# Class Introduction

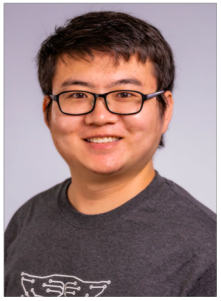

COS 463: Wireless Networks
Lecture 1
**Kyle Jamieson**

[Parts adapted from H. Hassanieh, P. Steenkiste]

# Course staff and office hours

**Kyle Jamieson**

CS room 306



**Yaxiong Xie**

CS room 103

**Minsung Kim**

CS room 103

**Raymond Sheng**

Lab TA

- **Office hours:** See website, and also by appointment, synchronized with Lab programming exercise deadlines on Piazza

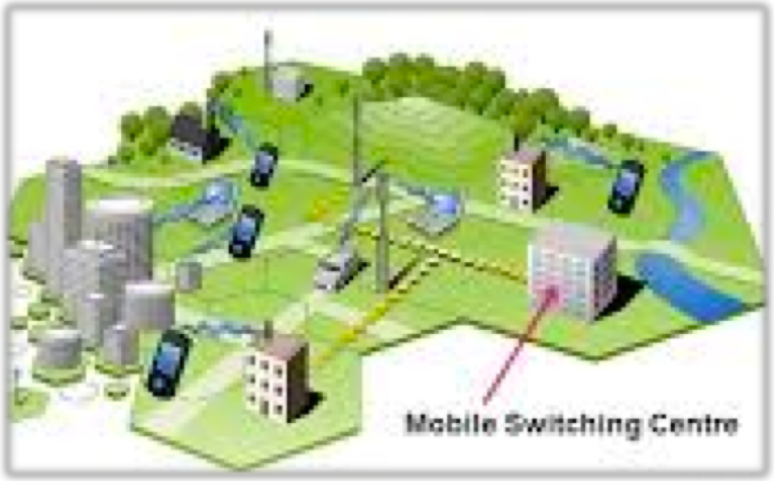
# Wireless is increasingly prevalent


Smart Home

- Health and Fitness
- Virtual Reality
- UAVs
- Internet of Things Sensors

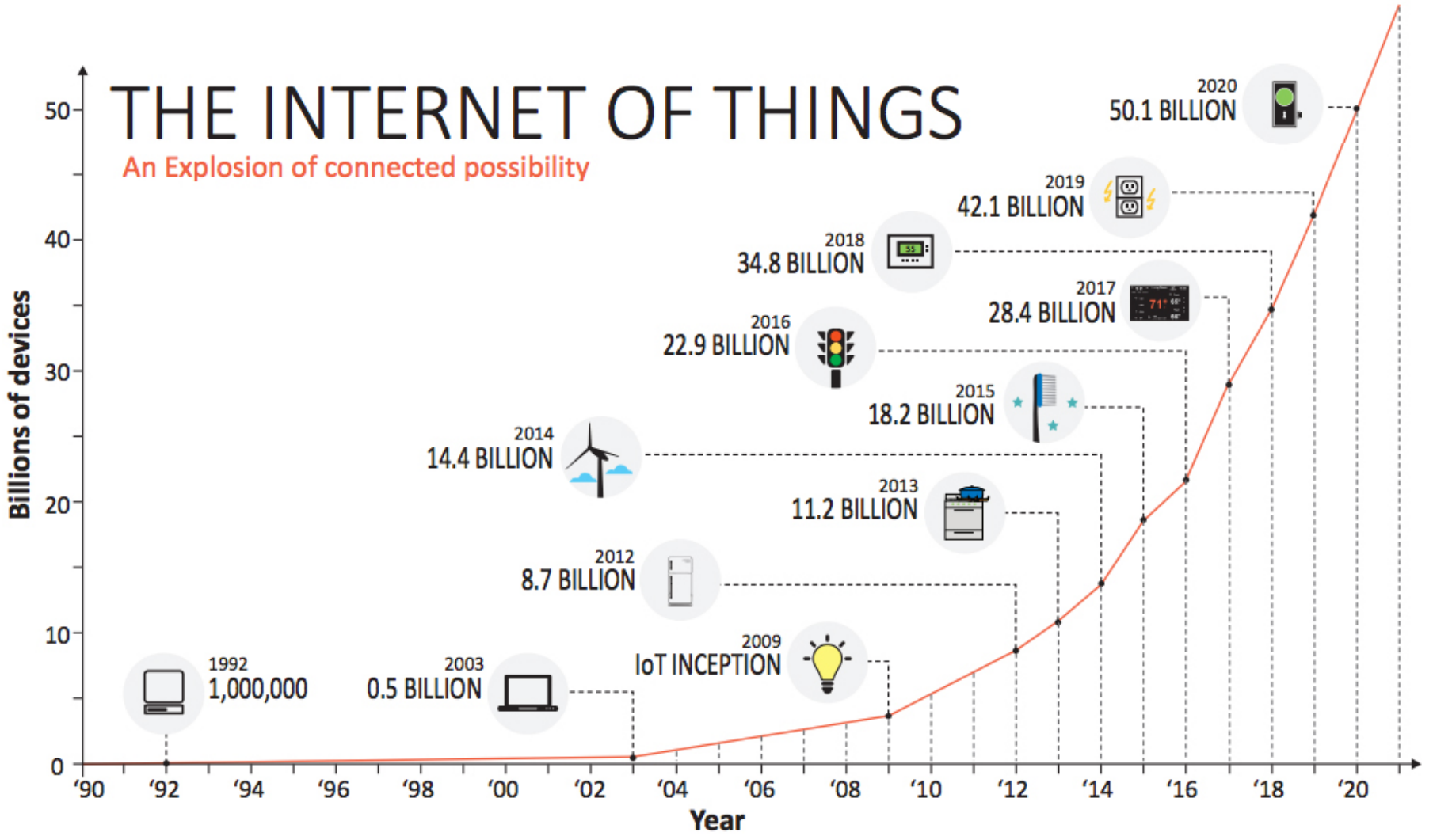
Vehicular Networks

Cellular Networks



# Mobile connectivity for people: Increased wireless demand

# Next demand driver: Billions of Wireless devices



# Industrial Impact: Cisco Meraki

- Founders Biswas, Bicket, Aguayo, PhD candidates who left program
  - Initial products: **mesh networking** technology from grad school

- Pivot three years later
  - Focus on **cloud-managed Wi-Fi**

Roofnet Mesh Network


- Cisco acquisition, new Cisco Wi-Fi product line

- **Takeaway:** Wireless technology → **industry impact**

# COS 463: Course Approach

- Gain **deep knowledge** of wireless networks by learning **across all layers** of the stack
  - Some "ELE" content, some "COS" content

- **Taught from first principles:** build up **Computer Systems, Signal Processing** knowledge

- Test that knowledge and **cement understanding** by hands-on programming lab assignments
  - **Build** something **>> "Know"** something
  - Labs on real software-defined radio hardware
    - Real-world **"surprises"**

# Goals of the Class

1. **Understand wireless networks'** design and architecture
   - From **signals** to **bits** to **datagrams**
   - **Understand** design choices and tradeoffs

2. Understand how the design of **wireless networks interacts with** the rest of the **wired Internet**

3. Gain proficiency in **building real** wireless networks

# Course Contents

1. **Wireless From the Transport Layer Downwards**
   - Transport over wireless, link layer, medium access

2. **Overcoming Bit Errors**
   - Error Detection/correction, convolutional & "Rateless" codes

3. **An Introduction to the Wireless Channel**
   - Noise, Multipath Propagation, radio spectrum

4. **Wireless Physical Layer concepts**
   - OFDM, channel estimation, MIMO etc.

5. **Boutique topics**
   - Visible light communication, low power, Wi-Fi localization

# Prerequisites and Administrivia

- Assume basic familiarity with computer networking concepts and programming
  - **COS 217** required
  - Knowledge of C and one other programming language helpful, but not required
  - Not open to freshmen
- COS 463 is a **COS systems-track** course

# Target audiences

- COS 463 is **cross-registered** with ELE (**ELE 463**)

1. COS students who want to extend their networking background to wireless communications

2. ELE students who want to extend their wireless communications knowledge to networks

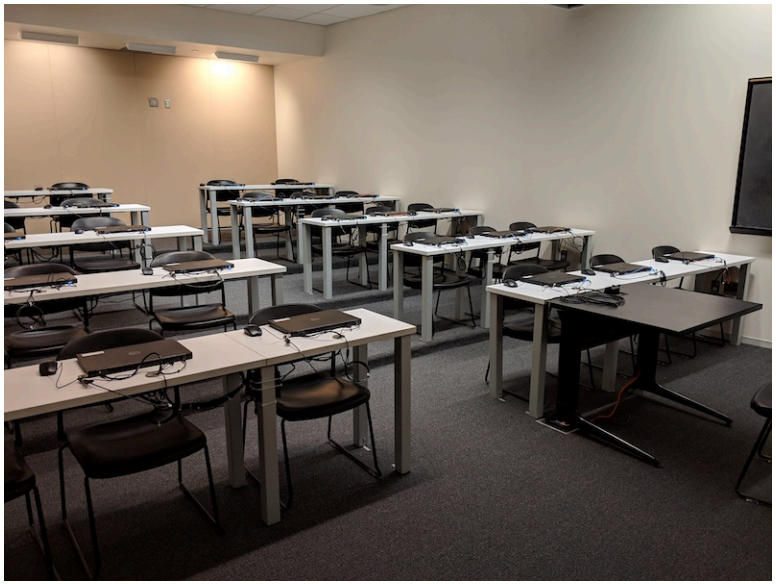
# Modes of delivery

- **Lectures:** Introduce concepts, gain background knowledge
  - New this year: Break time, quiz time (→ class participation)

- **Precepts & Lab:** hands-on training on wireless systems
  - **Learning by doing**: building wireless systems with a software defined radio platform
  - Precepts and labs **closely coupled**

# Lab logistics

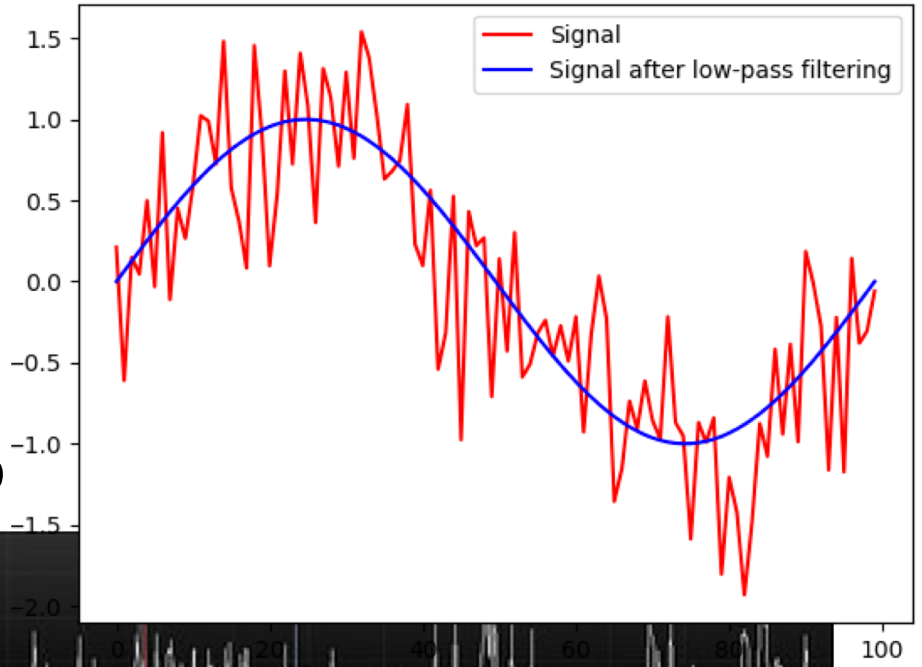
- **Friend Center, Room 003**

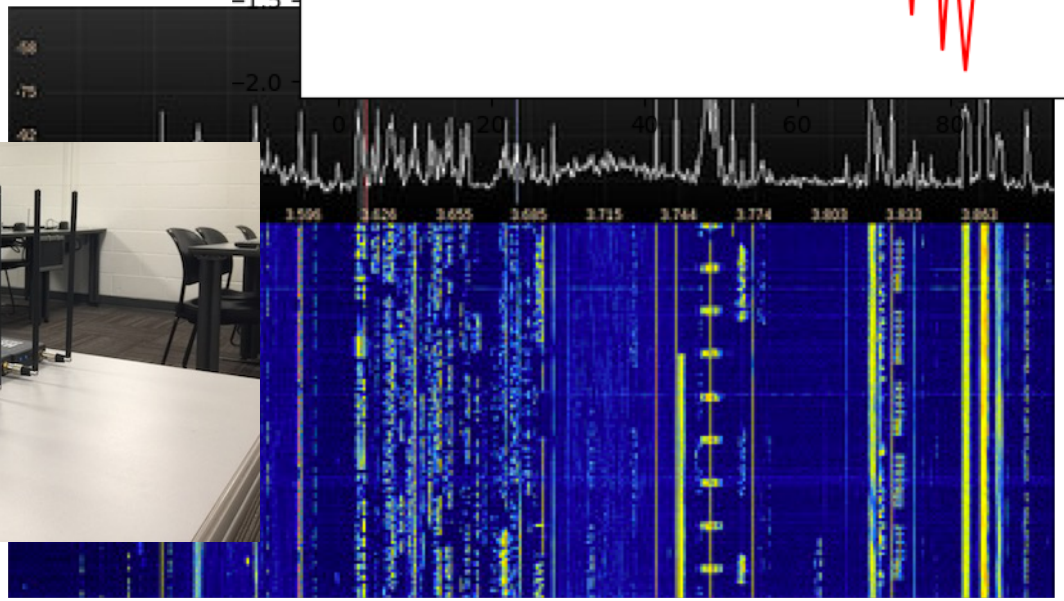


- Enrolled students as of Feb 1 on room access control list
  - **Visit a hotspot** and tap your TigerCard to update
  - If you weren't enrolled Feb 1, send instructors a private Piazza message requesting access

