MAS.S61:

Wireless & Mobile Sensing

Lecturer

Fadel Adib (fadel@mit.edu)

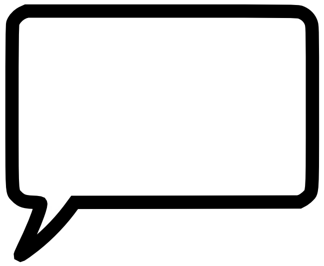
Website

https://www.mit.edu/~fadel/courses/MAS.wireless

Logistics & Norm Settings

- What to do now?
  1. Turn on your video (if your connection allows it)
  2. Mute your mic (unless you are the active speaker)
  3. Open the "Participant" List
     - Make sure your full name is shown

- If you have a question:
  - Use the chat feature to either write the question or to indicate your interest in asking the question
  - I will be monitoring the chat
  - Unmute -> ask question -> mute again
  - Once done asking/answering, please state "Done" to clearly mark it (helps translation/moderation)
  - Same procedure for answering questions



Let’s start with some trivia

1. How many “connected” (IoT) devices are there today?

2. What is the most widely deployed IoT/ connected device?

3. Which company was listed on NYSE as IOT? (And when was it founded?)

4. How was radar discovered?

5. Why is there growing interest in LEO satellites (e.g., SpaceX, Blue Origin)?

Where is wireless used today?
(Technologies, Applications)

IOT ANALYTICS

September 2024

Your Global IoT Market Research Partner

The top 10 IoT use cases

N=2,089 IoT projects

	Use case	Type	Global adoption[1] 2021	Global adoption[1] Q1 2024
1	Process automation	SO	33%	58%
2	Quality control and management	SO	30%	55%
3	Energy monitoring	SO	20%	55%
4	Real-time inventory management	SO	19%	54%
5	Supply chain track and trace	SSC	26%	54%
6	Operations planning and scheduling	SO	21%	53%
7	On-site facility track and trace	SSC	29%	50%
8	Asset performance optimization	SO	31%	48%
9	Remote asset monitoring	SO	34%	48%
10	Location tracking	CP	31%	45%

Outlook[2]

... of 27 use cases analyzed in total

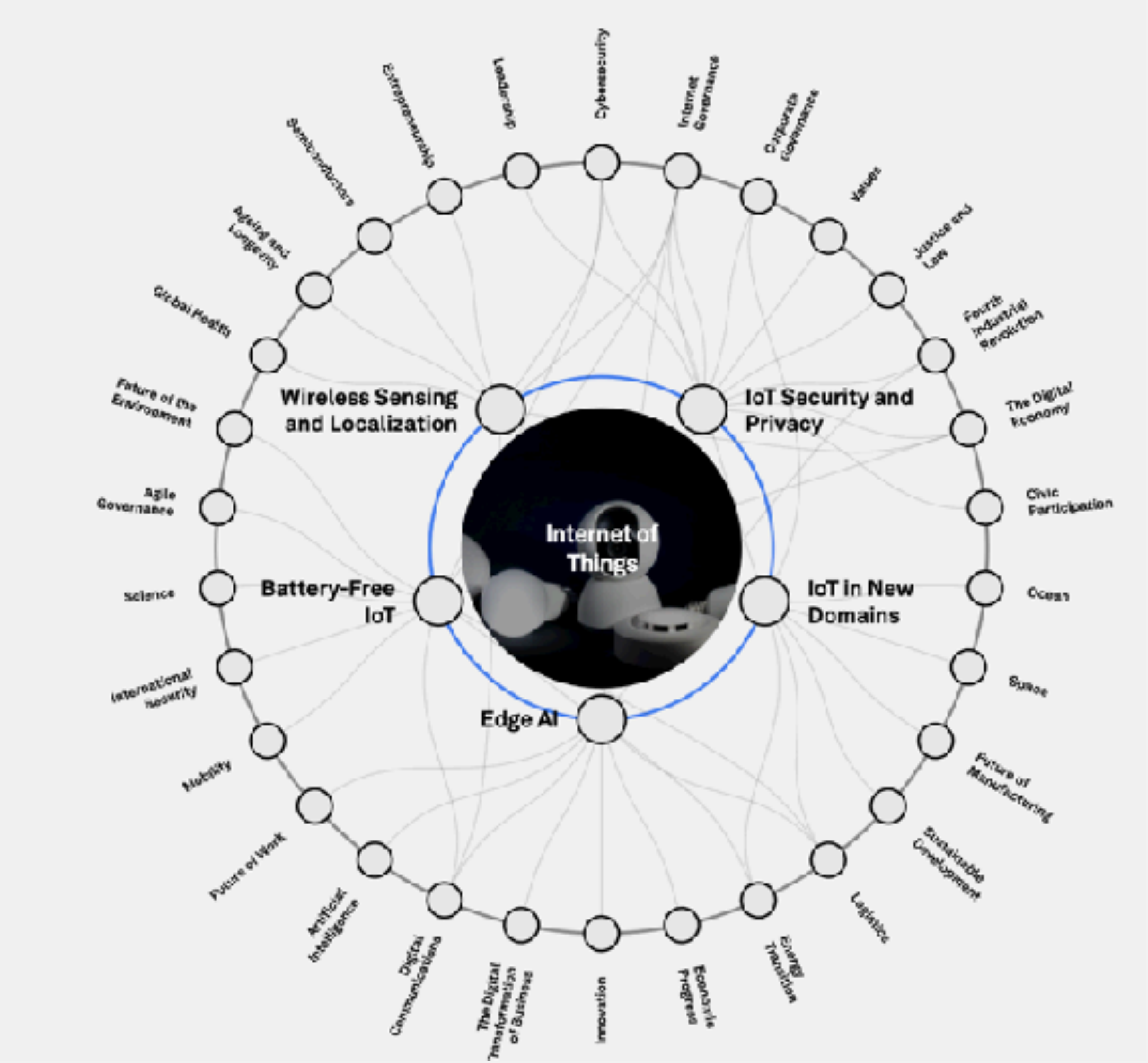
SO = Smart operations
SSC = Smart supply chain
CP = Connected products

2021
Q1/2024

Expected investment next 12 months: No meaningful change; +1% to +5%; >+5%

Note: [1]Share of organizations that are either currently rolling out or have fully rolled out each use case [2]Based on respondents' indication of expected spending changes for 2024 (compared to 2023). For more details about the methodology and definitions, refer to the corresponding blog that was published on the IoT Analytics website. **Source:** IoT Analytics Research 2024-IoT Use Case Adoption Report 2024. Conditions for republishing: Source citation with link to original post and company website.

WORLD ECONOMIC FORUM



https://intelligence.weforum.org/topics/a1Gb0000005LWrfEAG

Wireless & Mobile Sensing

sensing the physical world & transmitting data wirelessly

sensing via the wireless signals or mobile devices

This class will cover both of these

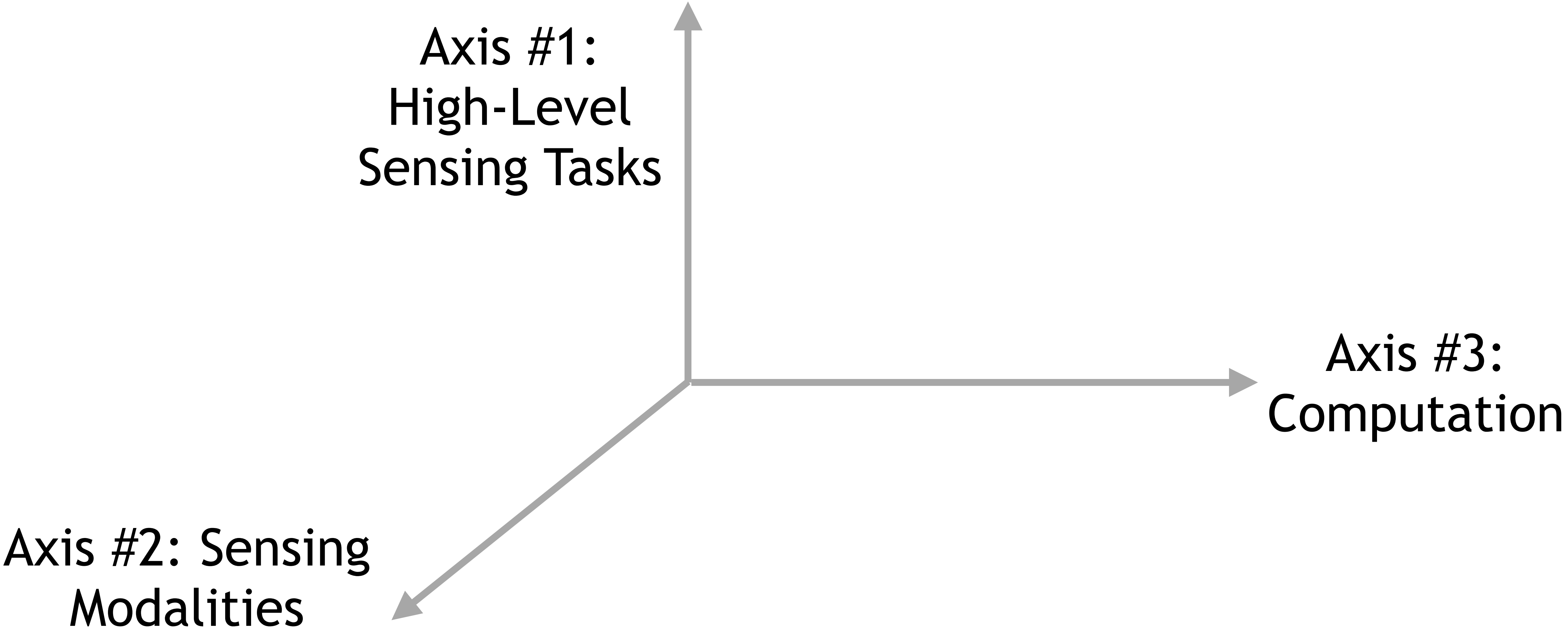
Fundamental primitives

- Signal propagation
- piezoelectricity
- energy harvesting
- ...

