ECE 257B: Principles of Wireless Networks

Lecture 2: Review: Wireless Communication

Dinesh Bharadia

*slides borrowed from Haitham

Announcements

- Discuss Project by end of Next week.
- Project Proposal due 25th January 2019
- Start on Homework 0 for the class, it is due in two weeks – don't wait till last minute.
- 5 Late days for entire quarter, can be used for HW0, HW1 and HW2
- Start reading OFDM thesis, it has six chapters
- Quiz on OFDM Thesis would be next Thursday first 5 minutes of the class!

Project Proposal Format

- Motivation and Problem statement
- Current state-of-art if any
- Stepwise proposed solution
- Risk mitigation

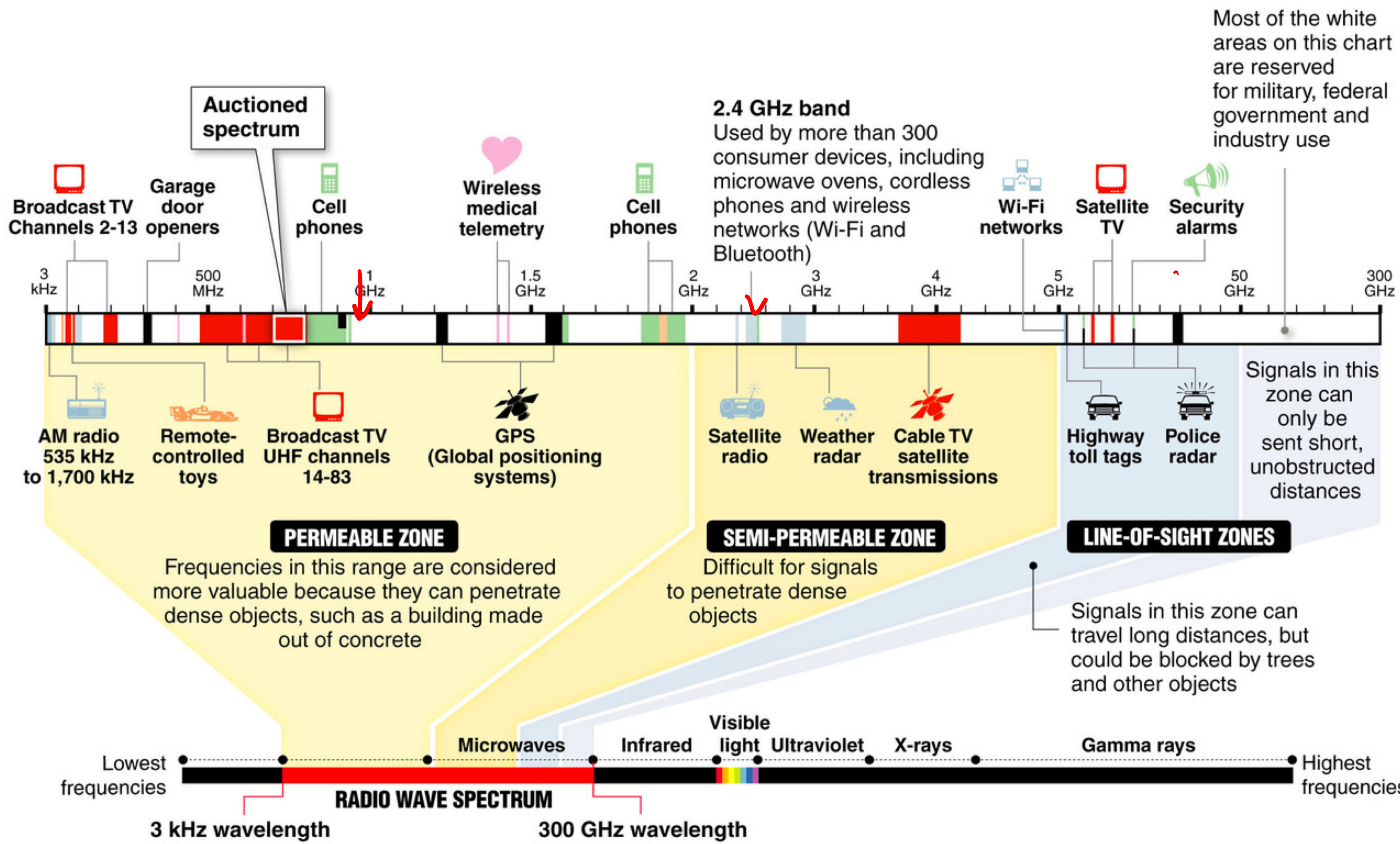
The Heilmeier Catechism

- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What is new in your approach and why do you think it will be successful?
- Who cares? If you are successful, what difference will it make?
- What are the risks?

Today's Class: Wireless Communication

- Intuition and Philosophy for research
- How do we communicate information wirelessly?
  - Why Passband Communication and not baseband?
  - Up-Conversion and Down conversion
  - Modulation
  - What is SNR?
  - Higher order modulation and it's relation to SNR
  - ML Decoder
- How to choose project?

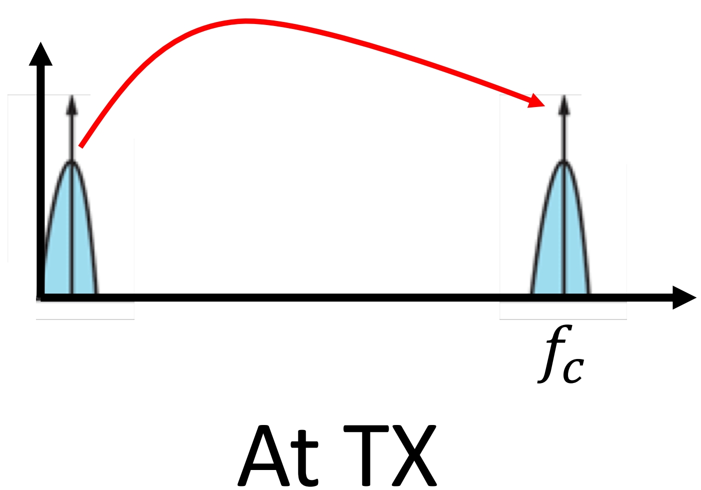
The Wireless Spectrum

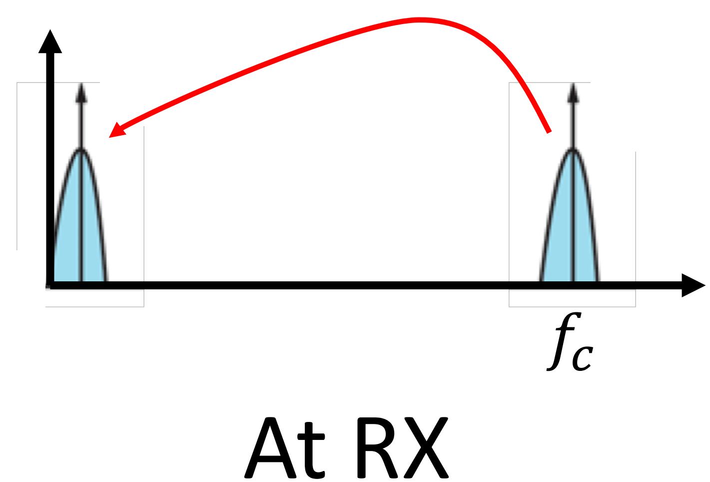


Transmitting & Receiving at Frequency f_c

- To recover signal, must sample at Nyquist: $2f_c$

- Upconvert and Downconvert the signal from baseband



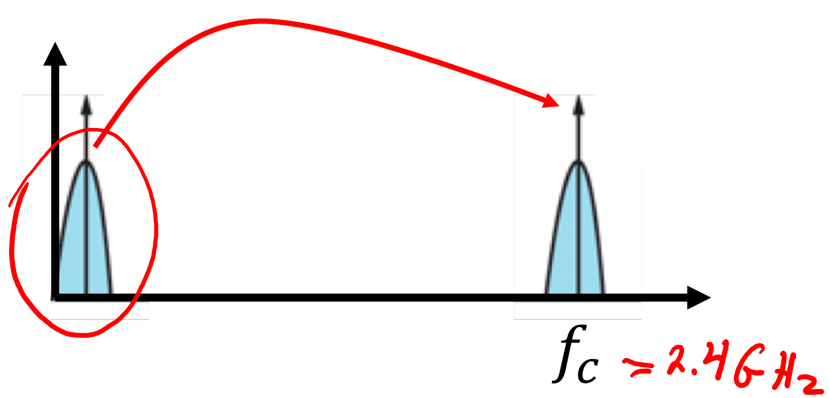


- In Baseband: sample at $2 \times Bandwidth$

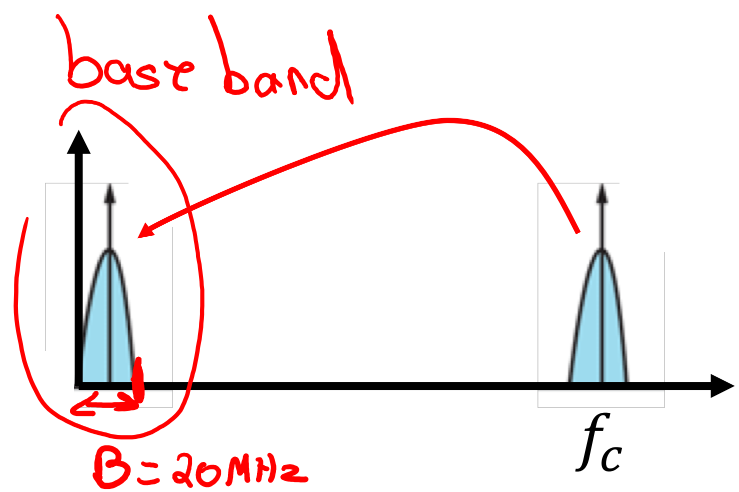
Transmitting & Receiving at Frequency f_c

- To recover signal, must sample at Nyquist: $2f_c$

- Upconvert and Downconvert the signal from baseband



At TX



At RX

- In Baseband: sample at $2 \times Bandwidth$

Up Conversion & Down-Conversion

$x(t)\cos(2\pi f_c t)$

$y(t) = x(t)\cos(2\pi f_c t)$

$y(t) \times \cos(2\pi f_c t) = x(t)\cos^2(2\pi f_c t)$

$= \underbrace{x(t)}_{\text{original}} \times \frac{1}{2}\left(1 + \underbrace{\cos(2\pi\, 2 f_c t)}_{\text{high frequency}}\right)$ → LPF

