COMP3516: Data Analytics for IoT

Lecture 5.1: Channel State Information

Chenshu Wu

Department of Computer Science

2025 Spring

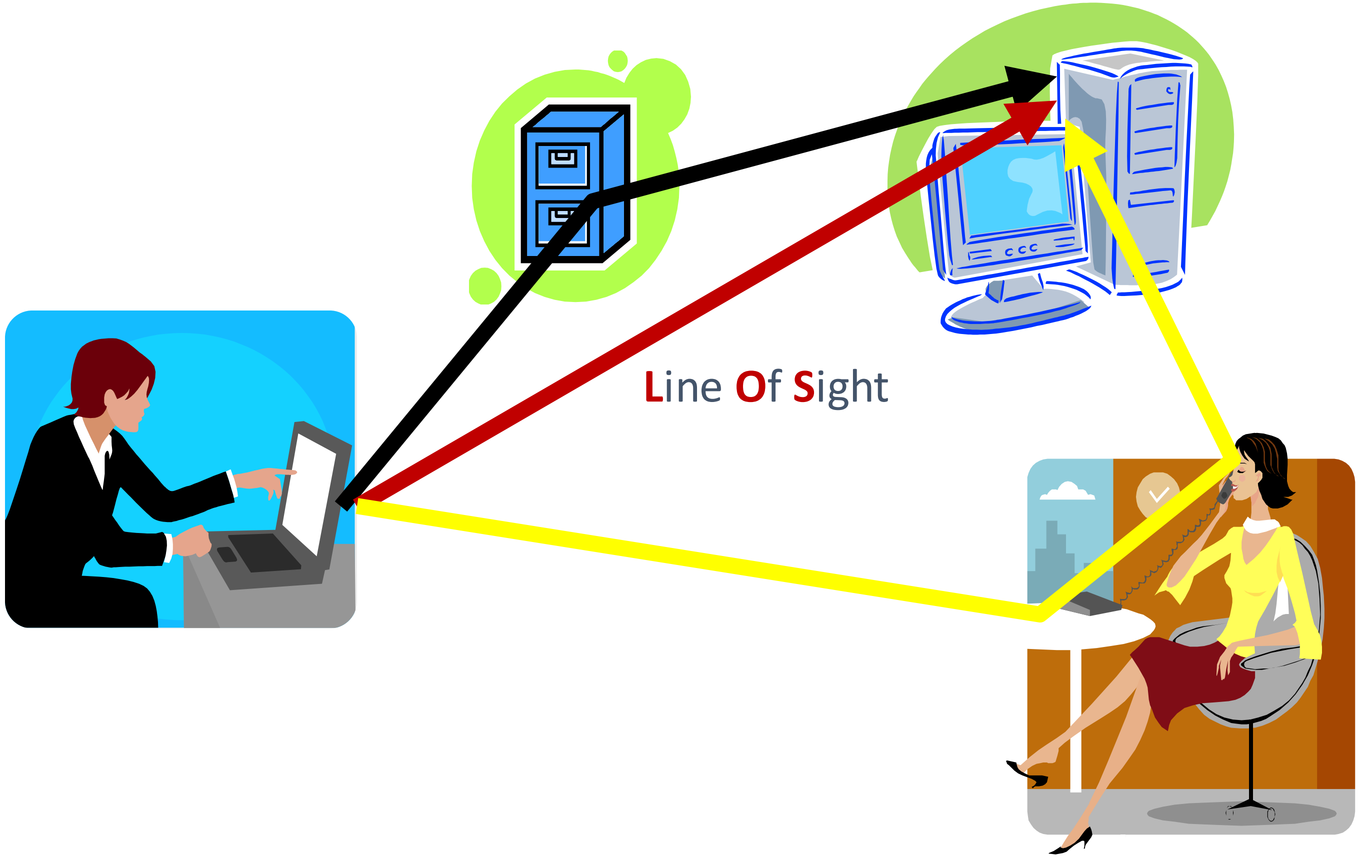
香 港 大 學
THE UNIVERSITY OF HONG KONG

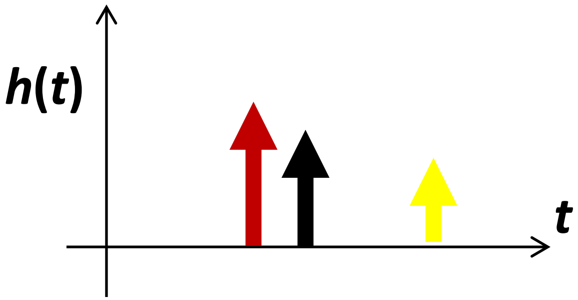
HKU AIoT LAB
香港大學人工智能物联网實驗室

Contents

- LOs: Learn the basic concepts of wireless channel and CSI, and understand why it can enable sensing

The Wireless Channel





Direct path:
Line-Of-Sight (**LOS**)

Reflected paths:
Non-Line-Of-Sight (**NLOS**)

What do we know about Channel?

- RSSI: Received Signal Strength Indicator

What can we learn from the Channel?

- An example: Human detection

RSSI Increase

RSSI Drop

It is possible to infer what happens from the Channel !!

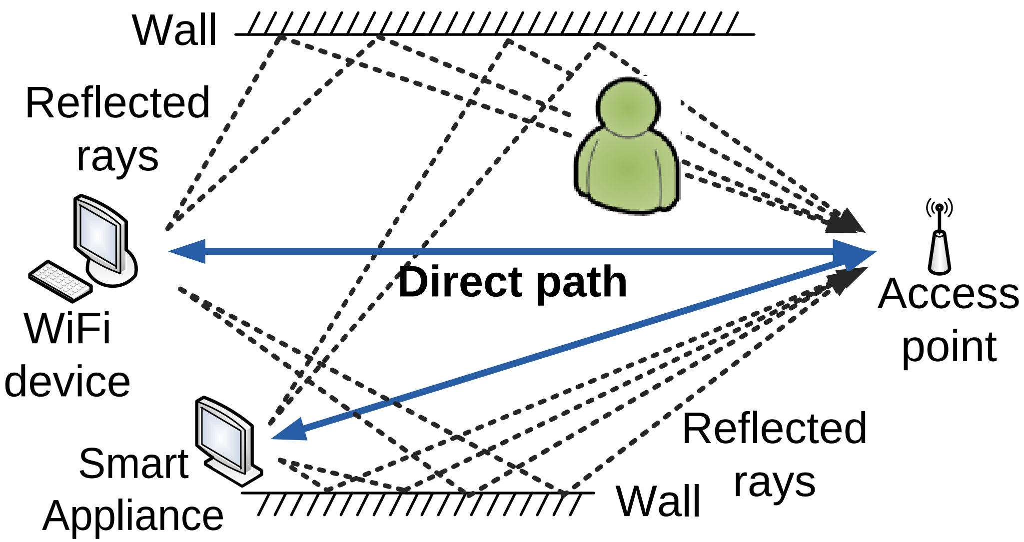
"I Am the Antenna Accurate Outdoor AP Location Using Smartphones", MobiCom, 2011

Why Channel can be used for Sensing?

