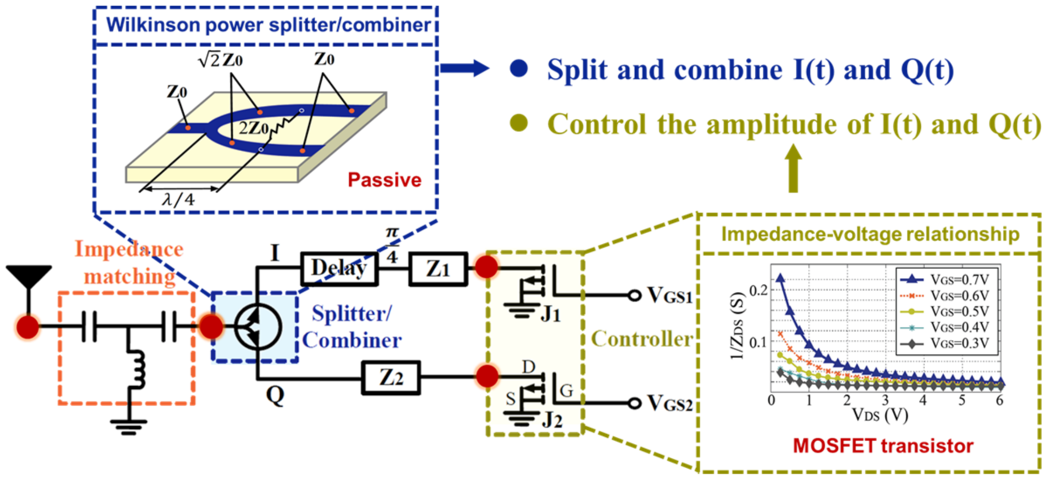
@MobiCom 2022 & GetMobile Issue 3, 2023



(a) Existing backscatter design

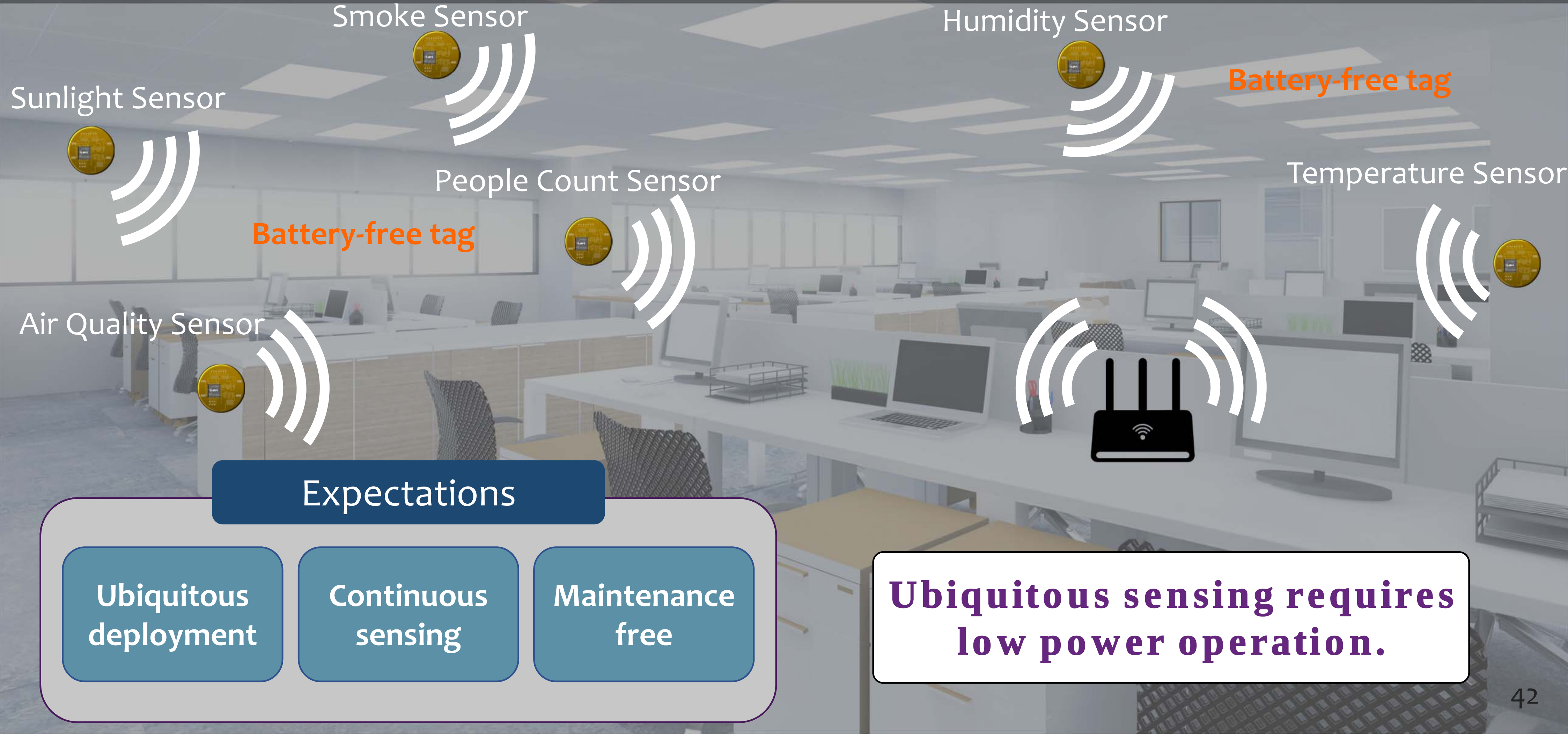


(b) RF-Transformer backscatter design



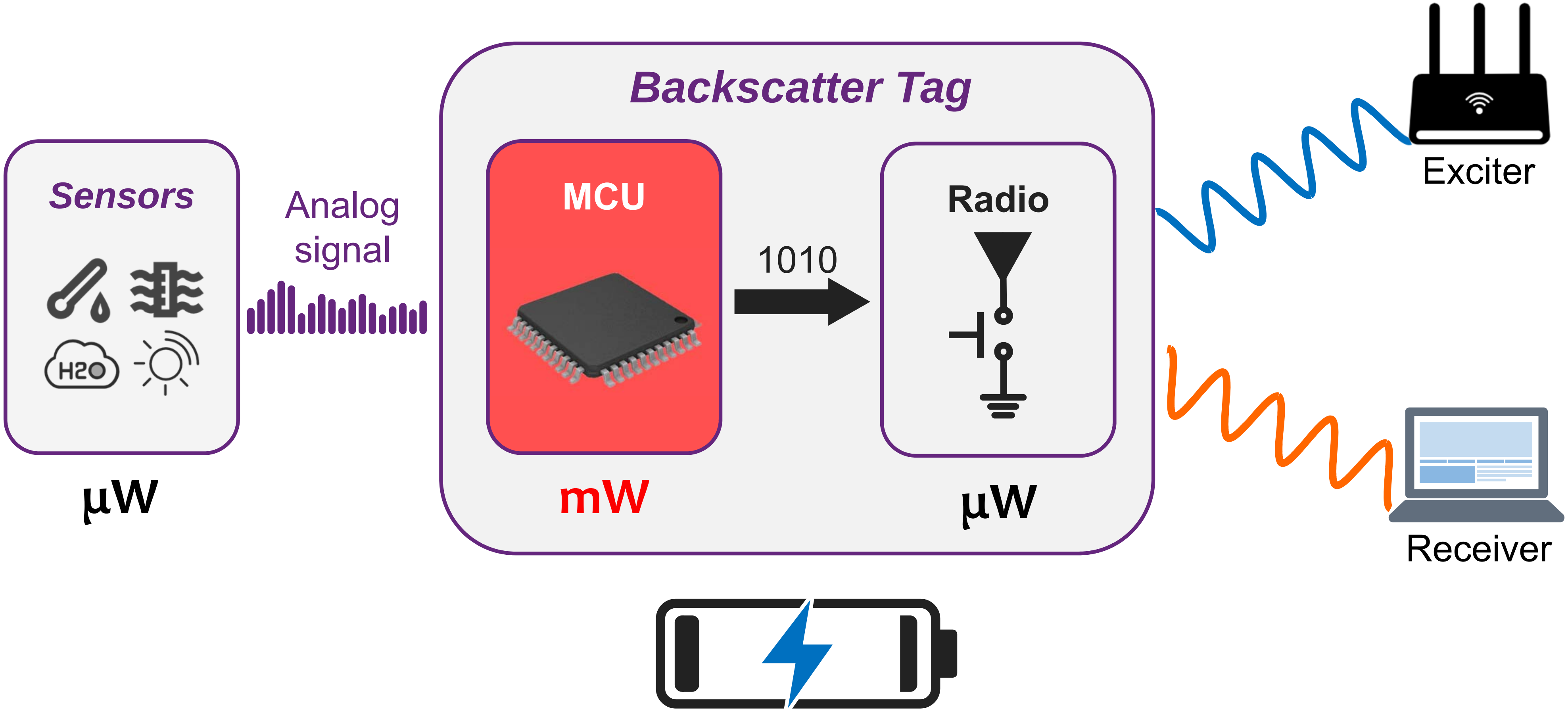
	Energy (uW)					ASIC (uW)				
	Oscillator	FPGA	DAC	RF Transistor	Total	Oscillator	FPGA	DAC	RF Transistor	Total
LoRa	78.8	7.6	234.2	18.6	339.2	10.8	1.4	33.1	2.5	47.8
Bluetooth	134.3	12.5	475.4	33.5	655.7	15.7	1.8	58.4	4.2	80.1
ZigBee	159.8	16.4	618.5	46.6	841.3	16.7	2.0	65.8	4.7	89.2
WiFi 802.11b	140.7	13.8	527.6	41.7	723.8	15.4	1.8	57.3	4.5	79.0
WiFi 802.11g/n/ac	1149.4	86.2	4391.3	242.3	5869.2	73.8	7.5	274.5	15.4	371.2