# Lab: Building a spectrum analyzer

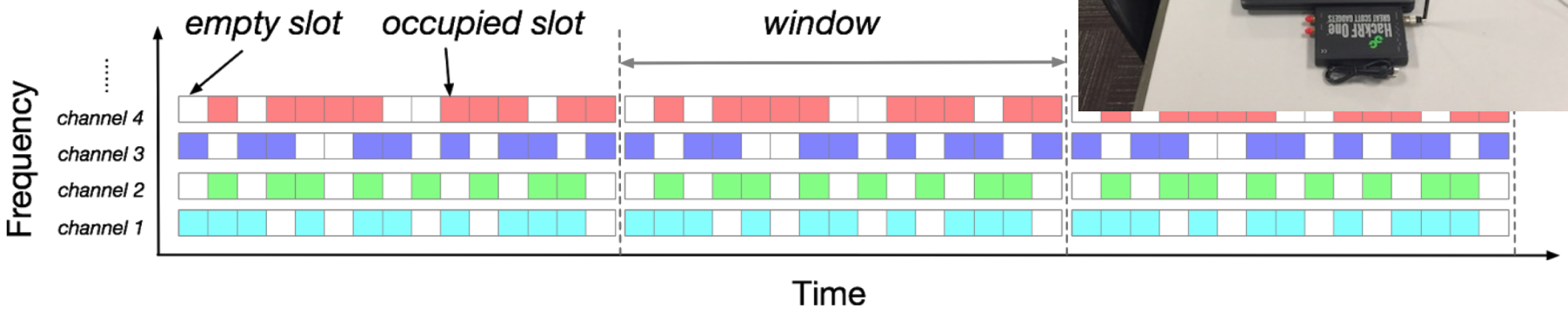
- Introduce you to basic signal processing concepts
  - Fast Fourier Transform (FFT)
  - Low-pass filtering
- Learning how to use the HackRF software-defined radio



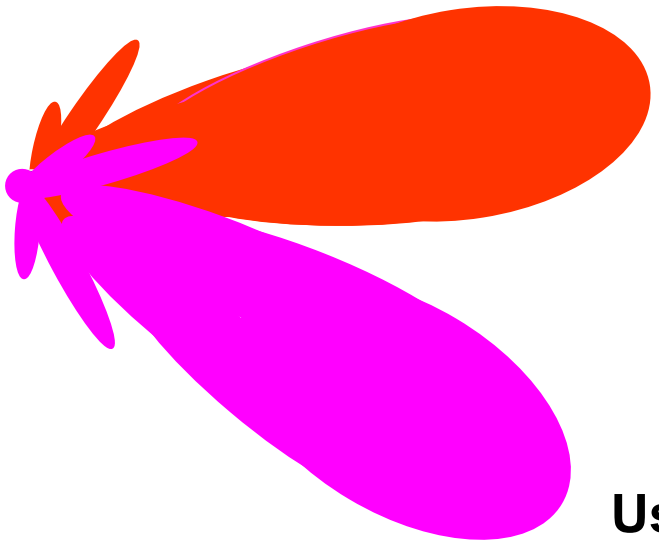
# Lab: Sharing the Wireless Medium

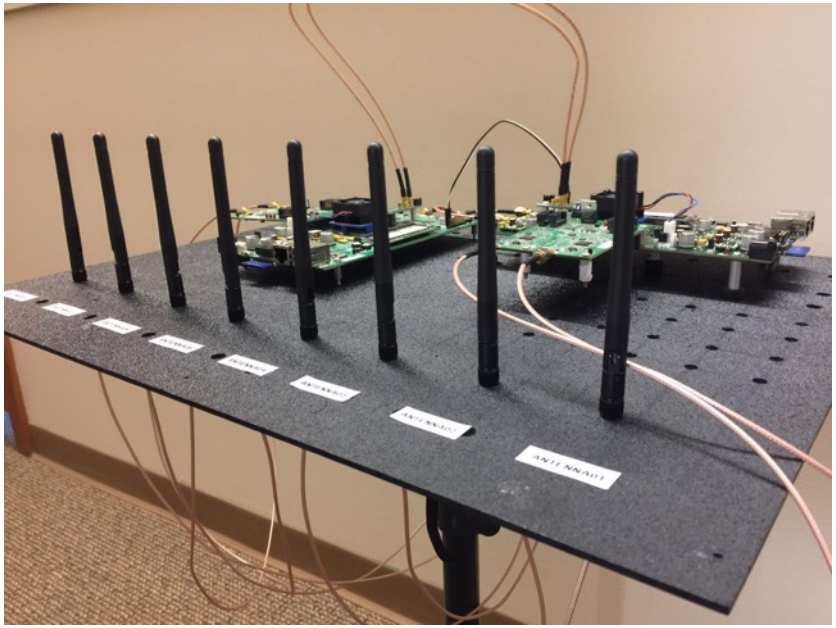
- We set up a **transmitter** in the room
- You **listen** for an empty time or frequency slot and **send** in that slot
- We show the result in a live “scoreboard”



# Lab: Array Signal Processing

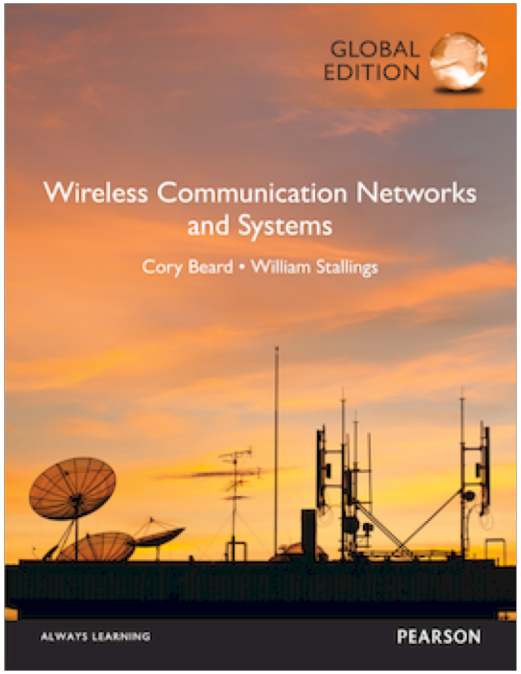
- **Angle-of-arrival estimation** using multiple antennas
- **Transmit beamforming** using multiple antennas

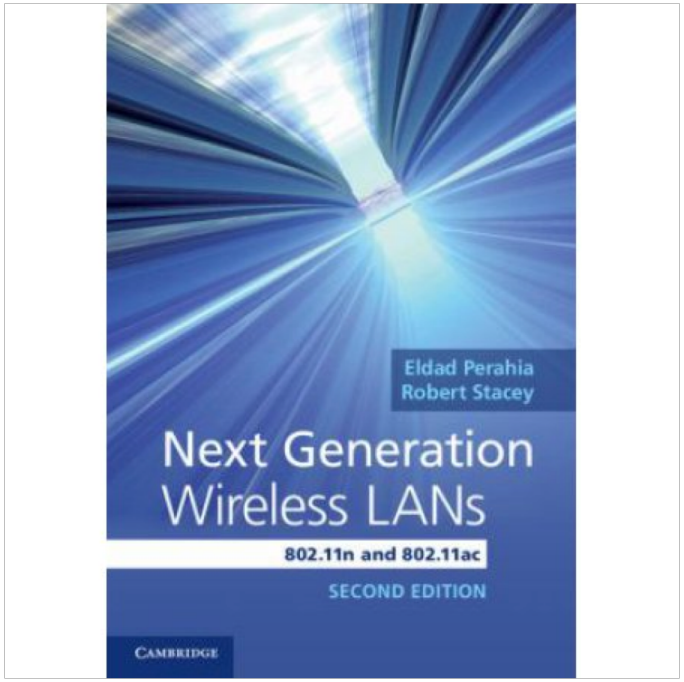


# Optional Readings, for reference

- **Text book**: Cory Beard and William Stallings, ***Wireless Communication Networks and Systems***
- **Reference material**: Eldad Perahia, Robert Stacey, ***Next Generation Wireless LANs***



# Class Grading

- Midterm exam: **20%**
- Final exam: **30%**
- Five lab programming assignments: **40%**
- Class participation: **10%**
  - Precept attendance and participation
  - Activity on Piazza, in-class exercises

- **Midterm and final exam coverage:** Everything mentioned in lecture and precept, all readings, all labs
  - **Emphasis** on the concepts discussed in lecture & precepts, and lab content

# Today

1. **How do wireless and wired networks differ?**

2. What makes wireless interesting?

3. What new services does wireless enable?

# Wireless is less reliable


- In wired networks, link **bit error rate** is **$10^{-12}$ and less**
- Wireless networks are **far from that target**
  - Bit error rates of **$10^{-6}$ and above** are common!

- ***Why?***

# Today

1. **How do wireless and wired networks differ?**
   - **A *shared* wireless medium**
   - Less reliable links
   - Mobility

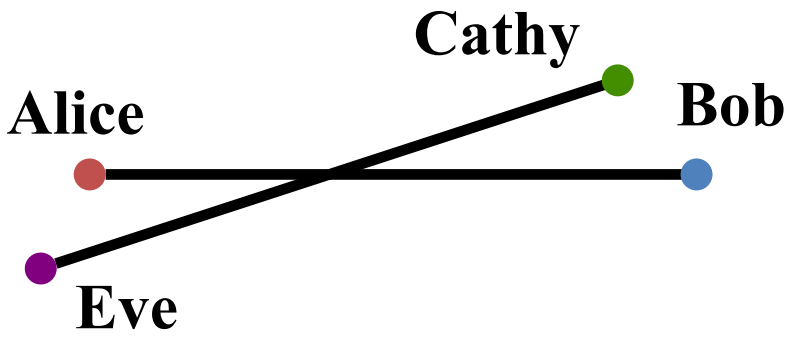
2. What makes wireless interesting?

3. What new services does wireless enable?

# Wireless is a shared medium

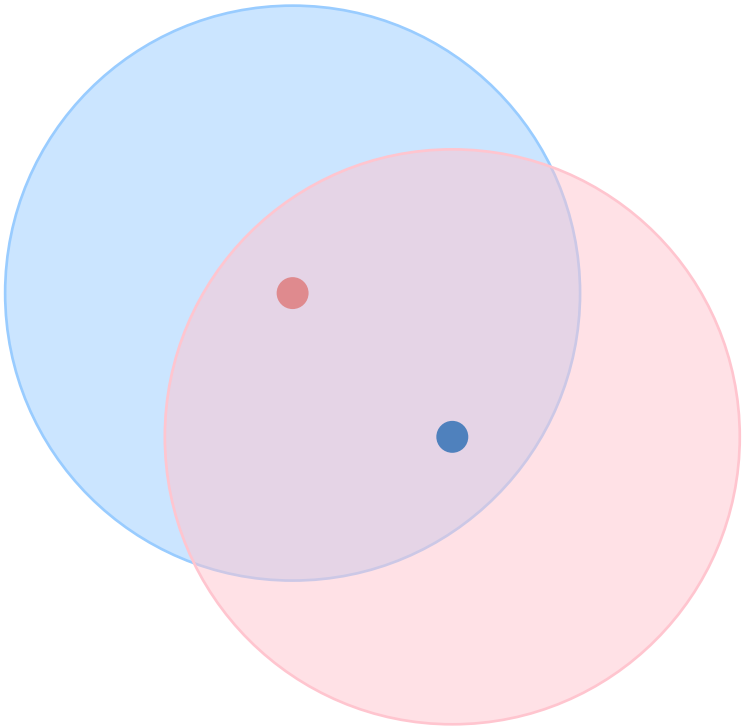
- **Wired networks:**

Alice and Bob's conversation is **independent of** Cathy and Eve's conversation




- **Wireless networks:**

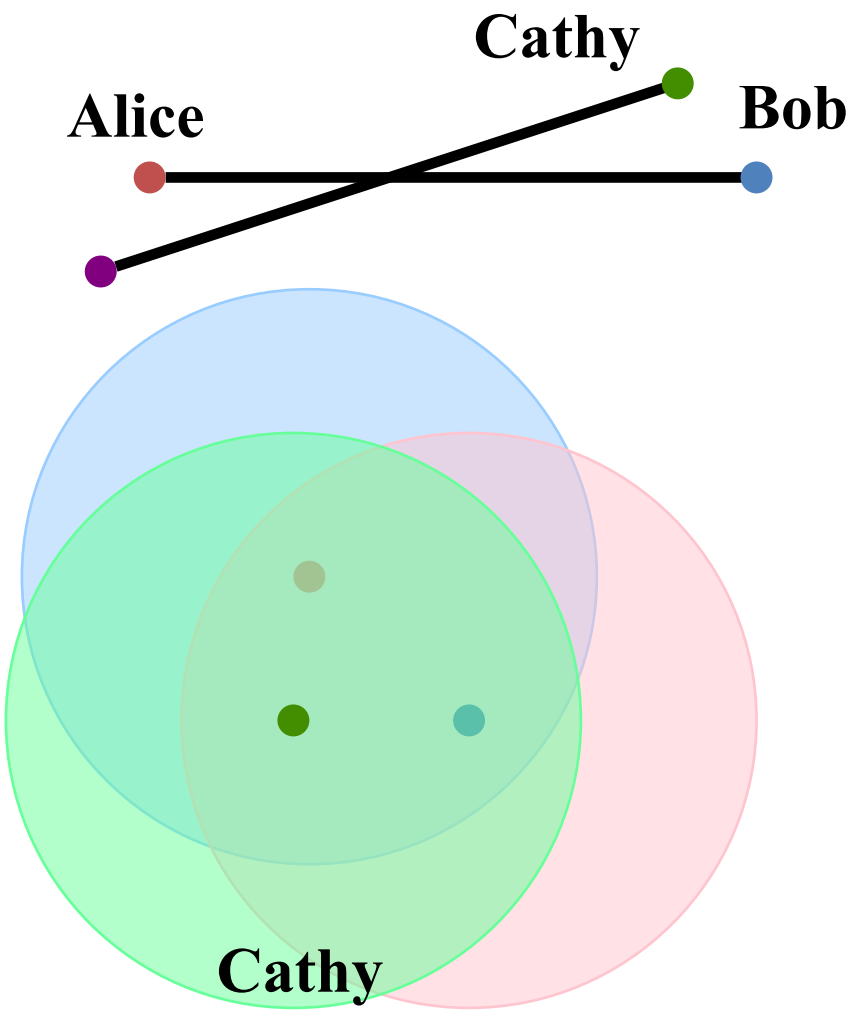
Close by **wireless** conversations **share the same wireless medium**



Why is a point-to-point link the wrong abstraction for building wireless networks?

