COS 563: Wireless Networks (G)

Lecture 1: Class Introduction
Kyle Jamieson
Wireless Networks Are Everywhere

- **Wireless Homes**
- **Wireless Biomedical Implants**
  - Deep Brain Neurostimulators
  - Gastric Stimulators
  - Foot Drop Implants
  - Cochlear Implants
  - Cardiac Defibrillators/Pacemakers
  - Insulin Pumps

- **Wireless Wearables**
  - Head-worn
  - Straps
  - Skirts
  - Wrist-worn
  - Clips
  - Shoe-worn/Foot pods

- **Wireless Sensors**
  - Head-worn
  - Straps
  - Skirts
  - Wrist-worn
  - Clips
  - Shoe-worn/Foot pods

- **Cellular Networks**
- **UAVs**
- **Wireless Data Centers**
- **Wireless VR**
- **Wireless Vehicles**
Increasing Demand for Wireless Connectivity

![Chart showing increasing demand for wireless connectivity](chart.png)

**2020**
- 4 BILLION Connected People
- $4 TRILLION Revenue Opportunity
- 25+ MILLION Apps
- 25+ BILLION Embedded and Intelligent Systems
- 50 TRILLION GBs of Data

Source: Mario Morales, IDC

**The Internet of Things**

An Explosion of connected possibility

![Chart showing growth of the Internet of Things](iot_chart.png)

- 1992: 1,000,000 Devices
- 2003: 0.5 BILLION Devices
- 2009: IoT INCEPTION
- 2012: 11.2 BILLION Devices
- 2015: 18.2 BILLION Devices
- 2016: 22.9 BILLION Devices
- 2018: 34.8 BILLION Devices
- 2019: 42.1 BILLION Devices
- 2020: 50.1 BILLION Devices
Increasing Demand for Wireless Connectivity

Connecting People
Increasing Demand for Wireless Connectivity

Connecting Everything
Increasing Demand for Wireless Connectivity

Connecting + Sensing Everything

6G to unify the experience across physical, digital and biological worlds
Course Information

• Staff
  – Instructors: Kyle Jamieson, Yaxiong Xie
  – Office hours: Tuesday after class

• Material
  – Mainly research papers
  – Lecture Slides
  – **Perusal** for discussions & questions

• Recommended Prerequisites
  – Any undergraduate networking, wireless, or digital communications class
  – Basic math and signal processing: probability, Fourier, ...
  – Programming maturity (important for the project)
Class Participation

• Papers will be discussed in a very involved manner. All students are expected to have thoroughly read and considered each assigned paper, and to be prepared to pose and answer questions about each reading.

• **Preparing for class.** Please prepare at least five comments or questions for each paper and post those comments or questions on Perusall

• Class participation grade will be determined based on attendance and, most importantly, your concrete contributions to the paper discussion both on Perusall and in class
Term Project

• Open-ended systems research project
  – topics reached after discussion with the class instructor
  – Projects should be done in groups of one or two
  – All software code/firmware, hardware designs, etc shared privately with instructor

• All group students expected to share equally in implementation
  – At end of semester, each student working in a group asked to describe contributions of teammate
Grading

• Class participation: 30%

• Precept lead: 20%
  – Organize discussion, may answer questions
  – Submit a 500-1000-word report that summarizes both discussion and paper

• Project: 50%, comprised of:
  – Checkpoint #1 - project proposal - 10%
  – Checkpoint #2 - preliminary demo - 10%
  – Checkpoint #3 - project presentation - 10%
  – Checkpoint #4 - final report (5 pages + biblio) - 20%
Overview

COS 563 is a graduate-level class that explores recent developments in wireless networks and sensing systems. Topics include an overview of general wireless network architecture, including the abstraction of underlying and overlaying hardware and layers in the networking stack, integration with overlaying applications, and concurrency, performance, and resource allocation in wireless networks. Further topics include millimeter-wave communication, multi-hop networks, underwater and water-air communications, low power backscatter and long range networks, Wi-Fi based localization, and wireless radar and sensing.

The course will include two precept based discussion meetings per week, in which students will read and discuss papers on the foregoing topics, and a semester-long project.

Class Participation

Papers will be discussed in a very involved manner. All students are expected to have thoroughly read and considered each assigned paper, and to be prepared to pose and answer questions about each reading.

