# Lecture 01
# Introduction

CS397/497 – Wireless Protocols for IoT
Branden Ghena – Winter 2021

Northwestern

# Today’s Goals

- Overview of the course
- Introduction to the Internet of Things
- Introduction to wireless communication

# Outline

- **Who and Why**
- Internet of Things
- Course Overview
- Overview of wireless networks

# Welcome to CS397/497!

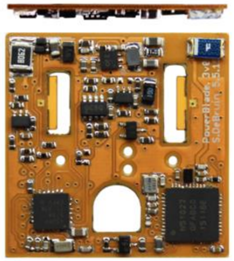
- ~16 students (9 undergrad, 7 grad)
  - Lots of different backgrounds and interests

- This is going to be like a graduate course
  - No exams!
  - Occasional paper reading
  - Majority of your grade is the final project

- This course is based on discussion and questions
  - Expect to attend course sessions, keep webcam on, and interact
  - You're hopefully here because you want to be and want to learn

# Branden Ghena (he/him)

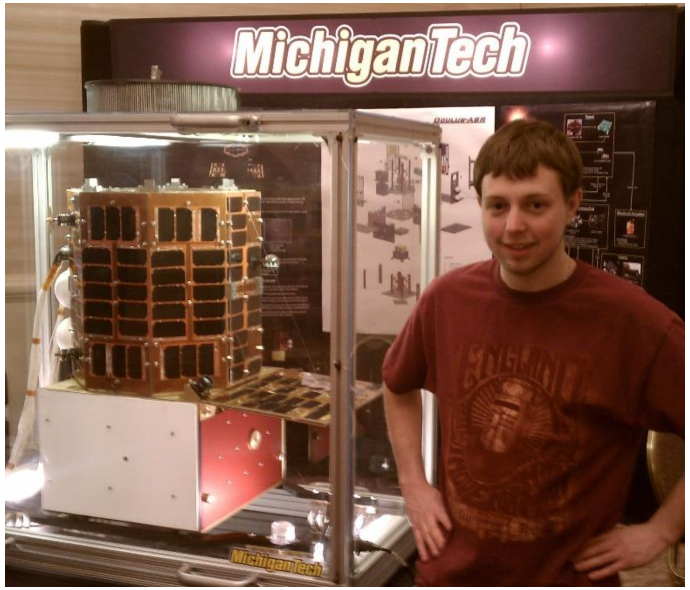
- Assistant Faculty of Instruction
- Education
  - Undergrad: Michigan Tech
  - Master's: University of Michigan
  - PhD: University of California, Berkeley
- Research
  - Resource-constrained sensing systems
  - Low-energy wireless networks
  - Embedded operating systems
- Teaching
  - Computer Systems
    - Intro to Computer Systems
    - Operating Systems
    - Microprocessor System Design

