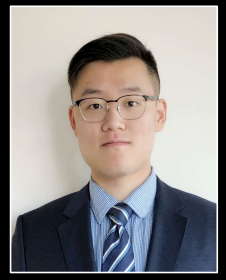
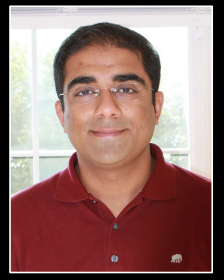
mmComb: High-speed mmWave Commodity WiFi Backscatter

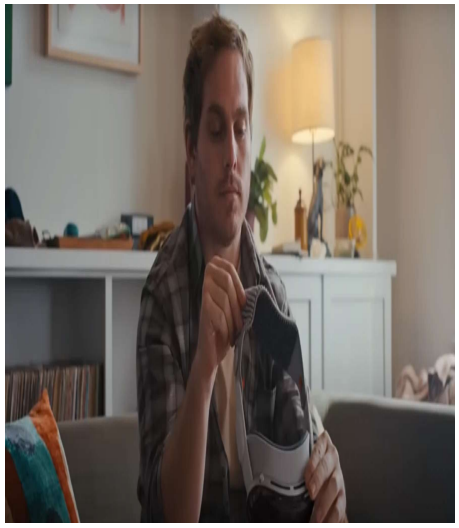
Yoon Chae † Zhenzhe Lin † Kang Min Bae § Song Min Kim § Parth Pathak †

† GEORGE MASON UNIVERSITY § KAIST

nsdi '24

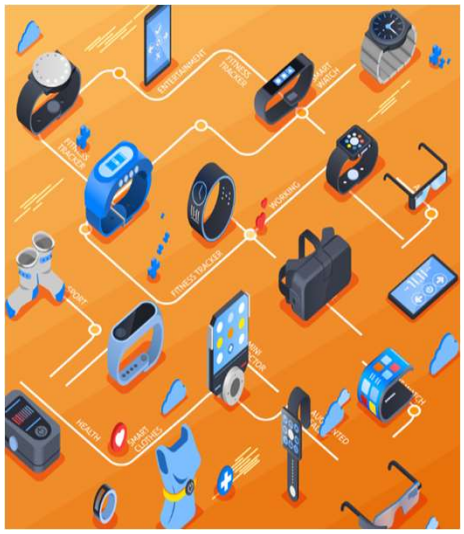
Today's Wireless Networks and Mobile Systems

High-speed (Gbps)



5G, 6G, 802.11ad, 802.11ay..

Low-power (<100uW)



RFID, Lora WAN, ZigBee..

Today's Wireless Networks and Mobile Systems

High-speed (Gbps)

Power hungry devices
(WiFi: 2-20 W)

5G, 6G, 802.11ad, 802.11ay..

Low-power (<100uW)

Low data rate
(RFID: 40 kbps)

RFID, Lora WAN, ZigBee..

High-speed (> Mbps)

&

High-power consumption (20W)

Low-speed (40 kbps)

&

Low power (uW) consumption

High-speed (> Mbps)

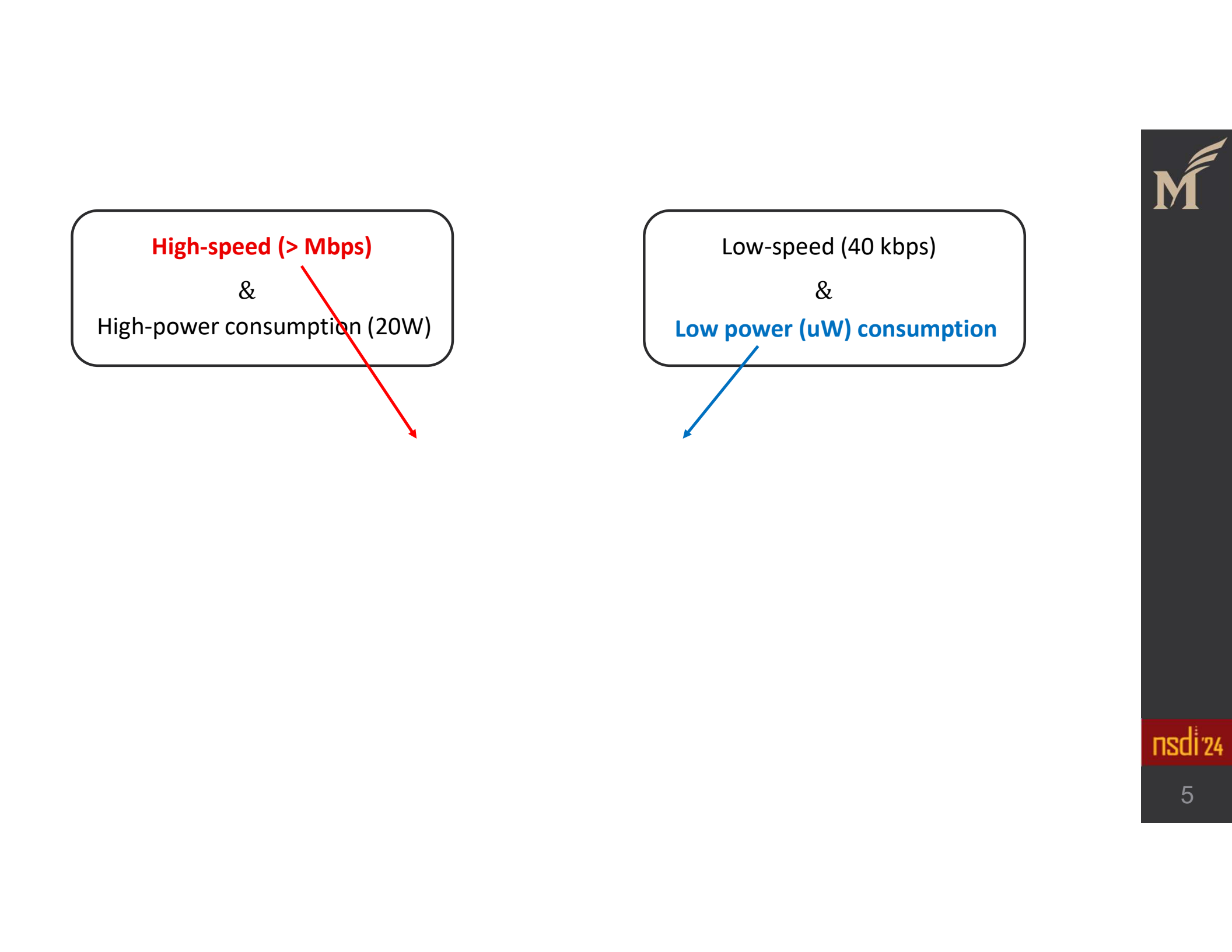
&

High-power consumption (20W)

Low-speed (40 kbps)

&

Low power (uW) consumption



&

High-power consumption (20W)

Low-speed (40 kbps)

&

High-speed (> Mbps) **Low power (uW) consumption**

&

High-power consumption (20W)

Low-speed (40 kbps)

&

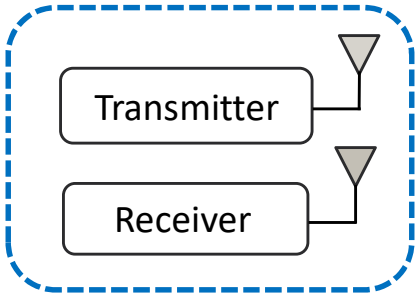
High-speed (> Mbps) **Low power (uW) consumption**

"mmWave backscatter"

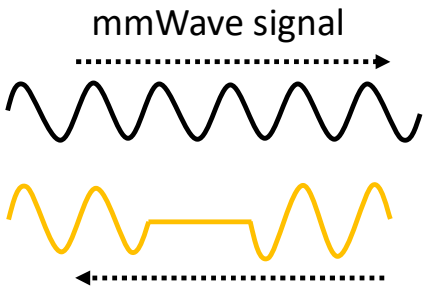
Large bandwidth & High data rate (up to 55 Mbps)

Ultra low power consumption (<100uW)

Existing mmWave Backscatter Systems



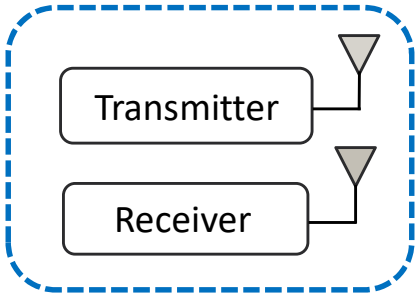
mmWave reader



Modulated, reradiated signal

mmWave Tag

Existing mmWave Backscatter Systems



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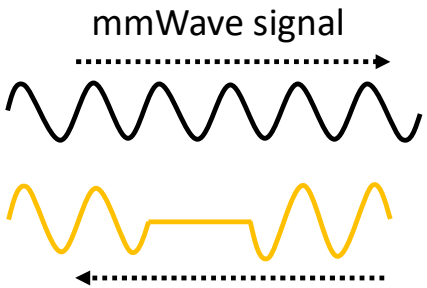
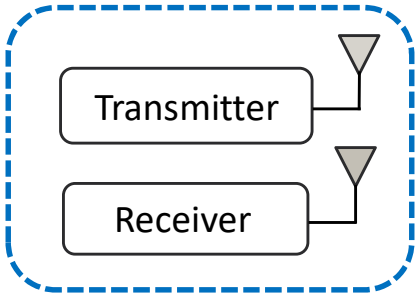


Modulated, reradiated signal

mmWave Tag

Systems	Data rate	Reader type
MilleMetro [Mobicom ’21]	Low	FMCW radar
Omniscatter [MobiSys ’22]	Low	FMCW radar
mmX [Sigcomm ’19]	High	Non-commodity reader
mmTag [Sigcomm ’21]	High	Non-commodity reader

Existing mmWave Backscatter Systems



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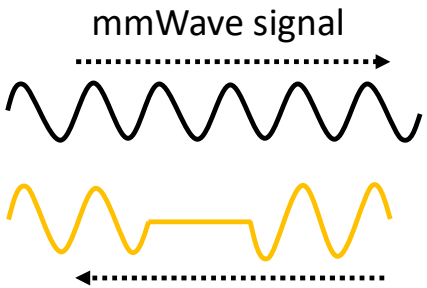

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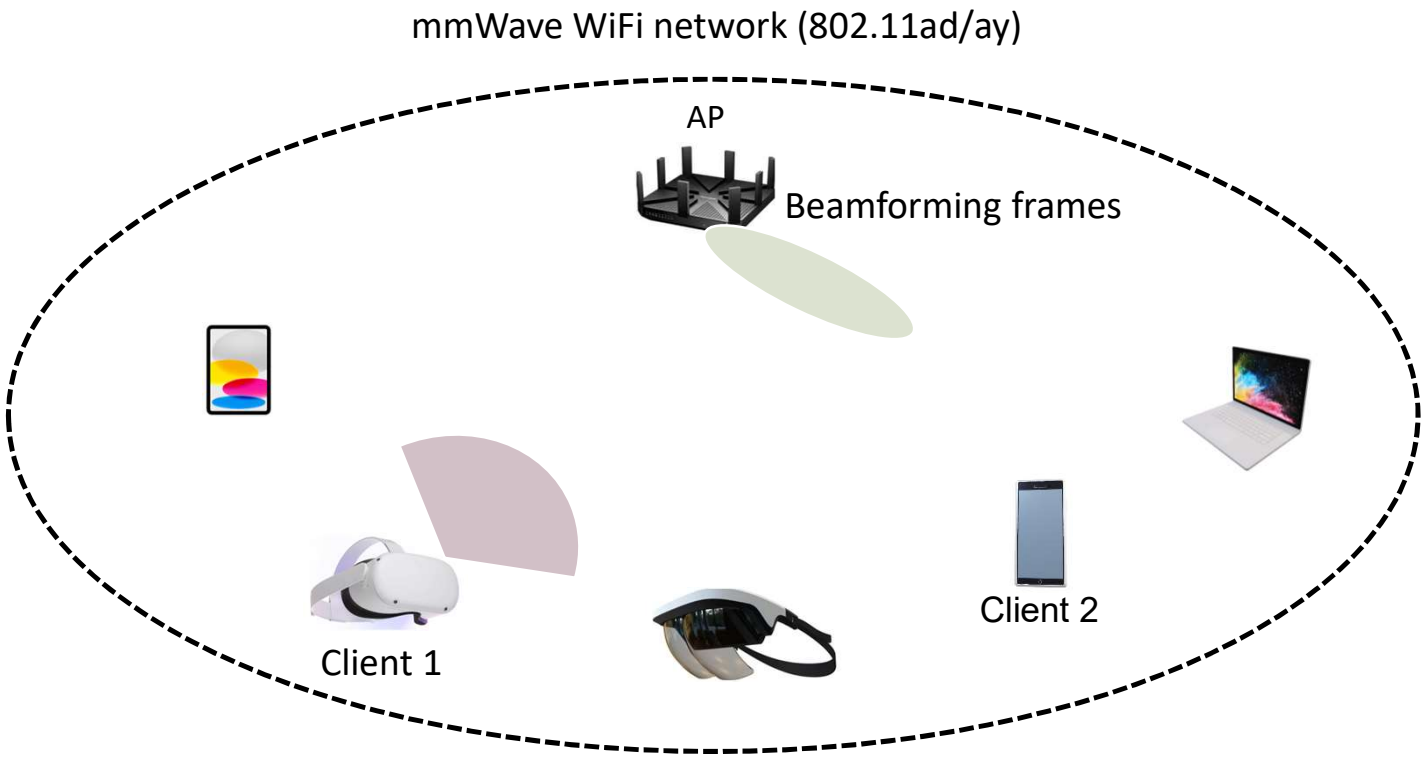
mmComb	High	Commodity off-the-shelf mmWave WiFi devices

Beamforming in mmWave WiFi

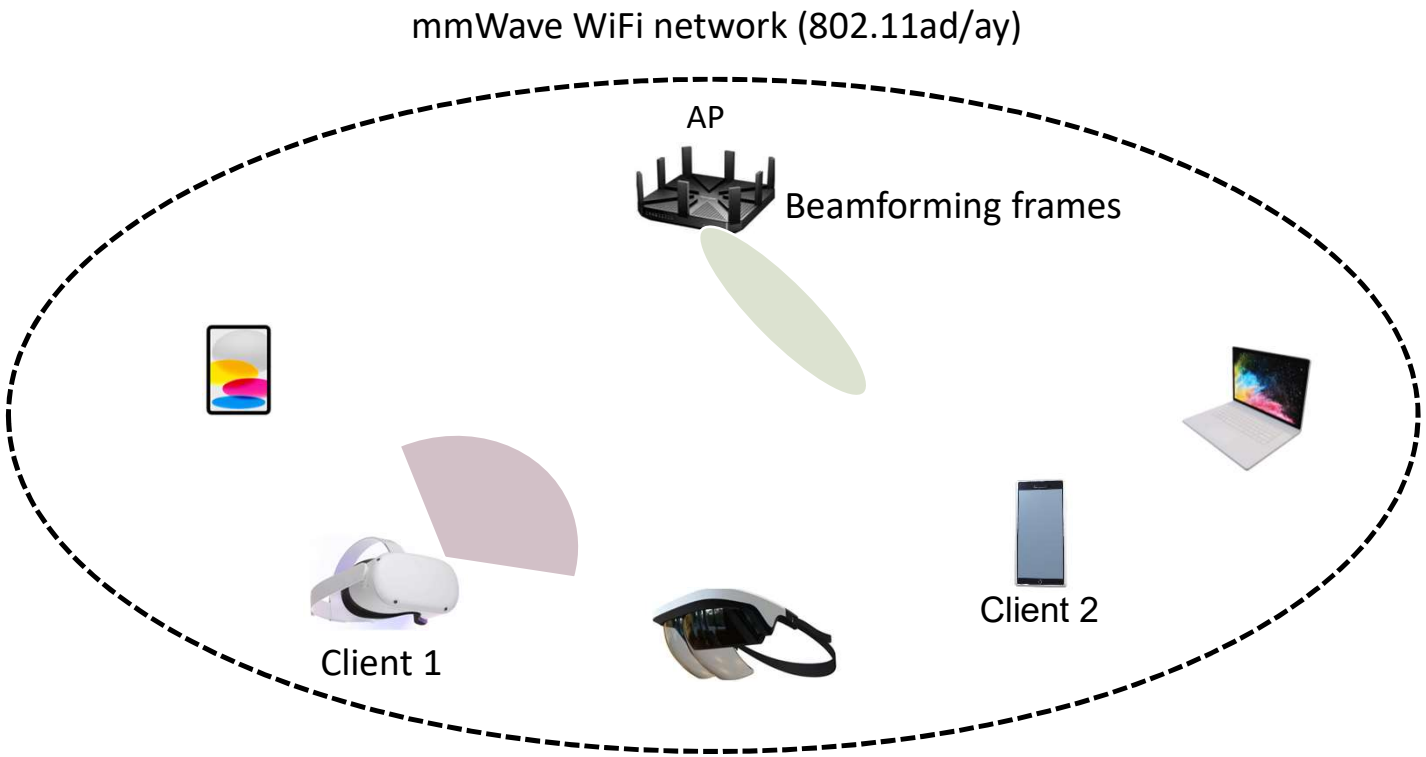


Directional transmit(TX) beam

Quasi-omni receive beam

Use of beamforming to deal with high attenuations at mmWave frequencies

Beamforming in mmWave WiFi



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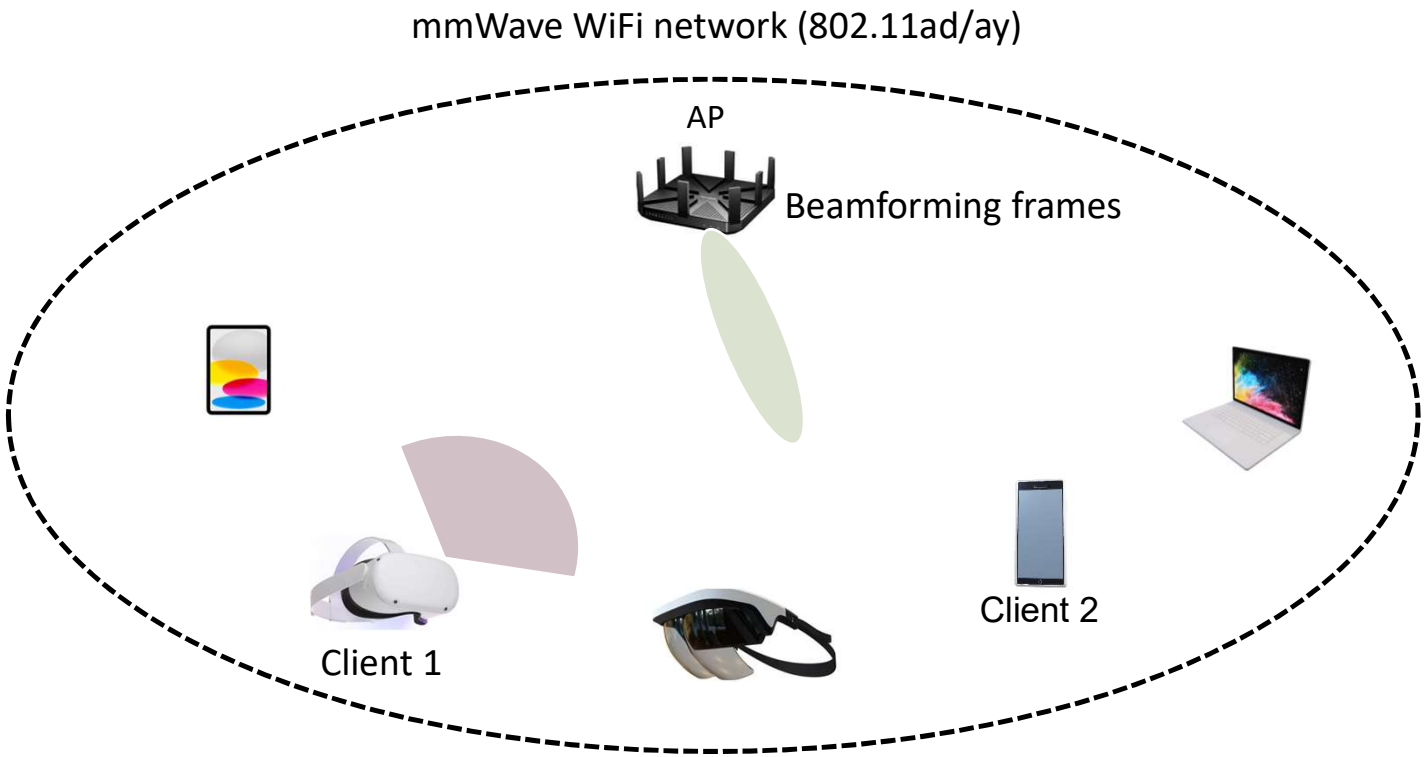