System design principles

- localization
- networking
- hybrid system architectures (ML + SP)
- ...

Wireless & Mobile Sensing Systems are designed along 3 axes



Axis #1: High-Level Sensing Tasks

WHAT do we want to sense?

(1) Location

- Outdoors, indoors
- Humans, objects

(2) Dynamics

- Velocity, Acceleration
- Activities, Monitoring

(3) Properties

- Identify, Characterize
- Environment, Humans

Axis #2: Sensing Modalities

HOW will we perform this sensing?

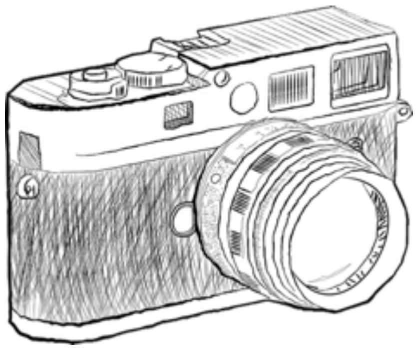
(1) Radio

- Wi-Fi
- Cellular
- Bluetooth

(2) Acoustic/ Ultrasonic

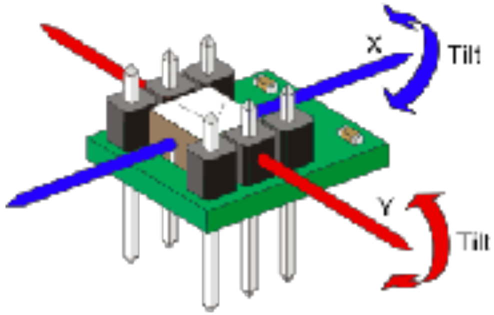
- Voices
- Engines
- Animals

(3) Visual



- Camera
- Infrared
- LIDAR

(4) Inertial



- Accelerometer
- Gyroscope
- Magnetometer

Axis #3: Computation

HOW can we use the sensing modalities to achieve the sensing task?

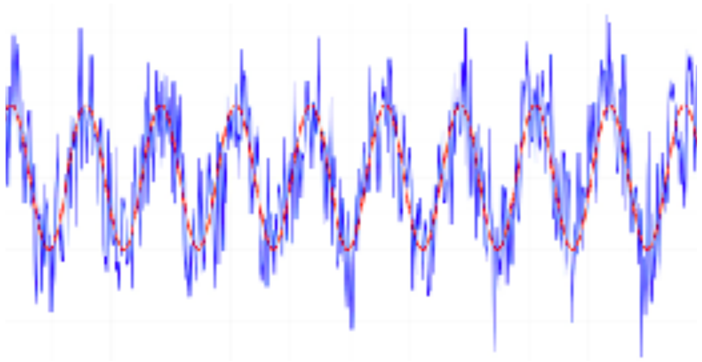
(1) Networking

- Connectivity
- Communication

(2) Data Management

- Storage
- Queries

(3) Signal Processing & Inference



- Digitization
- Inference & Machine Learning

(4) Security

- Digital, Analog
- Trust, Privacy

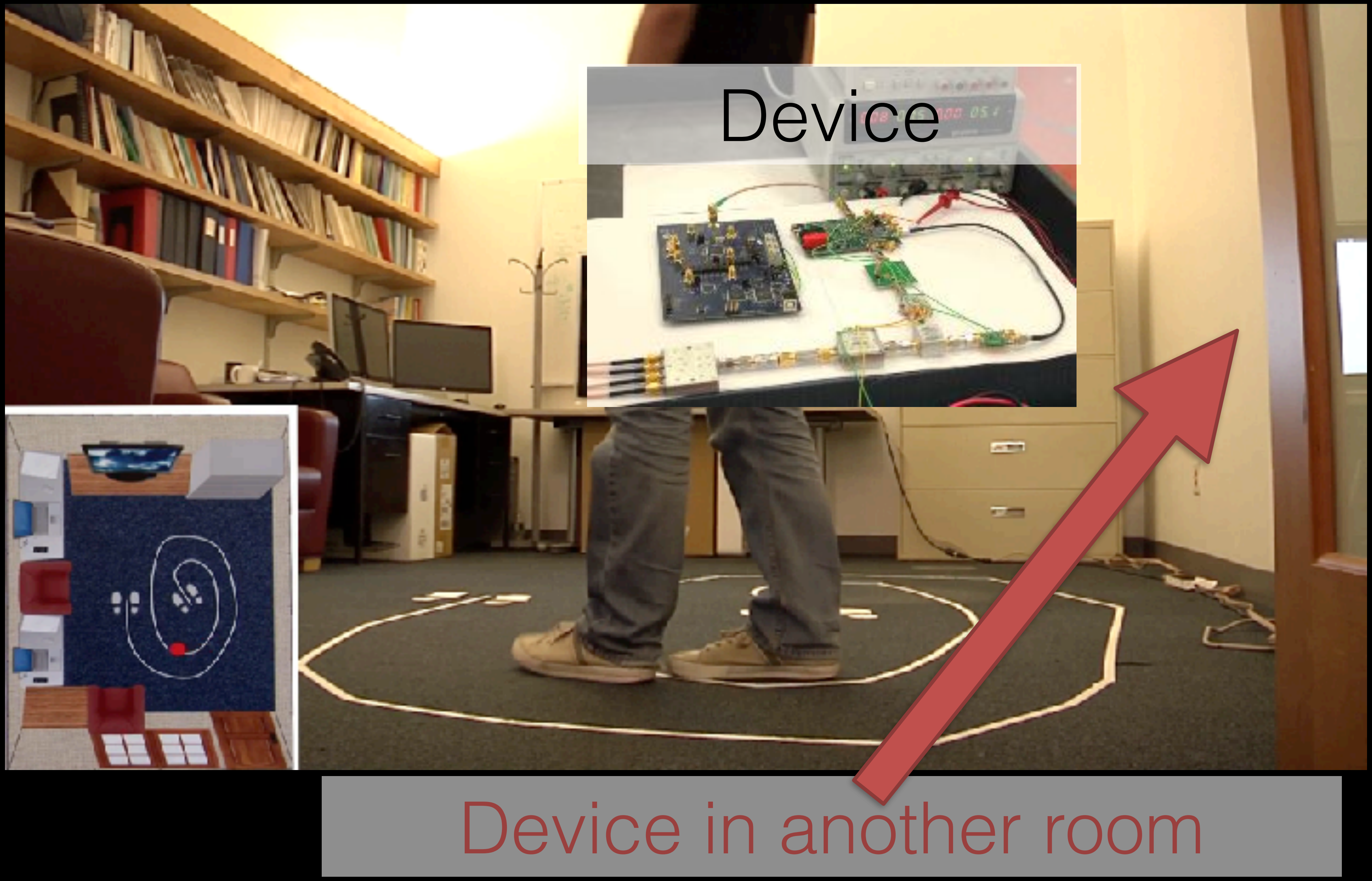
Wireless Sensing System Architecture

Axis #1: Sensing Tasks	(1) Location	(2) Dynamics	(3) Properties	
Axis #3: Computation	(1) Networking	(2) Data Management	(3) Signal Processing & Inference	(4) Security
Axis #2: Sensing Modalities	(1) Radio	(2) Acoustic/ Ultrasonic	(3) Visual	(4) Inertial