Leggiero: Analog WiFi Backscatter with Payload Transparency
@MobiSys' 23



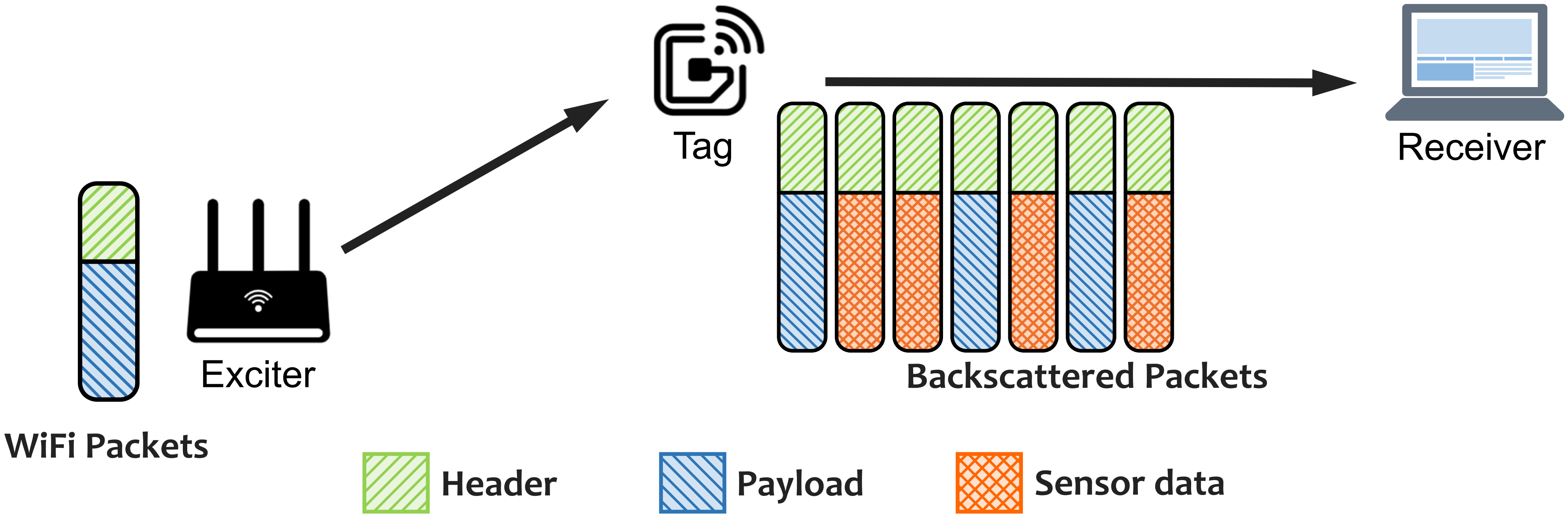
Main Obstacles

➢ ***Obstacle 1: unaffordable power consumption of the MCU***



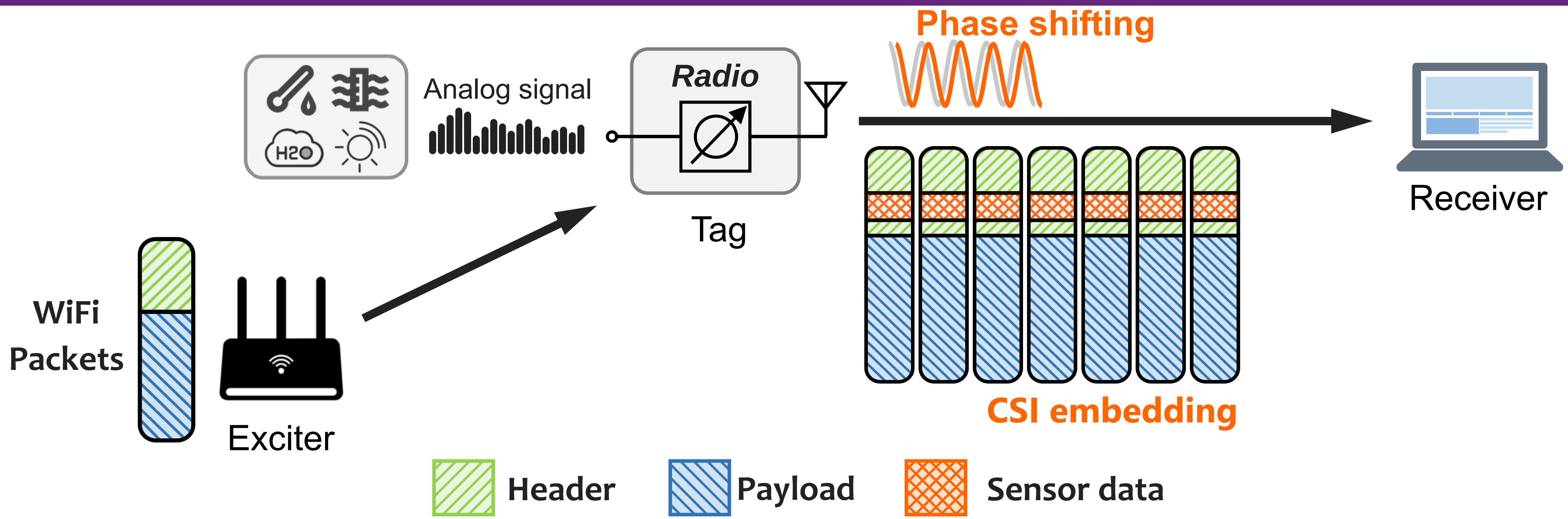
Main Obstacles

- *Obstacle 1: unaffordable power consumption of the MCU*
- *Obstacle 2: coexistence with the ambient carrier traffic*



Existing methods often modify payloads or corrupt entire frames to transmit backscatter data.

Design Overview



Innovation 1

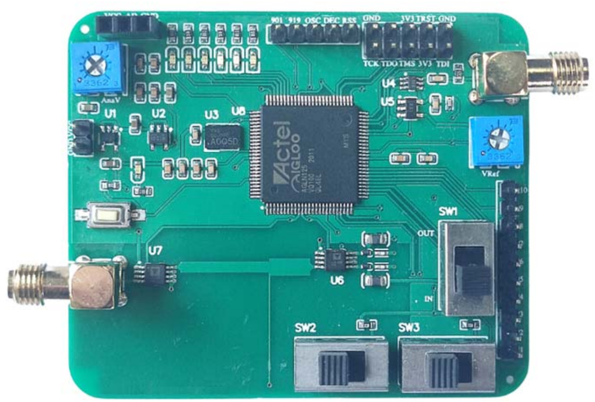
Low-power signal conversion in the analog domain

Innovation 2

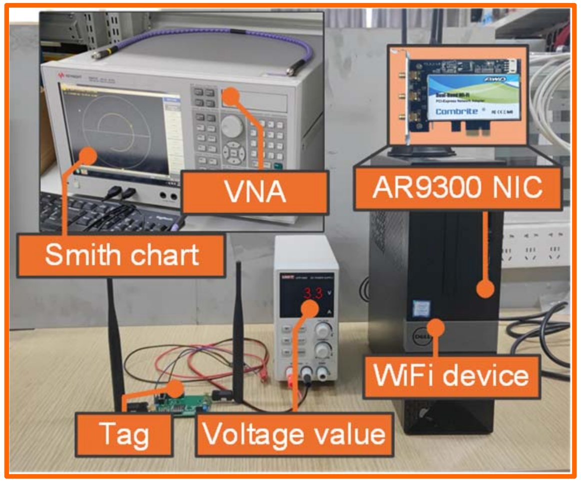
Analog modulation with payload transparency

Implementation

Leggiero Tag Prototype



- Prototype printed circuit board (PCB) using commercial components.
- Fully ***passive phase-shifting*** circuit using the SMV2201 varactor, simulated with ADS.
- Supports connection with analog sensors in a ***plug-and-play*** manner.



