ACM MobiSys 2025

Satori: In-band Analog Backscatter for Audio Transmission

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Background: Audio sensing

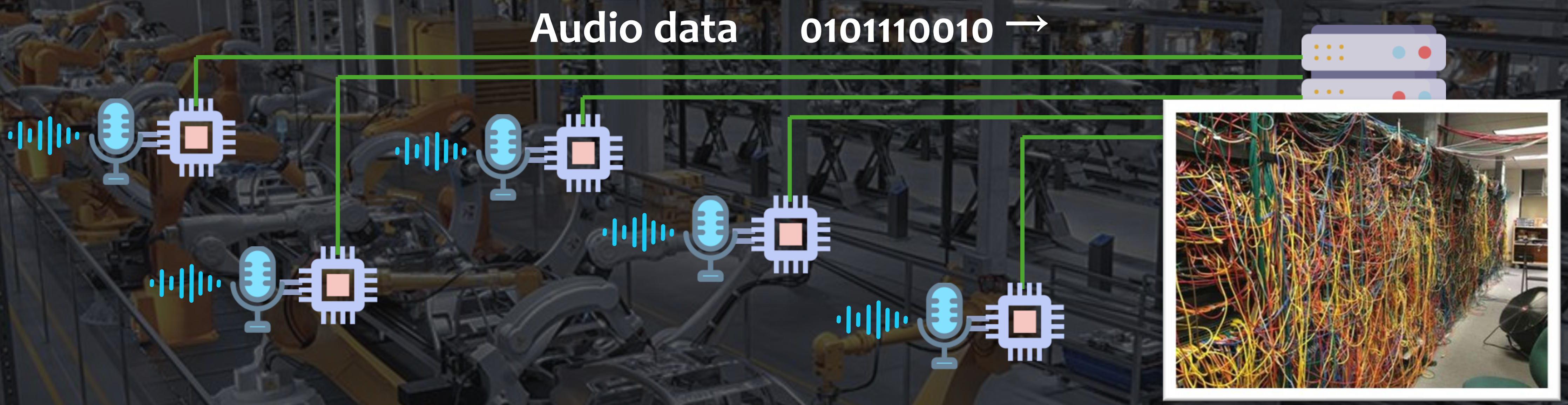
Machine failure detection

Security surveillance

Command recognition

Audio sensing supports various industrial applications.

Audio Transmission in Industrial Scenarios



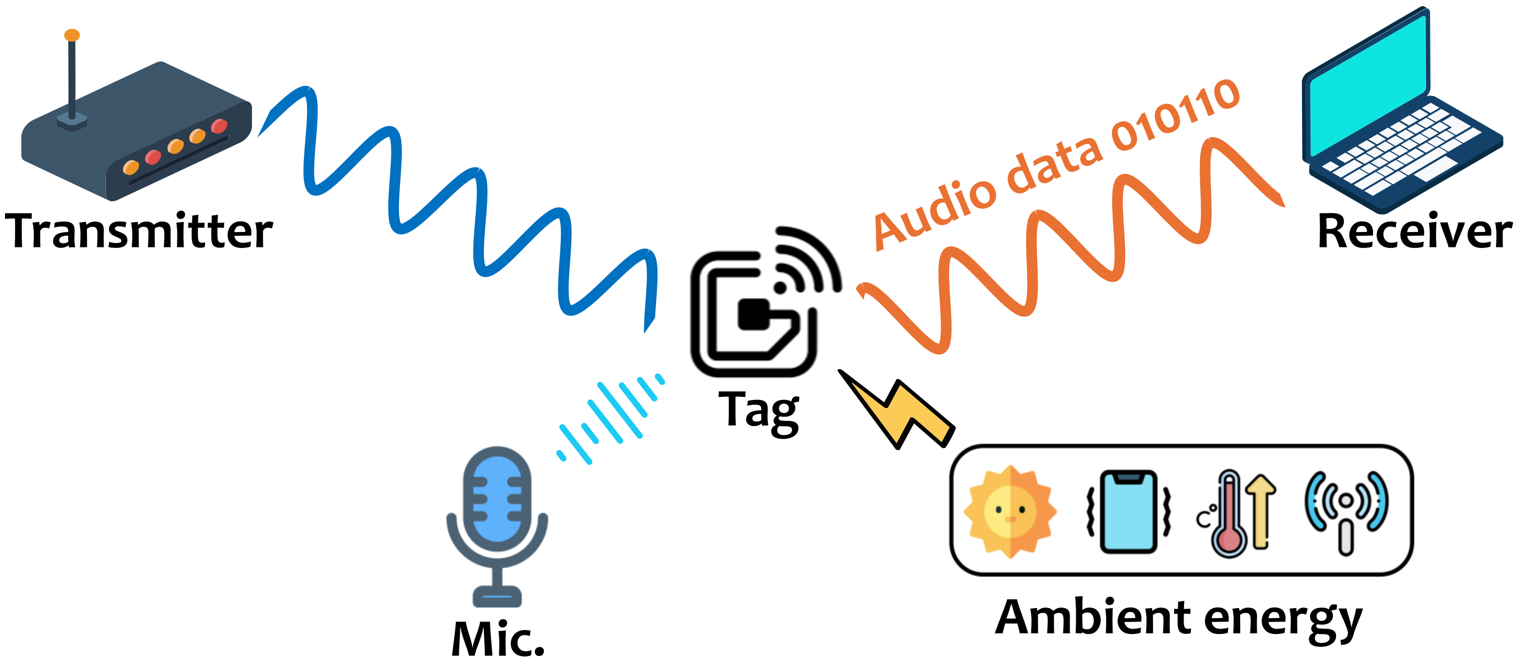
- ➢ The sensors are deployed close to the audio source and transmit audio data via networks.
- ➢ Extensive cabling is usually costly and impractical in industrial settings.

Audio Transmission in Industrial Scenarios

- Traditional wireless nodes bring battery waste and maintenance costs.
- These nodes are expected to transmit audio with ultra-low power consumption.

Backscatter Technology

- Backscatter for audio transmission



A backscatter tag harvests ambient energy and modulates the audio data *onto the backscattered signals*.

Existing Works

Digital backscatter

Single tone excitation
- **Passive WiFi** *NSDI'16*
- **RF Transformer** *MobiCom'22*

WiFi excitation

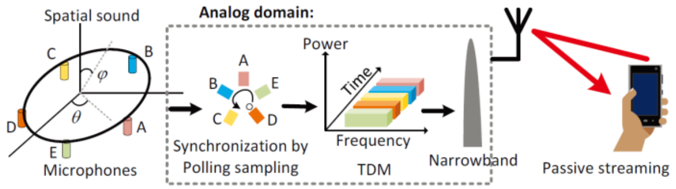
HitchHike *Sensys'16*	**FreeRider** *CoNext'17*	**MOXcatter** Mobisys'18
RapidRider *INFOCOM'21*	**Tscatter** *Mobisys'23*	**WiTAG** SIGCOMM'20
CAB *Mobisys'22*	**SyncScatter** *NSDI'21*	**Orthcatter** NSDI'24

……

They can achieve throughput of 100 kbps or even Mbps with ultra-low power consumption.

