Class Introduction

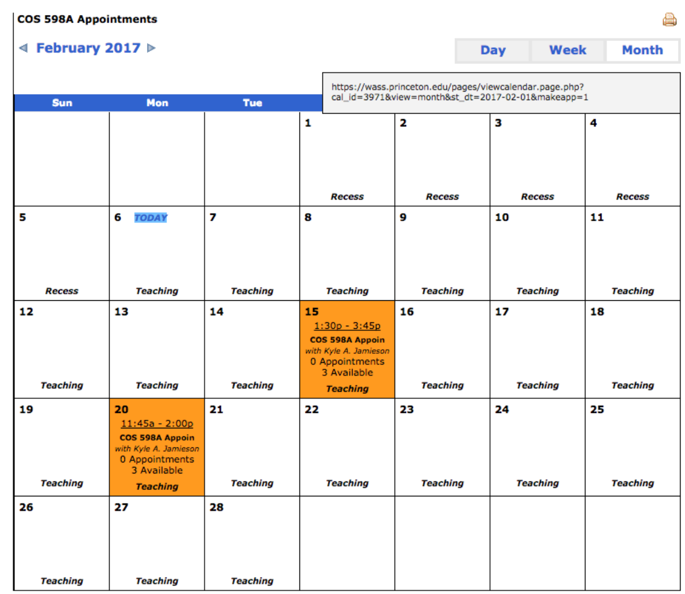
COS 598a: Wireless Networking and Sensing Systems

Kyle Jamieson

[Parts adapted from S. Shenker, P. Steenkiste]

Instructor and office hours

- **Kyle Jamieson,** CS room 305
  - Office hours on demand and by appointment
    - Follow link to Princeton Web Appt. Scheduling System (WASS) from course home page
    - Timeslots coincide with key project milestones
  - And by mail request to *kylej*, I'll add timeslots



Prerequisites

- Open to graduate students
  - Assume a basic familiarity with networking concepts
- Open to interested undergraduates with necessary experience/background
  - **COS-461**/equivalent required, **COS-318/333**/equivalent helpful
  - And with permission of the instructor
- Mostly taken by CS students who want to extend their networking background to wireless
- But, also accessible to students with more of an EE background
  - But need to read up on networking (see reading list)
  - Consider programming experience as well

Meeting times

- **Class meeting time:** Tue/Thu 1:30–2:50 PM
  – Room: CS Building, Room 301

- **Project milestone meetings** by appointment

- **Final project demos** by appointment on Dean's date

- **Exceptions** to regular meeting time:
  – Feb 28 (Tuesday) → Mar 1 (Wednesday)

- Will send Doodle poll, ask for your cooperation to reschedule

Course Contents

- **Lectures:** Introduce concepts, build up background knowledge
  - "Essential reading" in each sub-area
  - Introduction to the Physical layer

- **Reading discussions:** Dive deeper into each sub-area
  - Some "test-of-time," others current and timely
  - Exercise your **critical thinking** on exciting current research
    - Compare proposed solutions
    - Discuss applicability and limitations

- **Project:** individual or in pairs, hands-on
  - Topic is flexible; you choose it with consultation from me
  - Organized in multiple phases…

Readings

- ~40 research papers (some optional), varying coverage
  - Lots of ACM SIGCOMM & MobiCom, USENIX NSDI
  - Some "time-tested," others "hot"

- Explore the most important and recent developments in:
  - Wireless local-area, wide-area networking
  - Mobility, Interference, performance diagnosis
  - Wireless sensing and localization
  - **Boutique:** RFID, backscatter, general hacking w/signals

- Available on class web page; print them yourself

Goals of the Class

1. Understand the **state of the art** in wireless networks, network architecture, and wireless sensing systems

2. Understand how to **do research in wireless**

3. Investigate **novel ideas** in the above areas through a **hands-on, semester-long** research project

Soft outcomes

- To develop **taste** in research
  - What constitutes a good research problem? What constitutes convincing scientific evidence that a design solves a problem?
- To develop **"systems maturity"**
  - Ability to reason about sound computer system designs
- To develop skills in **delivering clear technical explanations** in informal settings
  - Might be encountered during one-on-one job interview meetings with engineers or academics
  - Or in grad school, or at work

Class Communication

- **Web:** www.cs.princeton.edu/courses/archive/spring17/cos598A
  - Primary means of **communication** with you
  - Calendar, coursework, policies, announcements, and errata
  - Your responsibility: **check web page daily!**

- Piazza news and discussion forum (Princeton COS 598A)
  - **Detailed, interactive technical discussions** on the papers
  - Your responsibilities:
    - Enroll in Piazza site after class, **check your email daily!**

Class Grading

- **50%** **project**, broken down into:
  - 15% proposal
  - 25% project status report, demo, code/design walkthru
  - 60% final report and demo (both written and presented)
- **20%** **"chalk talk"** presentation of a paper in class
  - PowerPoint slides may used if desired
- **30%** **class participation**, broken down into:
  - 50% paper reviews of selected readings (1 per class meeting)
  - 50% starting a discussion on your "chalk talk" paper on Piazza, and contributing to others' discussions

Evaluating a Paper

- Longer ago published, more you can judge impact:
  - Does everyone use systems now derived from it?
- Recent papers: more on cleverness, promise
- Other contributions possible:
  - Thorough investigation of complex phenomenon
  - Comparison that brings sense to an area

How to Read a Research Paper Critically

- Print the papers and take notes as you read
  - Question assumptions, importance of problem, important effects not mentioned by authors
  - Write questions to track what you don't understand
- Don't let ideas or design details pass until you understand them
  - May need to re-read a paragraph or section many times, or even discuss it with peers
  - Can't fully understand if the design is good unless you understand all the details: be vigilant!

Paper reviews (selected papers)

- Online with **HotCRP** reviewing system, **due at start of class**
  - Summarize paper, strengths, weaknesses
  - Pose a non-trivial discussion question & answer

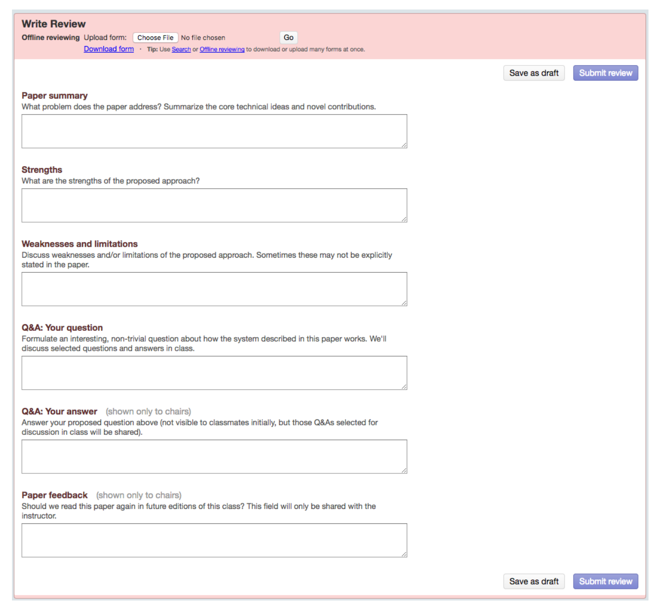
- **Read each others' reviews** after yours is submitted

- Graded on a 0-2 scale:
  - 0: not turned in at class start, or doesn't answer question
  - 1: answers the question asked
  - 2: precisely, correctly, thoroughly answers the question

- All equal weight; **total** contribution to final grade: 15%

HotCRP review form

- Paper summary
  - What's the problem? How does paper advance knowledge?
- Strengths
  - For older papers, positive impacts?
- Weaknesses/limitations
- Q&A: Your question
  - Will discuss in class
- Q&A: Your answer



Chalk talk (selected papers, by reservation)

- Why? Practice **explaining complex systems to your peers**
- Prefer you use **chalk**, really! Or may use slides, or both
- Presentation must:
  - Clearly explain ideas in paper
  - Constructively critique ideas and results in paper
- Papers to choose from **will be flagged** on class web site, allocated first-come, first-serve by emailing instructor <u>after class</u>
  - **Signup deadline for chalk talks:** Friday 2/17
- Presentation contributes 20% of final grade

Chalk talk guidelines

- Chalk talk or slides for **20-30 minutes**

- Then **open discussion**
  - Come prepared to **lead class discussion** after talk

Content of a chalk talk

- Motivation and problem statement
- State main contributions of work (core ideas)
- Description of central design
- Experimental evaluation
- Related work
- Future work
- “Opinion part”

Description of central design

- No time to discuss **every** detail, so present the **most important**:
  - To understanding **how and why the system**, design, or algorithm works
  - To **understanding results** in the experimental evaluation

- **Clarity,** not "parroting," is very important here:
  - Often, describe in a **top-down fashion**
  - Start with the overall problem
  - Identify parts of the solution, then identifying the sub-parts of those parts, & *c.*

Experimental evaluation

- **What questions** do the authors ask in their evaluation?
- What is the authors' hypothesis for each question and why?
- No time to present all results, so present most important
- For any **graph** you show or refer to:
  - First, **explain the axes**
  - Explain **overall trend:** why system behaves as it does
  - Justify explanation by **referring to relevant details** of the system's **design** and experiment's design
  - Does anything seem **anomalous**? Note and try to explain

Related and future work

- What are the **most closely related** other systems/results?
  - How are they **similar**? How are they **different**?
  - Is the difference between the work you are presenting and the related work **significant**?
- Should read citations enough to understand differences
- Should search for related work published after/with the paper
- **No need to claim** the work you are presenting is **"better" or "worse"** than a particular piece of related work
  - Often it is simply that the two pieces of work are different
- But, should **articulate the precise difference** (*e.g.*, "this work solves a slightly different problem…")

Opinion part

- Offer your final critical assessment:
  - What are the strengths of the work?
  - What are the weaknesses/limitations?
  - What important questions are left unanswered?

Today

1. Logistics and administrivia

2. **Course outline: Whirlwind tour**, and a bit more about the course project

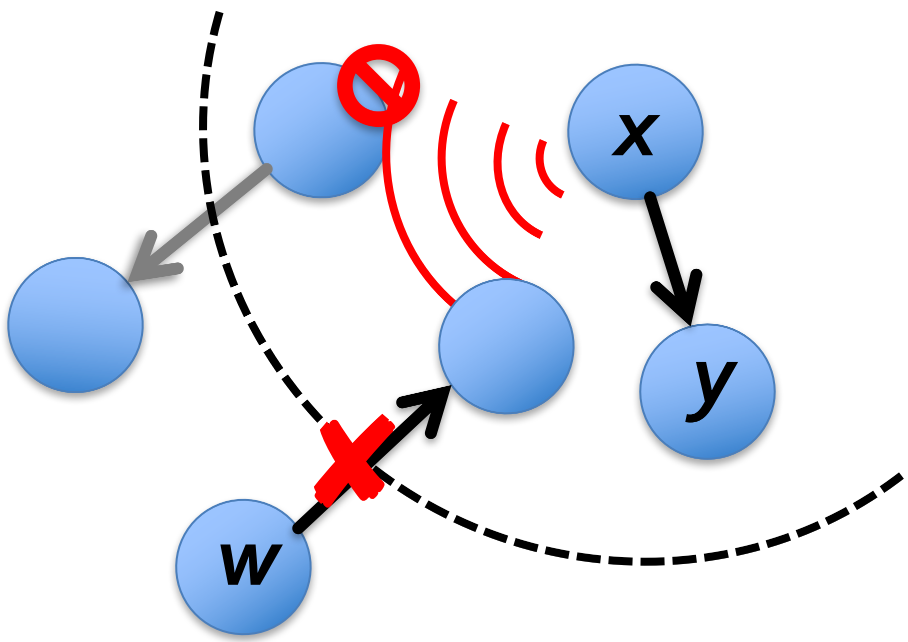
3. *Why is wireless interesting, and intellectually challenging?*


OMG!
I JUST GOT
BORN!