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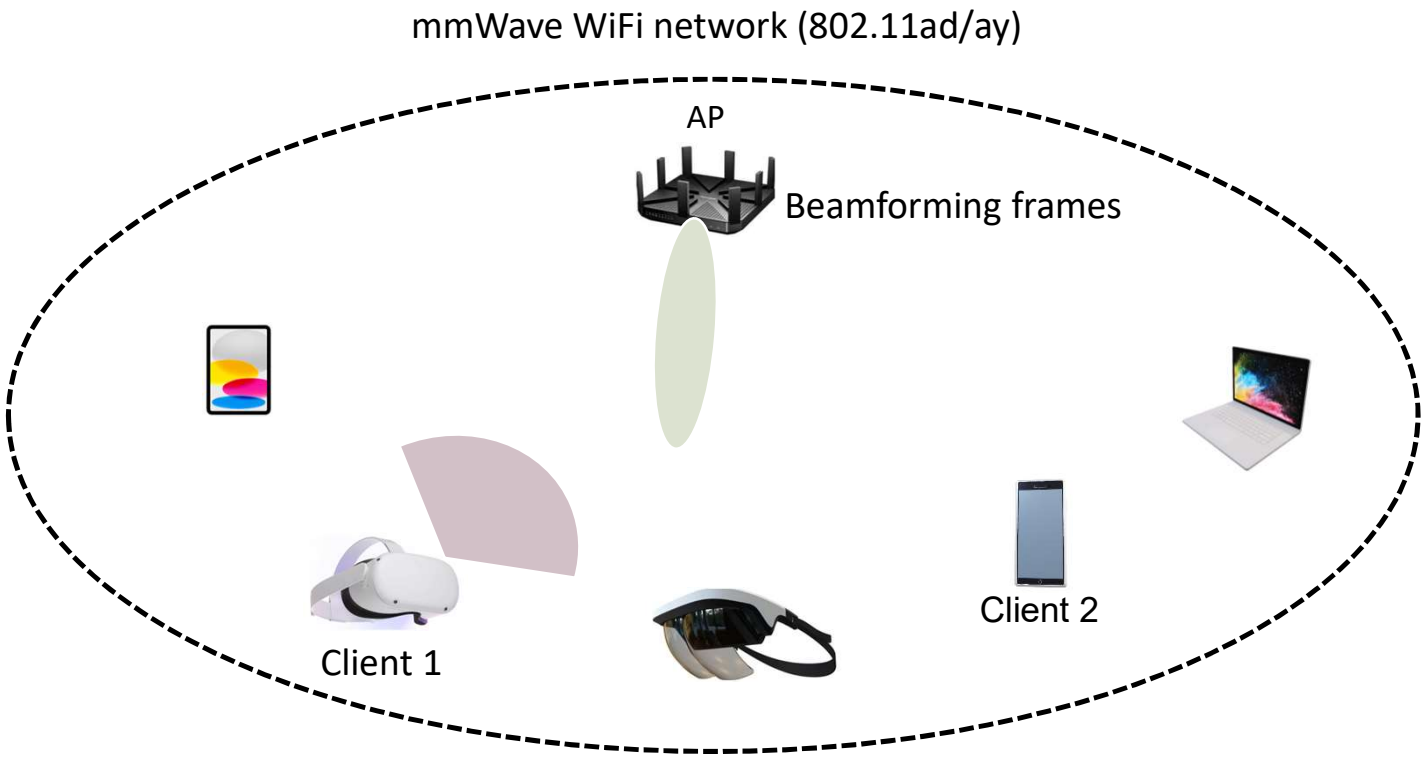

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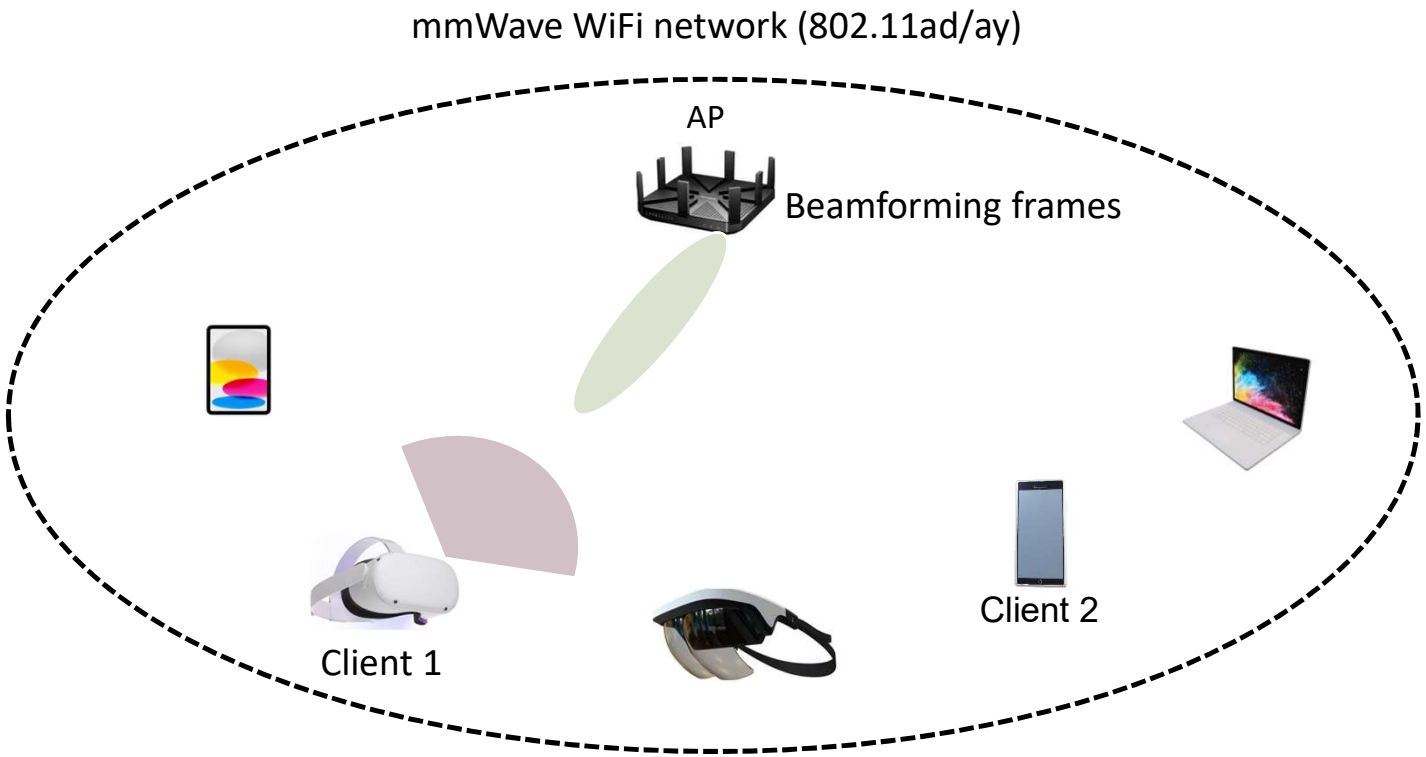

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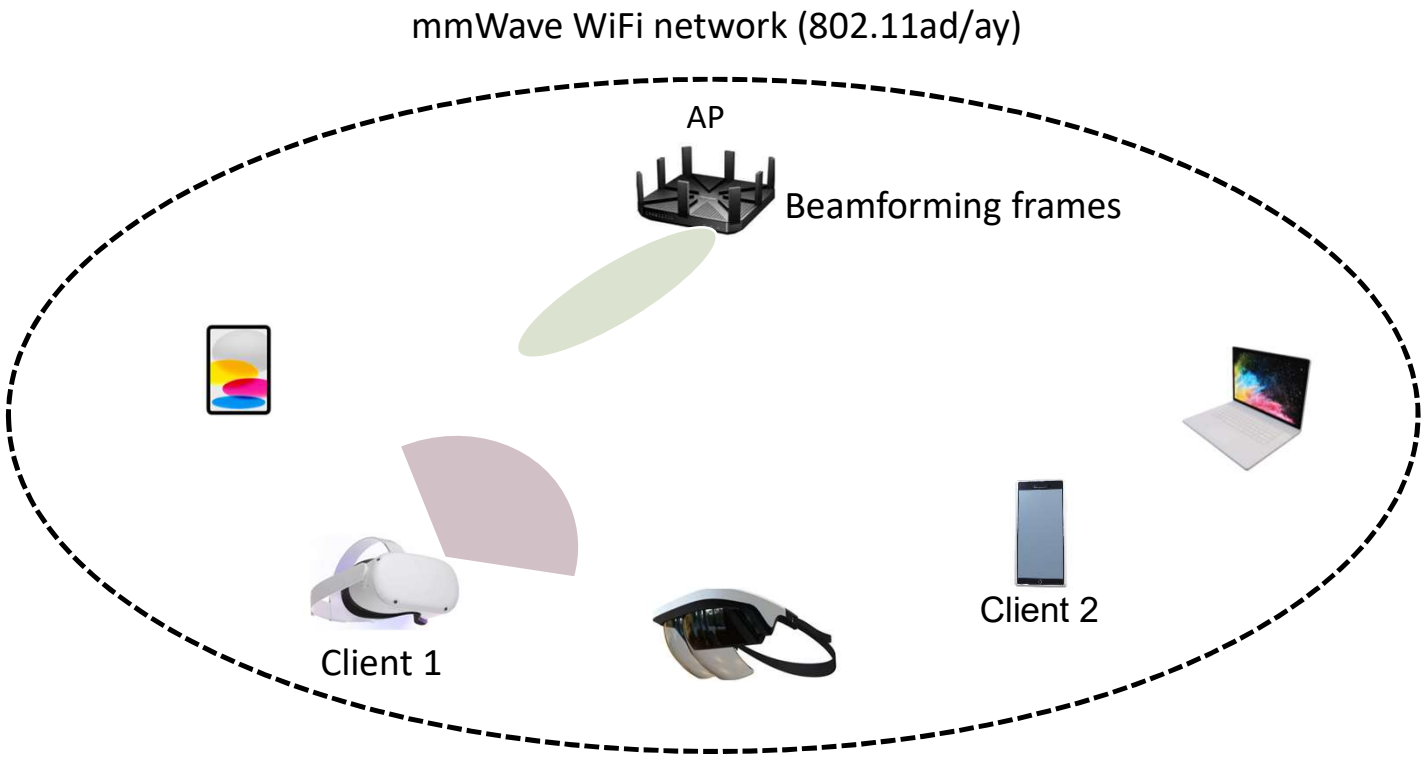

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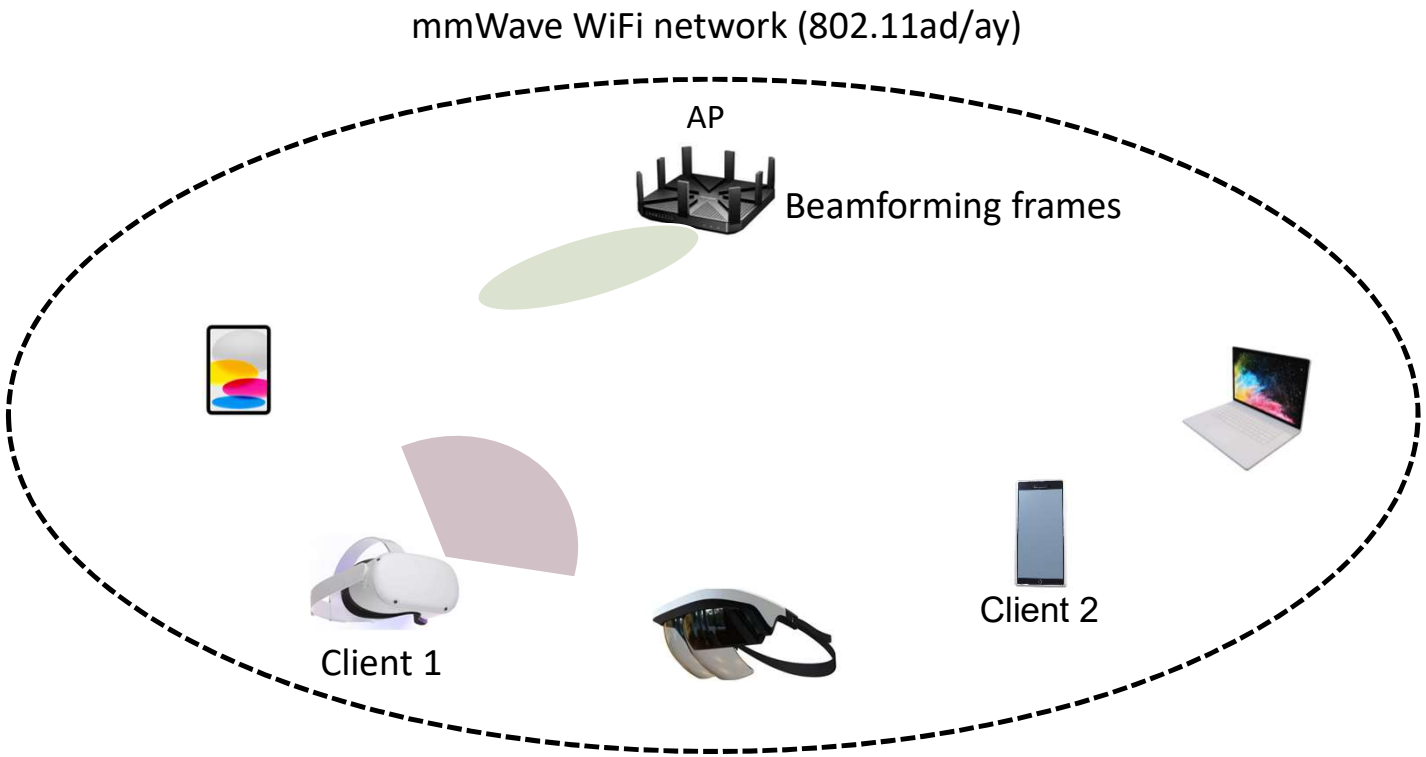

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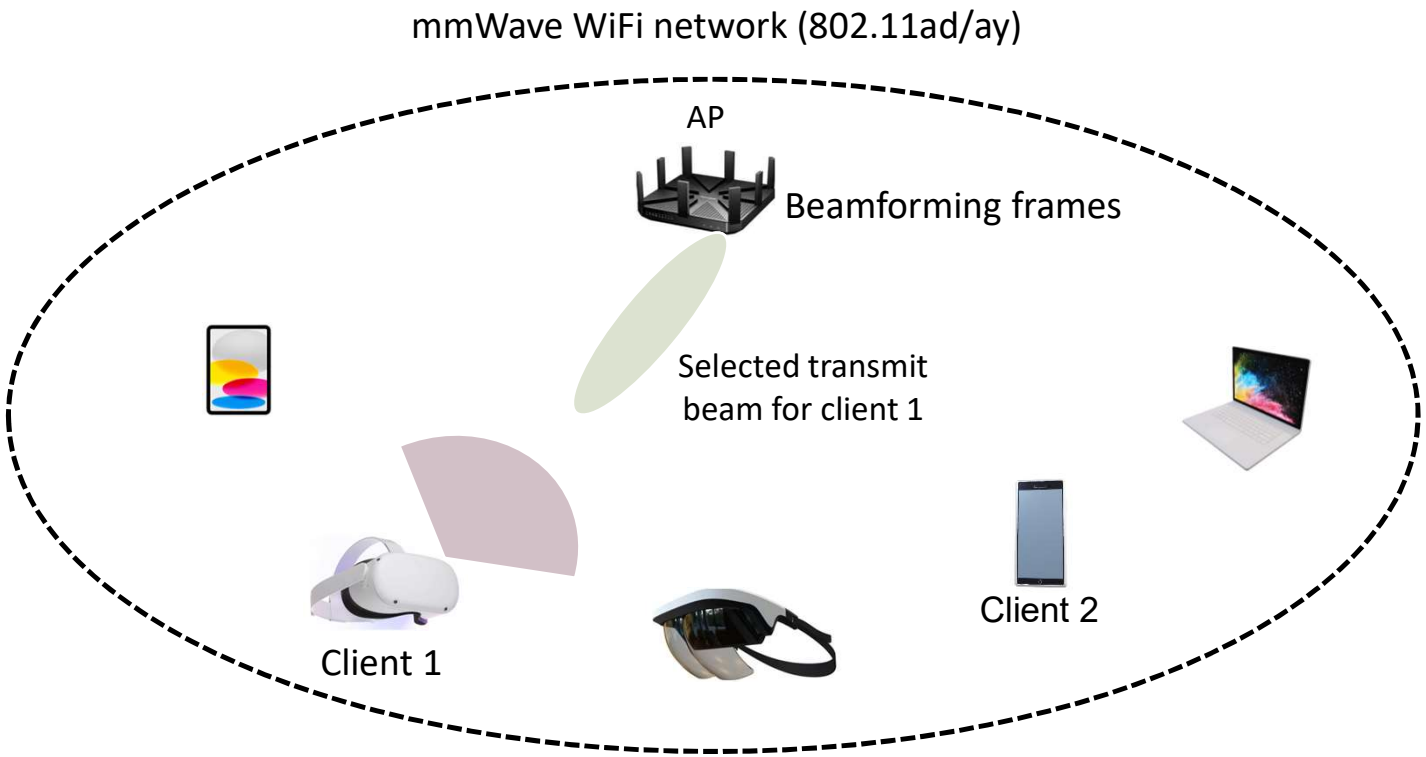

