Lend Me Your Beam:
Privacy Implications of Beamforming Feedback in WiFi

Rui Xiao[1], Xiankai Chen[1], Yinghui He[2], Jun Han[3], and Jinsong Han[1]

[1] Zhejiang University, [2]Nanyang Technological University, [3]KAIST

NDSS 2025

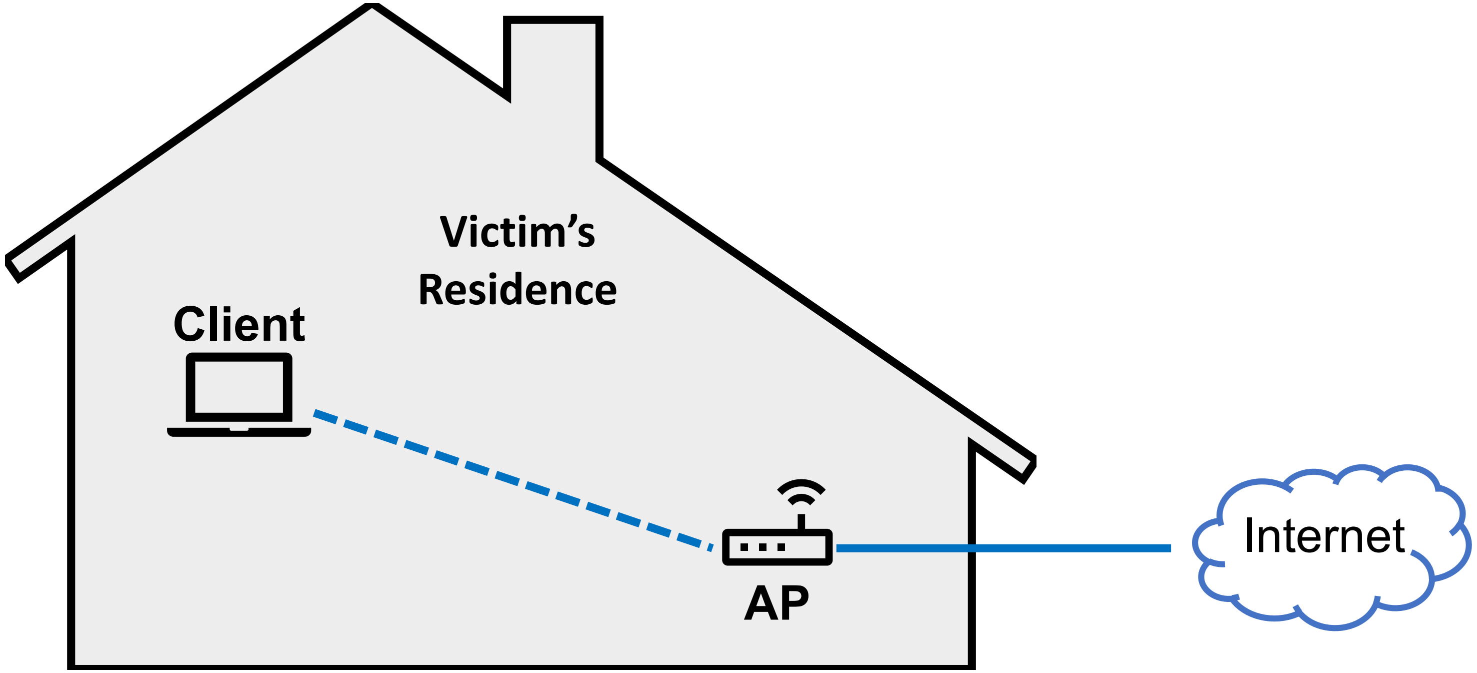
Smart WiFi Devices are Everywhere

Smart Home

Smart Factory

Smart Office

Attacks Enabled by WiFi Devices



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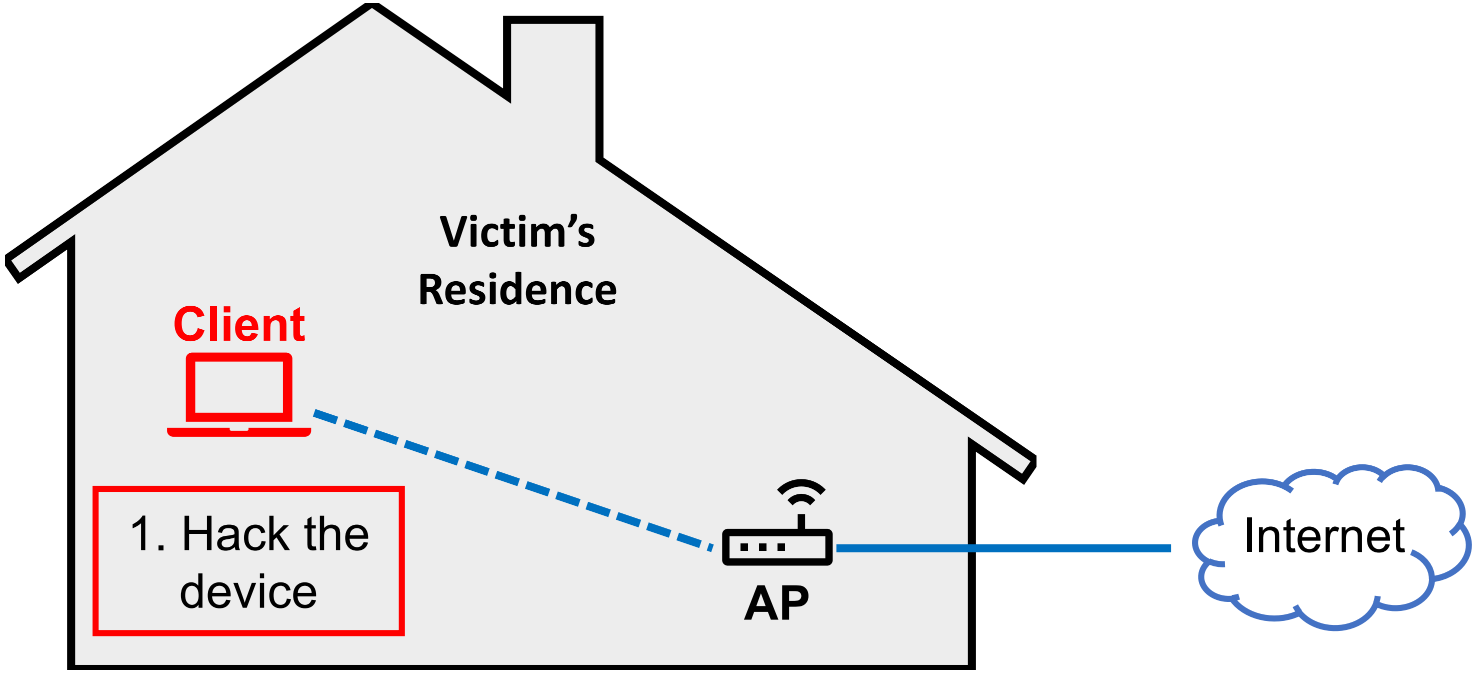
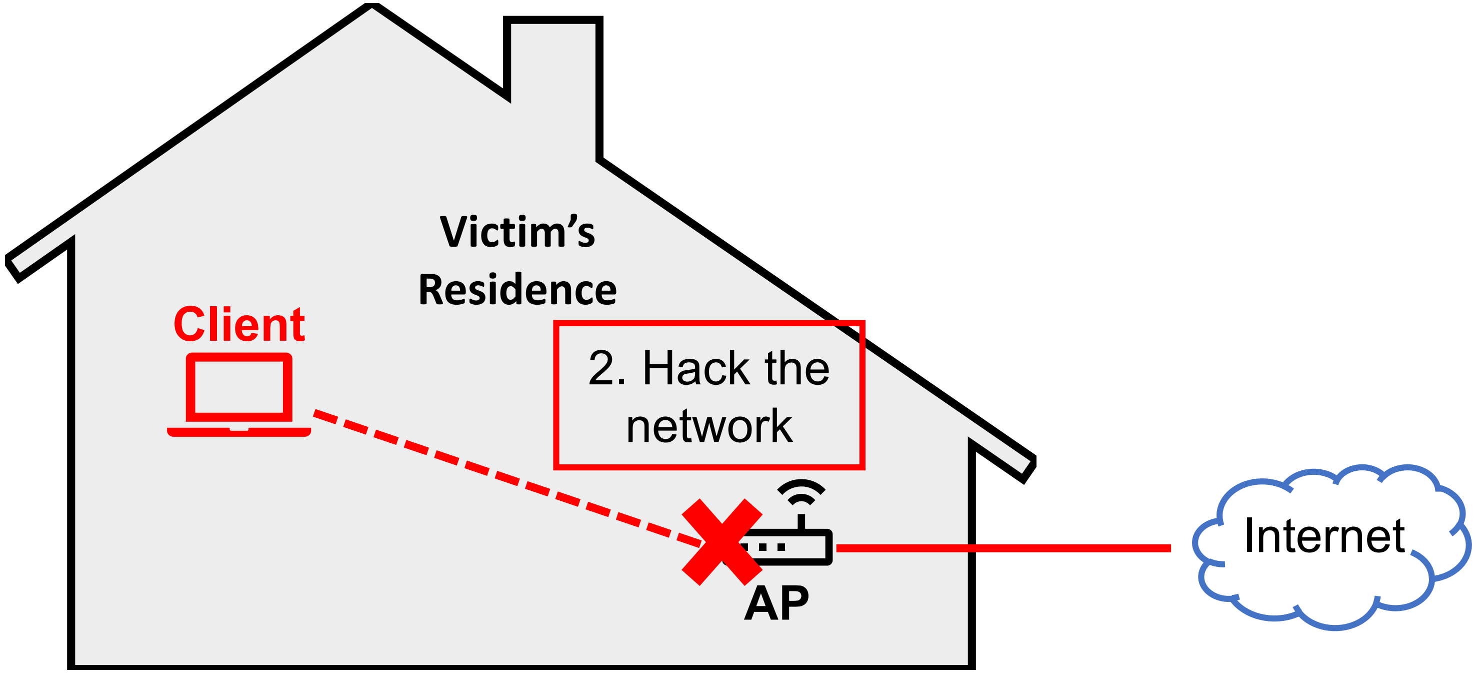


1. Hack the device

Attacks Enabled by WiFi Devices



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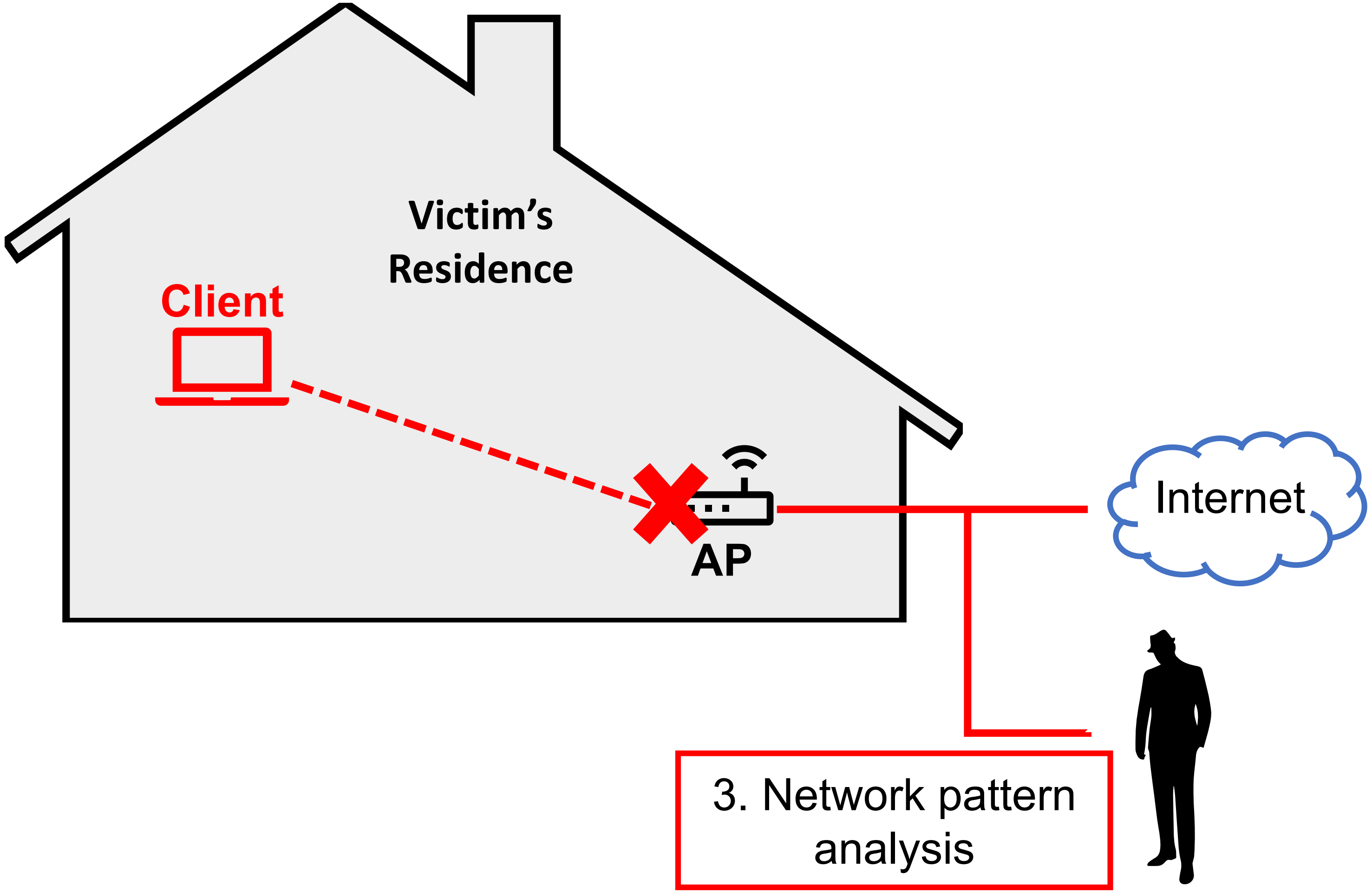

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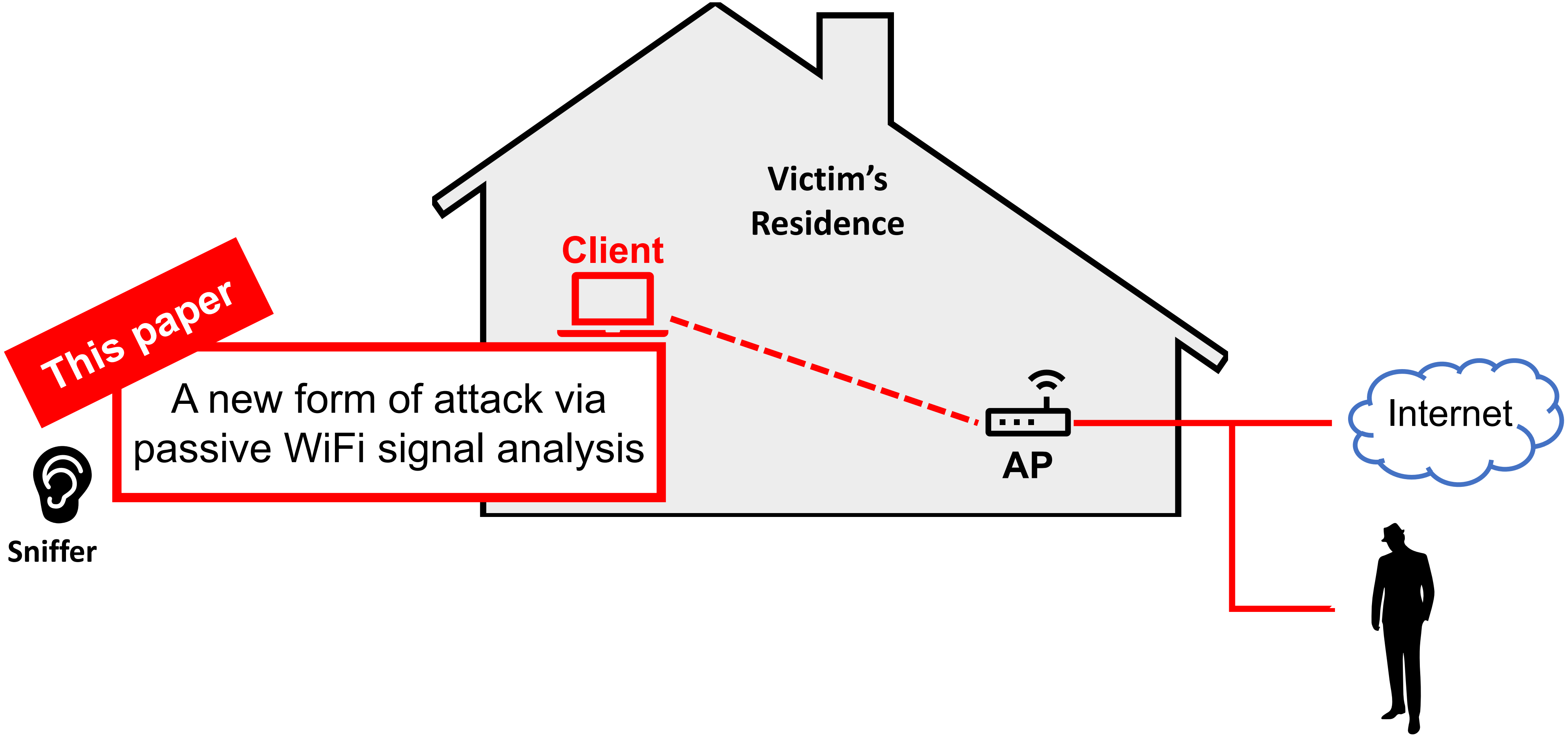
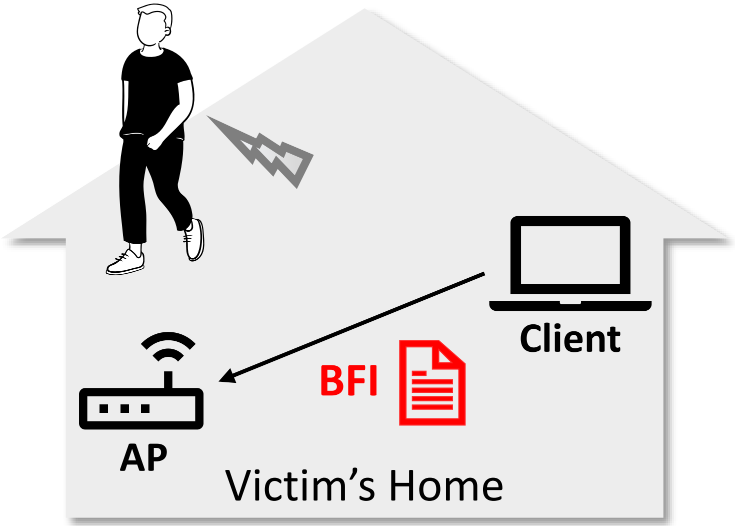