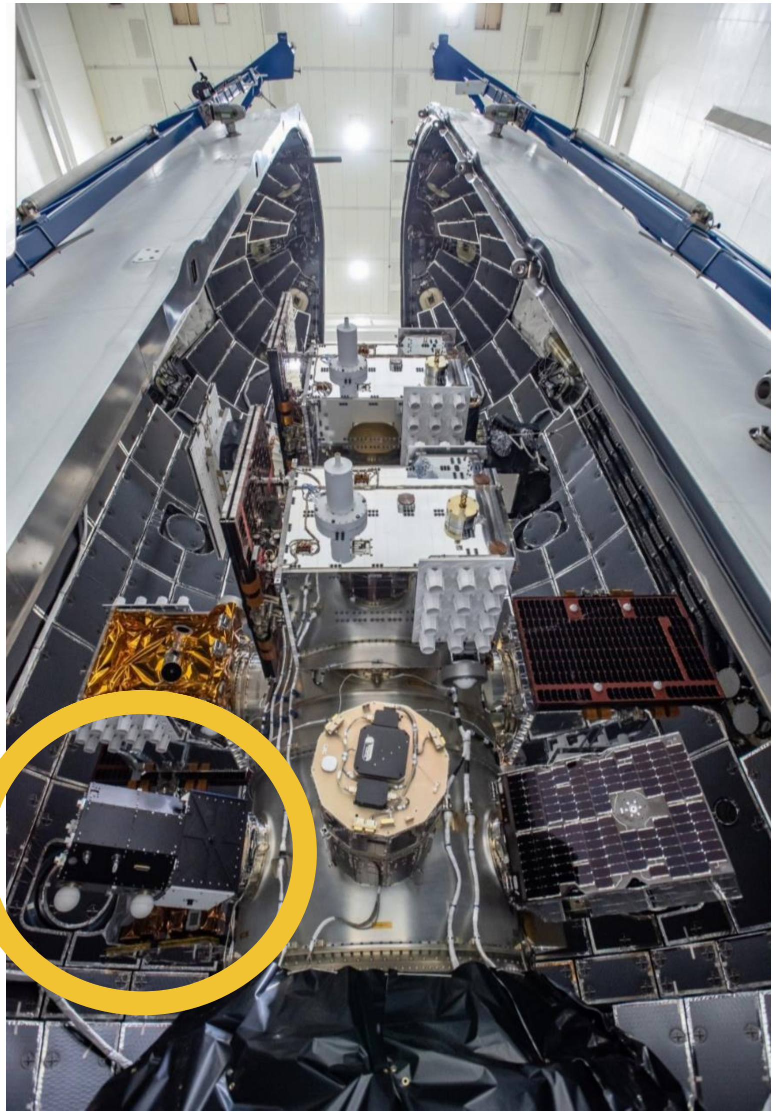
Things I love


# Undergraduate: satellite radios and computers

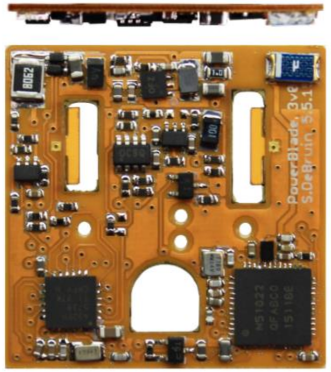
| Oculus -Sat<br>Uplink Command Budget: | NOTE: | | Oculus -Sat<br>Version: 2.4.1 | Date Data Last Modified:<br>2011 October 12 |
|---|---|---|---|---|
| *Parameter:* | *Value:* | *Units:* | *Comments:* | |
| ***Ground Station:*** | | | | |
| Ground Station Transmitter Power Output: | 50.0 | watts | This value is transferred from "Transmitters" W/S, Cell [E15]. | |
| In dBW: | 17.0 | dBW | Transmitter power expressed in dB above one watt | |
| In dBm: | 47.0 | dBm | Transmitter power expressed in dB above one milliwatt | |
| Ground Stn. Total Transmission Line Losses: | 3.3 | dB | This value is transferred from "Transmitters" W/S, Cell [I33] | |
| Antenna Gain: | 16.3 | dBi | This value is selected at "Antenna Gain" W/S, Cell [E11] | |
| Ground Station EIRP: | 30.0 | dBW | Ground Station Effective Isotropic Radiated Power (EIRP) [EIRP=Pt x Ltl x Ga] | |
| ***Uplink Path:*** | | | | |
| Ground Station Antenna Pointing Loss: | 0.3 | dB | This value is calculated in the "Antenna Pointing Losses" W/S, and transferred f | |
| Gnd-to-S/C Antenna Polarization Losses: | 3.0 | dB | This value is calculated in the "Polarization Loss" W/S and is transferred from C | |
| Path Loss: | 141.5 | dB | Lp = 22 + 20LOG(D/l); Transferred from "Orbit & Frequency" W/S | |
| Atmospheric Losses: | 1.1 | dB | This value is transferred from "Atmos. & Ionos. Losses" W/S, Cell [D23] | |
| Ionospheric Losses: | 0.7 | dB | This value is transferred from "Atmos. & Ionos. Losses" W/S, Cell [D47:D50] | |
| Rain Losses: | 0.0 | dB | This value should be estimated by the link model operator and place into Cell [ | |
| Isotropic Signal Level at Spacecraft: | -116.6 | dBW | This is the signal level received in space in the vacinity of the spacecraft using | |

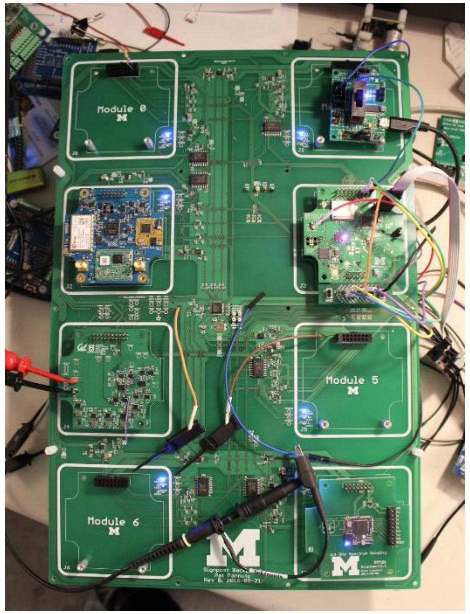



- How the heck are you supposed to learn this stuff?

