ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 1: Introduction to Wireless Research
Haitham Hassanieh
Wireless Networks Are Everywhere
Increasing Demand for Wireless Connectivity

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

Traffic Relative to 2009

Billions of devices

Year

1990 1,000,000
2003 0.5 BILLION
2009 IoT INCEPTION
2012 8.7 BILLION
2013 11.2 BILLION
2015 18.2 BILLION
2016 22.9 BILLION
2017 28.4 BILLION
2018 34.8 BILLION
2019 42.1 BILLION
2020 50.1 BILLION

Cisco
Coda
Yankee Group
Average
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

- Ubiquitous Compute
- Human Machine Interface
- Knowledge systems
- Precision Sensing & Actuation

2020

Physical World

Real time

Biological World

Real time

Digital World

Real time
The past, present, and future

2G
Voice
Each new generation is about optimizing the new use case of the previous generation to reduce cost and introduction of new use cases.

The past, present, and future.
The past, present, and future

- **2G**
  - Voice

- **3G**
  - Broadband Data
  - Low cost Voice & Voice capacity

- **4G**
  - MTC, Higher data rates
  - Low cost data & data capacity
  - Zero cost voice

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The past, present, and future

- **2G**
  - Voice
  - Low cost Voice & Voice capacity

- **3G**
  - Broadband Data

- **4G**
  - MTC, Higher data rates
  - Low cost data & data capacity
  - Zero cost voice

- **5G**
  - Industrial IoT, Higher data rates
  - Zero cost data & zero cost voice
  - MTC Optimized?
Each new generation is about optimizing the new use case of the previous generation to reduce cost and introduction of new use cases.
ECE 598HH

Wireless Networks

5G & Next Generation
- Millimeter Wave Networks
- Massive MIMO
- Full Duplex Radios
- Dynamic Spectrum Access
- Programmable Surfaces

Internet of Things
- LoRa Networks
- Backscatter Networks
- Smart Cities & Homes
- Acoustic IoT
- IoT security

Wireless Localization
- WiFi Localization
- Battery Free Localization
- Antenna Arrays
- Time of Flight
- Tracking

Emerging Areas
- Self-driving Cars
- Medical Micro-Implants
- Robotics & Drones
- Underwater Networks
- Noise Cancellation

Cross Layer Wireless
- Rateless Code & Soft PHY
- Interference Alignment
- Virtual MIMO
- Opportunistic Routing
- Network Coding

Wireless Imaging
- Radar Imaging
- Self Driving Cars
- Through wall Imaging
- Human Imaging
- 3D Mesh Recovery

Wireless Sensing
- Gesture Sensing
- Vital Sign Monitoring
- Behavioral Sensing
- Human Sensing
- Food Sensing
Course Information

• **Staff**
  – Instructor: Haitham Hassaninieh, [haitham@illinois.edu](mailto:haitham@illinois.edu)
  – Office hours: Tuesday after class

• **Material**
  – Mainly research papers
  – Lecture Slides
  – Piazza for discussions & questions
  – Gradescope for submitting reviews & assignments

• **Prerequisites**
  – Any undergraduate networking, wireless, communications or RF class
  – Basic math and signal processing: probability, Fourier, ...
  – Matlab or C programming (Important for the project).
Course Information

• **Grading**
  
  – **40% Research Project**: Proposal, Progress, Final report, Presentation
    • Research project: propose and try new ideas.
    • Negative results are OK
    • Project can/should be related to your research but not exactly your research.
    • Due to COVID, we allow writing a Survey paper as the project.
    • In Groups of 2-3

  – **20% Paper reviews**: Review 20 out of 24 assigned papers.
    • Read the assigned paper before each class and write short review
    • Review includes: Short summary (5 lines), 3 points describing paper strength, 3 points describing paper weakness, and future directions for the project.
    • Individual, not in groups.
    • Due before class on Gradescope.

  – **40% Lab Assignments**: 4 Labs
    • Due to COVID, we will run the experiments and collect the data.
    • You write code (mostly in MATLAB) to process data and answer questions.
    • In Groups of 2-3
**Course Description:**

Wireless and mobile systems have become ubiquitous, playing a significant role in our everyday life. However, the increasing demand for wireless connectivity and the emergence of new areas such as the Internet of Things present new research challenges. This course introduces advanced research topics in wireless networks and mobile communication systems. In each lecture, we will discuss recent research papers that introduce new wireless design algorithms, protocols, and applications. The papers are systems-oriented and focus on practical challenges and solutions for building wireless and mobile systems. However, the course will also introduce fundamental wireless principles. The topics covered in this semester are shown in the figure above. Students will also learn how to design and build wireless systems through a research-oriented course project that focuses on the implementation aspects of practical systems.

The course will be taught online through Zoom. Students are expected to attend the live lectures and ask questions. However, in case of a conflict with another class, all lectures will be recorded and made available to students.