This paper

A new form of attack via passive WiFi signal analysis

This Paper: Silent Occupancy Detection Attack



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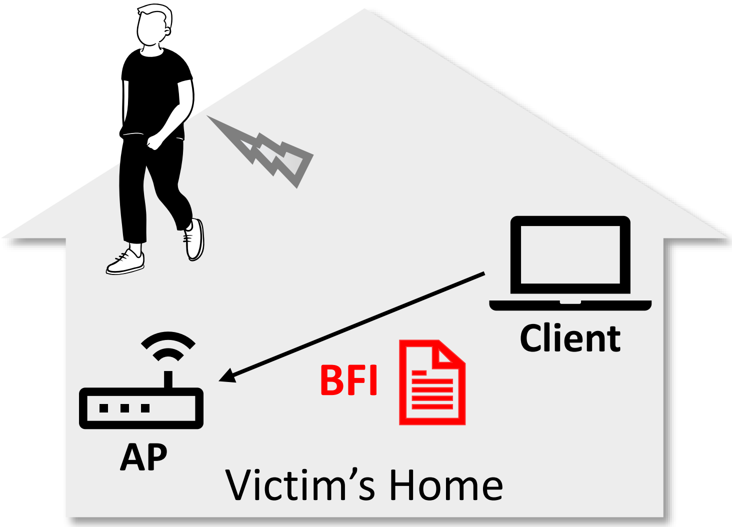
- New Side Channel from

Beamforming Feedback (BFI) Packets



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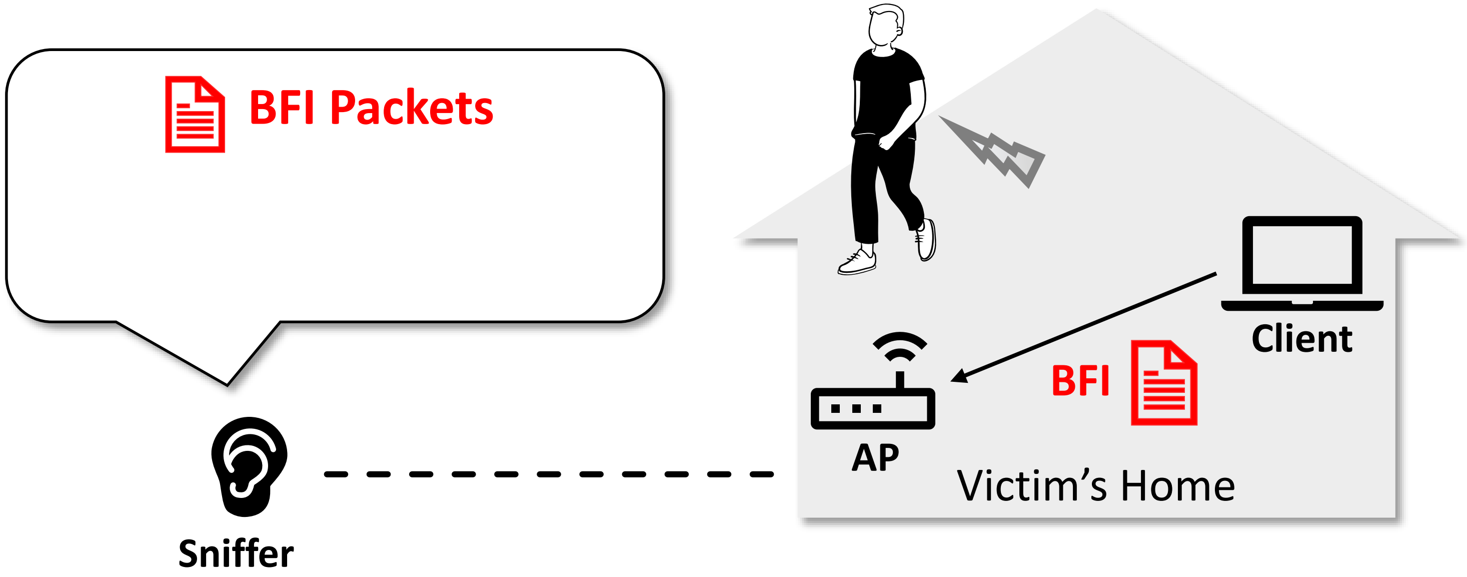

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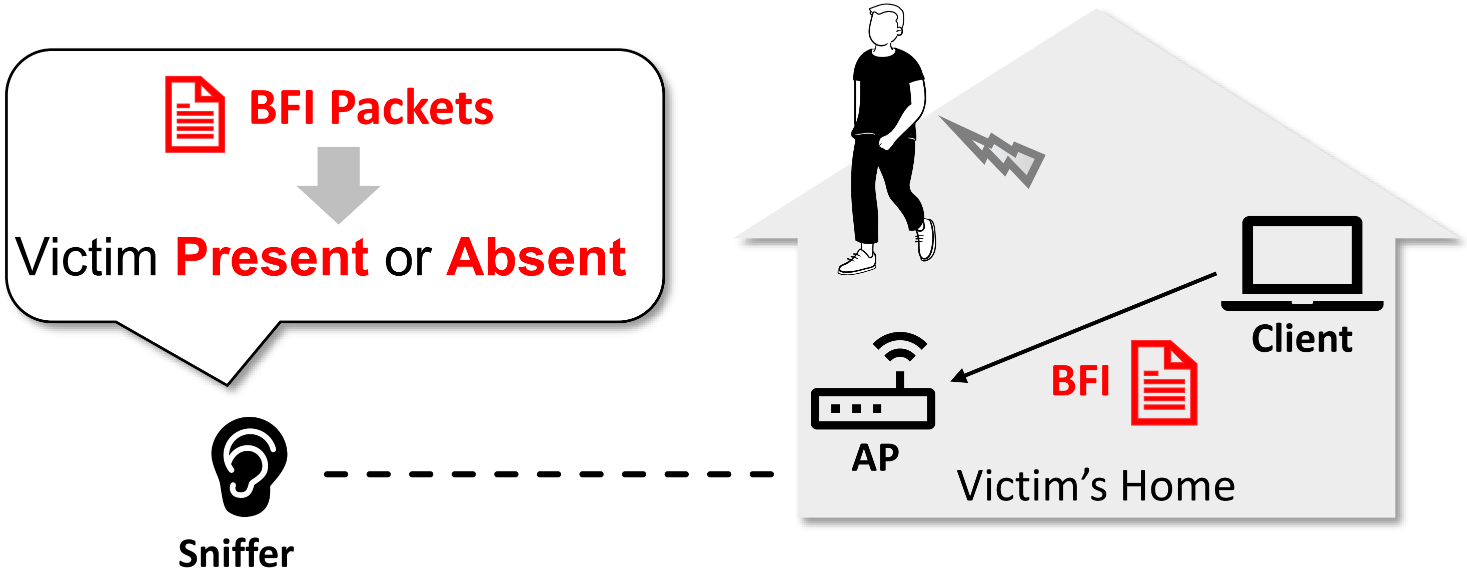

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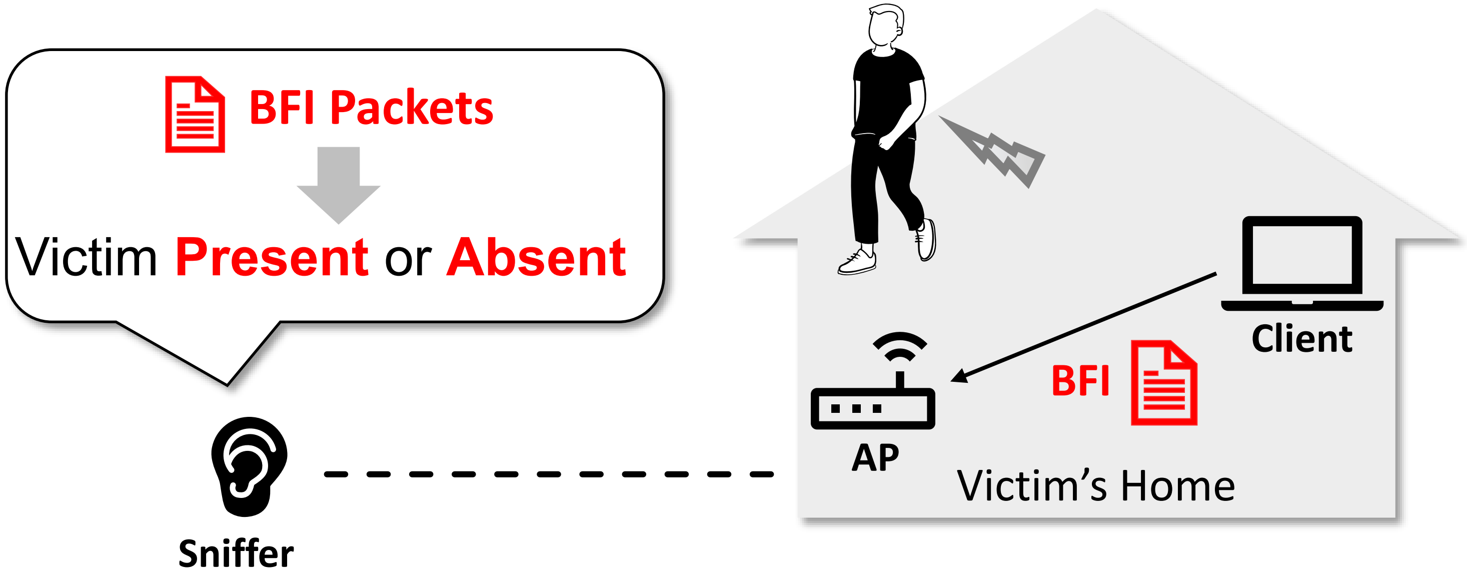

BFI Packets exists in 86% of WiFi 5/6 devices and is plaintext.

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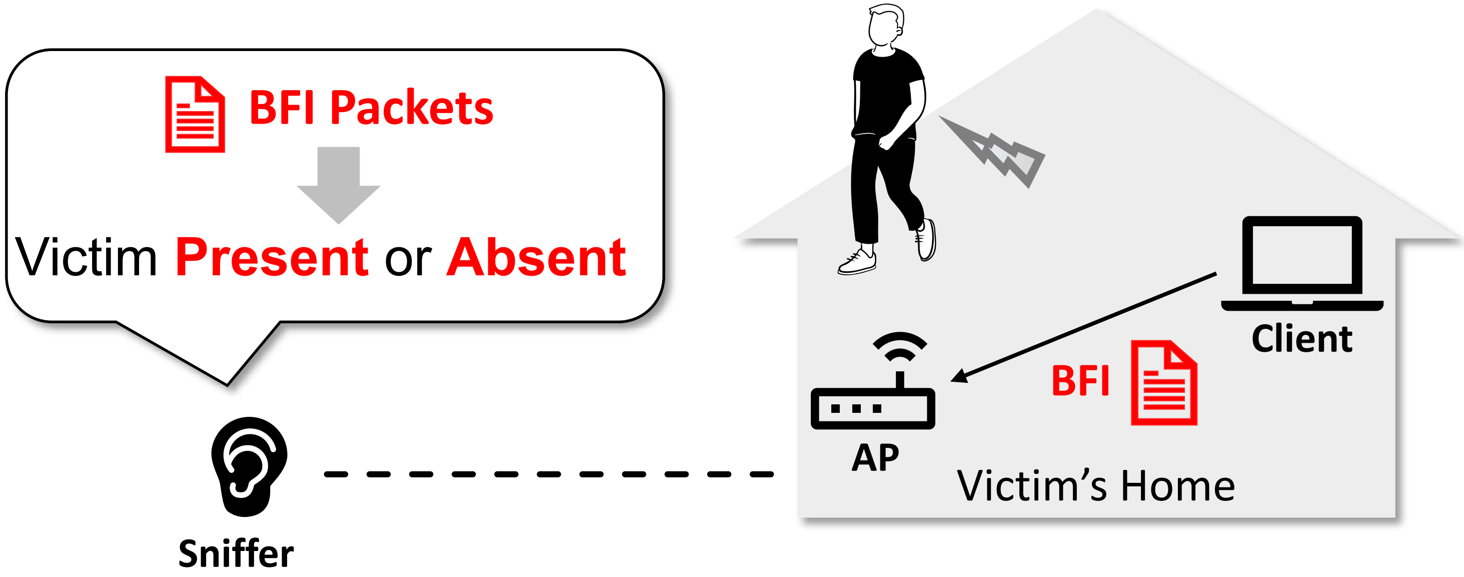


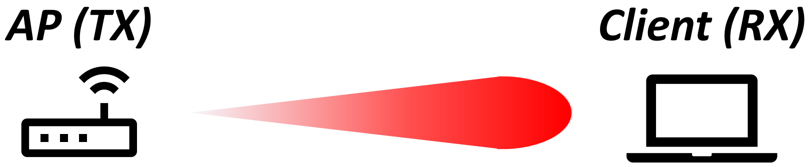
Spy Activity

Neighborhood Surveillance

BFI Packets exists in 86% of WiFi 5/6 devices and is plaintext.