Will cover 9 topics.
One topic/lecture

1. Localization & Sensing

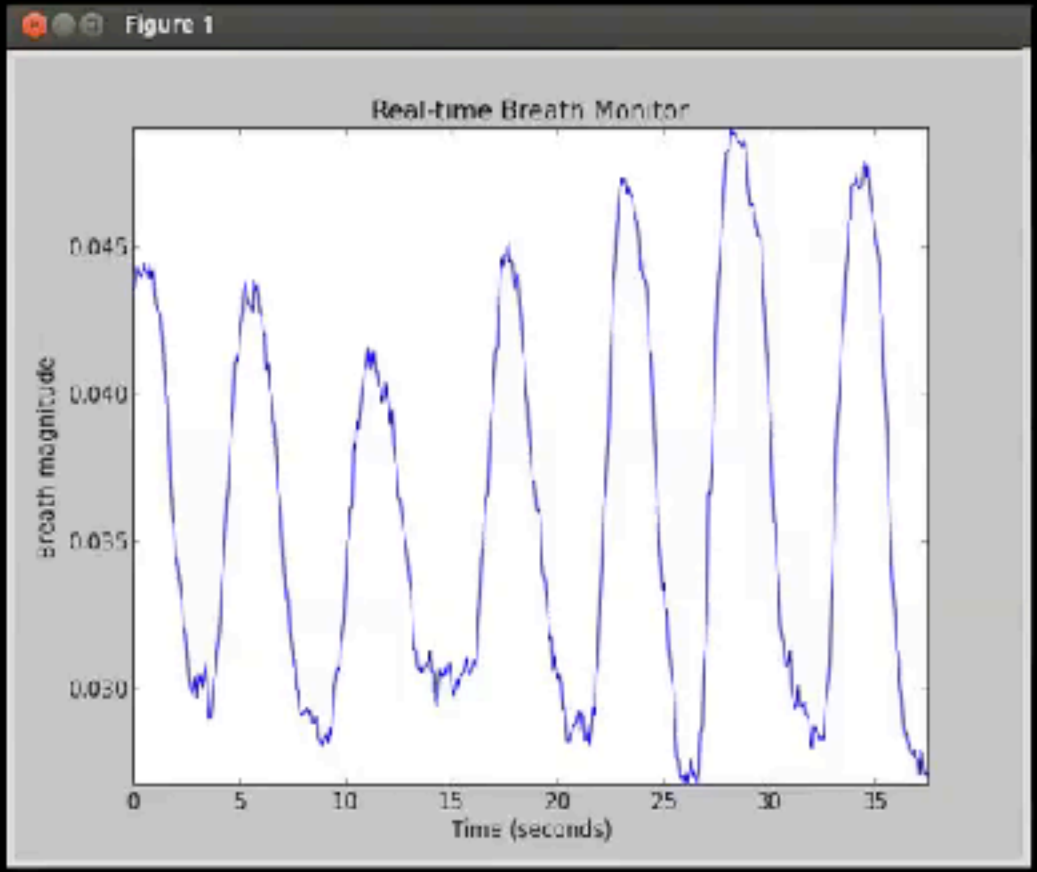
Device-Free Localization (WiTrack, 2014)



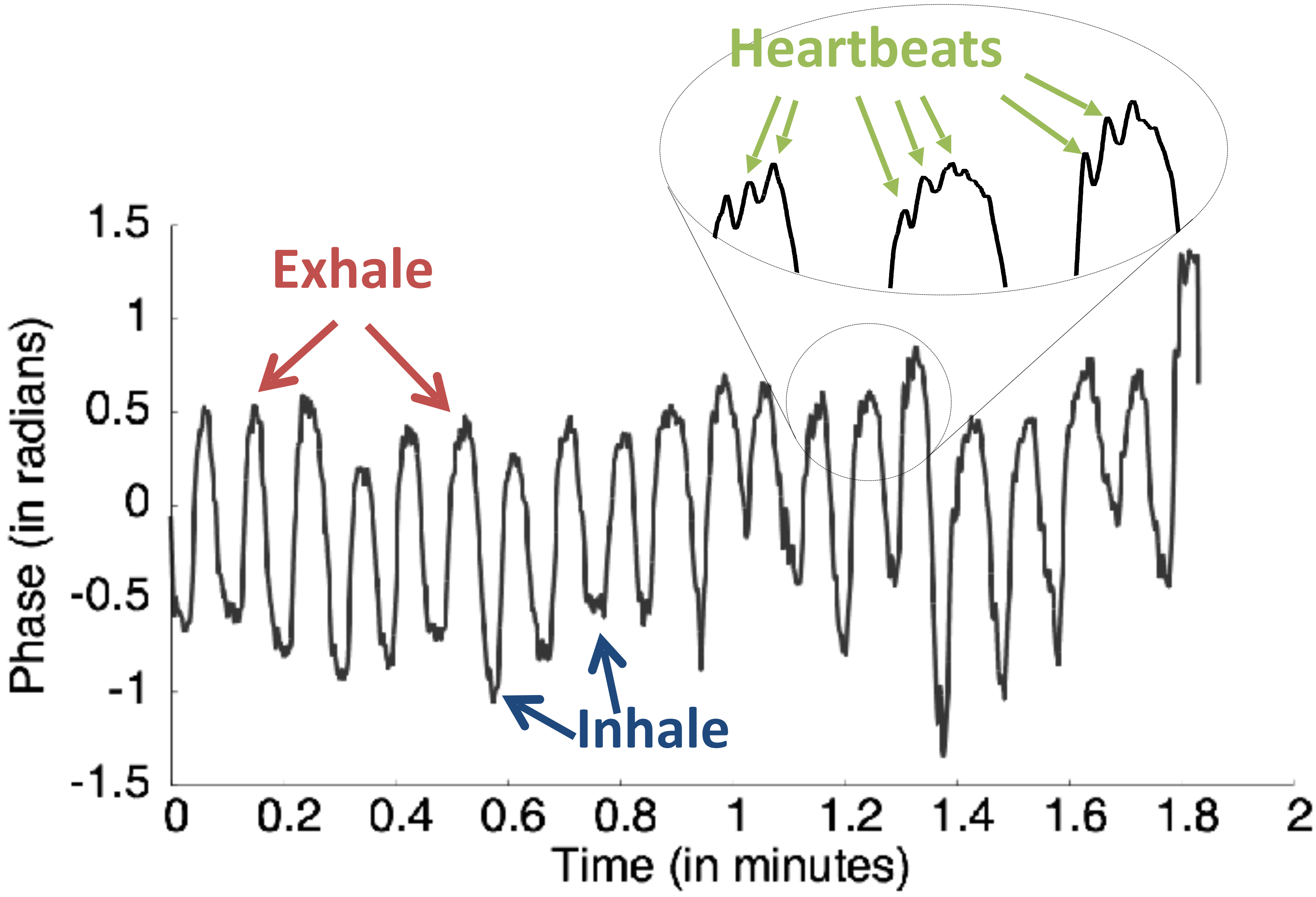
Seeing Through Walls (RF-Capture, 2015)


AI Senses People Through Walls

Breath Monitoring using Wireless (Vital-Radio, 2015)



Let’s zoom in on respiration signals



Heartbeats
Exhale
Inhale
1.5
1
0.5
0
-0.5
-1
-1.5
Phase (in radians)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (in minutes)

Baby Monitoring

2. Communications

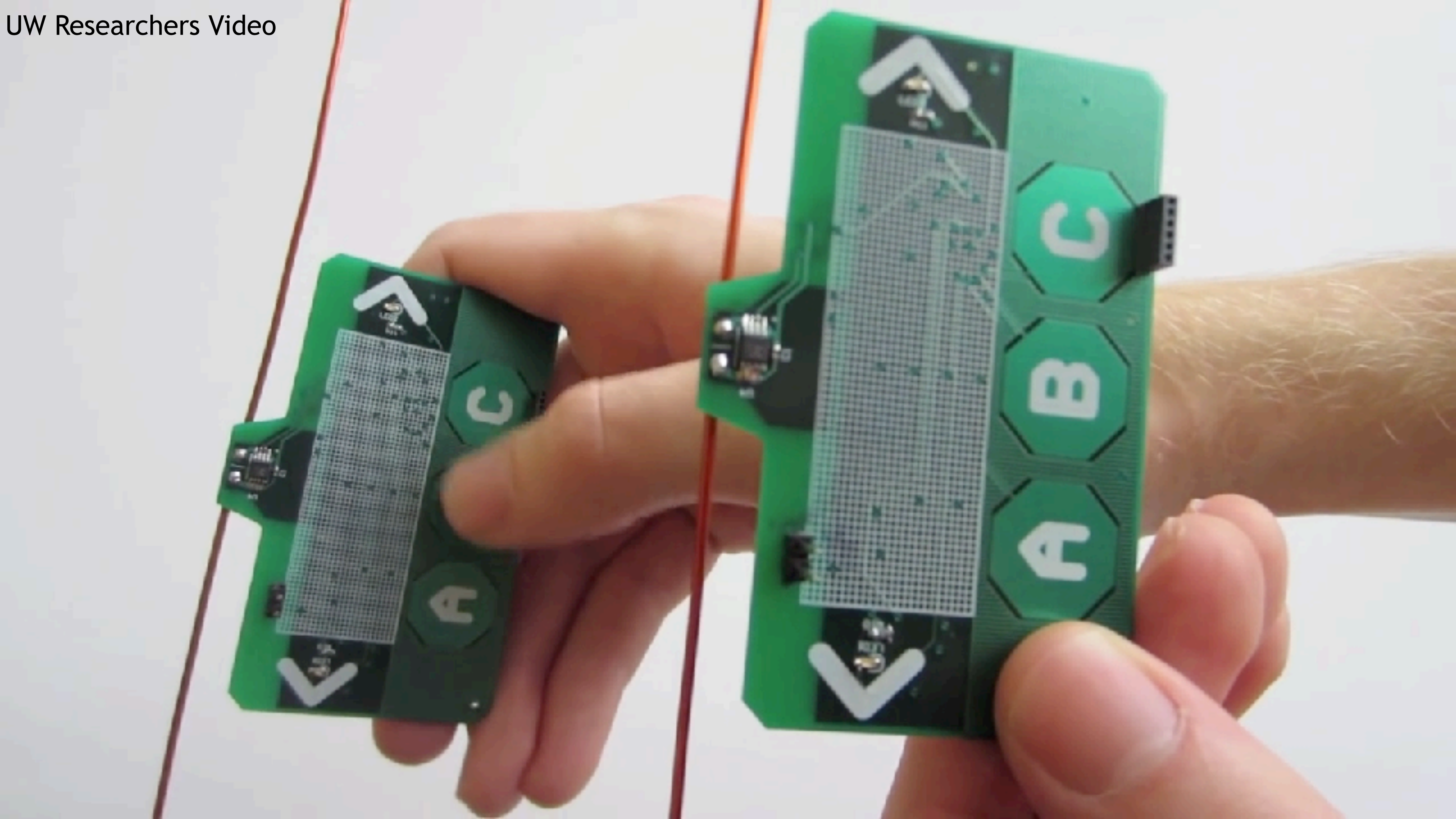
- Will cover fundamentals of comms (across Bluetooth, WiFi, cellular)
- These wireless technologies can work on Mars and the moon, but where can’t they work?