# Reason #1: Interference

- **Noise** is naturally present in the environment from many sources
- **Interference** can be from other users of the same technology, other technologies altogether
- Impacts the throughput users can achieve



# Reason #2: Can leverage broadcast

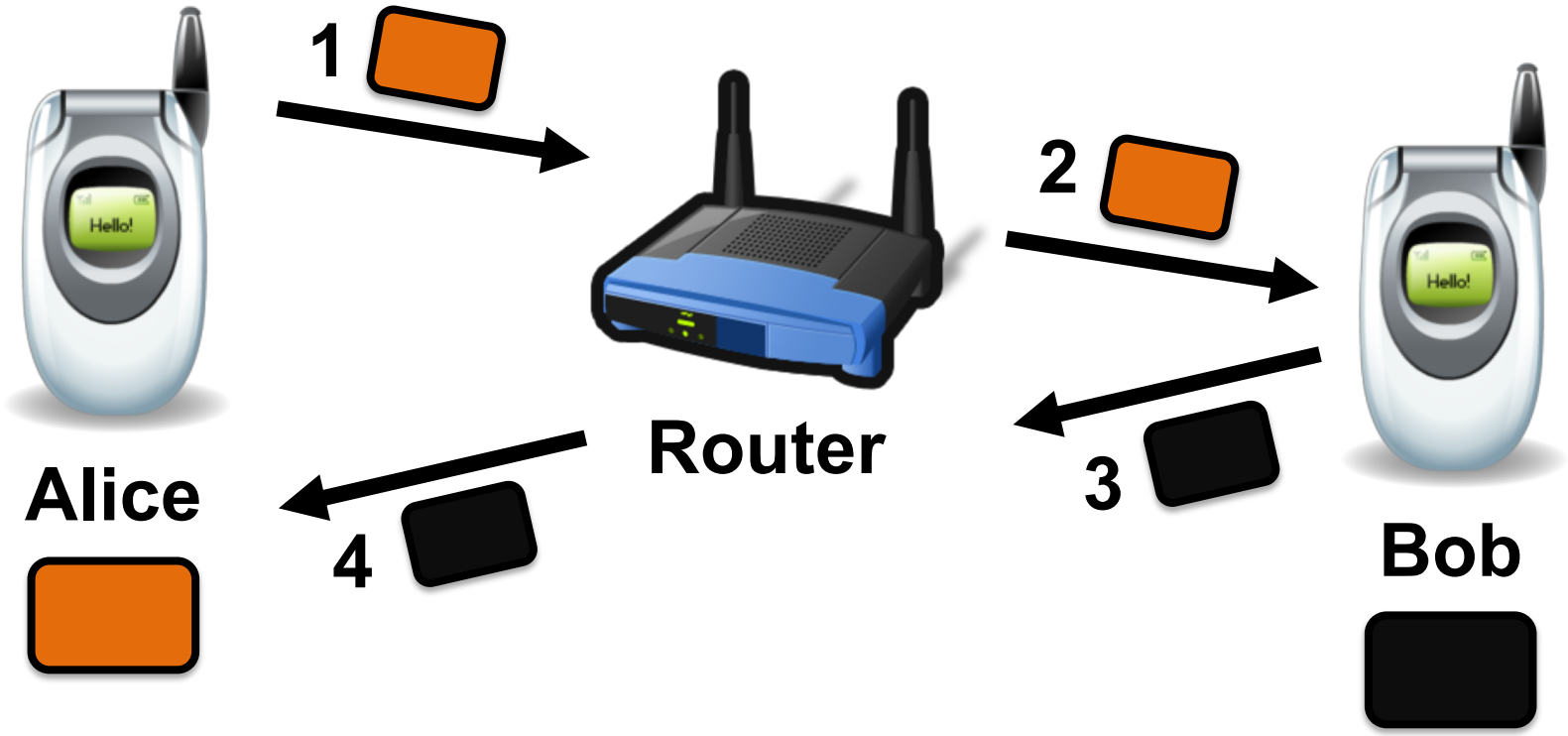

Alice

Router


Bob

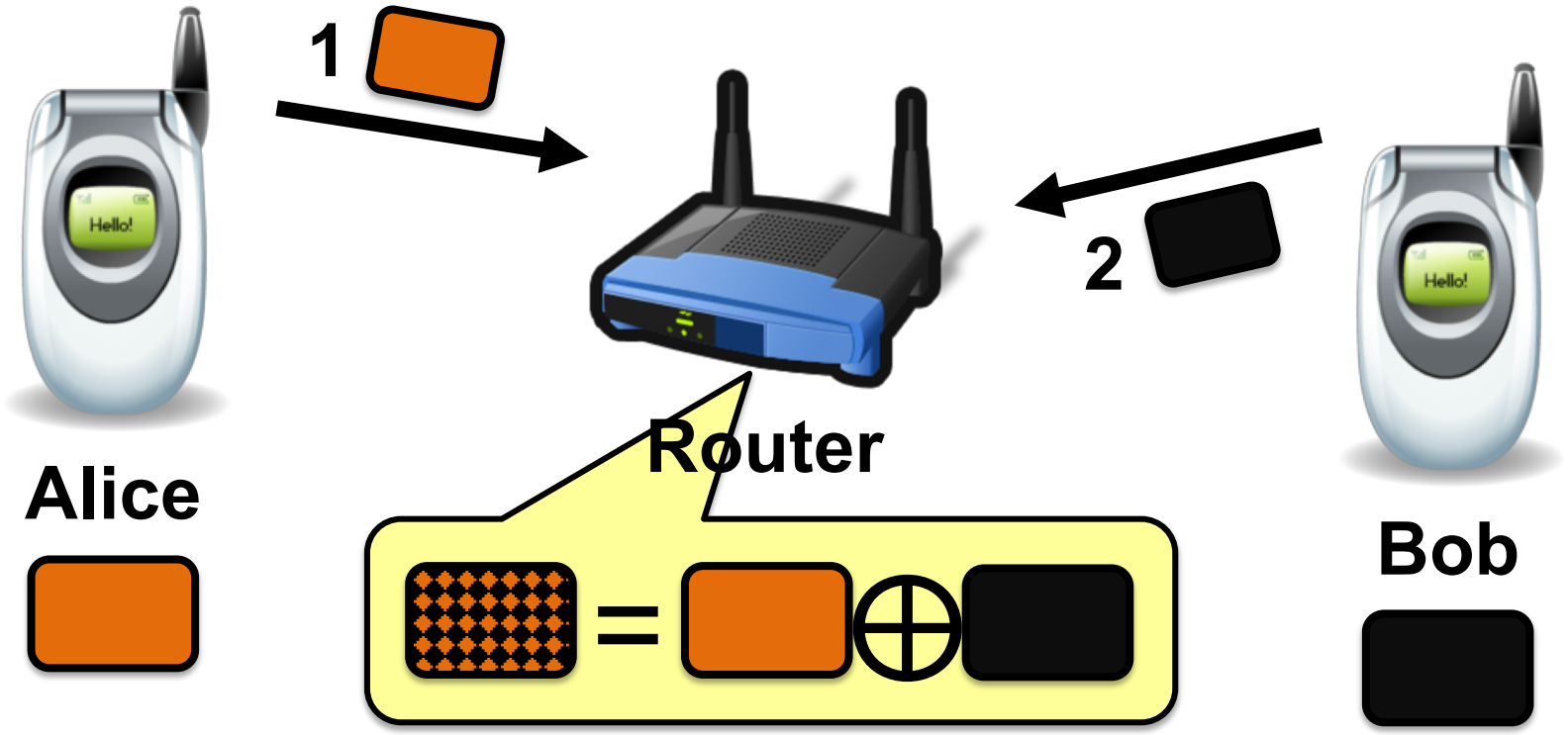
- Want to **exchange packets,** but **out of direct range**