Analog backscatter

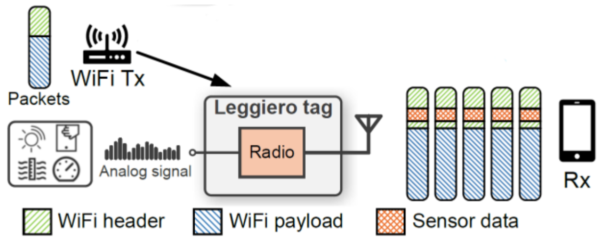
Microphone Array Backscatter



Pulse Position Modulation

Mobicom'21

Leggiero

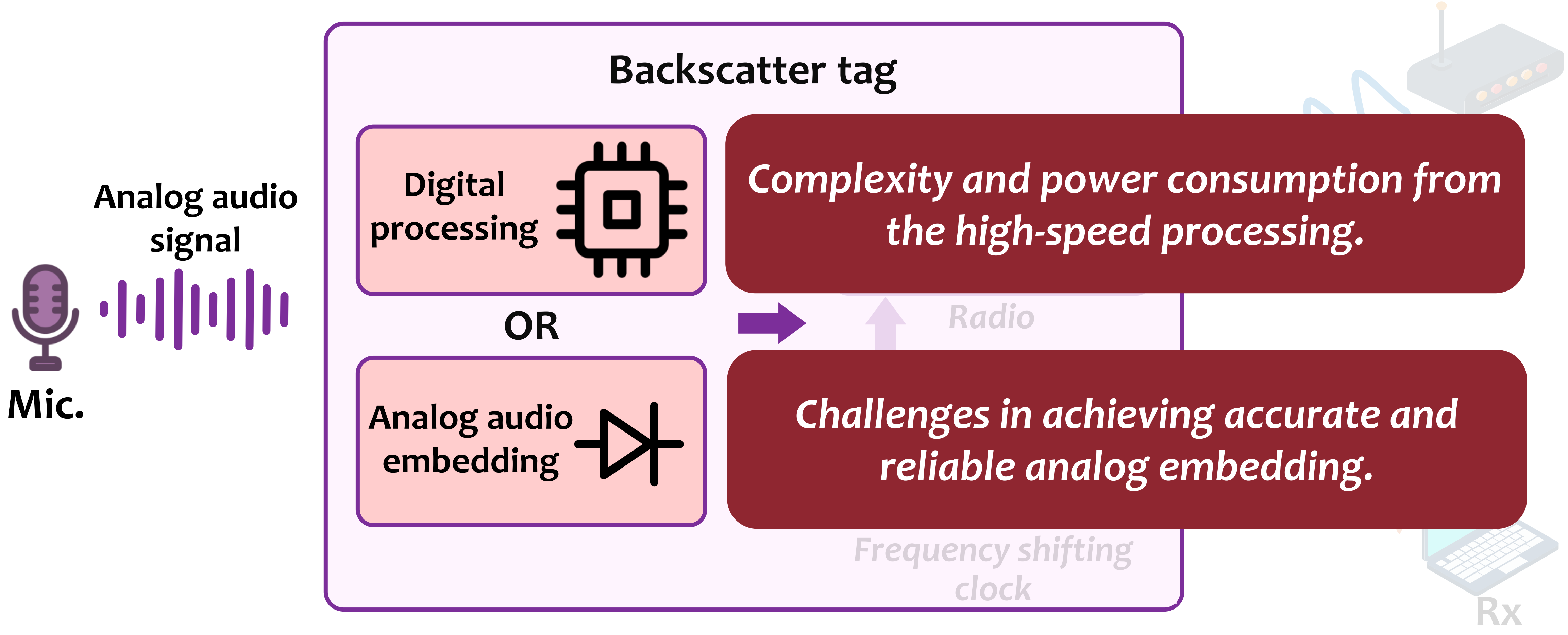


WiFi Excitation + Phase Modulation

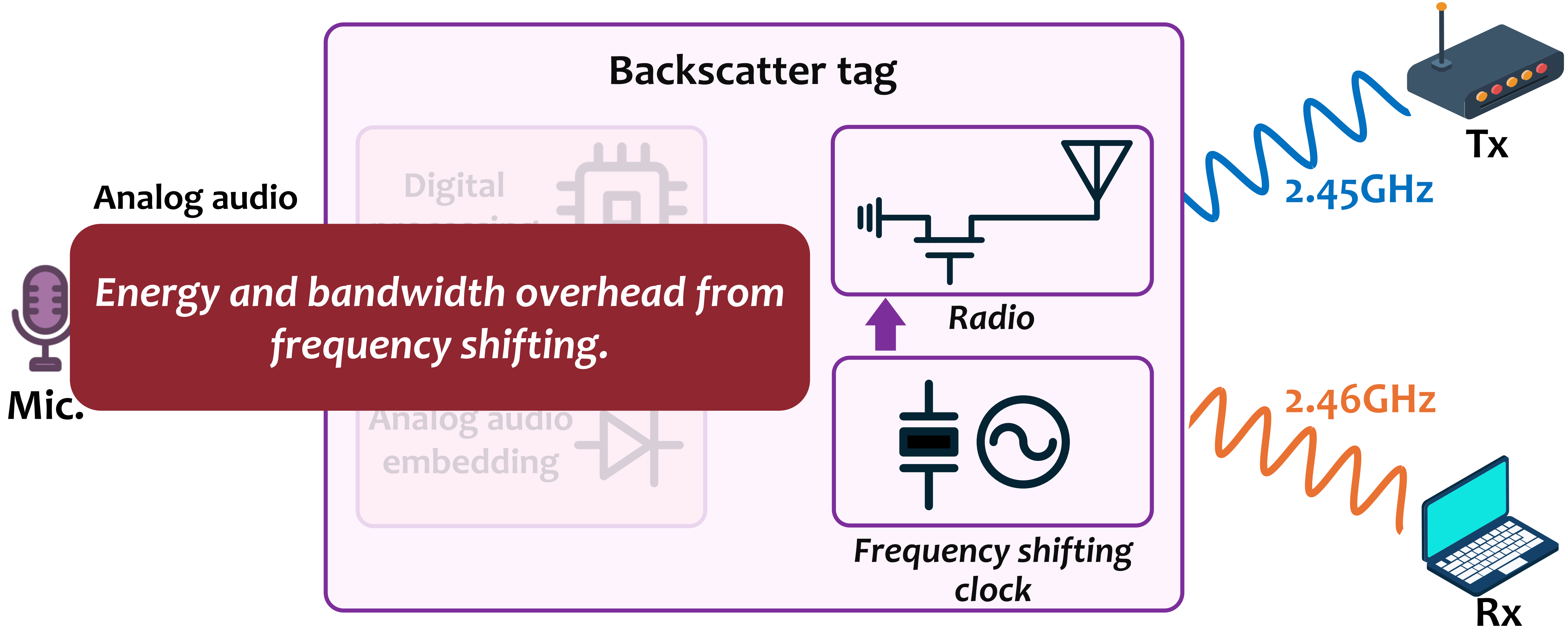
Mobisys'23

They directly embed the analog signals into reflected RF signals.

Obstacles


Backscatter tag
Digital processing
OR
Analog audio embedding
Analog audio signal
Mic.
Complexity and power consumption from the high-speed processing.
Radio
Challenges in achieving accurate and reliable analog embedding.
Frequency shifting clock
Rx

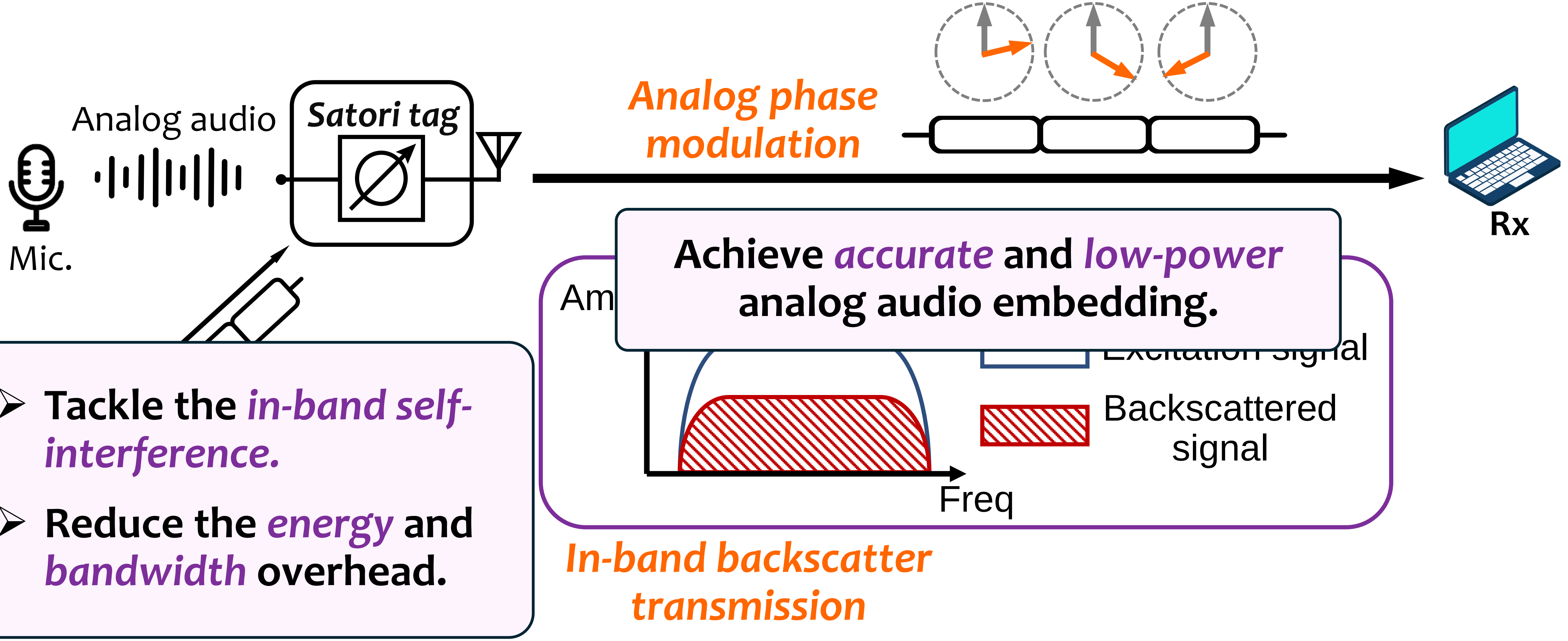
Obstacles



Energy and bandwidth overhead from frequency shifting.

Satori Overview

Satori explores the *in-band analog backscatter* for audio transmission.



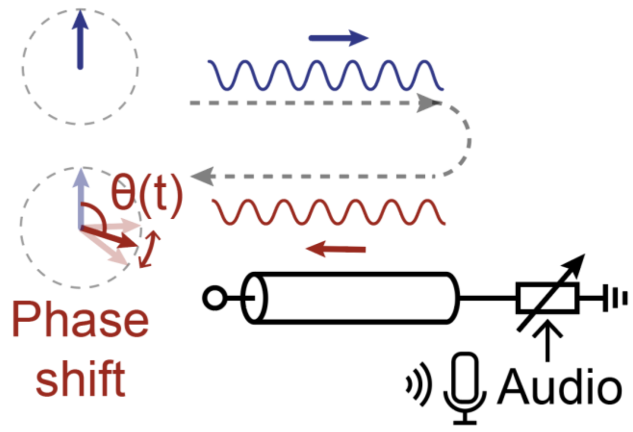
Achieve *accurate* and *low-power* analog audio embedding.

- ➢ **Tackle the *in-band self-interference.***
- ➢ **Reduce the *energy* and *bandwidth* overhead.**

Tag Design

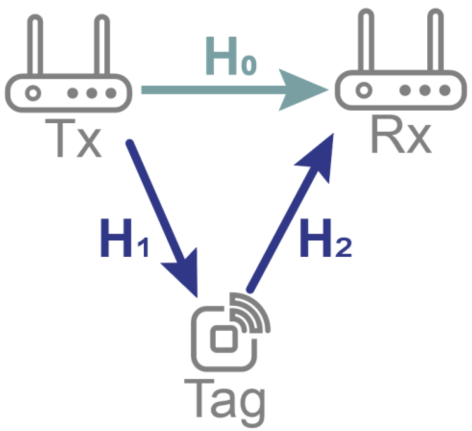
- *In-band analog backscatter*

Analog modulation

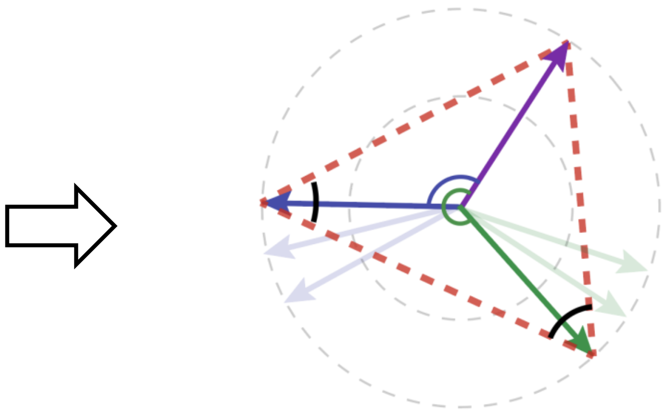


A *phase shifter* for analog phase modulation.

In-band transmission



Explore the *in-band backscatter channel*

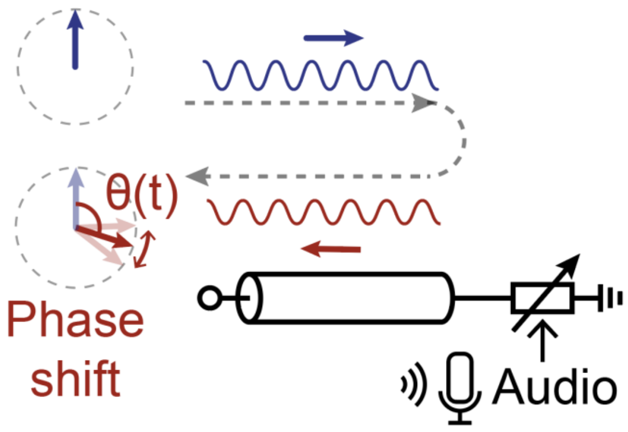


Design the *modulation scheme* to tackle the interference

Tag Design

➢ ***In-band analog backscatter***

Analog backscatter



A *phase shifter* for analog phase modulation.