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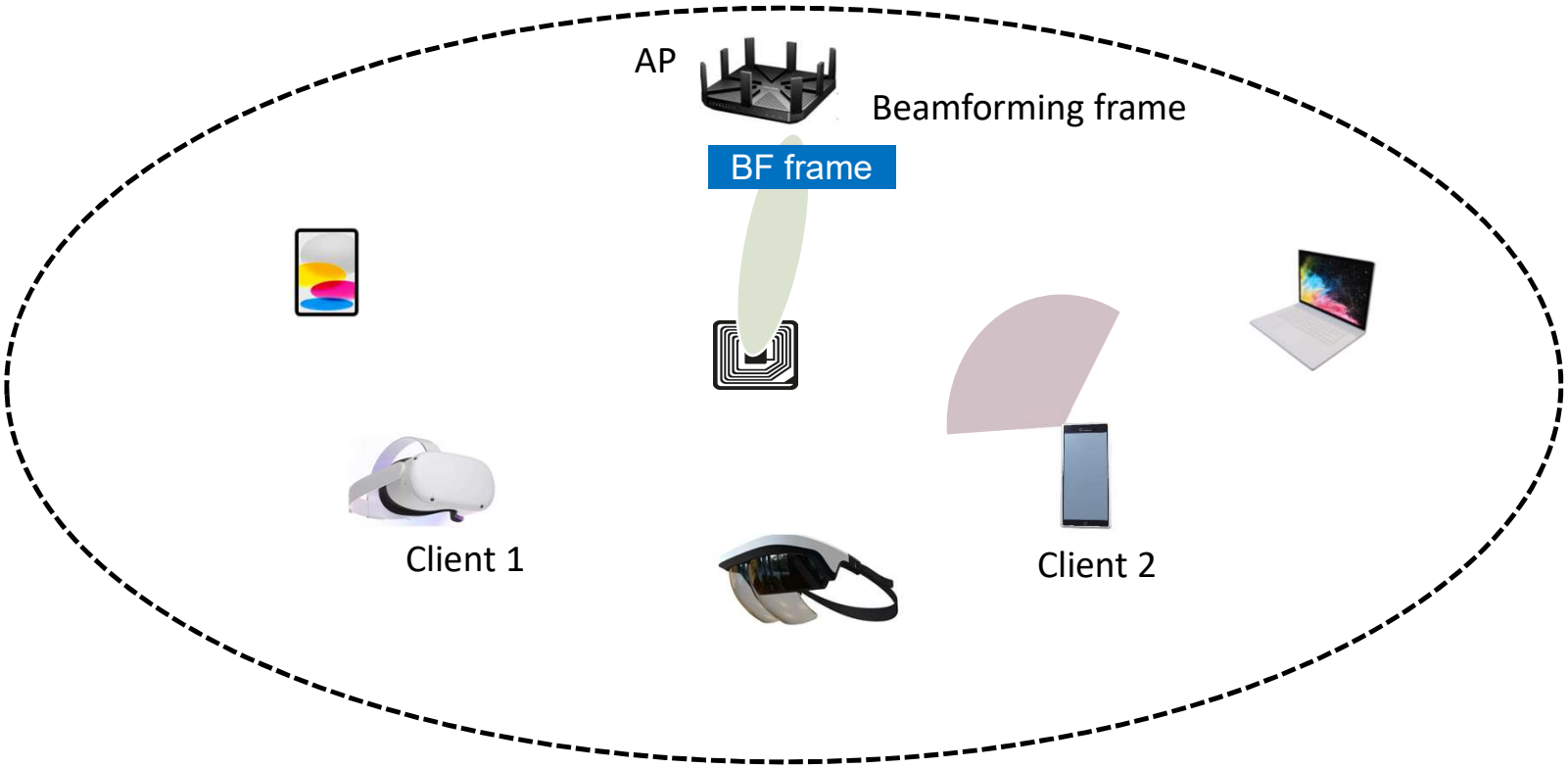
mmComb Overview

Seamlessly integrate mmWave backscatters into mmWave WiFi networks



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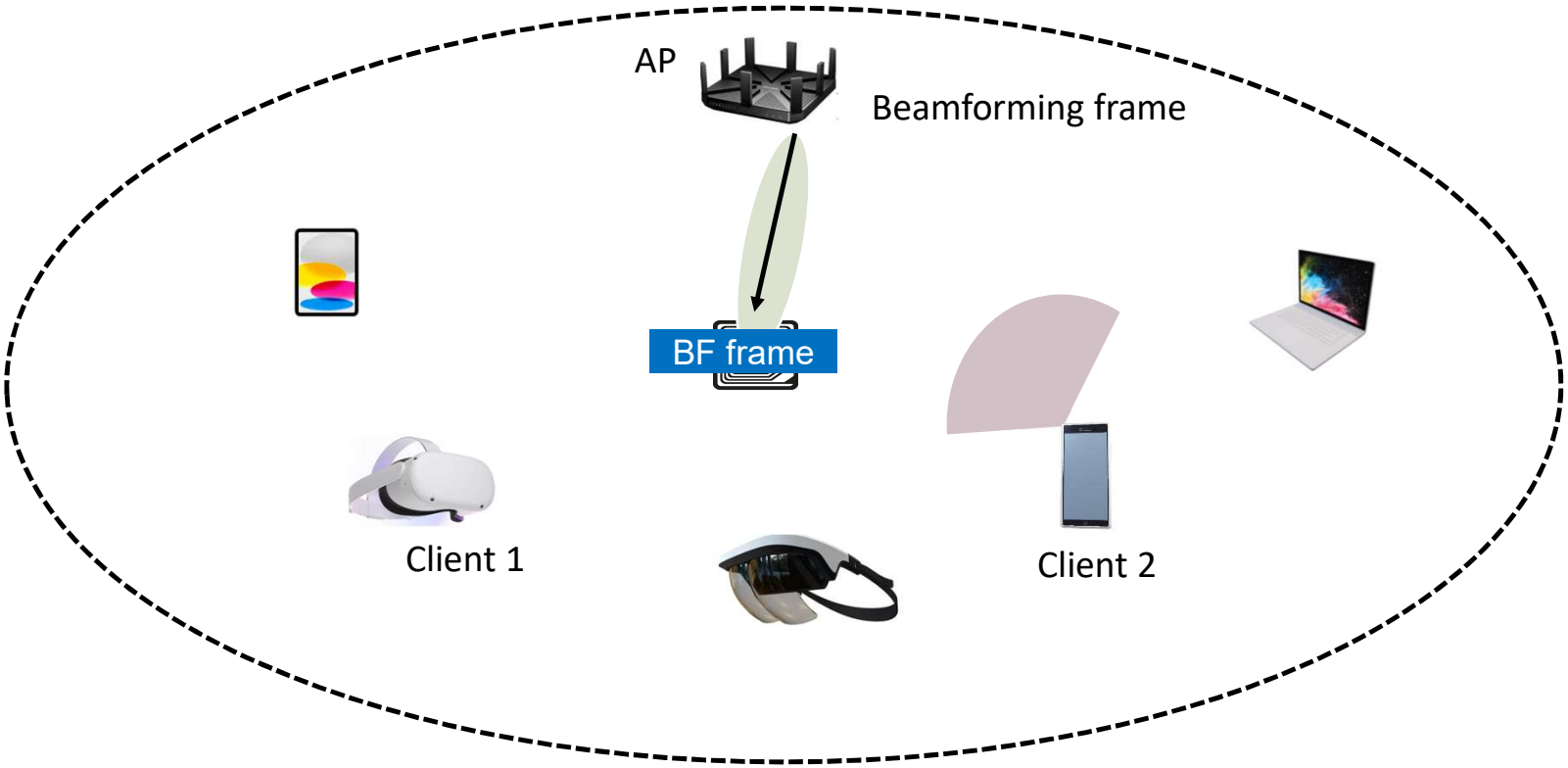

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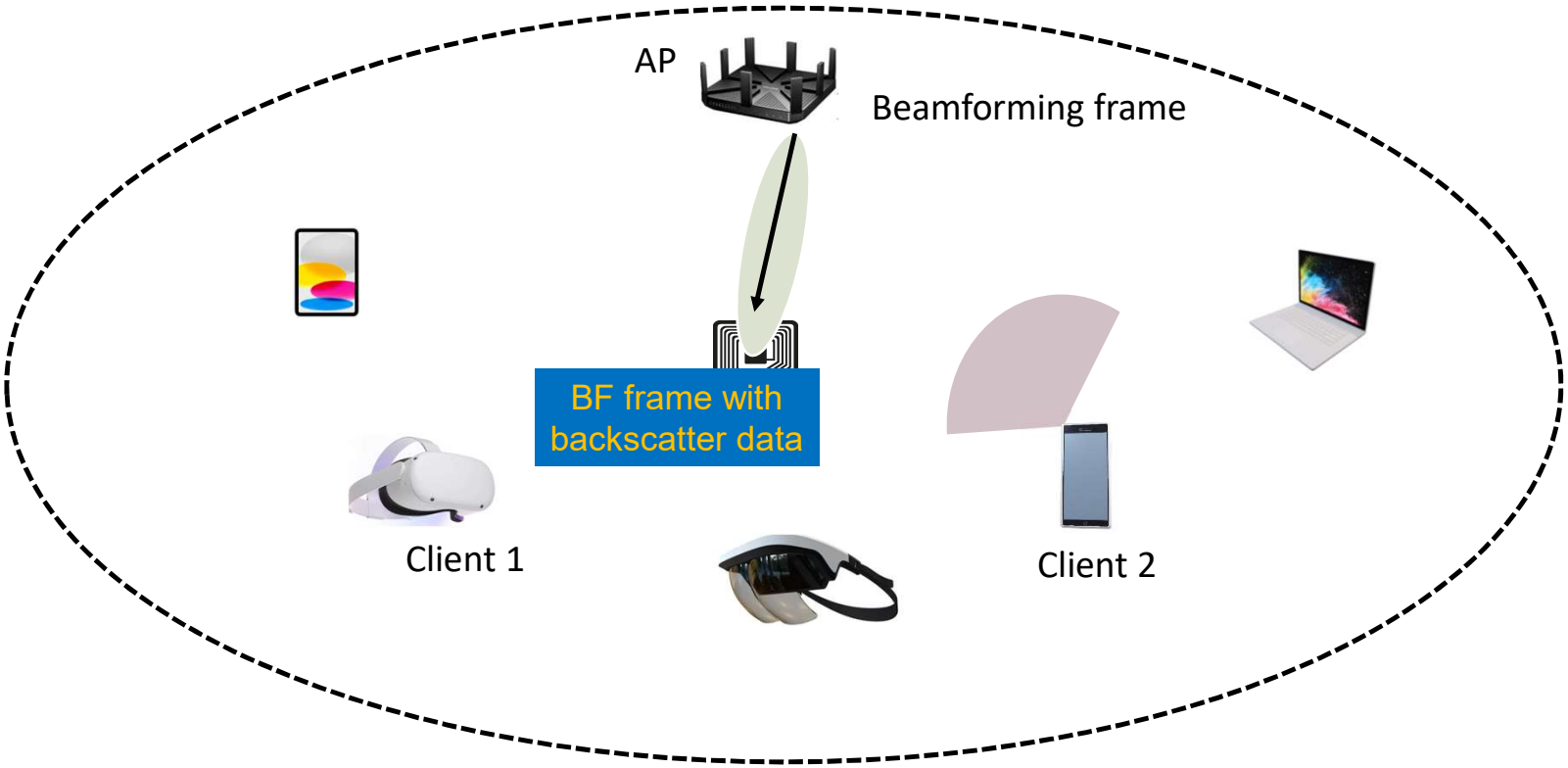

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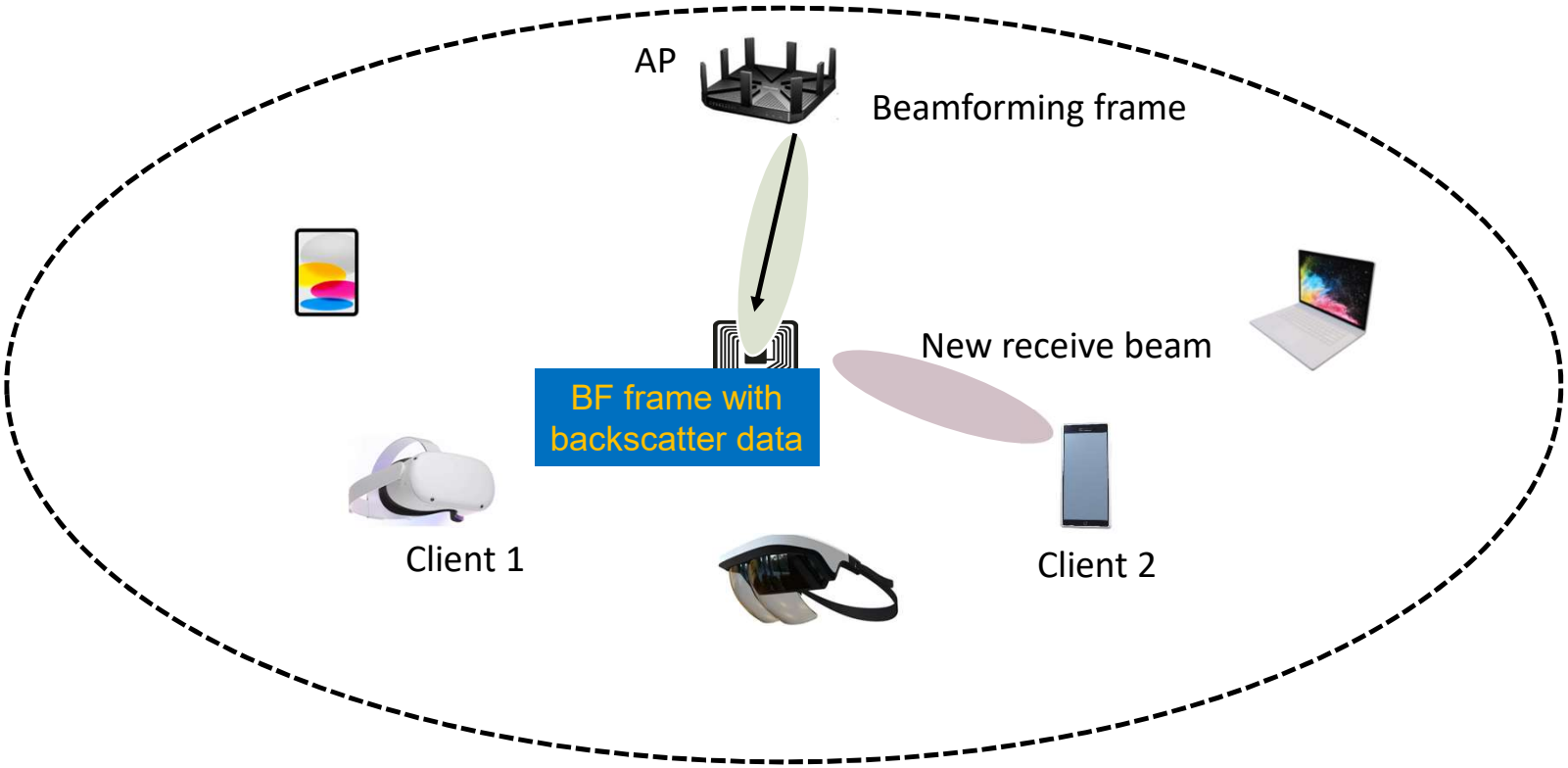

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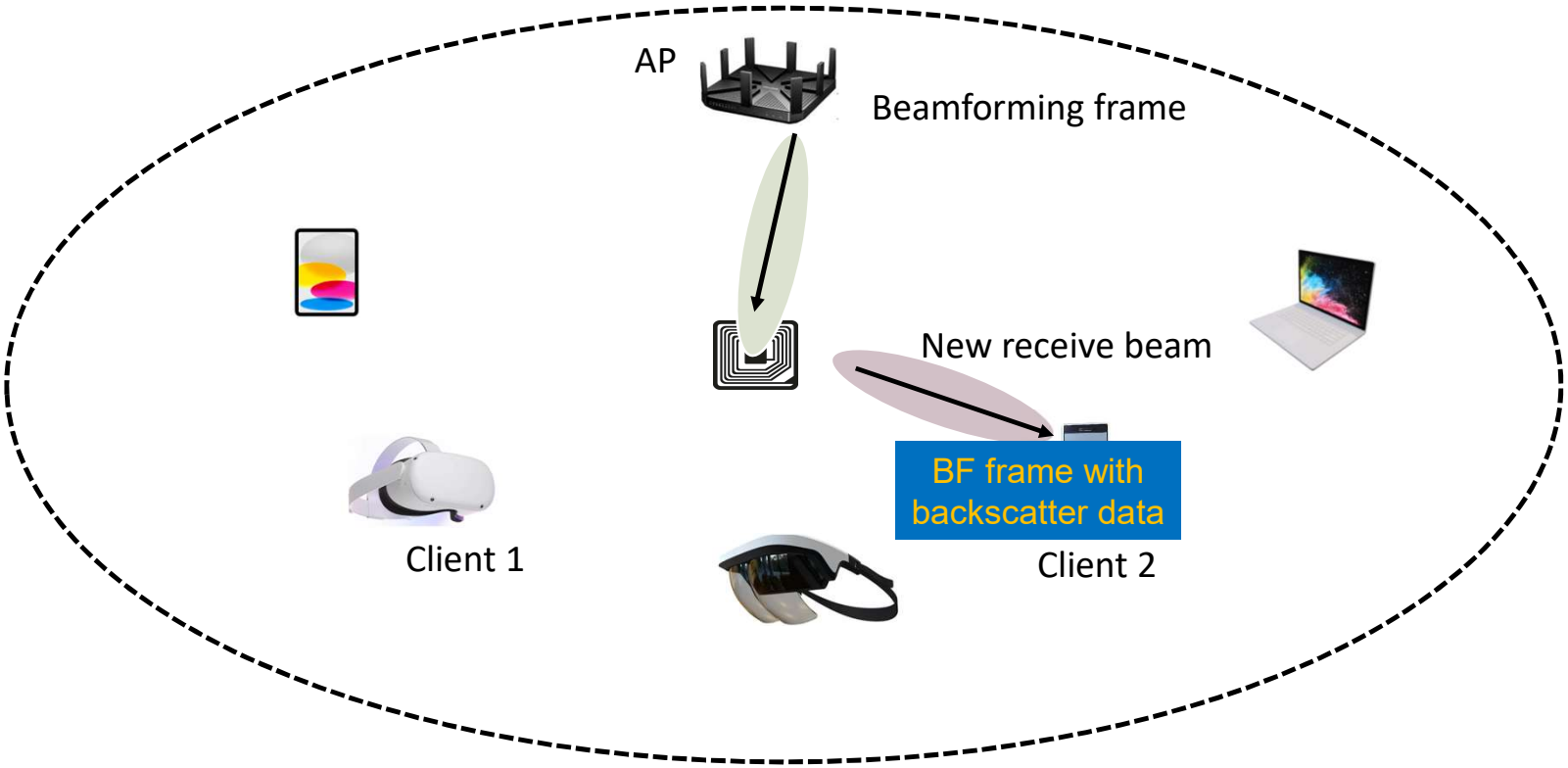

mmComb

- Embedding backscatter bits on 802.11ad/ay (60 GHz) WiFi beamforming frame

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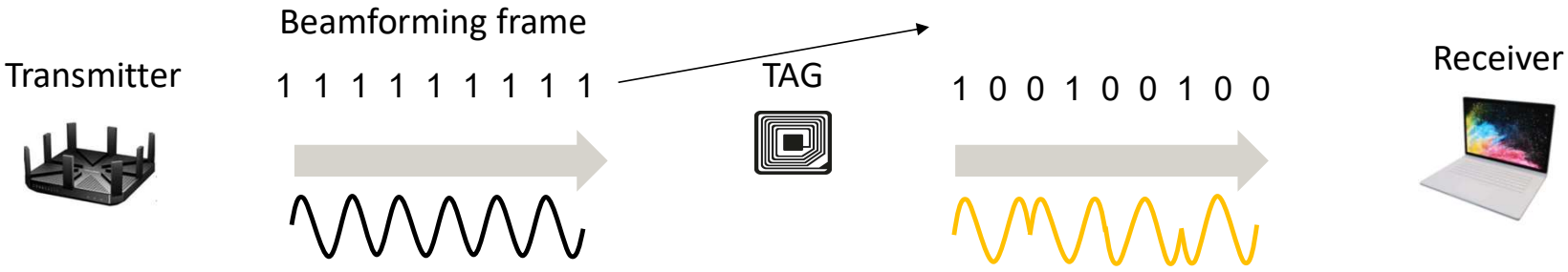