# Solution using wired abstraction

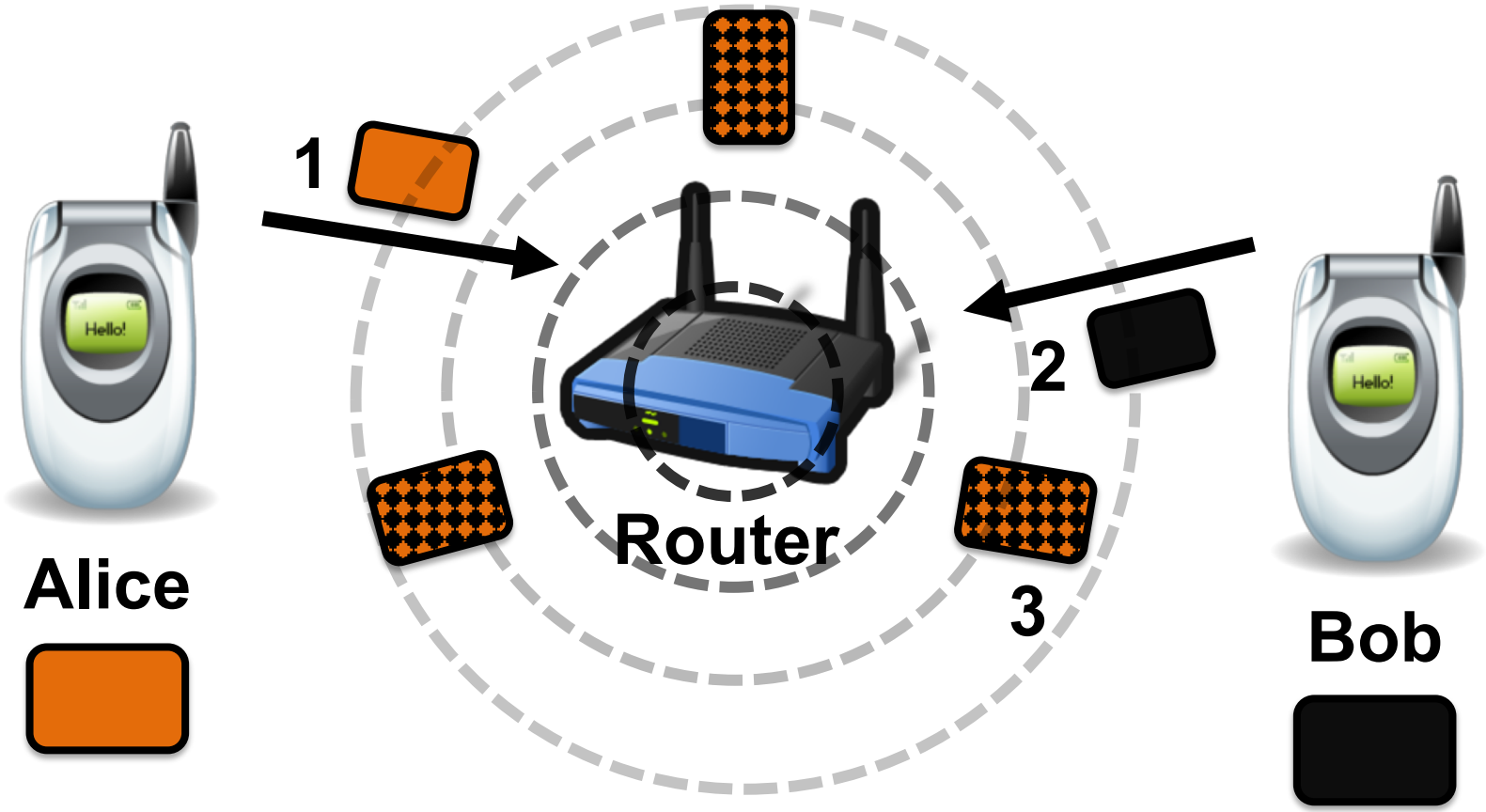



- Requires **four transmissions** in total

# Idea: Router combines the packets



# Router broadcasts the combination

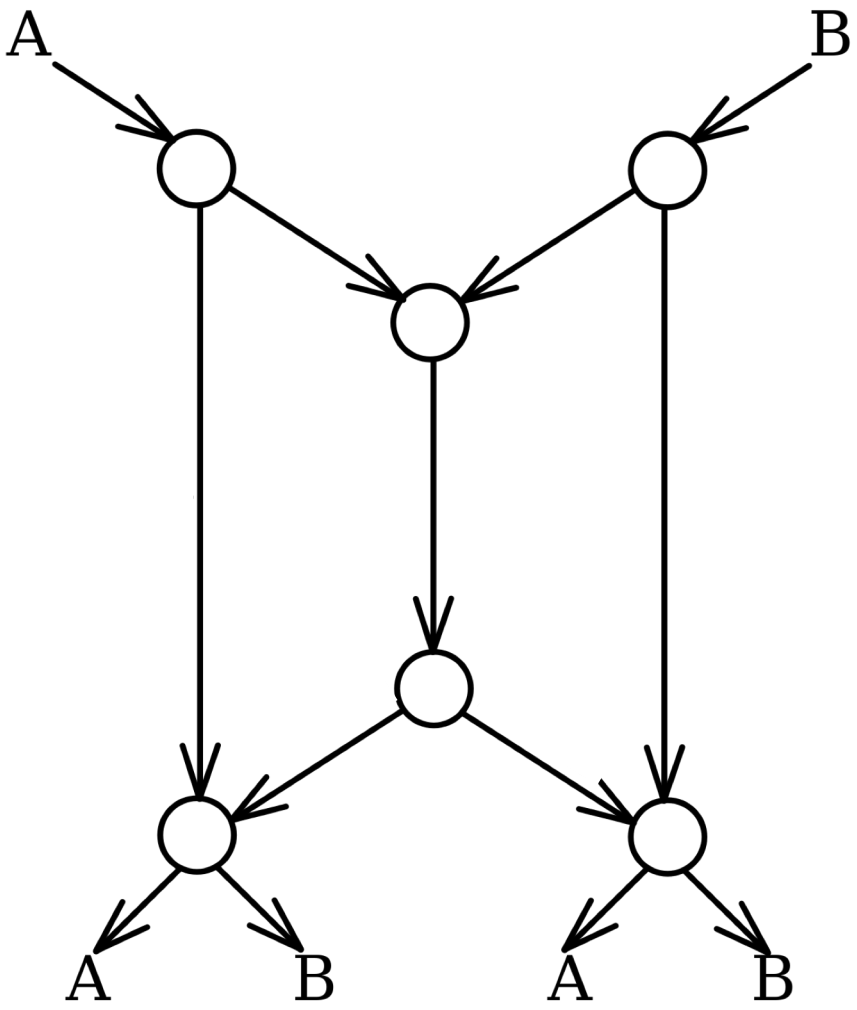



- Requires just **three transmissions** in total

# Sumary: Shared medium is very different

- Wireless' shared medium is **very different** than point-to-point wired links
- So need to **think about wireless networks differently**
- **Interference** is a **major problem**
- But also can **leverage broadcast nature** of wireless
  - **Four** to **three** transmissions **increases throughput**
  - Serve **more users** or **increase app performance**
    - **Better Skype calls**

# Break time and (Not Graded) Partner Quiz: Butterfly Network




- Two top ***source nodes*** have A and B, **respectively**
- Two ***destination nodes*** at bottom **each want both** A **and** B
- Each edge can carry just one value
- **Label each edge with a value** to deliver A and B to both destination nodes

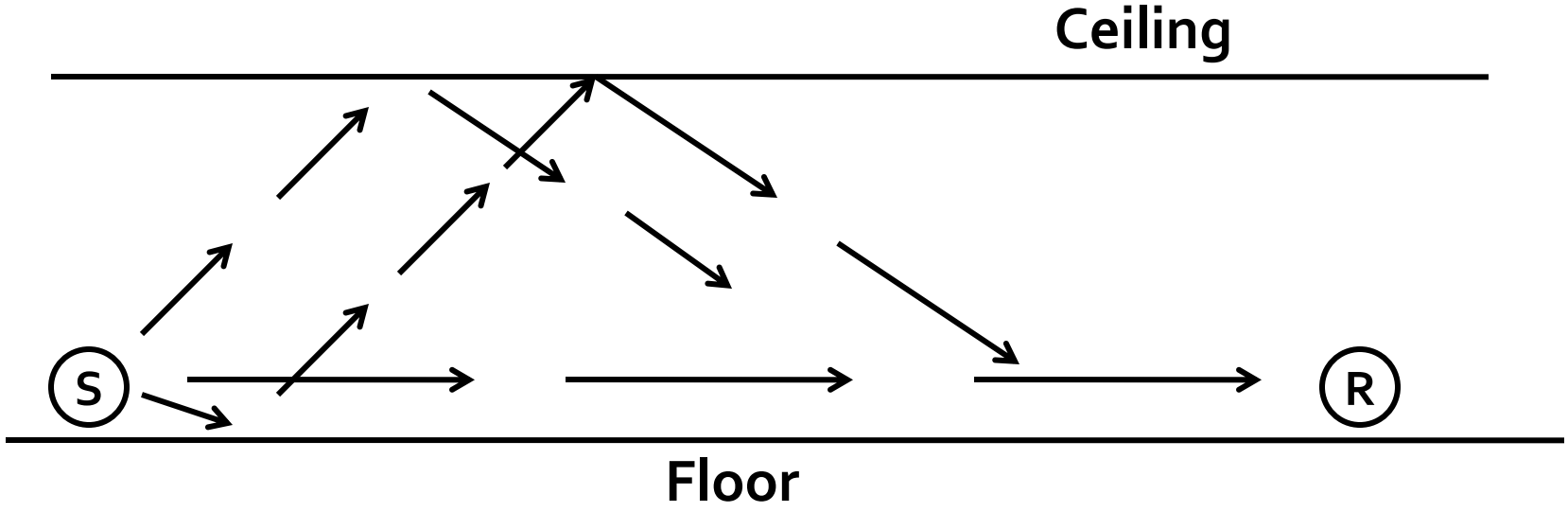
# Today

1. **How do wireless and wired networks differ?**
   - A *shared* wireless medium
   - **Less reliable links**
   - Mobility

2. What makes wireless interesting?

3. What new services does wireless enable?

# Less reliable links: Multipath propagation




- Signal **bounces off surface** and **interferes with itself**
- **Can be constructive** or **destructive,** depending on the respective path lengths
- Can be **more than two paths**

# Today

1. **How do wireless and wired networks differ?**
   - A *shared* wireless medium
   - Less reliable links
   - **Mobility**

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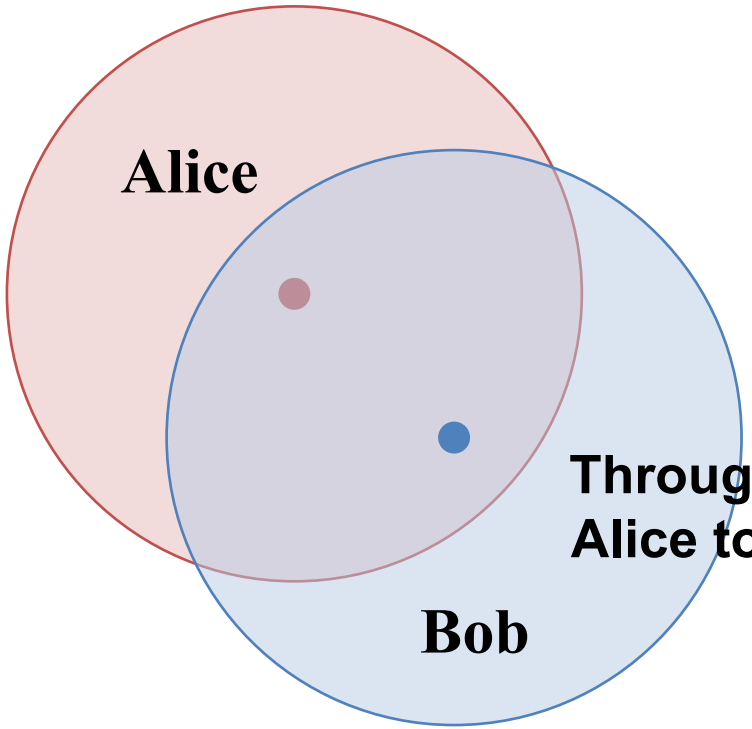
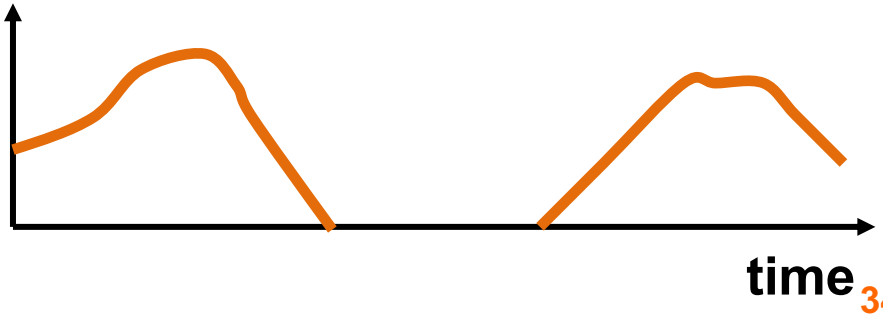
# Mobility affects link throughput

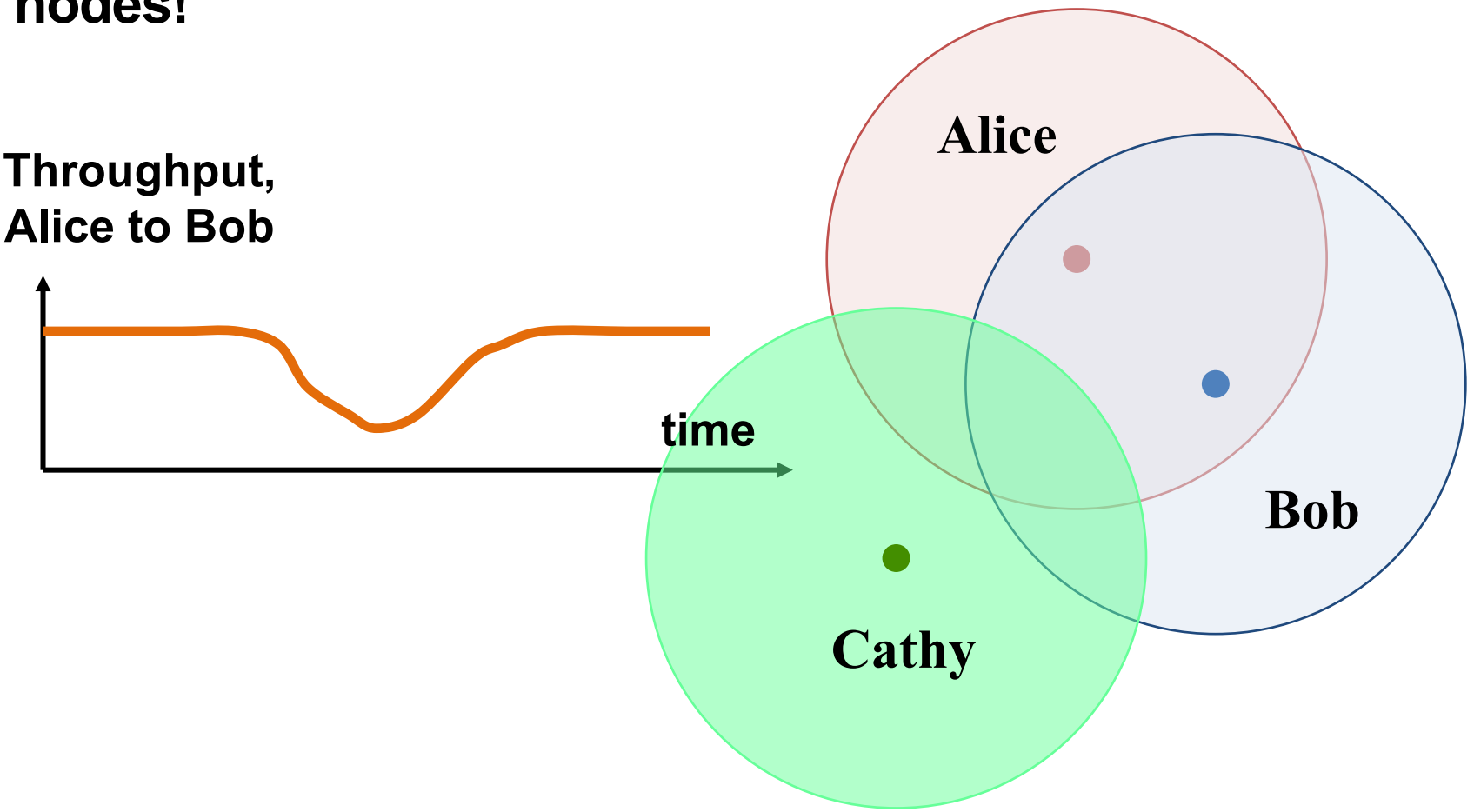
- Quality of transmission depends on distance, other factors
- Affects the **throughput** mobile users achieve
- Worst case: ***Outages***, periods with **no connectivity!**



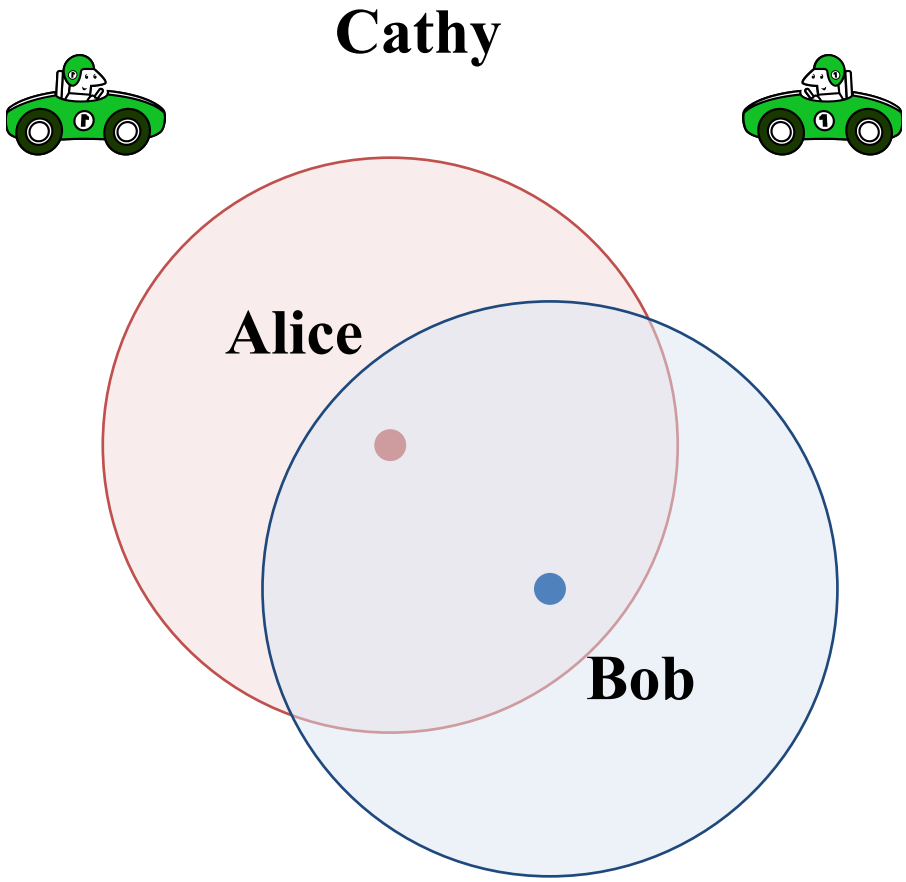
# Mobility matters, even if stationary!