$= \frac{x(t)}{2}$

Up Conversion & Down-Conversion

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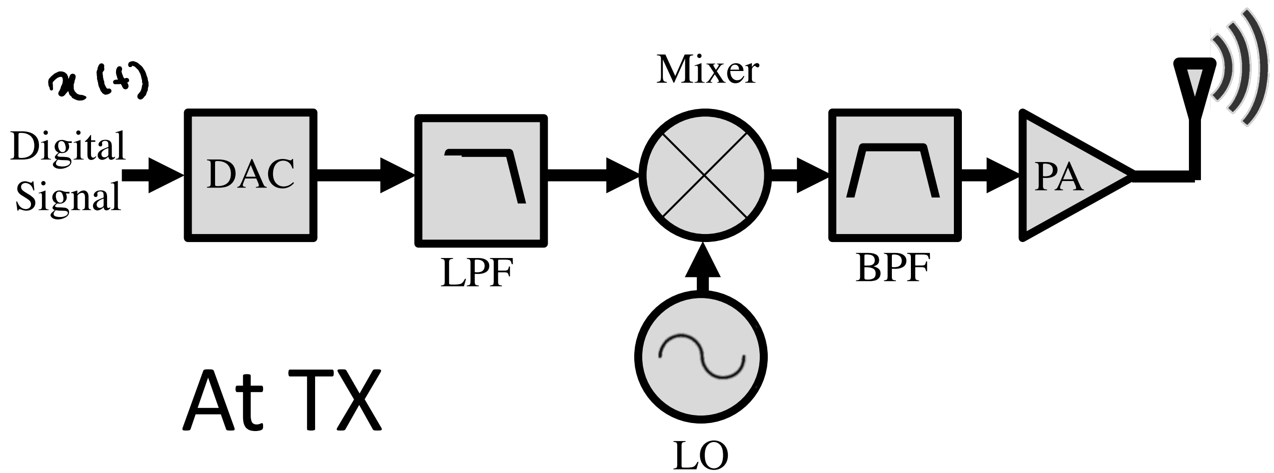
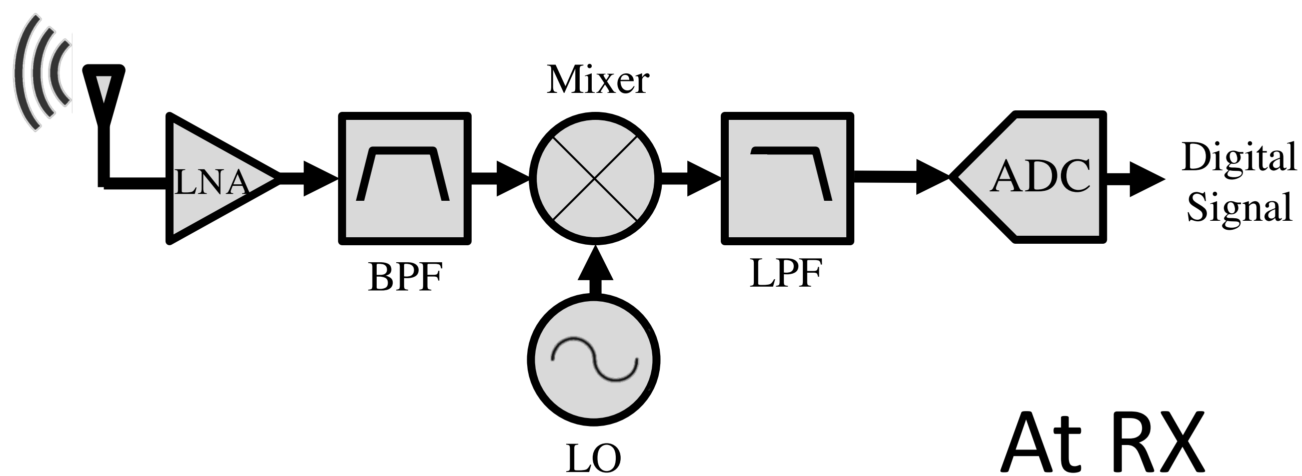
Up Conversion & Down-Conversion



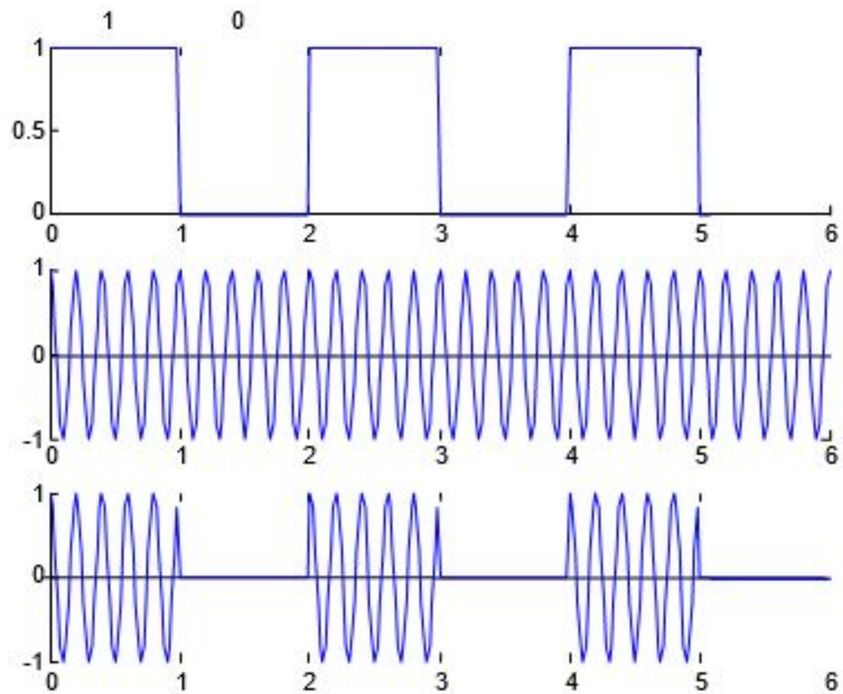
At TX

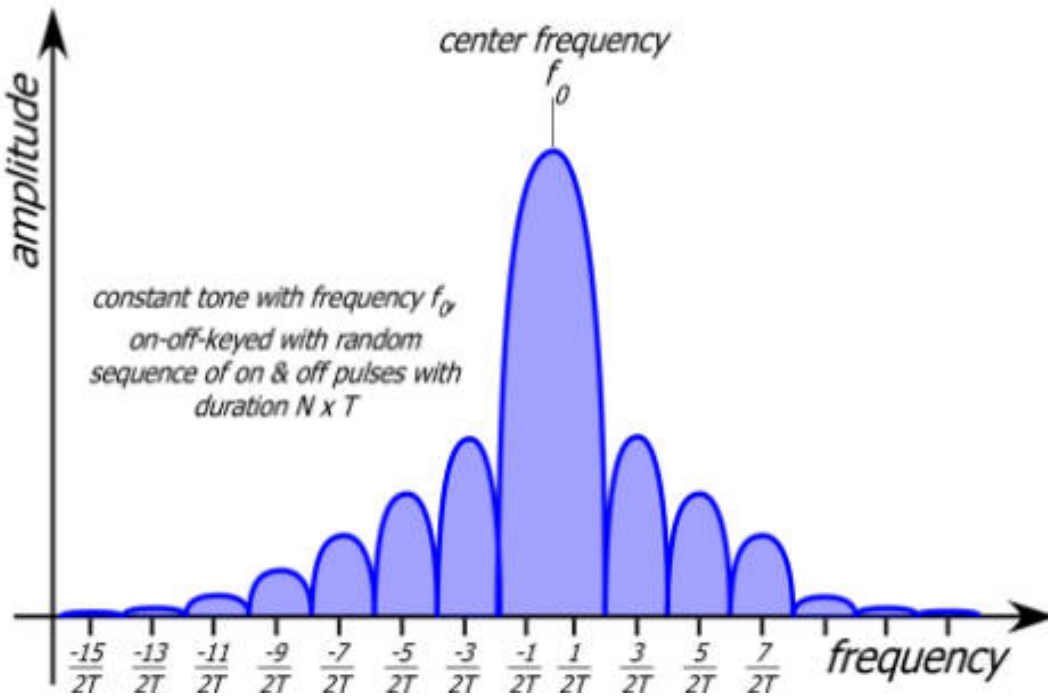


At RX

Digital Modulation

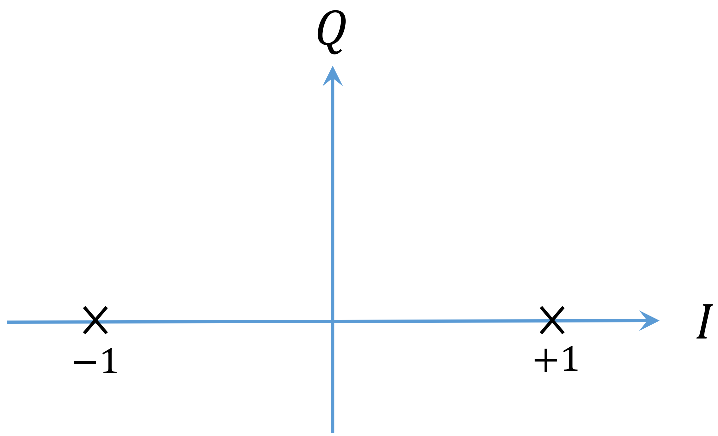
- Map Bits to Signal Values
- On-Off Keying (ASK):





Digital Modulation

- BPSK : Binary Phase Shift Keying



$$\pm 1 \cos(2\pi f_c t) = \cos(2\pi f_c t \pm \pi) = -1$$ } phase coherence

- DBPSK : Differential Binary Phase Shift Keying

$$\cos(2\pi f_c t + \phi)$$

$$\cos(2\pi f_c t + \phi + \pi) \rightarrow 1$$

$$\cos(2\pi f_c t + \phi) \rightarrow 0$$

SNR: Signal-To-Noise Ratio

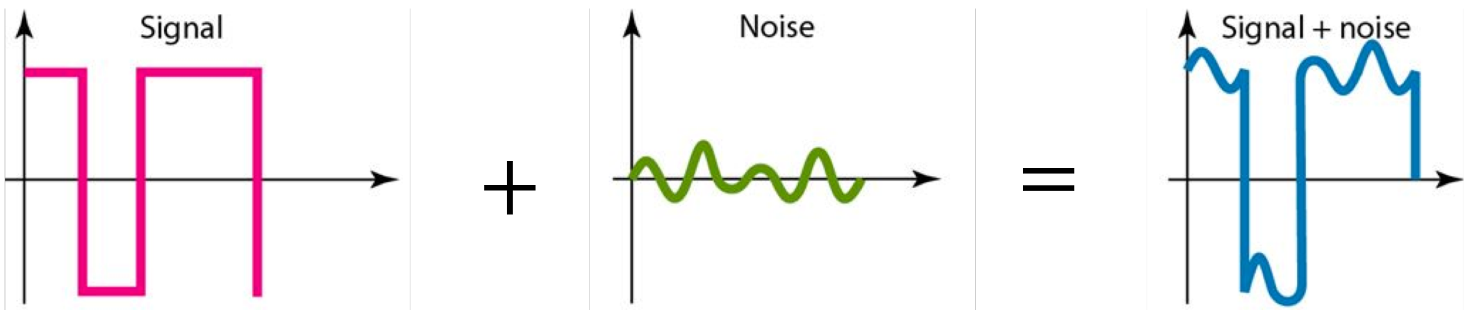
$$SNR = \frac{Received\ Signal\ Power}{Noise\ Power\ at\ RX}$$

Tx power

wirelechannel

Hardware

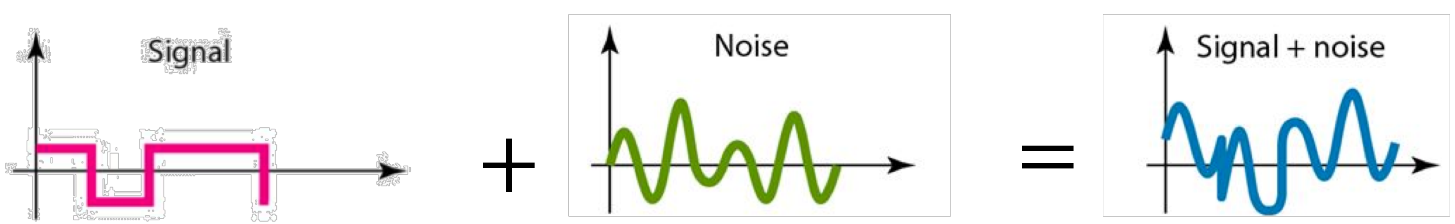
- High SNR – easier to extract signal from noise (a "good thing")



Bits: 0 1 0 0

0 1 0 0

- Low SNR – hard to extract signal from noise (a "bad thing")