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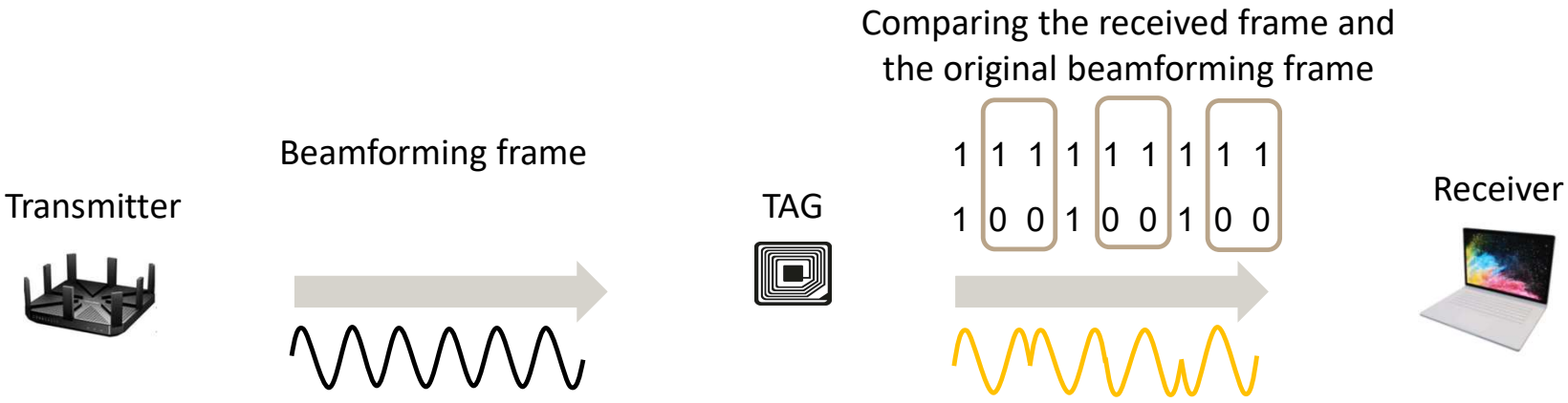

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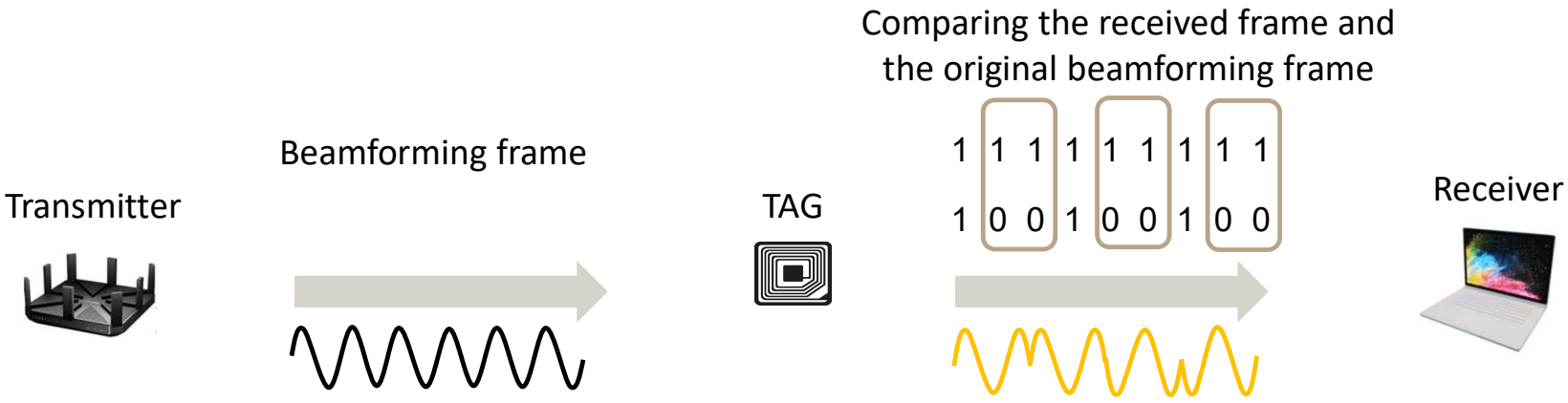
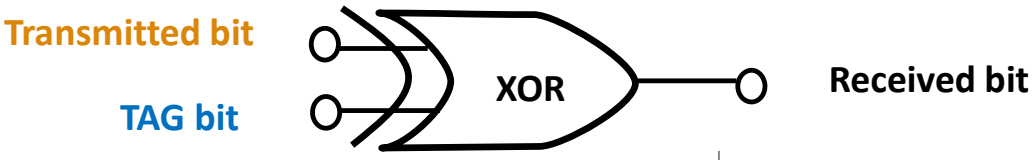


1. Compatibility with commercial WiFi → No hardware/protocol modification
2. High speed communication → 55 Mbps data rate
   - 1000x higher than legacy RFID backscatter (40kbps)
3. Ultra-low power consumption → < 100 μW

Modulation / Demodulation

- 802.11 ad/ay mmWave WiFi beamforming (control) frame – DBPSK modulation (55Mbps)
  - TAG can introduce either “0” (Bit 0) or“π” (Bit 1) phase shift



Transmitted bit	TAG bit	Received bit
0	0	0
0	1	1
1	0	1
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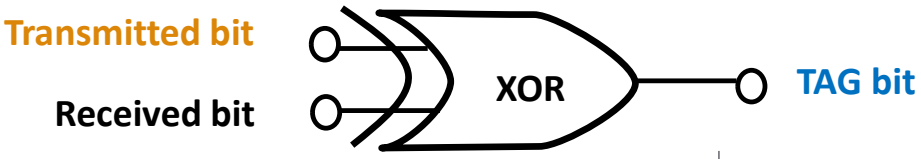

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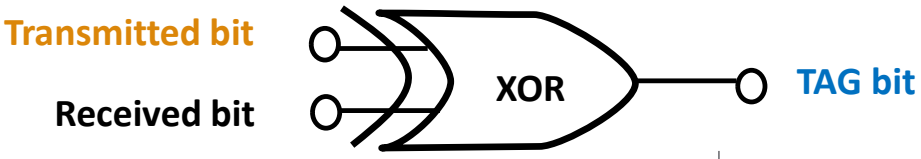

Transmitted bit	Received bit	TAG bit
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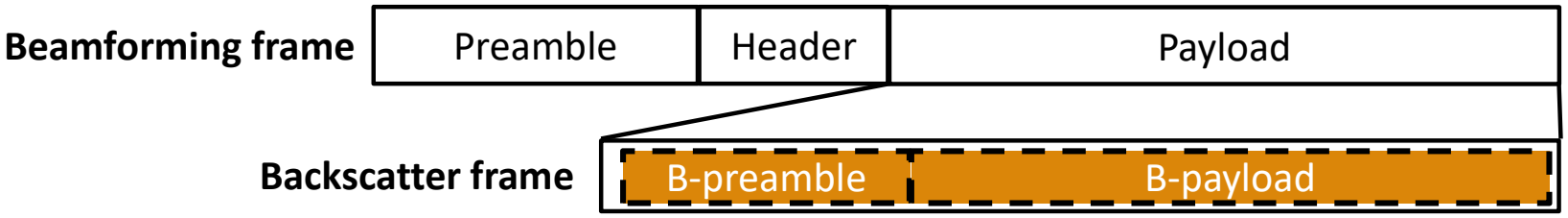
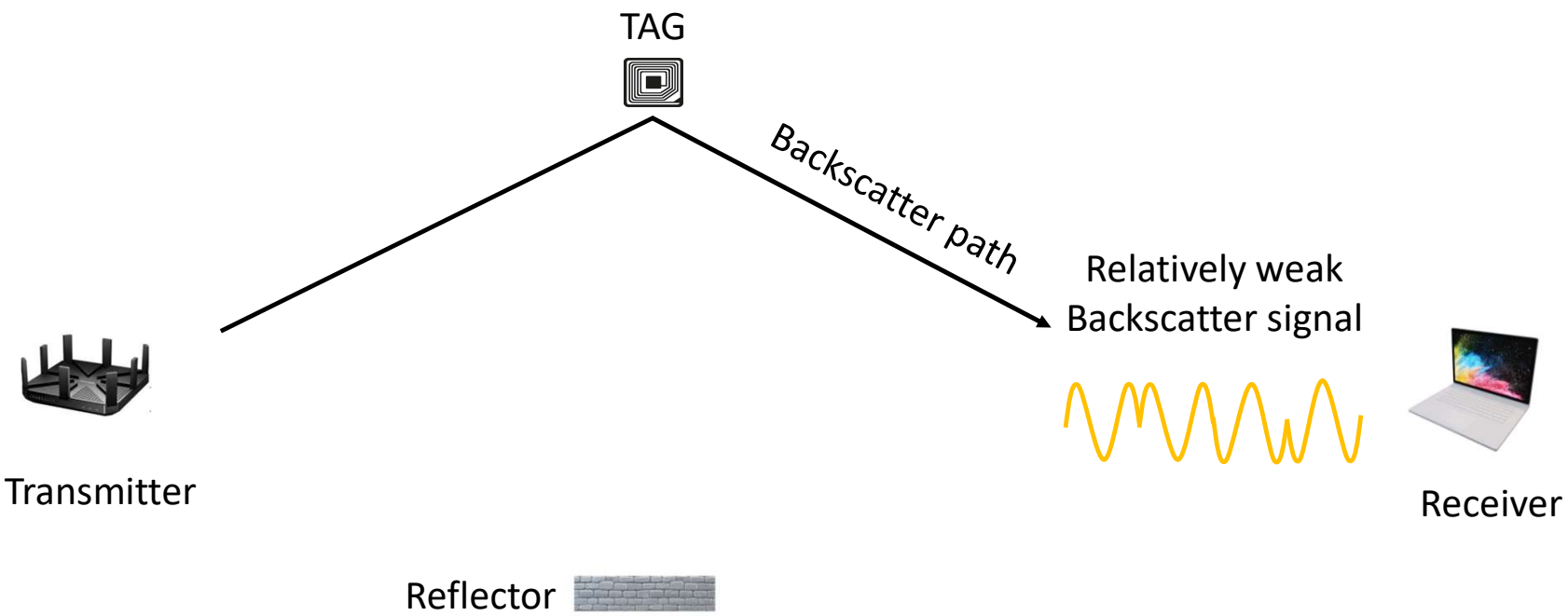
- Beamforming frame structure and payload do not change over time
  - Receiver can demodulate without actually receiving the original transmitted BF frame



Challenges

1. Self-interference from original WiFi signal
2. Identifying the backscatter path/AoA
3. Lightweight BF frame detection
4. Ensuring unaffected BF process

Challenge 1: Self-Interference



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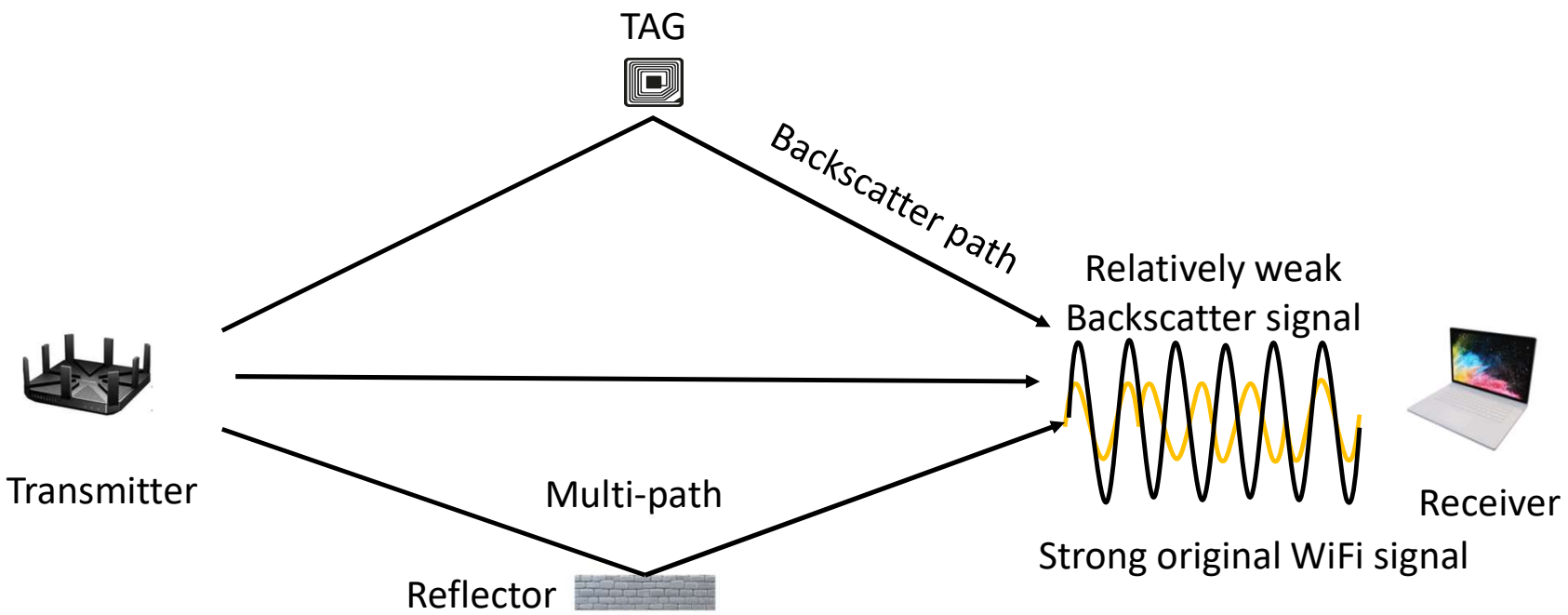

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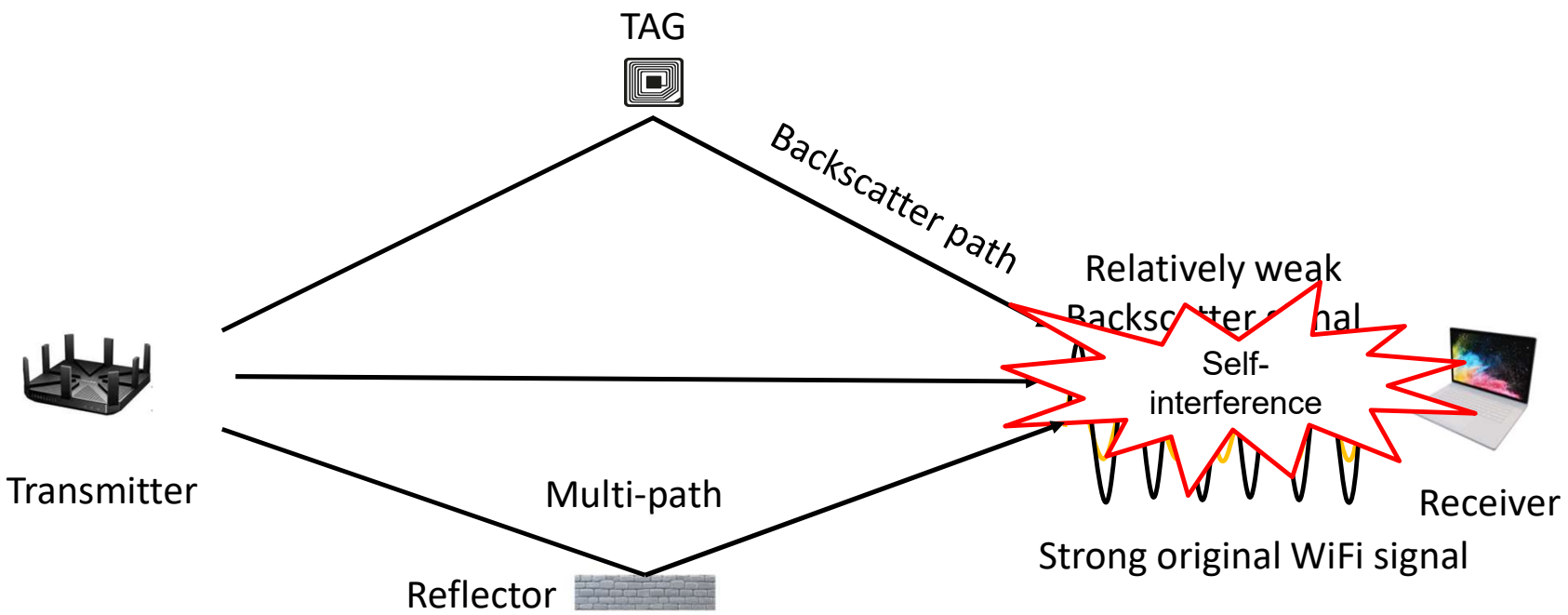
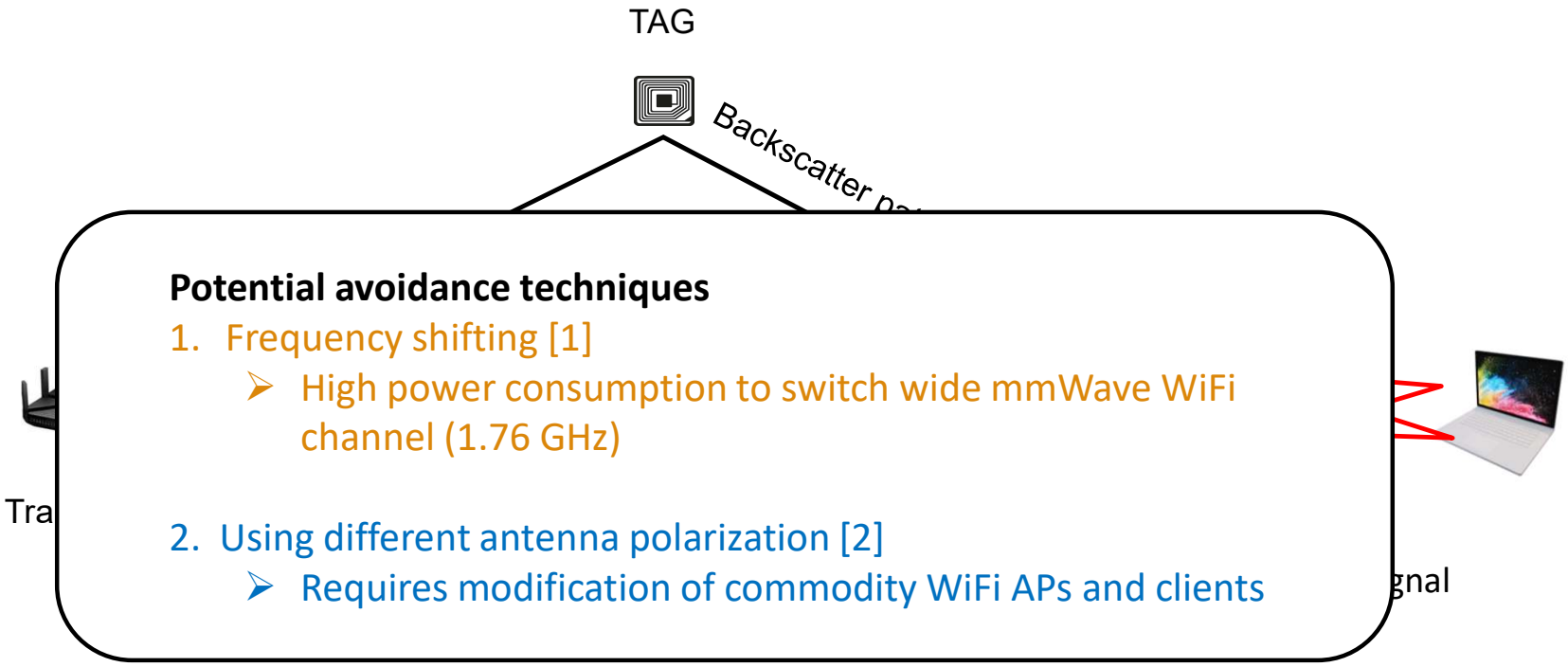