Did you know that a submerged submarine cannot wirelessly communicate with an airplane?

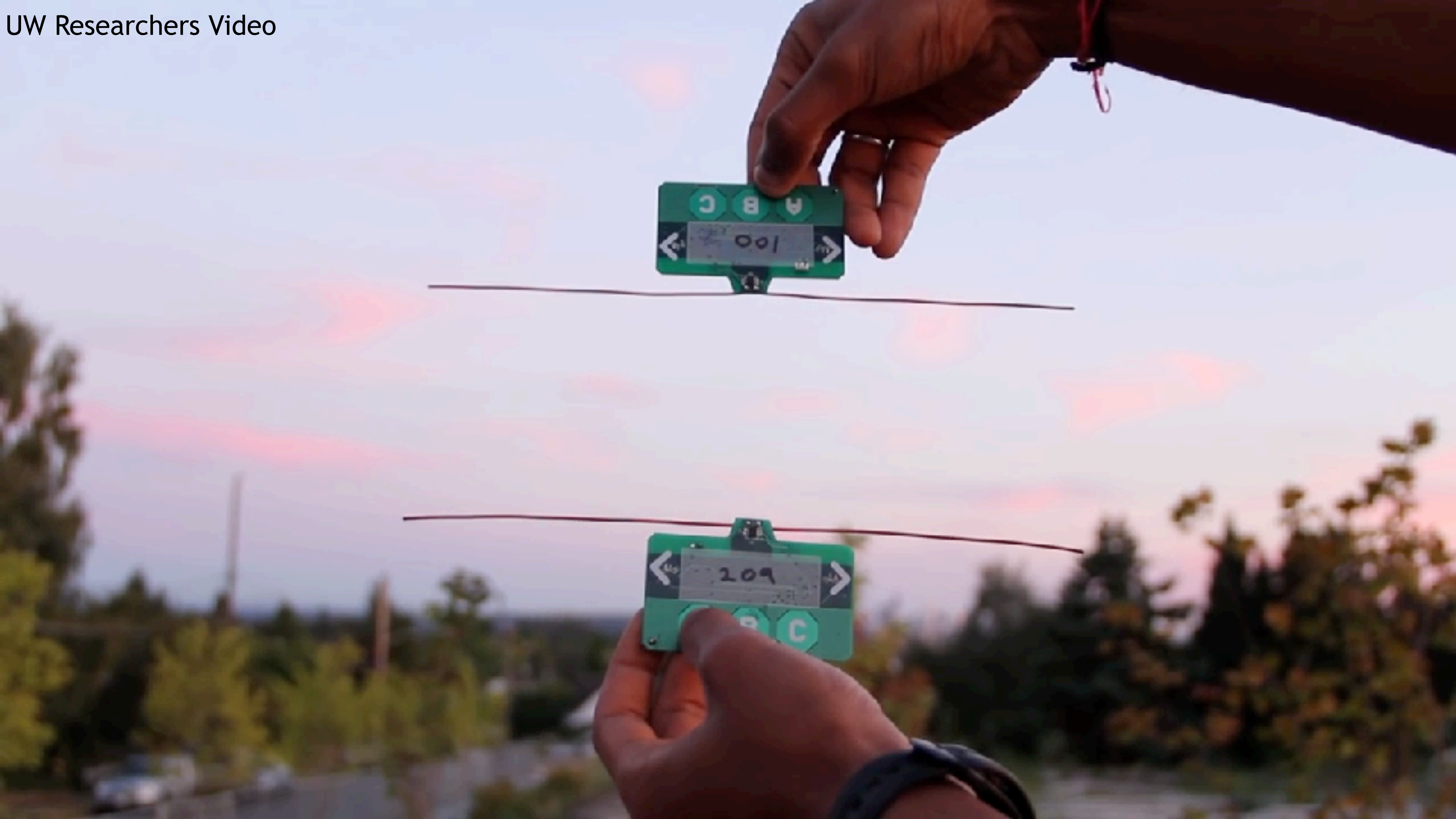
3. Battery-Free Computing

- What is battery-free computing?
- What’s the most common battery-free computer?

UW Researchers Video



UW Researchers Video



4. Non-Line-of-Sight Imaging with Millimeter-Waves

mmNorm

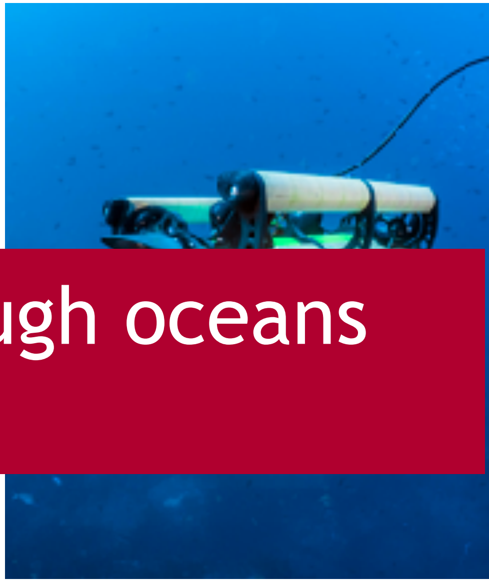
Reconstructing Hidden Objects with Wireless Signals

5. Ocean IoT

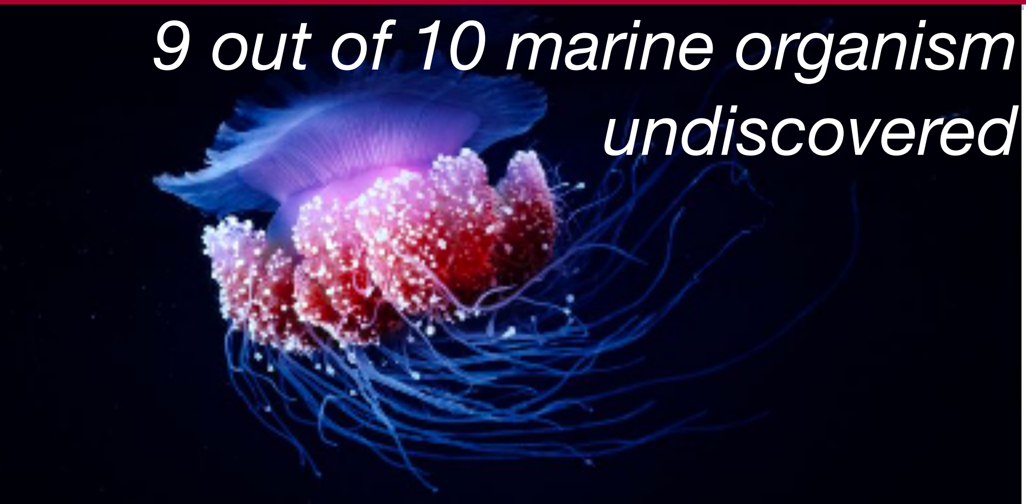
Taking the Internet of Things Underwater

“More than 95% of ocean remains unobserved and unexplored.”