- The Channel characterizes the signal propagation process, which interacts with the environments
- The received signals therefore "encode" the environmental information
- The environmental information can be deciphered by "decoding" the received signals

However, RSSI is not enough…

RSSI will not always drop because of multipath propagation

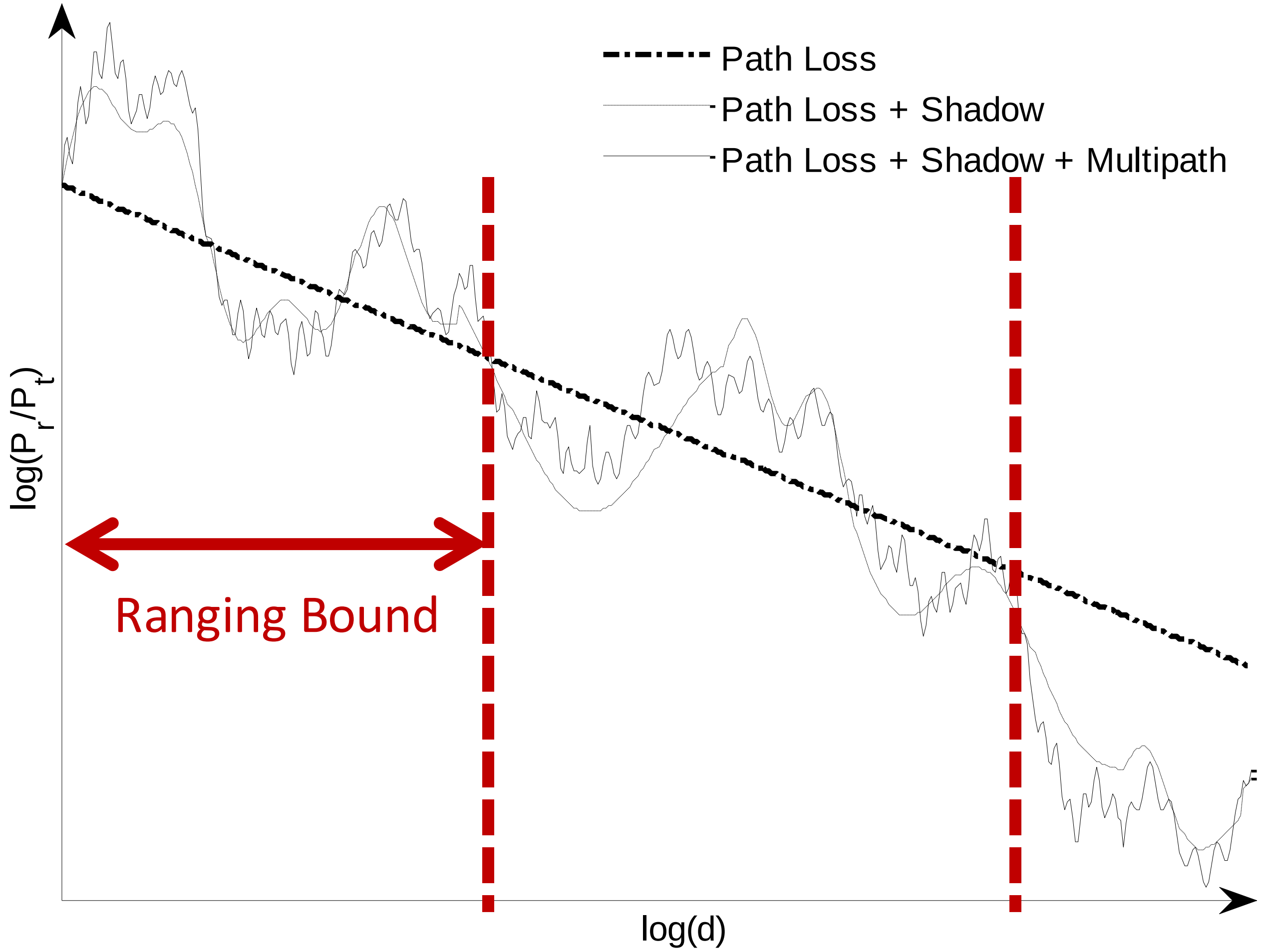


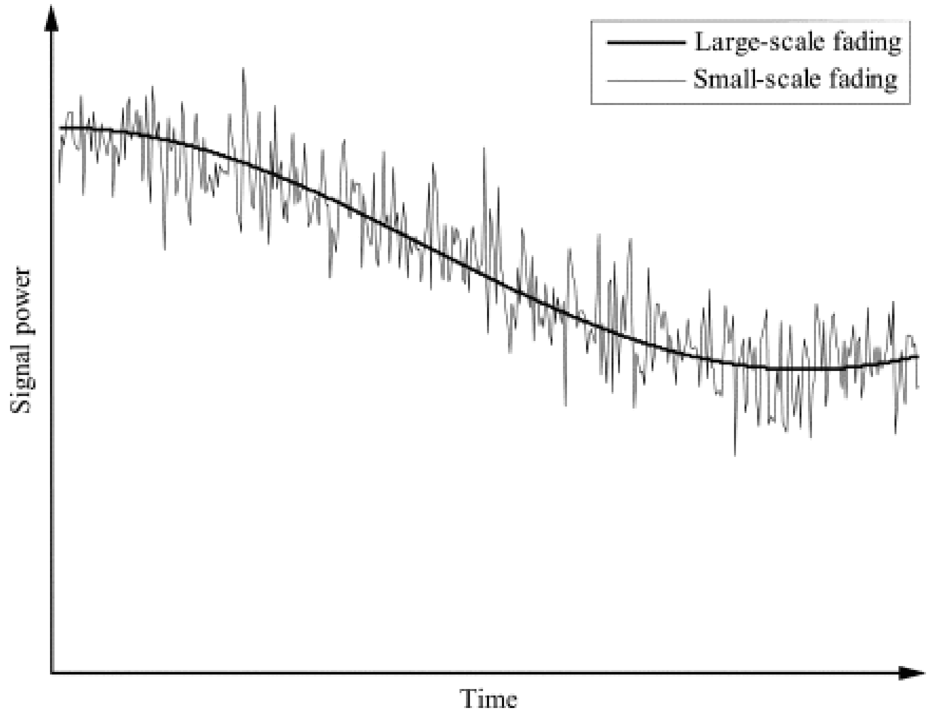
RSSI:
A single value indicating the overall amplitude of the superimposed received signals.

Multipath Channel

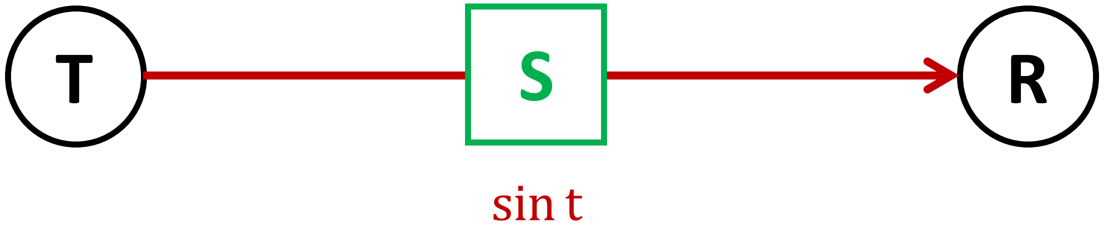
- Two fundamental aspects of wireless communications
  - Fading: Time variations of the channel
  - Interference: 1 Tx vs N Rx, N Tx vs 1 Rx, Different Tx vs Rx pairs
- Fading
  - Large-scale fading
    - Path loss (as a function of distance)
    - Shadowing by large objects
    - *At the scale of the order of the cell size, typically frequency independent*
  - Small-scale fading
    - Constructive and destructive interference of multipath signals
    - *At the scale of the order of carrier wavelength, frequency dependent*