- **Mobile people, devices** affect wireless channel of **stationary nodes!**

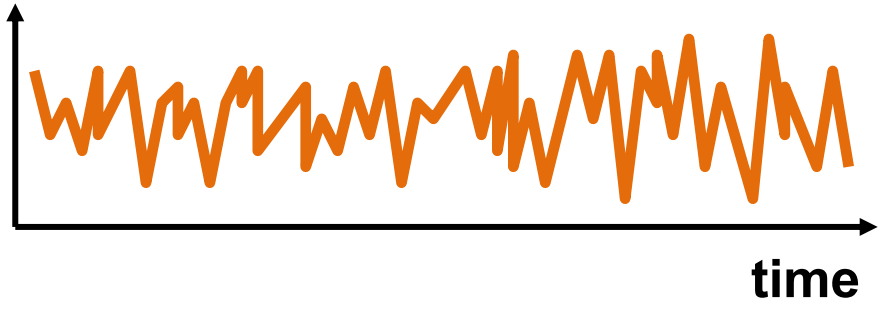


# Mobility matters, still!

- Impact of mobility on transmission is **complex:**
  - **Multipath effects**




**Throughput, Alice to Bob**



# Today

1. How do wireless and wired networks differ?

2. **What makes wireless interesting?**
   - **Deep intellectual challenges**
   - Cross-layer design

3. What new services does wireless enable?

# Some things are well understood…

Q: *What's the capacity of a point-to-point link?*
- **Bits/second** can "reliably" communicate

- Before Shannon:
  - *Only way to make probability of bit error arbitrarily small is to reduce the rate of communication.*

- After Shannon (with some assumptions):
  - **Up to some rate *C* (Shannon Capacity), coding can make chance of bit error arbitrary small!**

# …others aren't understood well at all!

*Q: What's the capacity of a wireless **network**?*

**A [Information Theory]: "  "**
**A [Computer Networks]: "Let's build a better medium access control protocol!"**

# Today

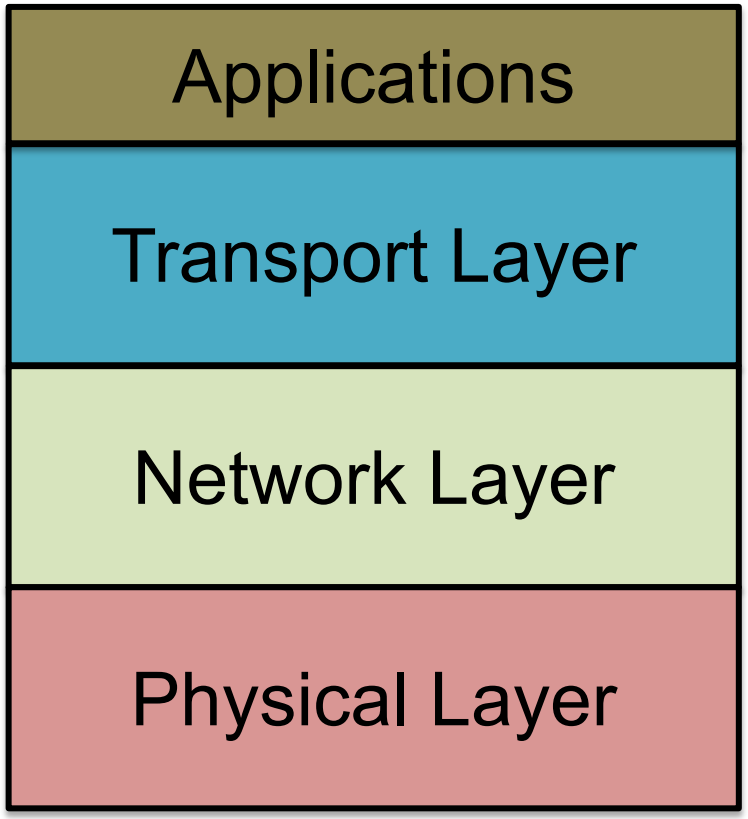
1. How do wireless and wired networks differ?

2. **What makes wireless interesting?**
   - Deep Intellectual challenges
   - **Cross-layer design**

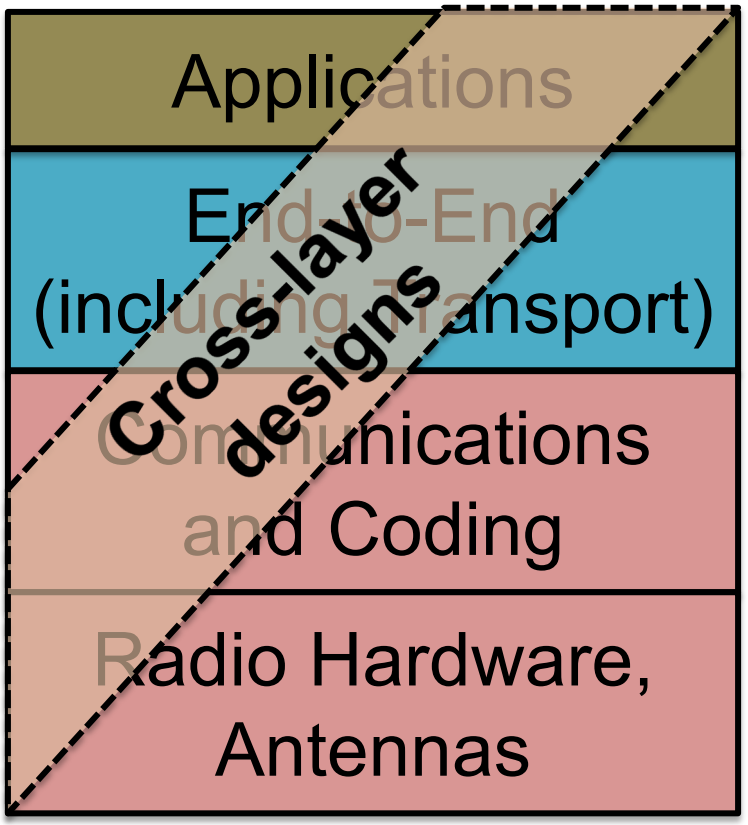
3. What new services does wireless enable?