- NOAA, 2018

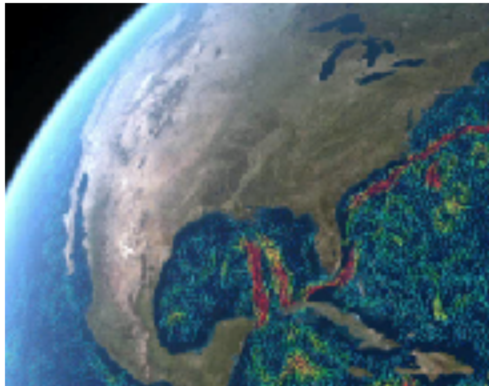


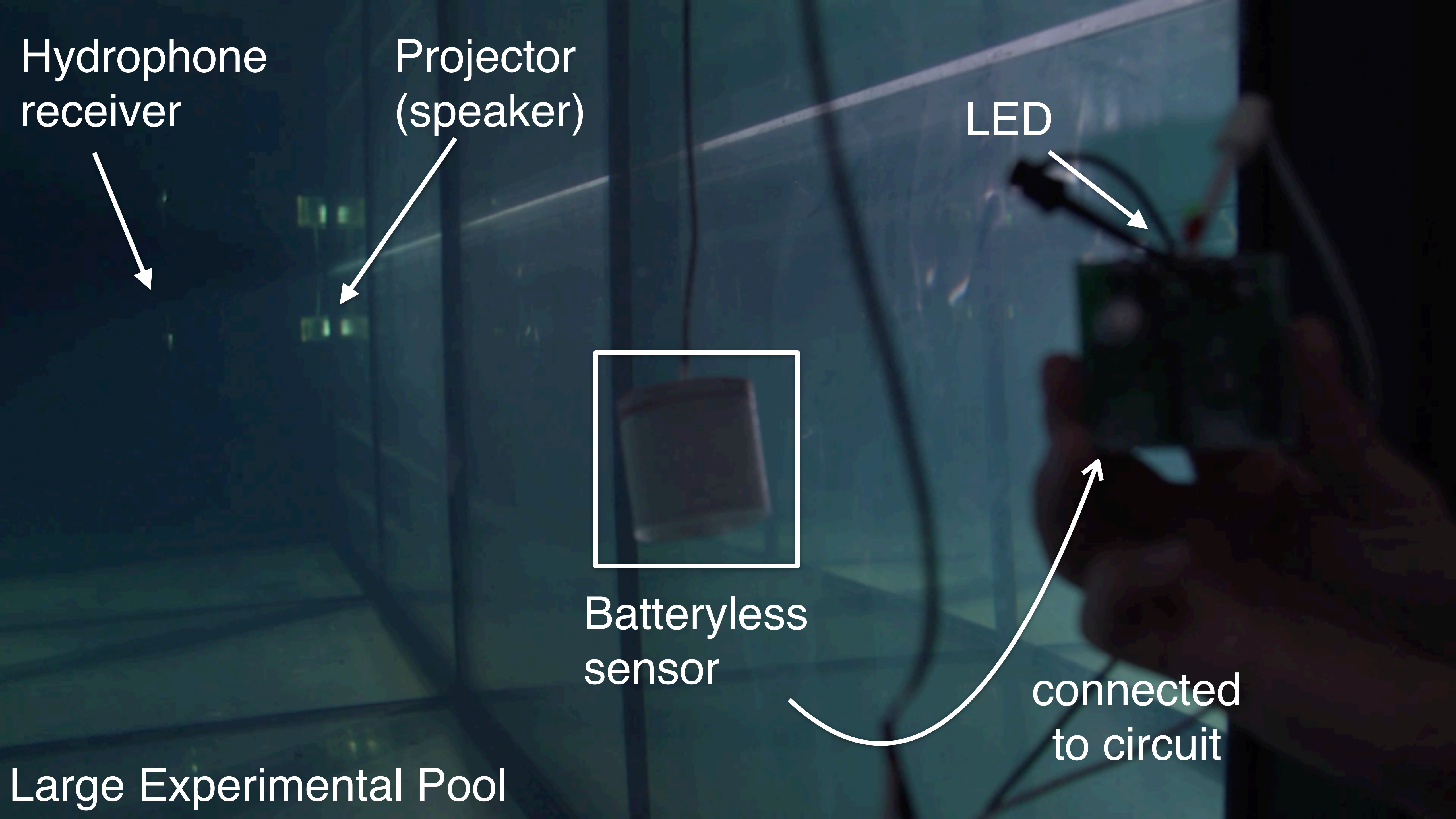
Less than 1 in a million of IoT is underwater, even though oceans cover more than 70% of the planet

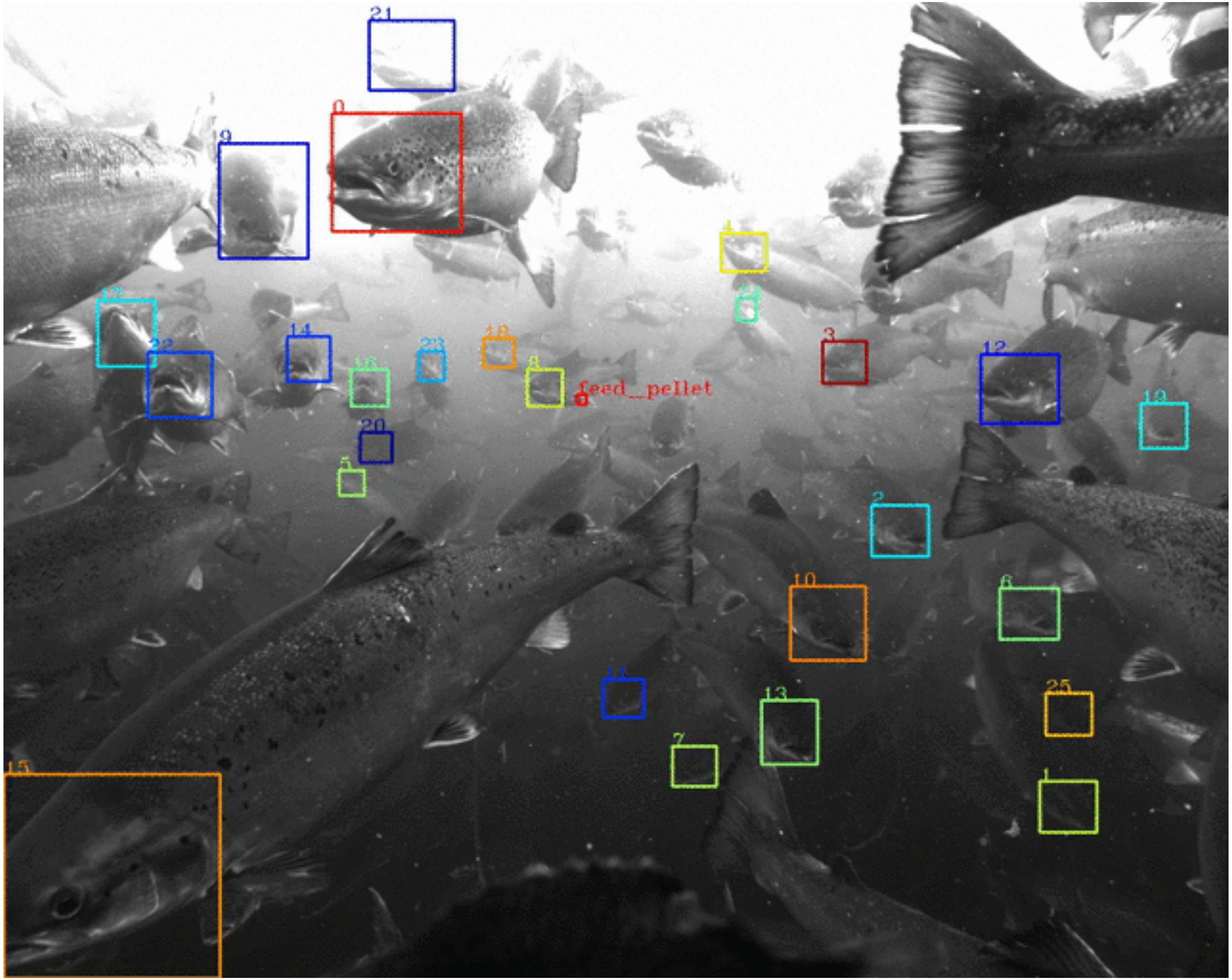


Aquaculture is the “fastest growing food sector”

- UN Food & Ag org, 2022




Hydrophone receiver
Projector (speaker)
LED
Batteryless sensor
connected to circuit
Large Experimental Pool


21
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feed_pellet
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1
15

6. Wireless + AI

- How is machine learning changing wireless communications & networking

Wireless + AI

Can we make FCC Experts out of LLMs?