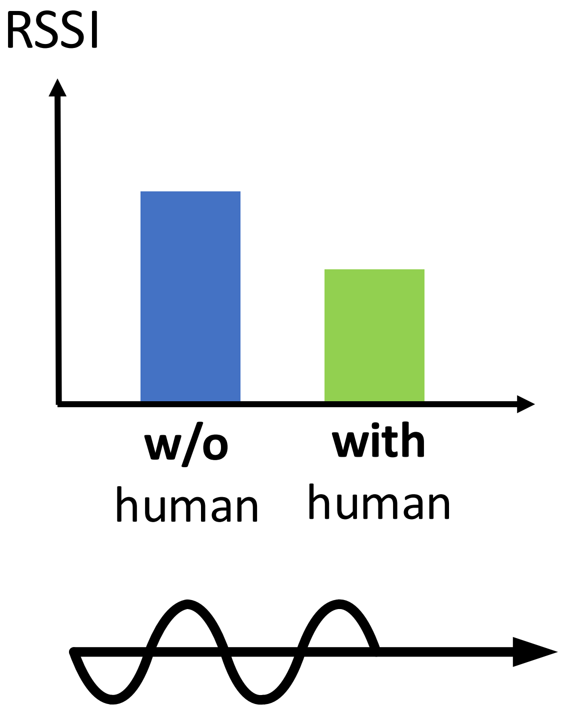
Fading of Wireless Channel



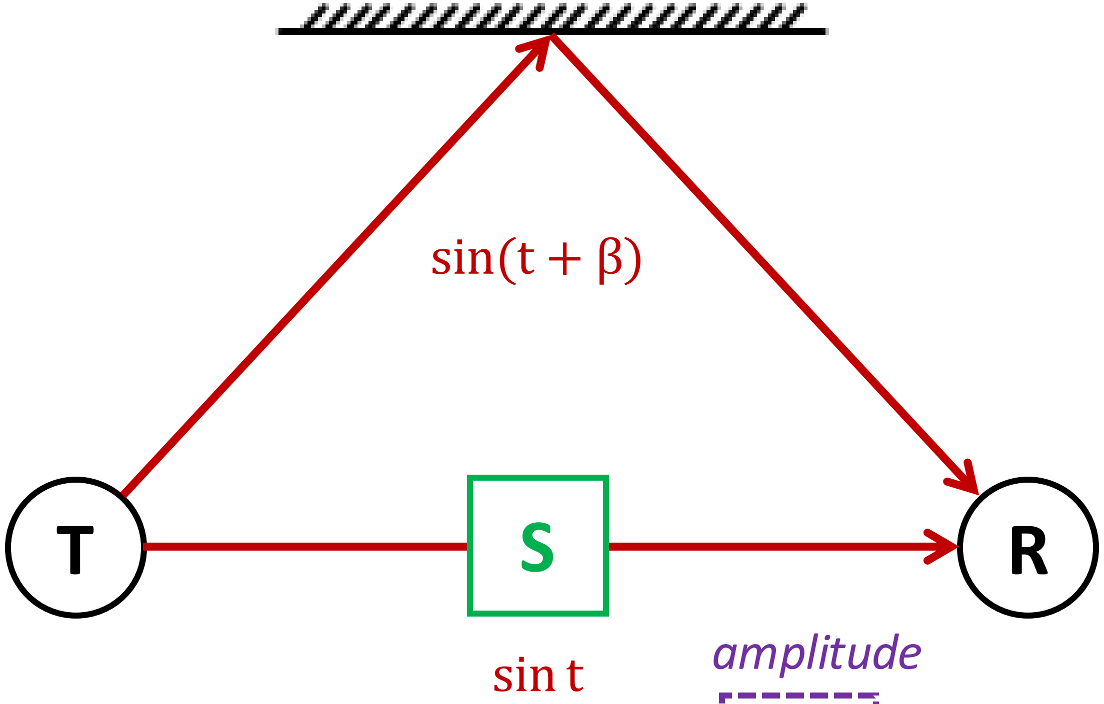


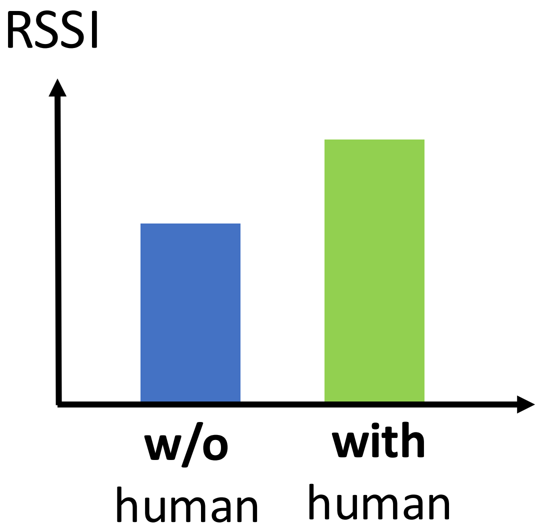
Human presence induced RSSI change without multipath propagation





Human presence induced RSSI change with multipath propagation





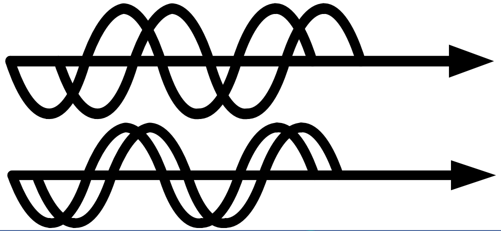
amplitude

Hint: $\sin(t+\beta) + \sin t = 2\cos\frac{\beta}{2} \sin\left(t + \frac{\beta}{2}\right)$

$0 \le |2\cos\frac{\beta}{2}| \le 2$

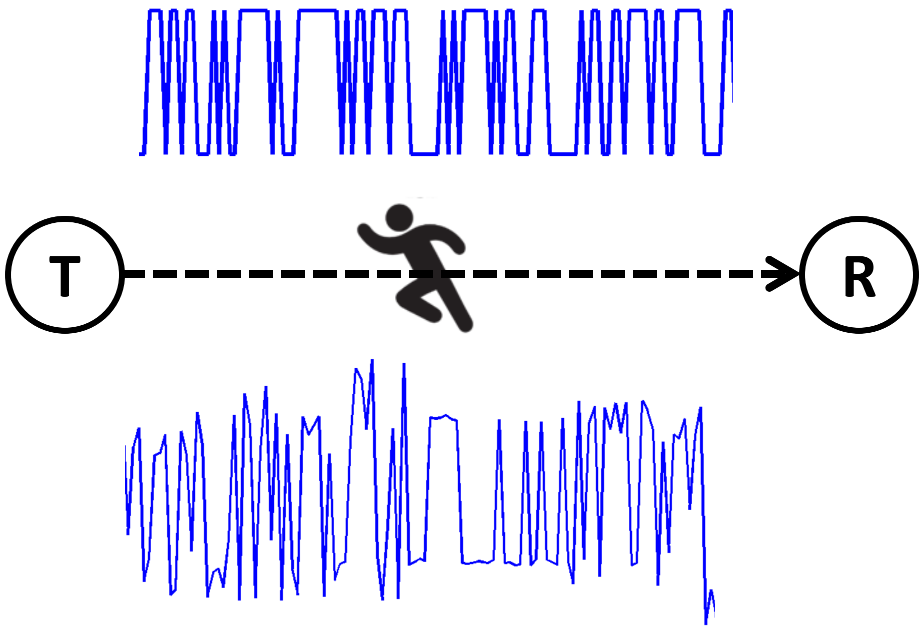
$0 \le |2\cos\frac{\beta}{2}| < 1$: **Destructive** Phases