Bits: 0 1 0 0

SNR: Signal-To-Noise Ratio

$$SNR = \frac{Received\ Signal\ Power}{Noise\ Power\ at\ RX}$$

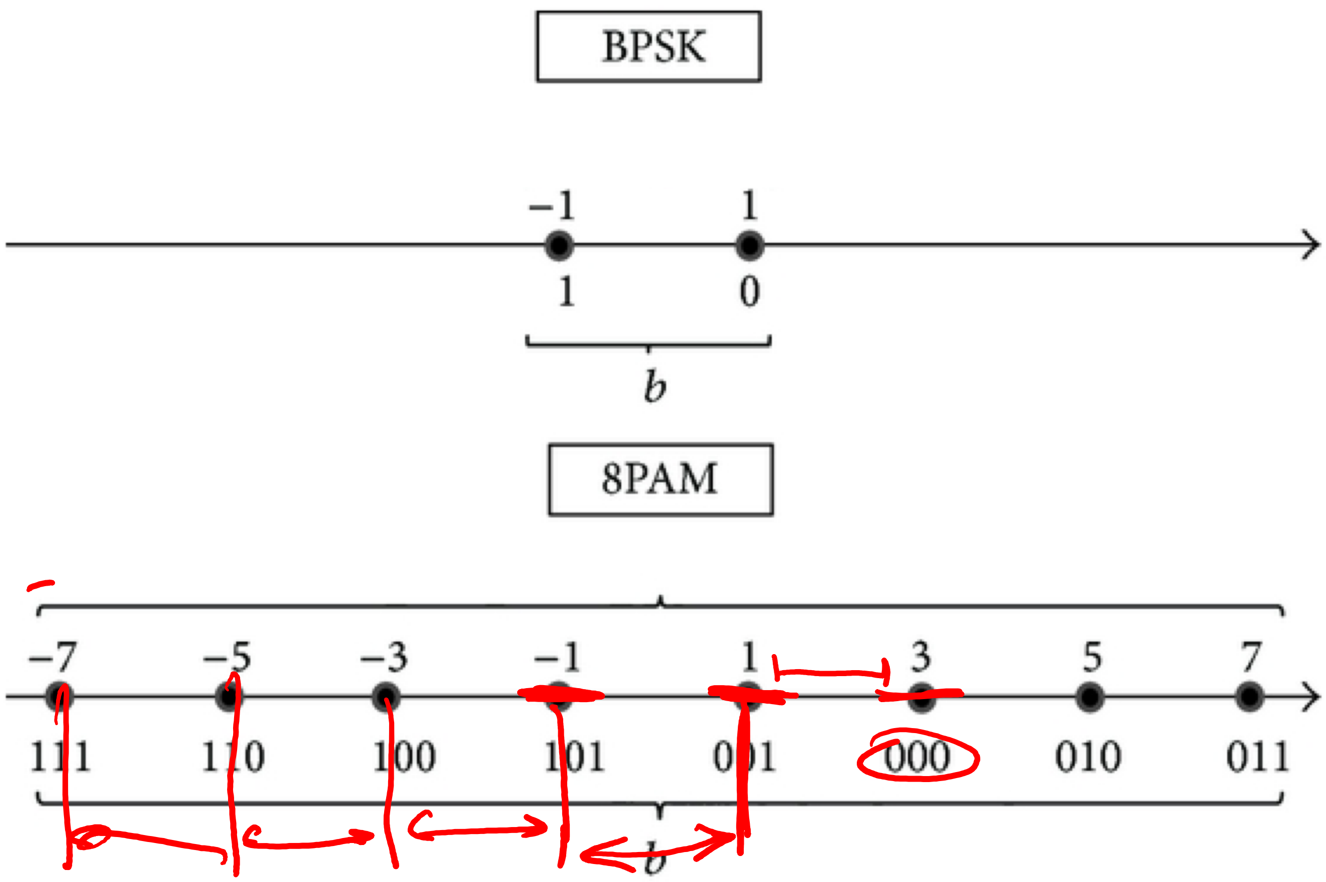
Why not increase SNR by increasing your transmit power?

- FCC regulation
- Battery
- Heat / Circuit limitations

} Power budget = P

Higher Order Modulation

- High SNR ➔ Lower Bit Error ➔ Use higher order modulation i.e. pack more bits per symbol



Digital Modulation

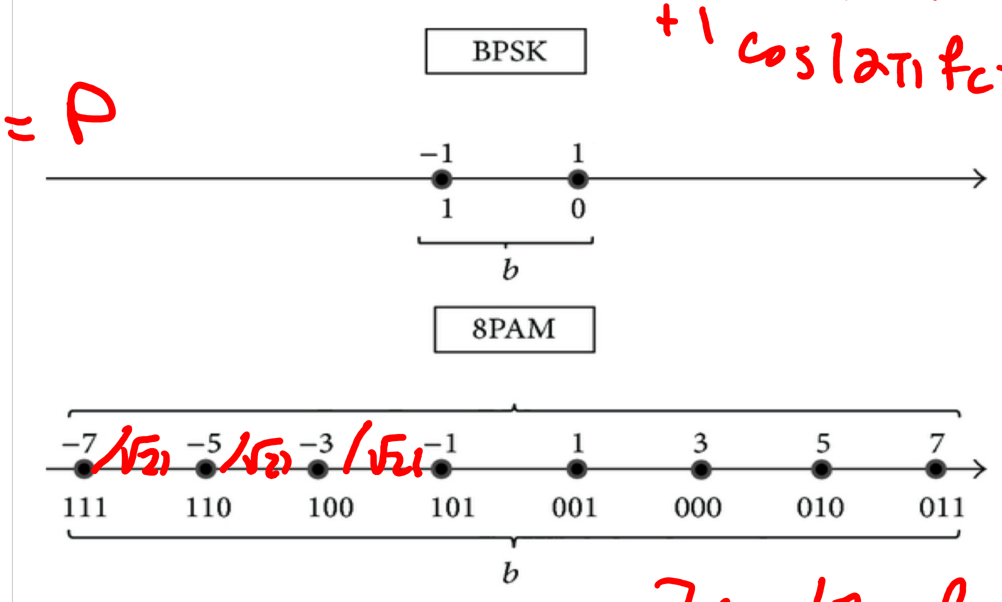
- PAM : Pulse Amplitude Modulation
  - Scale to maintain total average power

$$P_{avg} = \frac{1}{2}\left(\left(-1\times\sqrt{P}\right)^2 + \left(1\times\sqrt{P}\right)^2\right) = P$$

$$P_{avg} = \frac{1}{8}\left(\frac{49+25+9+1}{21}\right)\times 2 = \frac{21P}{21} = P$$

$\sqrt{P}$ $-1 \cos(2\pi f_c t)$

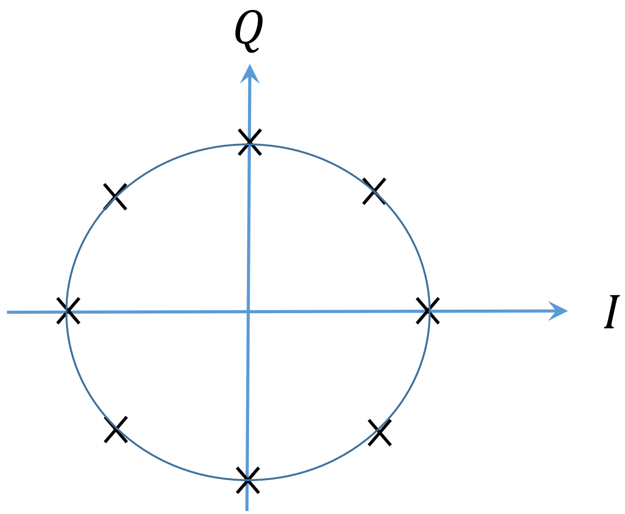
$+1 \cos(2\pi f_c t)$



$-7\cos(2\pi f_c t)$

Digital Modulation

- QPSK : Quadrature Phase Shift Keying



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$\cos(2\pi f_c + 0) \Rightarrow 000$

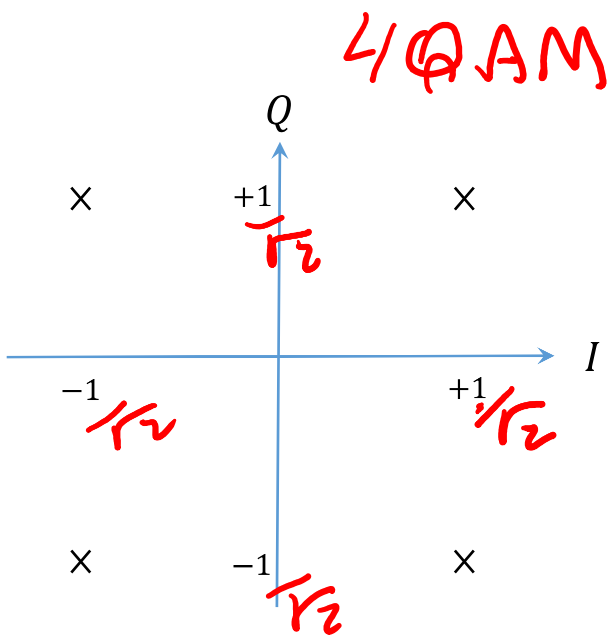
$\cos(2\pi f_c + \pi/4) \Rightarrow 001$

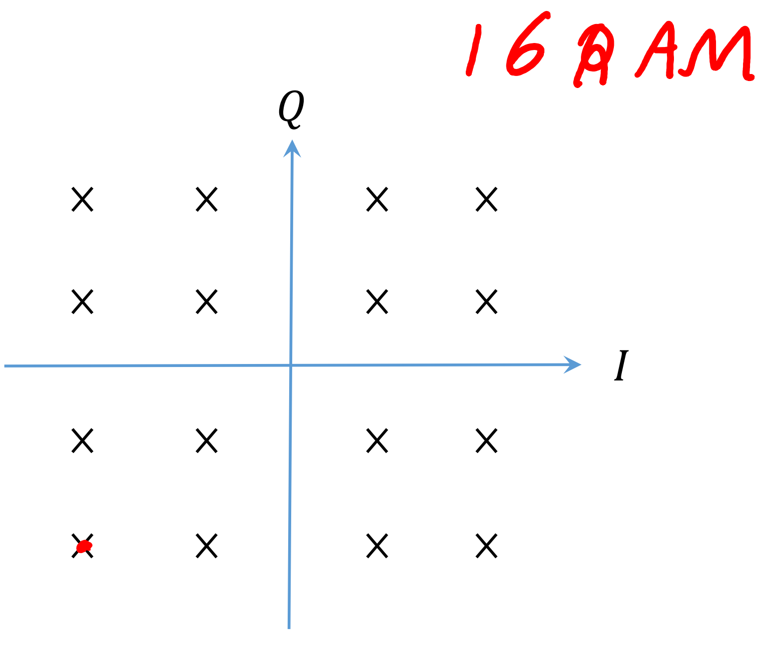
$\vdots$

- DQPSK : Differential Quadrature Phase Shift Keying

Digital Modulation

- QAM : Quadrature Amplitude Modulation





−3 −3j

Quadrature Modulation

$y(t) = I\cos(2\pi f_c t) + Q\sin(2\pi f_c t)$ $\qquad x(t) = I + Qj$

$y(t)\cos(2\pi f_c t) = I\cos^2(2\pi f_c t) + Q\cos(2\pi f_c t)\sin(2\pi f_c t)$

$= \frac{I}{2} + \frac{I}{2}\cos(2\pi 2 f_c t) + \frac{Q}{2}\sin(2\pi 2 f_c t)$

$= \frac{I}{2}$

$y(t)\sin(2\pi f_c t) = I\cos(2\pi f_c t)\sin(2\pi f_c) + Q\sin^2(2\pi f_c t)$

$= \frac{Q}{2}$

Quadrature Modulation

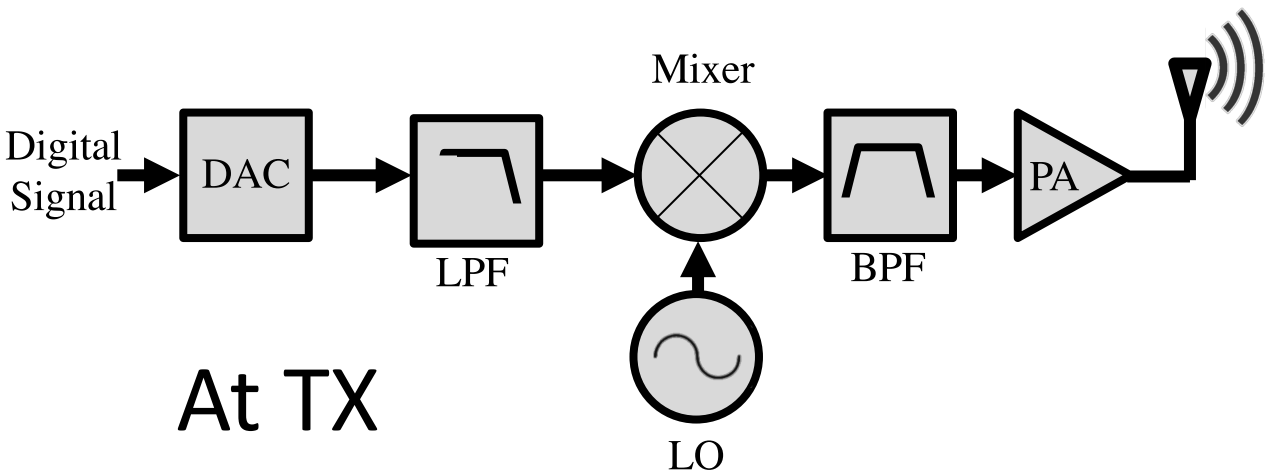
$$y(t) = I\cos(2\pi f_c t) + Q\sin(2\pi f_c t)$$