**Lecture Time & Location:** Tuesday & Thursday 11:00 am - 12:20 pm on Zoom.

**Instructor:** Haitham Hassanieh (haitham@illinois.edu)

**Office Hours:** Tuesday 12:20 pm - 1:00 pm on Zoom.

**Zoom:** Zoom links will be posted to Piazza.

**Piazza:** https://piazza.com/illinois/fall2020/course/598hh


**Grading:**

- **20% Paper Reviews:** Students will be asked to review 20 out of 24 assigned research papers throughout the semester. The review will consist of a summary of the paper (at most 5 sentences), 3 points of strengths of the paper, 3 points of weaknesses, and possible future directions for the research. All reviews are due on Gradescope before the week before the lecture. All assigned papers can be found on the course schedule. Students are encouraged to read additional papers as well.

- **40% Lab Assignments:** There will be 4 lab assignments using SDRs and Matlab. Ideally, the students will go to the lab and learn how to use USRP SDRs, RFID readers, and Radars. However, due to COVID-19, it is likely this year that we will collect the data for the students and ask the students to write the code to process the data. All submissions will be on Gradescope. For detailed lab release time and due dates refer to the course schedule.

- **40% Final Project:** Students will do a research-style project in groups of 2 or 3 where they demonstrate the feasibility of a new research idea, build a new wireless system, or write a survey paper. For more details refer to Course Project.

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**Course Schedule & Materials**

**Course Project**

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 → Interference
- Medium is shared → Throughput ↓ as Devices ↑
- Channel can bad & unstable → 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 Alice, Router, and Bob with packets being broadcast]

**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

Major opportunities!

**Cross-Layer Designs**
Why is layer separation suboptimal in wireless networks?
Scenario: Laptop in a Dead Spot

With Layer Separation

a few bit errors $\rightarrow$ persistent loss

But access points are unlikely to have same bit error
**Scenario: Laptop in a Dead Spot**

- **010101011111**
- **011101011011**

**High-speed Ethernet**

**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
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

First bit is “1” with 0.9 confidence

Assign to each bit the value that corresponds to a higher confidence
Experiment: Packet Delivery vs. Poor Coverage

Fraction of Packets Delivered

Cross-layer Approach

Layer separation

Average Bit Errors
High Data Rate Applications

5G Wireless Backhaul & Access

Virtual Reality

Connected Vehicles

60 GHz WiGi 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

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

Millimeter Waves Suffer from Attenuation

mmWave radios use phased antenna arrays to focus the power along one direction

Nokia & National Instruments
UCSD 256 elements
UCSD 64 elements
Bell Labs 384 elements
Anokiwave 256 elements
IBM 64 elements
Fujitsu 64 elements
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
Collision

Carrier Sense does not work in directional networks
We cannot align the beams of each AP and client independent of other APs and clients in the network.
Can both Transmit at the same time
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

- 36 LAIA elements are implemented in Princeton IoT house
- 4-bit phase shifters (16 phase shifts)
New Services: Wireless Localization

GPS does not work indoor ➔ Use WiFi to localize.

Indoor Navigation

Business Analytics

WiFi Geofencing

Indoor Robotic Navigation
New Services: Wireless Localization

Localize Everything and Anything!

Battery-free stickers to tag any and every object
Charger left behind!

RFIDs on the Door Frame

Charger left behind!
How Do We Get Virtual Touch Screens?
How Do We Get Virtual Touch Screens?
How Do We Get Virtual Touch Screens?

4 cm wide

“Clear”  “Jue”
Can your cellphone give you X-ray vision?
See through-walls with WiFi
Wall reflection is 10,000x stronger than reflections coming from behind the wall.

Solution: Use two transmit antennas and one receive antenna; the two transmitted waves cancel each other for static objects but not animated objects.
WiVi behind wall over here

DC line (static objects)
Wireless Device behind wall

Video Courtesy of Fadel Adib
Video Courtesy of Fadel Adib
Baby Monitoring

Video Courtesy of Fadel Adib
Smart homes that monitor and adapt to our breathing and heart rates?

Personal Health

Baby Sleep

Elderly Health

Adapt Lighting and Music to Mood
Today: technologies for monitoring vital signs are cumbersome

Breath Monitoring

Heart Rate Monitoring

Wireless enables contactless sensing: sense humans without any sensors on their bodies
Sensing Emotions & Sleep Stages

RF signals reflect off body and change with physiological signals

New Model

Awake
REM
Light
Deep

Time

High Excitement

Anger

Joy

Negativity

Positivity

Sadness

Pleasure

Low Excitement
Imaging through occlusions using radio frequencies

RF sensor

Camera image

Output

Head
Left Arm
Chest
Right Arm
Lower Left Arm
Lower Right Arm
Feet
Challenge: Don’t get reflections from most points in RF

At frequencies that traverse walls, human body parts are specular (pure mirror)
Human Walks toward Sensor
Use Deep Learning to Enhance RF Imaging
Use Deep Learning to Enhance RF Imaging

AI Senses People Through Walls
Self-Driving Cars in Fog: LiDAR & Camera Fail
Millimeter Wave radar can function in adverse conditions

Fog  Sandstorm  Blizzard  Low Lighting Conditions

State of the Art: Automotive Radars only used for 1D/2D Ranging

Radar Imaging is Low Resolution & Suffers from Specularity & Artifacts
Leverage Deep Generative Adversarial Networks to Enhance Imaging Resolution.
Food and Liquid Sensing
Existing Solutions

Dipping Probe

Chemical Analysis

Expensive
Food Quality Monitoring
Water Contamination
Airport Security
In Body Networking & Sensing