Course Outline

Part I: Introduction to Wireless

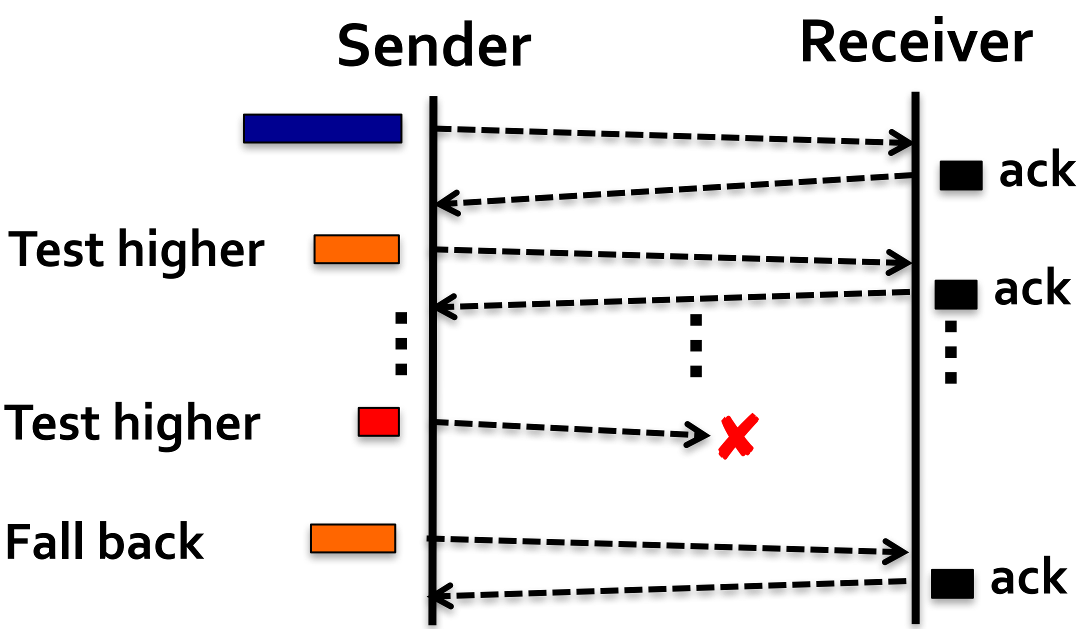
- **Sharing the wireless medium:** *Medium access control*
  - Who gets to speak, and what rules do they follow?



Course Outline

Part I: Introduction to Wireless

- **Bit rate control algorithms**
  - How fast to speak on the wireless medium?



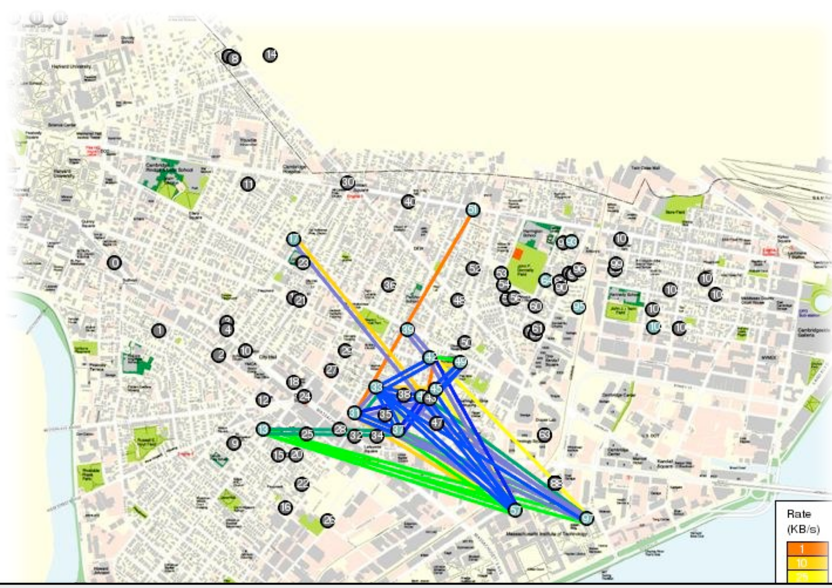
SampleRate (Bicket), Minstrel algorithms

Bitrate	Transmits	Acks
11 Mbits/s	1	0
5 Mbits/s	5	5
2 Mbits/s	1	1

Course Outline

Part I: Introduction to Wireless

- **Mesh networking**
  - *The Roofnet network*

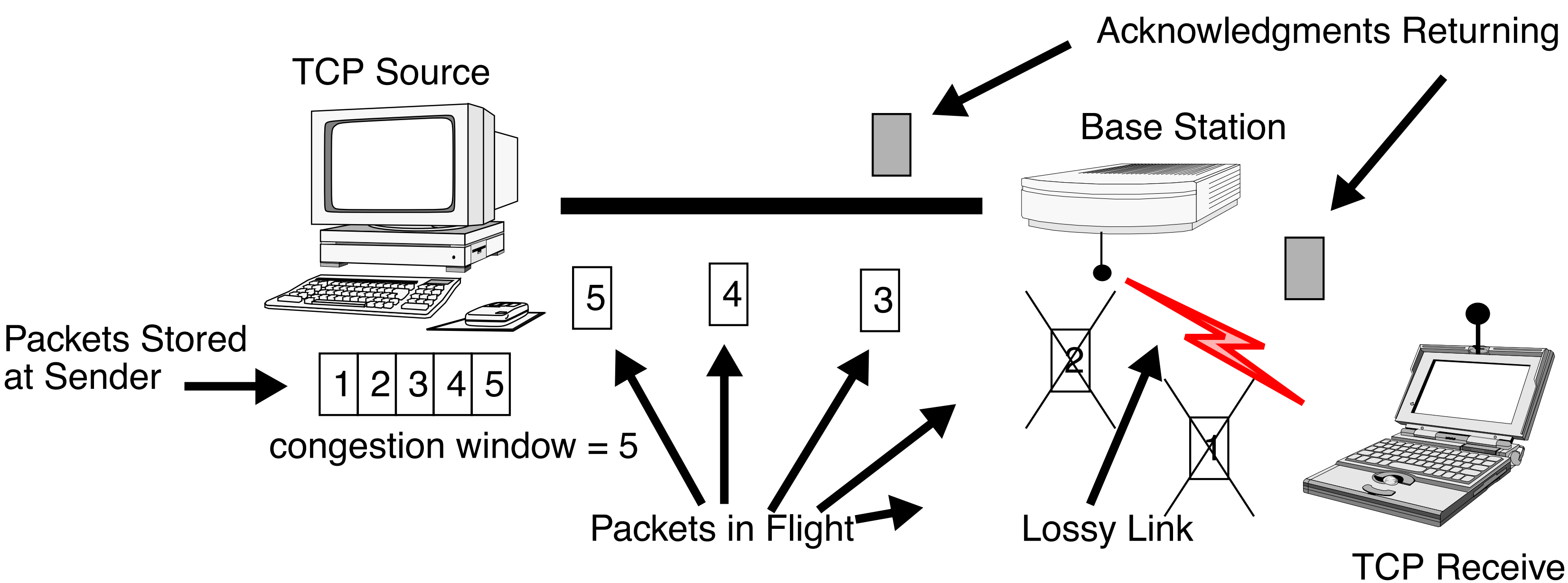


Architecture and Evaluation of an Unplanned 802.11b Mesh Network (Bicket et al., MobiCom '05)

Course Outline

Part I: Introduction to Wireless

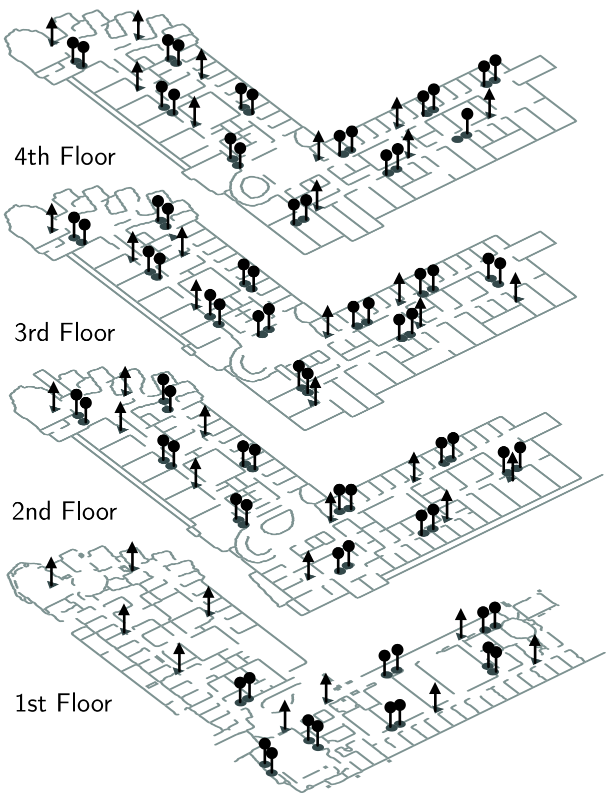
- **Transport over Wireless**
  - How does the Internet's transport layer interact with wireless?