BFI’s Original Purpose: Beamforming

- Beamforming is **Directional Signal Transmission** for SNR improvement



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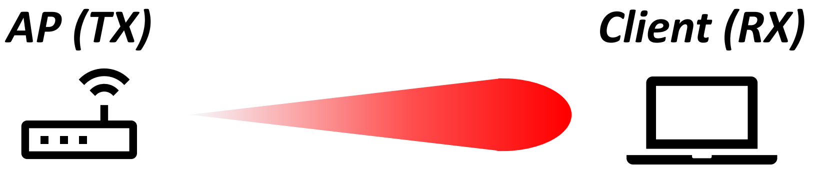
- AP needs a **steering matrix V (spatial information)** for beam direction control



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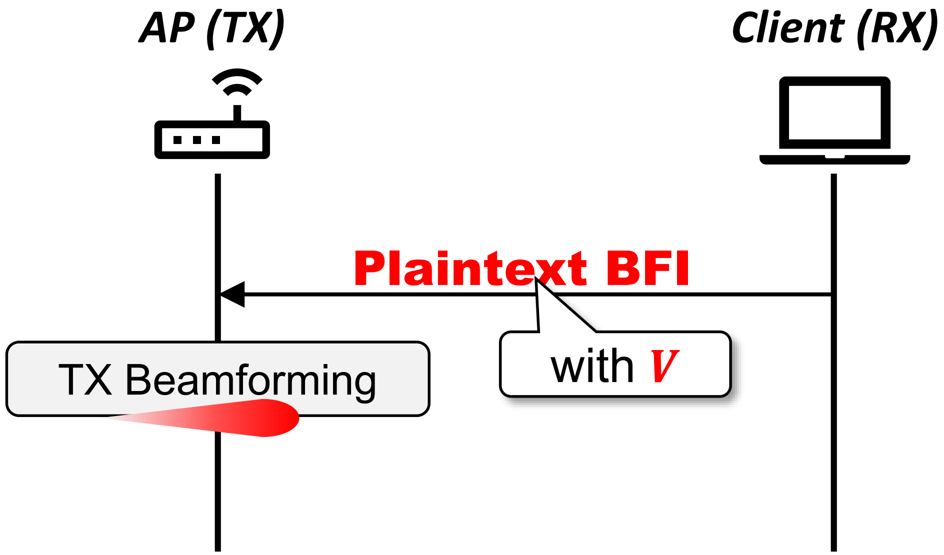

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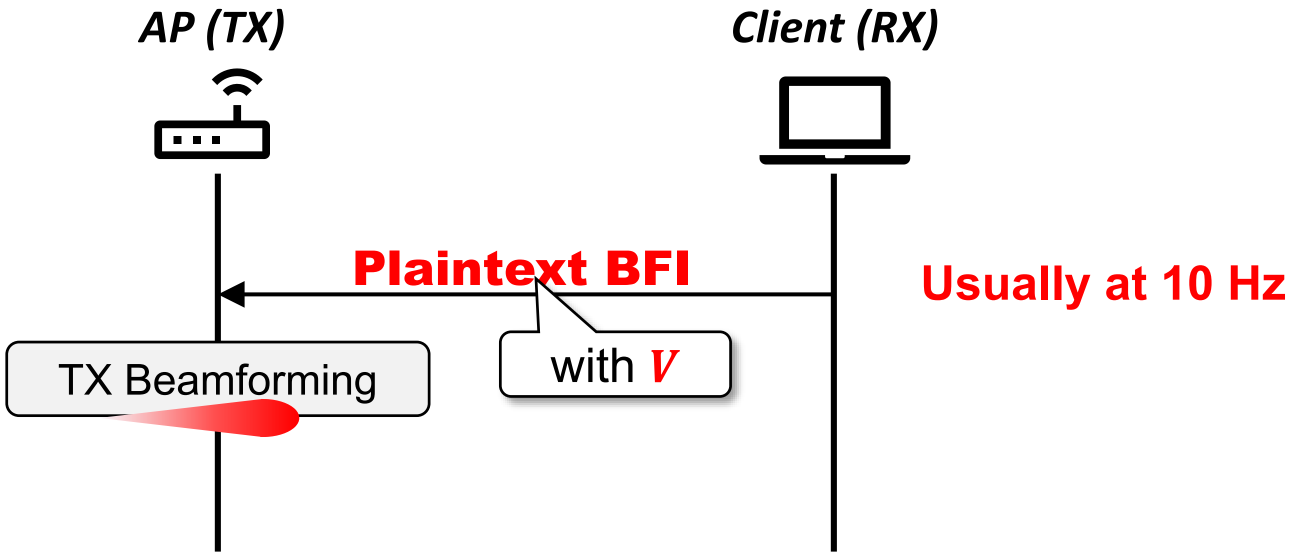

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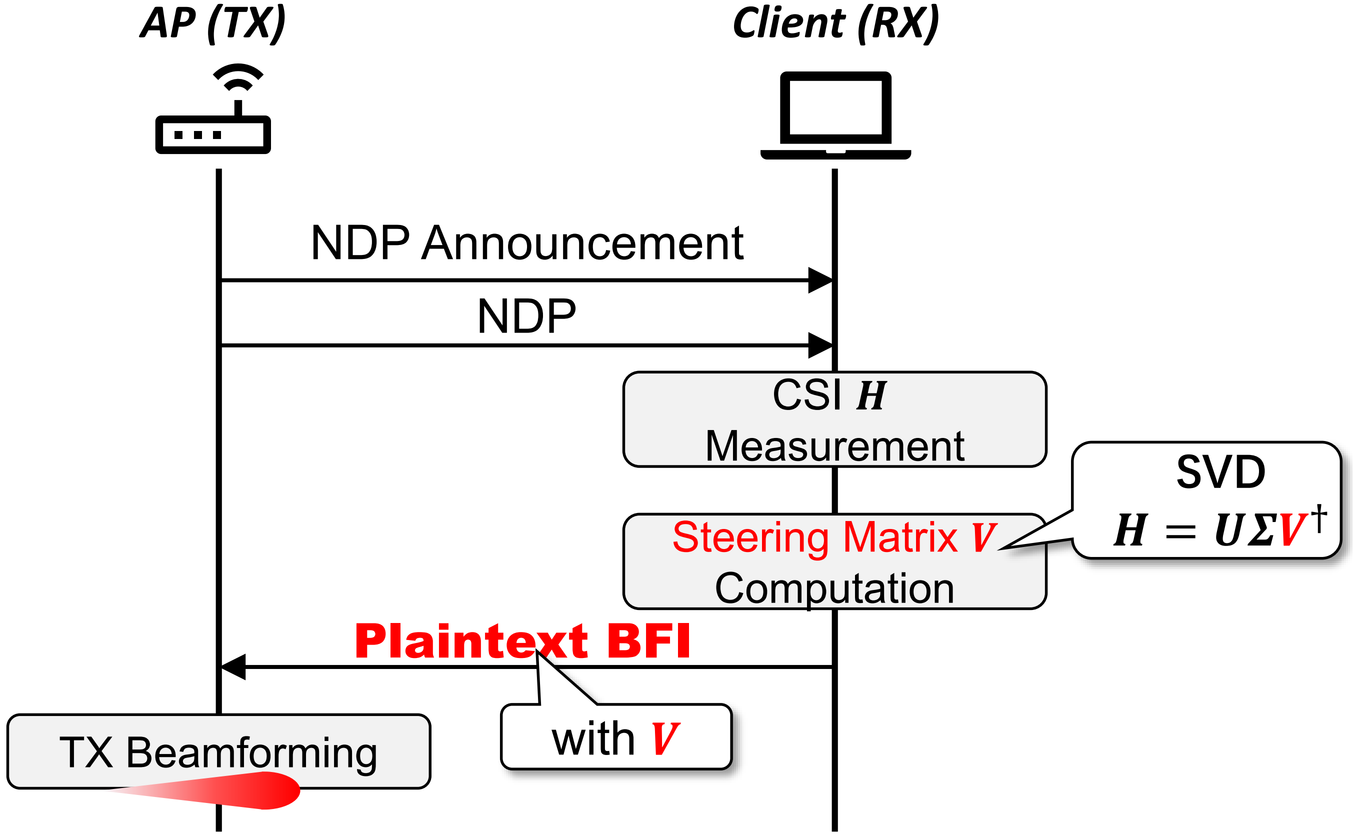

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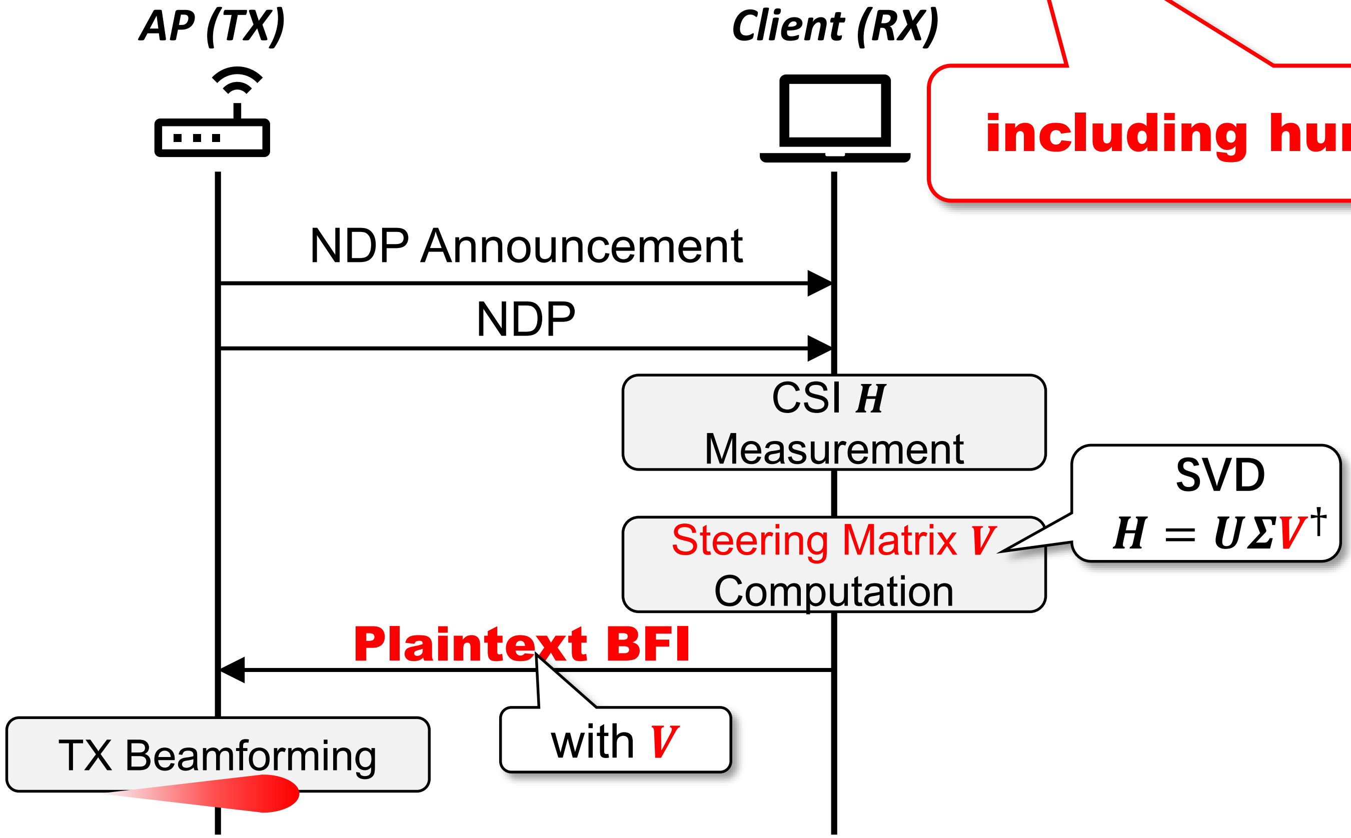
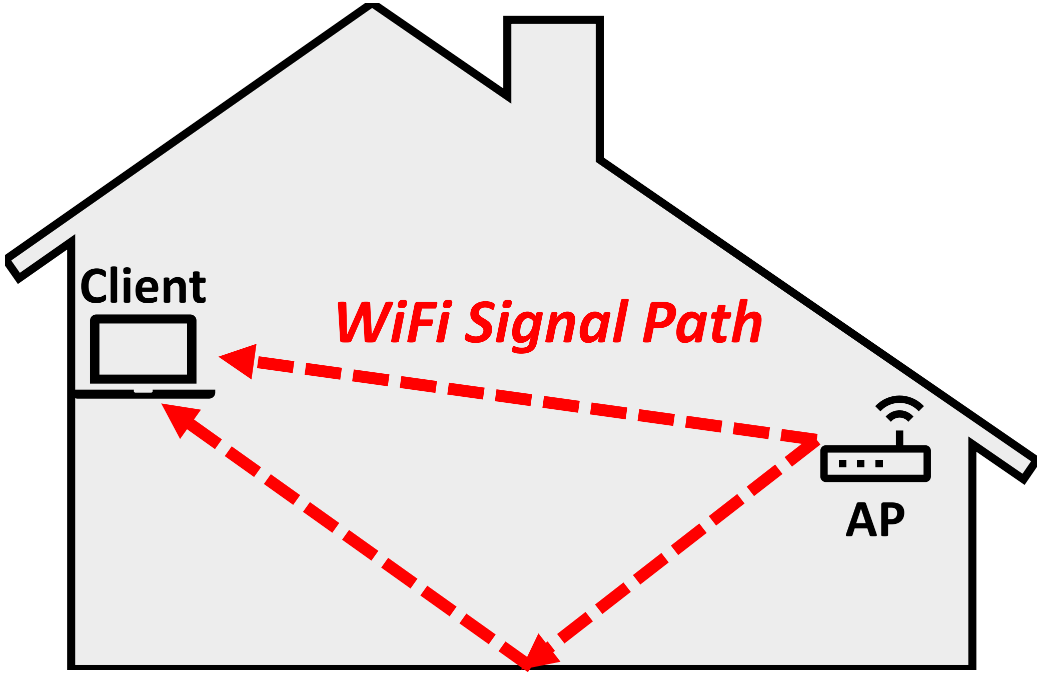
including human activity



How does BFI reveal human activity?



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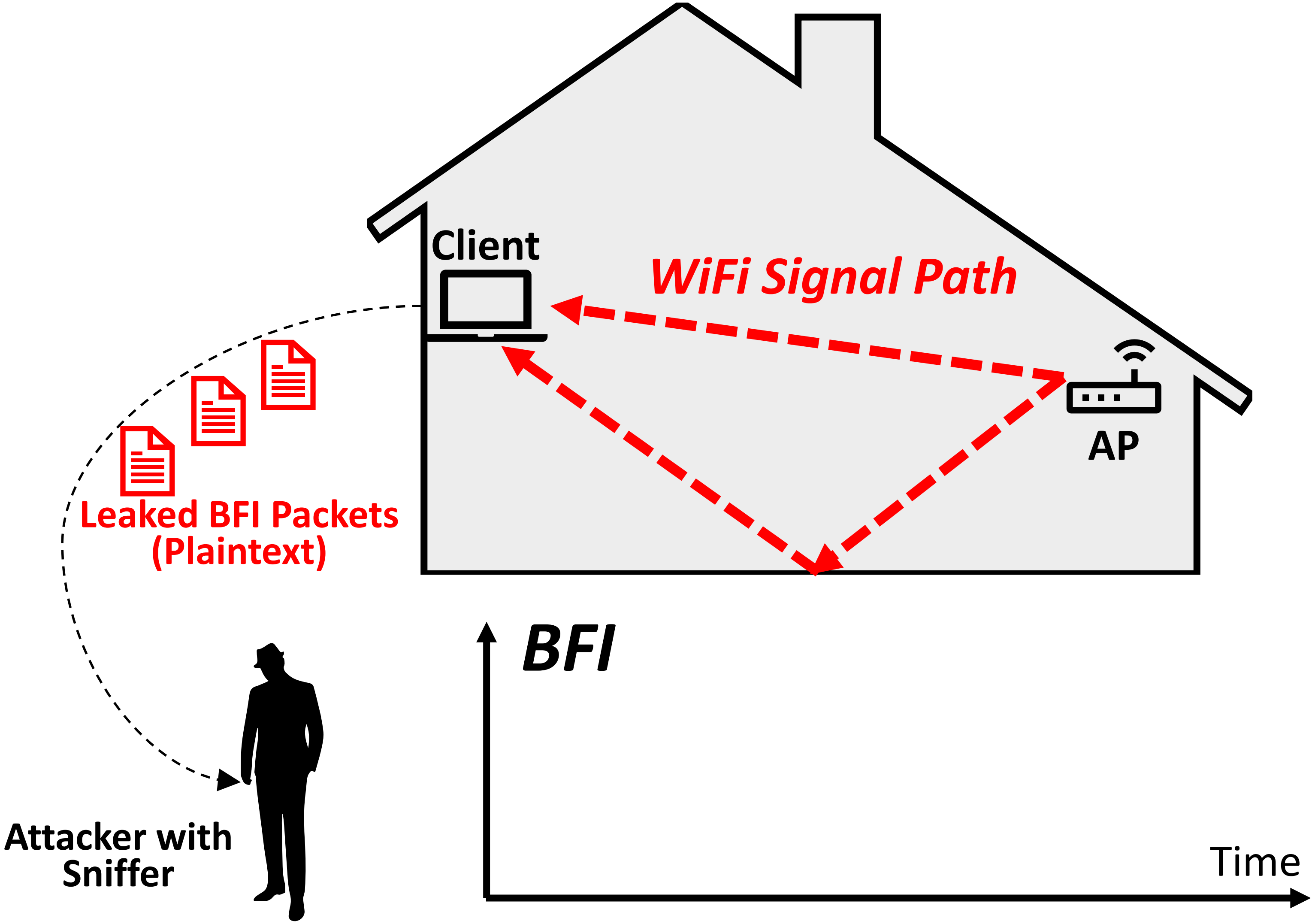