Atul Bansal, Veronica Muriga, Jason Li, Lucy Duan and Swarun Kumar
Carnegie Mellon University
United States of America

ABSTRACT

This paper investigates whether Large Language Models (LLMs) can provide wireless expertise, particularly in the context of spectrum regulations. For any wireless system designer, defining an effective set of wireless parameters, such as the frequency operating band and total radiated power, is one of the very first steps in designing any wireless system. The current approach to do this relies on human FCC experts, who have to consult large volumes of techno-legal documentation on government regulations, such as the FCC rulebook and other industry standards. To ensure the exhaustive coverage of various use cases of wireless systems, these documentations tend to be quite long and very hard to parse through, even for an FCC expert. Given the success of LLMs in providing expert and accurate responses to varied other domains, it is natural to wonder if they could also assist wireless system designers in ensuring their compliance to these techno-legal rules and regulations. In this paper, we present WiLL, a system built on a state-of-the-art LLM, designed to be an assistive tool for wireless system designers to ensure their wireless system complies with regulations. Specifically, we focus on ensuring compliance with FCC regulations for various wireless systems that are designed for technologies such as WiFi, Bluetooth, LoRaWAN and Ultra Wide Band (UWB). We observe that WiLL achieves an accuracy of 78.57%, as compared to an average 51.77% accuracy of off-the-shelf state-of-the-art Large Language Models.

CCS CONCEPTS

• Networks → Wireless access points, base stations and infrastructure; Network manageability; *Mobile networks*; • Computing methodologies → Natural language processing.

1 INTRODUCTION

In this paper, we explore if the ever-evolving capabilities of Large Language Models (LLMs) can assist wireless system designers, with a special focus on FCC spectrum regulations. Designing a complete wireless system requires expertise on various wireless communication parameters such as operating frequency, bandwidth, transmitted power, bit error rate, overall network performance etc. Among

Spectrum expertise is therefore inaccessible for many wireless system designers, especially radio enthusiasts and small businesses.

Recent advancements in natural language processing have led to the development of Large Language Models (LLMs) such as ChatGPT[1], which have greatly improved the creation of natural language interfaces for data interaction. Systems built on these models have demonstrated state-of-the-art performance on standard text-to-text datasets. Further, these models have also been extended to work for domain-specific problems such as software code review[20], responding to database queries[12], and biomedical research [24]. Indeed, there has also been prior research on LLMs in the wireless context [21, 22]. However, these works remain focused on either providing a detailed explanation of various wireless system parameters or discussing protocol specifications of specific wireless technologies. While these models act as a good resource for understanding wireless systems, they are not intended to support network design. Hence, a natural question to ask is: ***Can we exploit the power of LLMs to assist in designing a wireless system, specifically, to comply with spectrum regulation?***

We present WiLL, a system that exploits the power of existing Large Language Models (LLMs) to assist amateur wireless enthusiasts in designing a wireless system. Specifically, we focus on the first step that every wireless system designer needs to undertake – ensuring that their network design complies with FCC regulations. We observe that WiLL provides accurate responses to a wide variety of transmitter design questions across various wireless technologies such as WiFi, Bluetooth, Ultra Wide Band, LoRa etc, achieving an accuracy of 78.57% as compared to the average accuracy of 51.77% by the state-of-the-art Large Language Models such as ChatGPT, LLaMa and GPT-4.

We first motivate the need for WiLL by evaluating how existing state-of-the-art Large Language Models perform on a dataset of wireless system design queries and corresponding responses. This dataset is developed by an experienced wireless systems researcher by generating a wide range of queries and answering them after carefully consulting the FCC regulations [5]. The dataset includes various design questions across wireless technologies such as WiFi, Bluetooth, Ultra Wide Band and LoRa. We observe that state-of-the-art LLMs do not perform well in answering these queries. The

NeWRF: A Deep Learning Framework for Wireless Radiation Field Reconstruction and Channel Prediction

Haofan Lu [1] Christopher Vattheuer [1] Baharan Mirzasoleiman [1] Omid Abari [1]

Abstract

We present NeWRF, a novel deep-learning-based framework for predicting wireless channels. Wireless channel prediction is a long-standing problem in the wireless community and is a key technology for improving the coverage of wireless network deployments. Today, a wireless deployment is evaluated by a site survey which is a cumbersome process requiring an experienced engineer to perform extensive channel measurements. To reduce the cost of site surveys, we develop NeWRF, which is based on recent advances in Neural Radiance Fields (NeRF). NeWRF trains a neural network model with a sparse set of channel measurements, and predicts the wireless channel accurately at any location in the site. We introduce a series of techniques that integrate wireless propagation properties into the NeRF framework to account for the fundamental differences between the behavior of light and wireless signals. We conduct extensive evaluations of our framework and show that our approach can accurately predict channels at unvisited locations with significantly lower measurement density than prior state-of-the-art.

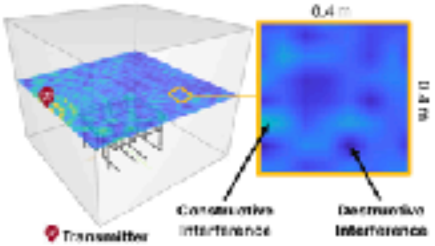


Figure 1. **The tomography of a wireless field (channel) in a simple environment.** Like water ripples, wireless signals can add up constructively or destructively, causing fine-scale spatial variation. Our algorithm, NeWRF, reconstructs this field from a sparse set of channel measurements.

1. Introduction

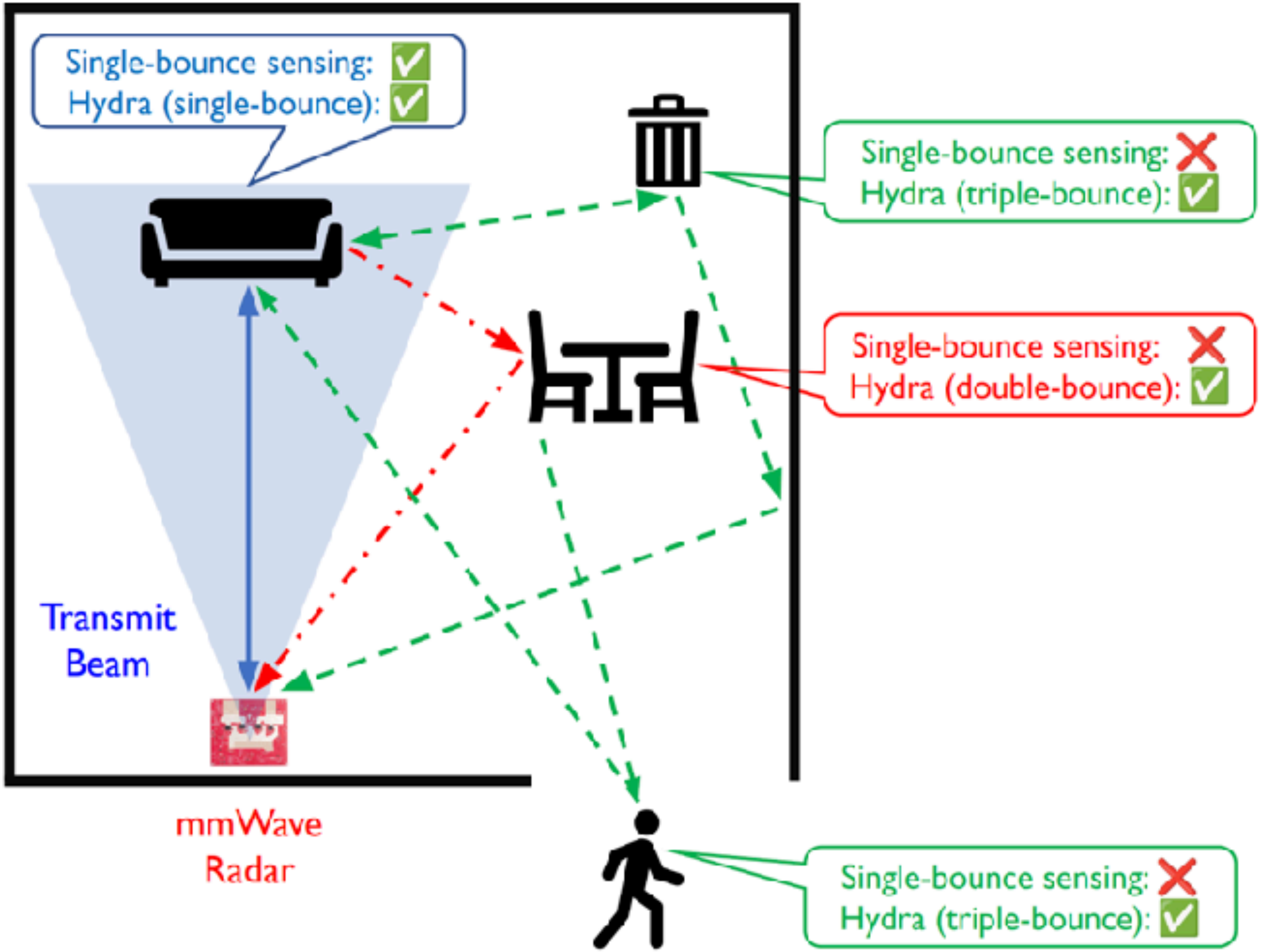
Wireless networks (such as WiFi and 5G) have become an essential part of our lives. Real-world WiFi and cellular deployments commonly encounter many issues such as dead spots, dropped signals, sudden outages, and slow through-

optimize the deployment of base stations. However, to conduct an effective site survey, an experienced engineer needs to perform measurements for a very dense grid of points. Today, this exhaustive measurement is rarely done due to its intractable time and cost. Instead, a sparse measurement approach is usually taken, where the engineer walks with a radio receiver in the site and measures the wireless channels at random locations. A wireless channel is a measure of the distortions imposed on wireless signals as they propagate from a transmitter to a receiver, which determines the quality of communication. The wireless channel is represented as a complex number that characterizes factors such as signal attenuation, phase rotation, and interference. Although the random sparse measurement approach is much more efficient than the exhaustive grid-based survey, it fails to uncover the signal quality at unvisited locations; therefore, can potentially miss many dead spots. As a supplement, wireless ray tracing simulations (Ramsom, 2021) are also performed