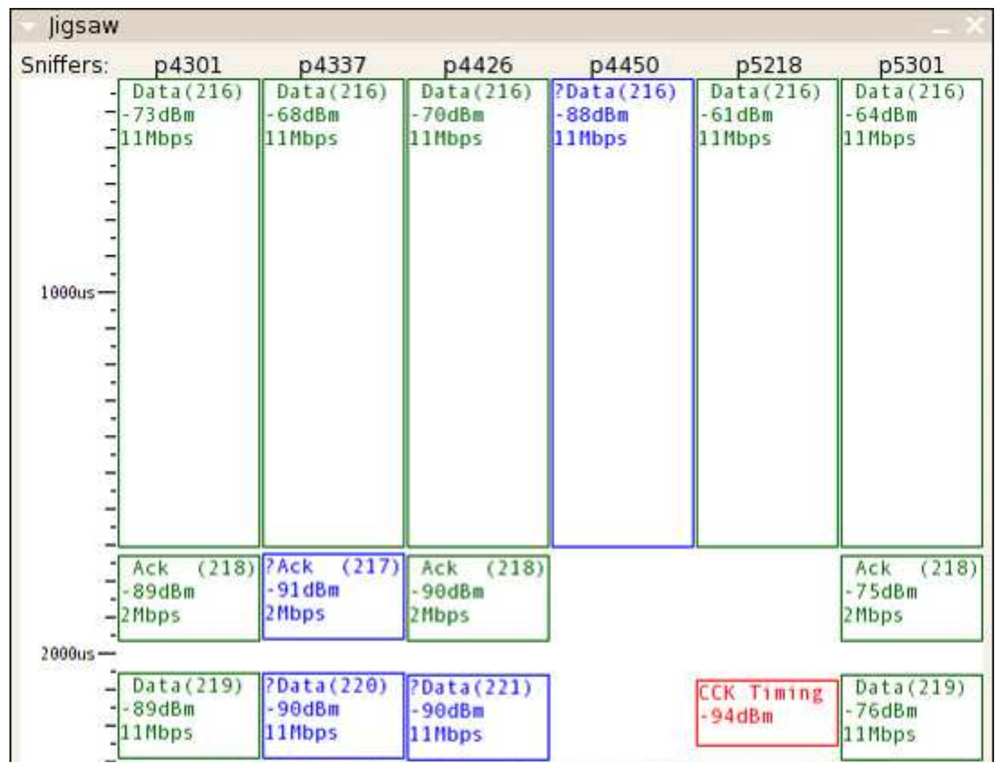


Course Outline

Part II: Wireless Network Performance

- Jigsaw: Enterprise wireless diagnosis

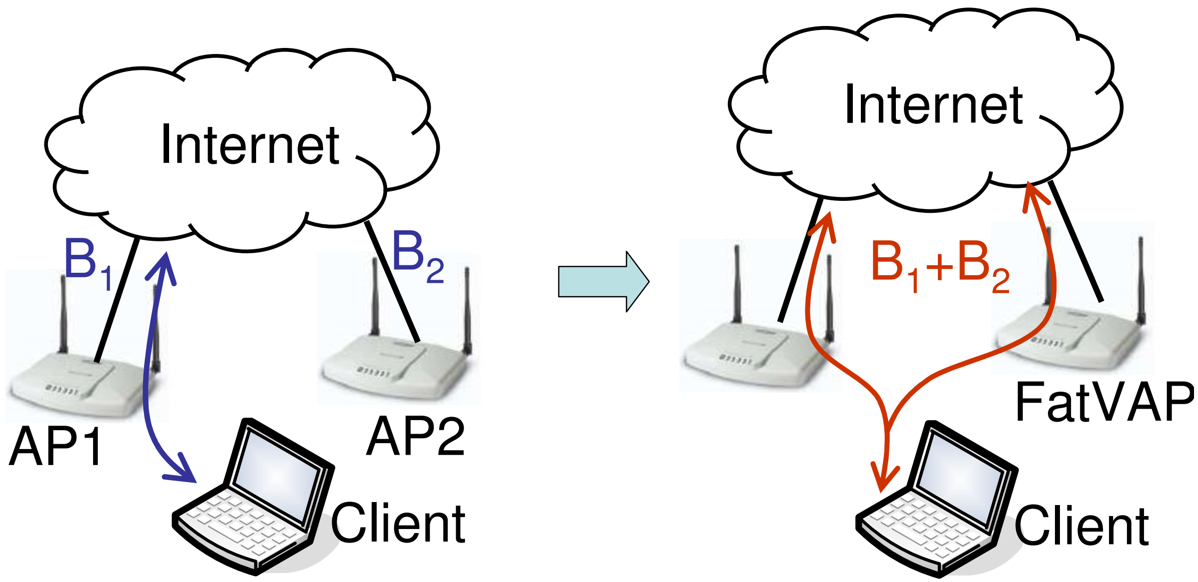




Course Outline

Part II: Wireless Network Performance

- Handoff, mobility, opportunistic communication



Summary of Parts I and II

Part I: Introduction to Wireless

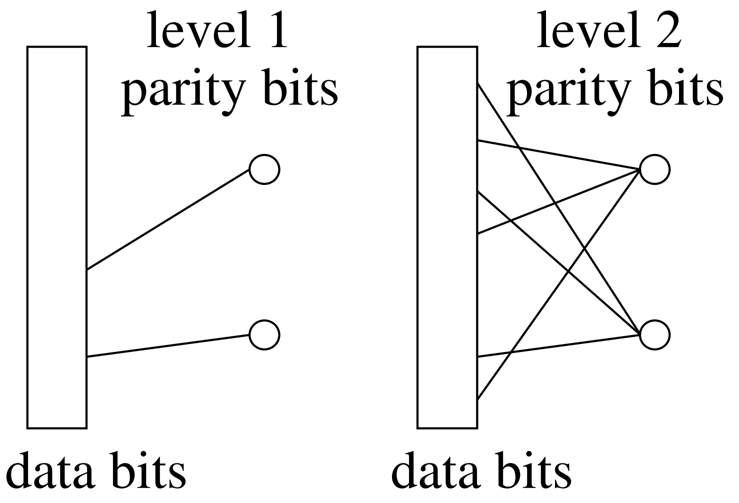
Part II: Wireless Network Performance

- Accessible papers for a broad systems & networking audience
- Roughly equal split between lecturing and paper discussion
- **Goal:** Be broad, gain knowledge in **essential wireless concepts**
  - So you know what you like!
    - Choose project at the end of Part II (early March)

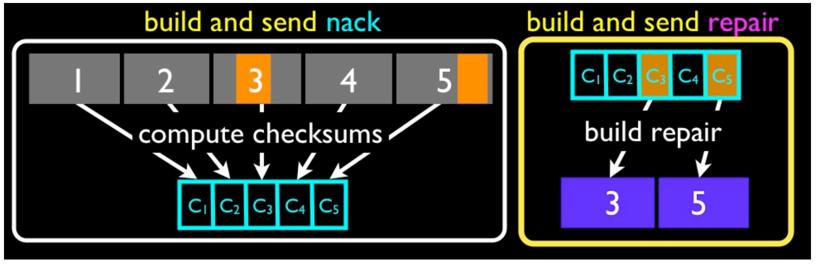
Course Outline

Part III: Wireless Physical Layer

- **Bit errors:** estimating their frequency, and correcting them



Error Estimating Codes

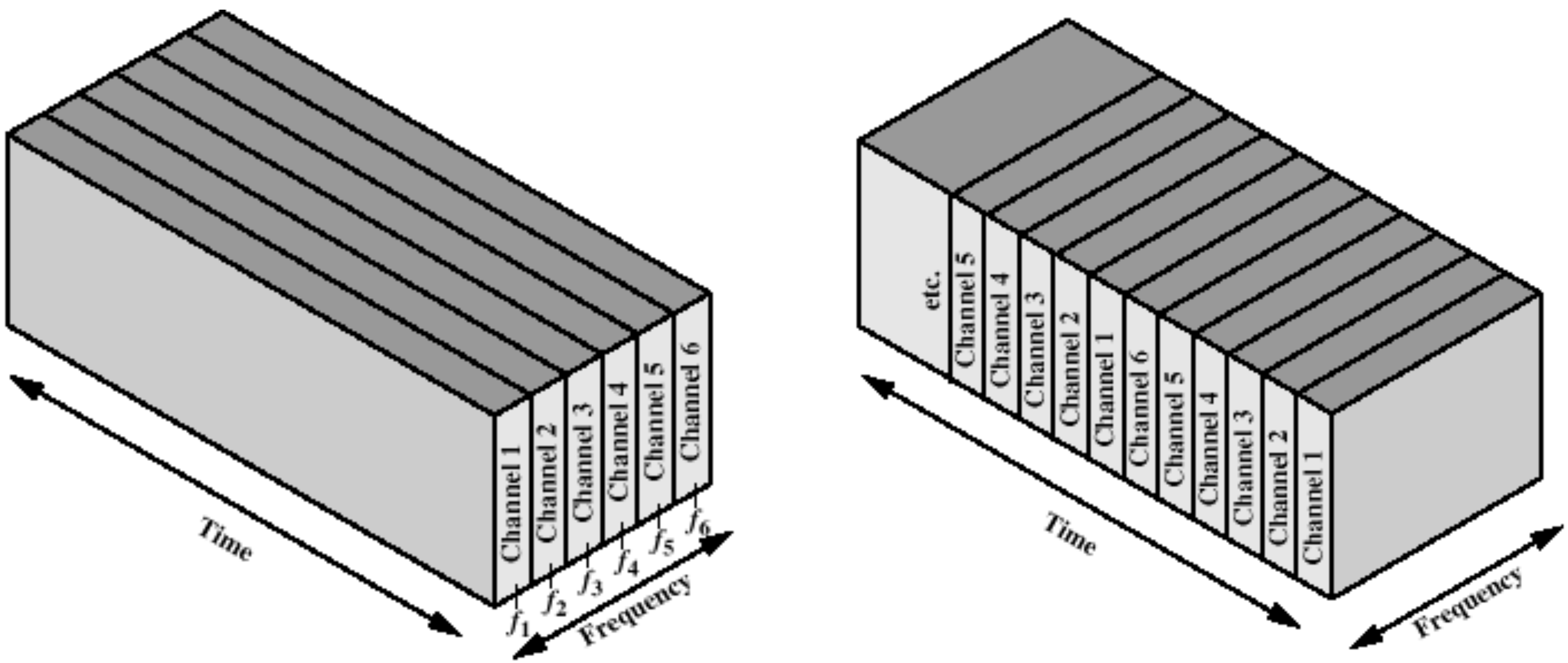


Maranello: Practical Partial Packet Recovery for 802.11

Course Outline

Part III: Wireless Physical Layer

- Introduction to **radio, sharing** the wireless medium



Course Outline

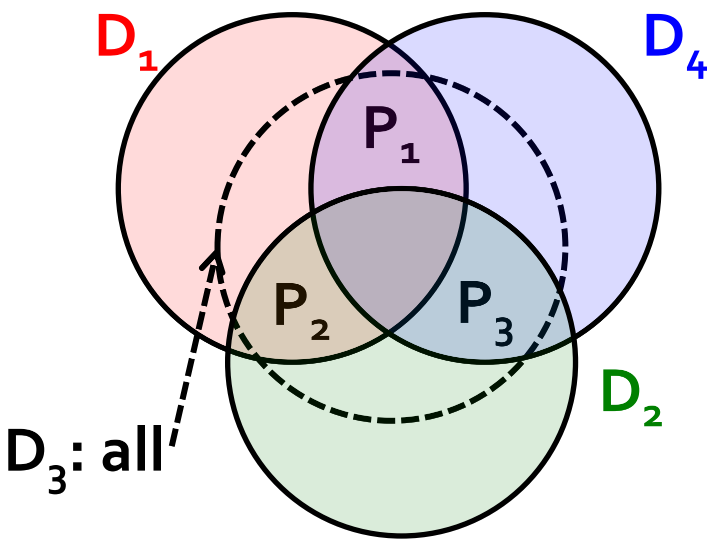
Part III: Wireless Physical Layer

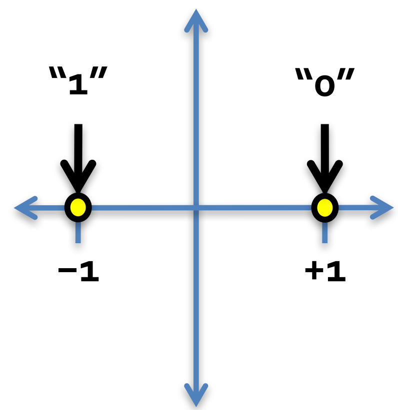
- Introduction to **antennas, multipath** propagation and the wireless channel