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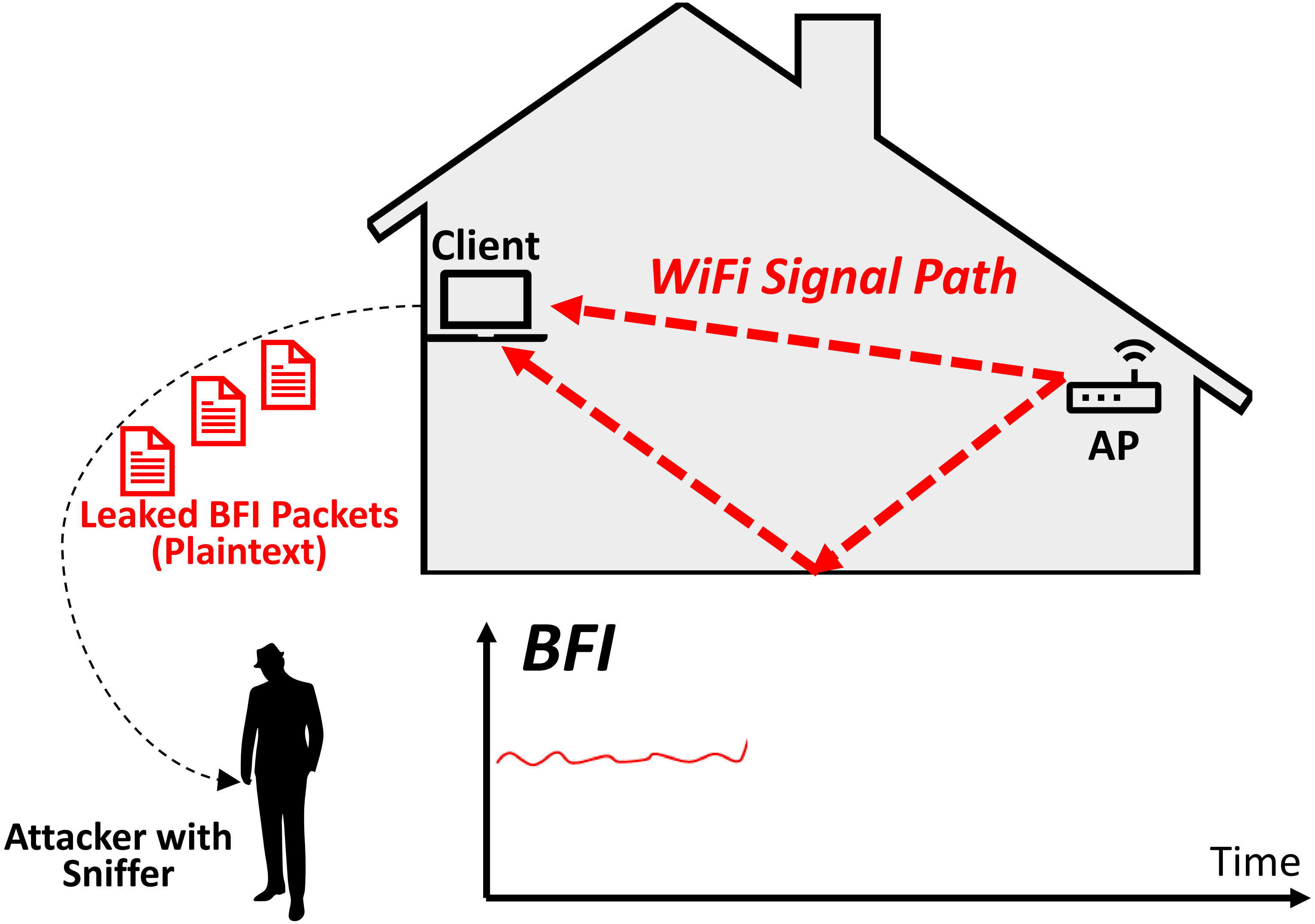

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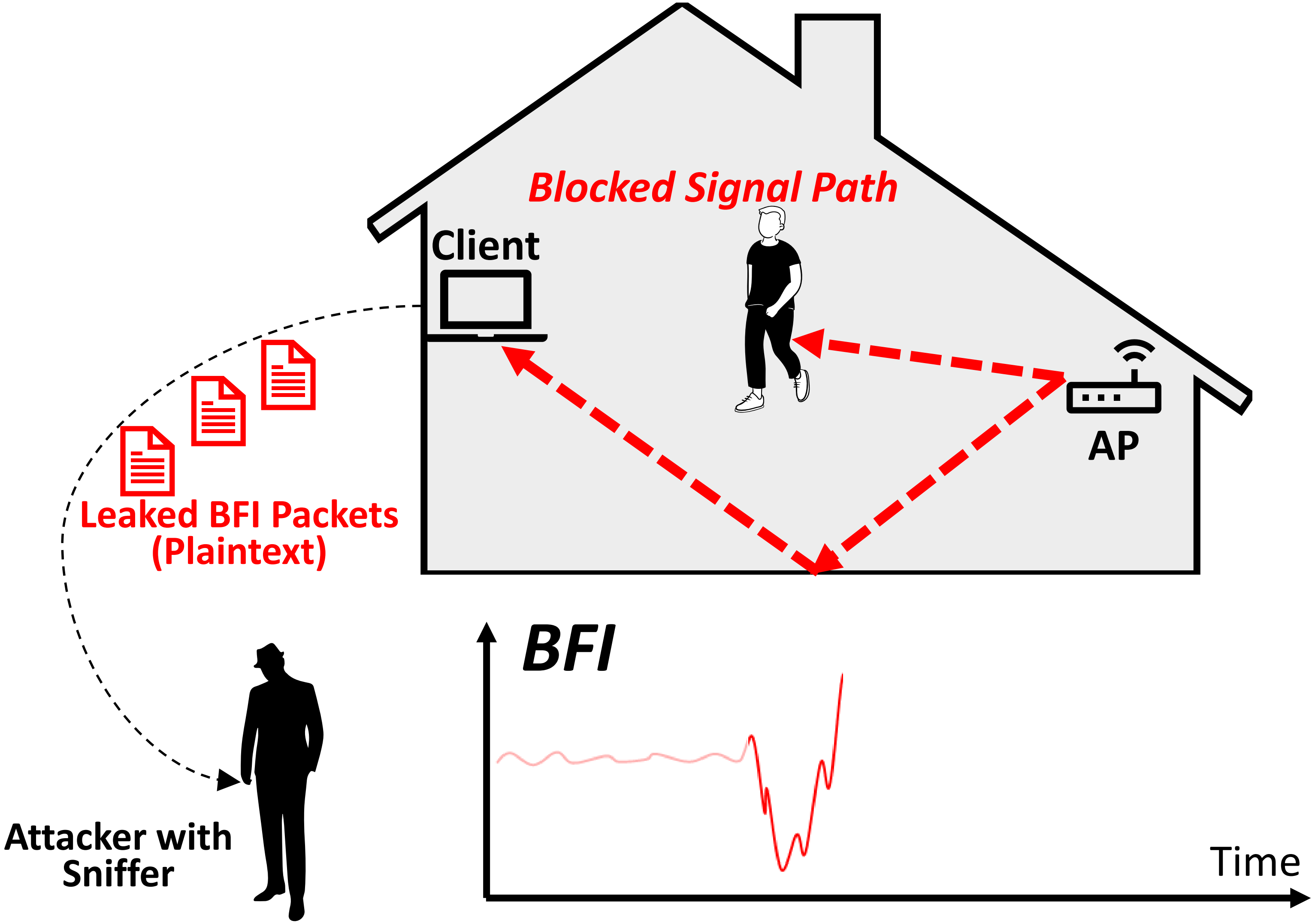

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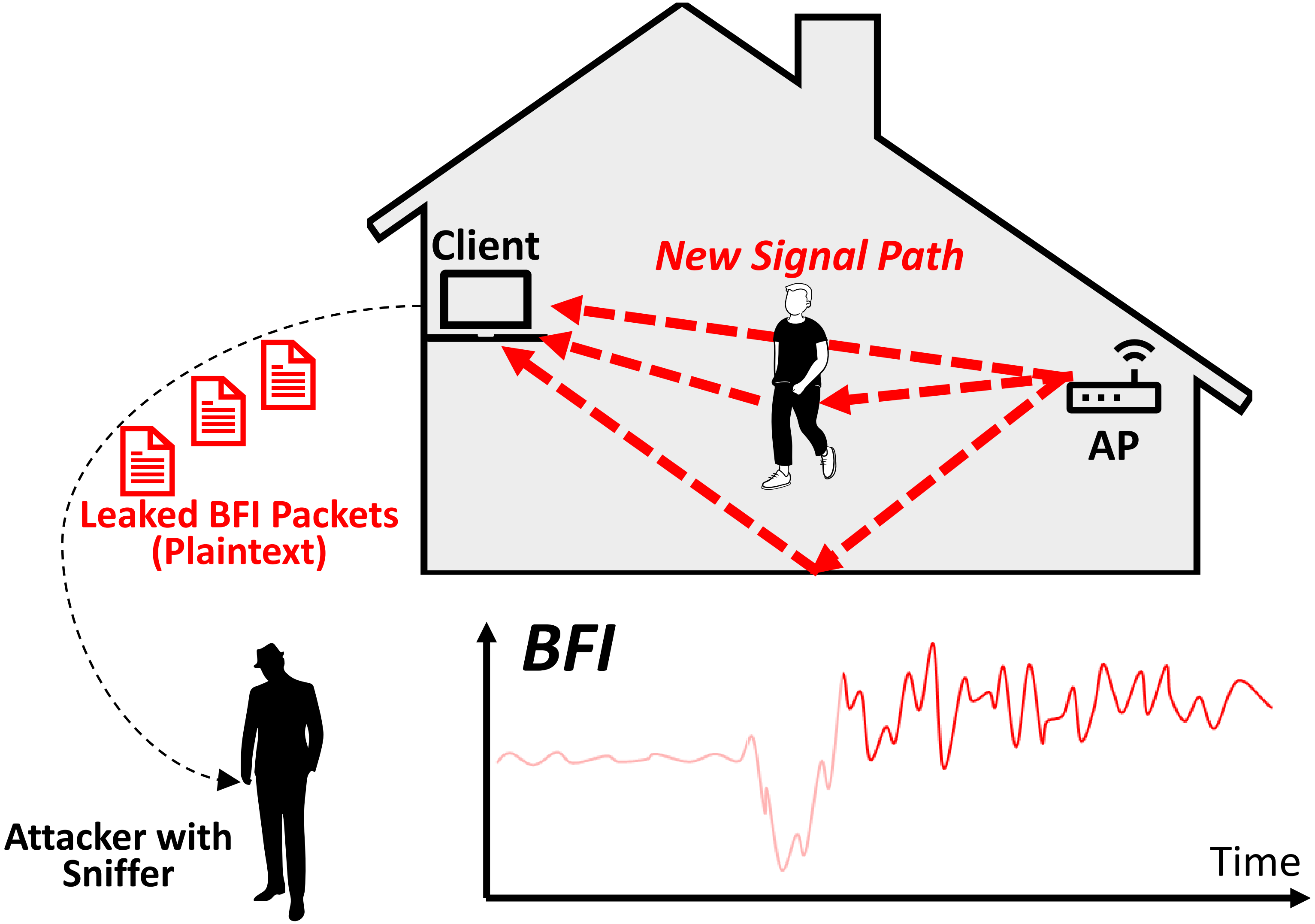
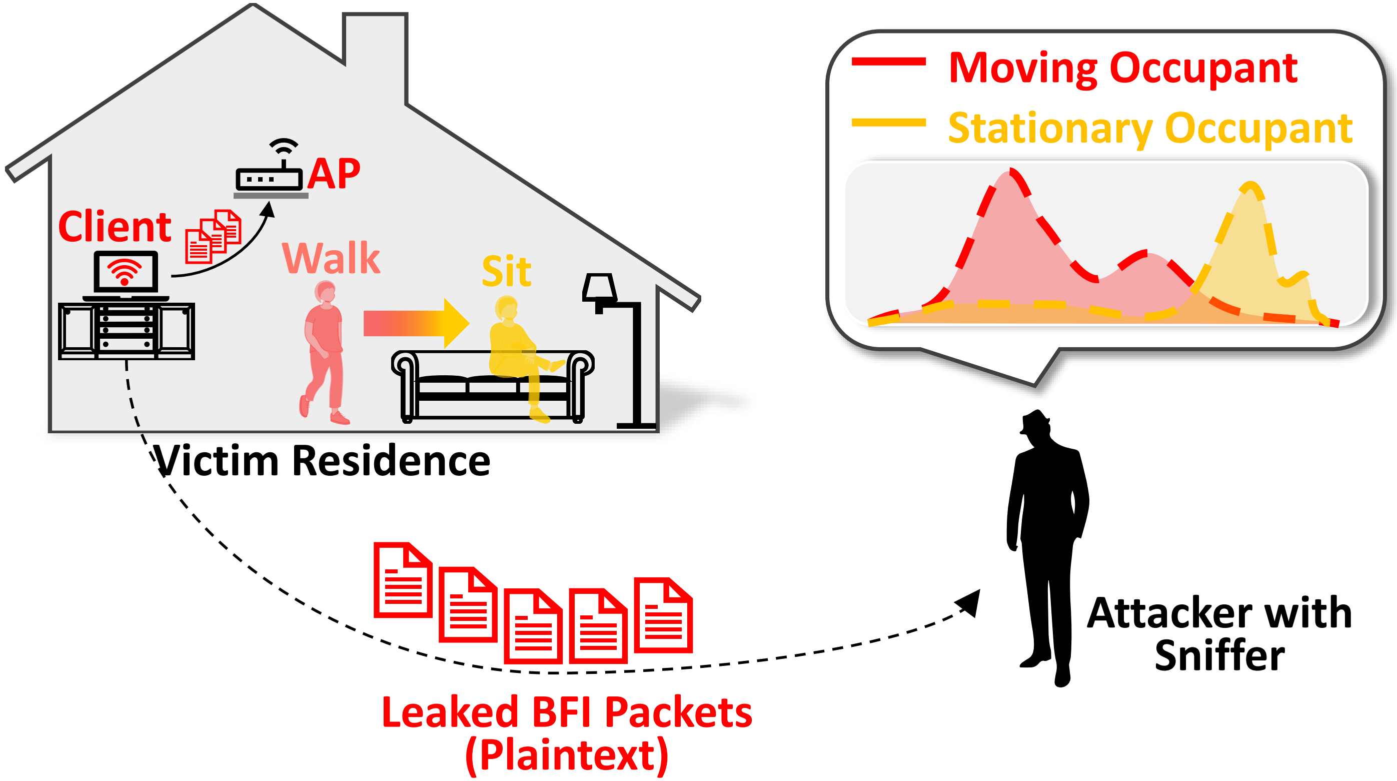