$$= \mathrm{Re}\left\{ x(t)\, e^{-j2\pi f_c t} \right\}$$

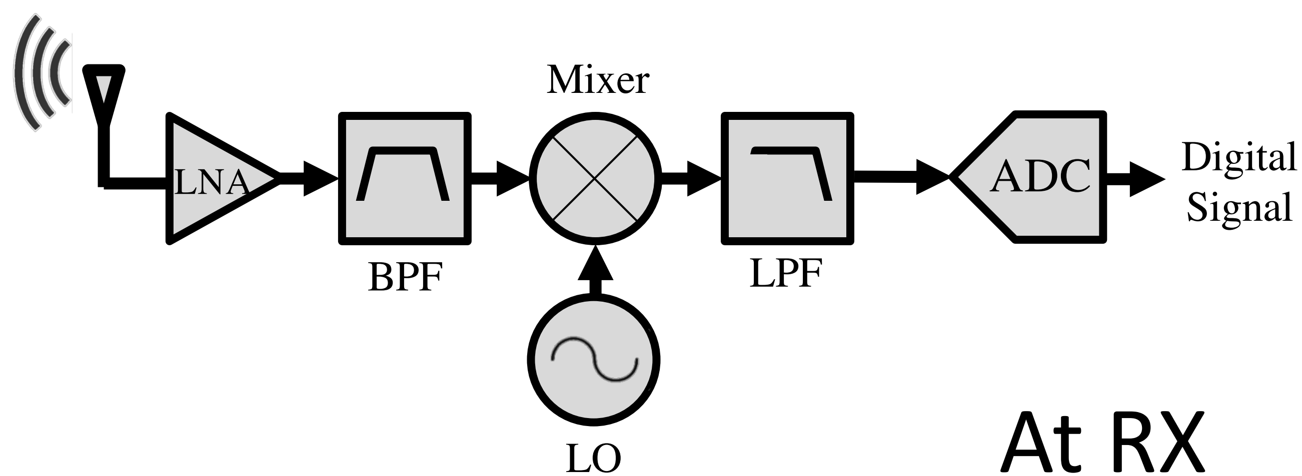
$$y(t) = x(t)\, e^{-j2\pi f_c t}$$

$$y(t)\, e^{j2\pi f_c t} = x(t)\, e^{-j2\pi f_c t}\, e^{j2\pi f_c t} = x(t)$$

Up Conversion & Down-Conversion



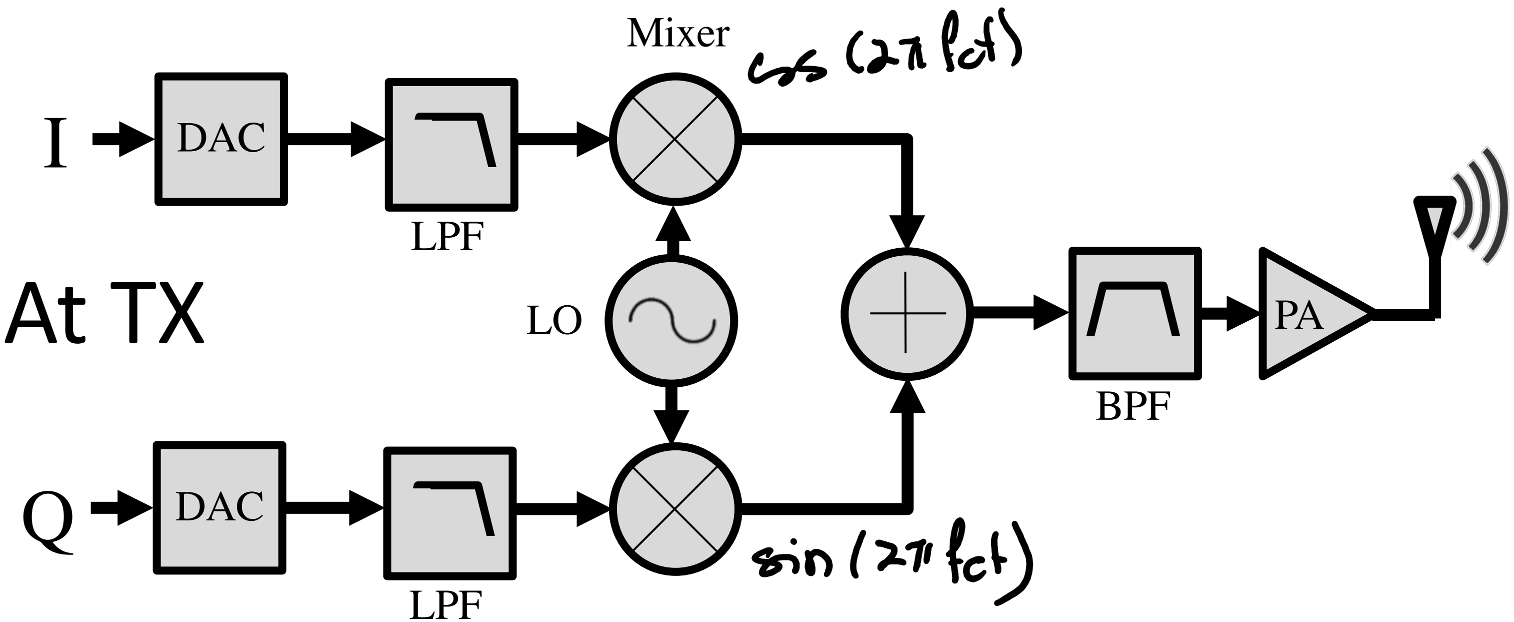
At TX

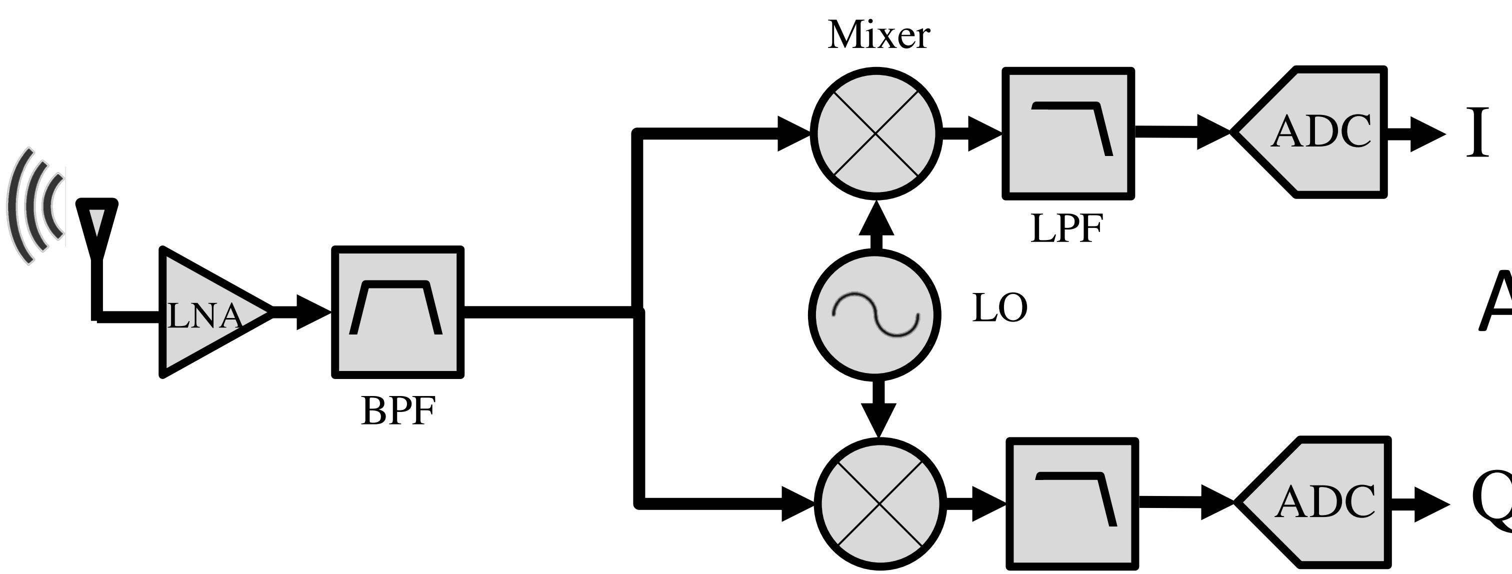


At RX

Up Conversion & Down-Conversion

At TX

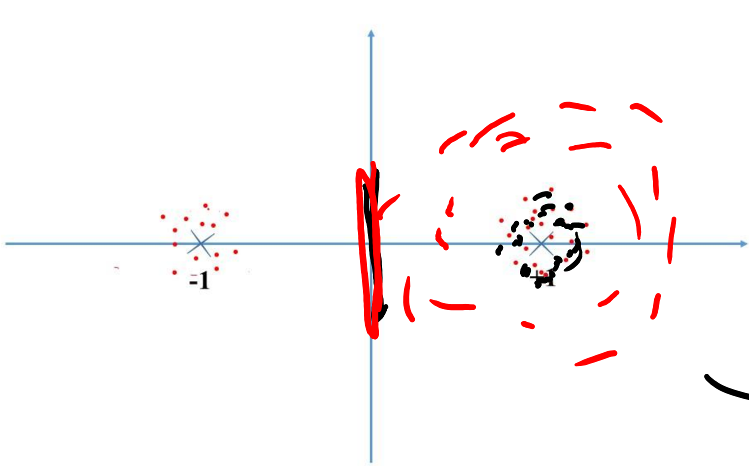




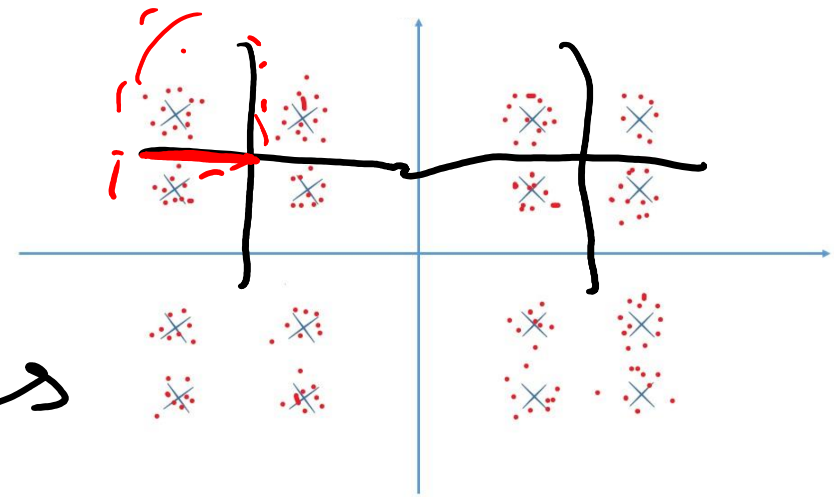
At RX

Additive White Gaussian Noise

BPSK: 1 bit per symbol



16 QAM: 4 bits per symbol



Maximum Likelihood Decoder

$b=0 \longrightarrow Y$

$$P(Y \mid b=0) \underset{b=1}{\overset{b=0}{\gtrless}} P(Y \mid b=1)$$

$b = \; \Rightarrow x = \pm 1$

$Y = X + N \longrightarrow \mathcal{N}(0, \sigma)$

Given $b=0 \Rightarrow Y \sim \mathcal{N}(1, \sigma)$

$b=1 \Rightarrow Y \sim \mathcal{N}(-1, \sigma)$

$$p(y \mid b=0) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(y-1)^2}{2\sigma^2}}$$