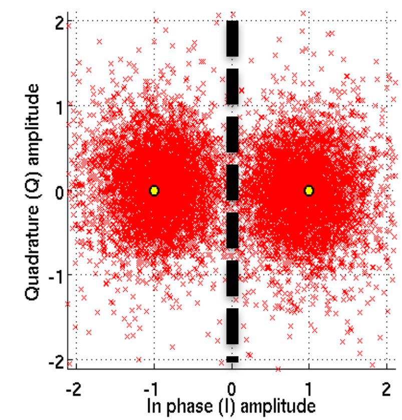
Course Outline

Part III: Wireless Physical Layer

- Error control coding, wireless modulation





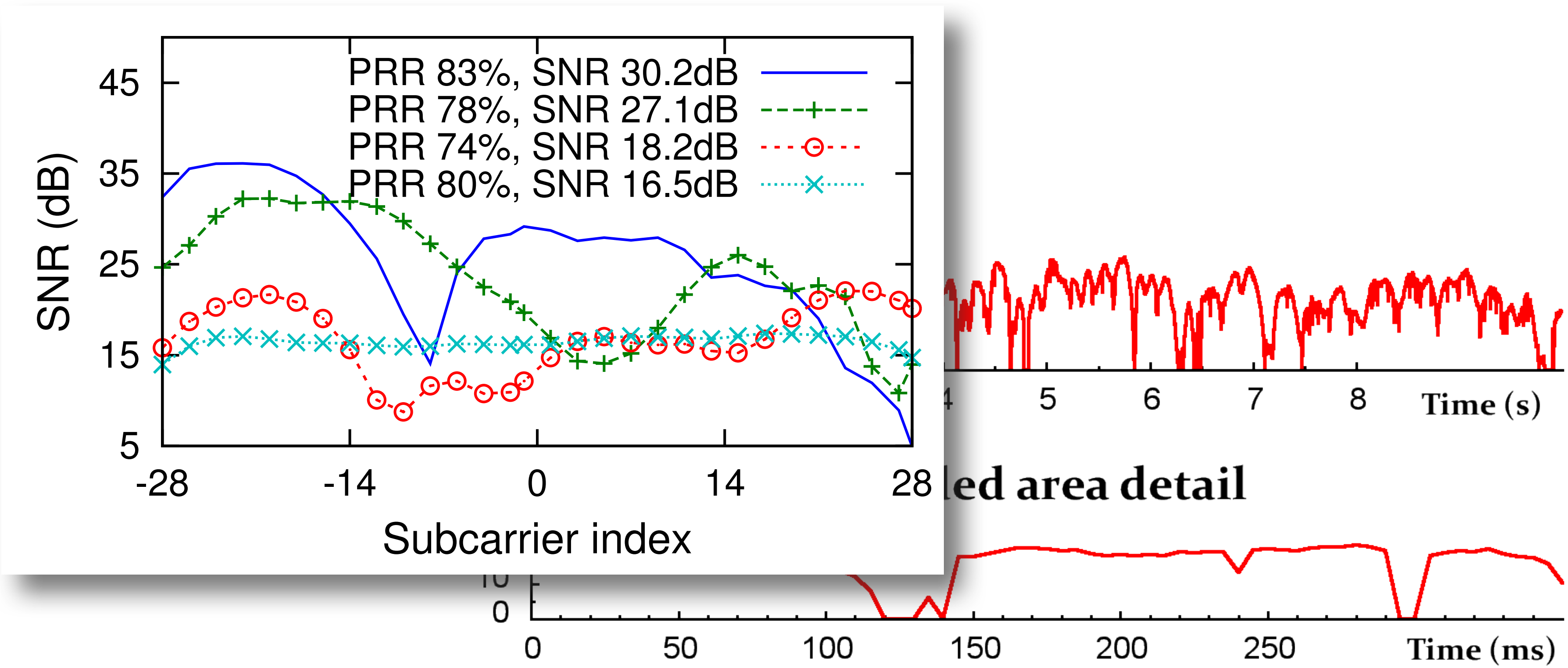


Spinal Codes (Perry et al., SIGCOMM '12)

Course Outline

Part III: Wireless Physical Layer

- Diversity. Wireless channel prediction.



Summary of Part III

Part III: An Introduction to the Wireless Physical Layer

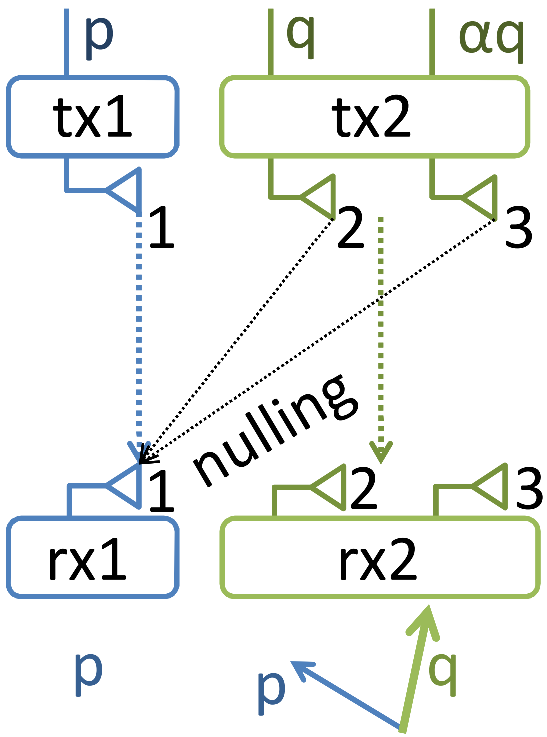
- More lecture material
- A **deep dive** into the PHY, but from **first principles**

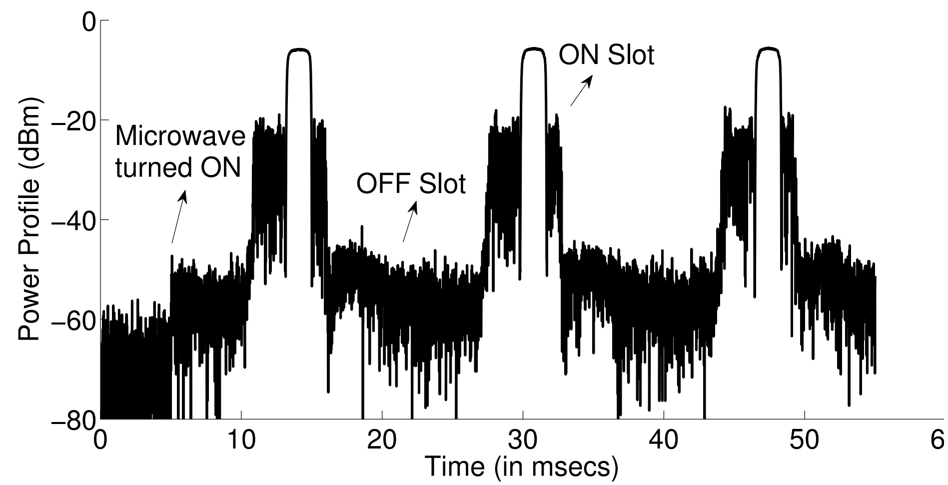
- **Goal:** Prepare you for the following readings on:
  - Taming wireless interference
  - Radio-based localization and sensing
  - Backscatter, RFID, Physical hacks

Course Outline

Part IV: Taming Wireless Interference

- Wi-Fi sources. Non-Wi-Fi sources.





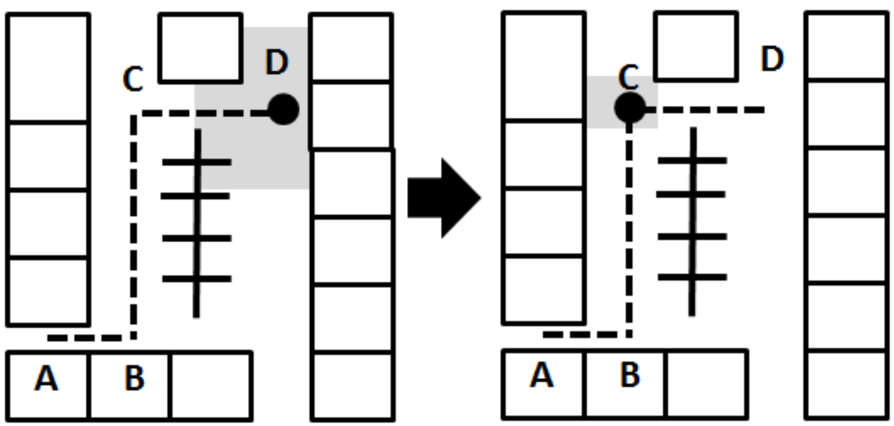
(c2) Time Profile

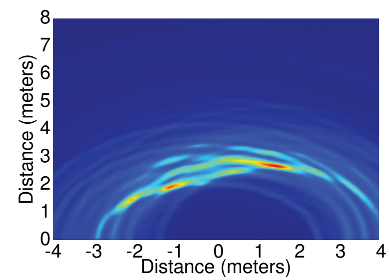
(c) Microwave Oven

Course Outline

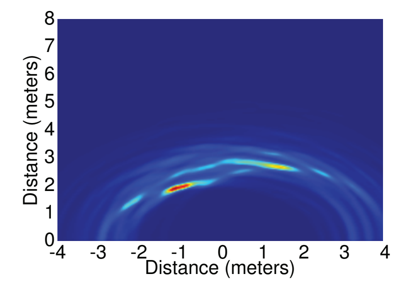
Part V: Radio Based Localization and Sensing Indoors

- Radio map. Fusing with other sensors. Decimeter-level tech.



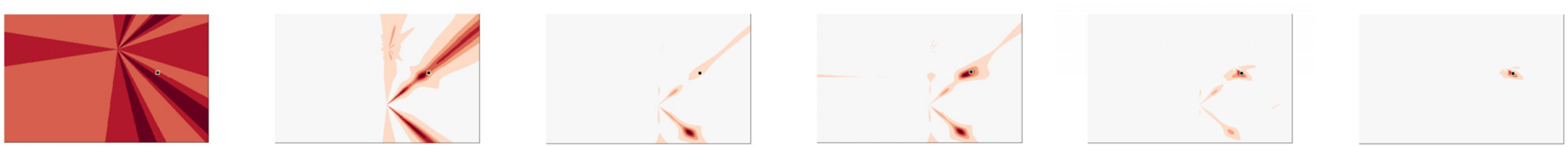


(c) **Three Tx-Rx pairs**



(d) **Four Tx-Rx pairs**

One AP **Two APs** **Three APs** **Four APs** **Five APs** **Six APs**

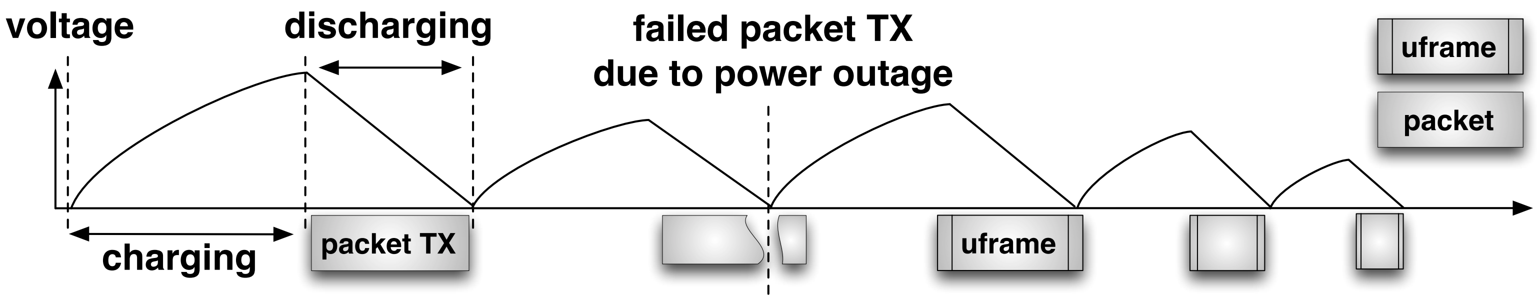


Course Outline

Part VI: Demo Days (more soon)

Part VII: Backscatter Communication and RFID

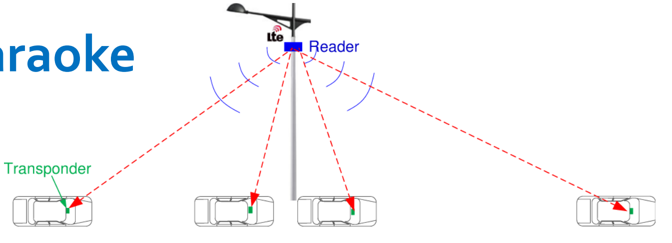
- Energy Harvesting. Passive radio. RFID applications & hacks.