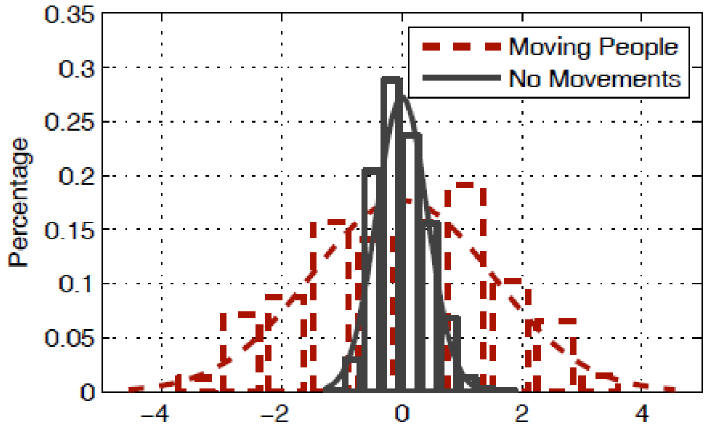
$1 \le |2\cos\frac{\beta}{2}| \le 2$: **Constructive** Phases



Human detection: A better solution

- Principle: RSSI **varies significantly** with environmental changes due to human motions

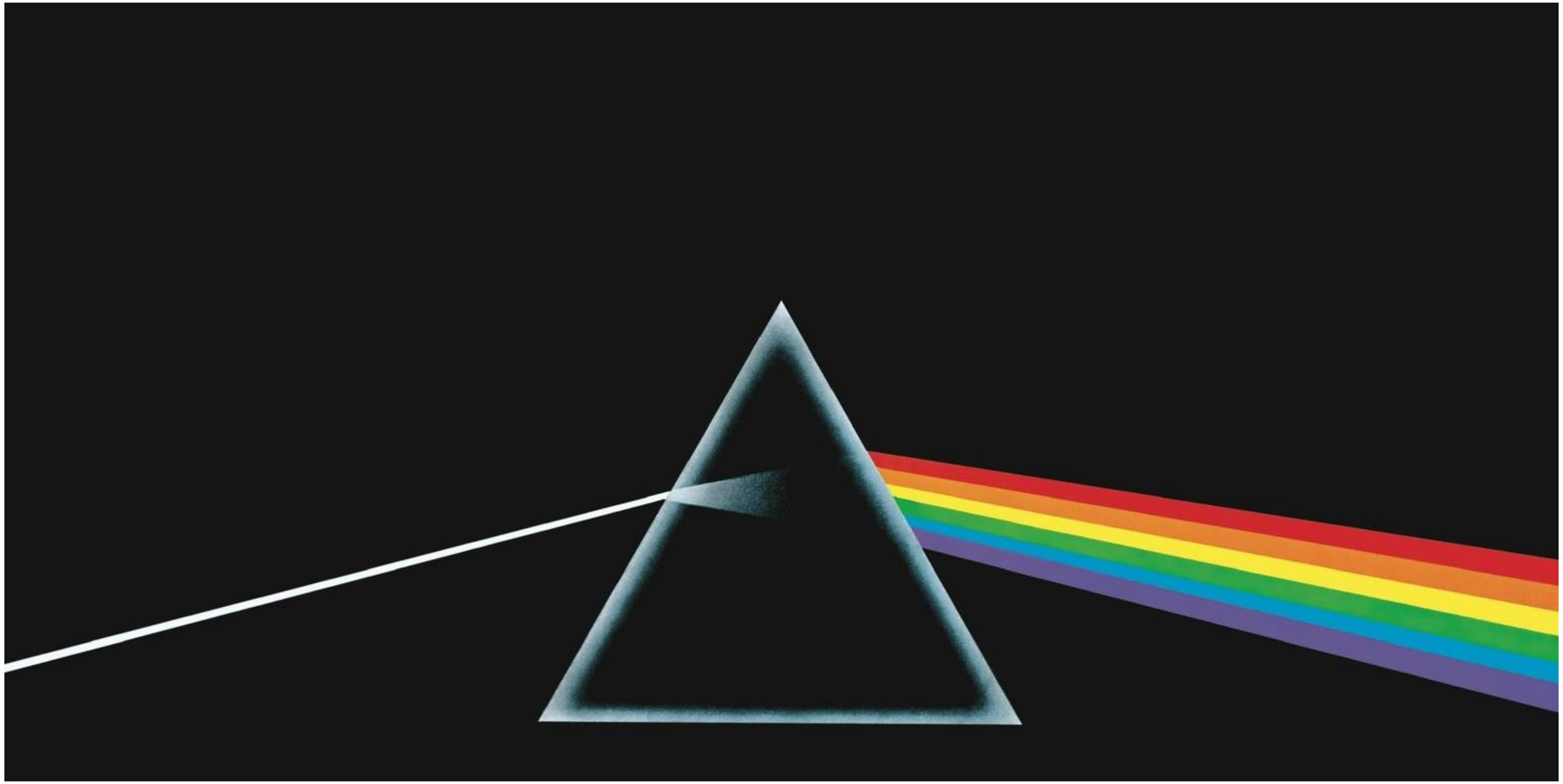




Hint: use **variance** or **standard deviation** to quantify

Still, RSSI is not enough…

- We need something finer-grained



Channel State Information (CSI)

- Channel
  - Characterizes how a signal propagates in the environment from the Tx to the Rx
- Channel Estimation: CSI
  - Standard information in wireless communications
  - Available on all commodity WiFi devices (also LTE, 5G, etc), but may need special driver modification
  - Using preamble

Rx signal

$$H = \frac{Y}{X}$$

Tx signal

CIR and CFR

Channel Impulse Response (CIR)

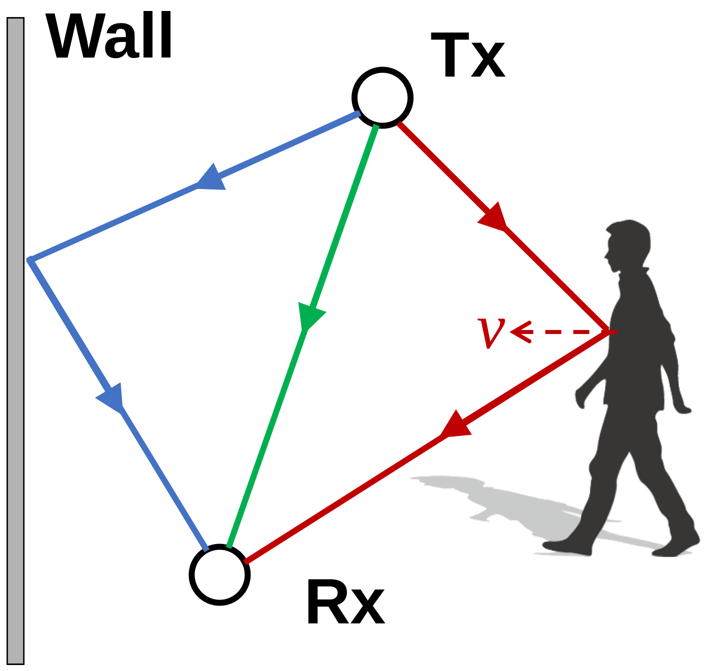
$$h(t,\tau) = \sum_{l\in\Omega} \alpha_l(t)\delta(\tau - \tau_l(t))$$

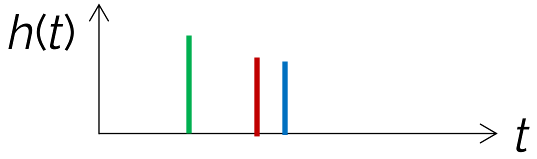
set of multipath — channel gain — propagation delay

Channel Frequency Response (CFR)