# The argument for cross-layer design

- **Traditional approach:** Optimize **within** layers

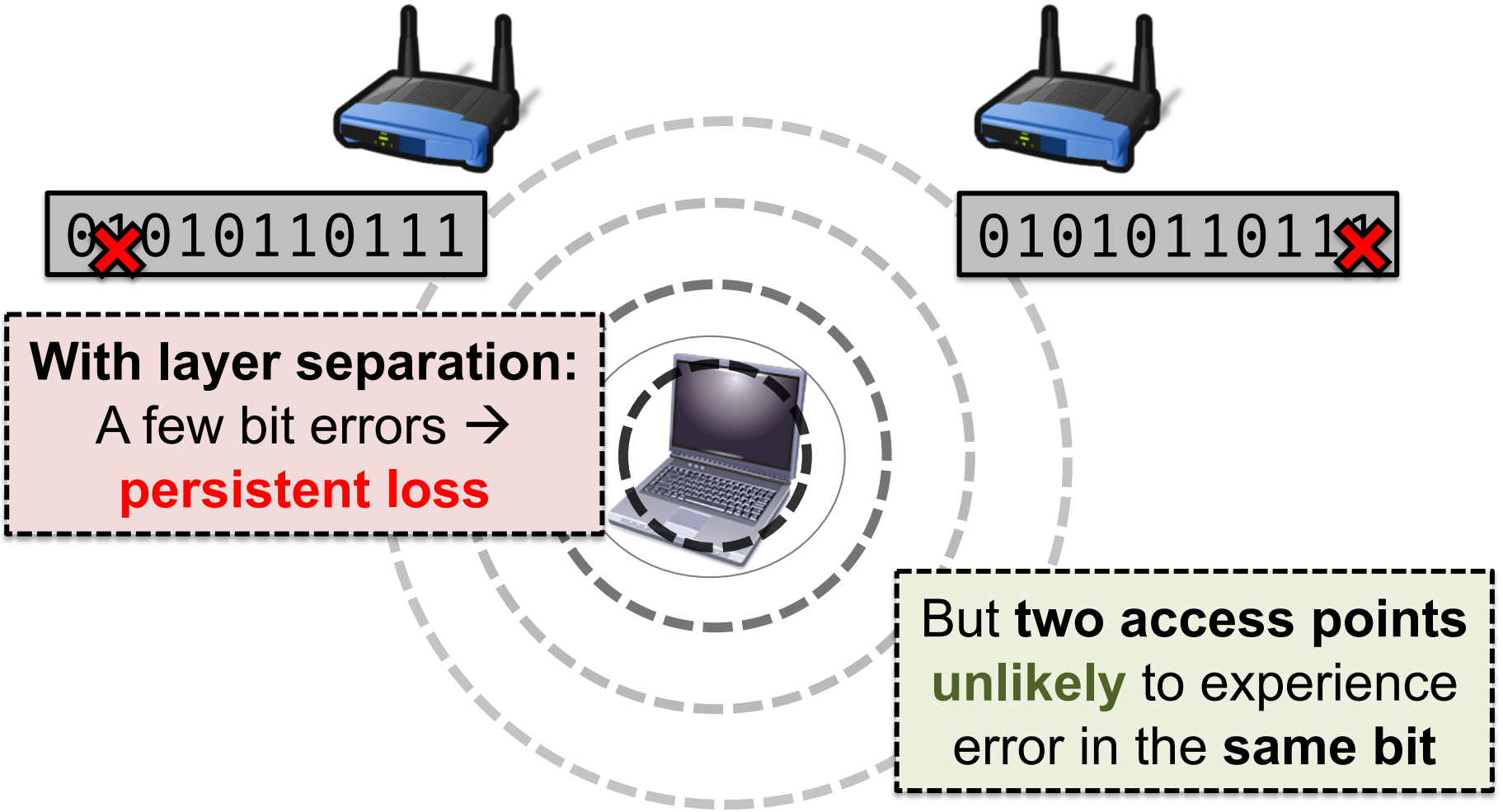



- **New Approach:** Design and optimize **across** layers

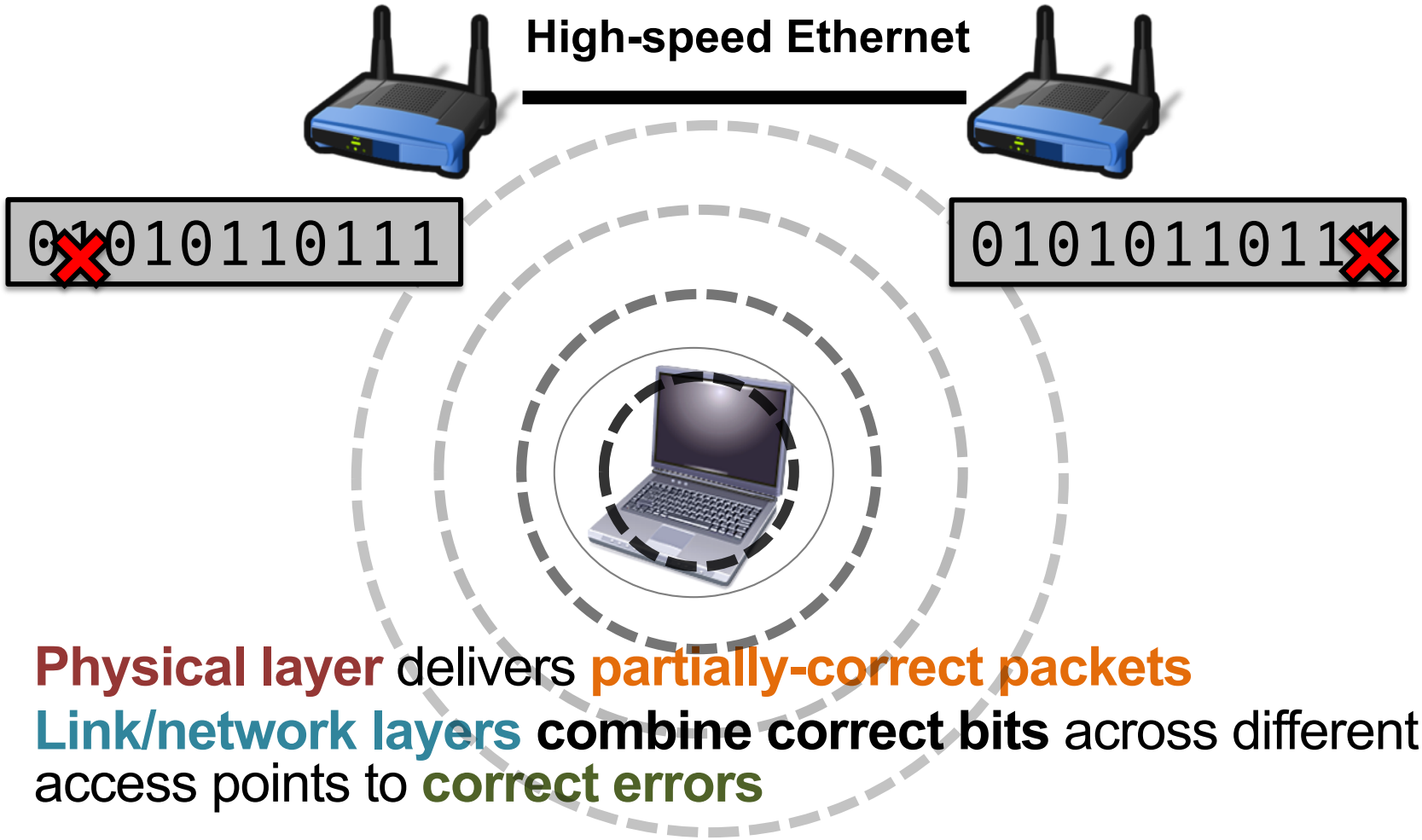


# Why is layer separation sub-optimal?

# Scenario: Laptop in a “dead spot”

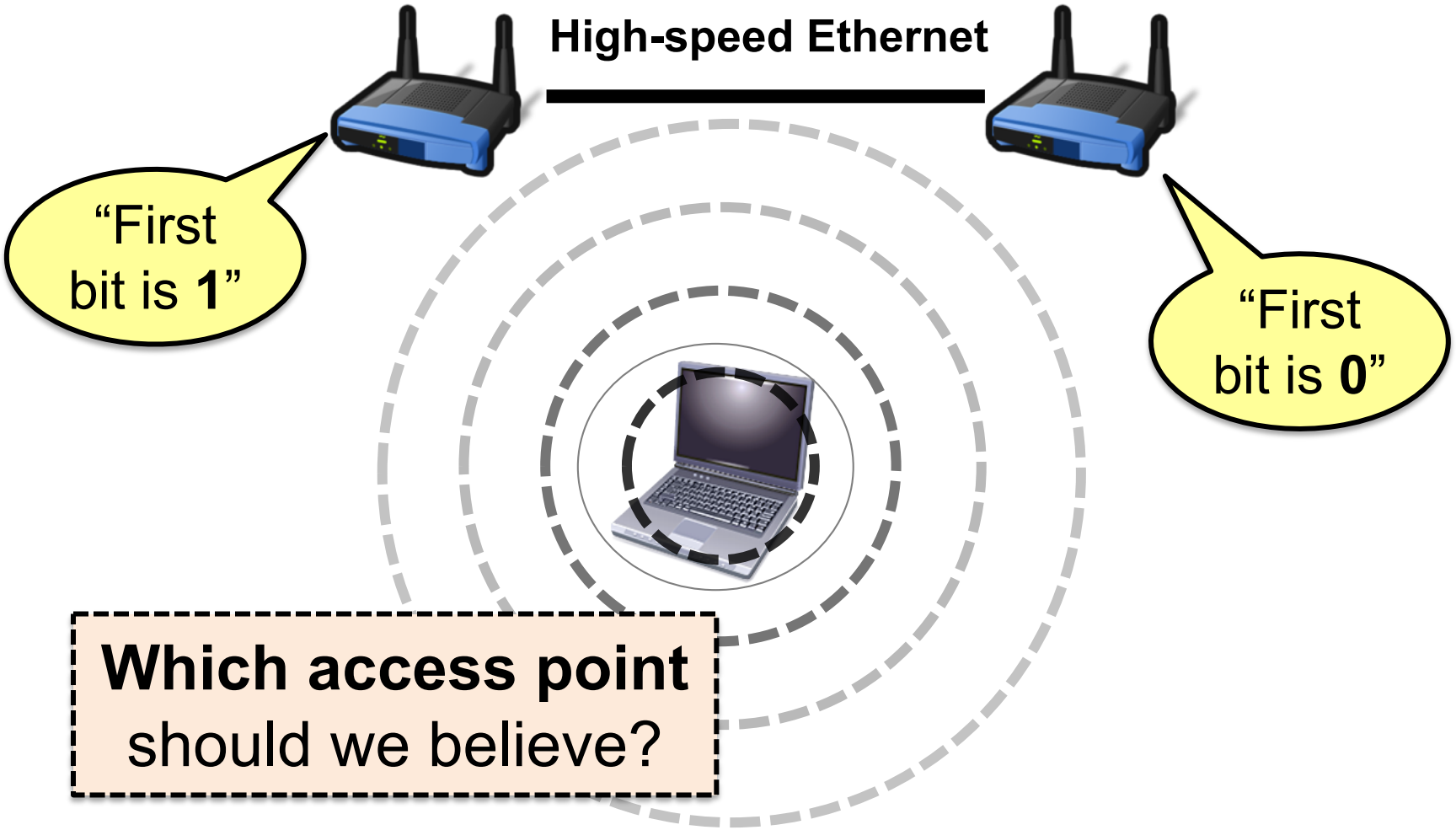


# Solution: A cross-layer Approach




- **Physical layer** delivers **partially-correct packets**
- **Link/network layers** **combine correct bits** across different access points to **correct errors**

# A challenge for bit combining

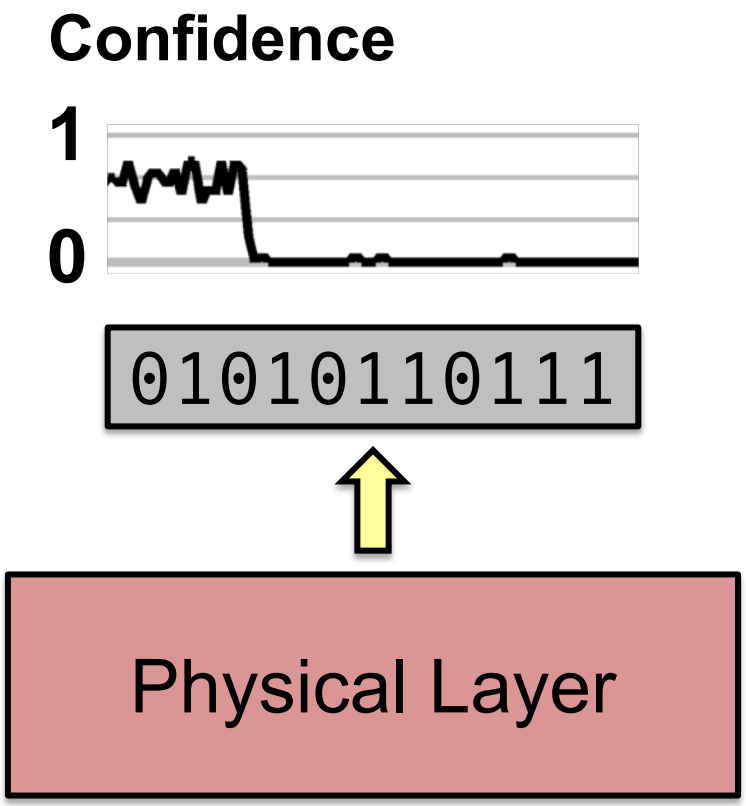



**Which access point** should we believe?

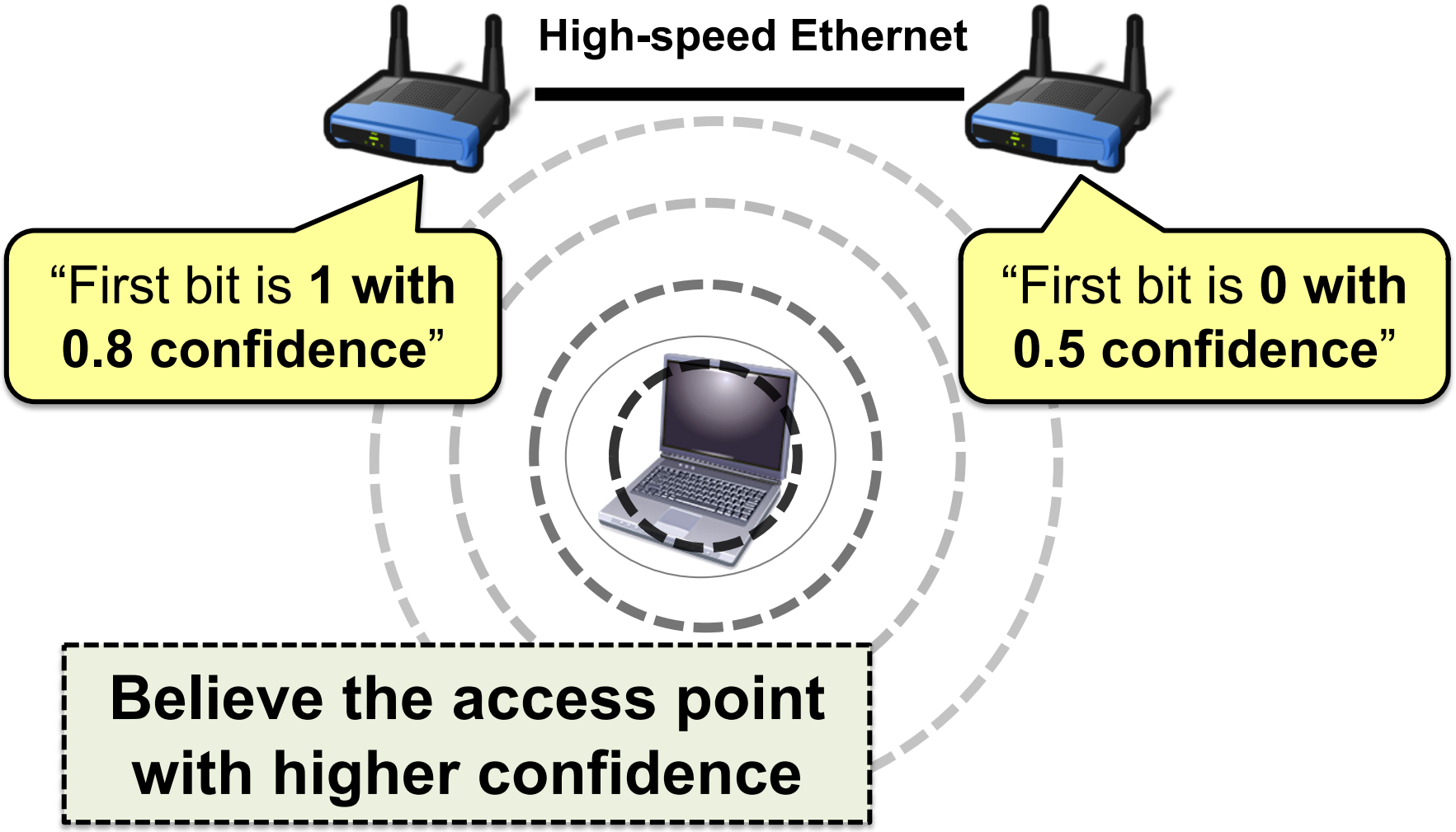
# Idea: Network cooperates with PHY layer

- Physical layer **already estimates probability of correctness (*confidence*)** in each 0/1 bit decision