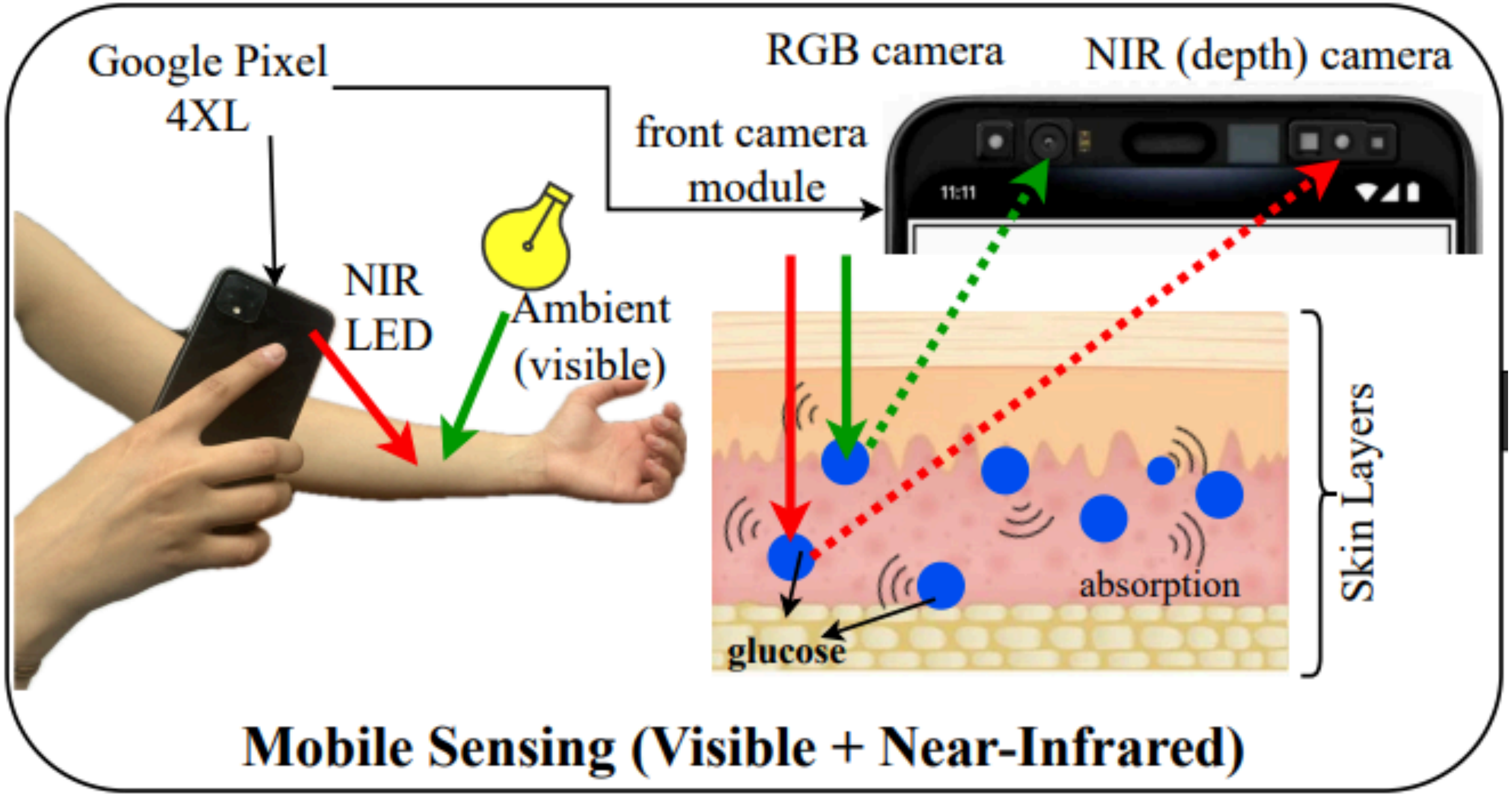
7. RF-based SLAM


Giving
Robots
Superhuman
Vision

8. Sensing from Multipath


Single-bounce sensing: ✅
Hydra (single-bounce): ✅
Single-bounce sensing: ❌
Hydra (triple-bounce): ✅
Single-bounce sensing: ❌
Hydra (double-bounce): ✅
Transmit Beam
mmWave Radar
Single-bounce sensing: ❌
Hydra (triple-bounce): ✅

9. Glucose Sensing using Mobile Devices



Google Pixel
4XL
RGB camera
NIR (depth) camera
front camera
module
11:11
NIR
LED
Ambient
(visible)
absorption
glucose
Skin Layers
Mobile Sensing (Visible + Near-Infrared)

Goal of This Class

1. Learn the fundamentals of wireless & mobile technologies for sensing and communications

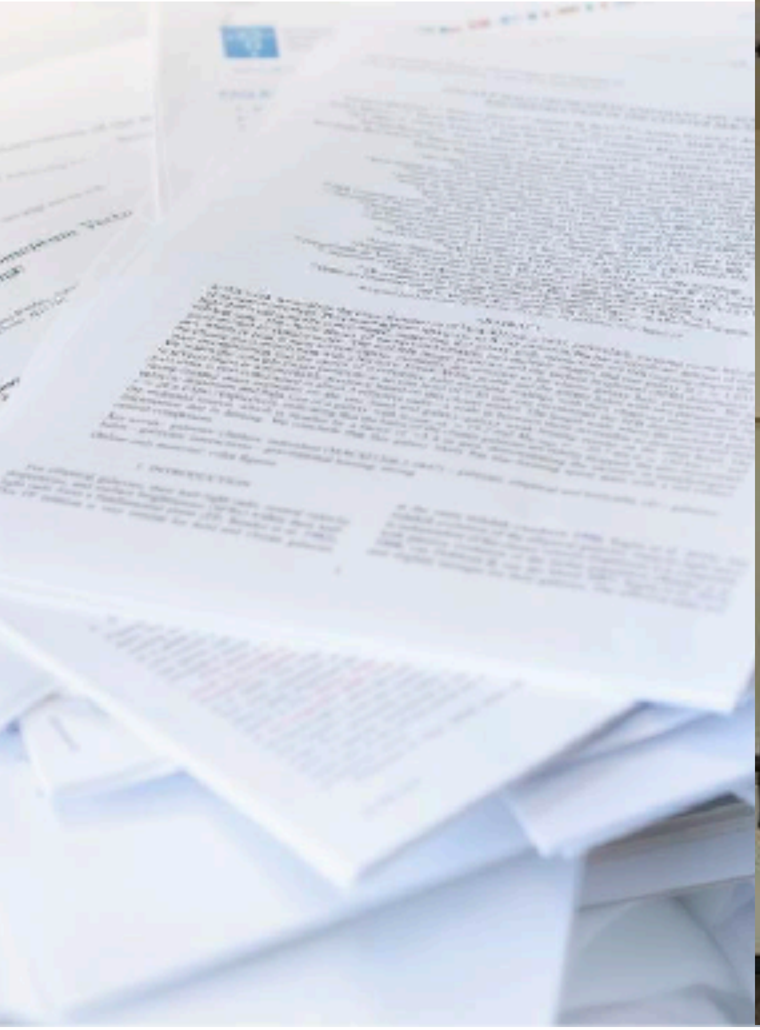
2. Discover about state-of-the-art systems and applications for wireless and mobile sensing