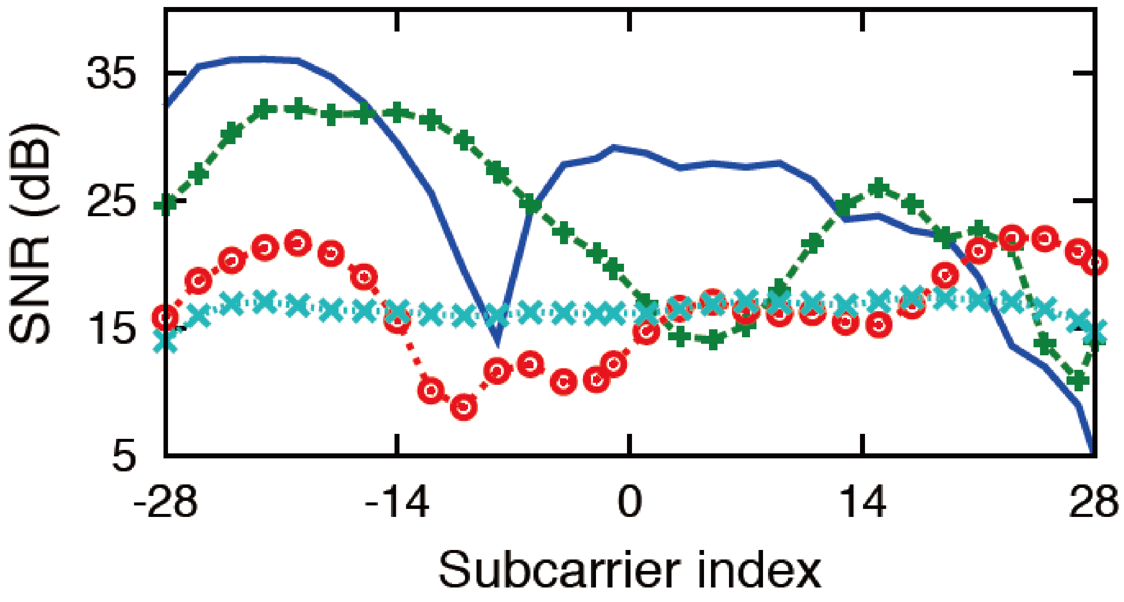
CSI

$$H(t,f) = \sum_{l\in\Omega} \alpha_l(t)e^{-j2\pi f\tau_l(t)}$$

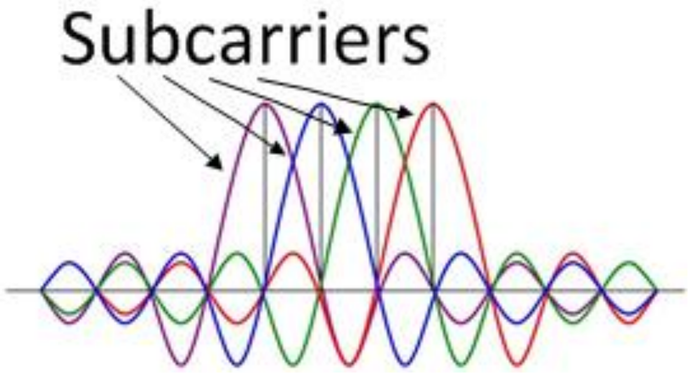




CSI Example



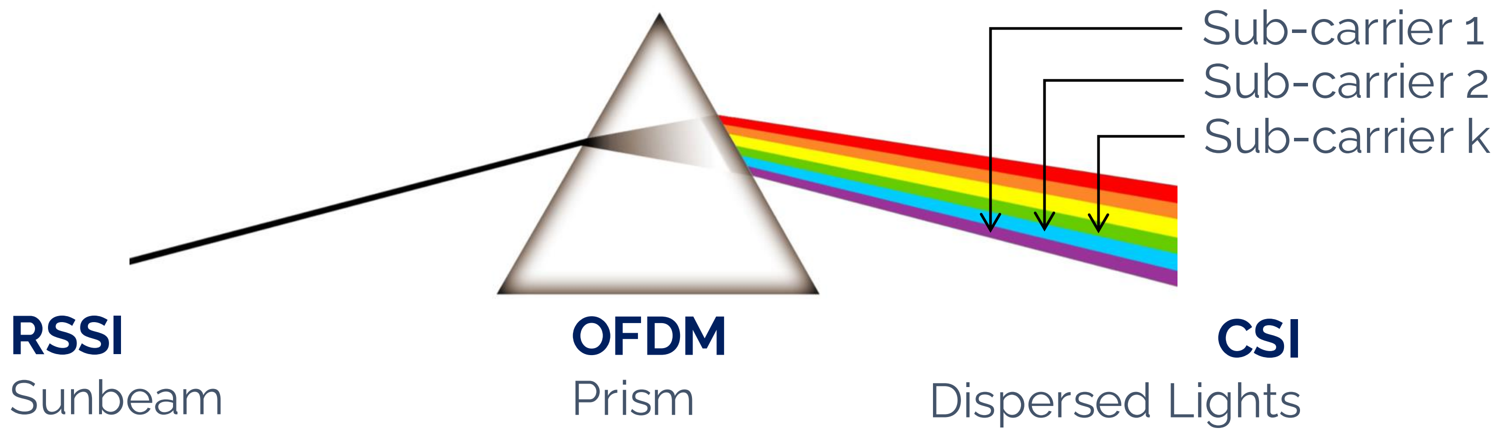
$$\mathbf{H} = [H(t, f_1), H(t, f_2), \cdots, H(t, f_N)]$$



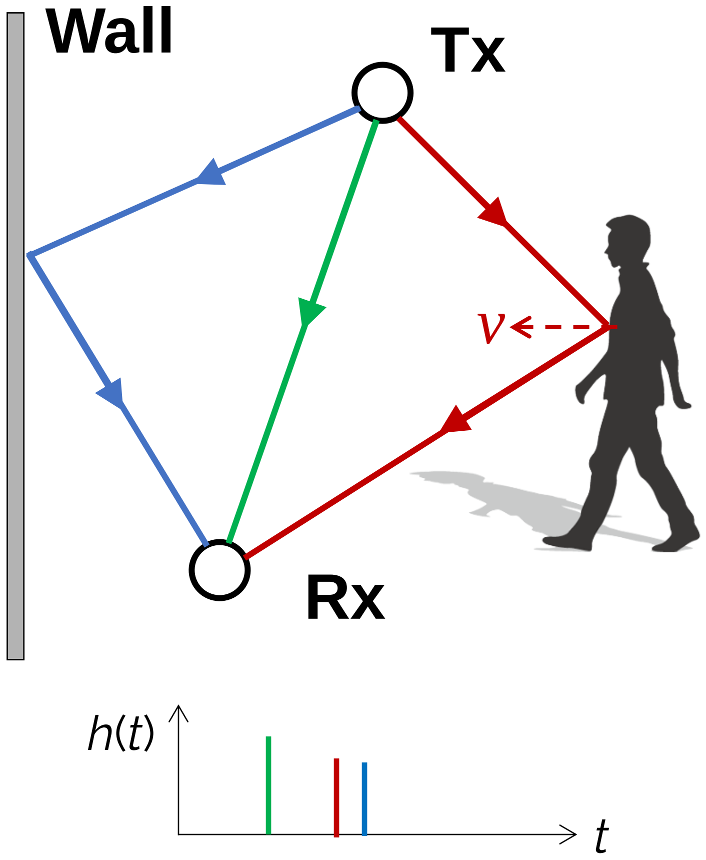
OFDM (Orthogonal Frequency-Division Multiplexing)

multi-carrier modulation system where data is transmitted as a combination of orthogonal narrowband signals known as subcarriers