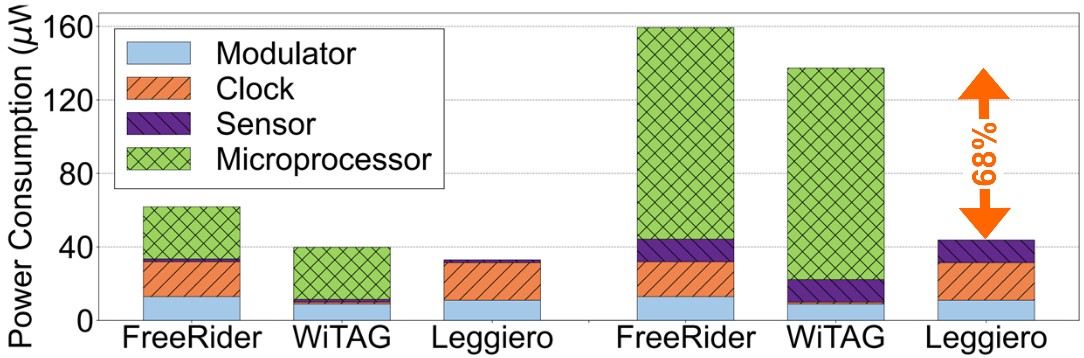
- WiFi transceivers implemented with Atheros AR9300 WiFi NIC.
- PicoScenes for transceiving packets with ***no modification on commercial hardware***.

Evaluation - Tag Power Consumption

Component	RF switches	Packet detector	Control logic	20MHz Clock generation	**Total**
Power in ASIC	1*2μW	7μW	1μW	20μW	**30μW**

- **Power consumption is 30μW when implemented in ASIC.**
- **For the PCB prototype implementation, power consumption is 40mW.**

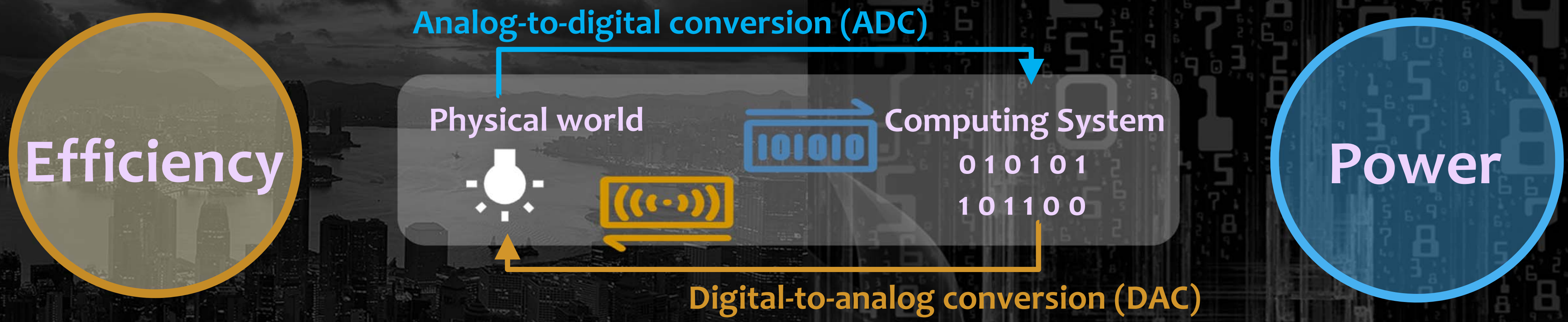
End to end evaluation



(1) Light sensor (Photoresistance) sampling at 100Hz

(2) Position sensor (Joystick) sampling at 400Hz

Information Flows in IoT



Loss of information

Excessive hardware costs

Unaffordable computational complexity

Intensive energy overhead

Inspirations from Other Areas: Analog Computing

The Soap Film: An Analogue Computer

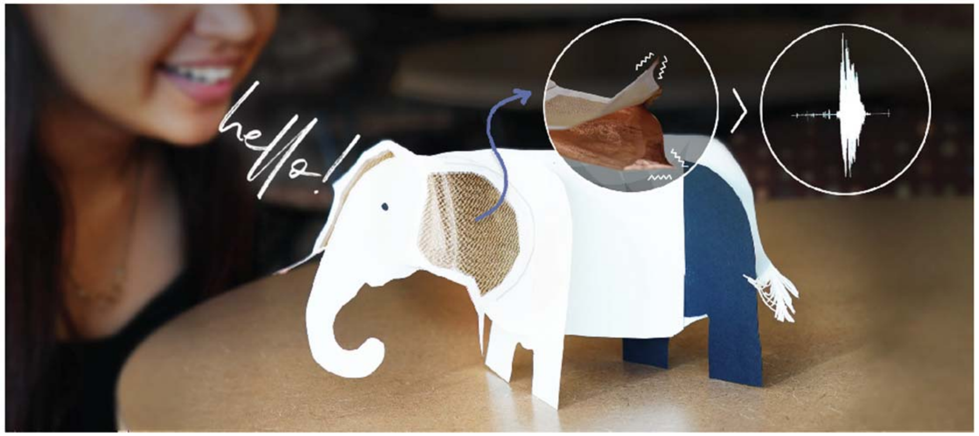
Steiner trees and spanning trees in six-pin soap films