QuarkNet: Bit-by-bit Backscatter Communication

Passive Wi-Fi

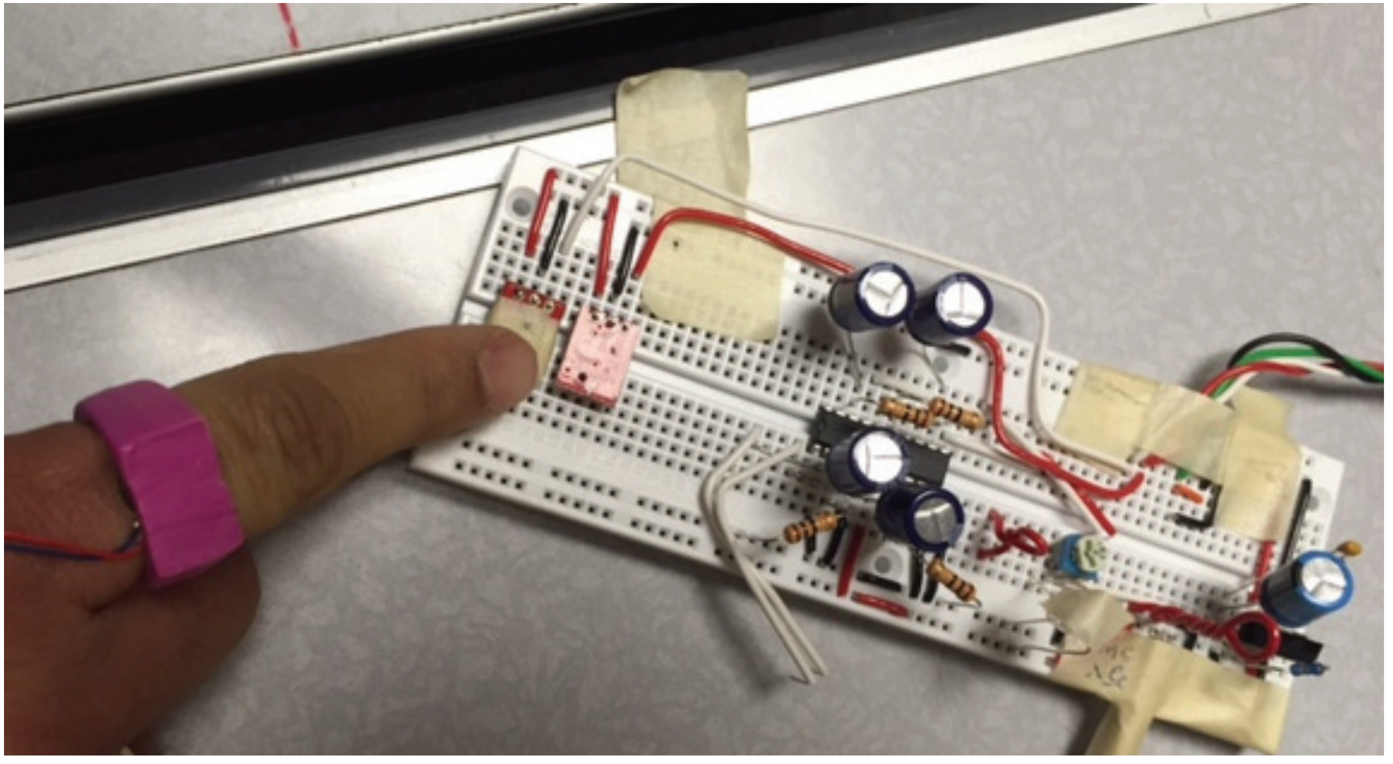
Caraoke



Course Outline

Part VIII: Physical Hacks

- Ripple, Ripple II. Others TBA, schedule permitting.

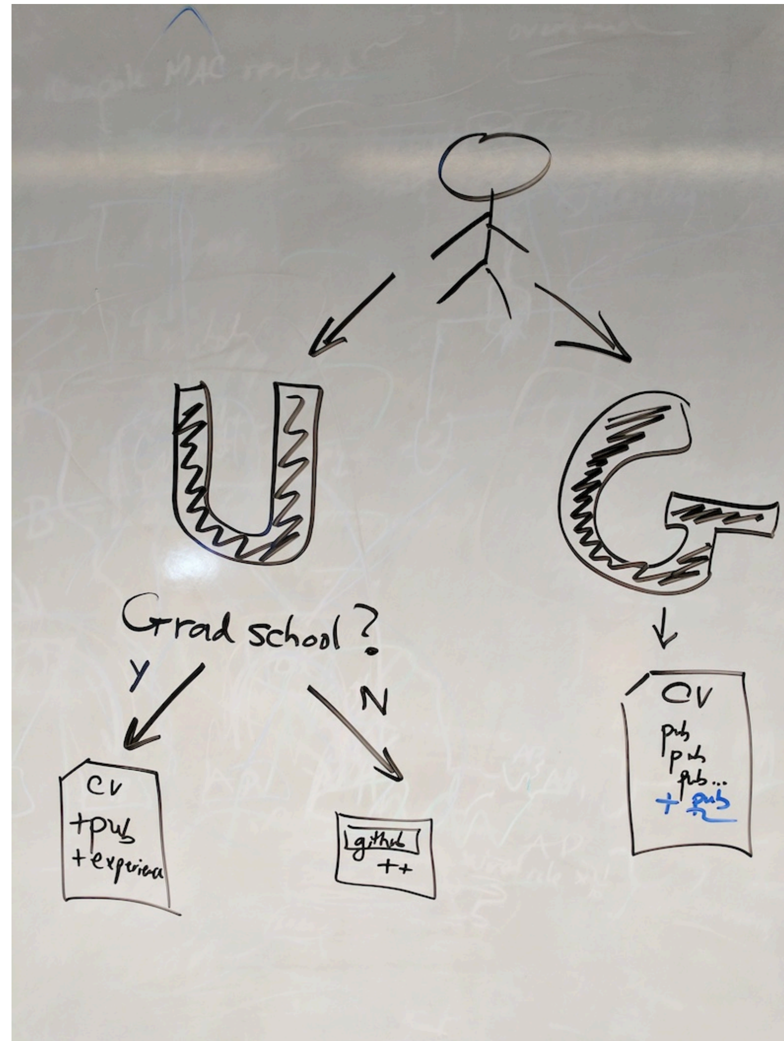


Final thoughts, on latter-half topics

- Looking **across the divide** between networking and digital communications/circuits
- Or, **across the divide** between networking and localization with signal processing
- For some very **powerful and compelling results**

Project: Why

- **In-depth study** of a topic
  - Performance evaluation studies, protocol modifications, applications, measurements, …
  - Must be wireless, but otherwise flexible
  - Discuss project ideas w/me
- **An opportunity →**



Project: What

- **New research,** or a new take on a **system we read about**
- At least partly **hands-on (implementation) projects**
  - **Individually, or in pairs of students**
  - Must be working code uploaded to Princeton University's github organization and shared with instructor
- Carefully consider platform options:
  - Real-world experiments (preferred)
  - Trace-driven simulation
- "*We believe in rough consensus and* ***running code***"

Project: When

Form a pair or not, tell KJ

Checkpoint #1: Written proposal (15% of project grade)

Checkpoint #2: Demo, design/code walkthru (25% of project grade)

Dean's date: Six-page write-up and demo (60% of project grade)

Today	2/20	3/3	4/18, 4/20	5/5

- **Once team formed:** read project ideas, then schedule a meeting with KJ in WASS to discuss your project choice, review writeup
- *"Plan to throw one away; you will, anyhow."*

Checkpoint #1: Written proposal

- Two pages in length
- *Introduce and clearly explain* the problem
  - Give context: most relevant related work with citations
- Sketch high-level system design (changeable!)
  - Highlighting new knowledge contributions
- If applicable, provide a plan for experimental evaluation (changeable!)
- Finally provide a work plan, including:
    - A rough division of labor
    - Highlight the systems programming work involved
    - When and where you propose to leverage existing code
    - How you will meet Checkpoint #2 and final product

Checkpoint #2: In-class demo & review

- Demonstration of your system or a part of it, functioning

- Technical design overview
  - High-level block diagram
  - Components: Protocol timelines, state machines

- Code review (100 LoC)
  - **You choose** the code
  - Comment and syntax-highlight your code

Final write-up and demo

- Same structure as the research papers we will read:

- Introduce and motivate the problem
  - Placing in context of some related work

- Describe your design clearly

- Present a performance evaluation
  - Comparing your design to a “strawman” system

- More related work, and conclusion

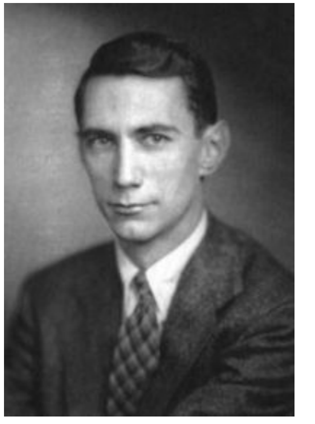
Today

1. Logistics and administrivia

2. Course outline: Whirlwind tour, and a bit more about the course project

3. ***Why is wireless interesting, and intellectually challenging?***
   - **Fundamental limits open**
   - (Most) wireless is a shared medium
   - Evaluation challenges

Some things are well understood…



Q: *What's the capacity of a point-to-point link?*

- **Bits per 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* (the 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 [CS community]: "Let's build a better medium access control protocol!"

What makes wireless networks different from wired networks?