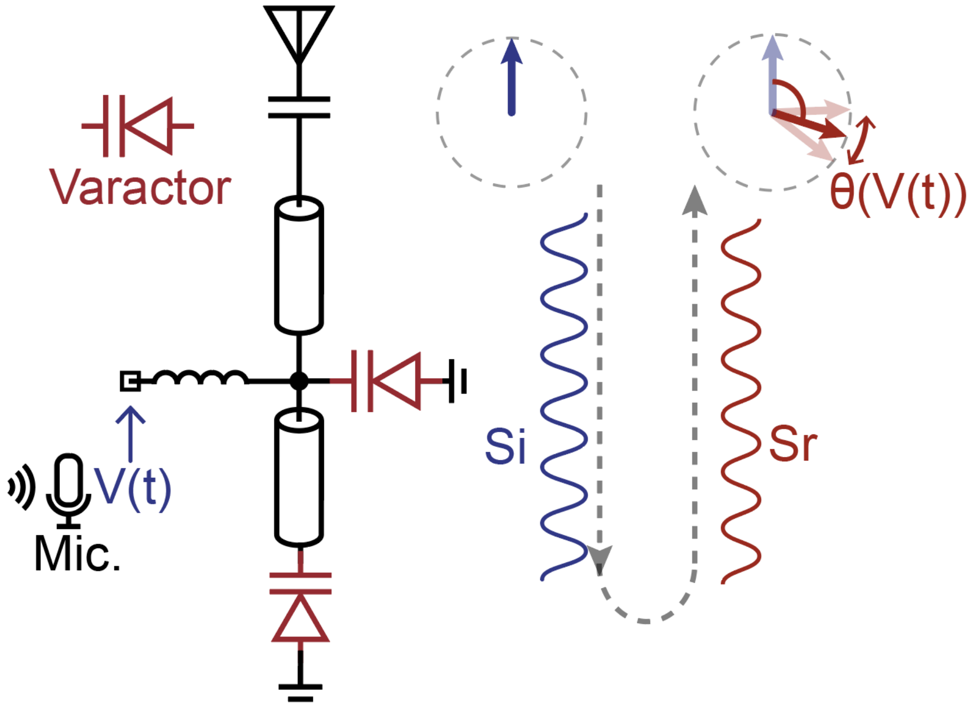
In-band backscatter

Explore the *in-band backscatter channel*

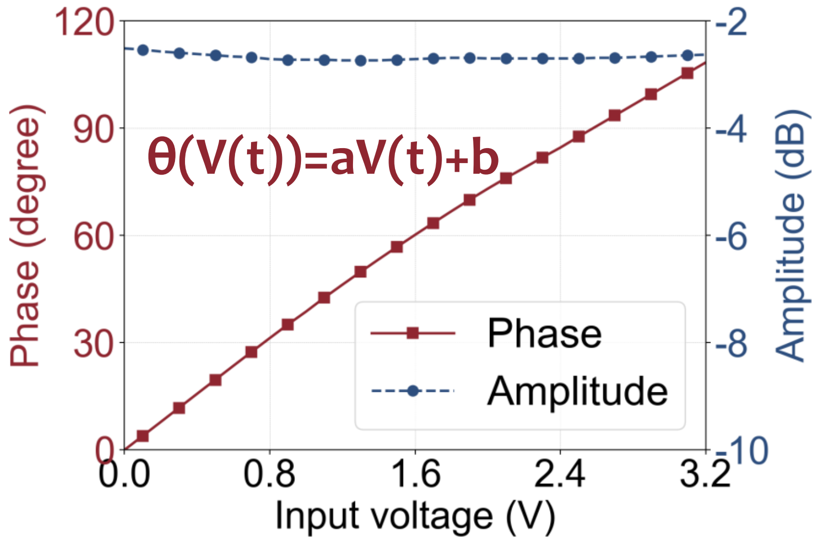
Design the *modulation scheme* to tackle the interference

Phase Shifter

Structure of the phase shifter



Accurate audio embedding



- The reflected phase is nearly linear with the voltage.

Satori leverages the phase shifter to achieve *accurate analog audio embedding* while *minimizing power consumption*.

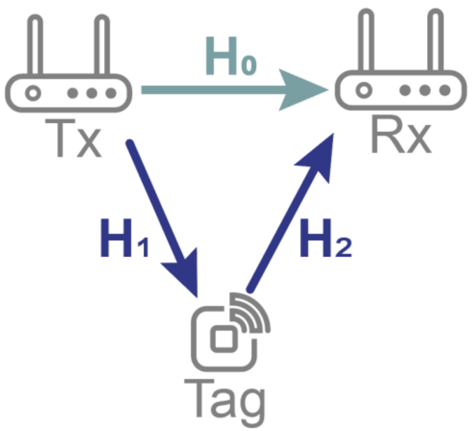
Tag Design

➢ ***In-band analog backscatter***

Analog backscatter

A *Phase shifter* for analog phase modulation.

In-band backscatter

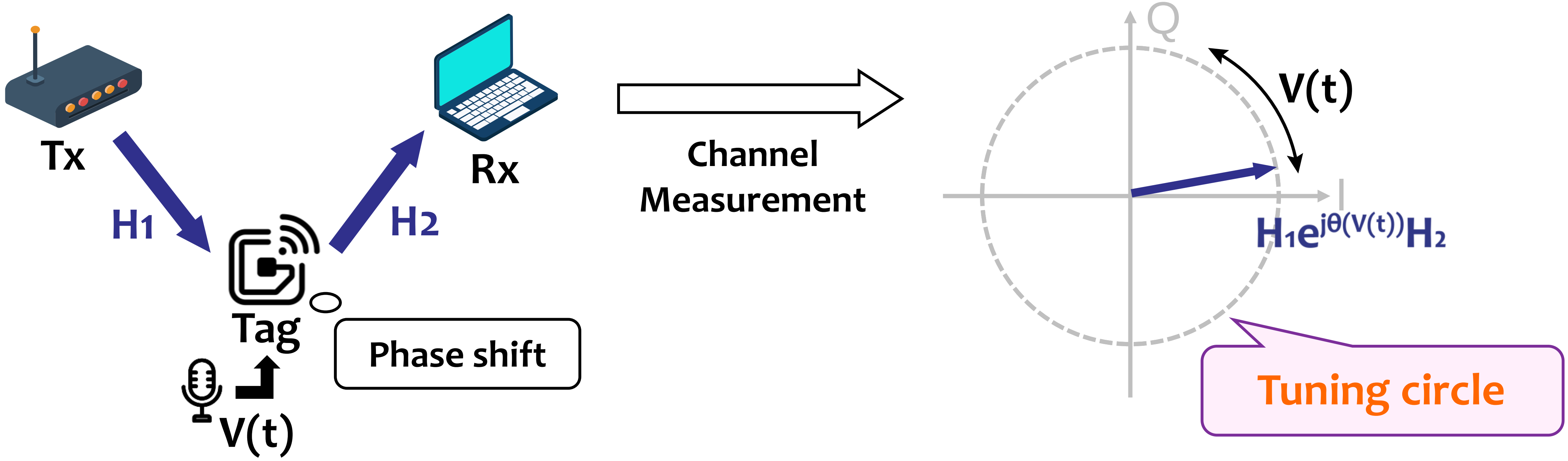


Explore the *in-band backscatter channel*

Design the *modulation scheme* to tackle the interference

Modeling the Channel

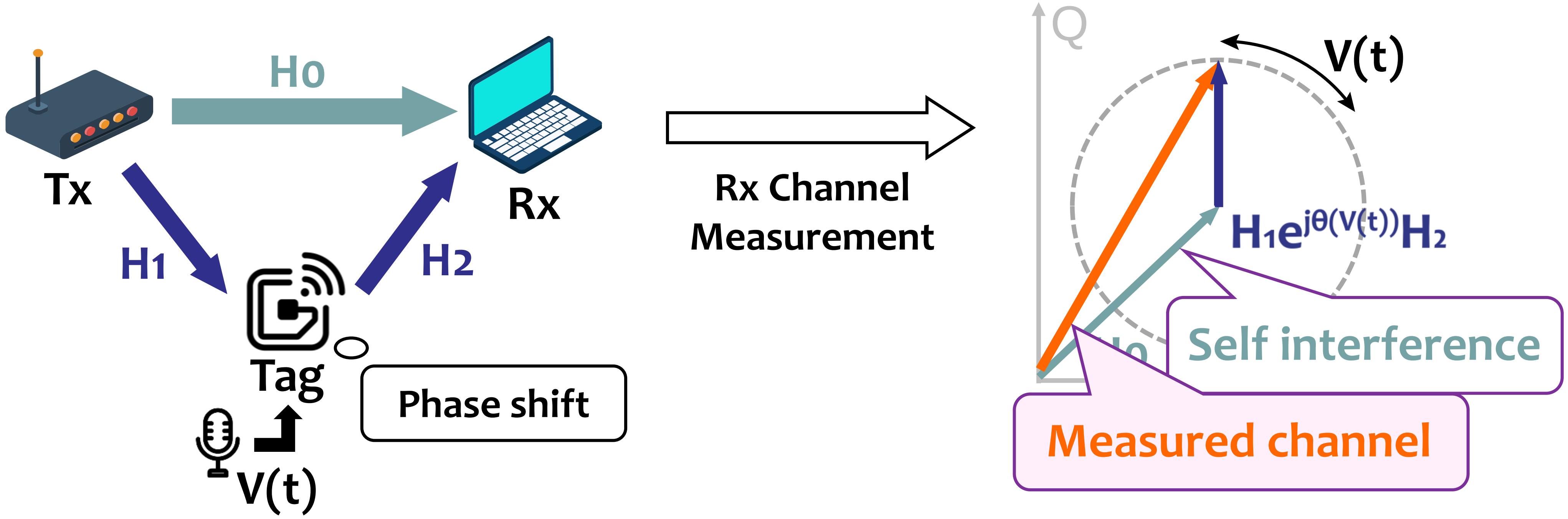
Channel model of the backscattered signal



The tuning circle represents the backscatter tag's phase shift effect on the wireless channel.

In-band Backscatter Channel

Channel model of in-band backscatter



- ➢ One channel measurement alone can't extract the tag's phase modulation.
- ➢ The tag should provide at least three points with distinct phases.