Maximum Likelihood Decoder

$$\frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y-1)^2}{2\sigma^2}} \underset{1}{\overset{0}{\gtrless}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(y+1)^2}{2\sigma^2}}$$

$$-\frac{(y-1)^2}{2\sigma^2} \underset{1}{\overset{0}{\gtrless}} -\frac{(y+1)^2}{2\sigma^2}$$

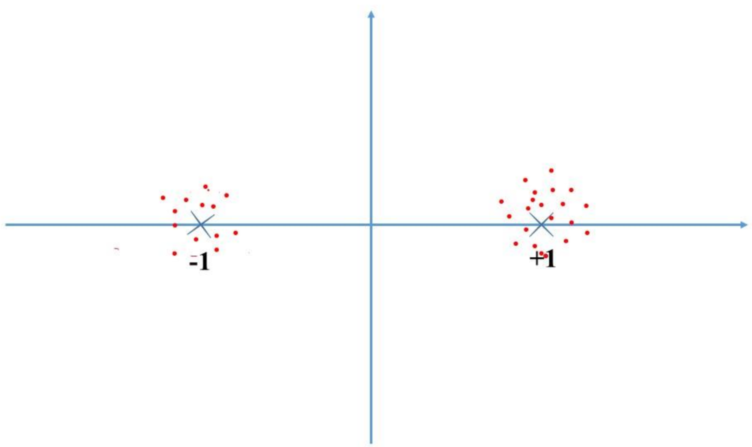
$$-y^2+2y-1 \underset{1}{\overset{0}{\gtrless}} -y^2-2y-1$$

$$y \underset{1}{\overset{0}{\gtrless}} 0$$

Maximum Likelihood Decoder

Additive White Gaussian Noise

BPSK: 1 bit per symbol



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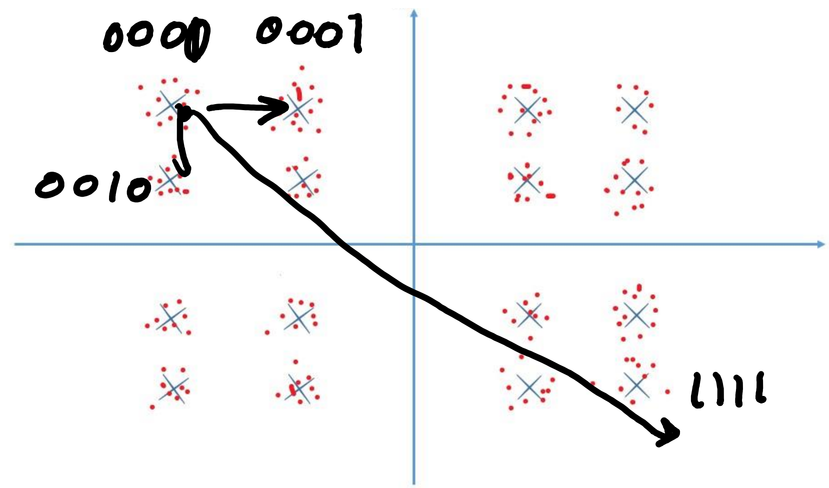


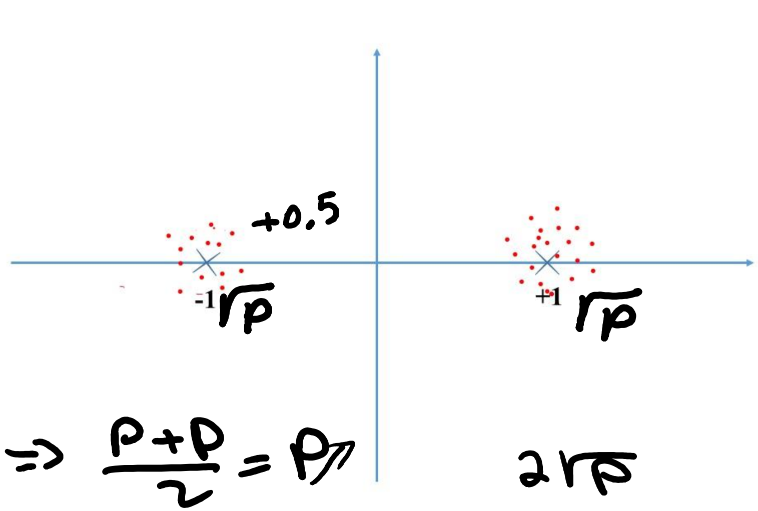
How to map the bits to constellation points?

Nearby constellation points have 1 bit difference

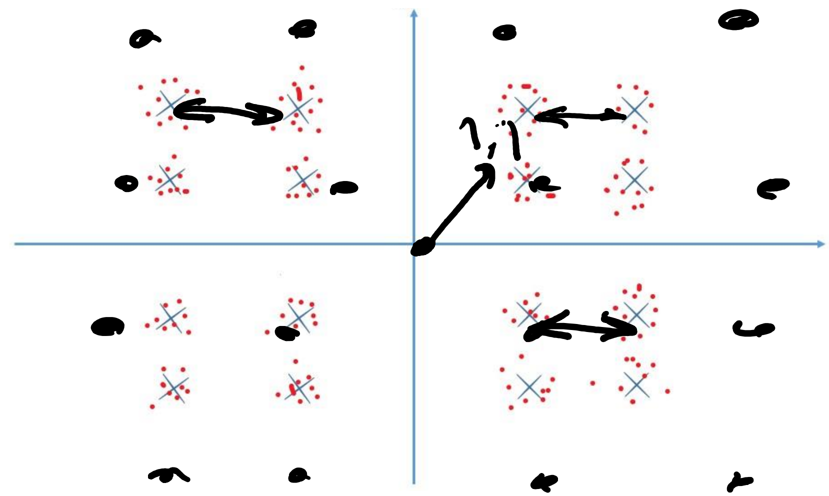
Gray Codes

Additive White Gaussian Noise

BPSK: 1 bit per symbol



16 QAM: 4 bits per symbol



Why is constellation centered at 0?

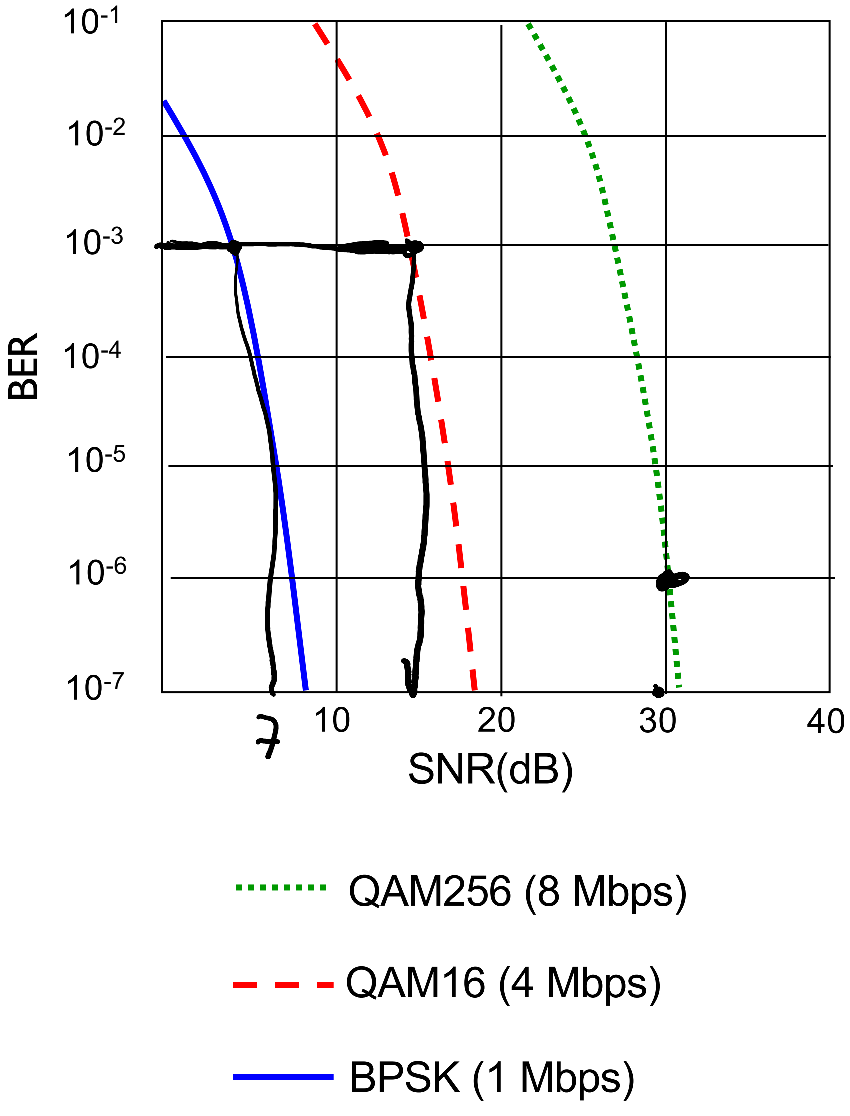
$0.5\sqrt{P}$ $1.5\sqrt{P}$ $\Rightarrow \frac{1}{2}\left(\frac{1}{4}P + \frac{9}{4}P\right) = 1.25P$

Bit-Error-Rate

- *SNR versus BER tradeoffs*
  - *given physical layer modulation:*

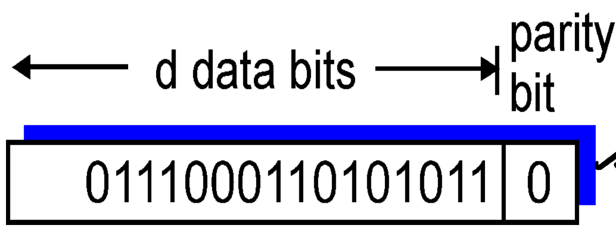
    Higher SNR → Low BER

  - *given SNR:* choose physical layer that meets BER requirement, giving highest throughput



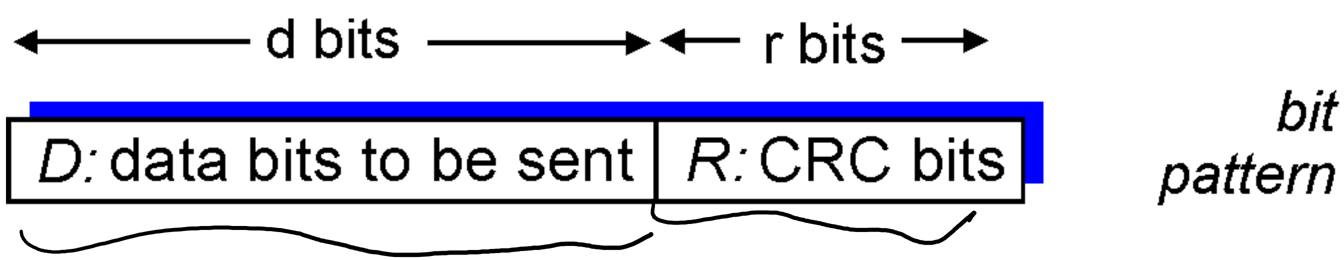
Error Detection and Correction

- Add Redundant bit to
- Checksums→ Detect Errors
  - Parity Check



even # of 1 ⇒ 0
odd # of 1 ⇒ 1
1 bit error
odd number of bit flips

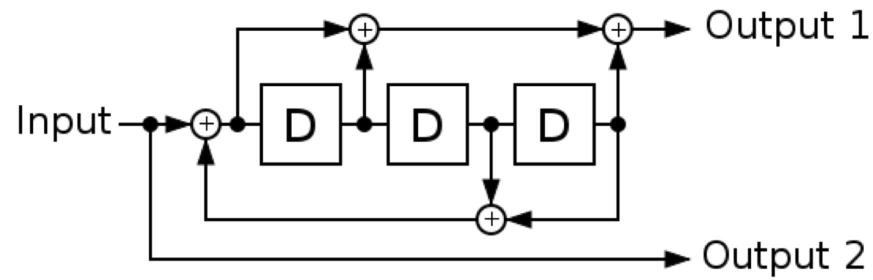
  - CRC: Cyclic Redundancy Check



larger r ⇒ detect more errors

Error Detection and Correction

- FEC: Forward Error Correction
  - Repetition Code
  - Convolutional codes
  - Reed Solomon codes
  - Turbo codes
  - LDPC codes