- In wired networks link bit error rate **10^{-12} and less**
- Wireless networks are **far from that target**
- Two quantities we care about:
  - Signal-to-interference plus noise ratio (**SINR**)
    - Signal Power / (Noise Power + Interference Power)
      - Measured at the receiver
  - Bit Error Rate (**BER**)

Path Loss

- Signal power attenuates by about ~r^2 factor for omni-directional antennas in free space
  - ***r*** is the distance between the sender and the receiver
  - The exponent depends on placement of antennas
    - Less than 2 for directional antennas
    - Greater than 2 when antennas are placed on the ground
      - Signal bounces off the ground and reduces the power of the signal

Throughput vs. distance (WiMAX)

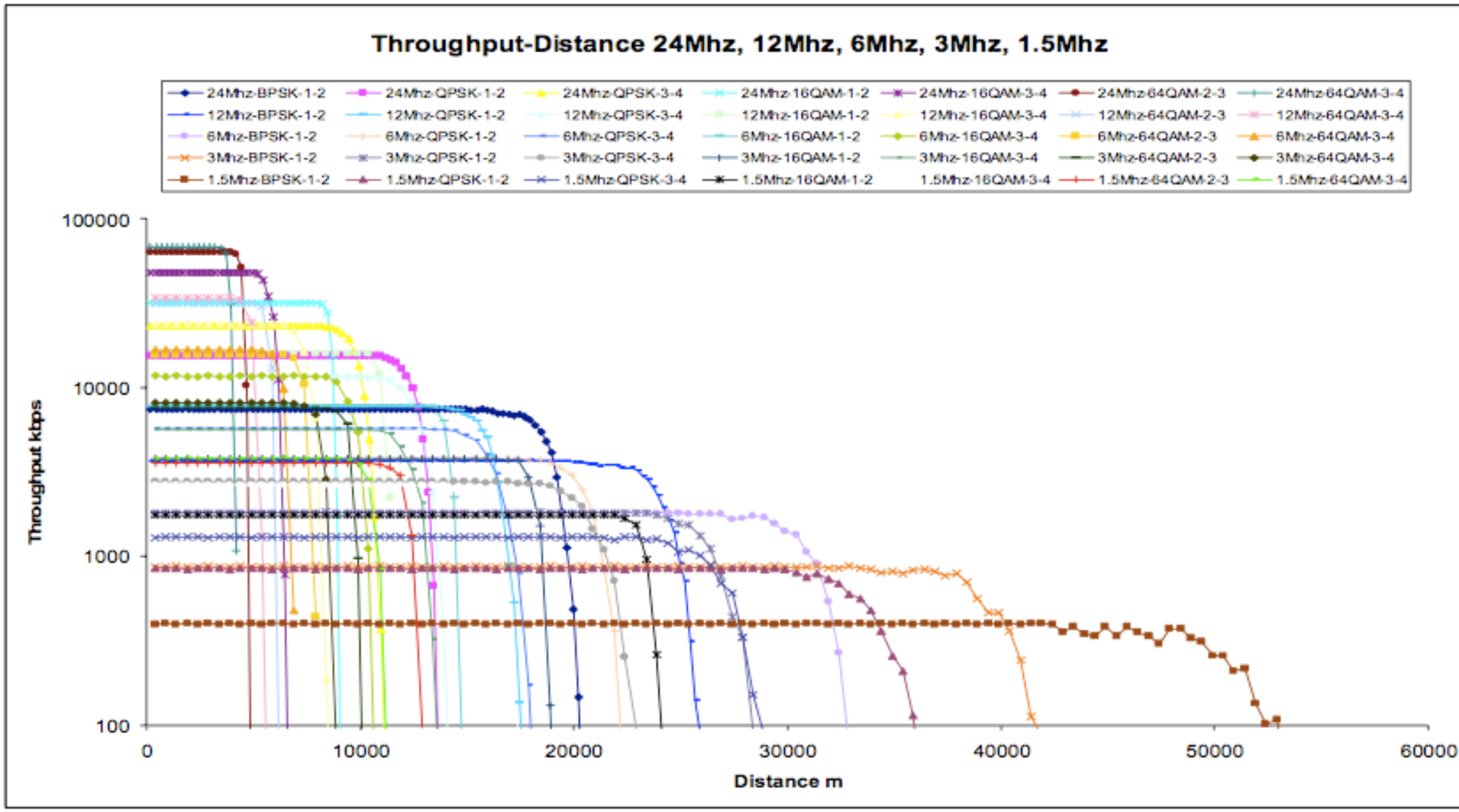
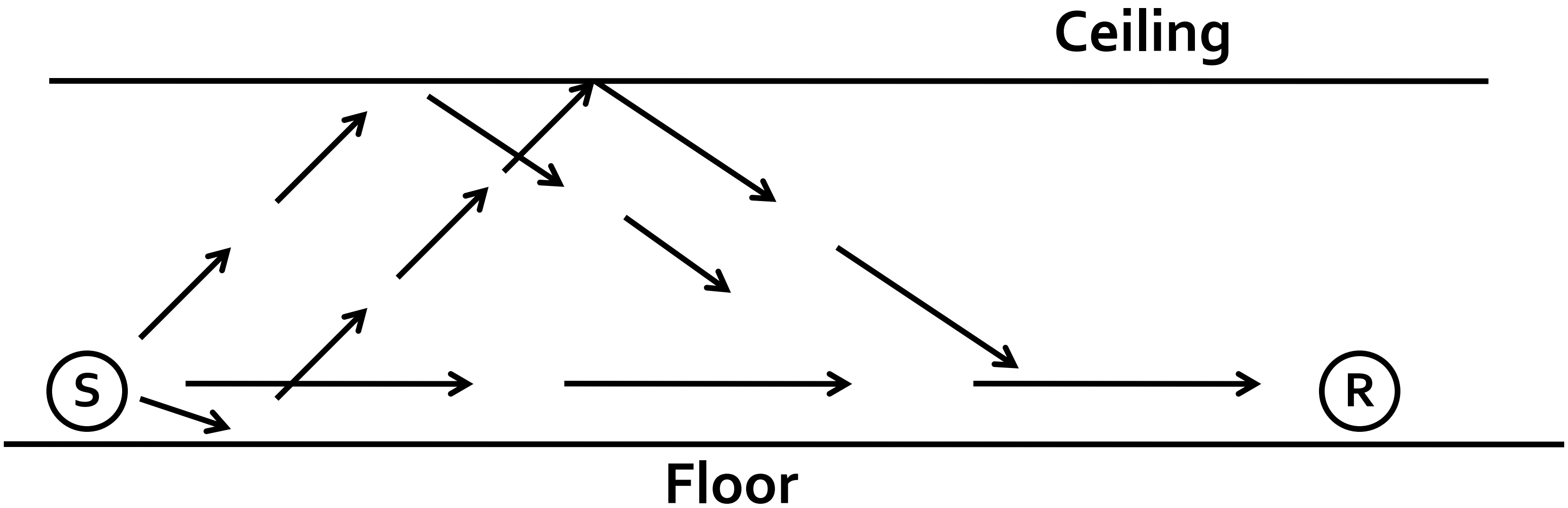


Fig. 6. Throughput-distance optimized lookup graph for IEEE 802.16e deployment.

http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04526126

Multipath Effects

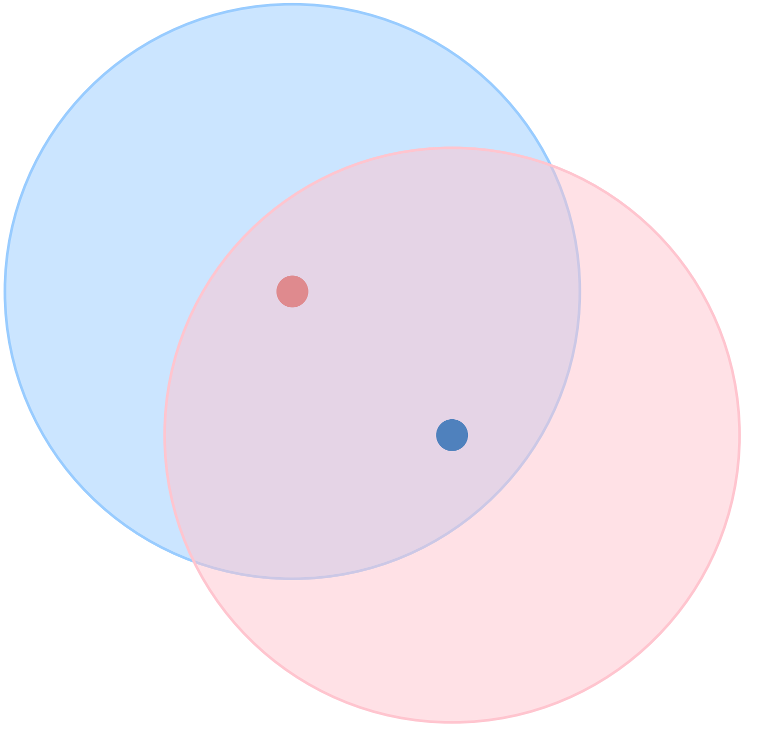


- Signal bounces off surface and interferes with itself
  - Constructively or destructively, depending on the respective path lengths

- A "self-interference" effect

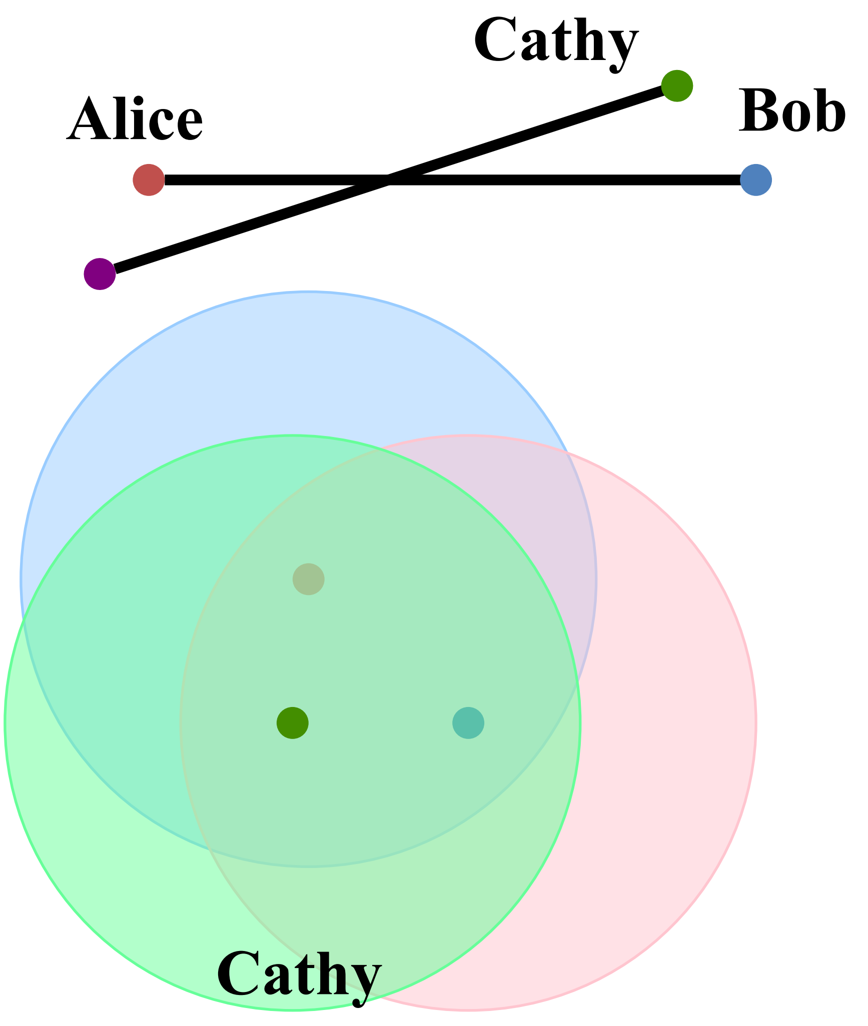
Wireless is a shared medium

- Transmitters broadcast
- Devices can operate either in transmit or receive mode
- How do you coordinate access to the medium?