LeakyBeam – Silent Occupancy Detection Attack



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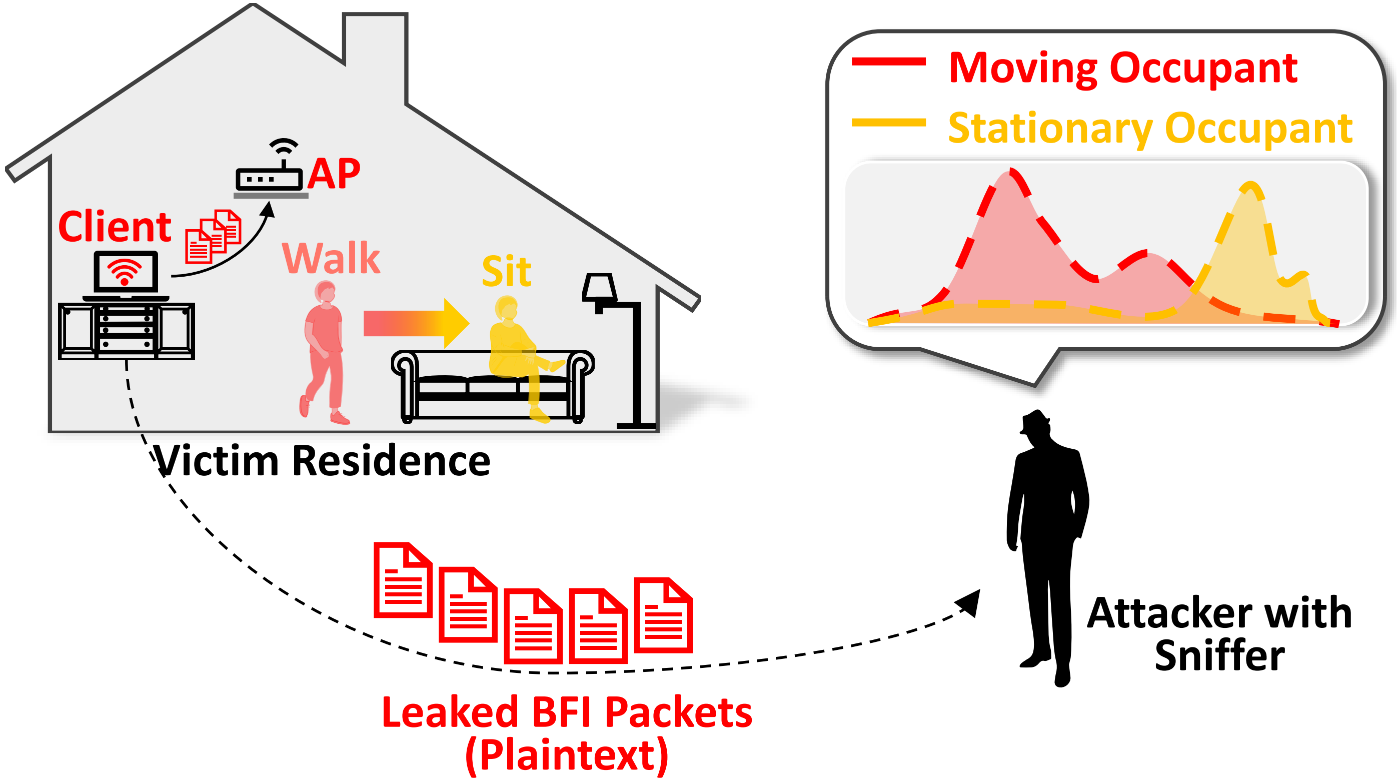
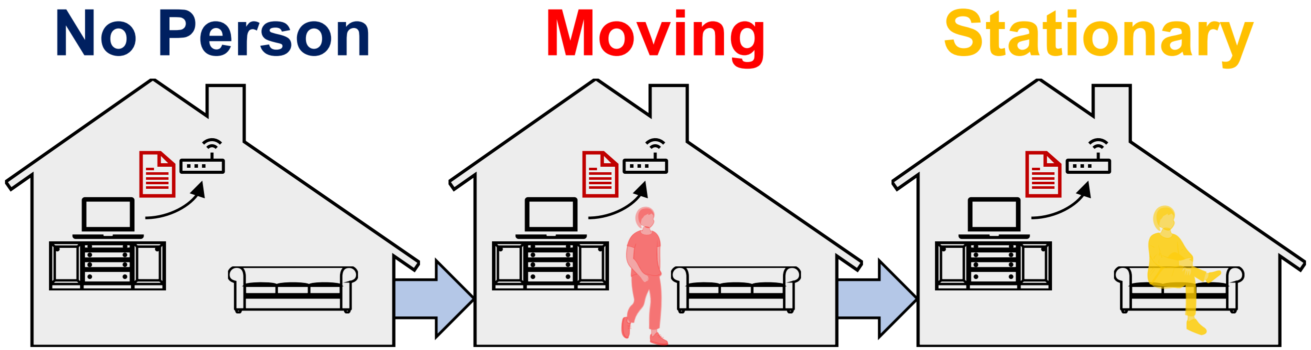


Key Features

- **High Accuracy**
  - Detect Stationary Occupant
- **Stealthiness**
  - Passive Sniffing
- **Accessibility**
  - Plaintext BFI packets
- **Long-Range**
  - Up to 20 meters

Overview: Measure Human Presence with BFI

Our Solution:



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Our Solution:

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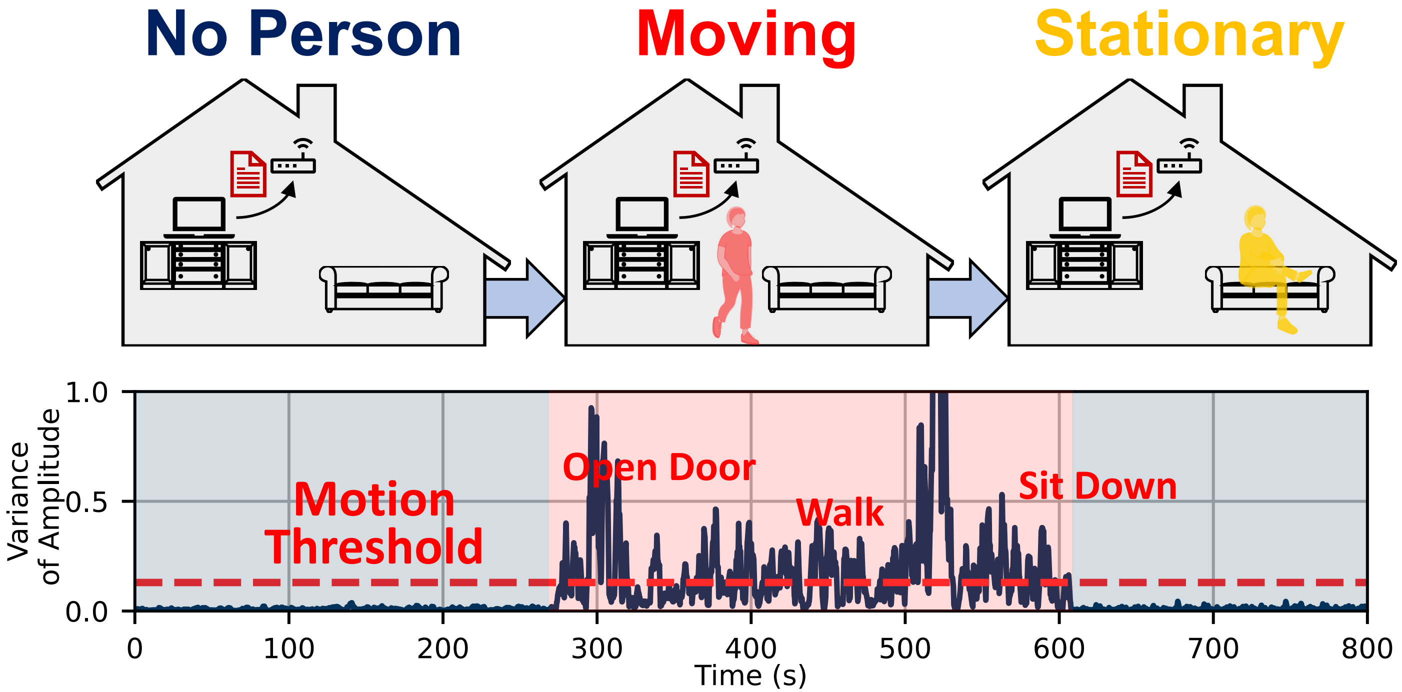
- Using **amplitude variance**
- Detect **moving** occupants



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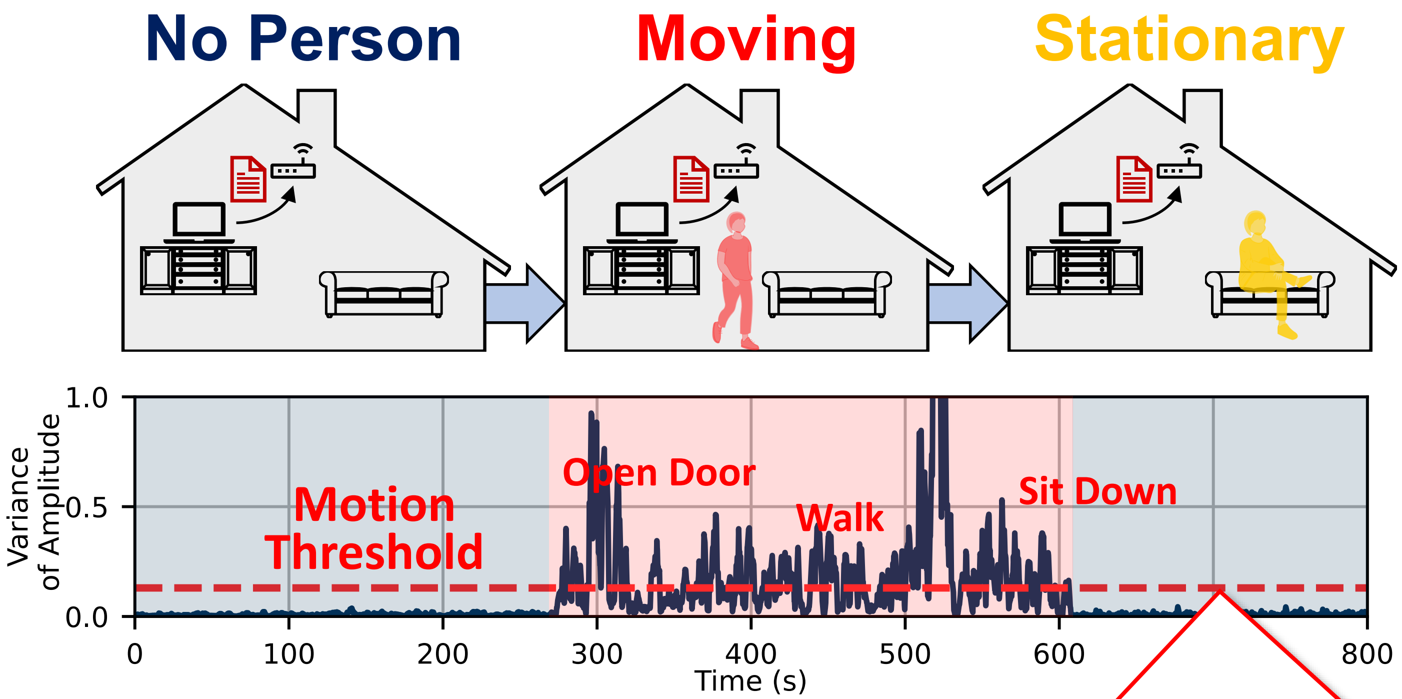

Cannot detect stationary occupant

Overview: Measure Human Presence with BFI

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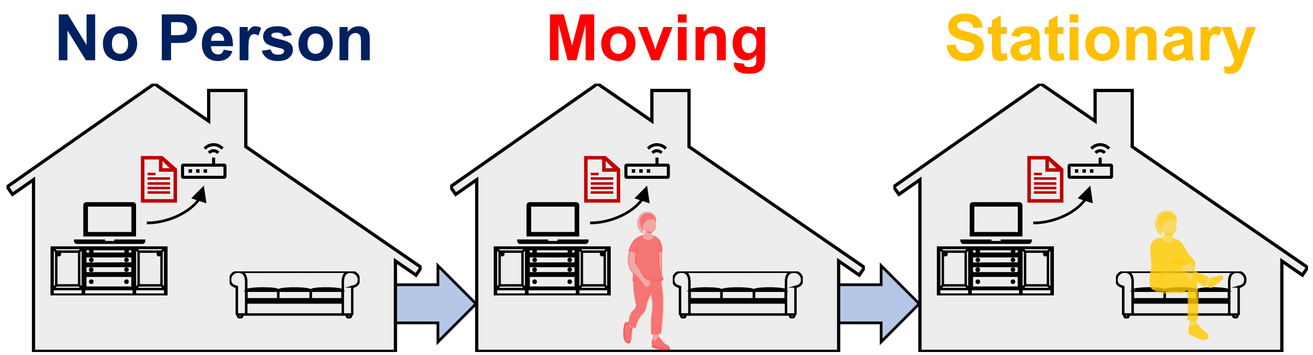
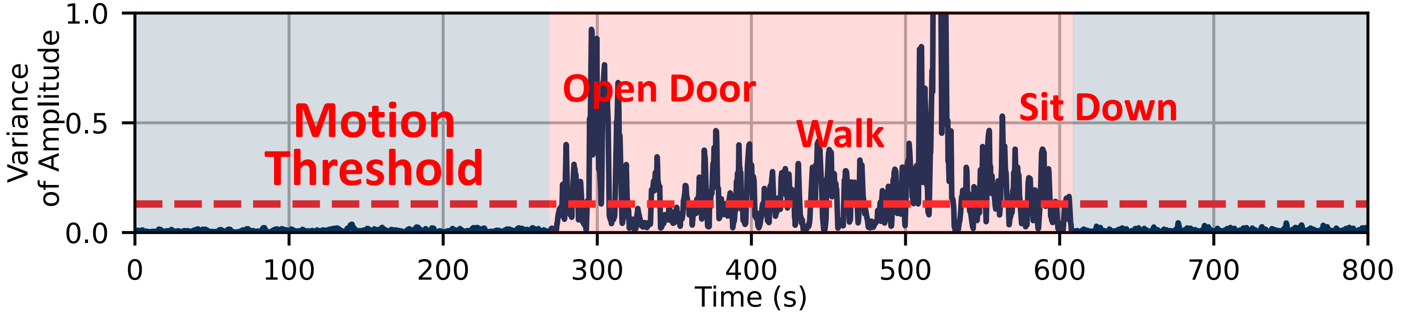
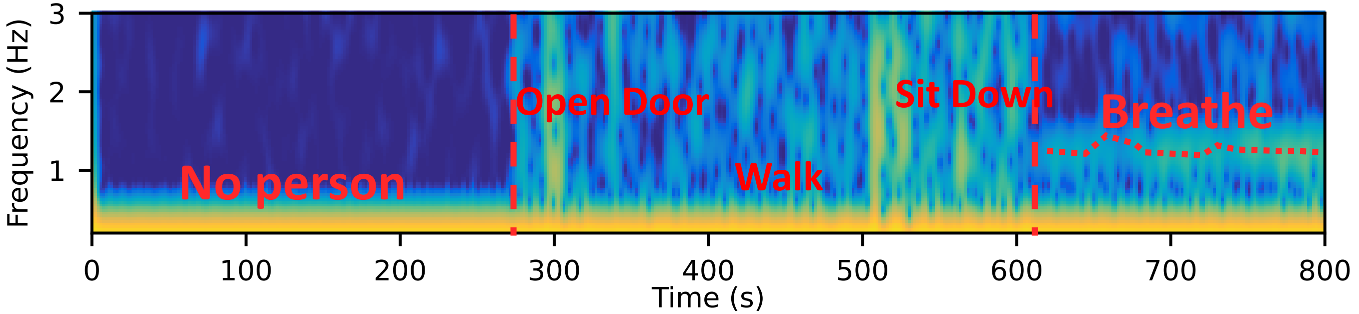
2) Breathe Detection

- Using **phase spectrogram**
- Detect **stationary** occupants







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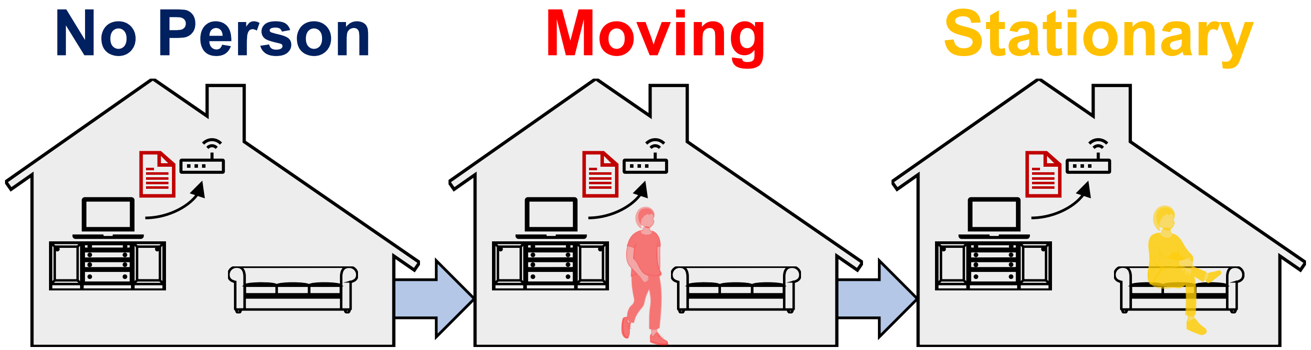

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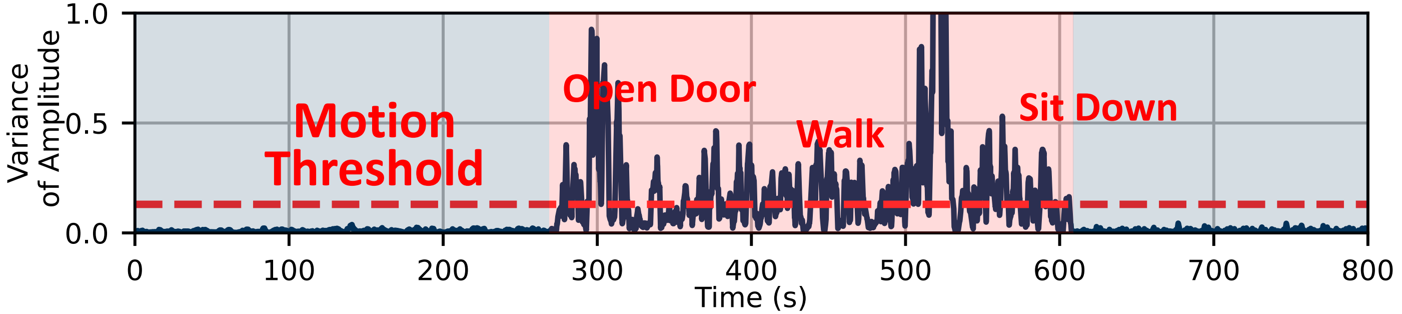