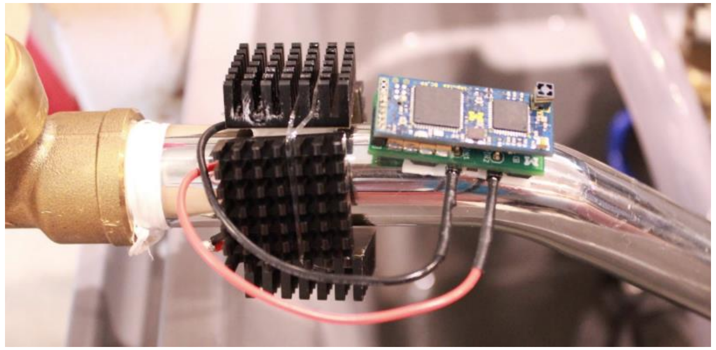


# Grad school: resource-constrained embedded systems






- Most interesting to me: the interfaces
  - Hardware and software
  - Applications and OS
  - Communication
- Again: learn by doing
  - And with significant assistance from your peers



# Faculty: now I can choose what to teach!

- Goal: provide classes that teach more advanced embedded systems topics
  - Hopefully, generally useful to other nearby domains of CS and ECE too!

- Result: this course!
  - Really would be much nicer in person, but 🤷
  - Course goals: make students familiar with a number of different wireless protocols and their tradeoffs
    - Practical hands-on experience with some networks
    - Open-ended project where students can choose their specific focus

# Outline

- Who and Why
- **Internet of Things**
- Course Overview
- Overview of wireless networks

# Perspective of this course

- This class is about wireless protocols
  - For a specific domain: the Internet of Things

- So we'll spend some amount of time discussing the Internet of Things and embedded systems
  - Including how to program embedded systems

# Discussion: what is the Internet of Things?

1. Name a few Internet of Things devices

2. What are the qualities that designate those devices at "IoT"?

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# Thought experiment on capabilities

- What if the Nest thermostat was powered by an entire desktop?
  - 8-core x86-64 processor, 32 GB RAM, 1 TB SSD
- Would that still count as IoT?
- Why don't we see that in practice?

# Thought experiment on capabilities

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**Cost**

# Thought experiment on energy

- IoT devices include a mix of batteries, wall power, (and energy-harvesting)

- Why do we put so much focus on systems with batteries?
  - Why do they need batteries?

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**Deployability**

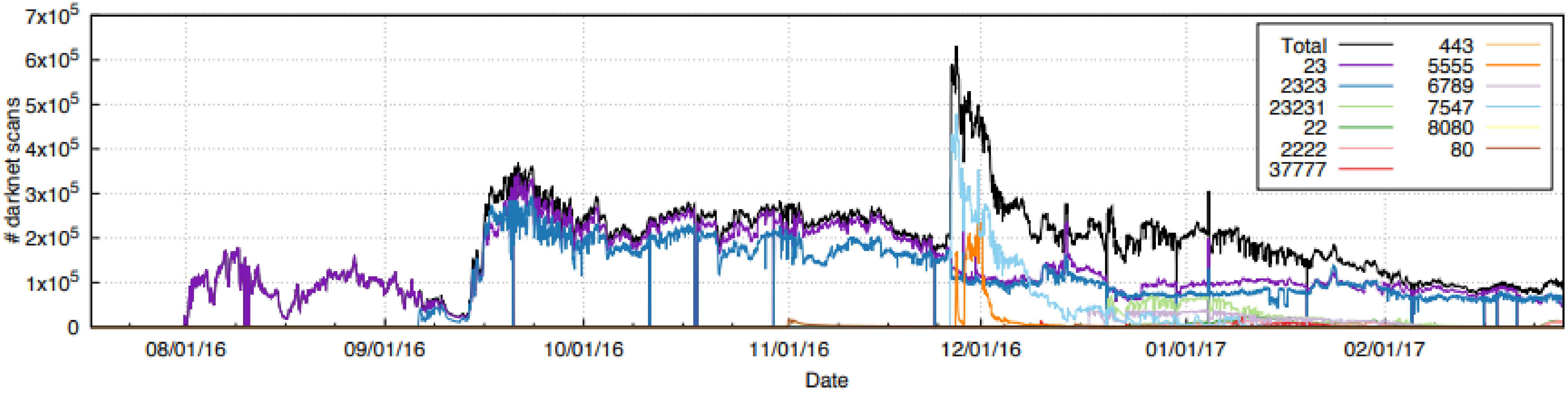
# Branden's take on the Internet of Things