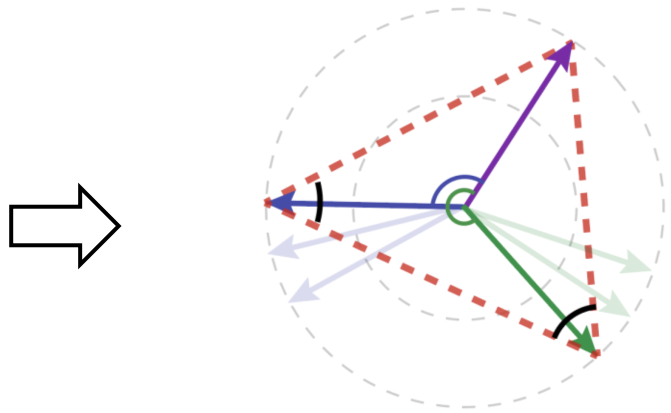
Tag Design

➤ ***In-band analog backscatter***

Analog backscatter

A *Phase shifter* for analog phase modulation.

In-band backscatter

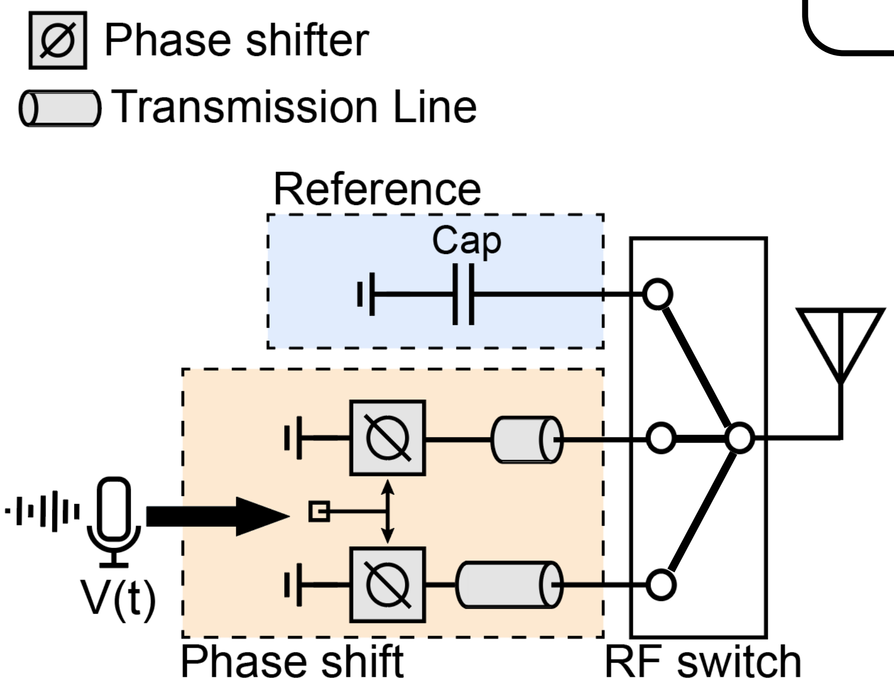


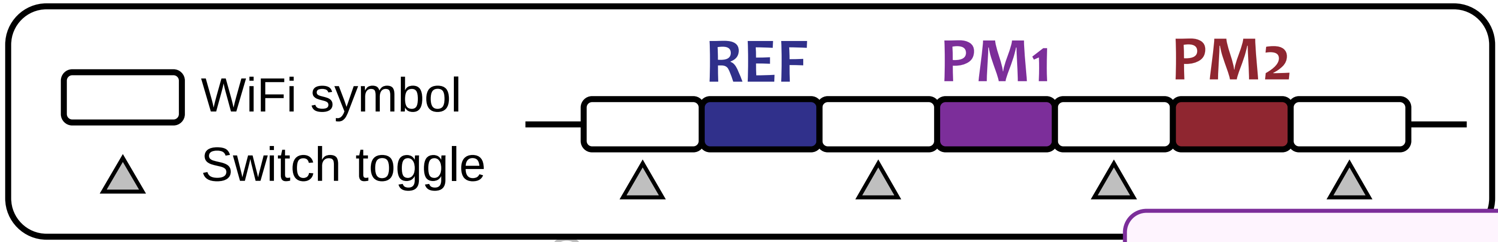
Explore the *in-band backscatter channel*

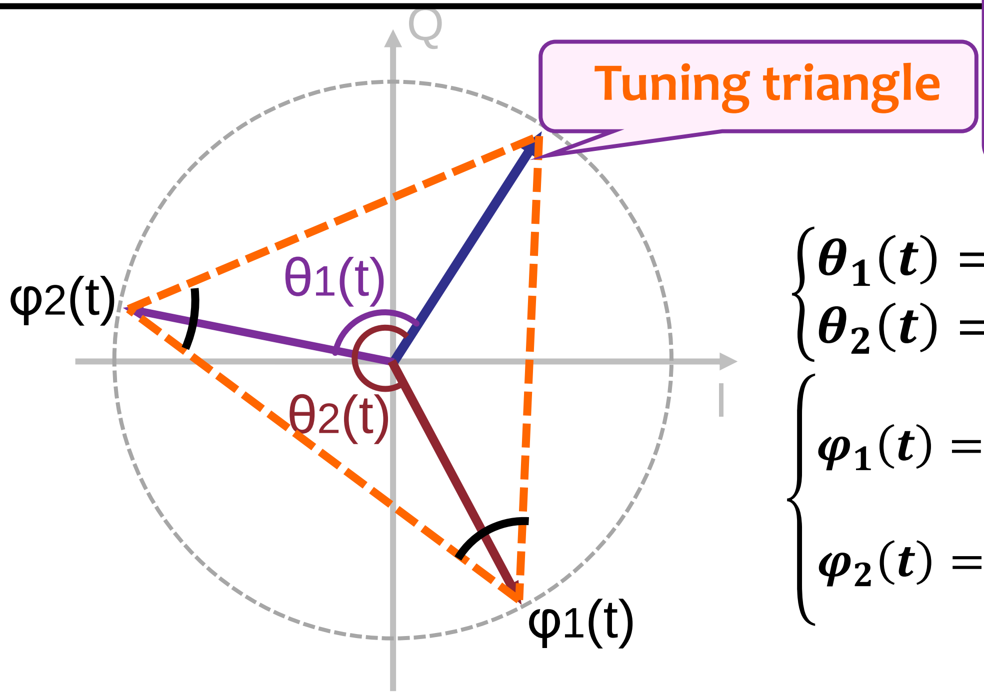
Design the *modulation scheme* to tackle the interference

In-band Analog Modulation

Satori tag







Embedding rate
41.67 kHz

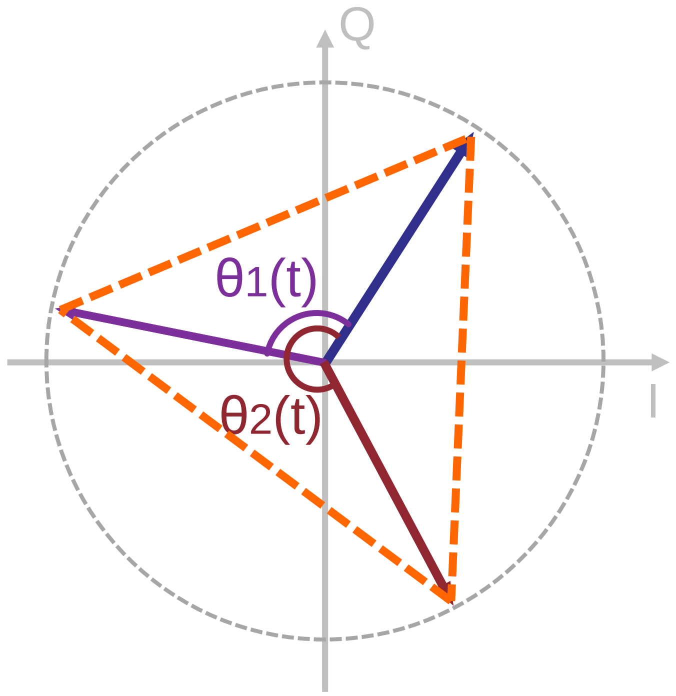
$$\begin{cases} \theta_1(t) = a_1 V(t) + b_1 \\ \theta_2(t) = a_2 V(t) + b_2 \end{cases}$$

$$\begin{cases} \varphi_1(t) = \frac{1}{2}\theta_1(t) \\ \varphi_2(t) = \frac{1}{2}(2\pi - \theta_2(t)) \end{cases}$$

The analog audio signal is carried in the internal angles of the tuning triangle formed by the three symbols.

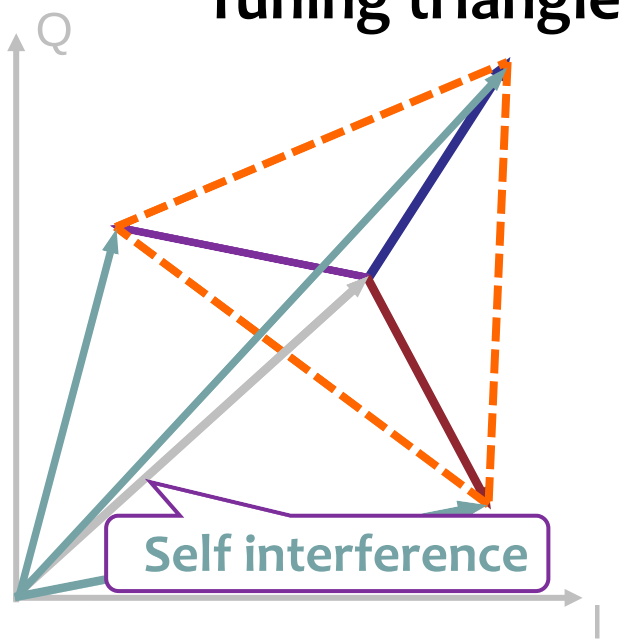
In-band Analog Modulation

Consider the in-band transmission



Add self-interference

Tuning triangle is unchanged.