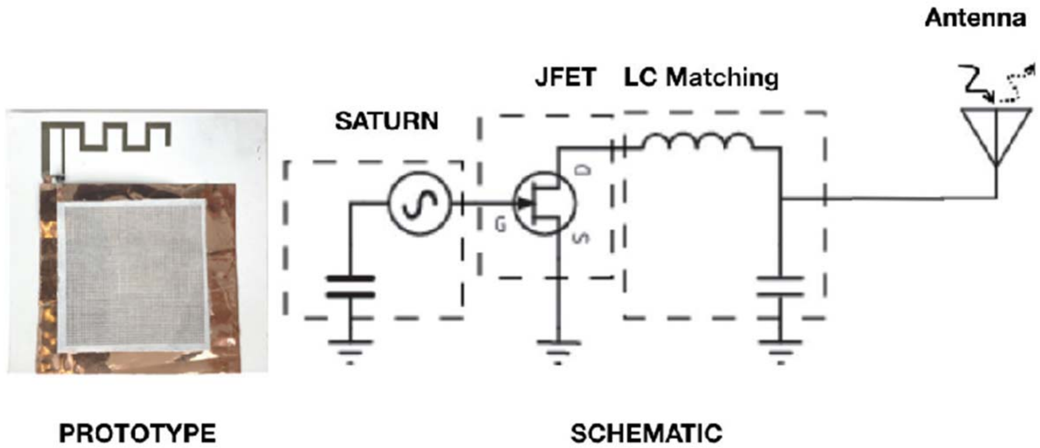
American Journal of Physics 78, 215 (2010);

Anti-shake camera on the chicken's head ☺

Inspirations from Other Areas: Analog Computing

SATURN: An Introduction to the ***Internet of Materials***
Communications of the ACM, Dec. 2020, Vol. 63 No. 12.

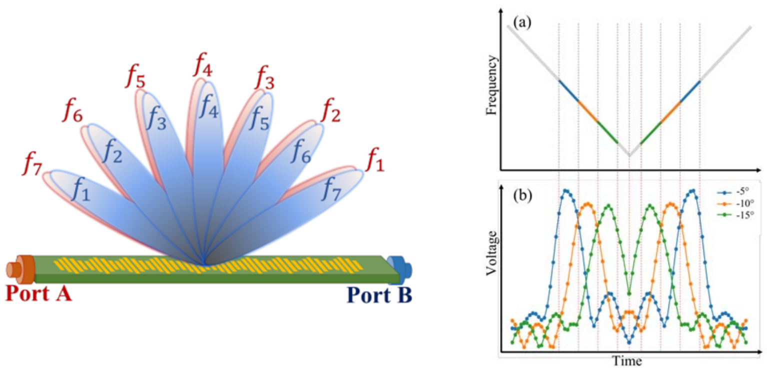




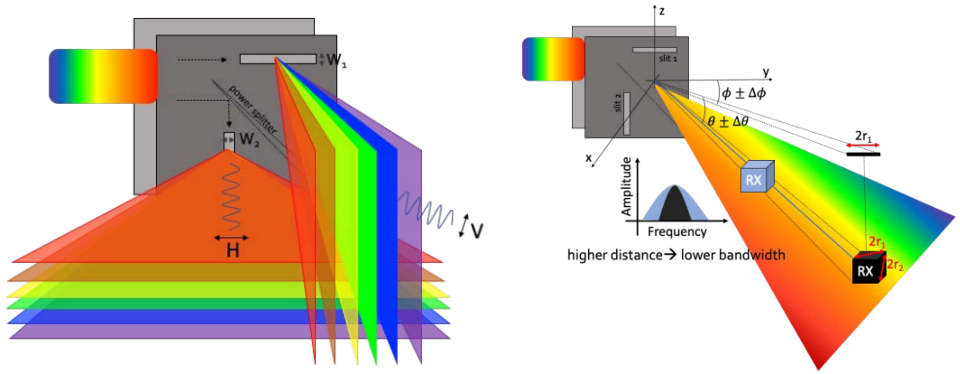
Self-powered **A**udio **T**riboelectric **U**ltra-thin **R**ollable **N**anogenerator

Research Works Sharing the Similar Insight

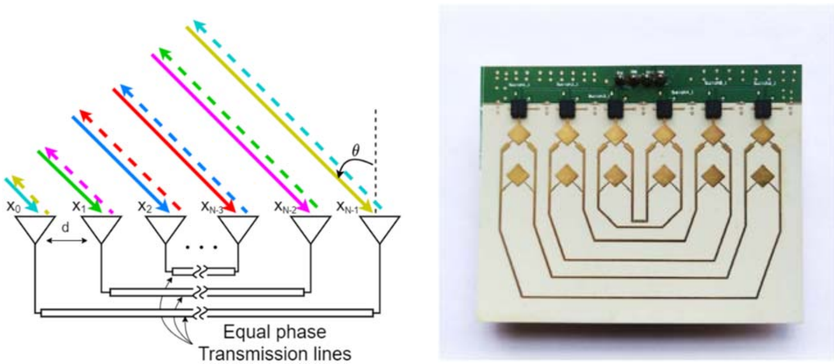
The signal is processed and manipulated at RF devices without the need of ADC/DAC.