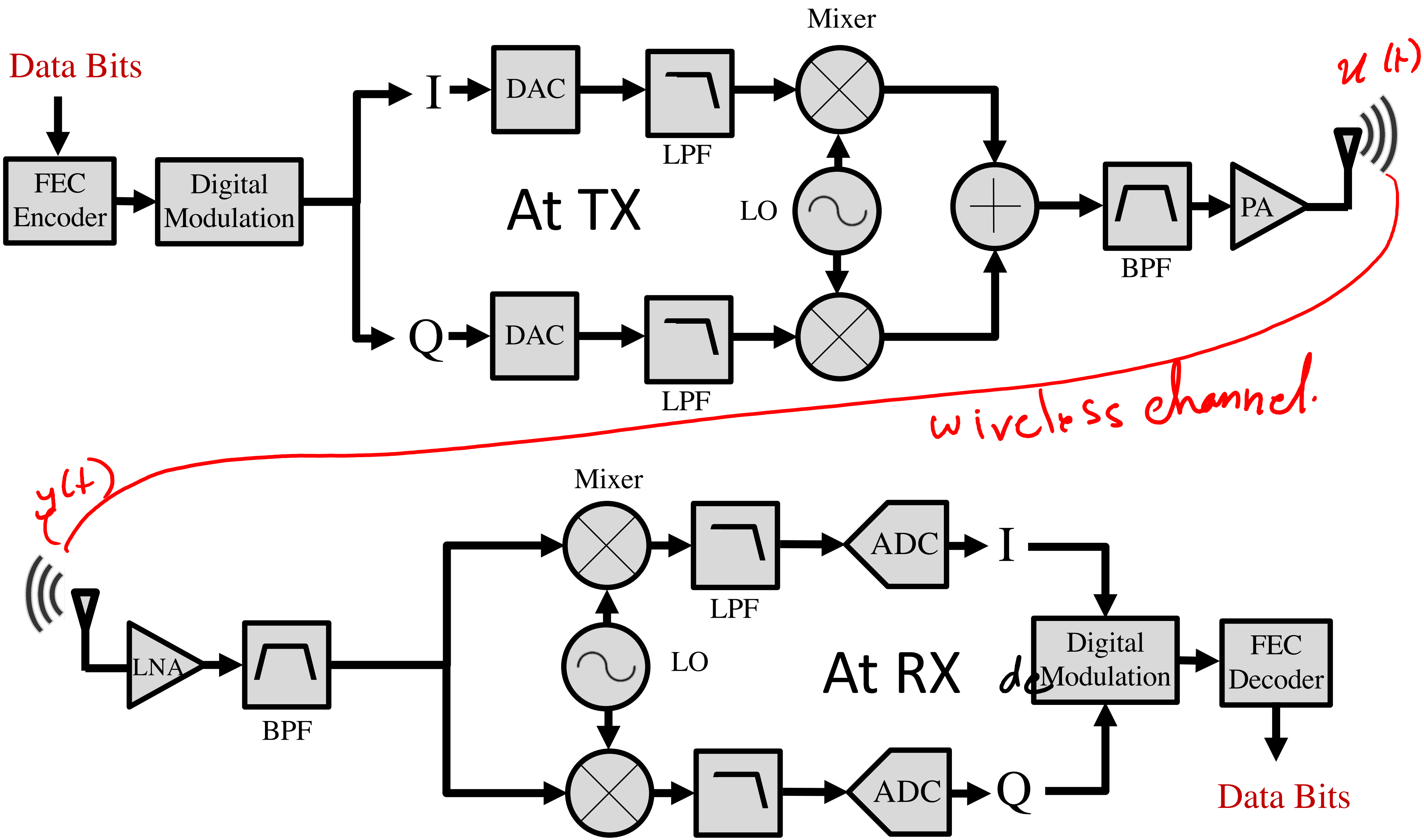


- Coding Rate $= \frac{2}{3}$ → every two bits add 1 more bit

↑ coding rate ⇒ less correct

↓ coding rate ⇒ ↑ redundancy ⇒ ↑ correct bits

Transmitter & Receiver Circuits



Data Rate

- Depends on Modulation & FEC

Bandwidth = B

$$\text{Data rate} = B \times \underbrace{\text{bits/sample}}_{\text{Modulation}} \times \underbrace{\text{coding rate}}_{\text{FEC Coding}}$$

Capacity of Wireless Channel

- *Given SNR, what is maximum rate that we can achieve?*
  - *Shannon Capacity Theorem:*

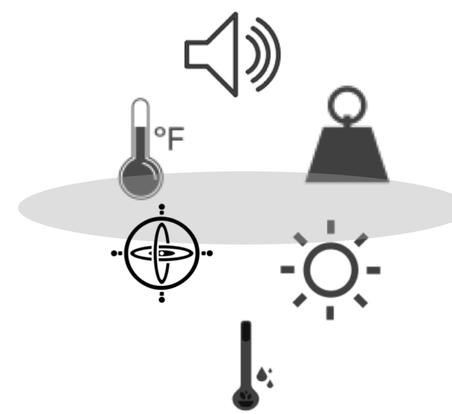
$$Capacity = Bandwidth \times \log_2(1 + SNR)$$