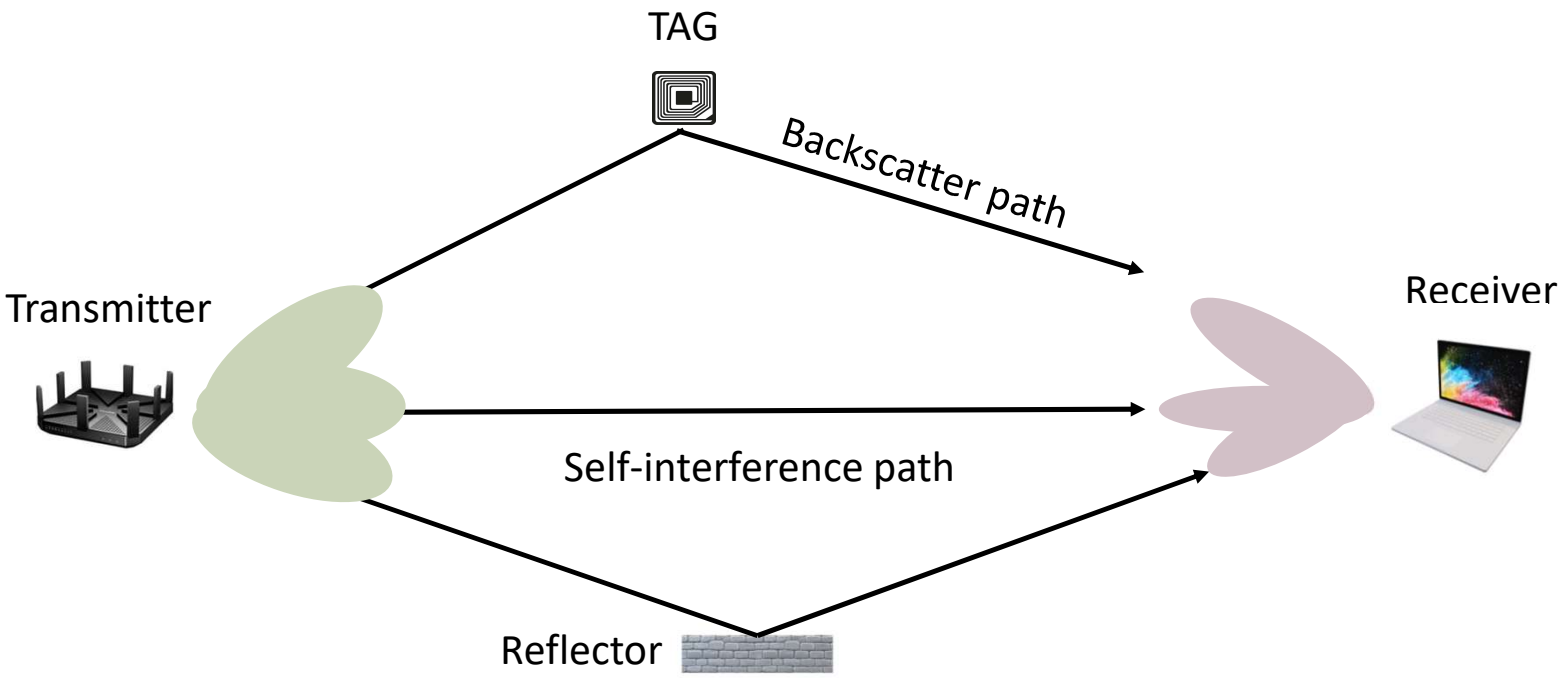
Self-interference makes it difficult to extract the weak backscatter signal

Challenge 1: Self-Interference



[1] Pengyu Zhang, Dinesh Bharadia, Kiran Joshi, and Sachin Katti. Hitchhike: Practical backscatter using commodity wifi. SenSys '16.
[2] Mohammad Hossein Mazaheri, Alex Chen, and Omid Abari. mmtag: a millimeter wave backscatter network.SIGCOMM'21.

Receive Beamforming for Backscatter



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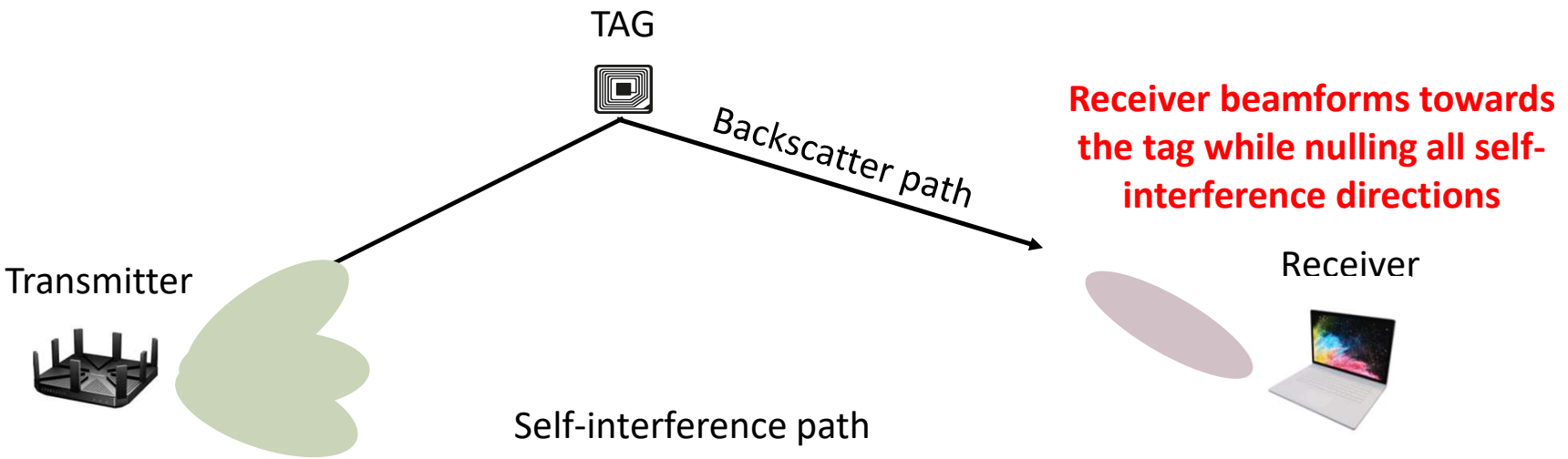
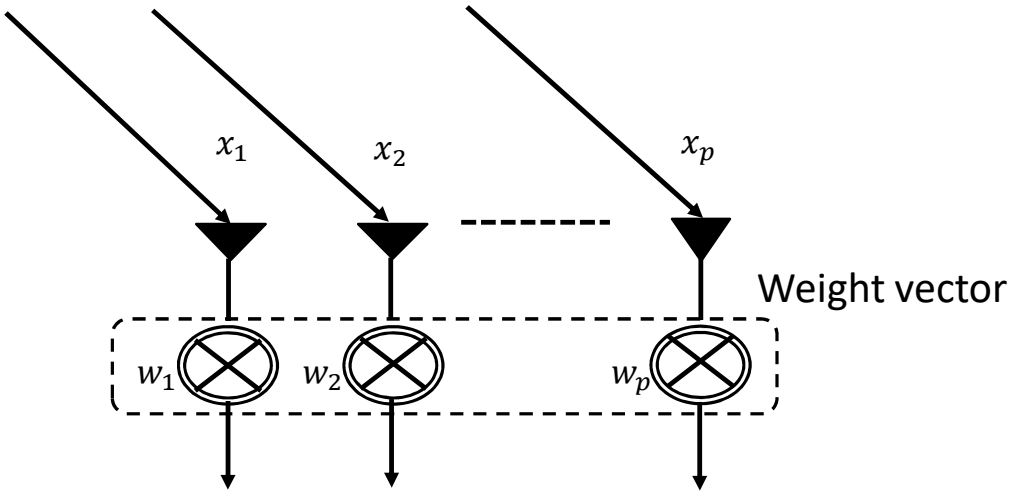


Separating the self-interference and backscatter signals in spatial domain

- No requirement of hardware modification
- Improving backscatter SINR $= \frac{Backscatter}{Self-interference+Noise}$

Receive Beamforming for Backscatter

Backscatter



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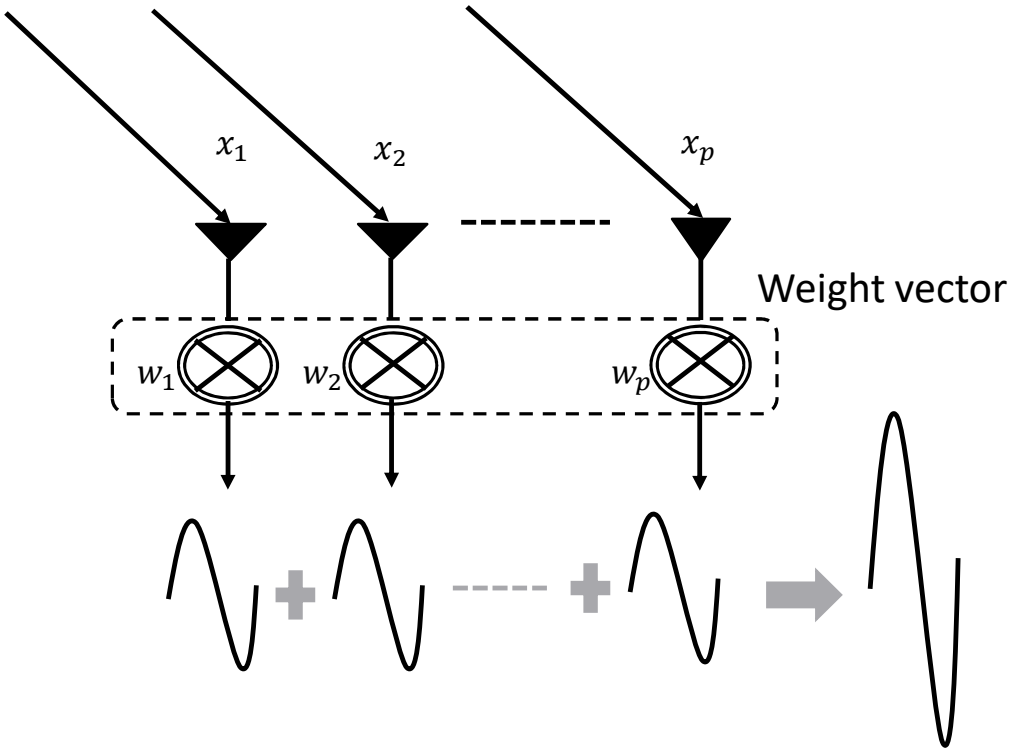

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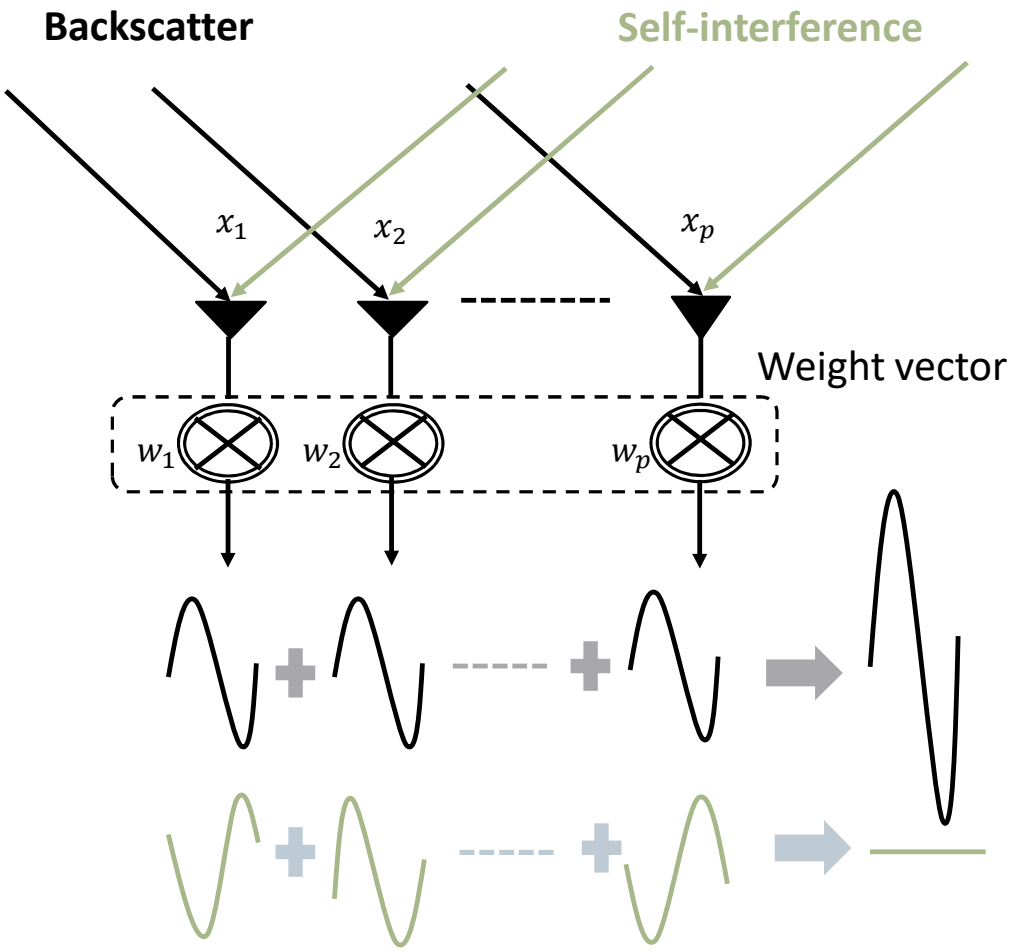

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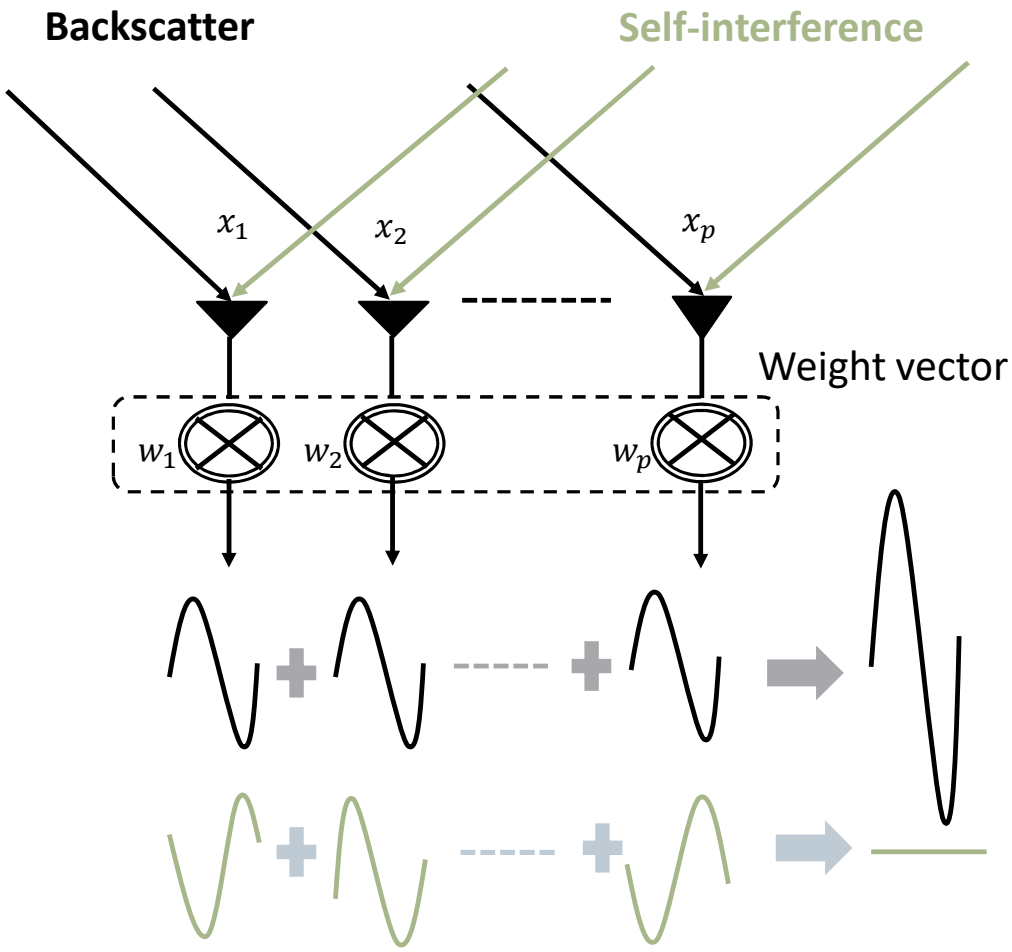