Preparing for class. Please prepare at least five comments or questions for each paper and post those comments or questions on Perusall one day prior to class. General instructions on how to read and review a paper can be found here.

Your class participation grade will be determined based on attendance and, most importantly, your concrete contributions to the paper discussion both on Perusall and in class. During the period discussion in class, we will divide the students into groups and select one student in each group as the paper discussion leader (leaders will be selected in a round-robin manner). The leader should organize the discussion and may answer questions from the group members. The leader is also required to submit a 500 to 1000-word report that summarizes both the discussion and the paper. The deadline for report submission is 48 hours after the class.

Note: Class attendance is required. With that being said, we understand that students sometimes can be in unexpected situations. Do let the instructors know if you have to miss a class, and we can make arrangements to accommodate the absence.
# COS 563 Wireless Networks: Syllabus

## Textbooks

The following optional texts are for your reference:

- Fundamentals of Wireless Communication (T & Y), by David Tse and Pramod Viswanath (available online).

## Schedule

Also available as an [ical file](#) that you can subscribe to. This schedule is preliminary and subject to change.

<table>
<thead>
<tr>
<th>Date</th>
<th>Topics</th>
<th>Readings</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Tue 02/02</td>
<td>Class Introduction; How to Read a Paper</td>
<td>Pre-Reading: HowToRead</td>
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<tr>
<td>Thu 02/04</td>
<td>Stochastic Forecasts for Wireless Cellular Networks</td>
<td>Pre-Reading: Stroustrup</td>
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<tr>
<td>Tue 02/09</td>
<td>Transport Protocol Design using Machine Learning</td>
<td>Pre-Reading: Remy</td>
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<tr>
<td>Thu 02/11</td>
<td>Introduction to 5G Cellular Networks</td>
<td>Pre-Reading: 5G overview</td>
<td>Student lead: AKS</td>
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<tr>
<td>Tue 02/16</td>
<td>Understanding Operational 5G Networks</td>
<td>Pre-Reading: 5GMeasure</td>
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<tr>
<td>Thu 02/18</td>
<td>Fine-grained PHY-layer Information for Congestion Control</td>
<td>Pre-Reading: PBHoCC</td>
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**Part 1: Wireless from the Transport Layer Downwards**

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<th>Date</th>
<th>Topics</th>
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<th>Notes</th>
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<tbody>
<tr>
<td>Tue 02/23</td>
<td>Packet Radio Medium Access Control</td>
<td>Pre-Reading: Maca</td>
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<tr>
<td>Thu 02/25</td>
<td>Medium Access in Wireless Local Area Networks</td>
<td>Pre-Reading: Masnaw</td>
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<tr>
<td>Mon 03/01</td>
<td>Medium Access in Wireless Local Area Networks</td>
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<tr>
<td>Tue 03/02</td>
<td>Mesh Networking</td>
<td>Pre-Reading: Roofnet85</td>
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**Part 2: Multi-hop and Mesh Wireless Networks**

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<tr>
<td>Thu 03/04</td>
<td>Bit Rate Adaptation in 802.11</td>
<td>Pre-Reading: RBAAP</td>
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<tr>
<td>Tue 03/09</td>
<td>Rateless Codes</td>
<td>Pre-Reading: Spinal</td>
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**Part 3: Bit Rate Adaptation and Rateless Codes**

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<th>Notes</th>
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<tbody>
<tr>
<td>Thu 03/04</td>
<td>Communication via Physical Vibrations</td>
<td>Pre-Reading: Ripple2</td>
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<tr>
<td>Tue 03/09</td>
<td>Visible Light Communication</td>
<td>Pre-Reading: DarkLight</td>
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<tr>
<td>Thu 03/11</td>
<td>No class</td>
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<tr>
<td>Tue 03/16</td>
<td>Spring recess week</td>
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<tr>
<td>Wed 03/17</td>
<td>Project proposal due</td>
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Sample Topics in this Class

- Network Coding
- Cross Layer Networking
- 5G Millimeter Wave
- Full Duplex
- Programmable surfaces
- Localization: Smart homes
- Human Sensing & Imaging
- Self Driving Cars
- Medical Implants
- Food Sensing
Introduction to Wireless Networks