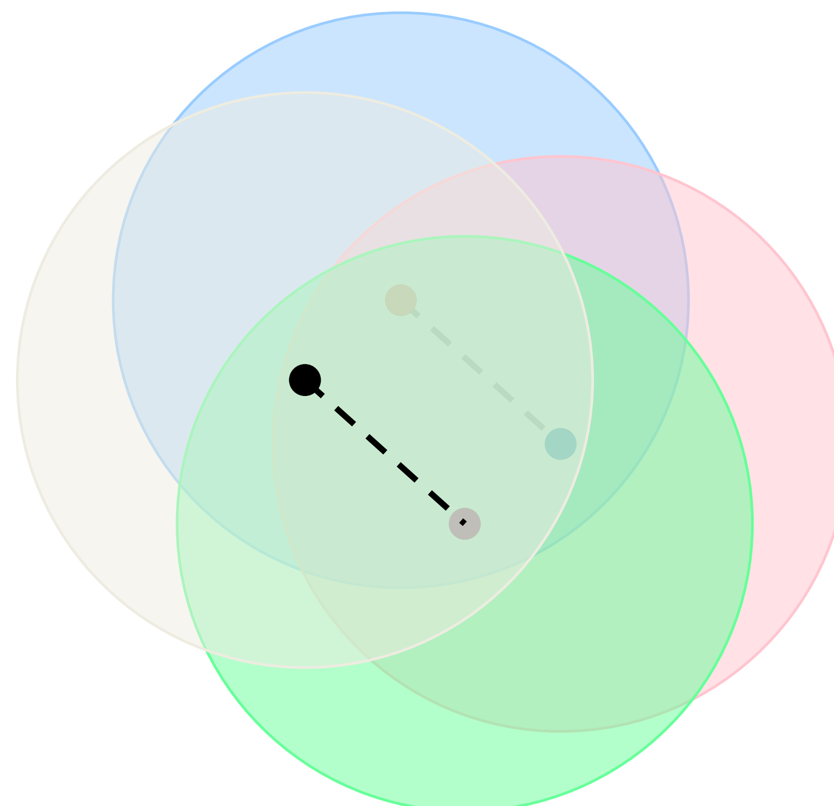
Interference

- **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



How might we boost a wireless network's capacity?

- Easy to do in wired networks: simply add wires
- But adding wireless "links" **increases** interference.
  - Frequency reuse can help … subject to spatial limitations
  - Or use different frequencies … subject to frequency limitations
- The capacity of a wireless network is fundamentally limited



Boosting capacity, second attempt

- In general, the lower the SINR the higher the BER
  - Higher BER → higher frame error rate → **lower capacity**

- So, we could make the signal stronger…
  - **Increase** the **S** part of SINR

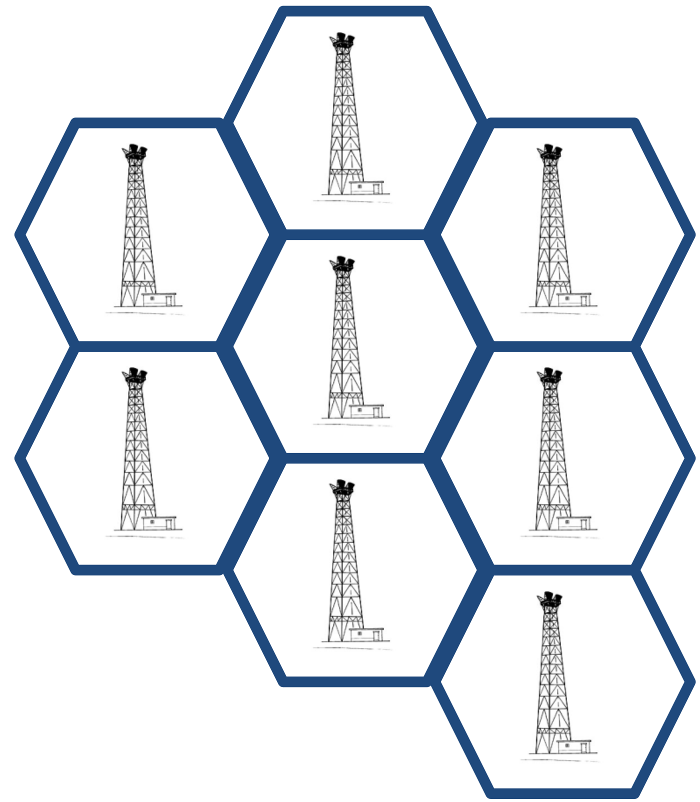
- Why is this not always a good idea?
  - Increased signal strength **requires more transmit power**

  - Increases the interference range of the sender, so **sender interferes with more nodes** around it
    - And then they increase their power…

Cellular architecture

- Deployment comprising cells – can reuse frequencies in different areas
  - Non-adjacent

- Challenge to provide consistent service even at the edge of the cell – be able to deal with intensity given the capacity of the cell

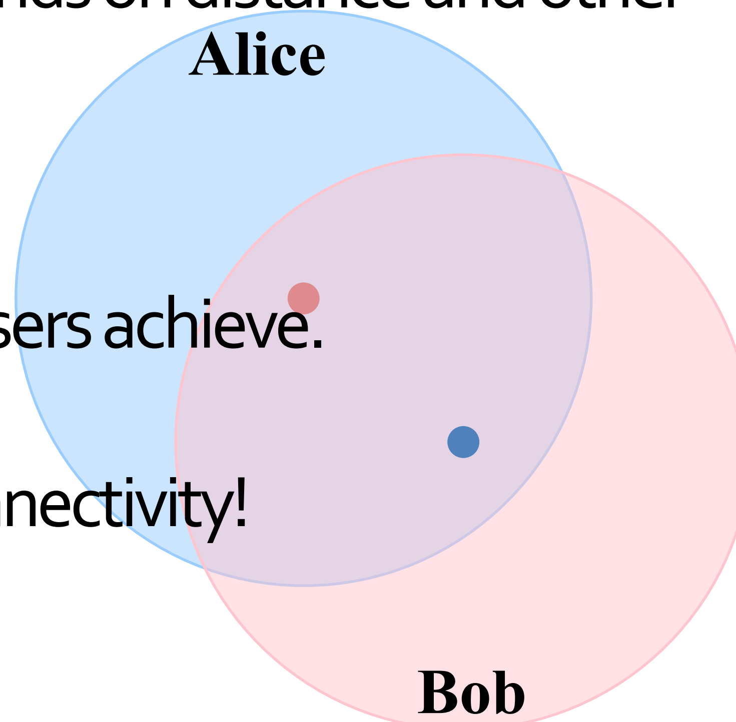


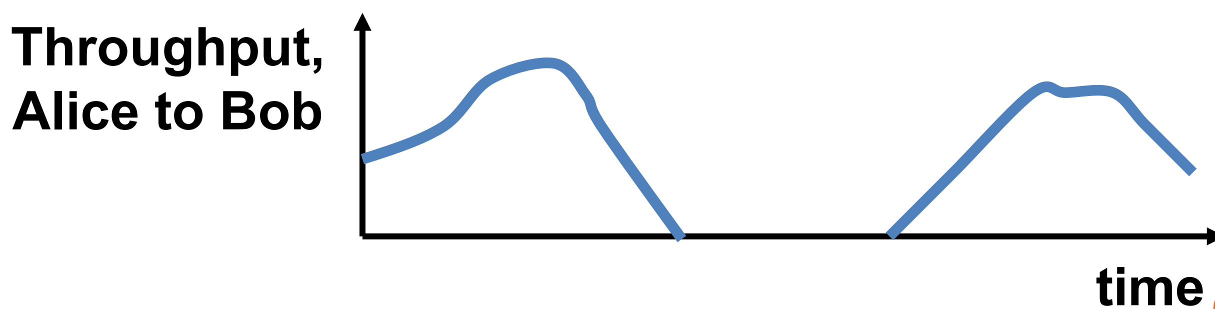
Wi-Fi architecture

- Could be chaotic or managed
- Limited spectrum – service guarantees hard to make
- Channel assignment, power control

Mobility affects link throughput

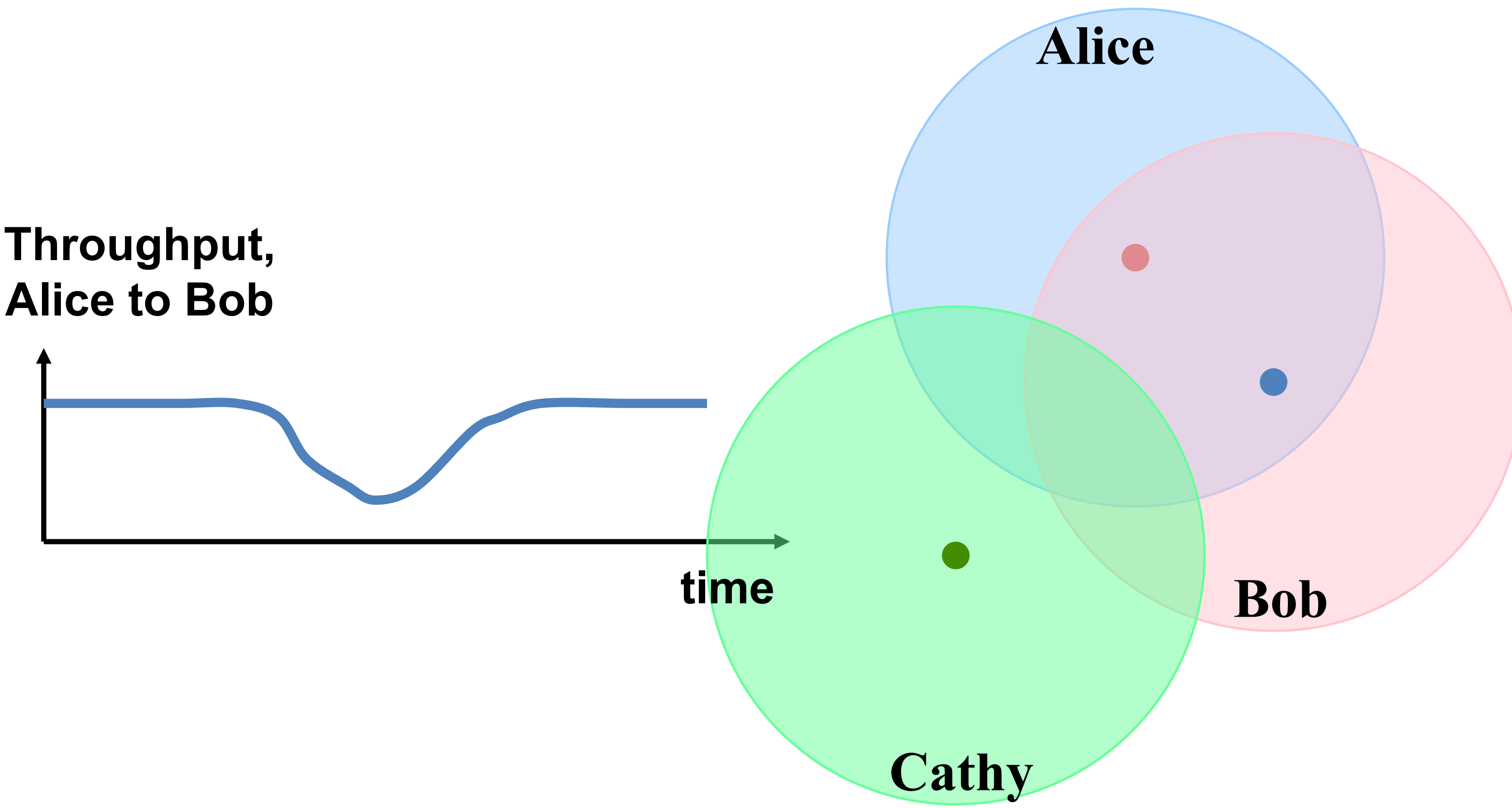
- Quality of the transmission depends on distance and other factors
  - Covered later in the course
- Affects the throughput mobile users achieve.
- Worst case is periods with no connectivity!