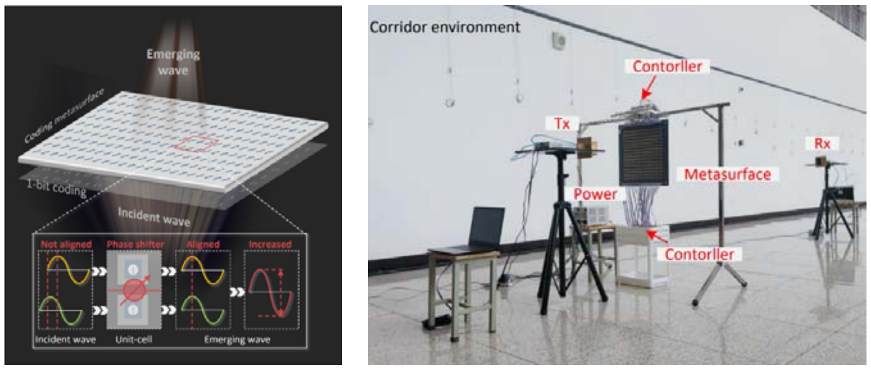
MilBack. SIGCOMM23: Leaky-wave Antenna-based mmWave Demodulation and Tag Localization



123-LOC. MobiCom22: Leaky-wave Antenna-based THz Localization



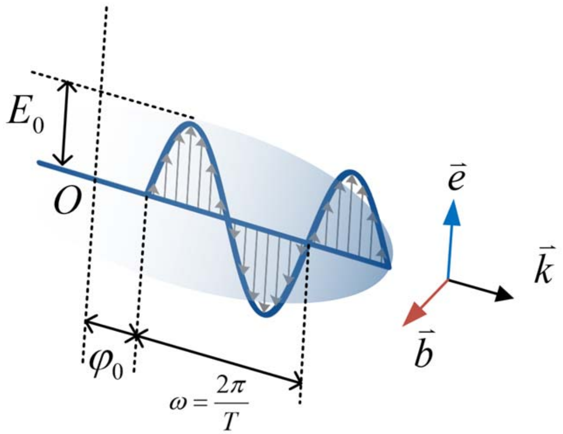
mmTag. SIGCOMM21: Van Atta Array-based mmWave backscatter network



RFlens. SIGCOMM21: Metasurface-based WiFi Beam-forming for IoT Communication and Sensing

RF Computing – the Concept

RF Computing regards RF signals as the information carrier and the computed object. It transforms RF signals in the RF space to achieve information processing and transition.



Angular Frequency

Amplitude

Polarization

$$\vec{E}(r,t) = E_0 \cos(\vec{k}r - \omega t + \varphi_0)\vec{e}$$

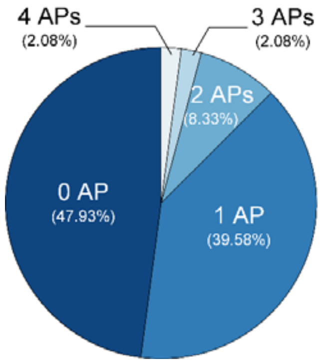
Propagation Direction

Phase

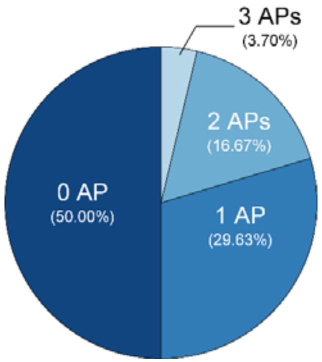
Basic Operation: <u>Only one</u> signal property is transformed in the computing process

Compound Operation: <u>More than one</u> signal property is transformed in the computing process

BIFROST: WiFi-based Indoor Localization Based on Dispersion Effect @SenSys' 23

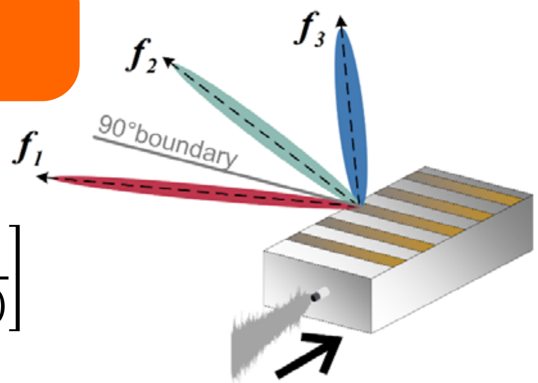


LoS AP in Library (48 rooms)



LoS AP in Office (54 rooms)

Frequency and Spatial Division Multiplexing (FSDM)



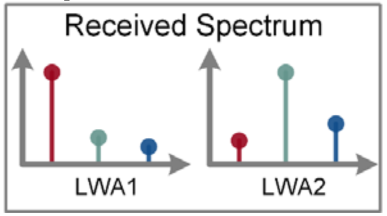
$$\theta(f) = arccos\left[\frac{\beta(f)}{k_0(f)}\right]$$

Leaky Wave Antenna: Signals with different frequencies will be radiated to different directions.

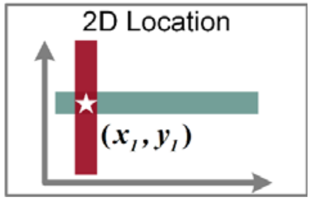
Basic Idea

1. **Exploit two LWAs to radiate FSDM signals**

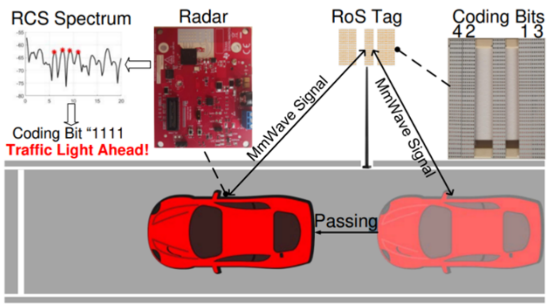
2. **Capture frequencies of the two FSDM signals**