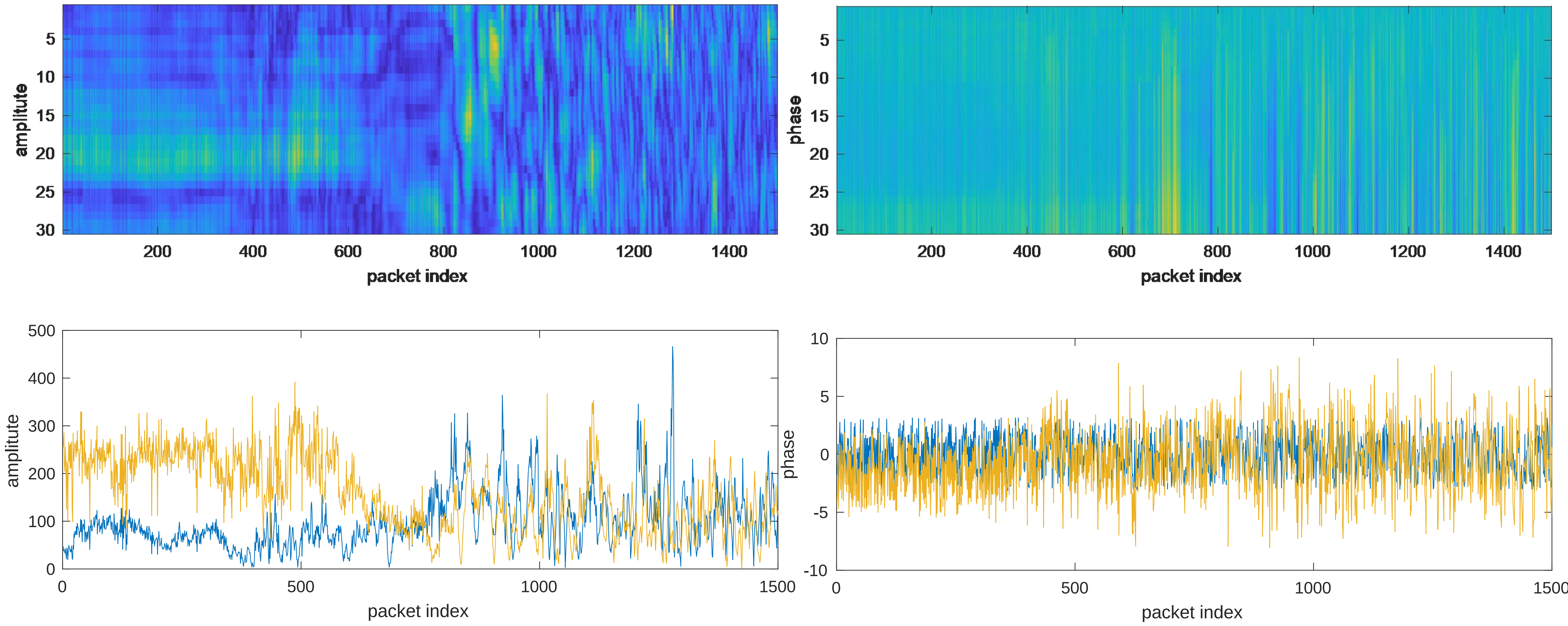
From RSSI to CSI



Category	RSSI	CSI
Layering	MAC layer	PHY layer
Time Resolution	Packet level	Multipath clusters
Frequency Resolution	N/A	Sub-carrier level
Stability	Low	High for CFR structure
Ubiquity	Handy access	Commercial Wi-Fi



Real CSI Measurements



Quiz: CIR Example

- Consider a mmWave radar with a bw = 4GHz. Assume 3 targets at different d=1m, 1.5m, and 6m, respectively. Draw the CIR.

- Considering the same scenario, but now using a pair of co-located WiFi devices with a channel bw=40MHz. The CIR?

- Anything missing?

Radar or WiFi?

- Difference between WiFi and FMCW radar?
  - Specialized radar vs. existing ubiquitous WiFi
  - Dedicated sensing vs. communication
  - Synchronized vs. non-synchronized transceivers
  - Monostatic vs. “bistatic”
  - Resolution
  - Coverage

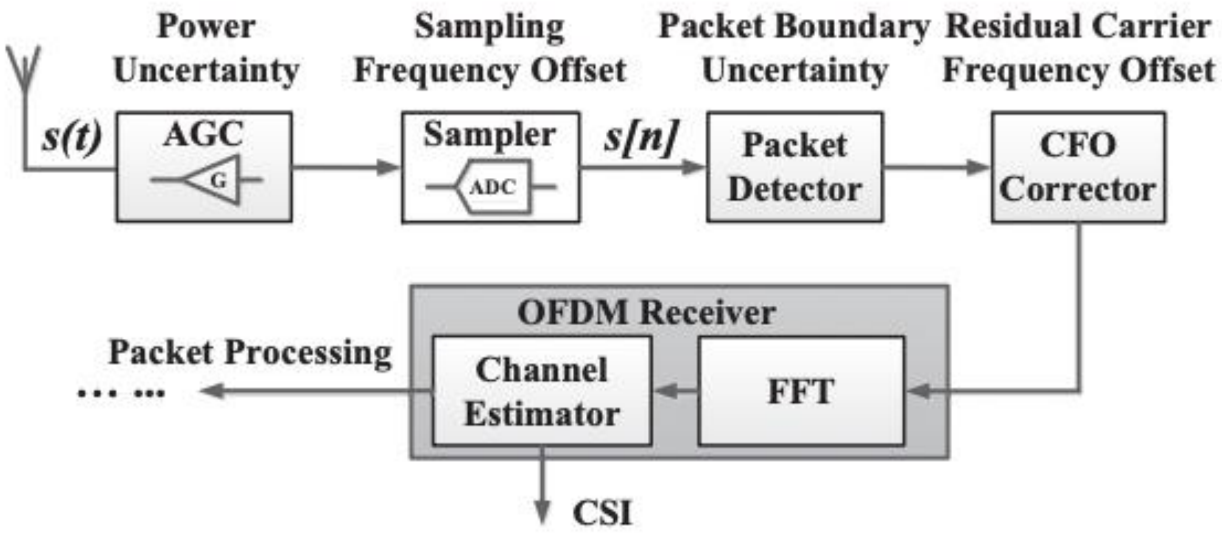
- Can we achieve WiFi sensing just like FMCW radar sensing?

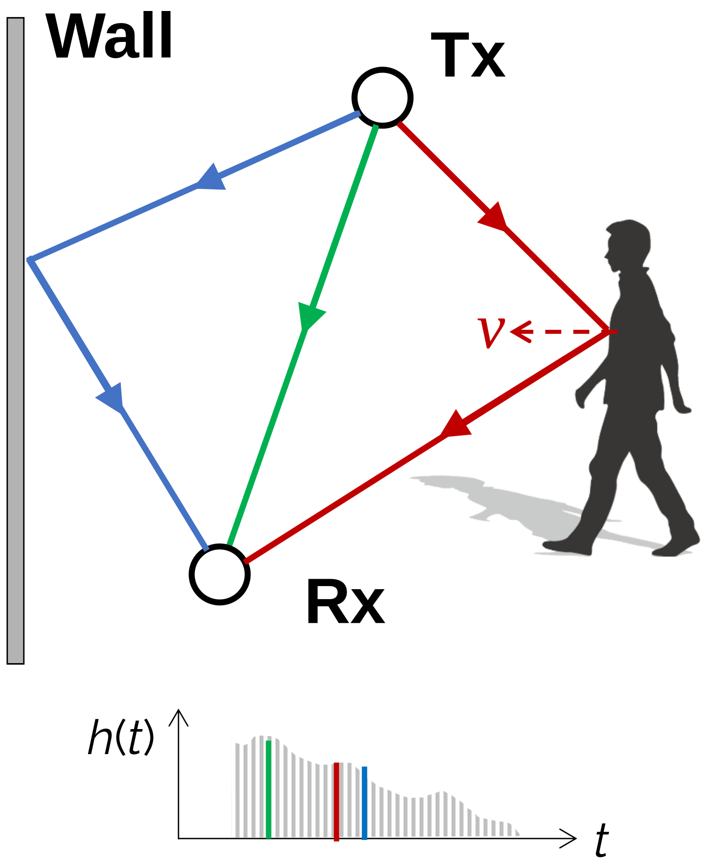
Challenges

- Measured CSI on WiFi

$$\widetilde{H}(t,f) = \exp\left(-j\left(\alpha(t) + \beta(t)f\right)\right)H(t,f) + n(t,f)$$

initial phase offset (α(t)) · linear phase offset (β(t)) · thermal noise (n(t, f))