$$y = (S_{inter} + S_{back}) * \text{weight vector}$$

$$y_b = (S_{back})$$

$$\varepsilon = y - y_b = w^* x - y_b$$

$$E[\varepsilon\varepsilon^*] = E[(w^* x - y_b)(w^* x - y_b)^*]$$

$$= w^* E[xx^*]w - 2w^* E[y_b x^*] + y_b y_b^*$$

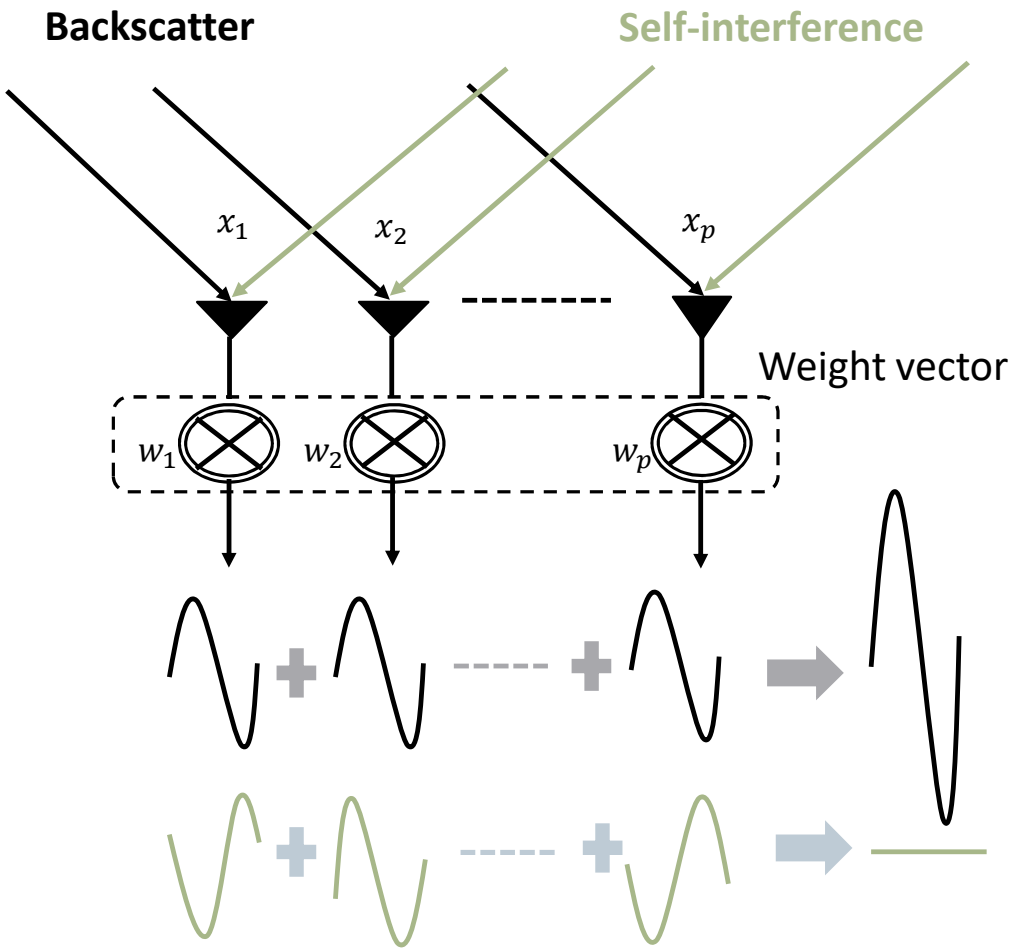
$$= w^* Rw - 2w^* r + y_b y_b^*$$

Auto-correlation Cross-correlation

$$\frac{dE[\varepsilon\varepsilon^*]}{dw} = 2Rw - 2r$$

$$\text{Optimal Weight Vector} = \frac{r}{R} = R^{-1}r$$

Receive Beamforming for Backscatter



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Auto-correlation Cross-correlation

Spatial smoothing

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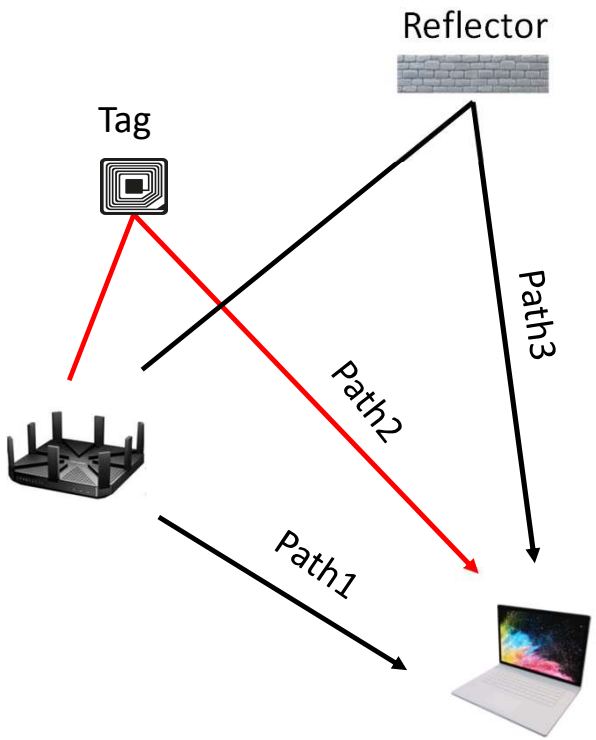
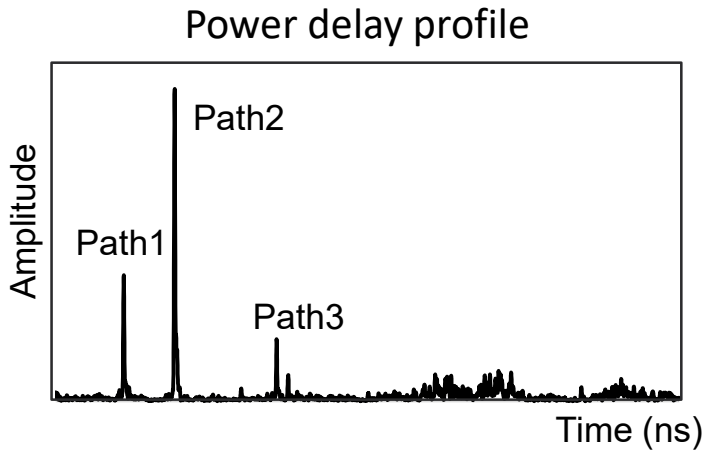
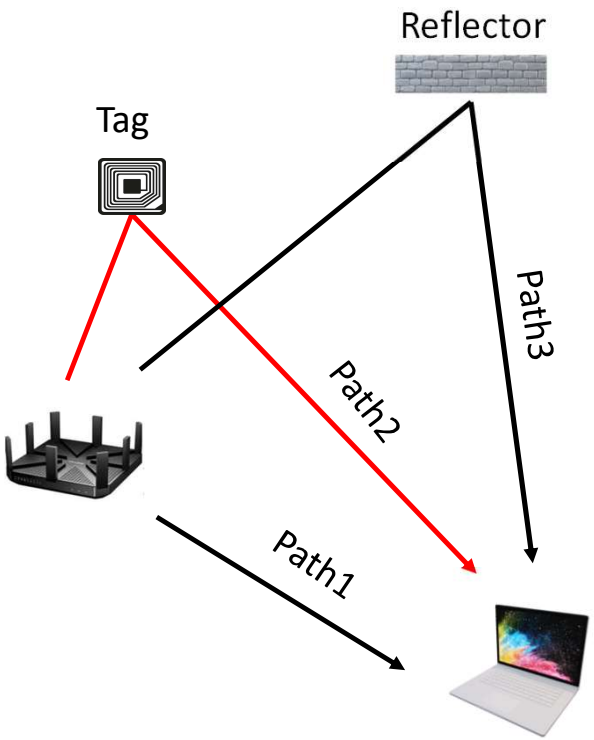
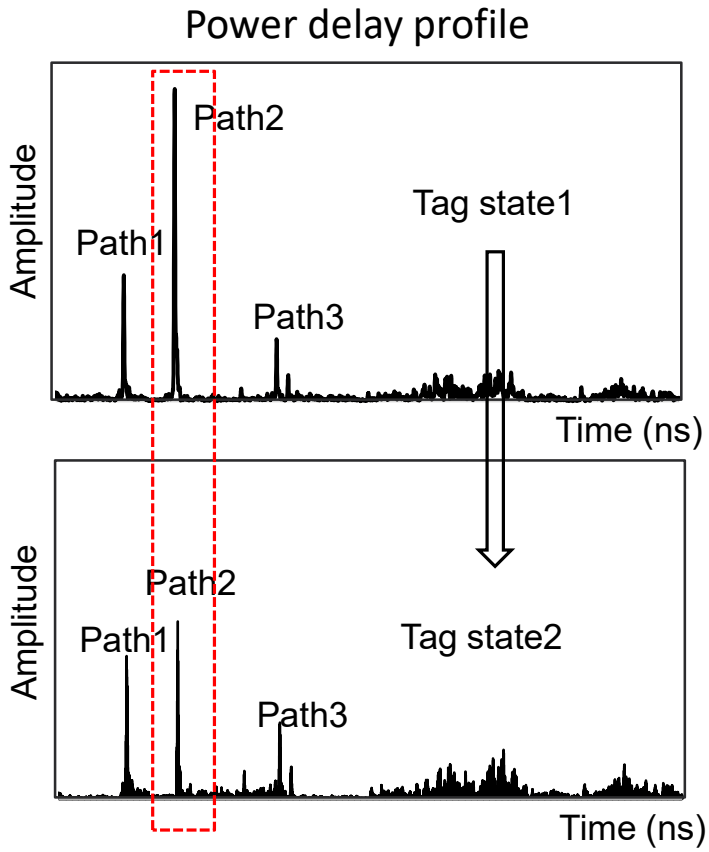
Challenge 2: Identifying the backscatter path





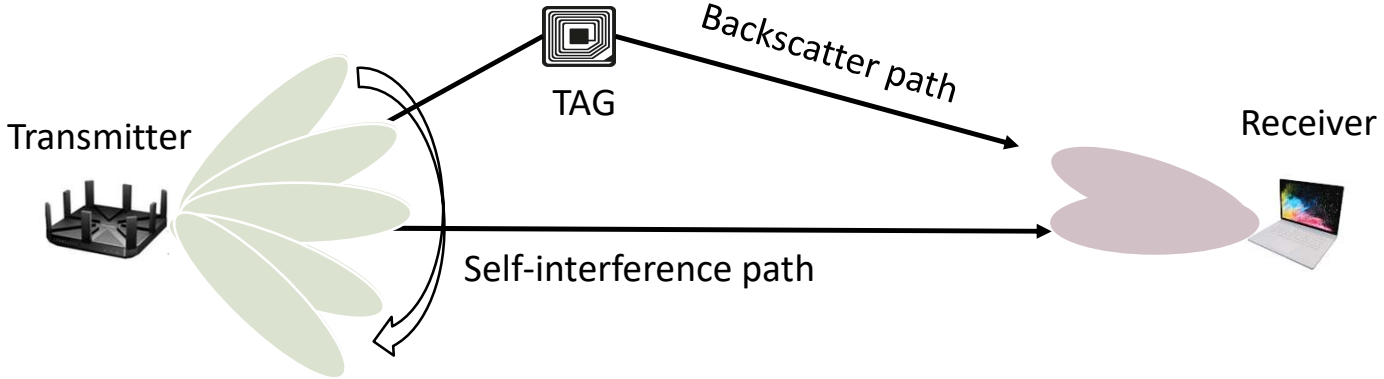
Challenge 2: Identifying the backscatter path

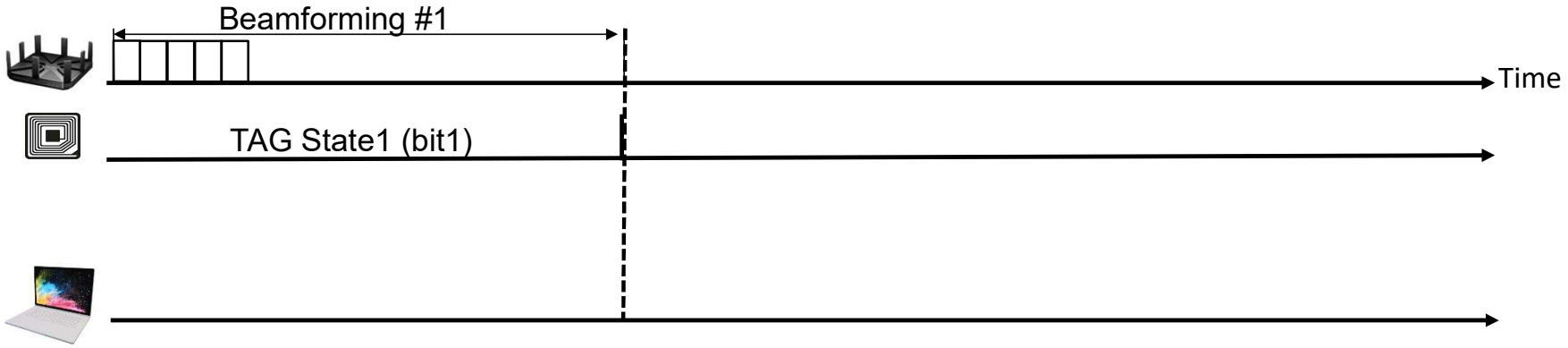




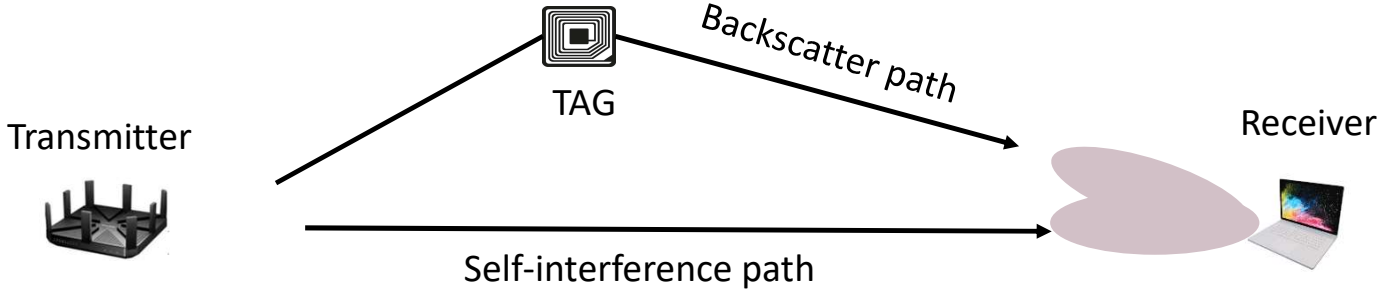
The tag operation changes only the peak of the backscattering path.