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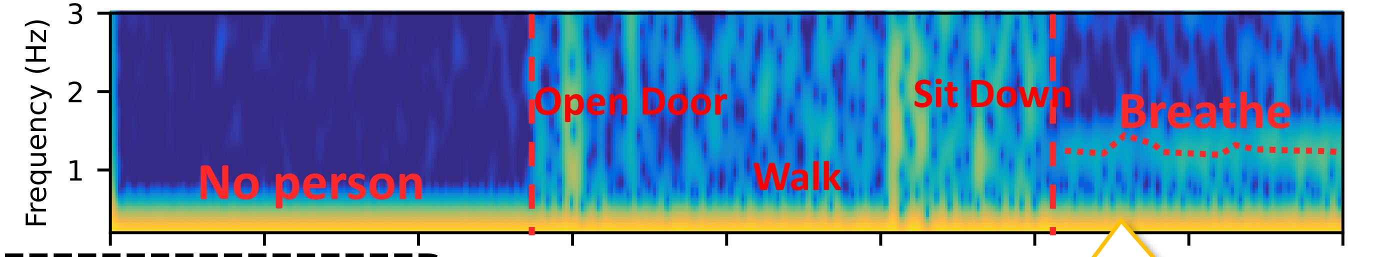
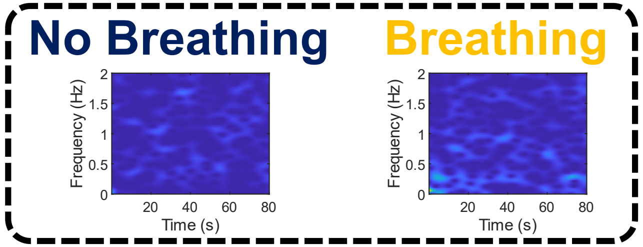




Challenge: Phase Offset

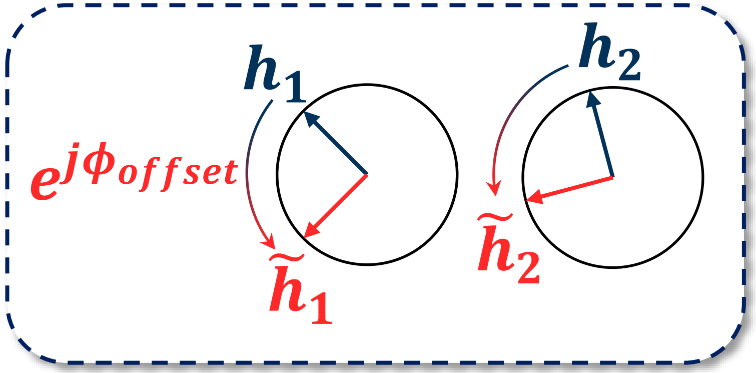
Challenge: Phase Offset from CSI to BFI

- Phase offset in CSI measurement:

$$\mathbf{H} = [\boldsymbol{h}_1, \boldsymbol{h}_2]$$

Phase Offset ϕ_{offset}

$$\widetilde{\mathbf{H}} = [\widetilde{\boldsymbol{h}}_1, \widetilde{\boldsymbol{h}}_2]$$


$\boldsymbol{h}_1$
$\boldsymbol{h}_2$
$e^{j\phi_{offset}}$
$\widetilde{\boldsymbol{h}}_1$
$\widetilde{\boldsymbol{h}}_2$

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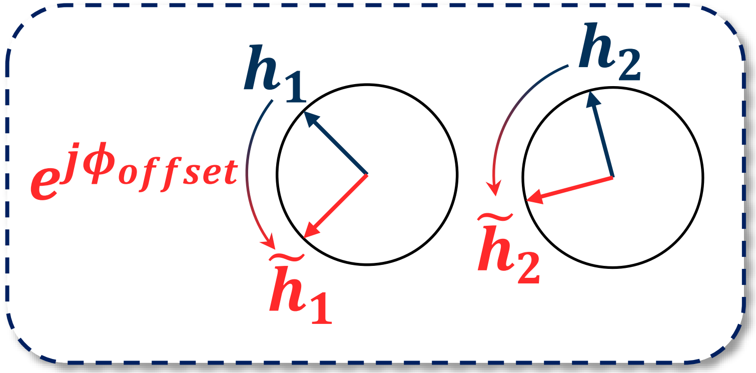
$\boldsymbol{h}_1$
$\boldsymbol{h}_2$
$e^{j\phi_{offset}}$
$\widetilde{\boldsymbol{h}}_1$
$\widetilde{\boldsymbol{h}}_2$

- BFI $\boldsymbol{V}$ is the right singular matrix of $\boldsymbol{H}$, i.e., $\boldsymbol{H} = \boldsymbol{U\Sigma V}^{\dagger}$:

$$\mathbf{V} = [\boldsymbol{v}_1, \boldsymbol{v}_2]$$

$$\Big\downarrow \quad \mathbf{V} = \left(\boldsymbol{\Sigma}^{-1}\mathbf{U}^{\dagger}\widetilde{\mathbf{H}}\right)^{\dagger}$$

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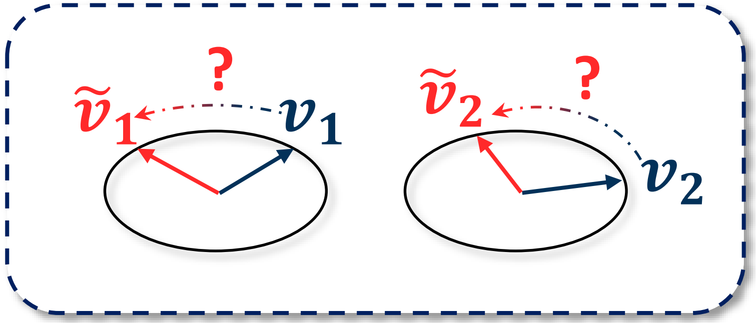
$\widetilde{\boldsymbol{v}}_1$
?
$\boldsymbol{v}_1$
$\widetilde{\boldsymbol{v}}_2$
?
$\boldsymbol{v}_2$

Solution: Deriving a Phase-Offset-Free Feature

- New Feature $\mathrm{R} := \widetilde{\mathrm{V}}\Sigma^2\widetilde{\mathrm{V}}^\dagger$

R is phase-offset-free

Solution: Deriving a Phase-Offset-Free Feature

- **New Feature** $\mathbf{R} := \tilde{\mathbf{V}}\boldsymbol{\Sigma}^2\tilde{\mathbf{V}}^\dagger$
- Proof:

$$\boldsymbol{R} = V\Sigma U^\dagger U\Sigma V^\dagger = \left(U\Sigma V^\dagger\right)^\dagger\left(U\Sigma V^\dagger\right) = \boldsymbol{H}^\dagger\boldsymbol{H} = \begin{pmatrix} \boldsymbol{h}_1^\dagger\boldsymbol{h}_1 & \boldsymbol{h}_1^\dagger\boldsymbol{h}_2 \\ \boldsymbol{h}_2^\dagger\boldsymbol{h}_1 & \boldsymbol{h}_2^\dagger\boldsymbol{h}_2 \end{pmatrix}$$

Conjugate Multiplication
Between Antennas

⬇

Phase-Offset-Free

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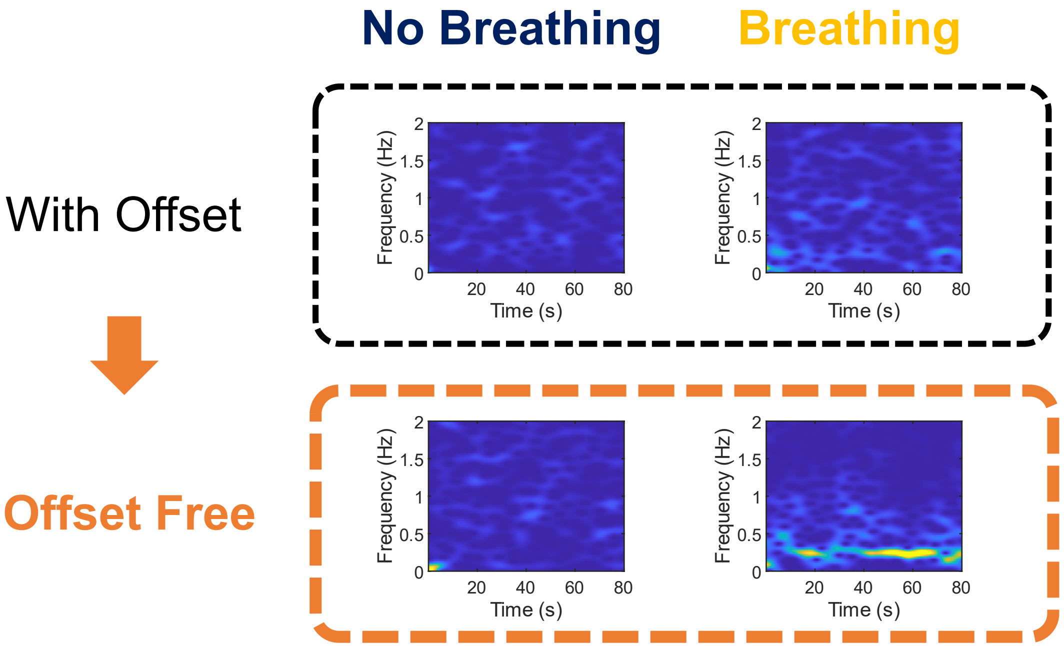
Conjugate Multiplication Between Antennas

↓

Phase-Offset-Free



Evaluation Setup

Sniffer

Dell Laptop
(**no external antenna**)

with

Wireshark

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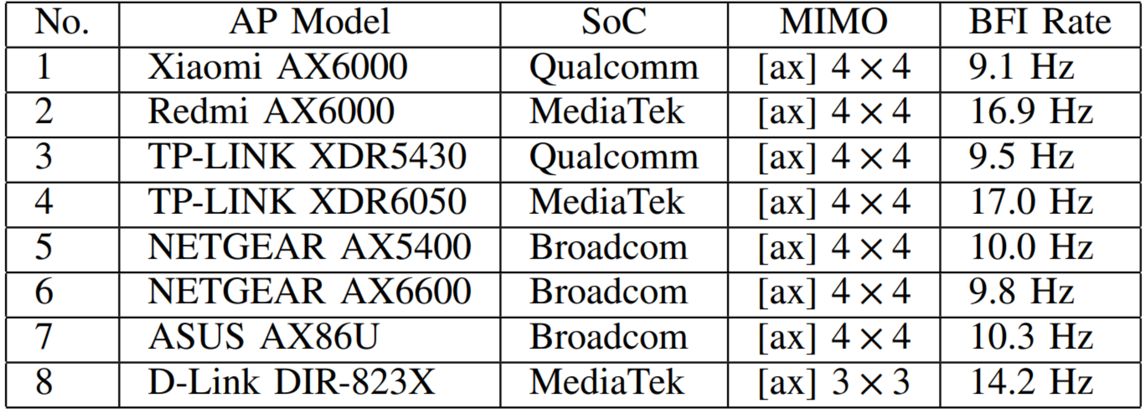
8 WiFi APs



No.	AP Model	SoC	MIMO	BFI Rate
1	Xiaomi AX6000	Qualcomm	[ax] 4 × 4	9.1 Hz
2	Redmi AX6000	MediaTek	[ax] 4 × 4	16.9 Hz
3	TP-LINK XDR5430	Qualcomm	[ax] 4 × 4	9.5 Hz
4	TP-LINK XDR6050	MediaTek	[ax] 4 × 4	17.0 Hz
5	NETGEAR AX5400	Broadcom	[ax] 4 × 4	10.0 Hz
6	NETGEAR AX6600	Broadcom	[ax] 4 × 4	9.8 Hz
7	ASUS AX86U	Broadcom	[ax] 4 × 4	10.3 Hz
8	D-Link DIR-823X	MediaTek	[ax] 3 × 3	14.2 Hz

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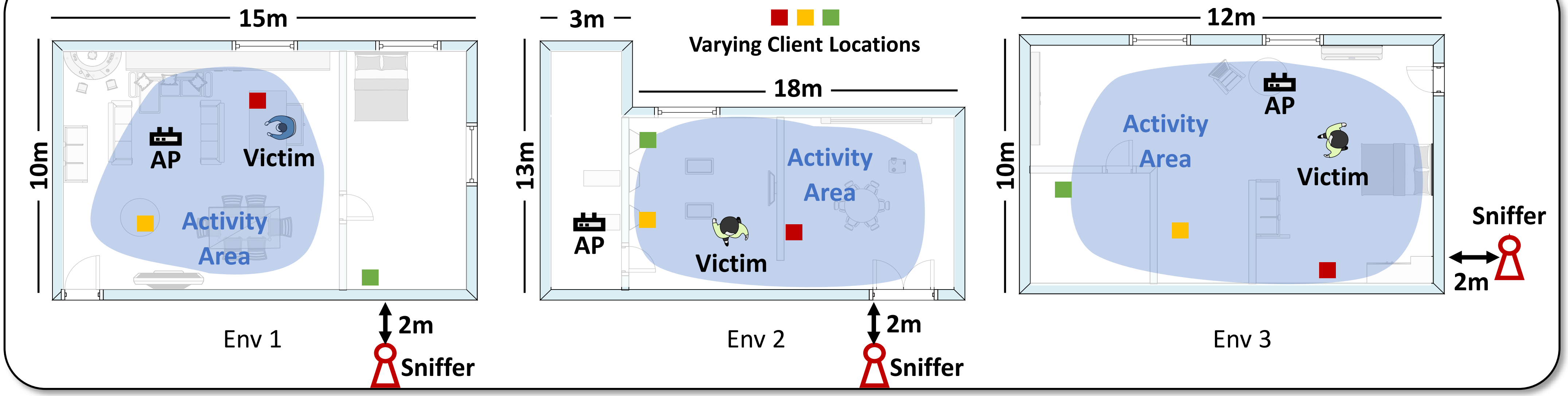
6	NETGEAR AX6600	Broadcom	[ax] 4 × 4	9.8 Hz
7	ASUS AX86U	Broadcom	[ax] 4 × 4	10.3 Hz
8	D-Link DIR-823X	MediaTek	[ax] 3 × 3	14.2 Hz

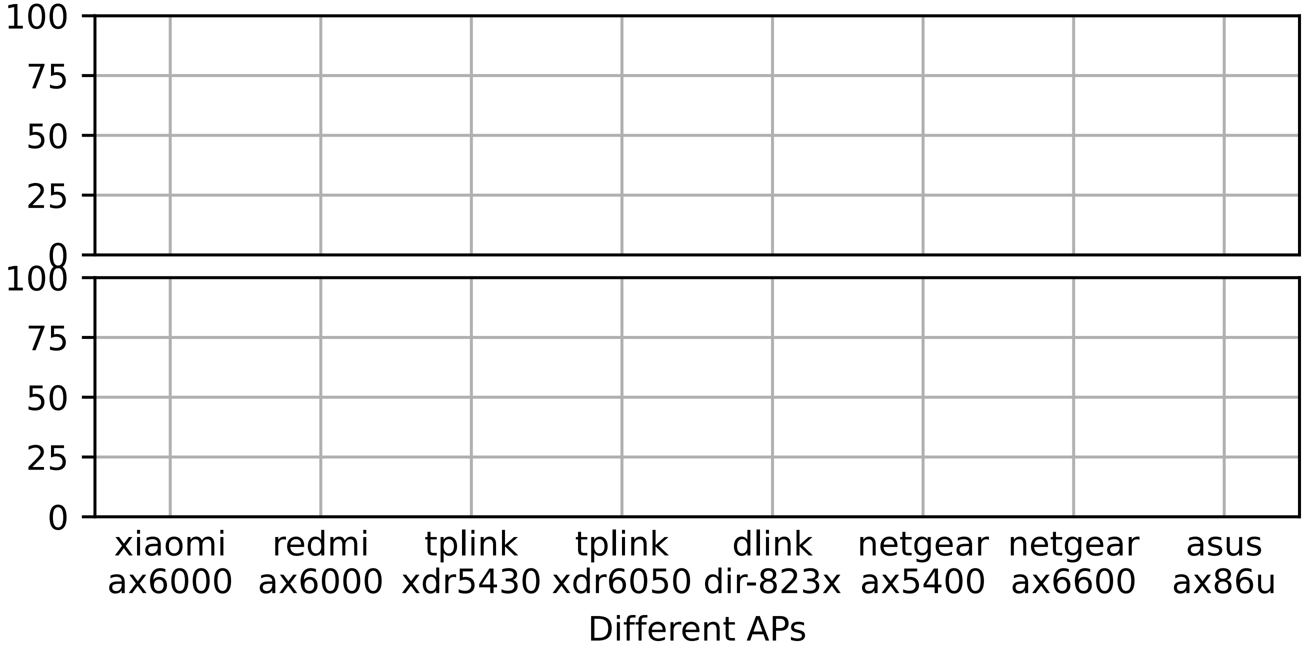
3 Environments with 9 Layouts



Summary of Evaluation Results

True Positive Rate (TPR)