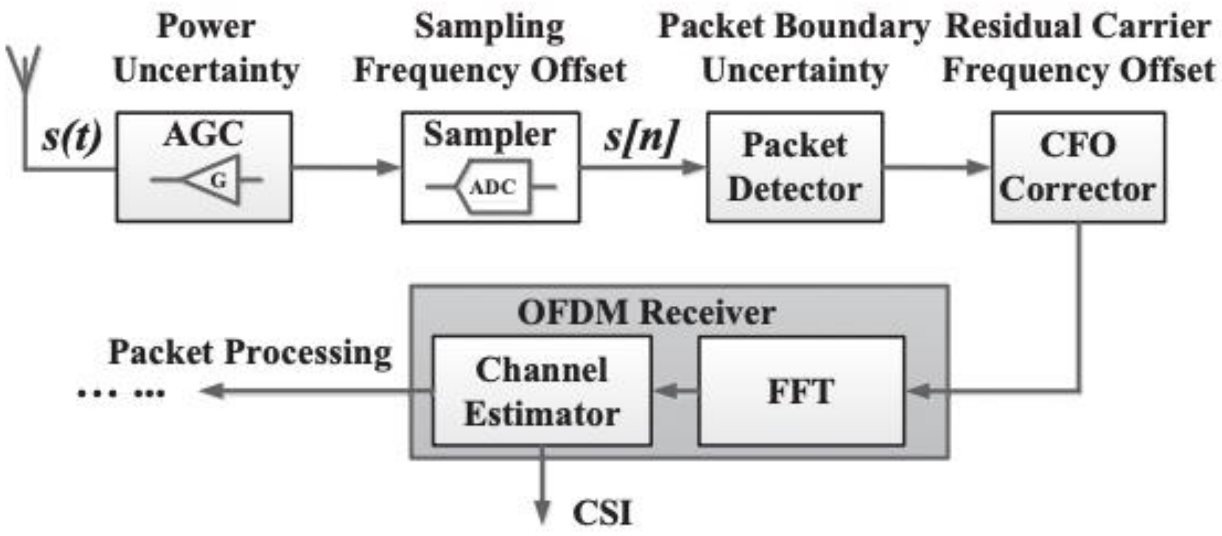


Challenges (1)

- Measured CSI on WiFi contains significant noises

$$\widetilde{H}(t,f) = \exp\big(-j(\alpha(t) + \beta(t)f)\big)H(t,f) + n(t,f)$$

initial phase offset — linear phase offset — thermal noise

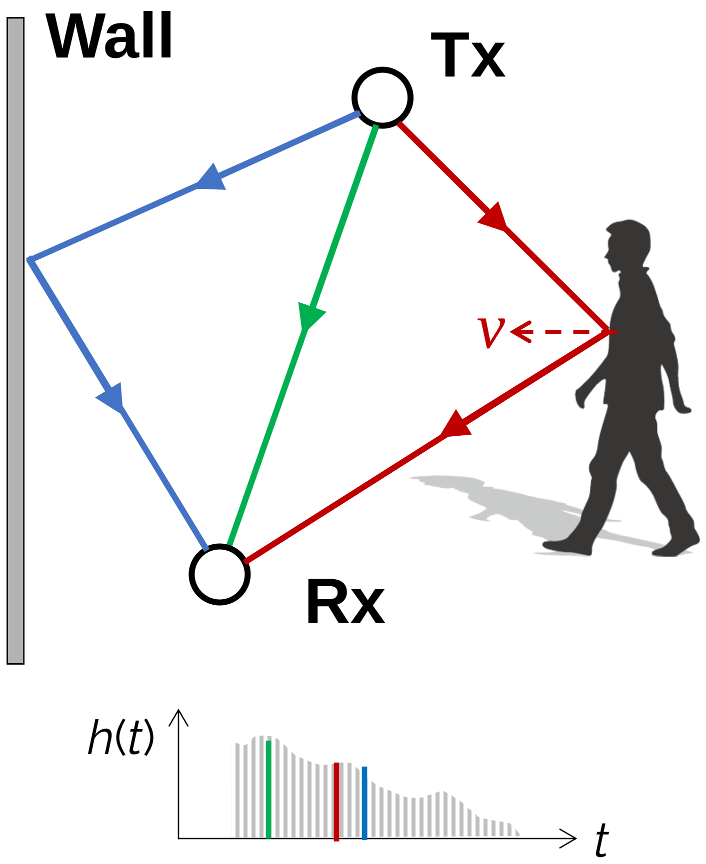


Sources of phase errors:

- Sampling Frequency Offset (SFO)
- Carrier Frequency Offset (CFO)
- Symbol Timing Offset (STO)
- Initial Phase Offset

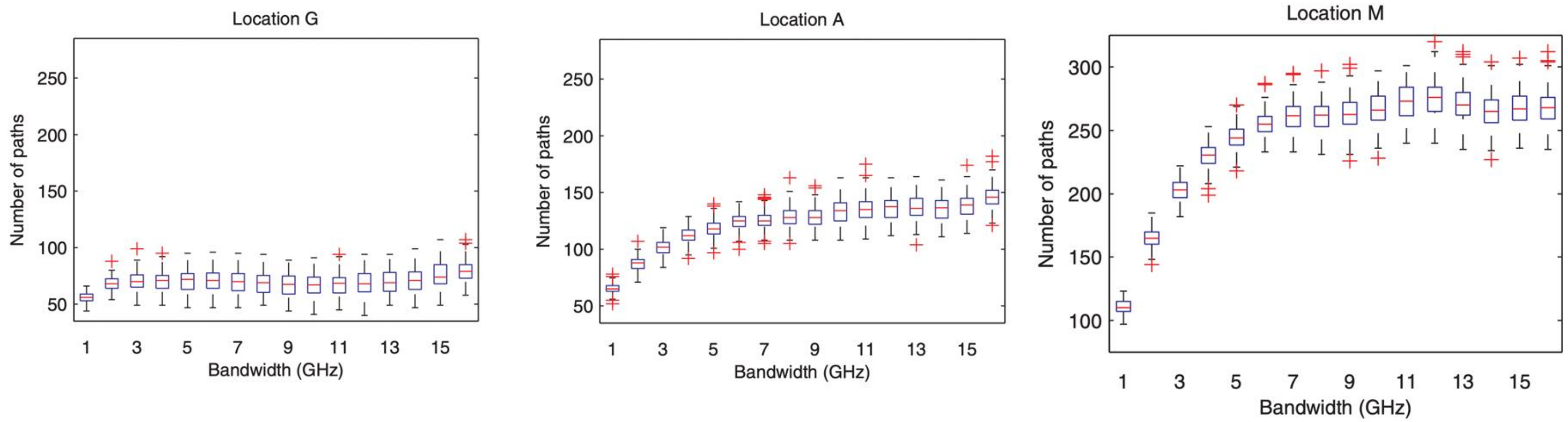
Challenges (2)