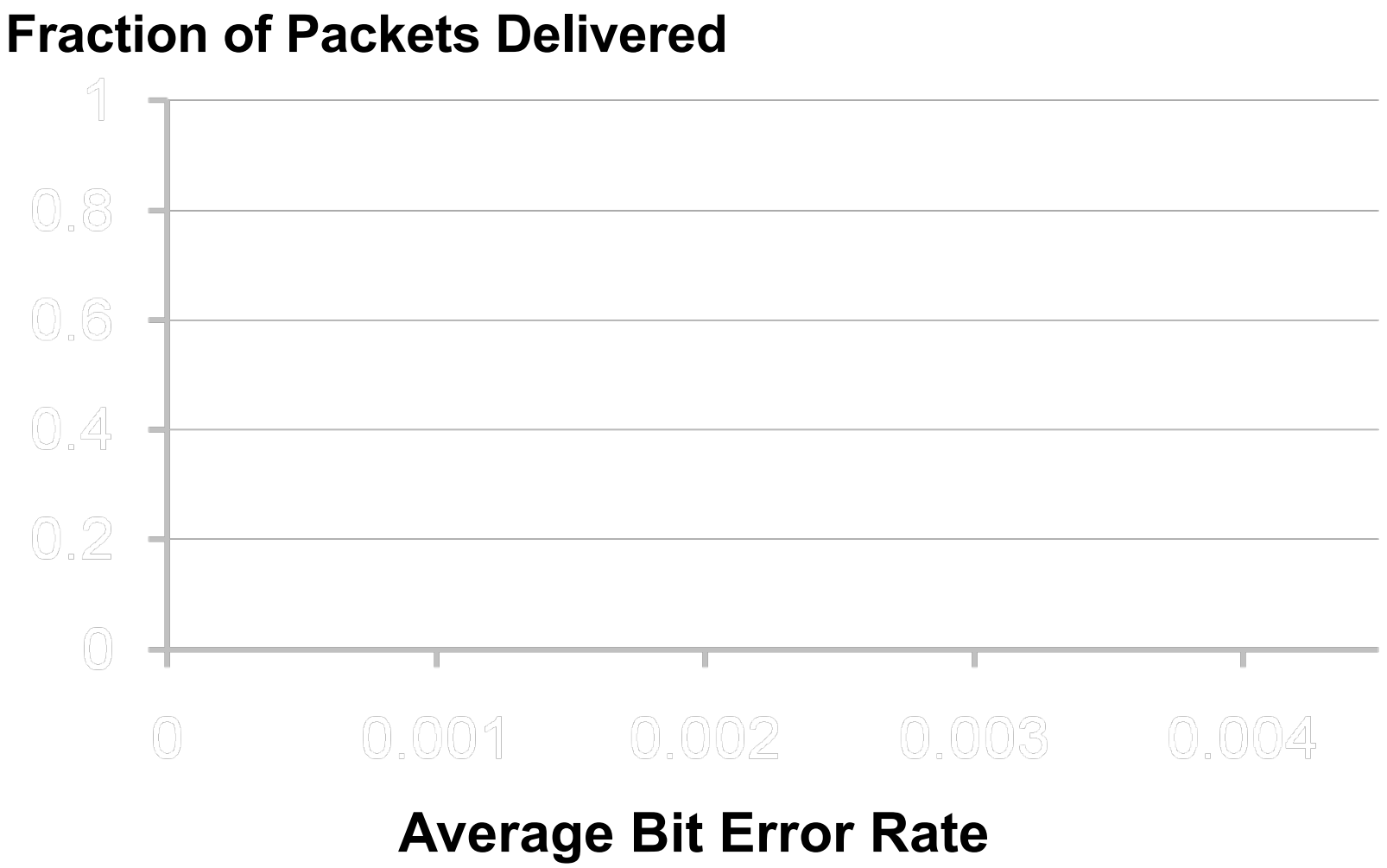
- **Idea: Expose confidence** to the higher layers



# Solution: Use confidences across layers



# Experiment: Packet delivery v. poor coverage



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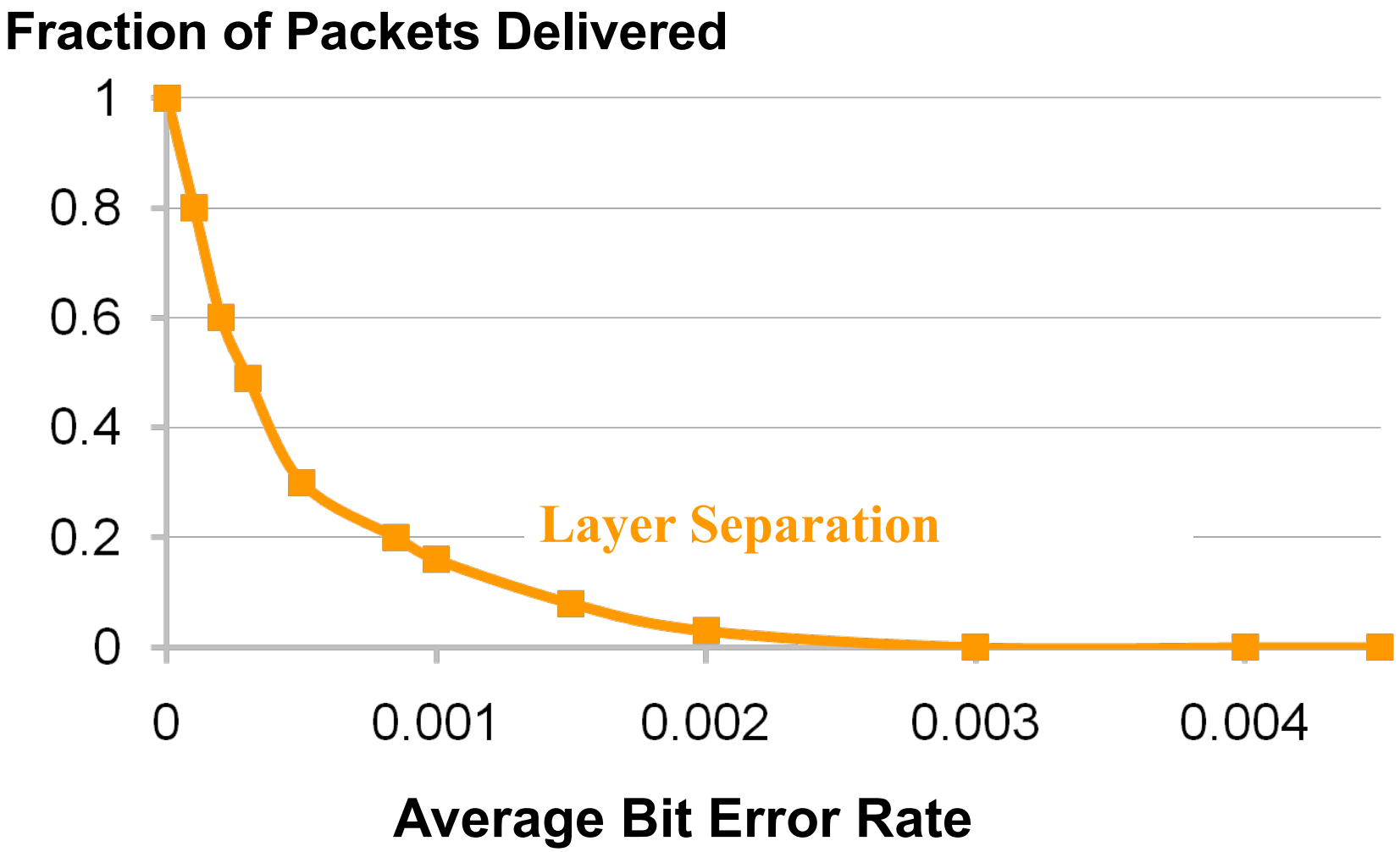
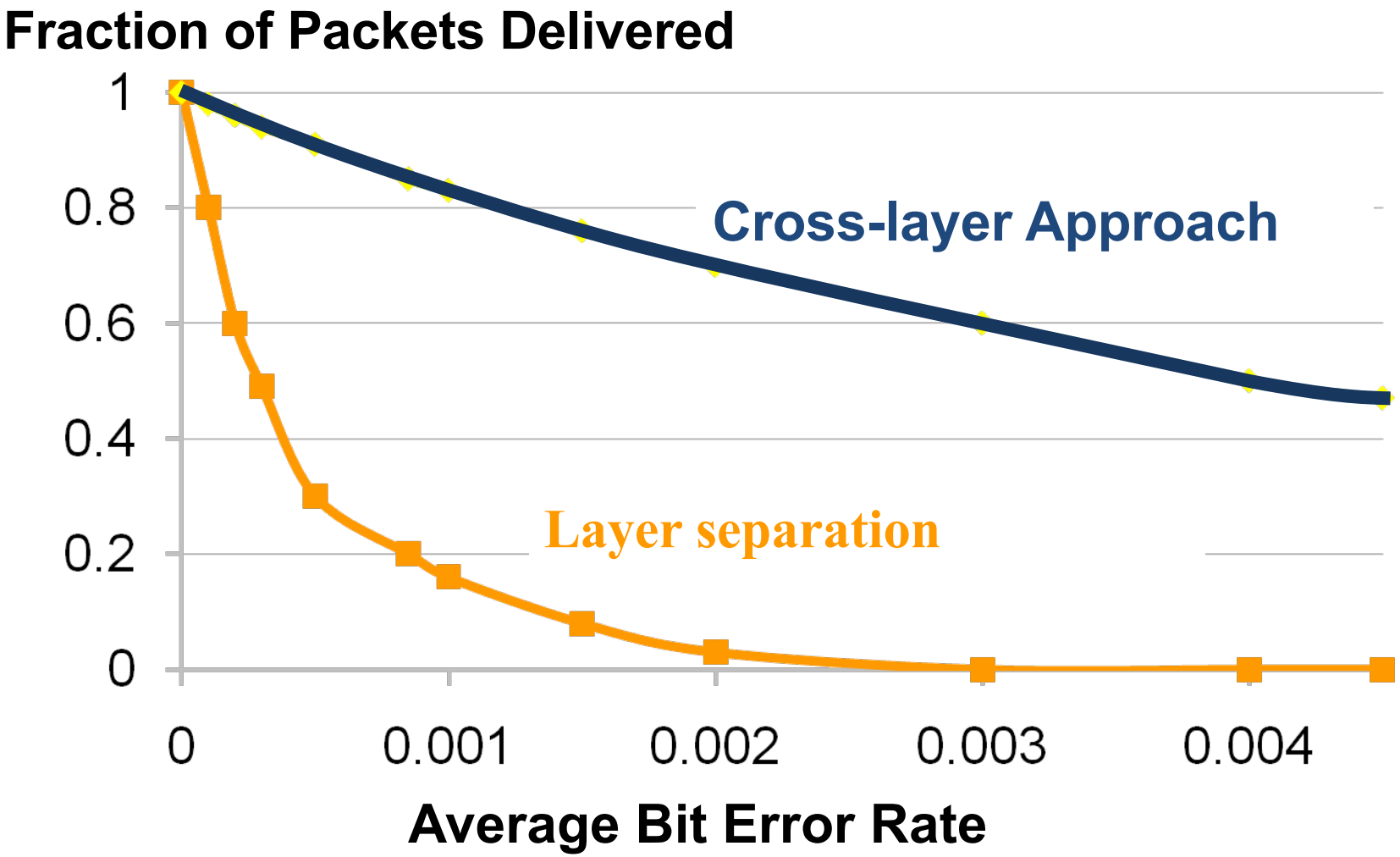
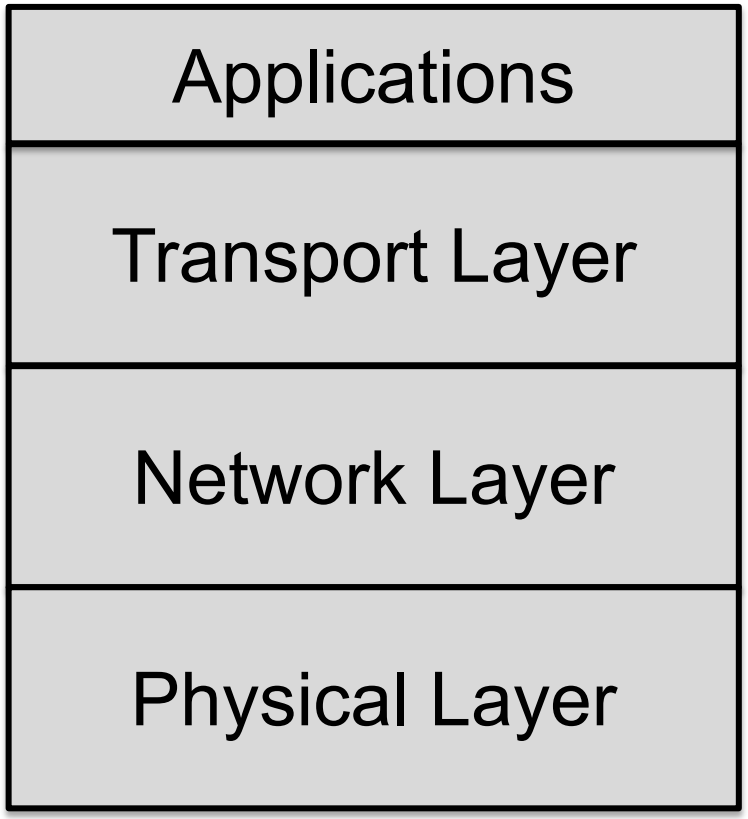