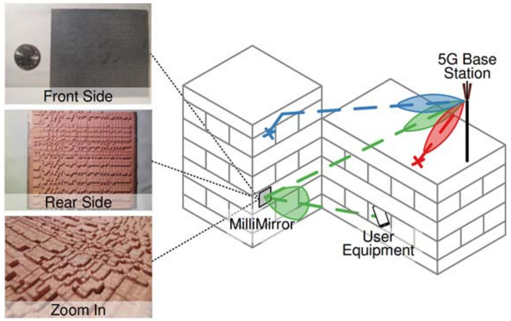
3. **Estimate AoAs and location by finding the frequencies with the highest energy.**



Future Direction 1: Passive Computing

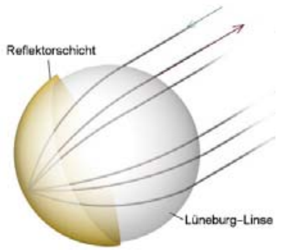


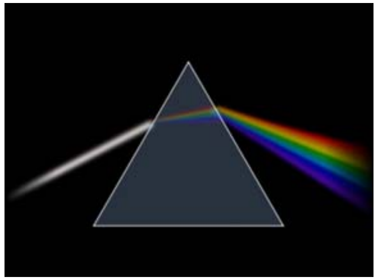
RoS. SIGCOMM21: Using passive Van Atta Array to change the polarization and propagation of the incident signal.



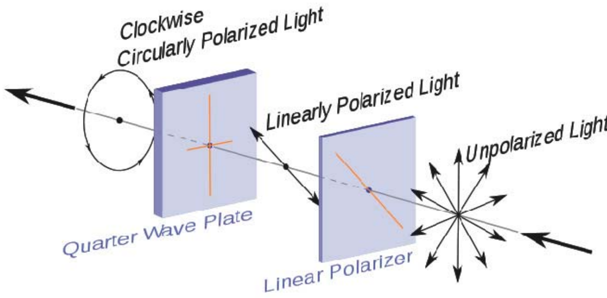
MilliMirror. MobiCom22: Using passive metamaterial to change the phase and propagation of the incident signal.

Exploiting the EM property of material to develop passive computing devices, so that the corresponding power consumption of signal processing can be reduced to zero.



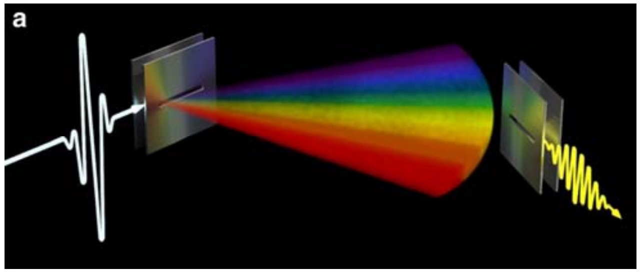


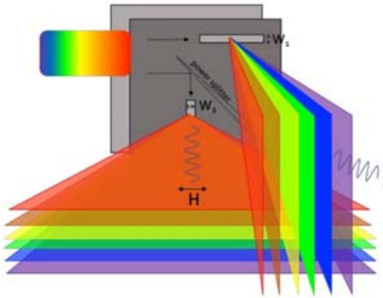
(a) Luneburg lens **(b) Prism**



(c) Quarter Wave Plate and Polarizer

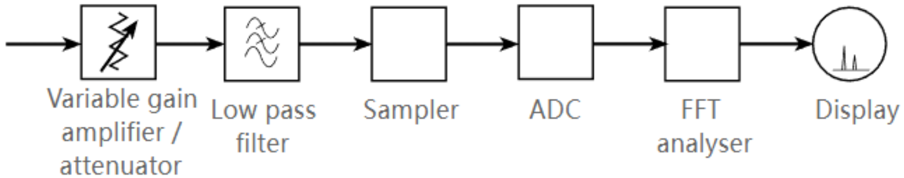
Future Direction 2: Quasi-zero Delay Signal Processing



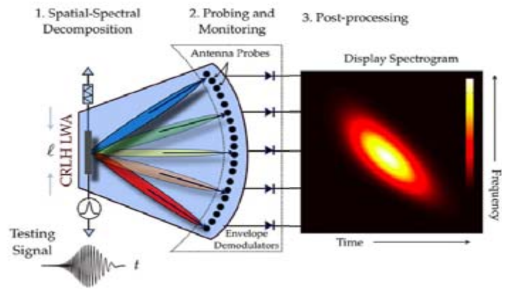


123-LOC. MobiCom22: Using LWA and dispersion effect to perform "Fourier Transform" at the speed of light.

Exploit the EM property of devices to directly transform the signal in the analog domain, omitting complex processing modules and significantly saving the time of signal processing.

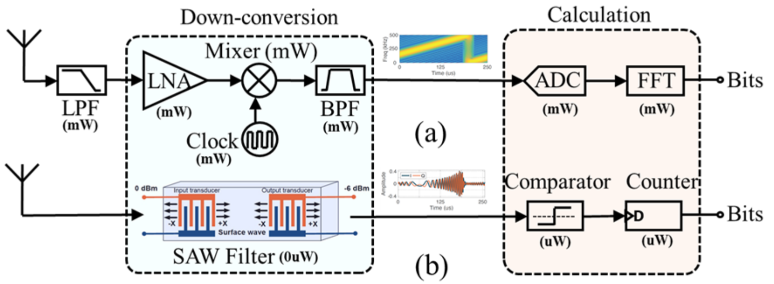


(a) Digital spectrum analyzing based on RF chain

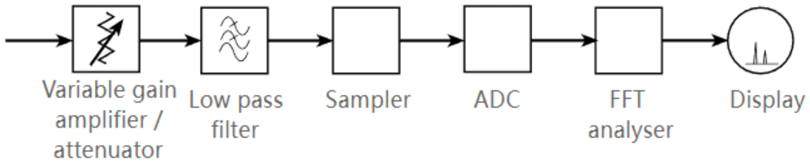


(b) Analog spectrum analyzing based on LWA and envelope detector

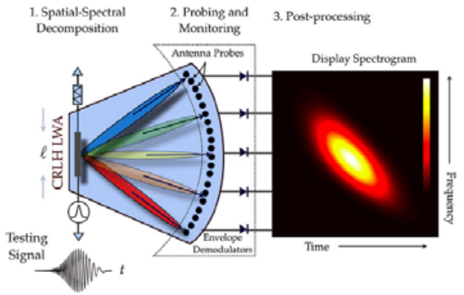
Future Direction 3: Programming of the RF System