True Negative Rate (TNR)



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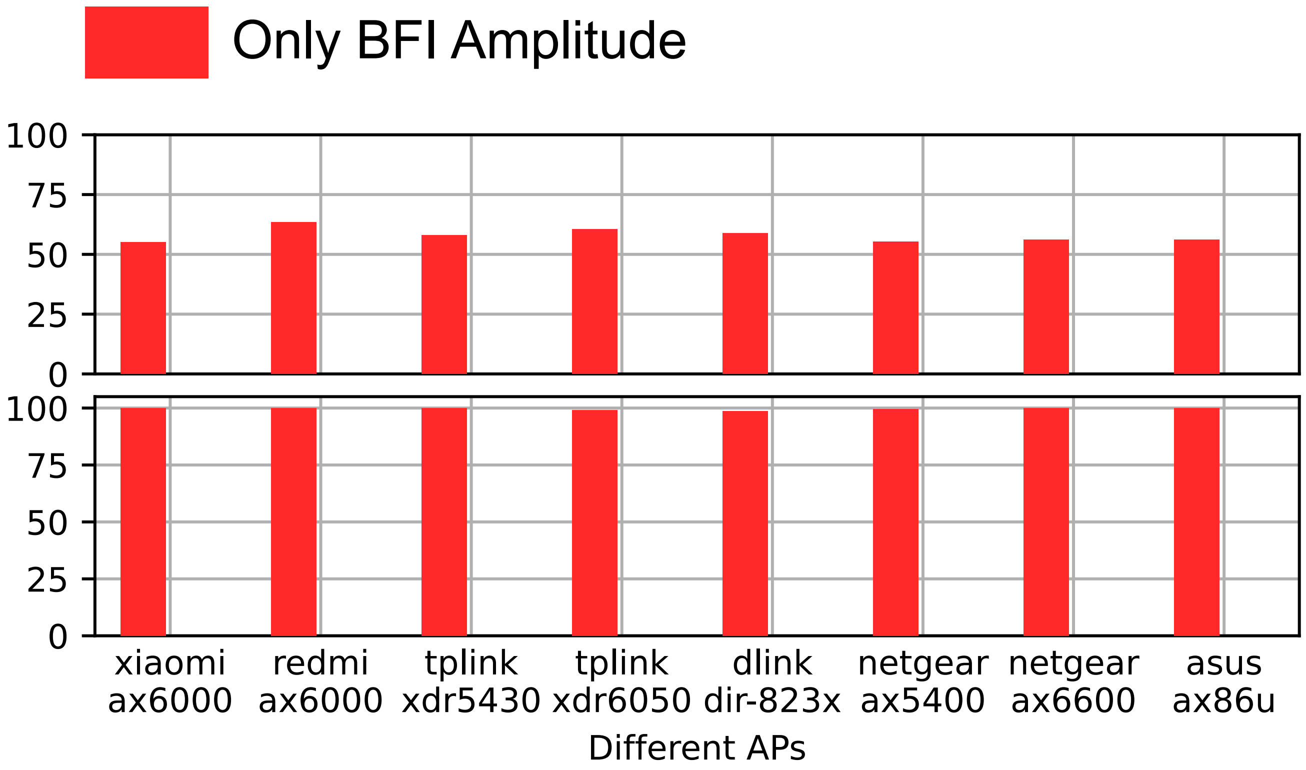

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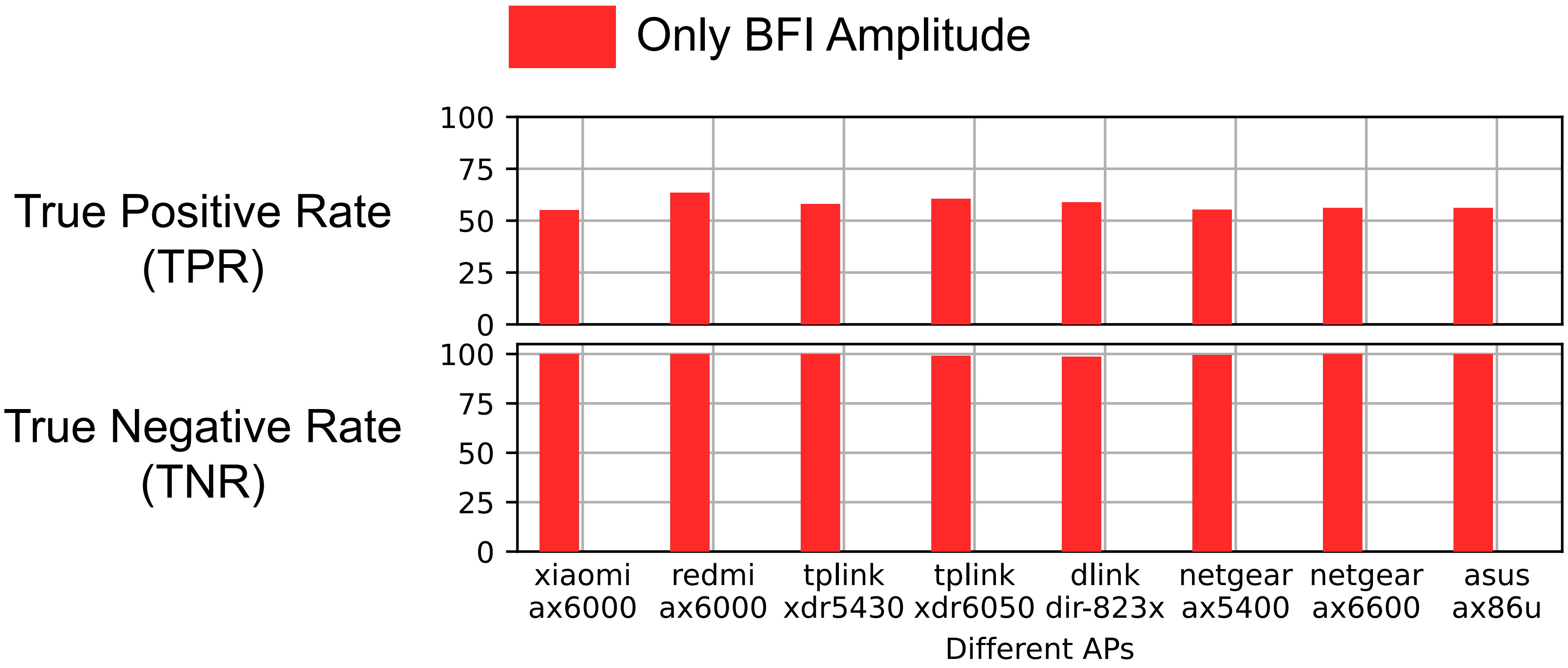

- Detecting **occupancy** states with 58% TPR and 99% TNR ☹

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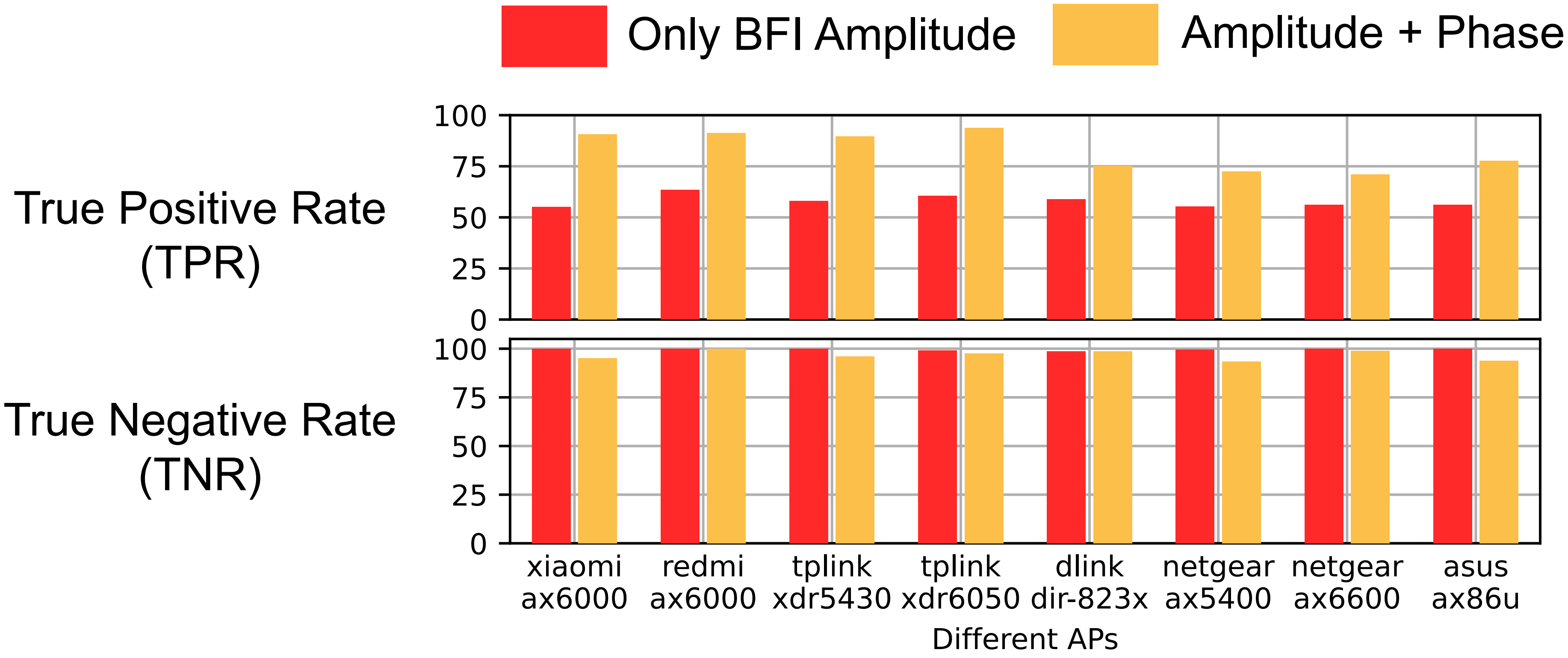

- Detecting **occupancy** states with **83%** TPR and **97%** TNR

Summary of Evaluation Results

- Accurate at detecting **occupancy** states (**83%** TPR and **97%** TNR)

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- Accurate at detecting **occupancy** states (**83%** TPR and **97%** TNR)

- Works across **different client devices**

- Performs well with varying **background traffic types**, even when **idle**

- **88.3%** accuracy at a distance up to **20 meters**

Our Defense: Stay Plaintext But Preserve Privacy

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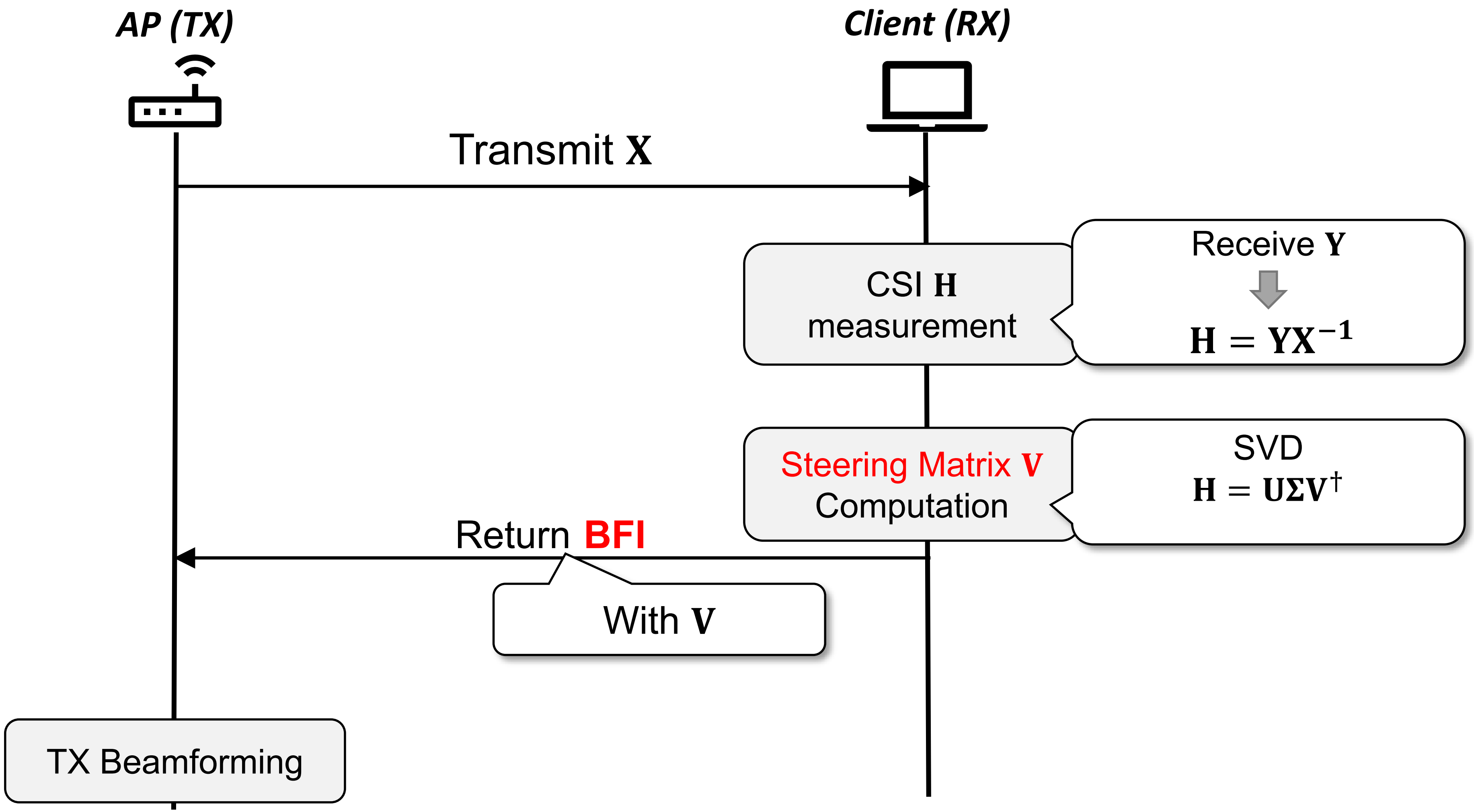
- Original BFI Measurement:



AP (TX)
Client (RX)
Transmit $\mathbf{X}$
Receive $\mathbf{Y}$
$\mathbf{H} = \mathbf{Y}\mathbf{X}^{-1}$
CSI $\mathbf{H}$ measurement
SVD
$\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^{\dagger}$
Steering Matrix $\mathbf{V}$ Computation
Return BFI
With $\mathbf{V}$
TX Beamforming