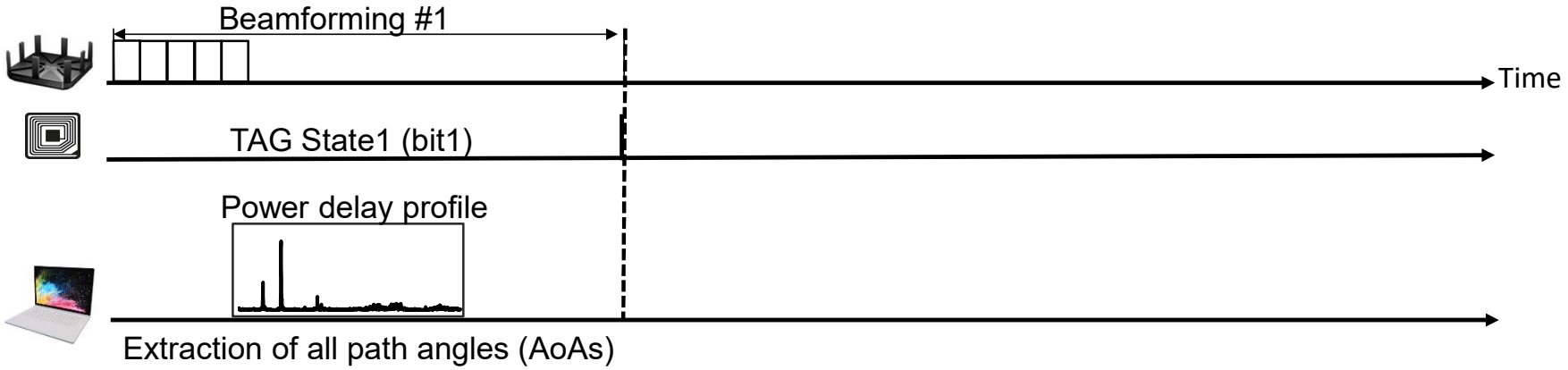
mmComb protocol over mmWave WiFi



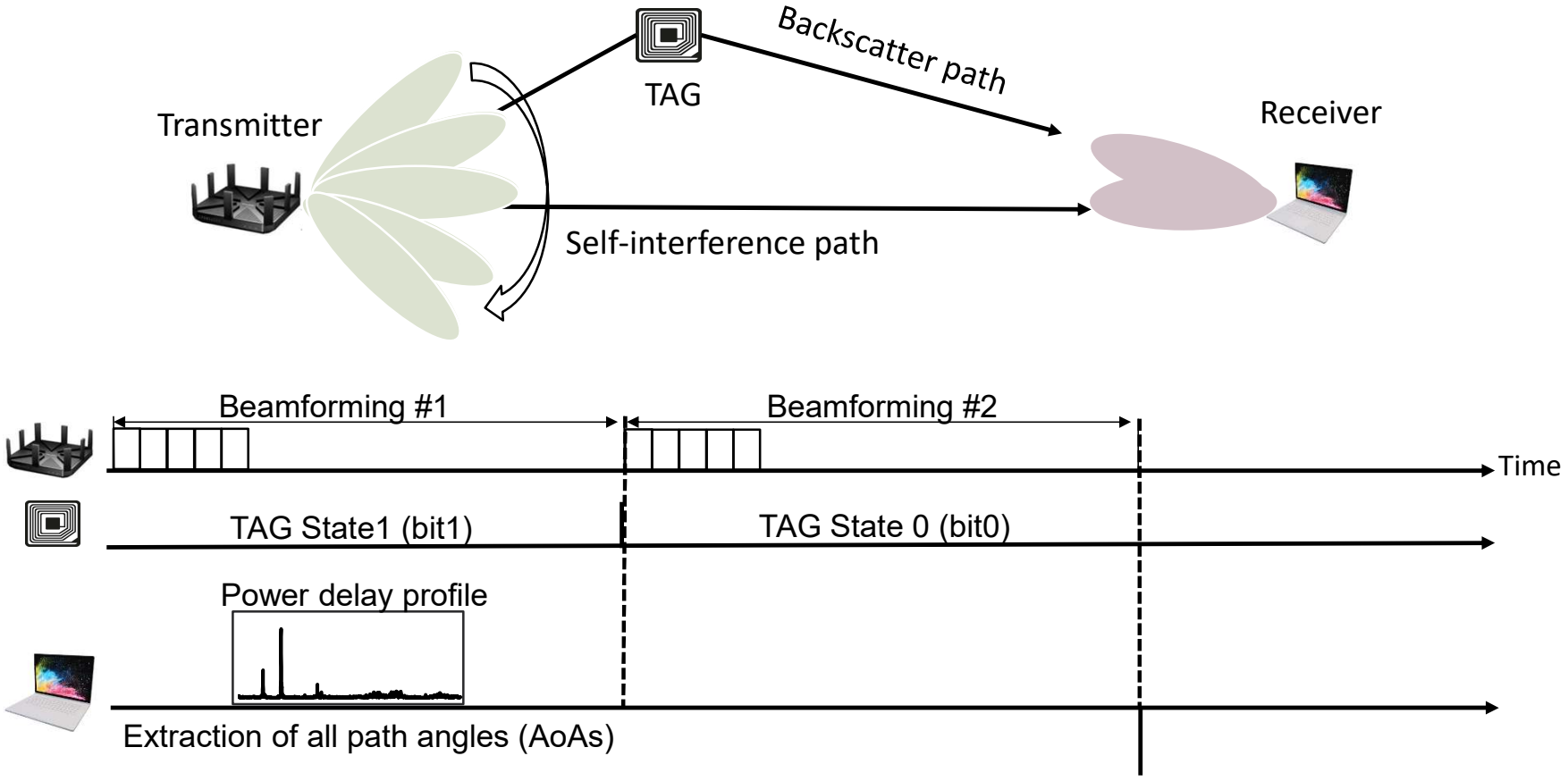


mmComb protocol over mmWave WiFi

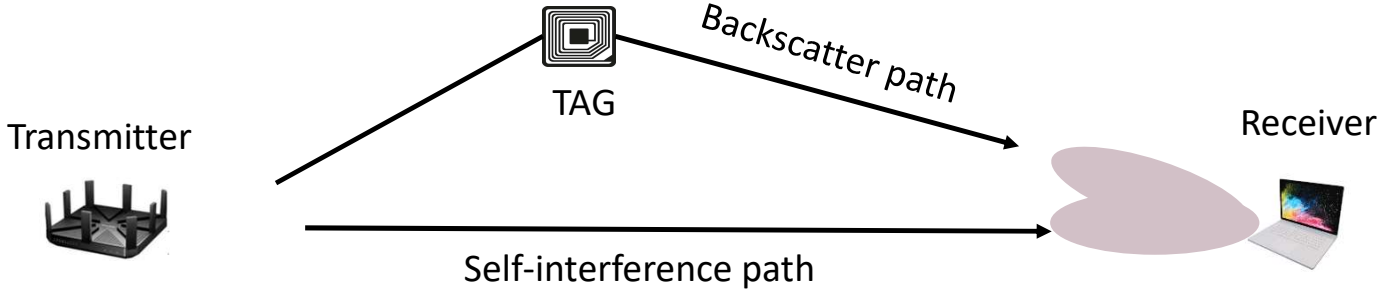


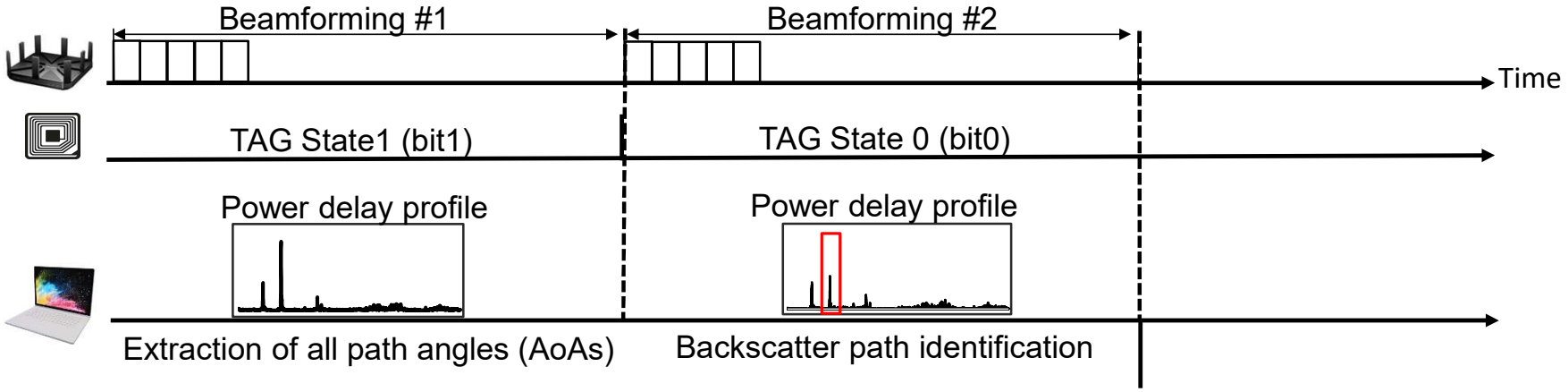


mmComb protocol over mmWave WiFi

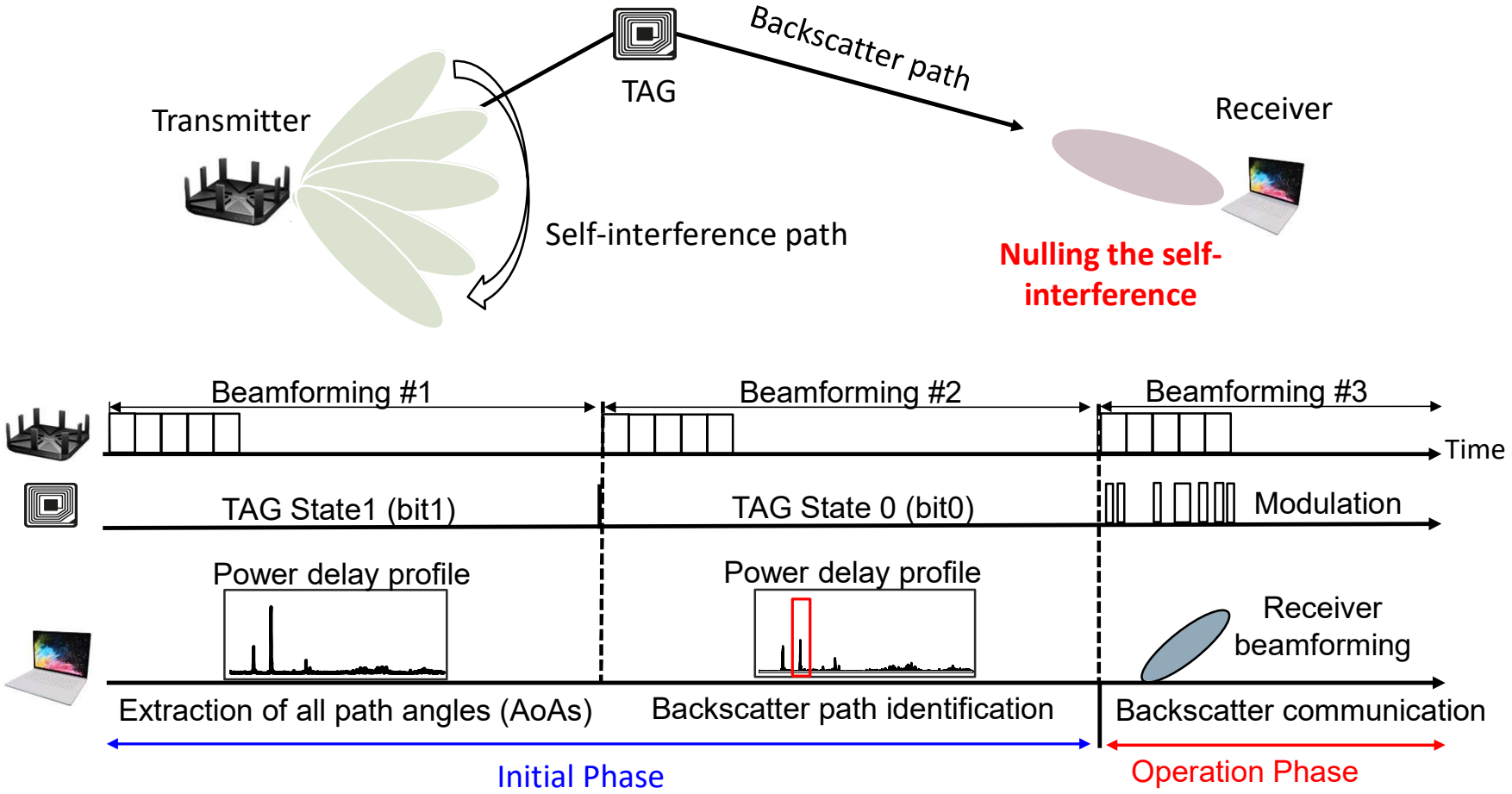


mmComb protocol over mmWave WiFi





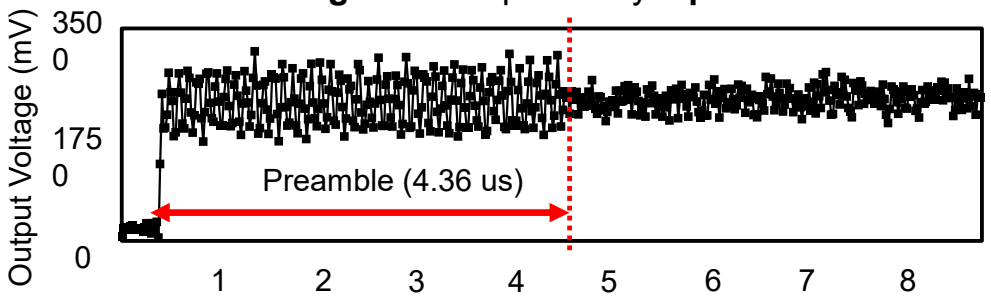
mmComb protocol over mmWave WiFi



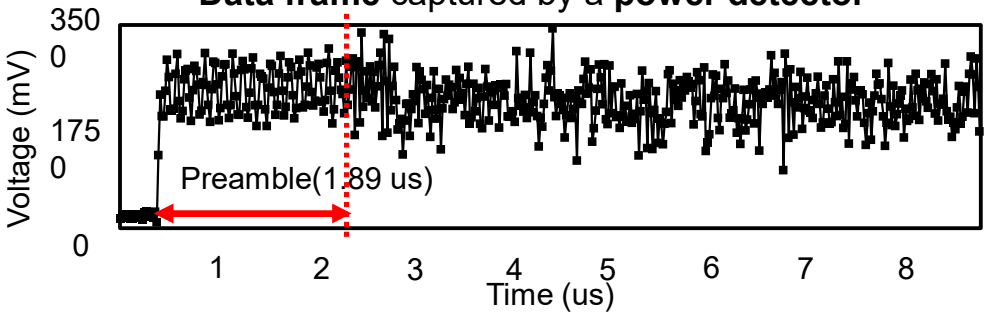
Challenge 3: Ultralight Beamforming Frame Detection

- Power detector (passive component): Covert received RF signals into voltages
- **Two distinctive aspects to the beamforming frame**
  - Long preamble duration (Control frame: 4.63us vs. Data frame: 1.89us)
  - Each bit of the control frame is spread with the Golay sequence

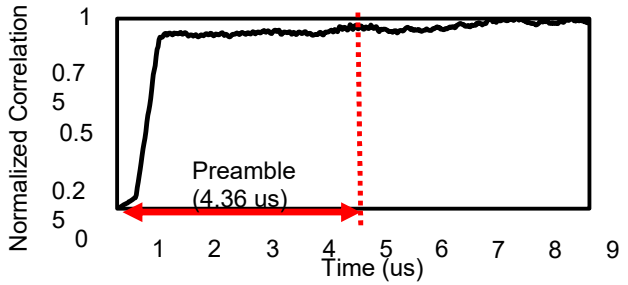
Beamforming frame captured by a **power detector**



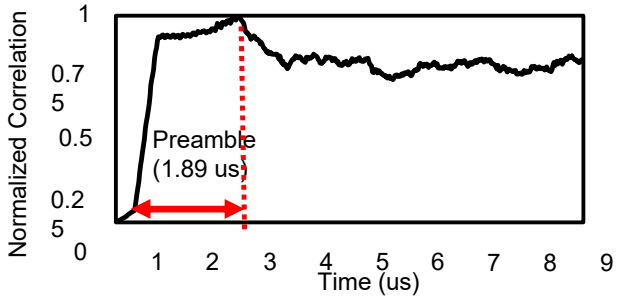
Data frame captured by a **power detector**



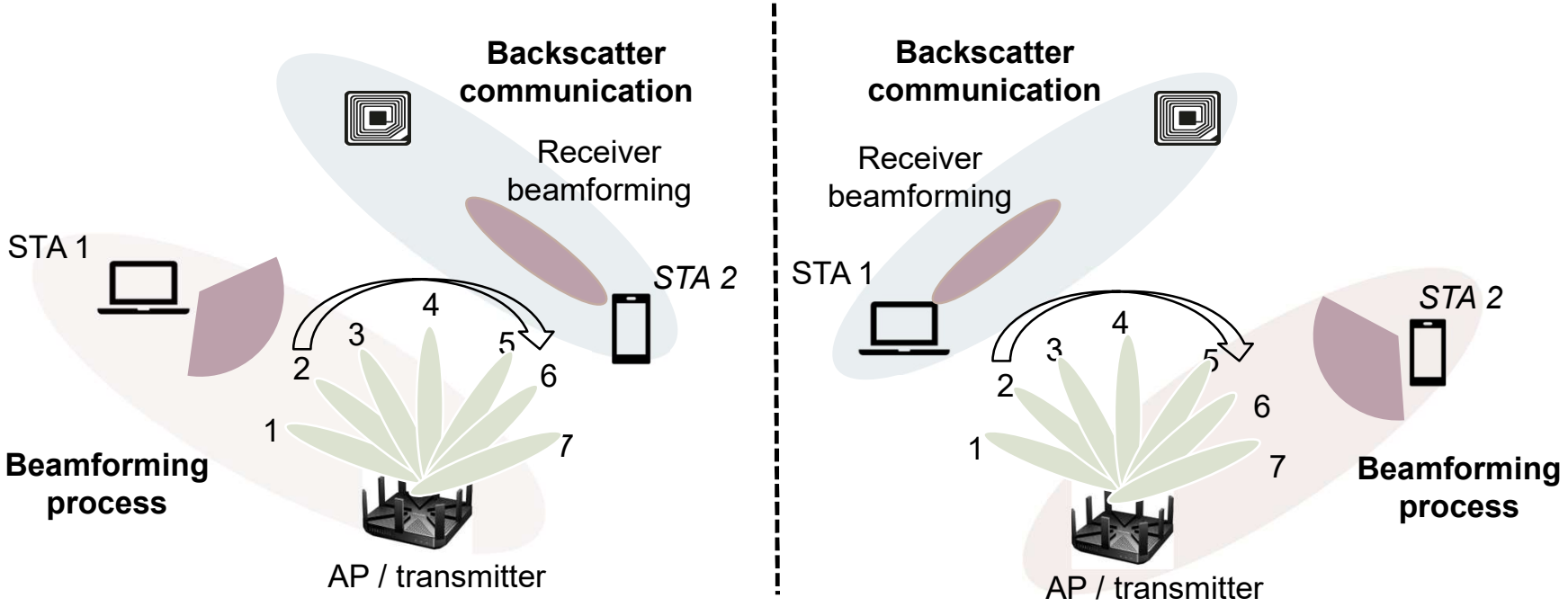
Cross-correlation of beamforming frame



Cross-correlation of data frame



Challenge 4: Impact on Beamforming Process

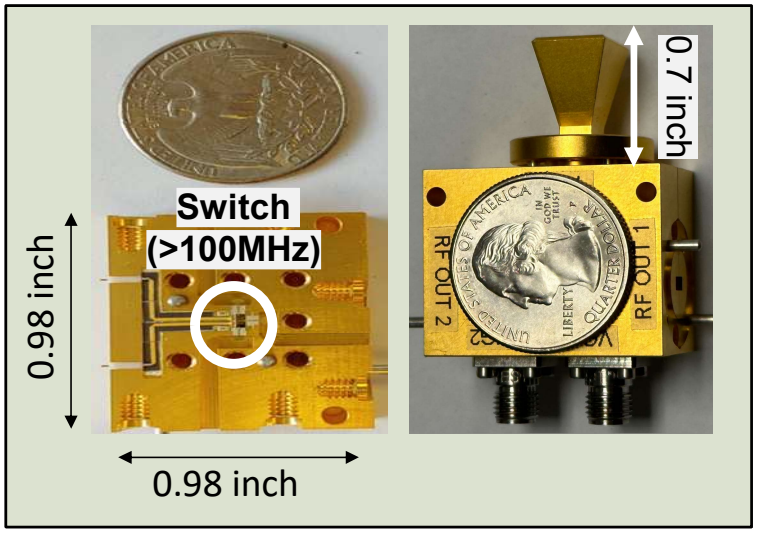


Beamforming for STA 1
& backscattering for STA 2

Beamforming for STA 2
& backscattering for STA 1

Implementation

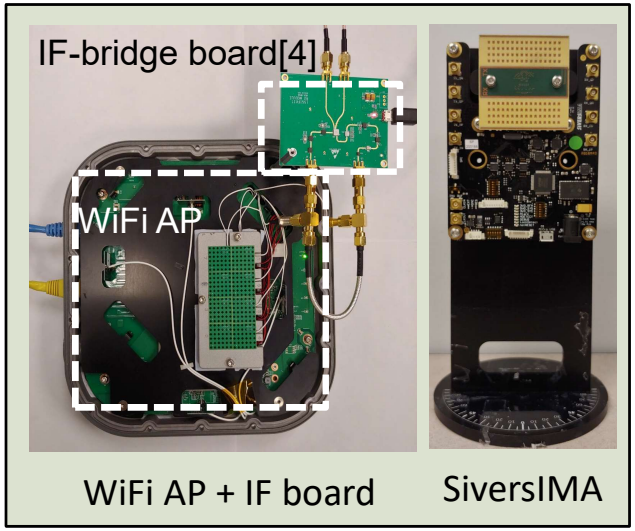
Tag prototype



Commodity setup

Mikrotik WiFi

SDR setup



WiFi AP + IF board

SiversIMA

Tag antenna

- 15 dBi V-band antenna
- Half-power beamwidth of 41 degrees

Tag switch

- > 100MHz switching speed
- Less than 1uW power consumption

Mikrotik WiFi TX & RX

- Qualcomm QCA6310 chipset
- Phased array (6×6 antenna elements)

WiFi AP RX + IF bridge board [4]

- Extract I/Q data from WiFi AP antenna
- Keysight 81199A Wideband Waveform Analyzer

SiversIMA

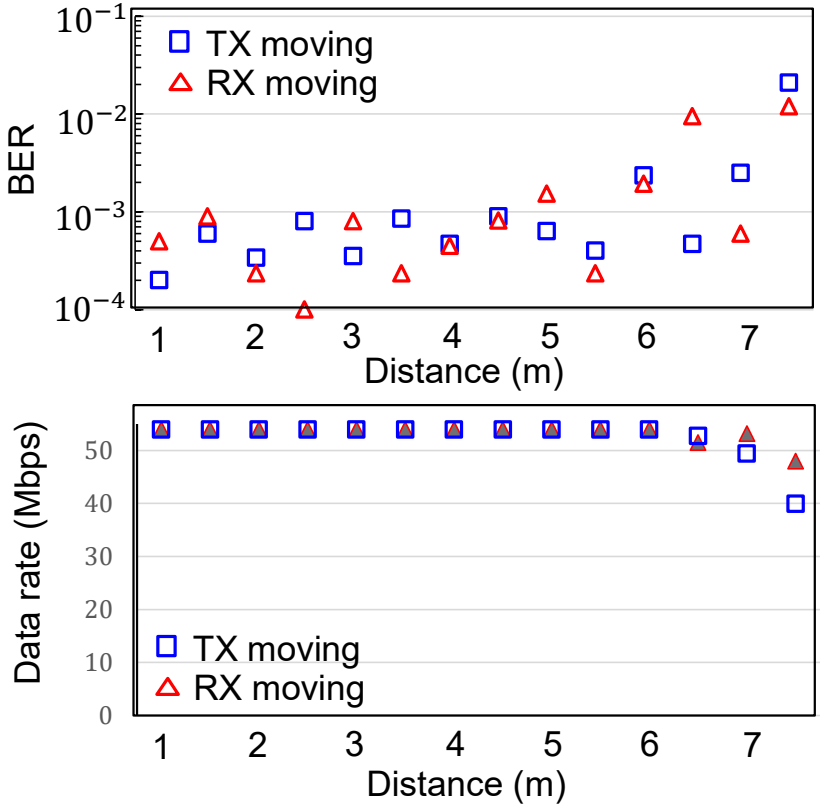
- Connected to oscilloscope to analyze BER

[4] Renjie Zhao, Timothy Woodford, Teng Wei, Kun Qian, and Xinyu Zhang. M-cube: A millimeter-wave massive mimo software radio. MobiCom'20.