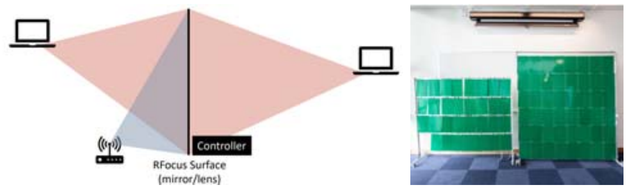
(a) SAW Filter-based Method



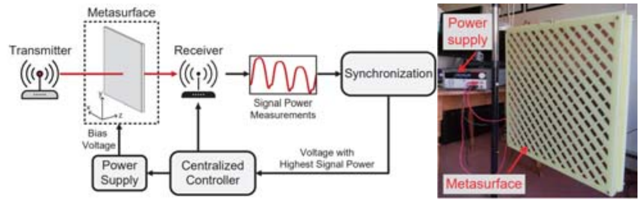
(b) RF Chain-based Method



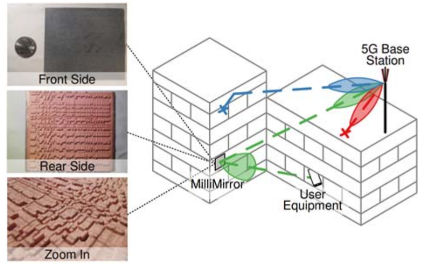
(c) Leaky Wave Antenna-based Method



(a) Metasurface for Beamforming (NSDI'20)



(b) Metasurface for Polarization Manipulation (NSDI'21)



(c) 3D-Printed Metasurface
(Mobicom'22)

Three different way to transform the information from frequency to amplitude.

Three different types of metasurface

Related publications:

1. Chengkun Jiang, Junchen Guo, *Yuan He, Meng Jin, Shuai Li, Yunhao Liu, "mmVib: Micrometer-Level Vibration Measurement with mmWave Radar", ACM MobiCom 2020.
2. Junchen Guo, *Yuan He, Chengkun Jiang, Meng Jin, Shuai Li, Jia Zhang, Rui Xi, Yunhao Liu, "Measuring Micrometer-Level Vibrations with mmWave Radar", IEEE Transactions on Mobile Computing.
3. Junchen Guo, Meng Jin, *Yuan He, Weiguo Wang, Yunhao Liu, "Dancing Waltz with Ghosts: Measuring Sub-mm-Level 2D Rotor Orbit with a Single mmWave Radar", The 20th IEEE/ACM IPSN, 2021.
4. Jia Zhang, Yinian Zhou, Rui Xi, Shuai Li, Junchen Guo, *Yuan He, "AmbiEar: mmWave Based Voice Recognition in NLoS Scenarios", ACM IMWUT 2022.
5. Jia Zhang, Xin Na, Rui Xi, Yimiao Sun, *Yuan He. "mmHawkeye: Passive UAV Detection with a COTS mmWave Radar", IEEE SECON 2023.
6. Xiuzhen Guo, Longfei Shangguan, *Yuan He, Nan Jing, Jiacheng Zhang, Haotian Jiang, Yunhao Liu, "Saiyan: Design and Implementation of a Low-power Demodulator for LoRa Backscatter Systems", USENIX NSDI 2022.
7. Xiuzhen Guo, Yuan He, Zihao Yu, Jiacheng Zhang, Yunhao Liu, Longfei Shangguan, "RF-Transformer: A Unified Backscatter Radio Hardware Abstraction", ACM MobiCom 2022.
8. Xin Na, Xiuzhen Guo, Zihao Yu, Jia Zhang, *Yuan He, and Yunhao Liu. "Leggiero: Analog WiFi Backscatter with Payload Transparency", ACM MobiSys 2023.
9. Yimiao Sun, Yuan He, Jiacheng Zhang, Xin Na, Yande Chen, Weiguo Wang, Xiuzhen Guo, "BIFROST: Reinventing WiFi Signals Based on Dispersion Effect for Accurate Indoor Localization", ACM SenSys 2023.
10. Weiguo Wang, Luca Mottola, *Yuan He, Jinming Li, Yimiao Sun, Shuai Li, Hua Jing, Yulei Wang, "MicNest: Long-Range Instant Acoustic Localization of Drones in Precise Landing", ACM Sensys 2022.
11. Jia Zhang, Rui Xi, *Yuan He, Yimiao Sun, Xiuzhen Guo, Weiguo Wang, Xin Na, Yunhao Liu, Zhenguo Shi, Tao Gu. "A Survey of mmWave-based Human Sensing: Technology, Platforms and Applications", IEEE Communications Surveys & Tutorials, 2023.
12. Yuan He, Weiguo Wang, Luca Mottola, Shuai Li, Yimiao Sun, Jinming Li, Hua Jing, Ting Wang, Yulei Wang, "Acoustic Localization System for Precise Drone Landing", IEEE Transactions on Mobile Computing.

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Thanks for listening!

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