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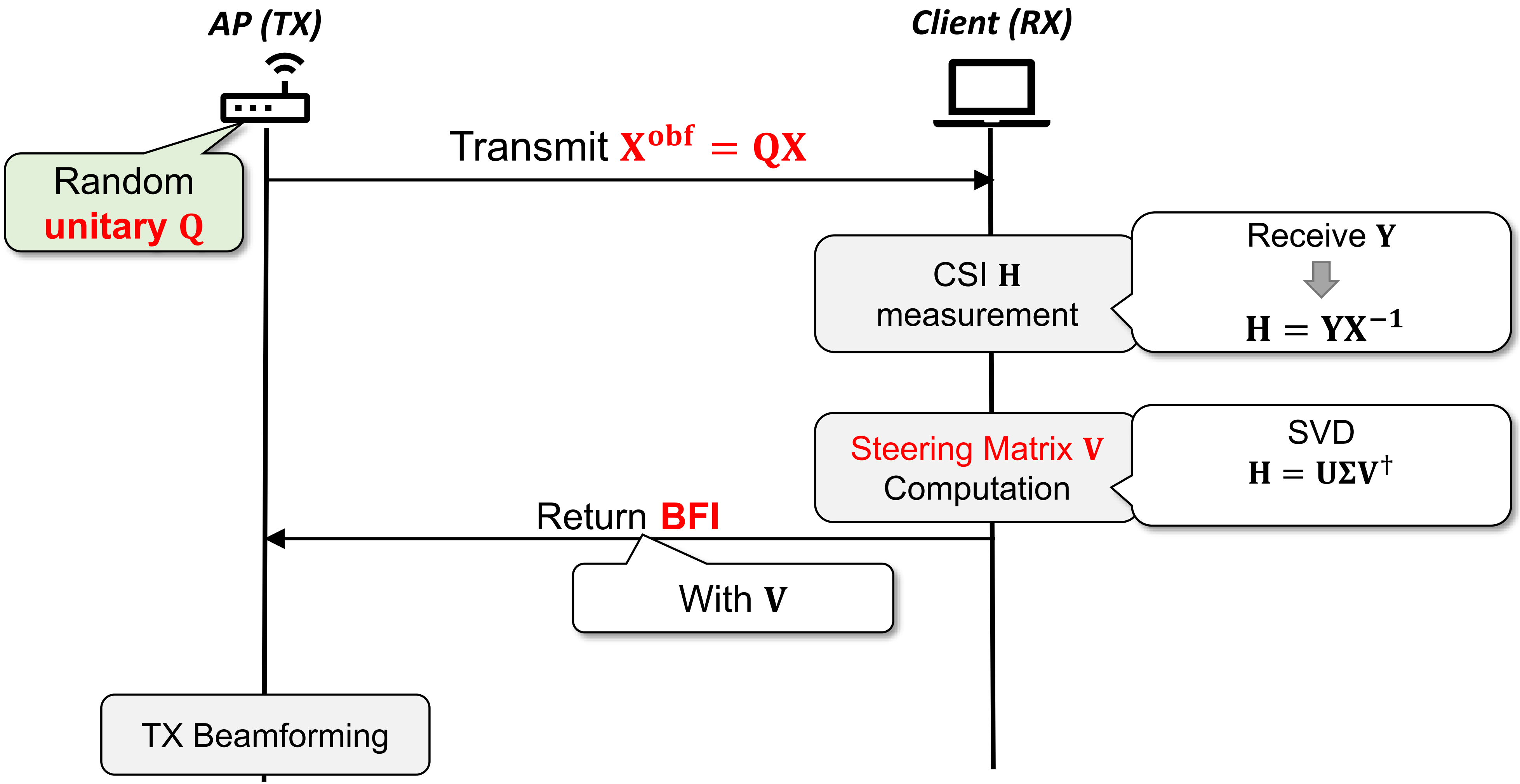
- BFI Measurement with **a random mapping $\mathbf{Q}$ on training symbol $\mathbf{X}$:**



AP (TX)
Client (RX)
Random unitary $\mathbf{Q}$
Transmit $\mathbf{X}^{\mathbf{obf}} = \mathbf{QX}$
CSI $\mathbf{H}$ measurement
Receive $\mathbf{Y}$
$\mathbf{H} = \mathbf{YX}^{-1}$
Steering Matrix $\mathbf{V}$ Computation
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$\mathbf{H} = \mathbf{U\Sigma V}^{\dagger}$
Return BFI
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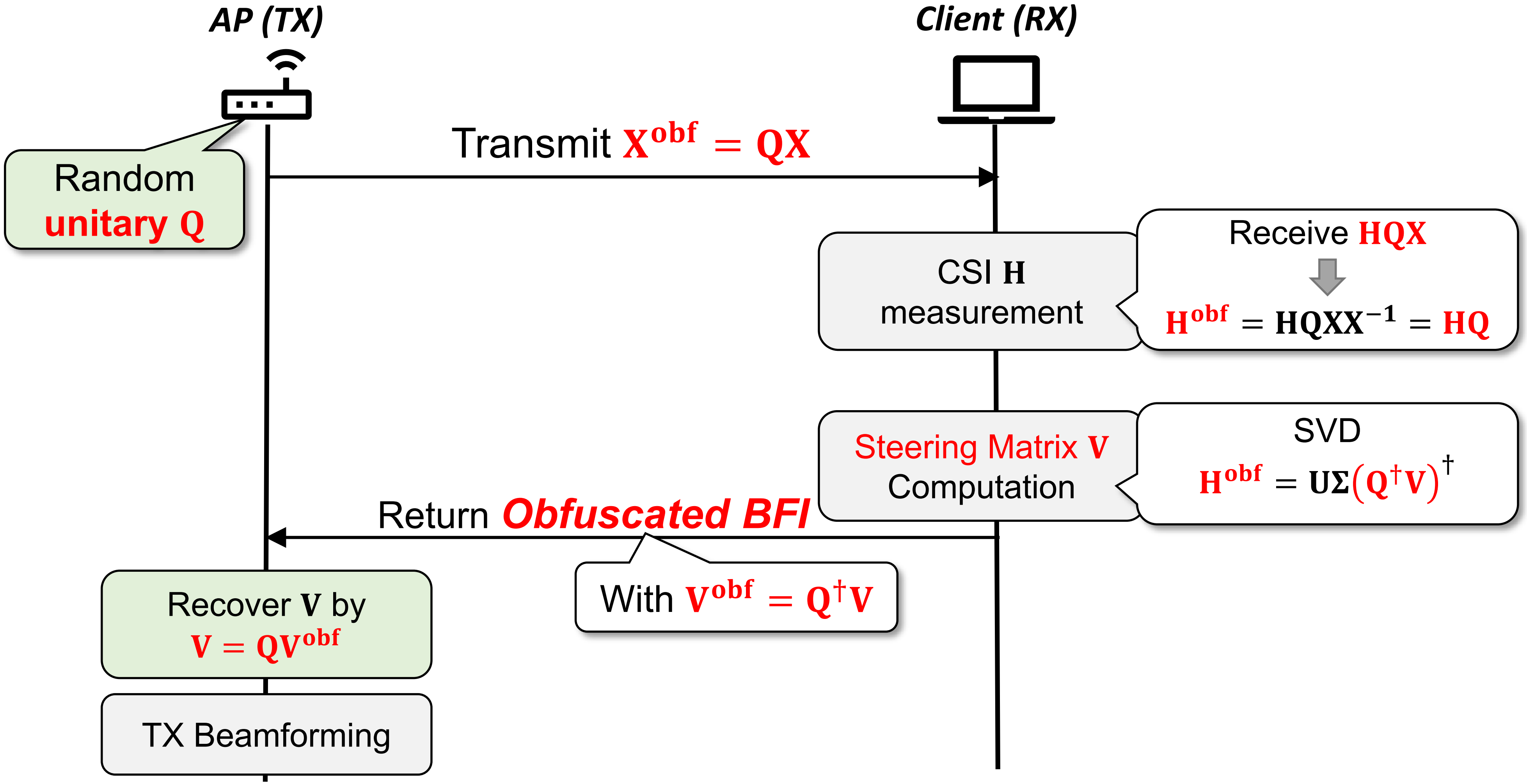


AP (TX)

Client (RX)

Random **unitary $\mathbf{Q}$**

Transmit $\mathbf{X}^{\mathbf{obf}} = \mathbf{QX}$

CSI $\mathbf{H}$ measurement

Receive $\mathbf{HQX}$

$\mathbf{H}^{\mathbf{obf}} = \mathbf{HQXX}^{-1} = \mathbf{HQ}$

Steering Matrix $\mathbf{V}$ Computation

SVD

$\mathbf{H}^{\mathbf{obf}} = \mathbf{U\Sigma}\left(\mathbf{Q}^{\dagger}\mathbf{V}\right)^{\dagger}$

Return ***Obfuscated BFI***

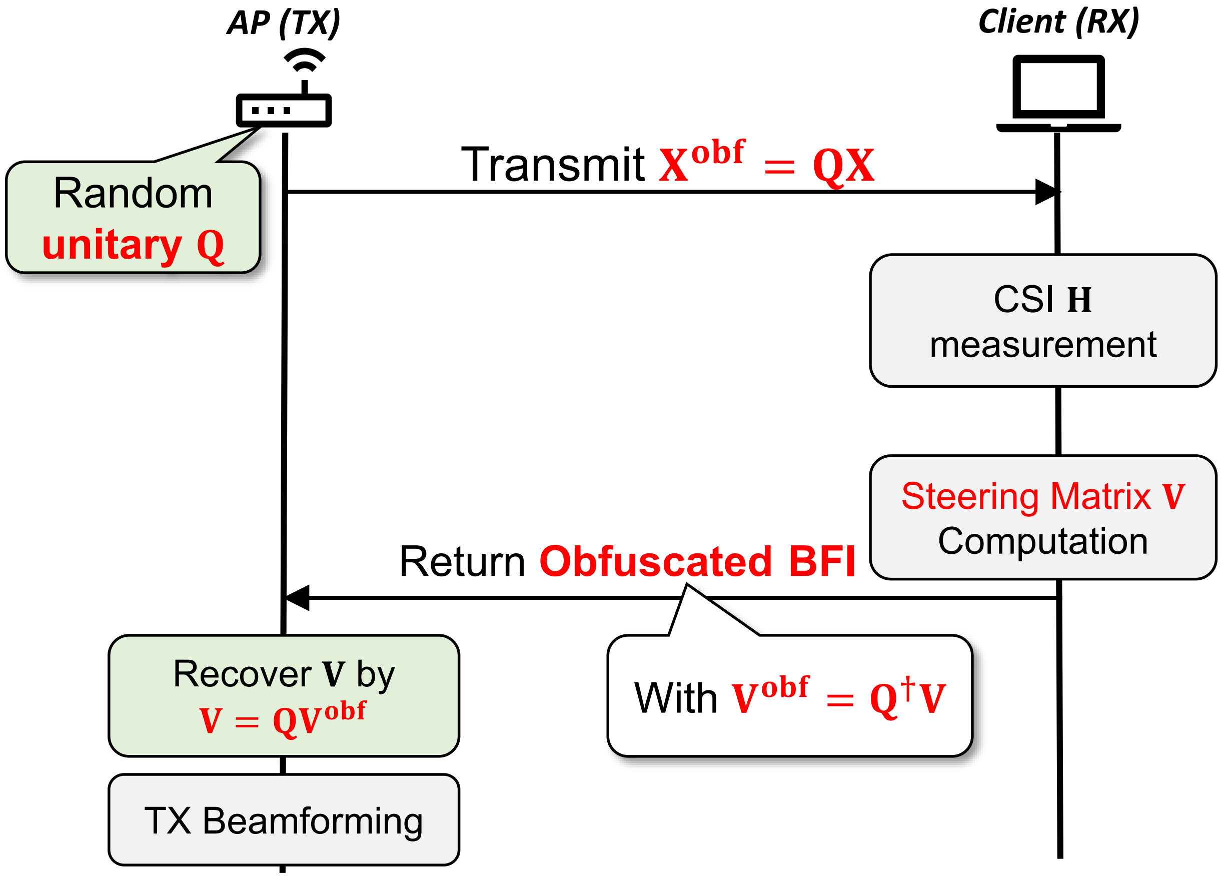
With $\mathbf{V}^{\mathbf{obf}} = \mathbf{Q}^{\dagger}\mathbf{V}$

Recover $\mathbf{V}$ by $\mathbf{V} = \mathbf{QV}^{\mathbf{obf}}$

TX Beamforming

Our Defense: Stay Plaintext But Preserve Privacy

- BFI Measurement with **a random mapping $\mathbf{Q}$ on training symbol $\mathbf{X}$:**



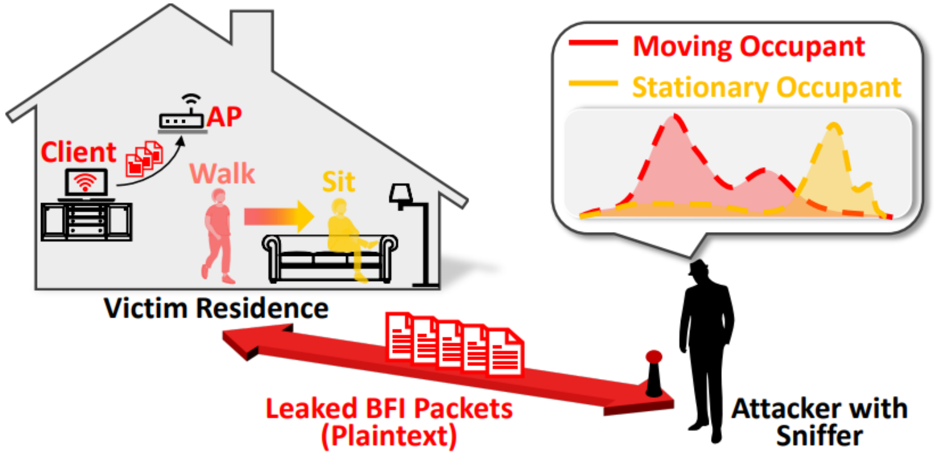
AP (TX)
Client (RX)
Random unitary $\mathbf{Q}$
Transmit $\mathbf{X}^{\mathrm{obf}} = \mathbf{QX}$
CSI $\mathbf{H}$ measurement
Steering Matrix $\mathbf{V}$ Computation
Return Obfuscated BFI
With $\mathbf{V}^{\mathrm{obf}} = \mathbf{Q}^{\dagger}\mathbf{V}$
Recover $\mathbf{V}$ by $\mathbf{V} = \mathbf{QV}^{\mathrm{obf}}$
TX Beamforming

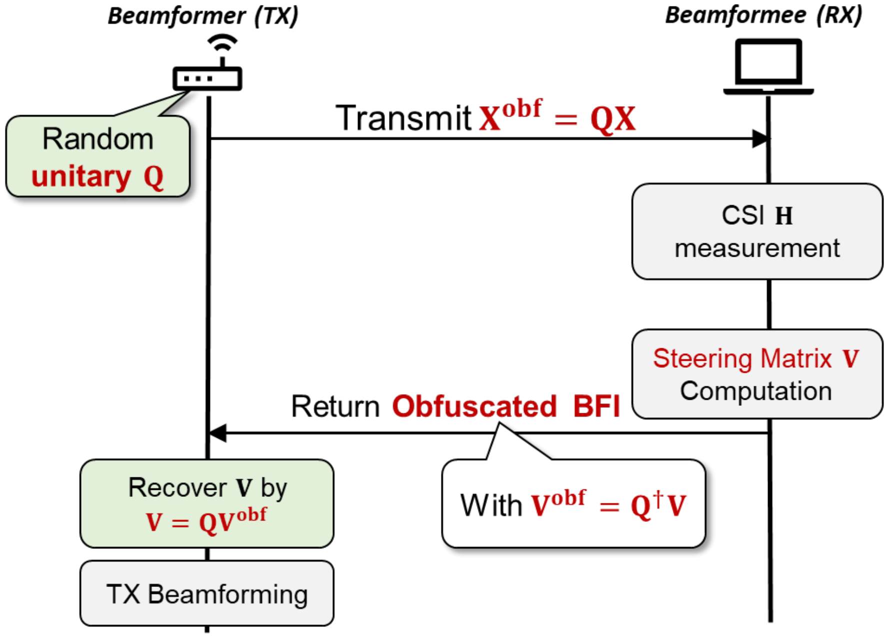
Key Features:

- **Minimal Hardware Modification**
  - Client: Unaffected
  - AP: Reusing Spatial Mapping Mechanism
- **Minimal Impact on Communication**
  - Beamforming is still effective.
- **Effective Privacy Preserving**
  - Obfuscated BFI cannot infer occupancy state.

Conclusion

- We introduce LeakyBeam, **a practical adversarial occupancy detection attack** utilizing the **BFI side channel**.
- We propose **a novel defense mechanism** to potential attacks with plaintext BFI packets.





Beamformer (TX)
Beamformee (RX)
Random unitary $\mathbf{Q}$
Transmit $\mathbf{X}^{\mathrm{obf}} = \mathbf{QX}$
CSI $\mathbf{H}$ measurement
Steering Matrix $\mathbf{V}$ Computation
Return Obfuscated BFI
With $\mathbf{V}^{\mathrm{obf}} = \mathbf{Q}^{\dagger}\mathbf{V}$
Recover $\mathbf{V}$ by $\mathbf{V} = \mathbf{QV}^{\mathrm{obf}}$
TX Beamforming

Thank you!

Homepage

Mail: ruixiao24@zju.edu.cn

Rui Xiao

PhD candidate at Zhejiang University

Wireless, Mobile, Sensing, Security

I’m seeking a ***post-doctoral position*** starting in ***Fall 2025***.
Please feel free to contact me!