- Key features
  - Computation
    - Local to the device
    - With some capability for arbitrary compute and storage
  - Connectivity
    - Almost certainly wireless
    - Likely Internet, possibly local
  - Interaction
    - Sensing or Actuation
- Secondary features
  - Low energy
  - (Relatively) Low cost

# Warning: Internet of Crap



# Internet of Insecure Crap




- Mirai botnet (2016)
- Takes control of up to 600,000 insecure connected devices
  - IP-attached cameras, DVRs, routers, printers
- Used to DoS websites

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# General course structure

- Mondays and Wednesdays
  - Lecture and discussion about networks
- Fridays
  - Labs and projects
  - A brief overview from me about what's going on
  - Open work period while on zoom still
    - Closest I can get to a "lab" setting

# Grading

- 35% Lab projects
- 65% Final project

- Seriously, no exams or homework or participation points
  - The point of in-class material is to teach you and prepare you for projects
  - Come because you want to learn it

# Labs

- Semi-guided efforts of getting wireless communication working on real hardware
    1. Get embedded software working
    2. Bluetooth Low Energy advertisements
    3. Bluetooth Low Energy connections
    4. Thread network

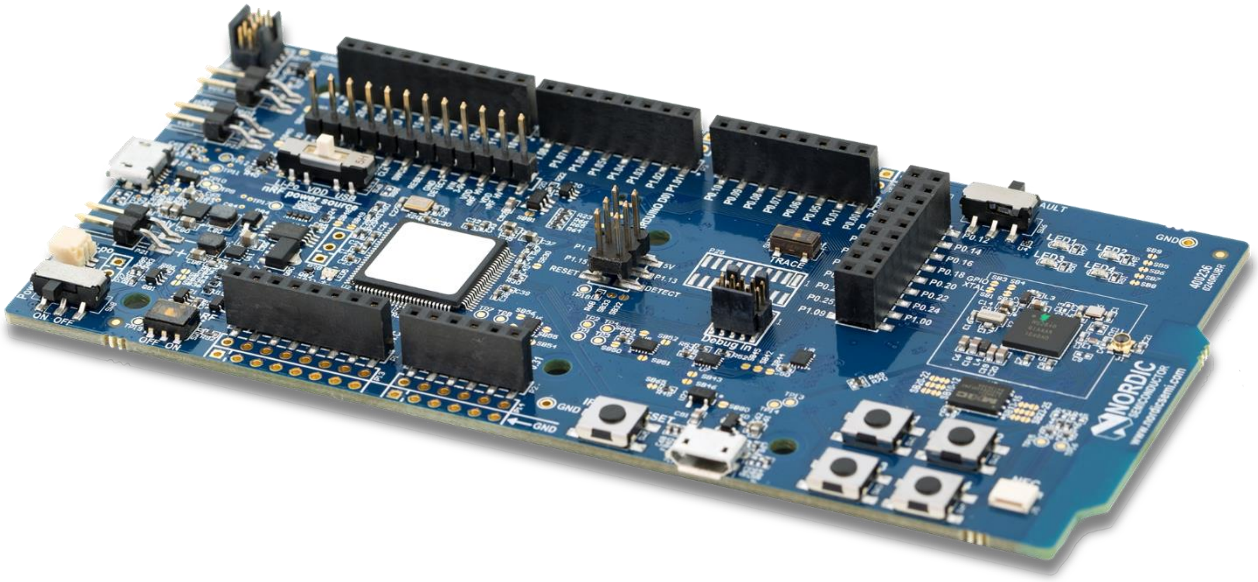
- In a perfect world we would also do something with WiFi and something LPWAN
    - Would need additional hardware
    - And extra time that we don't have this quarter

# Lab hardware

- nRF52840dk
  - Microcontroller with BLE and Thread support
  - JTAG support built into the board

- Hopefully also useful for final projects for some portion of you!