# Experiment: Packet delivery v. poor coverage

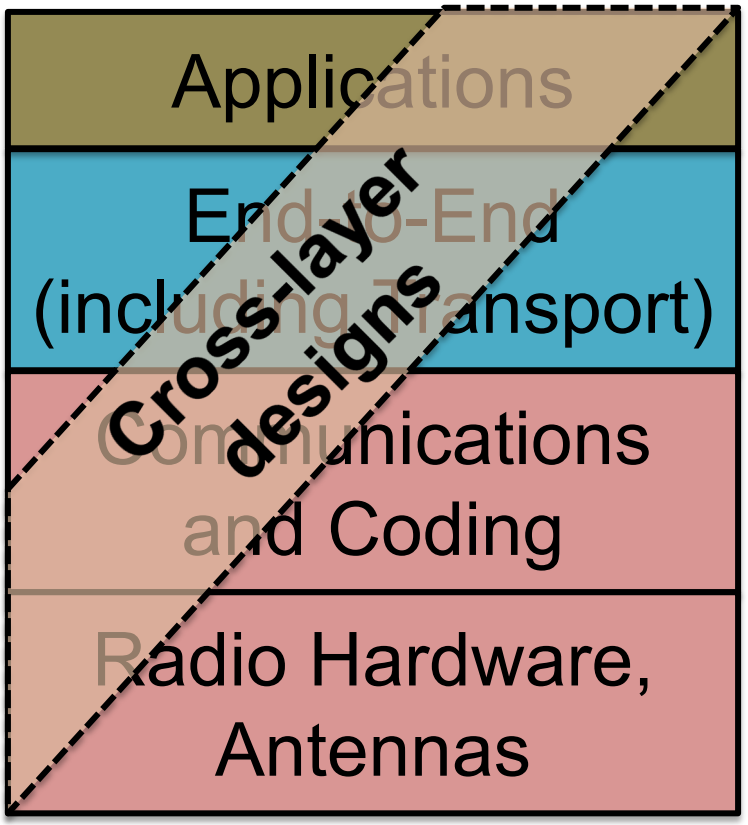


# Fundamental change in network architecture

- **Traditional approach:** Optimize **within** layers




- **New Approach:** Design and optimize **across** layers



# Today

1. How do wireless and wired networks differ?

2. What makes wireless interesting?

3. **What new services does wireless enable?**

# New Services: Wireless localization

- GPS does not work indoors → **use Wi-Fi to localize**

Indoor Navigation

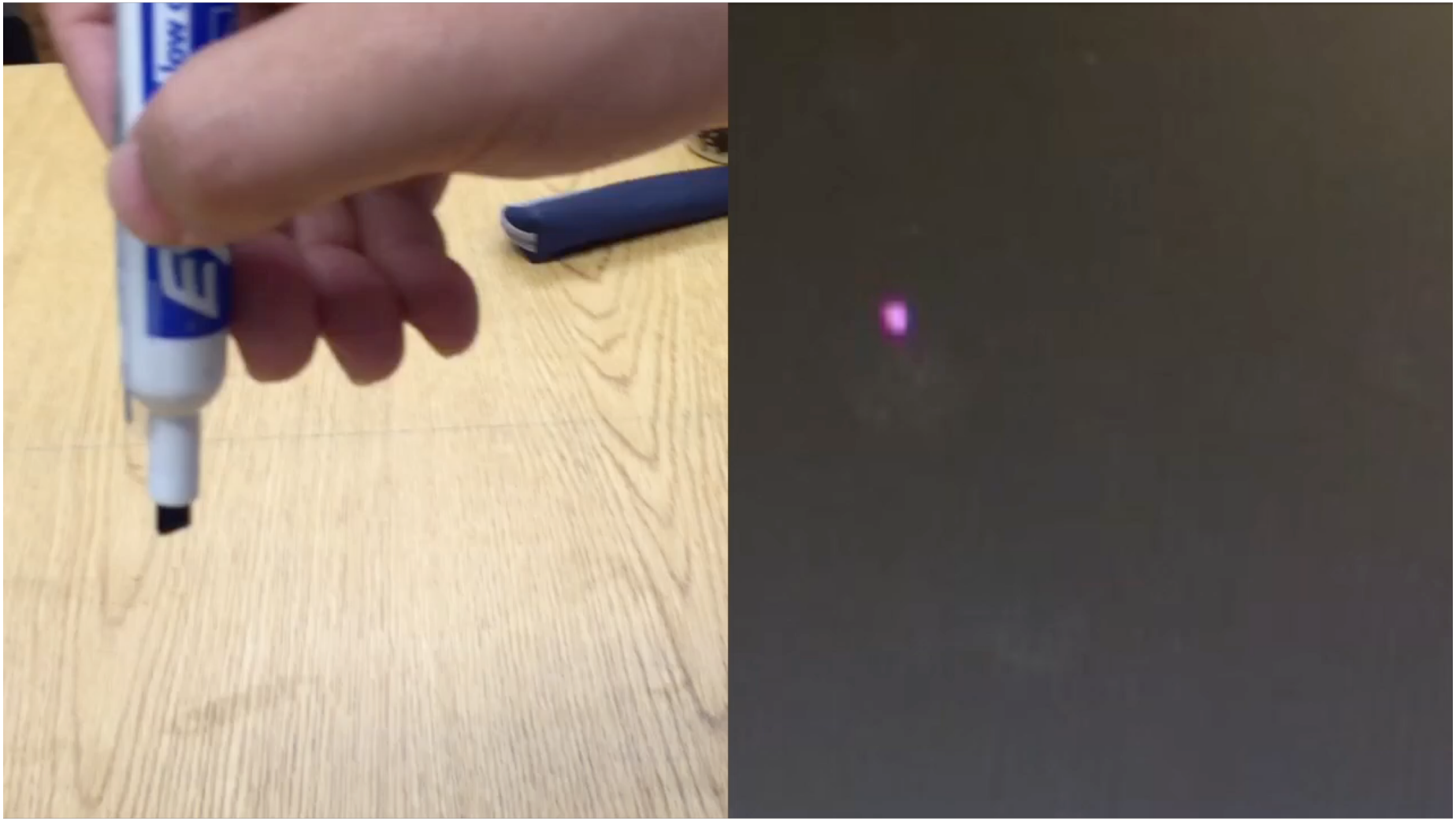
Business Analytics

WiFi Geofencing

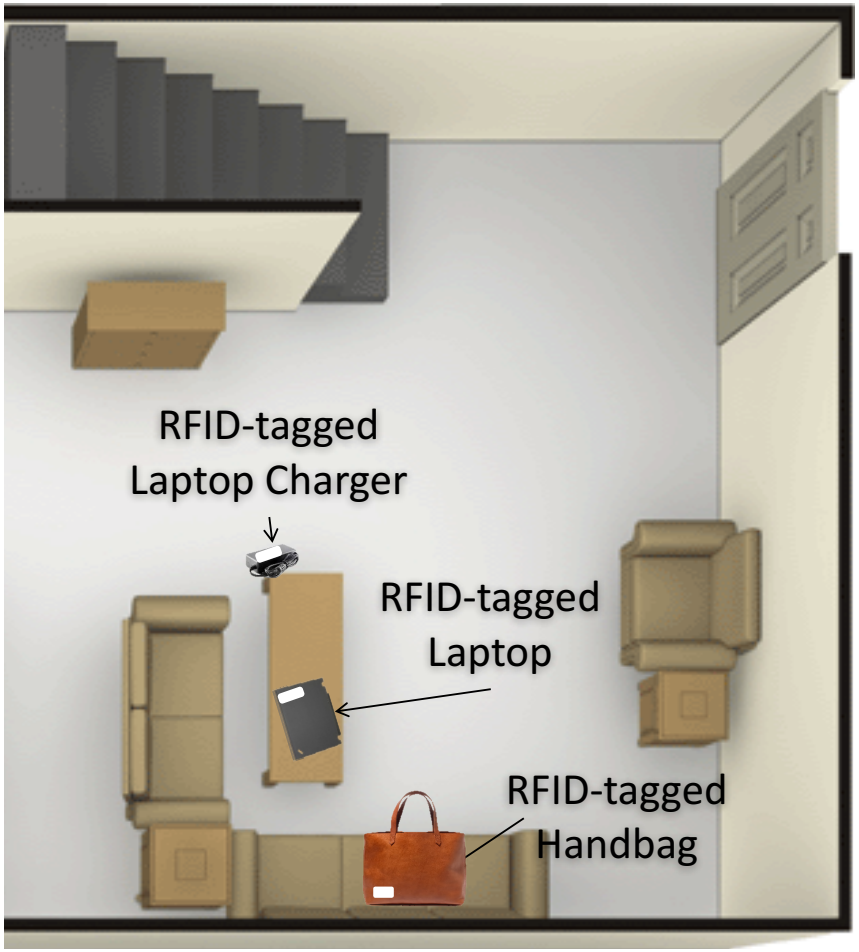
Indoor Robotic Navigation

# How do we get virtual touch screens?

# RFID motion tracking in the air



# RFID technology: Smart homes



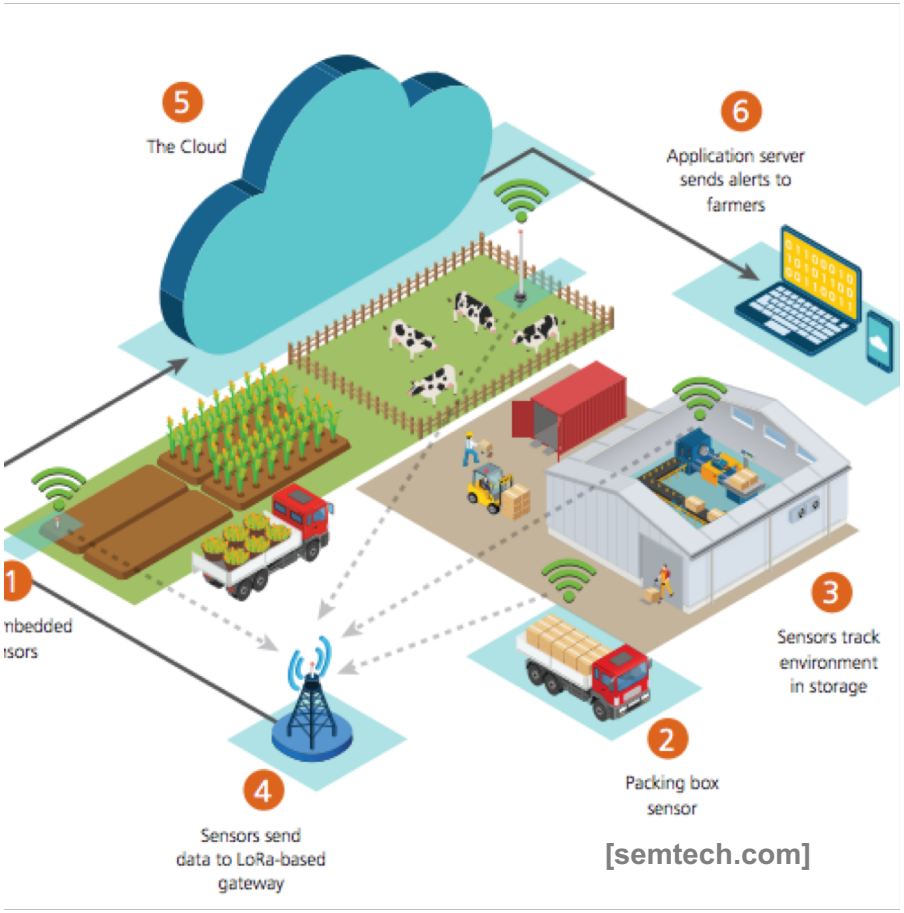

- Localize everything and anything in the home
- **RFID:** Battery-free stickers to tag any and every object

# Low Power, Wide Area Networks

- Wireless, battery operated sensors and devices

- **Long Range:** Kilometers
- **Long lifetime:** 10-20 years
- **Low cost**

- **Applications:**
  - Smart electricity, water, utility meters
  - Asset tracking: e.g. Vehicle fleet monitoring
  - **Agriculture monitoring**



# Class Website

www.cs.princeton.edu/courses/archive/spring19/cos463

## COS 463/ELE 463 Wireless Networks (Spring 2019)

Home Syllabus Reading List Assignments Announcements Piazza

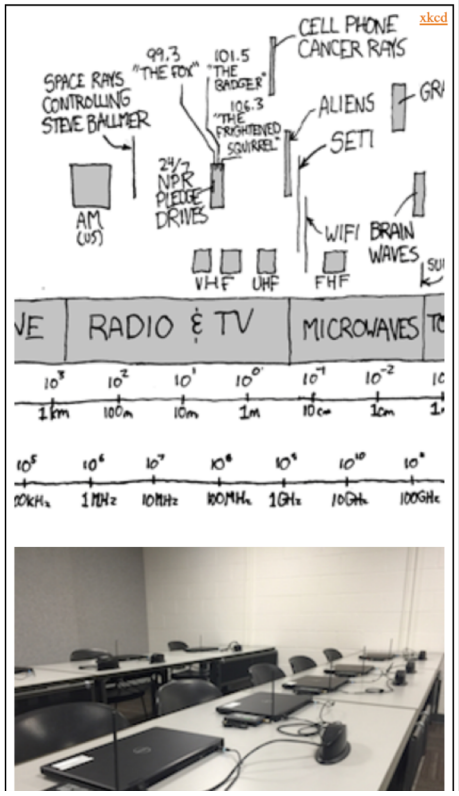
### Overview

Over the past one and a half decades, we have seen a polar shift in the way we access the Internet, our usage patterns moving from tethered workstations, to laptops, then to a variety of smaller mobile devices. Furthermore, in the next decade, we are headed on a trajectory to bring the internet to many millions of sensors and embedded computational devices. A wireless first or last hop figures prominently into the needs of each such device.

But in contrast with wired networks, wireless networks must cope with several challenges stemming from several fundamental differences between radio links and wired links:

1. Over a certain link, portions of a packet may be received correctly, while the remaining portions may contain bit errors. Background noise, reflections, and obstructions in the physical space between sender and receiver impact the delivery of individual bits proabilistically.
2. Concurrent transmissions from different nearby senders result in interference between nearby wireless links that is difficult to model or predict.
3. At certain wireless frequencies, transmissions are inherently omnidirectional (broadcast), and may reach or affect unintended receivers.

**COS 463/ELE 463** is an undergraduate-level class that presents students a broad view of the entire wireless networking stack, including the physical layer, presented in a way that is accessible for students with solely a computer systems and networking background. Through laboratory-based programming exercises in C++, Python, and Matlab in a lab environment equipped with many software-defined radios operating in proximity, students will apply the understanding they gain to build real wireless networks of their own.



## Thursday Topic

Systems & Networking Concepts: Layering, End-to-End Arguments

Transport over Wireless I: TCP Split Connection

## Monday/Tuesday Precepts

Python Intro and Signal Processing Primer

Location: Friend Center, Room 003