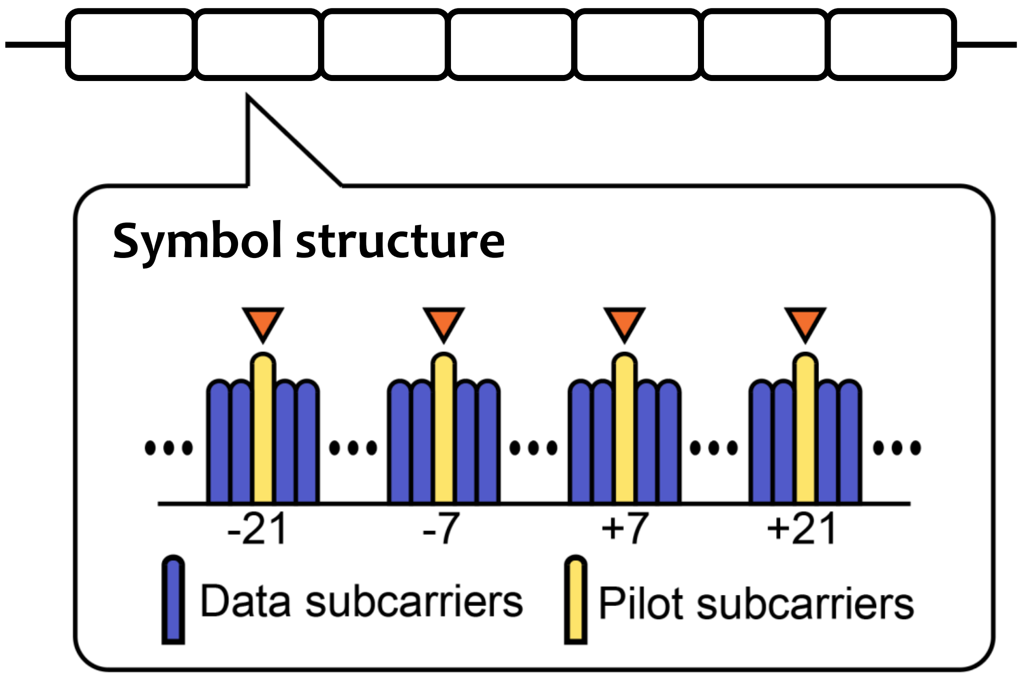


The tuning triangle can reliably carry the audio signal in the in-band backscatter transmission with self-interference.

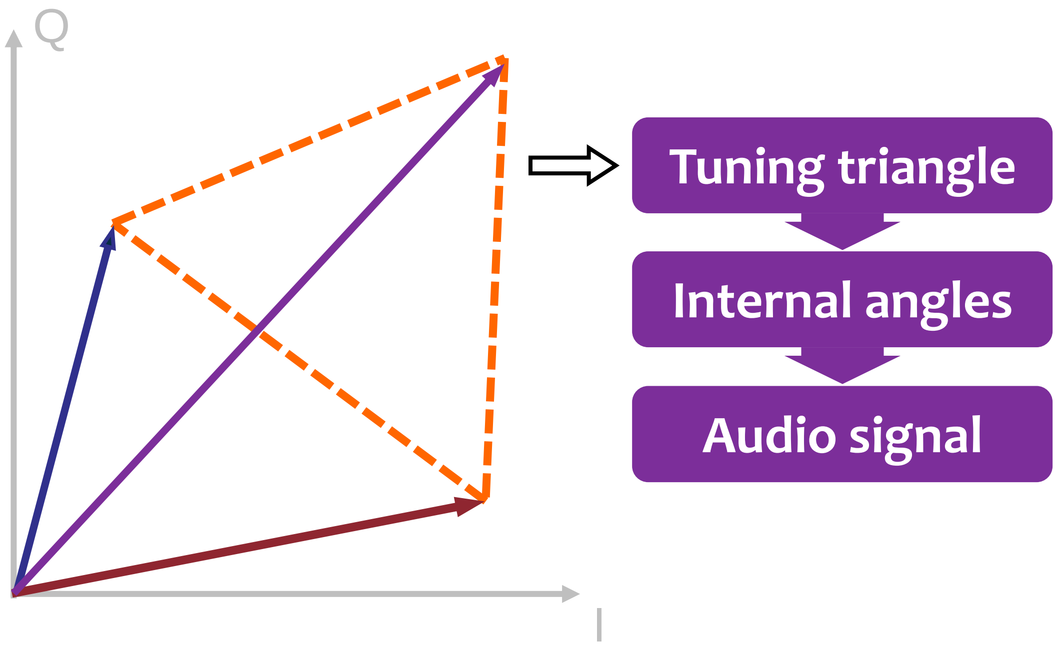
Satori Receiver Design

Receiving process

Received WiFi symbols



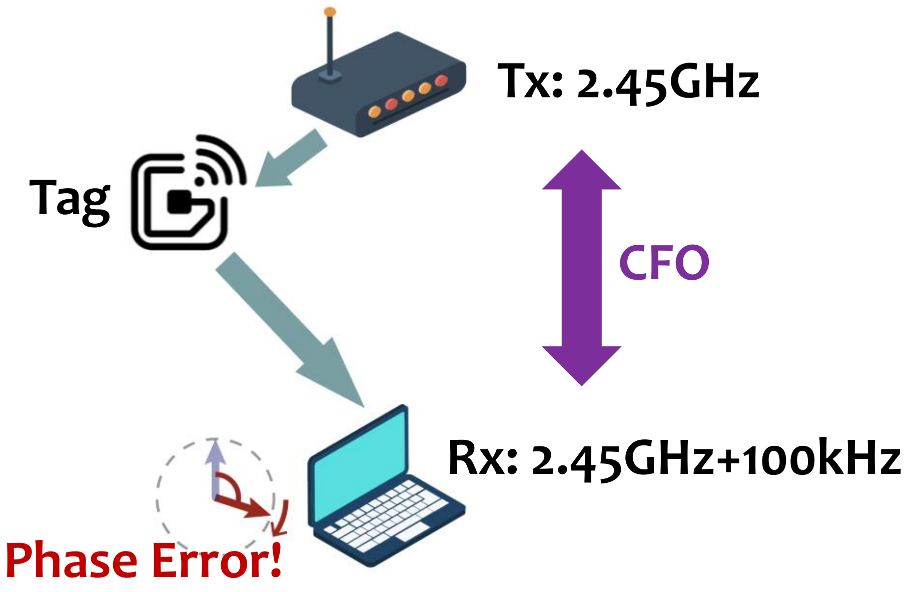
Estimated channel:



- ➢ Leverage four pilot subcarriers for per-symbol channel estimation.
- ➢ Extract the tuning triangle from the estimated channel and recover the audio signal.

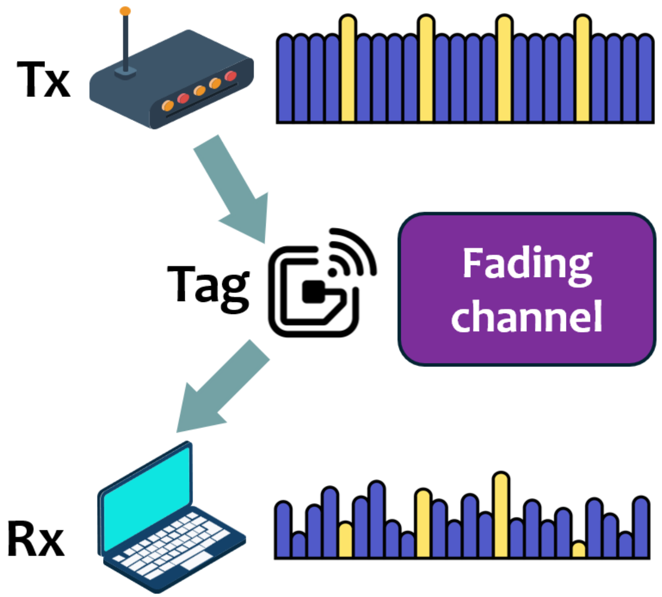
Problems

Carrier frequency offset



Carrier frequency offset causes continuous phase rotation.

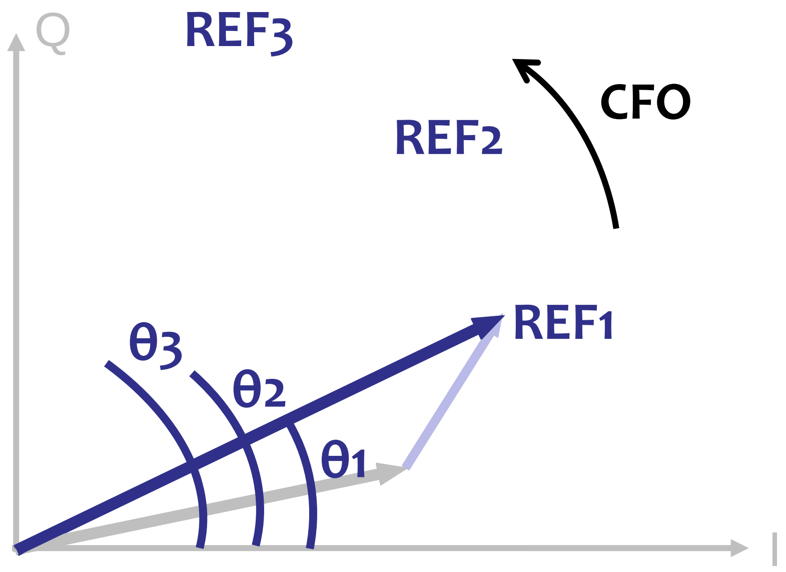
Deep fading



Deep channel fading severely attenuates the backscattered signals.

2-steps CFO Calibration

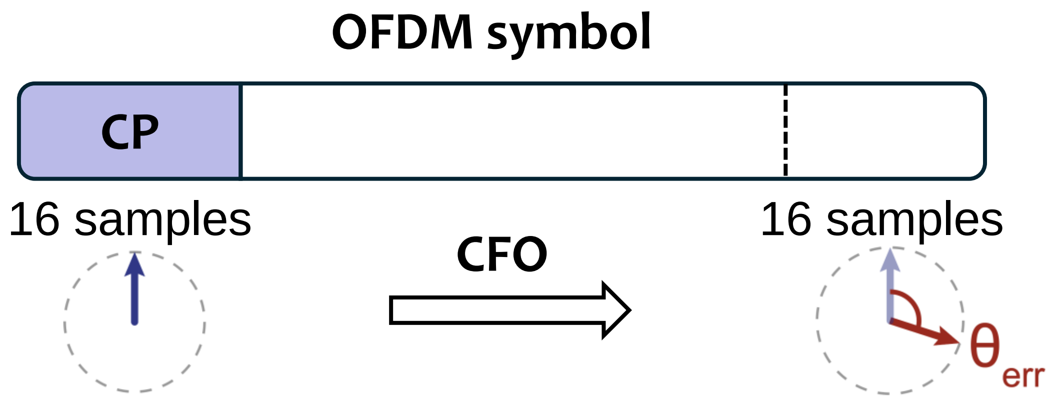
- **Average CFO calibration**



- $\boldsymbol{\theta_i \approx 2\pi \times f_{cfo} \times i \times T + \theta_0}$

Use the linear fitting method to estimate the average CFO.