ECE257B projects

Autonomous Systems

Wireless

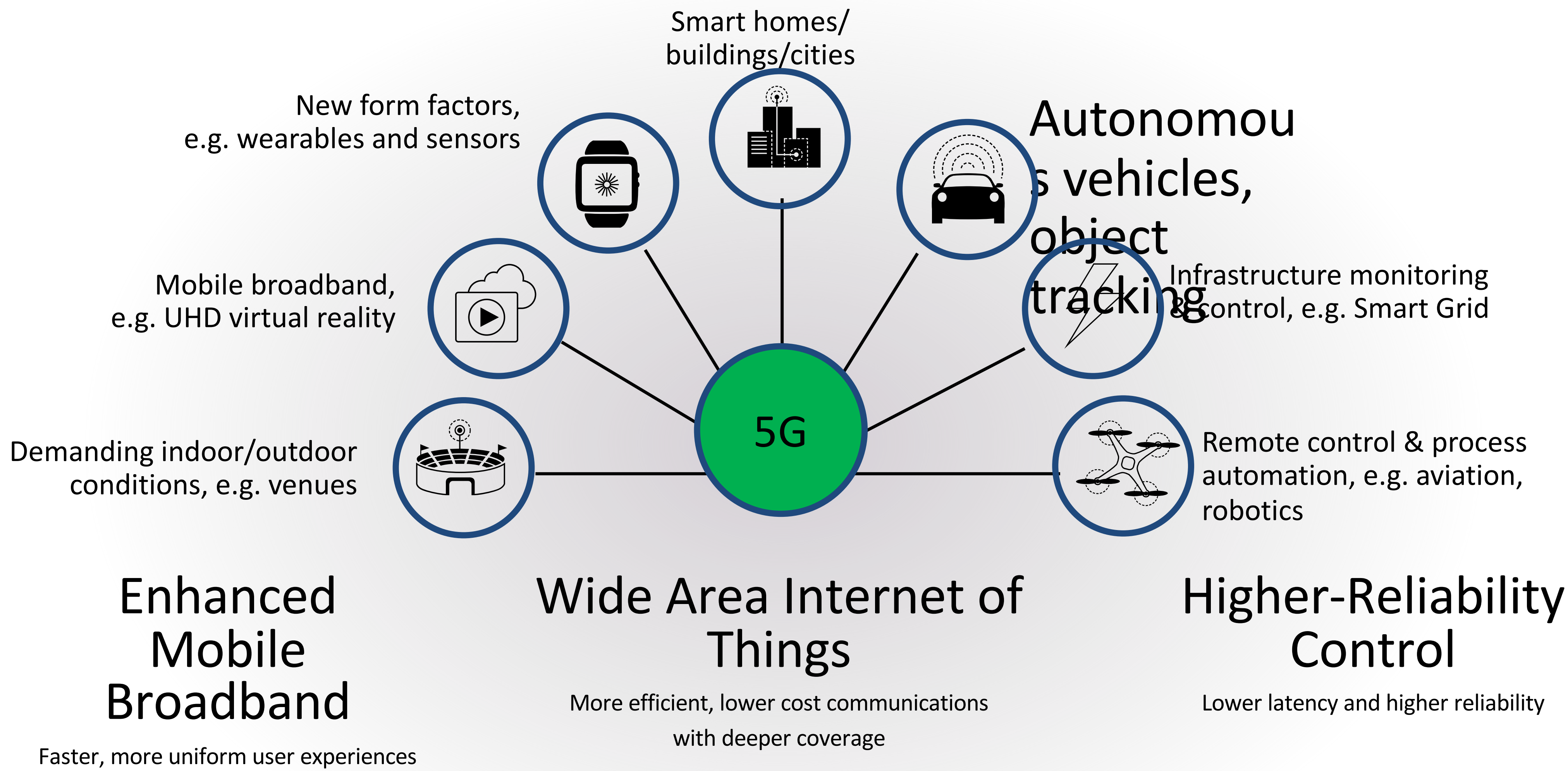
Sensing



Dinesh Bharadia

dineshb@ucsd.edu

Pillars of 5G



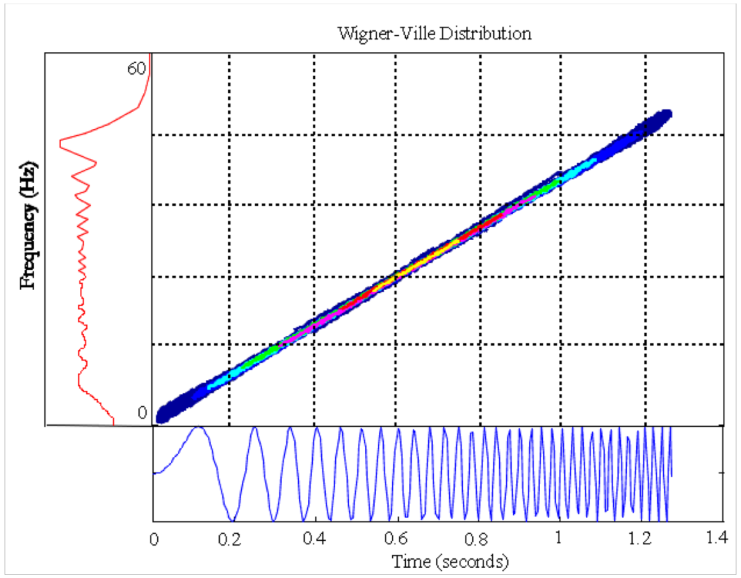
Source: Qualcomm

Any project addressing above challenges in within the scope of the course

Motivation for RF Deep sensing

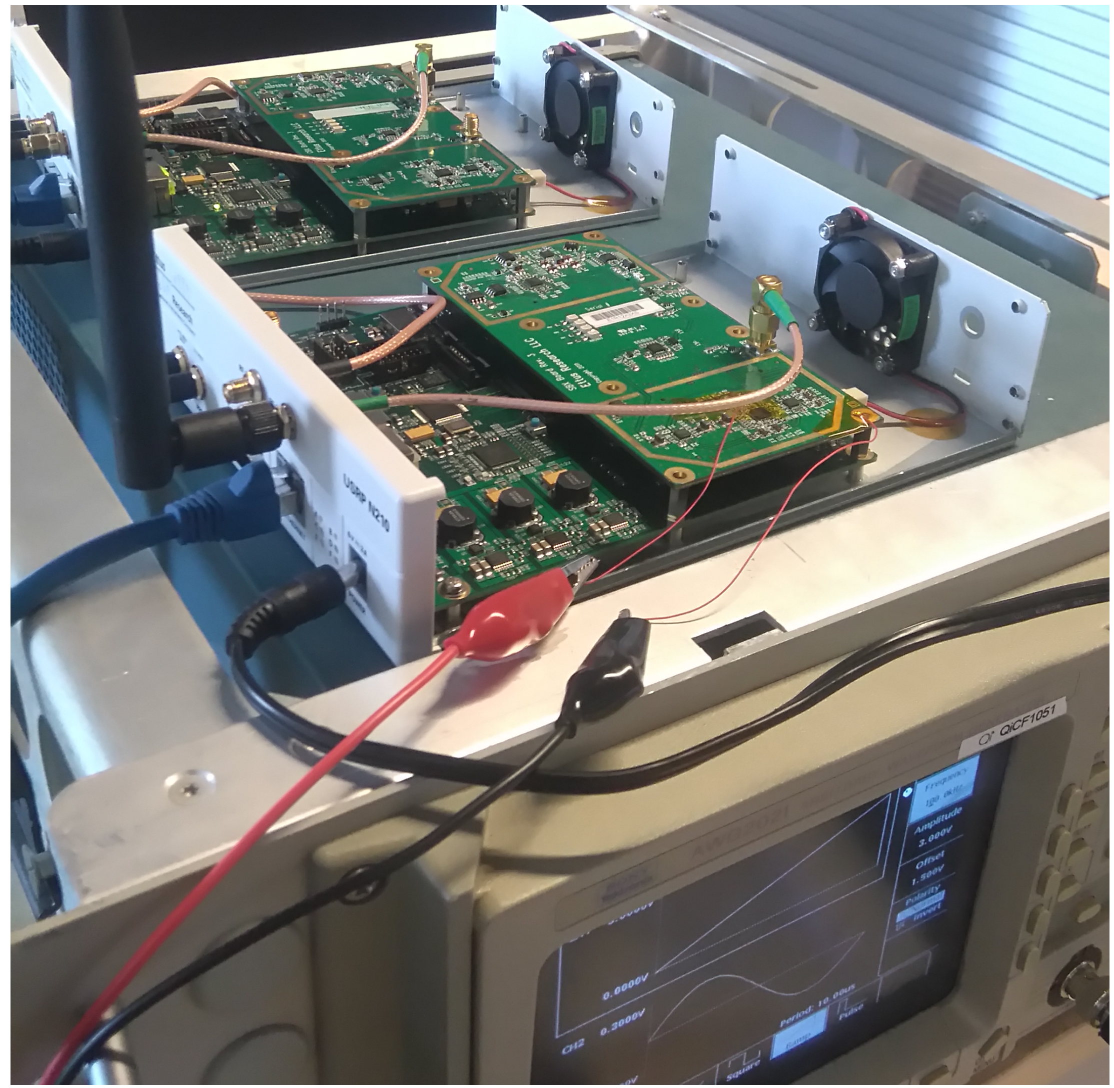
- What was Google when it started?
- Current spectrum sensing techniques consist largely of sensing channel power and occupancy.
- To capture and analyze the entire DC to 6 GHz from multiple vantage points.
- The ability to capture the spectrum in its entirety will allow us not only to determine whether a particular band is used, but also how it is used: how many transmitters, where they are located, and how the information is modulated.
- Build complete RF forensics applications.

Wideband Signal Capture



- Sensing Radios : Sweep the bands (DC-6GHz) to determine activity in spectrum

- Dedicated Rx : Sample Capture and occupancy Analysis



Non-linear Communication

- Most Front-ends are non-linear, however, most communication system assume linear communication channels?

- Why not design non-linear communication waveform?

MoVR: Cutting the Cord in Virtual Reality
(Hotnets'16, NSDI'17)

Vision for VR headset

Can we untether the VR experience? What we need:

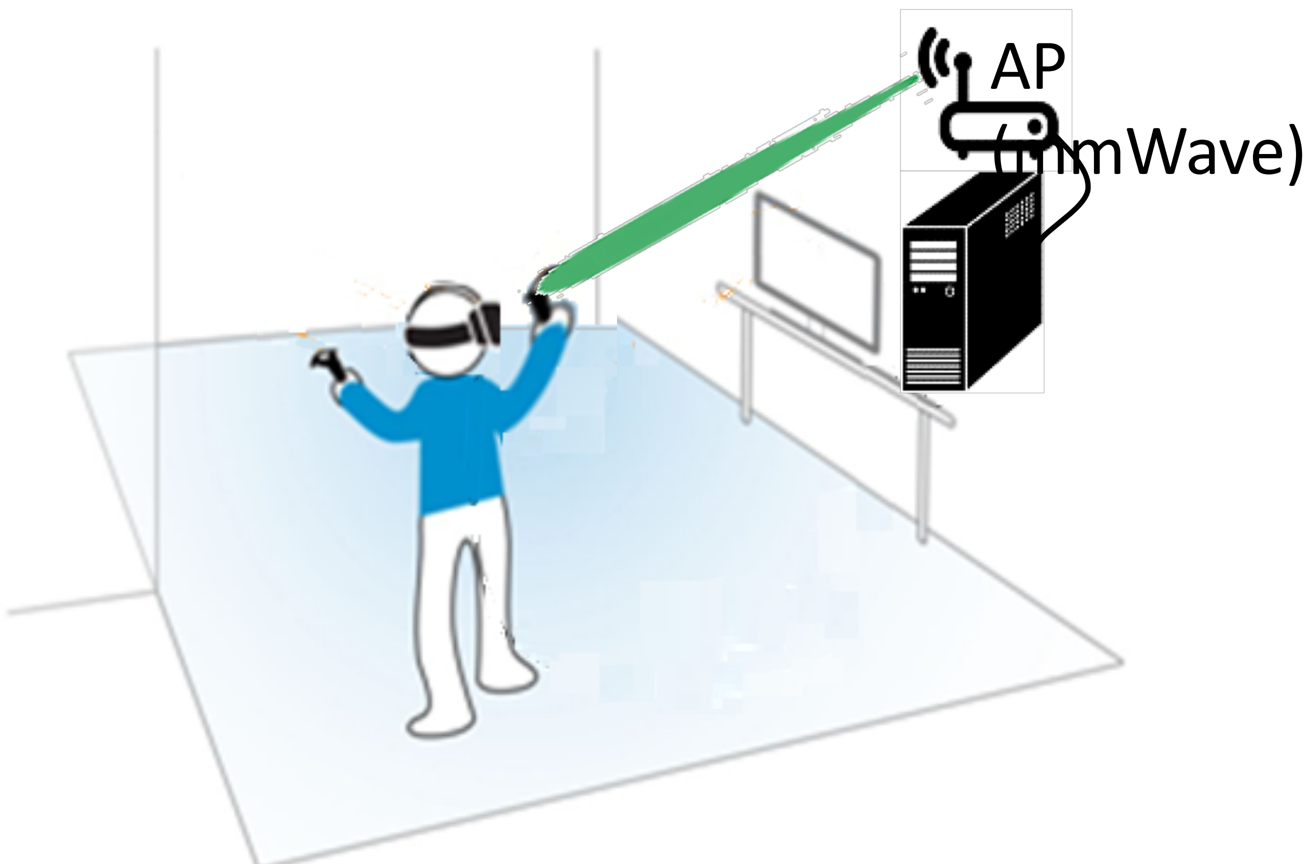
- Off-load compute and sensing to existing network infrastructure
- Fine-grained user context and sensing (head position, direction, speed) provided by the network
- Requires < 20ms RTT latency including compute, high bandwidth, move with user and rich video content

Can the wireless network become the platform for VR / AR?

Light Weight Low Power Headset design

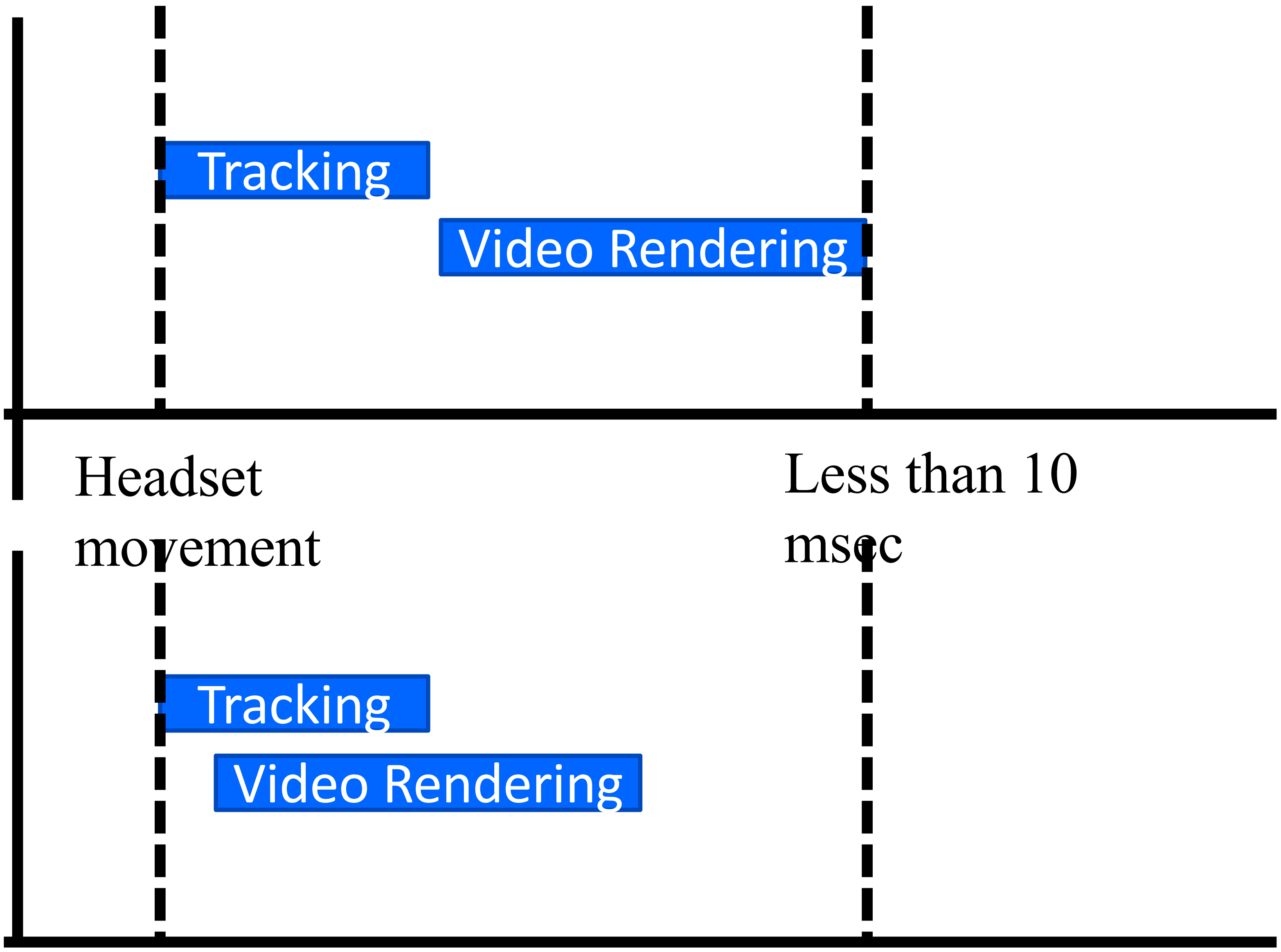
Can we design an embedded system, which can provide us with tracking information at the AP side by just using wireless signals?

mmWave based wireless Video delivery



Wireless Tracking for VR headset

Video delivery from graphics



Wireless Video delivery using WiFi and WiGig

- WiFi is more reliable
- Wi-Gig is less reliable
- Combing Application layer video coding and Physical Layer for VR

Low Power Communication and Localization

Limiting factors — limited energy and Internet connectivity

Limited energy budget

Low battery energy density

Limited Internet connectivity

High-power wireless radios

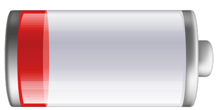
Cannot support continuous health monitoring

Cannot pack battery+bluetooth+sensors into each lego brick

X

Why low power localization?