Mobility matters, even for stationary users

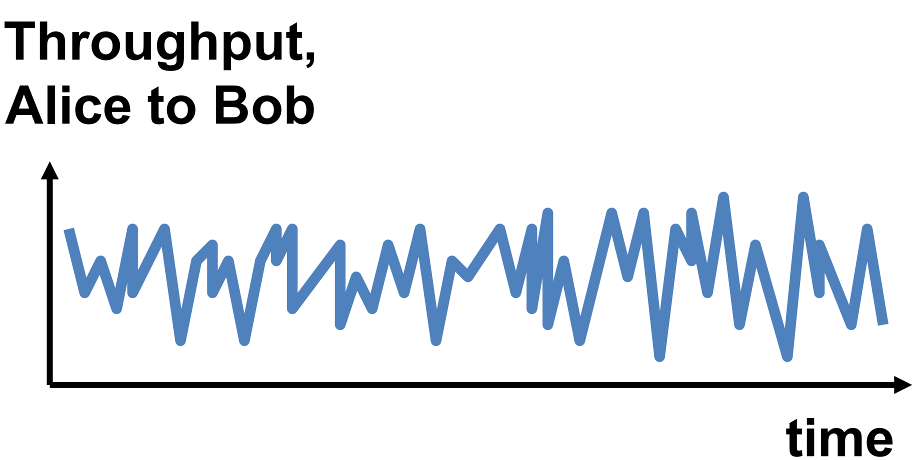
- Mobile people and devices affect the transmission channel of stationary nodes.

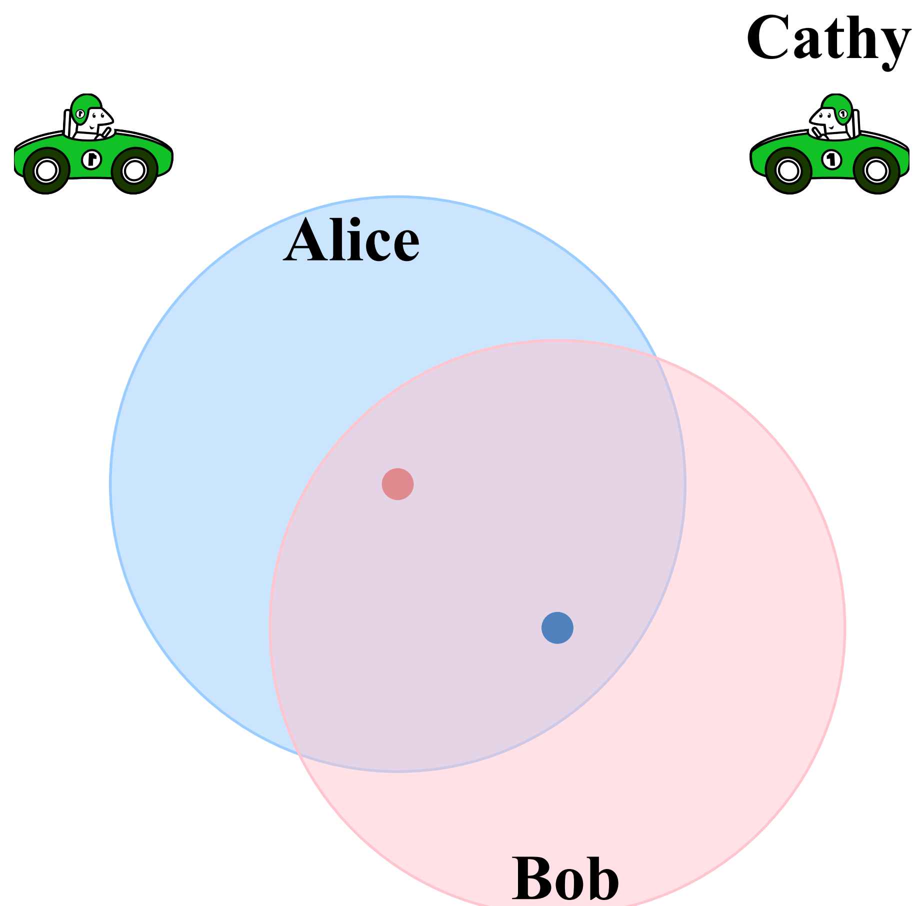


And it gets worse…

- The impact of mobility on transmission can be complex
  - Multi-path effects – much more on this later

- Mobility also affects addressing and routing





Diagnosis of wireless bit errors

- Bit errors can be due to:
  - Signal errors that lead to a packet that cannot be decoded, or
  - Corruption of the transmitted information due to collisions, SINR too low

- Understanding the reason behind a loss requires cross-layer information
  - Is it PHY, or MAC-related?
  - Need to look across more than one layer to diagnose

Today

1. Logistics and administrivia

2. Course outline: Whirlwind tour, and a bit more about the course project

3. ***Why is wireless interesting, and intellectually challenging?***
   – Fundamental limits open
   – (Most) wireless is a shared medium
   – **Evaluation challenges**

Evaluation: Challenges and Tradeoffs

- Wireless testbeds are hard to manage
  - Interference, production networks, control node movement, ..
- Wireless network research has largely been simulation based
  - Questionable accuracy
  - Difficult to evaluate real hardware and applications

- Emulation provides an attractive middle ground between simulation and testbeds

Why these Differences?

Networking Stack

MAC
Firmware
PHY

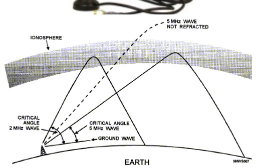


Figure 1-7.—Effect of frequency on the critical angle.

	Reality	Simulation	Physical Emulation
Applications	✓	✗	✓
OS	✓	✗	✓
Networking Stack	✓	~	✓
Host Device	✓	✗	✓
Wireless Device (MAC)	✓	~	✓
Wireless Device (Firmware)	✓	✗	✓
Wireless Device (PHY)	✓	✗	✓
Antenna	✓	✗	✗
Signal Propagation	✓	✗	✗

Gives Control

A Very Naïve Model

- A radio's transmission area is **circular**
- All radios have **equal range**
- If I can hear you, you can hear me (symmetry)
- If I can hear you at all, I can hear you perfectly
- Signal strength is a simple function of distance
- The world is flat

- Sometimes alright, when explaining concepts, but **not for serious work (or learning)**

Some Improvements

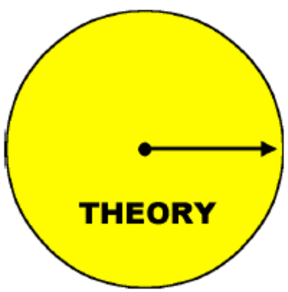
- Two ray ground model
  - Still very simple – too static and regular

- Models that include a "grey" region
  - Packet delivery rate still depends on distance
  - But model includes a region where PDR is probabilistic
  - Possible to "fit" to different environments

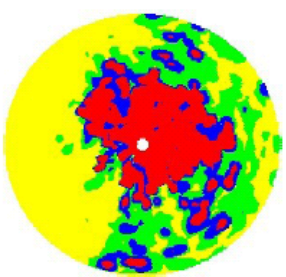
- Modeling of interference
  - Very relevant for both PHY and MAC layer effects
  - Advanced models also model fading, impact of transmit rate, terrain factors, etc.

Simulation v. Reality: Experimental examples

- Proofs used for criticism:



Typical theoretical model



Source: Comgate Engineering
http://www.comgate.com/ntdsign/wireless.html

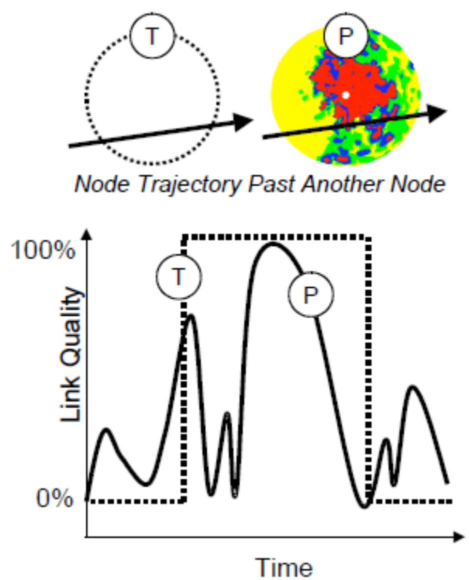


Figure 3: Difference between theory (T) and practice (P).

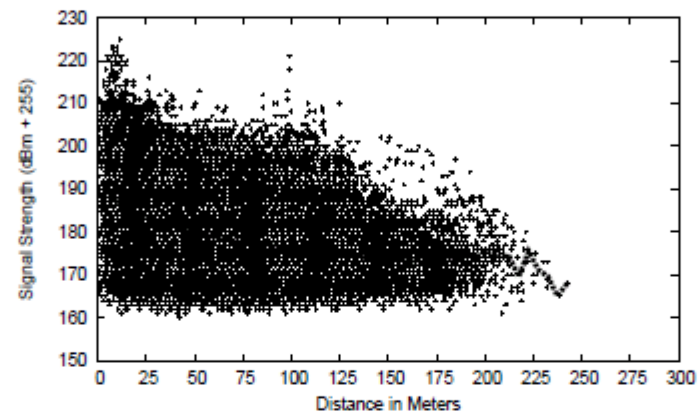


Figure 12: A scatter plot demonstrating the poor correlation between signal strength and distance. We restrict the plot to beacons both sent and received on the western half of the field, and show the mean signal strength as a heavy dotted line.

Simulation Accuracy

- Several papers show major differences between wireless experiments in simulation vs. in the real world
  - *Experimental evaluation of wireless simulation assumptions.* David Kotz, Calvin Newport, Robert S. Gray, Jason Liu, Yougu Yuan, and Chip Elliott. Technical Report TR2004-507, Dept. of Computer Science, Dartmouth College, June 2004
- Shows that **standalone simulations are not enough**
  - OPNET, NS-2, GloMoSim
  - NS-3 is already much more realistic
- Hybrid approach of simulation and real testbed is more appropriate: ***trace-driven simulation***

Testbeds

- **Fully realistic,** but:
  - **Hard to control** and repeat experiments
  - Representative for **just one particular location**

- A number of testbeds available over the Internet
  - **Emulab** in Utah
  - Indoor and outdoor Orbit at **Rutgers**

Topics for next time:

Medium Access Control

Your task:

Read papers, file HotCRP reviews