- **Fluctuating CFO calibration**



Relationship between θ_{err} and CFO:

$$\theta_{err} = \angle\left(\sum_{t=1}^{16} x[t]x^*[t+64]\right)$$
$$\approx 2\pi \times f_{cfo} \times 3.6\mu s$$

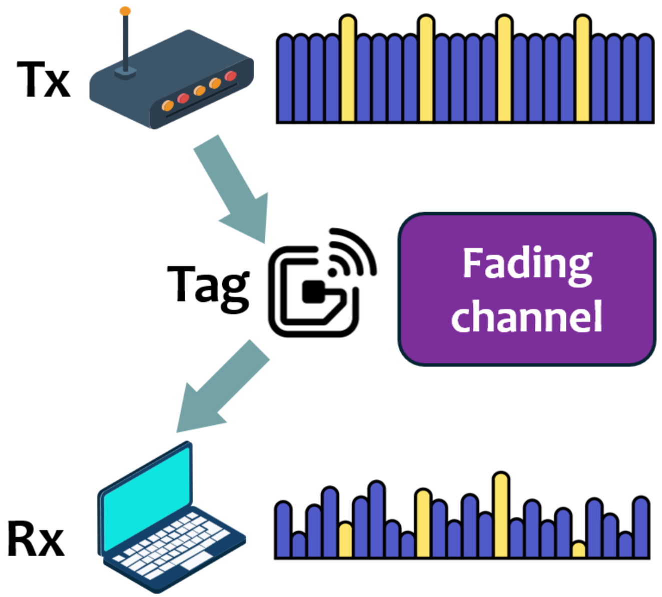
Use the cyclic prefix (CP) to estimate the fluctuating CFO symbol by symbol.

Problems

Carrier frequency offset

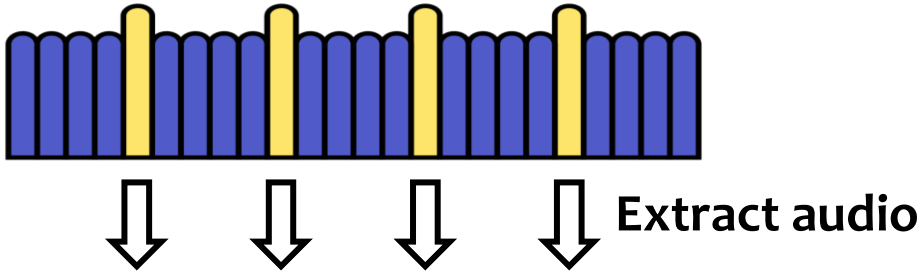
Carrier frequency offset introduces phase error.

Deep fading



Deep fading severely weaken the backscattered signals.

Fading-adaptive Audio Recovery

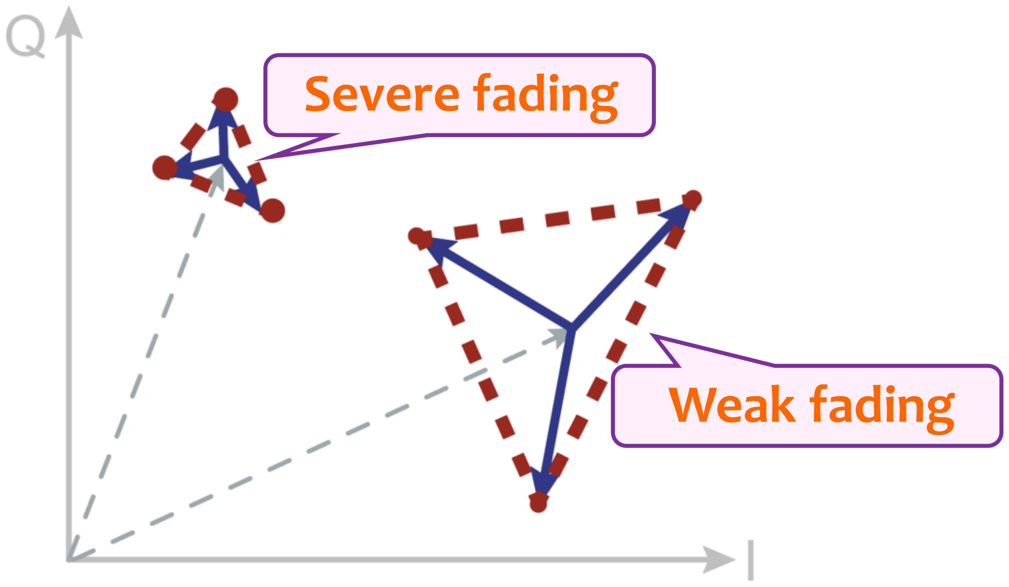


$V_1(t)$ $V_2(t)$ $V_3(t)$ $V_4(t)$

$$V(t) = \frac{\sum_{i=1}^{4} \omega_i V_i(t)}{\sum_{i=1}^{4} \omega_i}$$

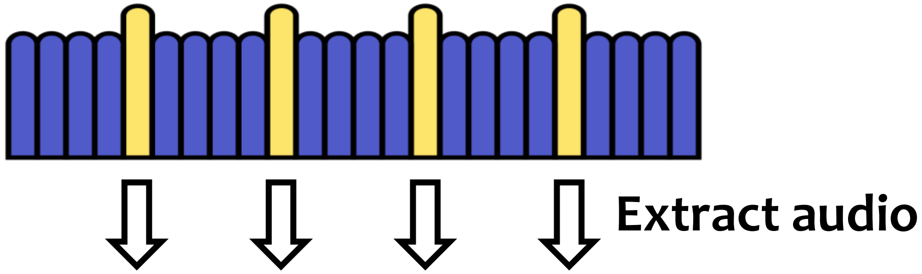
Assign lower ω_i to pilots with deeper fading.

How to determine ω_i ?



Severe fading leads to smaller tuning triangles.

Fading-adaptive Audio Recovery



$V_1(t)\ V_2(t)\ V_3(t)\ V_4(t)$

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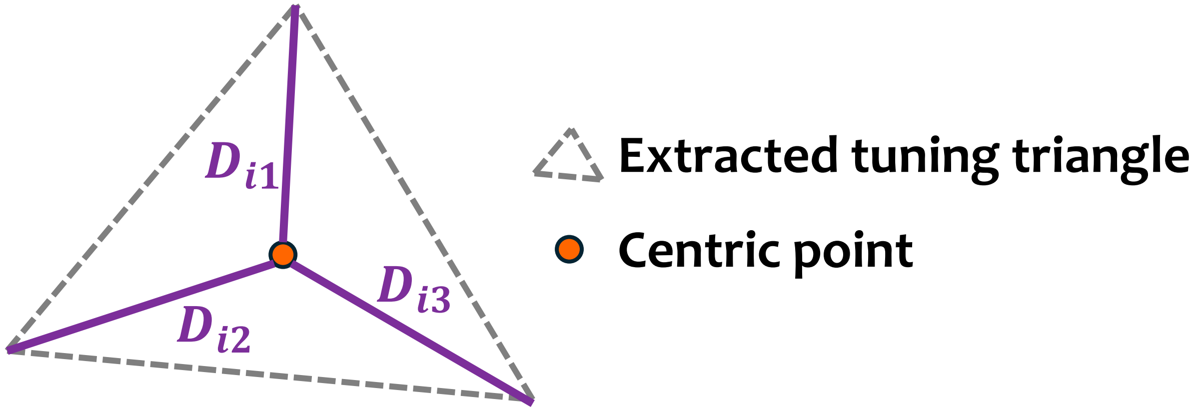


Weight assignment:

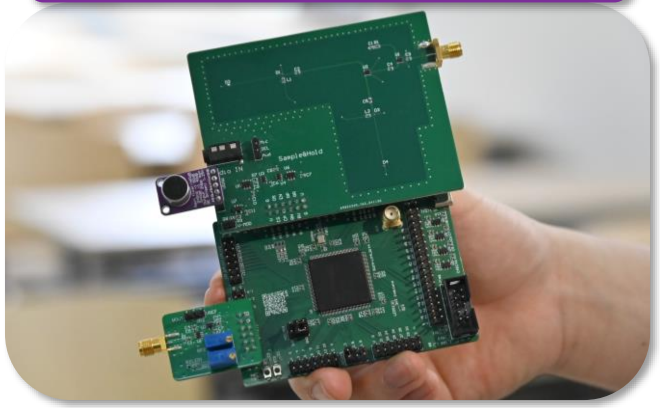
$\omega_i = D_{i1} + D_{i2} + D_{i3}$

The fading-adaptive audio recovery improves robustness against deep fading.

Implementation & Evaluation

Implementation

Satori Tag Prototype



- The prototype is implemented on a 4-layer printed circuit board (PCB) with commercial components.
- 2 simple RF switches and 4 varactors for in-band analog modulation consume uW-level power.

- The transceivers are implemented with USRP B210/N210 SDR.
- The transmitter sends *802.11n signals* generated by MATLAB Wireless Waveform Generator.

Evaluation Setup

Transceiver

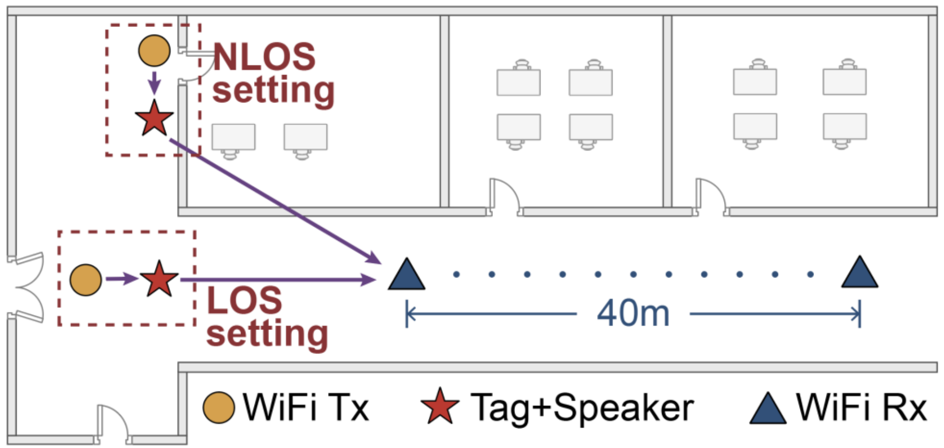
- Implemented with USRP
- Transmission power: 20 dBm
- Antenna: 6 dBi gain
- Signal: IEEE 802.11n packets

Tag

- Antenna: 6 dBi gain
- Tx-to-Tag distance: 0.5m (default)
- Varying Tag-to-Rx distance.