Limiting factors — limited energy and Internet connectivity

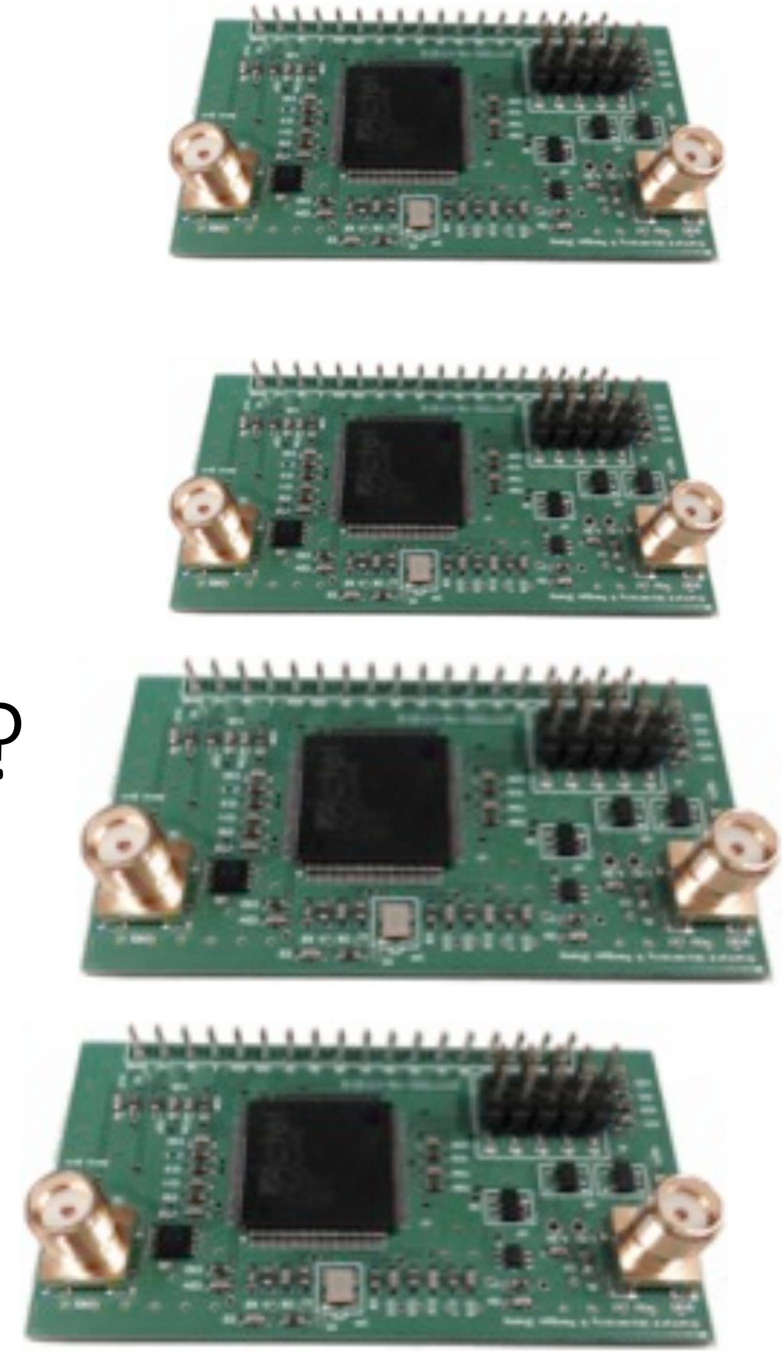
Limited energy budget	Limited Internet connectivity
 Low battery energy density	 High-power wireless radios

Cannot support continuous health monitoring

Cannot pack battery+bluetooth+sensors into each lego brick

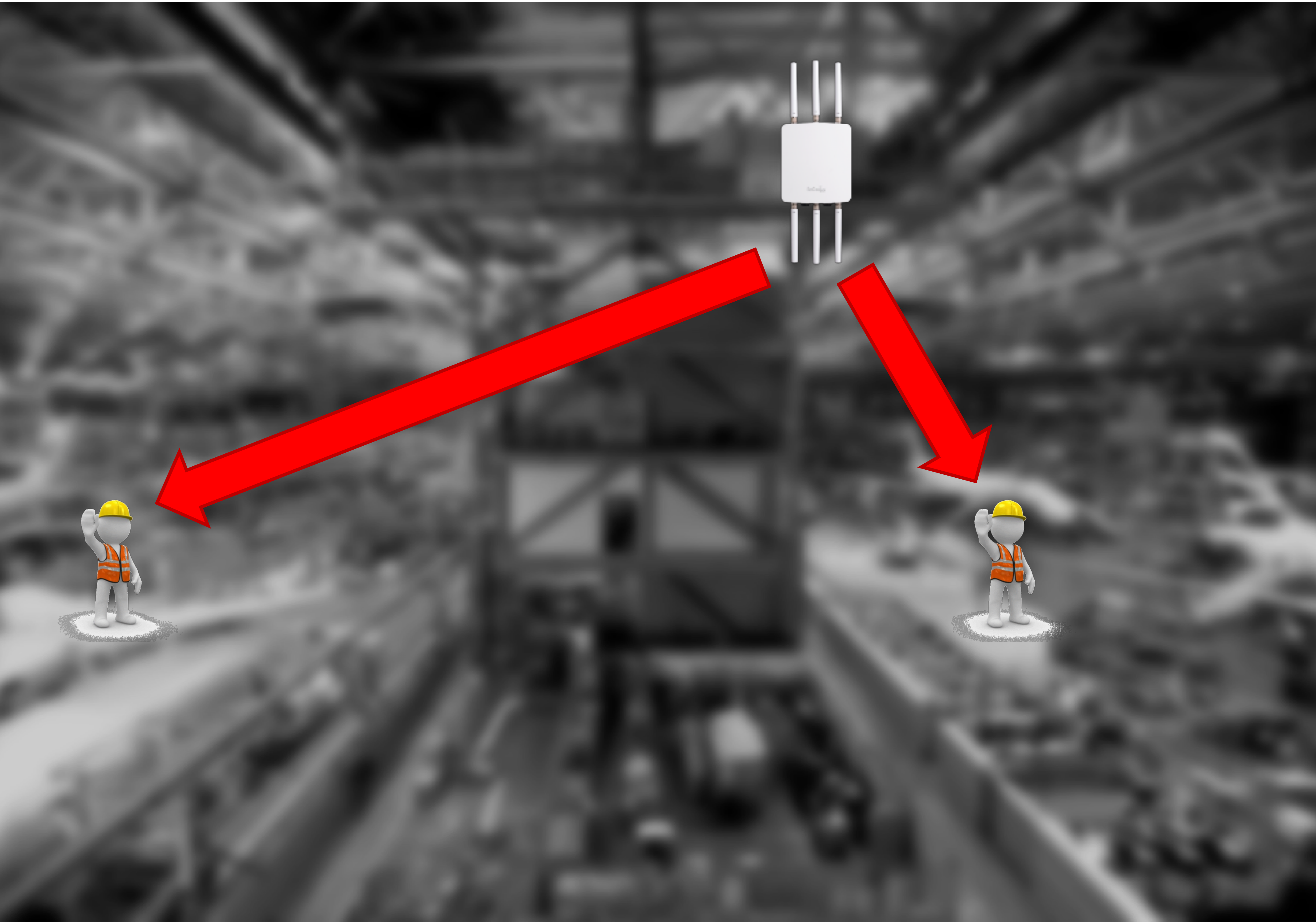
X

How do we build Scalable Low Power Communication?



How do we build Scalable wireless power transfer?

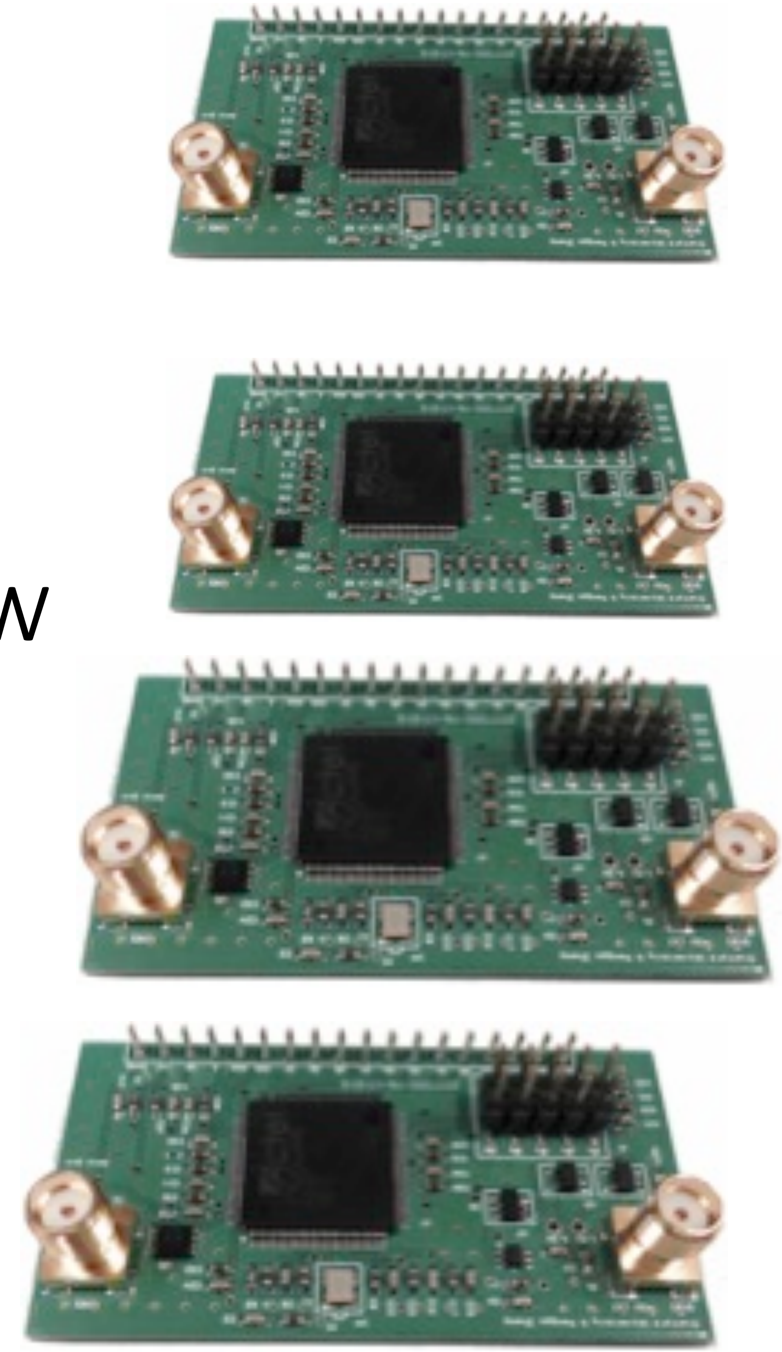

M-3



Solution Characteristics

1. Want to locate personnel inside factories or enterprises
2. Mobile phones not permitted, no localization infrastructure
3. Need to localize using a small, low-power badge
4. Should scale to a large number of workers
5. Be trackable to within 1-2m.

How do we build Scalable low wireless localization?



Passive Sensing using mmWave Signals

WiDeo: Fine-grained device-free human-motion tracing using wireless signals, Bharadia et. al. NSDI'2015

mmWave communication signals have large bandwidth 14 GHz in total

- Wireless VR tracking?
- Human Motion detection without any on-body sensor
- Write in the air?
- Can we use these signals to passively measure breathing or heart-rate, while communicating with other devices?
- Passively measure human sleep quality or detect sleep apnea?
- Passively detect neurons firing in the brain?