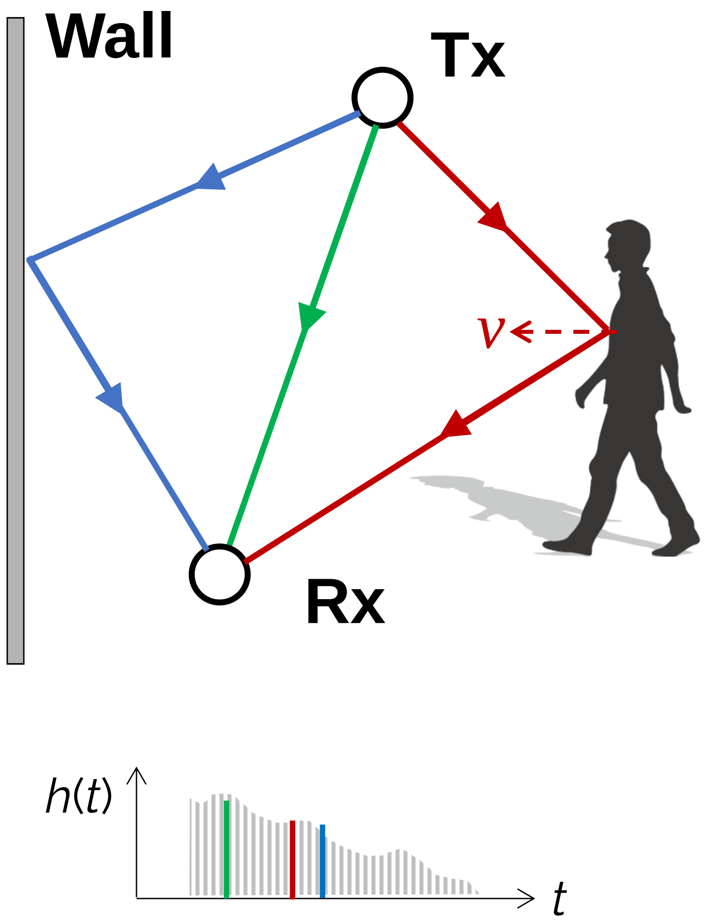
- Fundamental limits on multipath resolvability
- Limited bandwidth (20MHz~80MHz)
  - $\Delta d = c/B$
  - 20MHz: 15 m
  - 40MHz: 7.5 m
- Limited # of antennas (typically <=3)
  - Many IoTs only have one single antenna



Challenges (3)

- Many multipaths in complex indoor environments

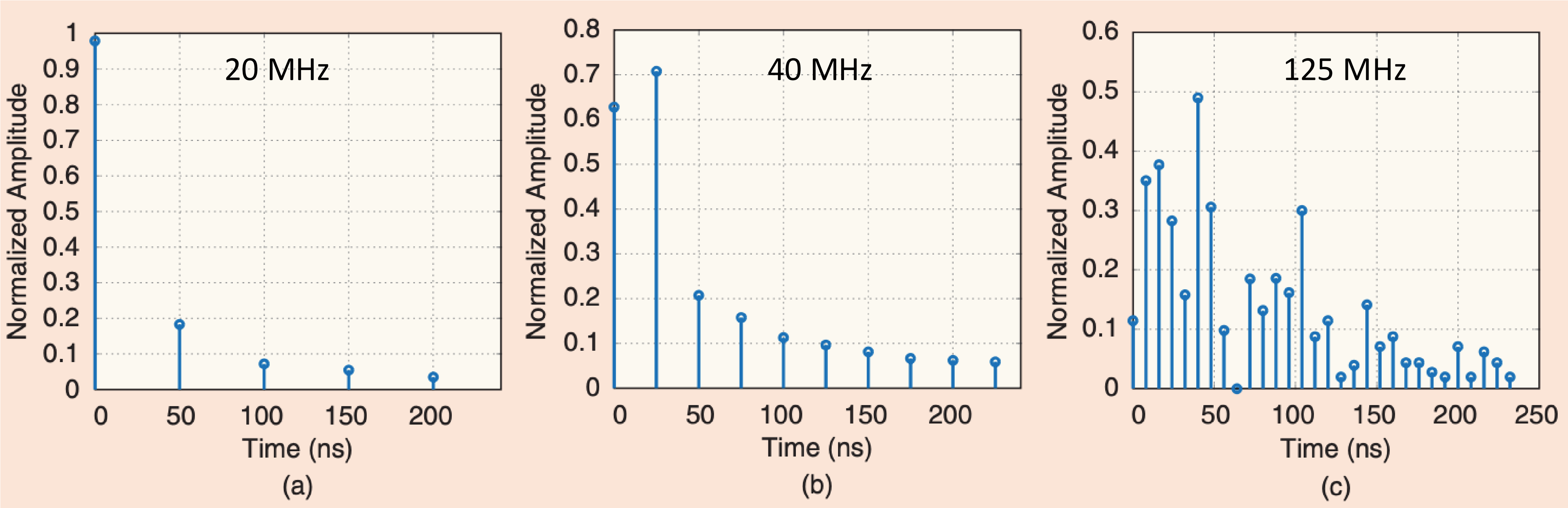




Cannot resolve the parameters of these many multipaths!

Gifford, W. M., Li, W. W.-L., Zhang, Y. J., & Win, M. Z. (2011). Effect of Bandwidth on the Number of Multipath Components in Realistic Wireless Indoor Channels. 2011 IEEE International Conference on Communications (ICC).

Multipath channel vs bandwidth



Wang, Beibei, et al. "The promise of radio analytics: A future paradigm of wireless positioning, tracking, and sensing." IEEE Signal Processing Magazine 35.3 (2018): 59-80.

Summary: What is CSI

A data perspective w/ zero SP background & zero memory about previous lectures

- $\mathbf{H(t)} = [H(t, f_1), H(t, f_2), \cdots, H(t, f_N)]$
  - Complex number: $H(t, f_i) = a_i + jb_i$
  - Amplitude: $|H(t, f_i)| = \sqrt{a_i^2 + b_i^2}$ ← abs()
  - Phase: $\phi_i = \tan^{-1}\frac{b_i}{a_i}$ ← phase()
- Time series of $\mathbf{H(t)}$

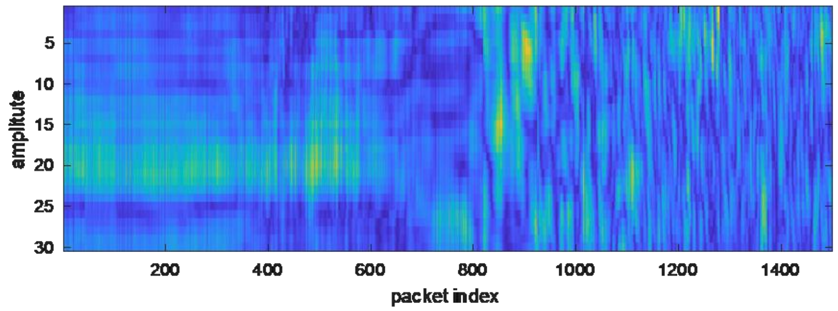
Time Series of CSI

$$\begin{bmatrix} H(1, f_1) & \cdots & H(M, f_1) \\ \vdots & \ddots & \vdots \\ H(1, f_N) & \cdots & H(M, f_N) \end{bmatrix}$$

Time Series of CSI Amplitude

$$\begin{bmatrix} |H(1, f_1)| & \cdots & |H(M, f_1)| \\ \vdots & \ddots & \vdots \\ |H(1, f_N)| & \cdots & |H(M, f_N)| \end{bmatrix}$$

Time Series of CSI Amplitude



Questions?

- Thank you!