Audio

- Two speakers generate audio signals
- Audio frequency: 200~3600 Hz
- Audio data rate: 320 kbps

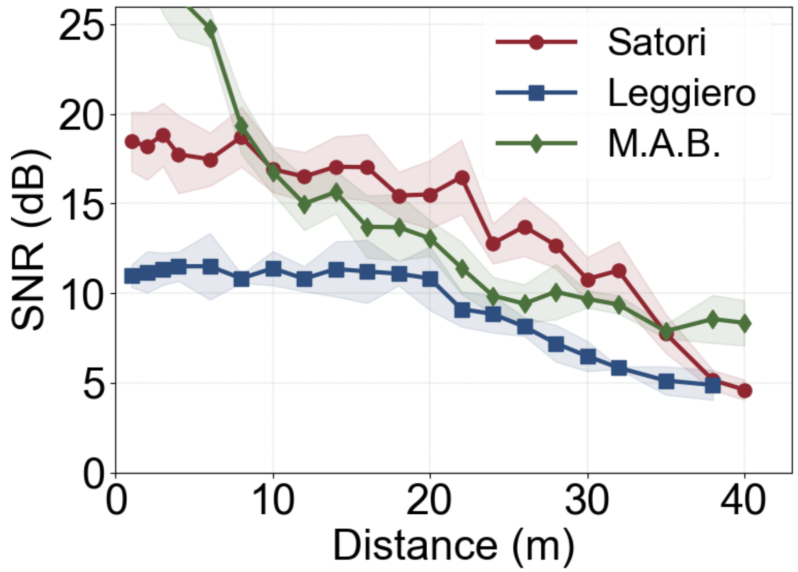


Floorplan of the experiment environment.

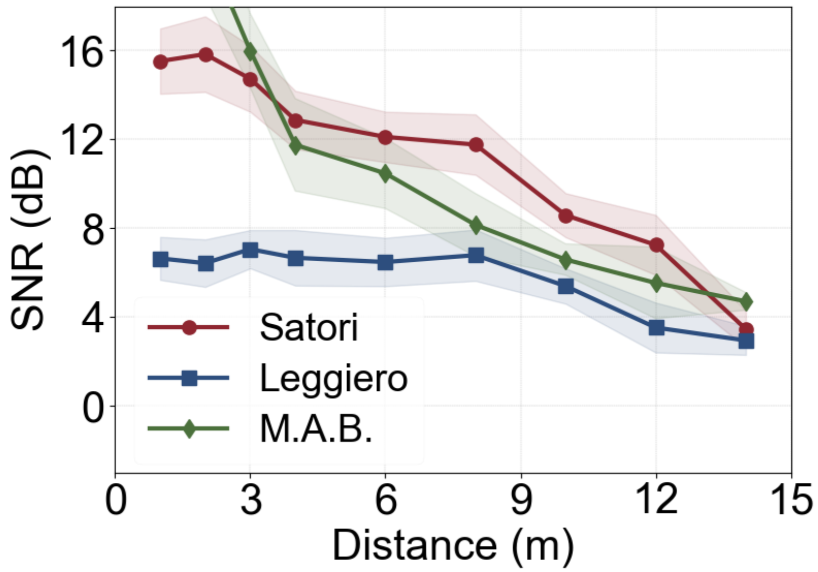
Key Metric: SNR of the received audio

Evaluation: SNR

SNR in LOS scenarios



SNR in NLOS scenarios

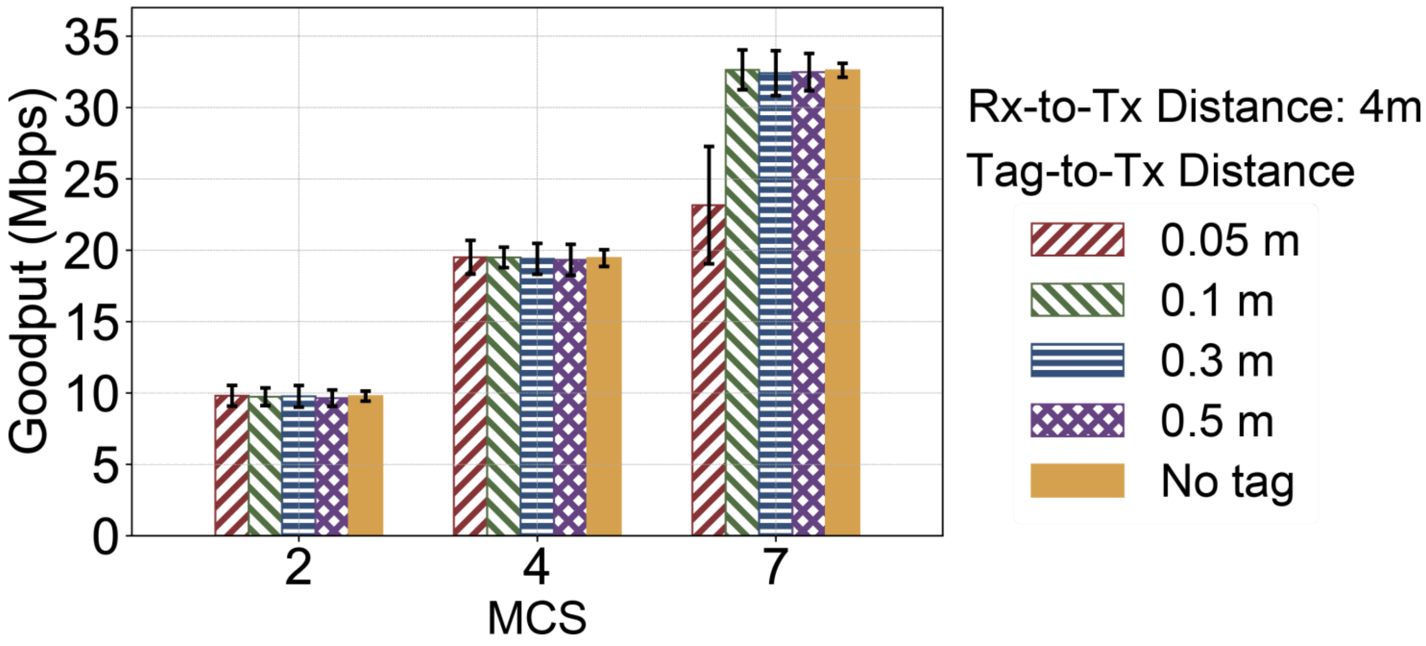


Satori supports transmission range of *35 m* and achieves an SNR exceeding *18 dB*.

[Leggiero]: Xin Na, Xiuzhen Guo, Zihao Yu, Jia Zhang, Yuan He, and Yunhao Liu. Leggiero: Analog WiFi Backscatter with Payload Transparency. ACM Mobisys 2023.

[M.A.B.]: Jia Zhao, Wei Gong, and Jiangchuan Liu. 2021. Microphone array backscatter: An application-driven design for lightweight spatial sound recording over the air. ACM MobiCom 2021

Evaluation: Impact on WiFi Traffic

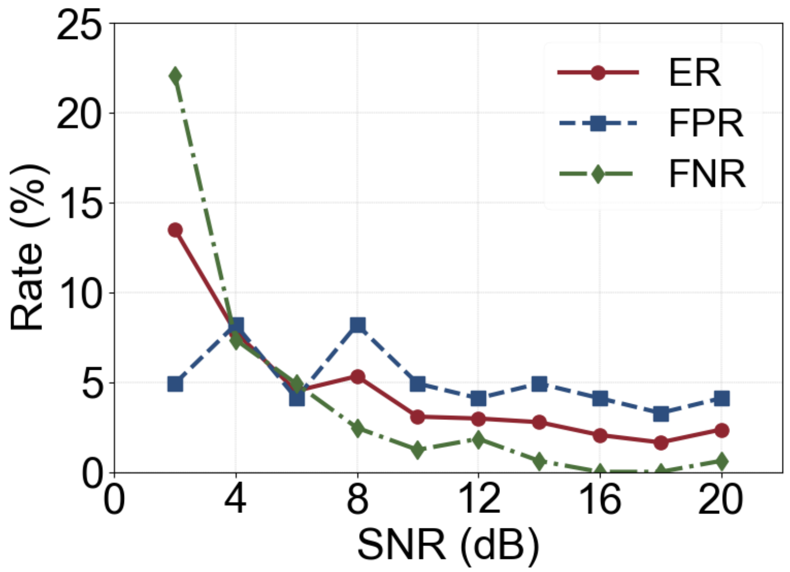


- **Goodput fluctuation is less than 1% when Tag-to-Tx > 0.1m.**
- **Goodput decreases only when the tag is very close to Tx and MCS is high.**

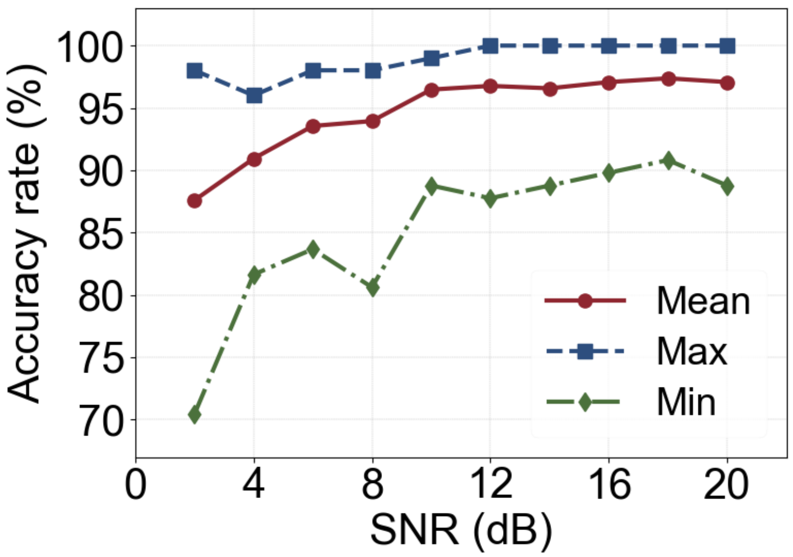
Satori does not significantly impact WiFi traffic across most distance and MCS settings.

Proof-of-concept Application

Machine Failure Detection



Speech Command Recognition



- The audio transmitted by Satori can be accurately recognized.
- Satori effectively supports downstream audio sensing tasks.

Datasets:

[Machine Failure Detection]: Purohit Harsh, Tanabe Ryo, Ichige Kenji, Endo Takashi, Nikaido Yuki, Suefusa Kaori, and Kawaguchi Yohei. MIMII Dataset: Sound Dataset for Malfunctioning Industrial Machine Investigation and Inspection. DCASE 2019.