Wireless networks provide advantages

• Mobility

• Eliminates piles of wires at home and office

But wireless networks present different challenges

• Medium is shared $\rightarrow$ Interference

• Medium is shared $\rightarrow$ Throughput $\downarrow$ as Devices $\uparrow$

• Channel can bad & unstable $\rightarrow$ Losses + Dead Spots
Traditional Design of Wireless Networks

Traditional design of wireless networks mimics wired networks
- Assumes links are *point-to-point*
- But wireless links have a *broadcast* nature
Why point-to-point is a suboptimal abstraction for wireless links?
Scenario: Alice and Bob want to exchange two packets; their radio range doesn’t allow them to reach each other → they need a router to relay the packets between them.
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**Traditional Approach**

![Diagram showing the traditional approach where Alice and Bob use a router to exchange packets.]

**Requires 4 transmissions**
- Alice to router; Router to Bob; Bob to router; Router to Alice

But wireless links are *broadcast* not *point-to-point*!
- Can we exploit broadcast to do better?
**Scenario:** Alice and Bob want to exchange two packets; their radio range doesn’t allow them to reach each other → they need a router to relay the packets between them.

**Approach: Network Coding**

- Requires 3 transmissions instead of 4
  - Alice to router; Bob to router; and router to both Alice and Bob

Harnessing the broadcast nature of wireless via network coding increases throughout.
Traditional Approach
Optimize within isolated layers

- Network & Apps
- Comms. and Coding
- HW and Radios

Disruptive gains are unlikely

New Approach
Optimize across the layers

- Network and Apps
- Comms. and Coding
- HW and Radios

Cross-Layer Designs

Major opportunities!
Why is layer separation suboptimal in wireless networks?
Scenario: Laptop in a Dead Spot

With Layer Separation, a few bit errors → persistent loss.

But access points are unlikely to have the same bit error.
Solution: Cross-Layer Approach
- Allow the layers to collaborate instead of acting separately
- PHY layer delivers partially correct packets
- Network layer combines correct bits across different access points to obtain correct packet
Challenge

Which access point should we believe?

First bit is “0”

First bit is “1”
Solution: Network cooperates with physical layer

- Physical layer already estimates a confidence in its 0-1 decision
- If we expose this information to the network layer, we can compare bits in packets received at different APs

First bit is “0” with 0.6 confidence
- Assign to each bit the value that corresponds to a higher confidence

First bit is “1” with 0.9 confidence
Experiment: Packet Delivery vs. Poor Coverage

Fraction of Packets Delivered

Average Bit Errors

Cross-layer Approach

Layer separation
High Data Rate Applications

- 5G Wireless Backhaul & Access
- Virtual Reality
- Connected Vehicles
- mmWave Mesh Networks
- Robotic Networks
- Wireless Data Centers
VR requires a cable connection to a PC

Significantly limits mobility & experience
Millimeter Wave Technology

Huge bandwidth available at millimeter wave frequencies

Millimeter Wave Bands

Currently we operate here

Millimeter Wave can support data rates of multi-Gbps
Small Wavelength enables thousands of antennas to be packed into small space ➔ Extremely narrow beams
Today's Networks: Broadcast
mmWave changes how wireless systems operate

mmWave: Narrow-beam Antennas
Need to quickly find the right beam alignment and track the user.

Suffers in case of:
- Mobility
- Blockage
- Multi-users
mmWave changes how wireless systems operate

mmWave: Narrow-beam Antennas
mmWave changes how wireless systems operate

mmWave: Narrow-beam Antennas
Today’s Radios Are Half Duplex

Self Interference is hundred billion times 110dB+ stronger than the received signal!

But we know the signal which we are transmitting!
→ Cancel the self-interference on the hardware
→ 1.97x increase in throughput

Full Duplex Radios: Major change in communication protocols
Today: Wireless Communication Adapt to Channel Conditions

• Wireless Channel changes quickly and is unpredictable.

• If Channel is Bad
  → Reduce data Rate, more coding

• If Channel is Good
  → Increase data rate, less coding
Today: Wireless Communication Adapt to Channel Conditions

New Approach: Programmable Radio Surfaces
Change the wireless channel itself

AP side
LAIA control board
Access point
Arduino board
USB cable

Client side
Client
Antennas

Princeton IoT house

- 36 LAIA elements implemented in Princeton IoT house
- 4-bit phase shifters (16 phase shifts)
How to Read a Paper

S. Keshav
Next class meeting: Sprout