3. Develop an understanding of wireless and mobile systems and technologies at an intuitive and practical level

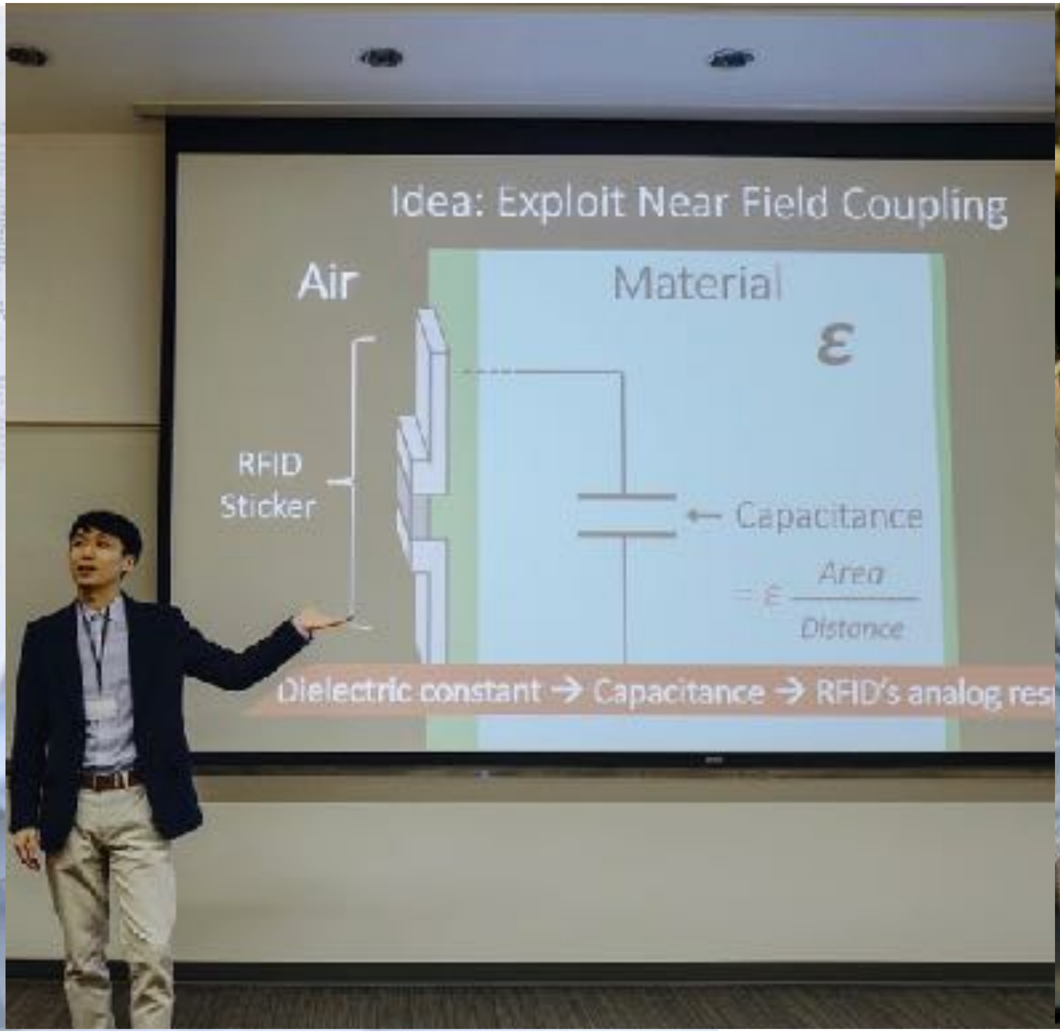
4. Learn how to reason about wireless & mobile systems with knowledge of technology, constraints, and applications

5. Design and build your own wireless or mobile sensing system project (budget/team)

Course Organization



Reading & Reviewing Papers



Discussing Papers

Class Project

Each lecture =

Fundamentals + State-of-the-art system(s)

Necessary background?

advanced undergrad-level knowledge in engineering

or computer science

Logistics

Grading:

- 1 Course Project (60%)
  - Proposal (10%); Progress Report 1 (10%); Progress Report 2 (10%); Presentation (20%); Final Report (15%)
- Reading Questions & Participation (30%)
  - Includes submitting reviews before every lecture (15%)
  - Participation via Attendance+Interaction (15%)
  - May skip one review without affecting grade
- Paper Presentation (10%)

Website: https://www.mit.edu/~fadel/courses/MAS.wireless/index.html

Readings

We will read 1-2 papers/references per class:

- Everyone is expected to read the papers in advance
- Submit a short review of the required readings by midnight the night before the class
- Say something that is not in the paper

Submit Reviews here:

- https://www.mit.edu/~fadel/courses/MAS.wireless/reviews.html

Projects

- All projects involve system implementation
- Work in groups of two (ideally)
- Will suggest project ideas; students can choose their own projects
- Can be (very) related to your research (come talk to me)

Timeline:

- Proposal (1-2 pages): October 7
- Progress Report 1: October 28
- Progress Report 2: November 18
- Final Presentation: December 9
- Final Report (6-8 pages): December 11

We will discuss project updates in class as time permits

Introductions

- Name
- Position (undergrad year, grad year, postdoc, industry)
- Major
- Why are you interested in this class?

How to Read a Paper

First Pass:

- Title, Abstract
- Figures (illustrations? important results?)
- skim intro & conclusions
- References

Then: probably use ChatGPT to give you a summary

Second Pass

- Intro in details
- Overview, related work, or background sections
- Figures in details

Third pass:

- Read in detail
- Mark references for future read

How to Review a System Paper

How to think when reviewing a paper?

How to Review a System Paper

How to think when reviewing a paper?

1) Motivation
Is this an important problem?

- New problem? → Worthwhile or artificial?
- Existing problem? (i.e., have others worked on it) → Does it improve over prior work?

2) Related Work

- Does it really outperform prior work?
- Does it accurately represent prior work?
- Do you know past work? If not, search Google Scholar to get a sense of past work

3) Techniques

- Are they novel? intellectually interesting?
- Are they technically sound? Is there a key technical flaw?

How to Review a System Paper

How to think when reviewing a paper?

4) Implementation

- Significant effort?
- Matches the motivation?
- Simulation or real-world prototype?

5) Evaluation

- Comprehensive? Convincing?
- Does the system deliver what it promises?

How to Review a System Paper

How to think when reviewing a paper?

1) Motivation

2) Related Work

3) Techniques

4) Implementation

5) Evaluation

How to Review a System Paper

How to write a review?

1) Summary

2) Strengths & Weaknesses

3) Comments to authors

How to Review a System Paper

How to write a review?

1) Summary

- 5-10 sentences
- If someone hasn't read the paper at all, they should understand what it's about
- Should sound like a "brutally honest and straightforward abstract"

Rough structure:

This paper presents XXX, a system that does YYY. **The goal is to** XXX. The **main challenge** the authors try to address is YYY.

The key idea is to do XXX. The authors do this by introducing/proposing ZZZ

The authors implement (or simulate) their system and **demonstrated** (results) that it outperforms the baseline?

How to Review a System Paper

How to write a review?

1) Summary

- 5-10 sentences
- If someone hasn't read the paper at all, they should understand what it's about
- Should sound like a "brutally honest and straightforward abstracT"

2) Strengths & Weaknesses

- Use your answers to the questions of "How to think when reviewing"
- List 2-4 pros/cons
- Each should be a direct statement about the paper

<u>Rough structure:</u>

Pros:
+ Statement 1
+ Statement 2

Cons:
-
-
-

How to Review a System Paper

How to write a review?

1) Summary

2) Strengths & Weaknesses

3) Comments to authors

- Detailed comments to authors
- Elaborate on your pros/cons, areas for improvement, key concerns
- Ask questions about techniques, figures, results, etc.
- Based on the 5 points from how to think as well as technical details

Examples:

- If you listed a weaknesses small delta over prior work, specify in details why with references
- If experimental details are missing, state exactly what is missing and why it is problematic
- Include typos/grammar mistakes, potential suggestions to correct

How to Review a System Paper

How to write a review?

1) Summary

2) Strengths & Weaknesses

3) Comm… to authors

- Detailed c… to
- Elabor… r pro
- … s about t
- … the 5 points

Examples:

- If you liste… all delta o
- If exper… g, state
- Inclu… ramma… potent

For the sake of this class, we will drop "comments to authors".

Instead, you should add a paragraph on "suggestions for improvement".

- If you could improve this paper, how would you do it?
- How do you envision your proposed technique will improve the work

How to Review a System Paper

How to write a review? (for this class)

1) Summary

2) Strengths & Weaknesses

3) Suggestions for Improvement

ChatGPT to proofread it! (and maybe if you missed something)

Next Class (Localization)

1) Required Readings

- **Chapter on Localization -** Covers fundamentals
- **Seeing through walls paper** - Covers fundamentals of wireless sensing + FMCW

2) Optional Readings

- **Cricket -** More than 100,000 deployed (hospitals); Cited > 5,000 times
- **Radar paper** - Transitioned to real-world products (Microsoft, many startups); Started a new field; Cited > 10,000 times
- **GPS** - how it works
- **Contactless vitals sensing**