Microbenchmark Evaluation

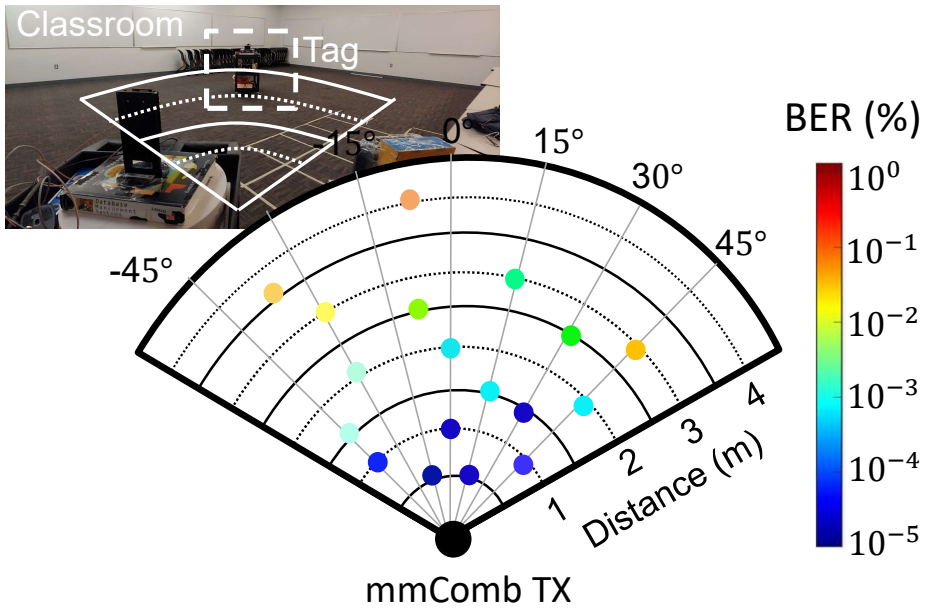
Backscatter distance evaluation

- mmComb can support higher than 50Mbps up to 7m

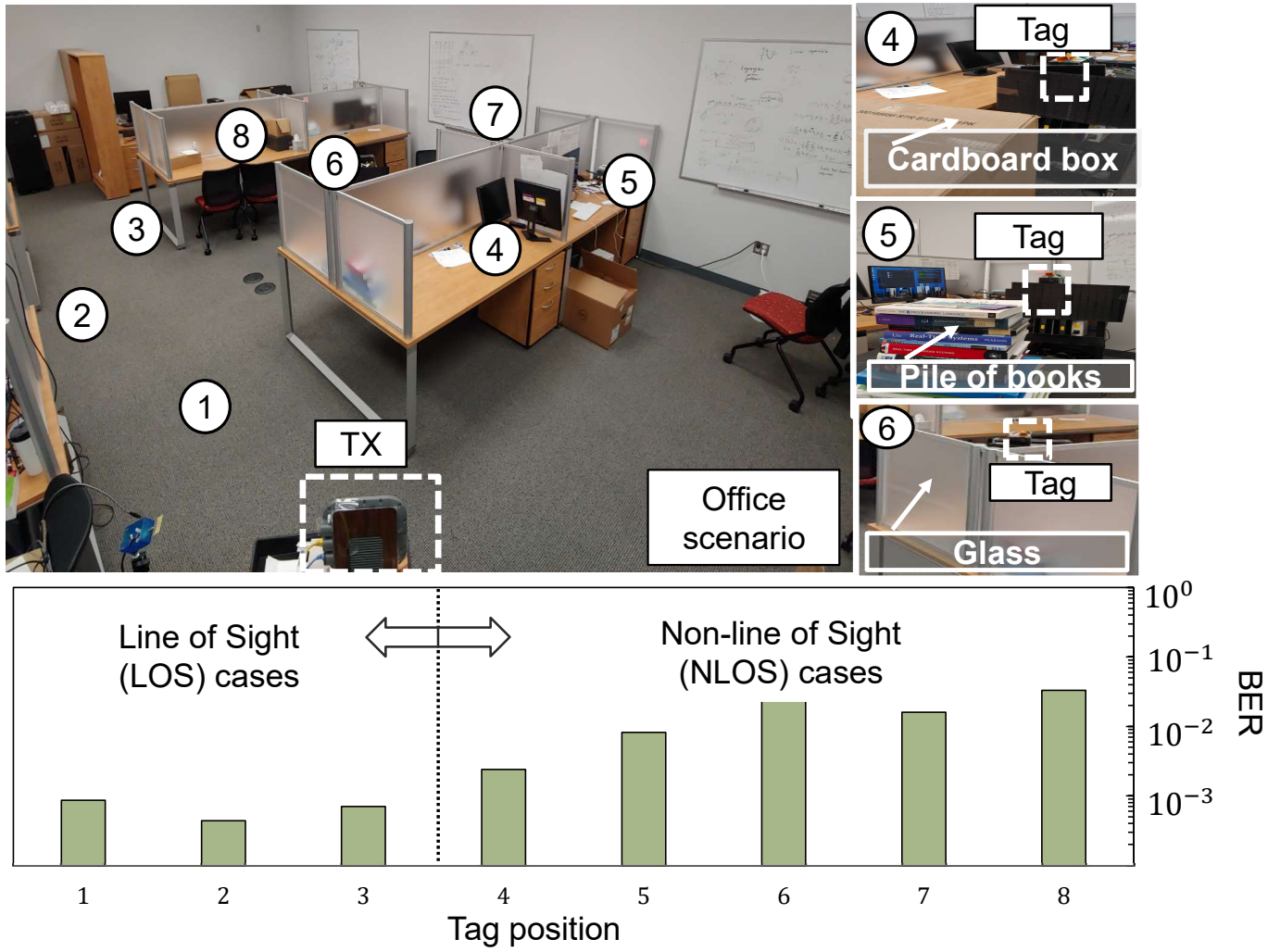


Tag at different locations

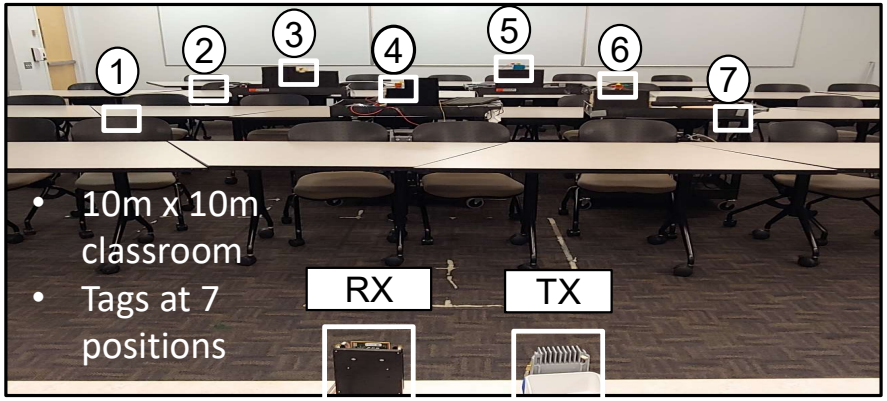
- 10m x 10m room where we collect over 200 measurements at 18 different locations
- mmComb can cover around 90°.

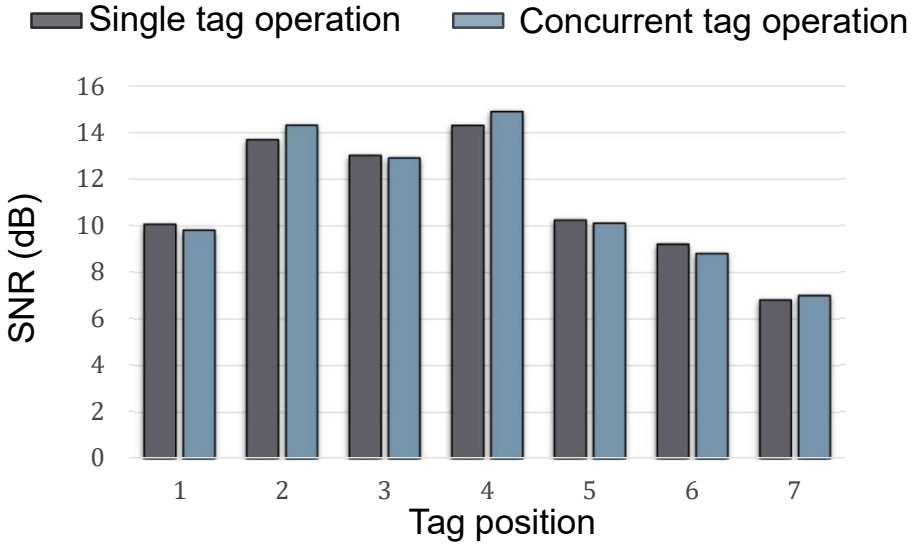


Practical Deployment



Multiple Concurrent Tags

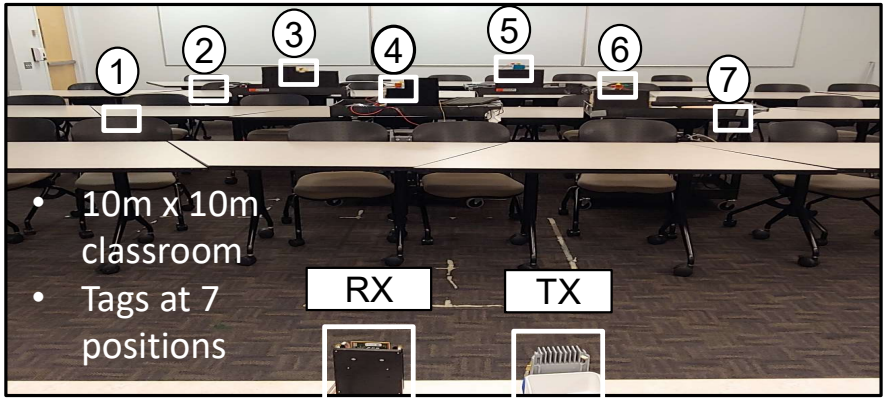


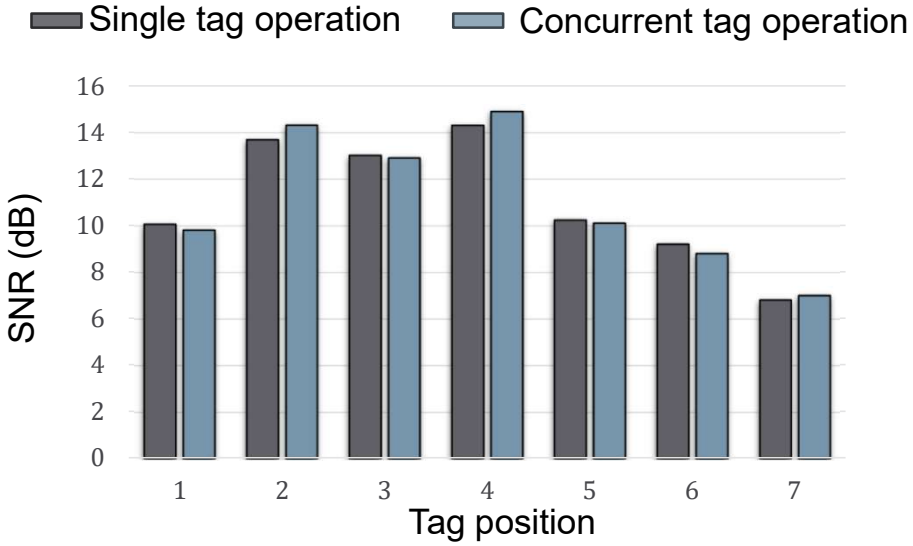


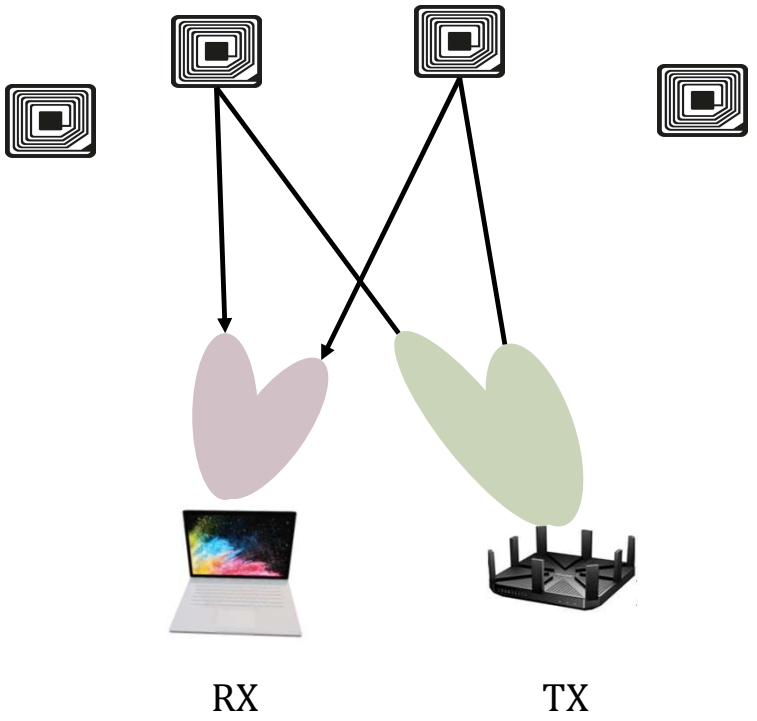
RX

TX

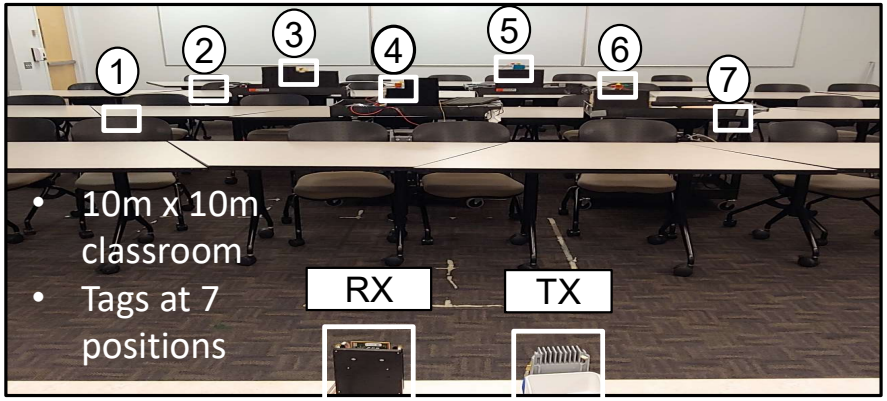
Multiple Concurrent Tags

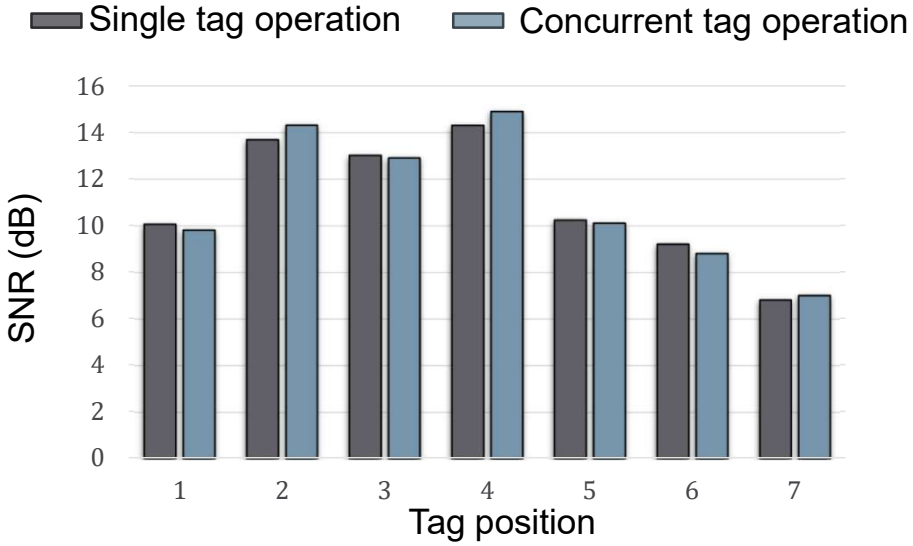


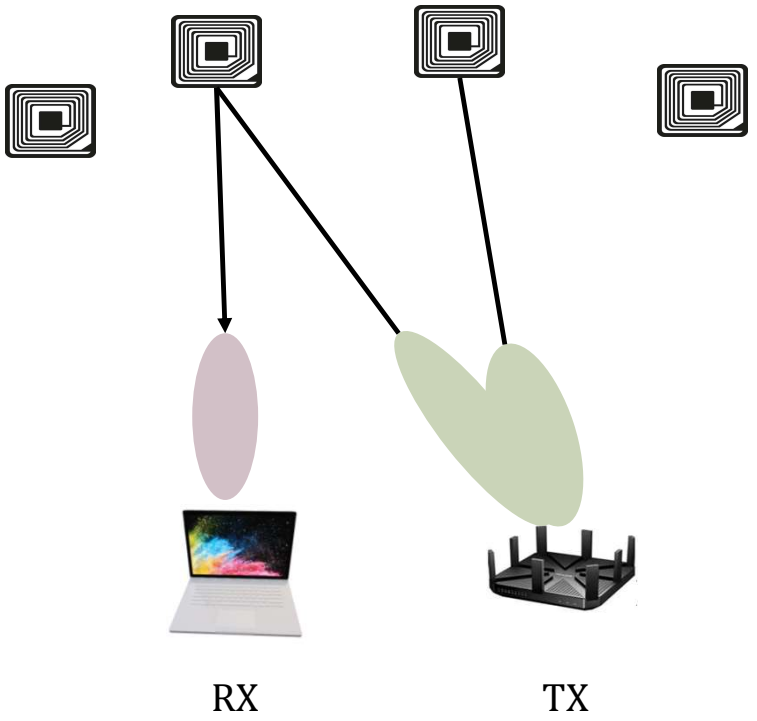




Multiple Concurrent Tags







Conclusion

- We introduce a **high-speed mmWave WiFi backscatter system** using commercial WiFi devices.
- mmComb seamlessly integrates backscatters into mmWave WiFi network without any hardware or protocol modifications.
- High data rate of backscatter communication up to 55Mbps
- Low power consumption (< 100μW)

nsdi '24

Thank you!

mmComb: High-speed mmWave Commodity WiFi Backscatter

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§ KAIST