[Speech Command Recognition]: Pete Warden. Speech commands: A dataset for limited-vocabulary speech recognition. arXiv preprint 2018.

Conclusion

- We propose Satori, an in-band analog backscatter that enables ultra-low-power audio transmission.
- Satori transmits audio at a 41.67 kHz embedding rate, achieve an SNR exceeding 18 dB , and supports transmission distances more than 35 m.
- Satori follows the paradigm of RF computing, offering a direct manipulation from analog audio to the phase of RF signals.

Yang Zou

Xin Na

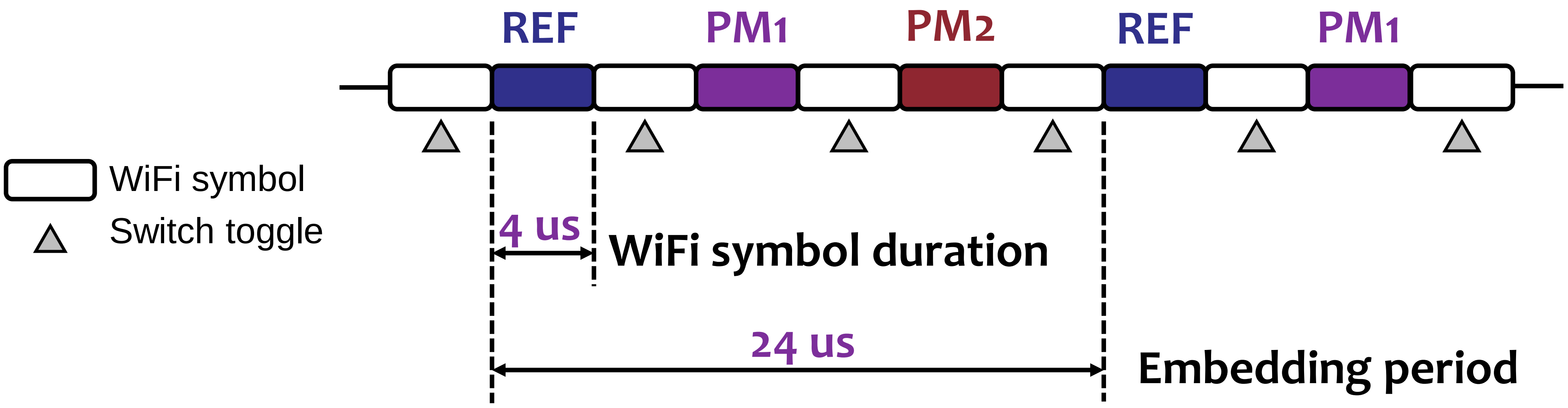
Yimiao Sun

Yande Chen

Yuan He

Please find more details in: http://tns.thss.tsinghua.edu.cn/sun/ https://ling-yanghui.github.io/

Embedding Rate

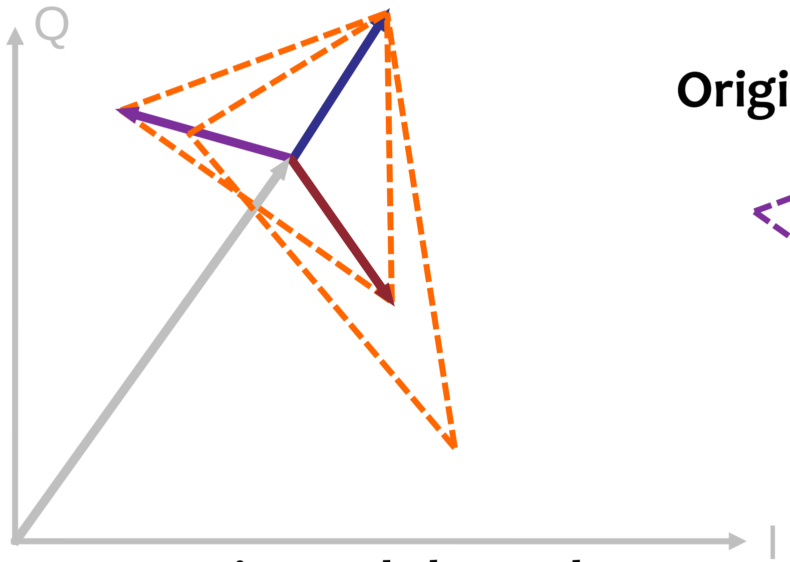


- Satori takes 6 WiFi symbols to embed one audio signal sample.
- It achieves a sampling rate of 41.67 kHz, sufficient for audio signal of 20Hz~20kHz.

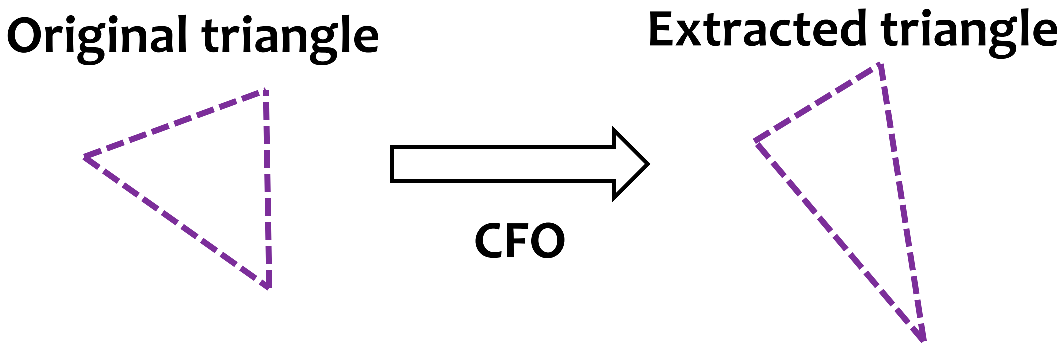
CFO Problems

Carrier frequency offset (CFO) introduces phase error:

$$\theta_{err}(t) = \int 2\pi f_{cfo}(t)\, d_t$$



Estimated channel



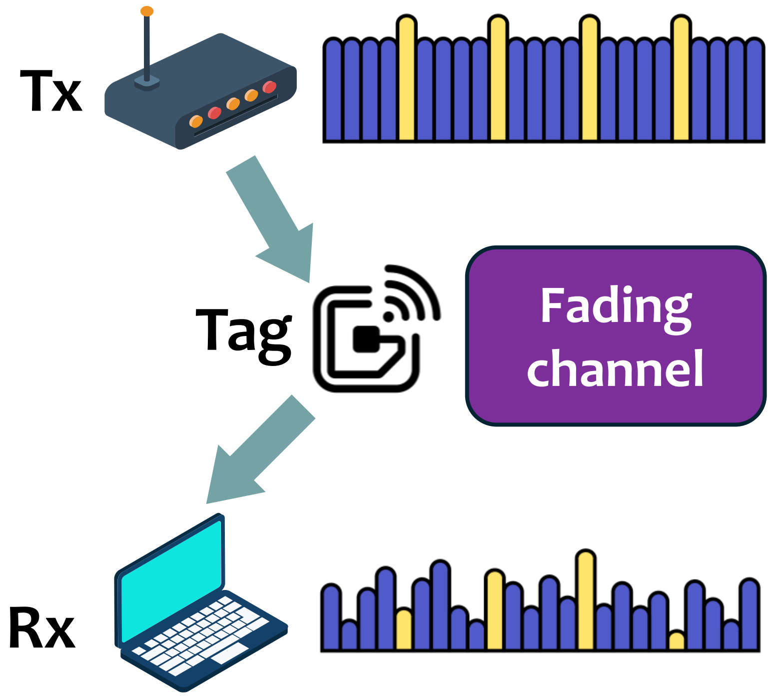
Triangle deformation!

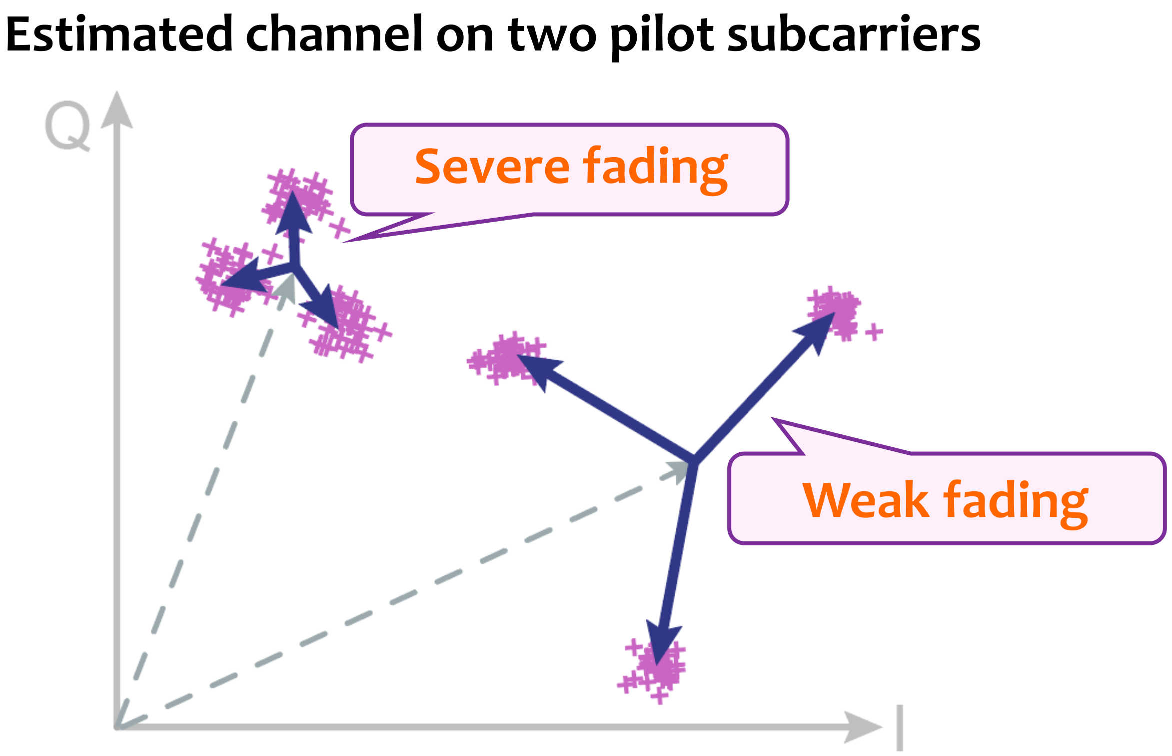
⇩

Audio error

The phase error caused by the CFO causes the deformation of the extracted tuning triangles, leading to audio recovery failure.

Deep Fading





The channel fading significantly weakens some pilot subcarriers, making the tuning triangle severely affected by the noise.