- Fill out campuswire survey!
  - I'll start ordering stuff tomorrow



# Lab grading

- Around one page submission on canvas
  - "Prove to me that you did this lab"
  - Point me at public Github code. Include pictures of debug output/network visualization. Discuss what did/didn't work.
  - **NOT** a formal lab writeup

- Playing this pretty loose since it's a small, experimental class
  - There's always a chance something in labs *won't* work

# Project

- Classic grad school "do a project"

- Come up with something you're interested in exploring that is linked to the topics of class
  - Definitely acceptable to overlap with research or other classes
  - Work in small groups of 2-3 students

- This is your chance to decide what you're actually interested in and to guide your own learning
- Good ideas should be a lot of work too

# Project proposals

- Proposals due Monday, February 1st
  - 3 weeks from today
  - Want to provide plenty of time to work on the project

- Start thinking about project ideas and finding partners now
  - Preferably two-three people. One is possible. Four+ needs to be justified.

- I am very happy to talk about ideas during office hours
  - Goal is that we'll have talked about it at some point *before* you submit the proposal

# Project ideas

- Analyze and optimize a deployed network
  - Measure throughput, or energy, or latency, etc.
  - Determine how to improve network for application use case

- Implement and evaluate a modified network protocol
  - Change something about the specification of an existing protocol
  - Measure the effect that it has on a deployment

# Project ideas

- Simulate a wireless network
  - Accurately predict throughput, energy, latency, etc.
  - Could be done in any language or platform (e.g. NS-3)

- Visualize network performance
  - Provide tools for understanding and debugging performance
  - Real-time or historical snapshot

# Hardware for projects

- Mostly up to you to provide

- Talk to me about your needs, and I might have ideas or things to lend out that will help
    - I’ve got lots of random stuff on hand, as does Josiah

# Outline

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# Schedule

| **Week** | **Monday** | **Wednesday** | **Friday** |
|---|---|---|---|
| **Jan 11-15** | Introduction | *Slack*<br>*(ComEd hates Branden)* | MAC Protocols<br>+Recorded Lab Embedded |
| **Jan 18-22** | *MLK Day* | BLE Advertisements | Lab Advertisements |
| **Jan 25-29** | BLE connections | Bluetooth Classic | Lab Connect |
| **Feb 1-5** | 802.15.4 | Thread | Lab Thread |
| **Feb 8-12** | Zigbee/Advanced | WiFi | *slack* |
| **Feb 15-19** | WiFi 2 | LPWANs | Updates |
| **Feb 22-26** | Cellular | Cellular 2 | *slack* |
| **Mar 1-5** | Localization | Backscatter | Updates |
| **Mar 8-12** | Wrapup + Extra | Presentations | Presentations 2 |

# Bluetooth Low Energy

- Bluetooth Classic was good for enabling device to device communication
  - But not particularly fast or low energy
- Bluetooth Low Energy was developed to improve this
  - Focuses on low-energy interactions
  - Much lower throughput that Bluetooth
- Supported by hardware devices already in smartphones
  - Humans can interact directly with nearby devices!!

# 802.15.4 & Thread

- 802.15.4 is a low-energy physical layer
  - Radio chips have been widely available for 15-20 years

- *Significant* amounts of sensor network research have focused on building layers on top of 802.15.4
  - Access control layers
  - Network layers

- Thread is a selection of these possibilities to make a network
  - Uses IPv6 networking!!

# WiFi (802.11)

- Ubiquitous wireless communication
  - High energy requirements for high throughput communication

- Now accessible through relatively low power radios
  - ESP32, Electric Imp, and company
  - Still significantly more effort than BLE or Thread

- IoT devices can use the same WiFi that’s already available
  - No need for additional infrastructure!!

# LPWANs (Low-Power Wide-Area Networks)

- How do we collect data from city-scale deployments?
  - There's an unmet need for long-range, but low-throughput networks
  - Existing cellular technologies focus on human requirements

- Still a brand new space (relatively)
  - Unlicensed-band technologies in last 5 years: Sigfox and LoRaWAN
  - Cellular technologies in last 2 years: LTE-M and NB-IoT

- Focus on long-range, low-energy, low-throughput
  - One gateway can cover an entire city!!

# Extras

- Extremely active research areas

- Backscatter
  - Insanely low-energy communication
  - Enables energy-harvesting indoor devices

- Localization
  - How do we find all this stuff?
  - And how do devices determine where they are relative to each other?

- Other topics are possible if desired. Tell me what focus you want.

# Why use wireless?

- There are no wires!

- No need to install and maintain wires
  - Reduces cost
  - Simplifies deployment – place devices wherever makes sense

- Supports mobile users
  - Move around office, campus, city
  - Move devices around home

# What is hard about wireless?

- There are no wires!

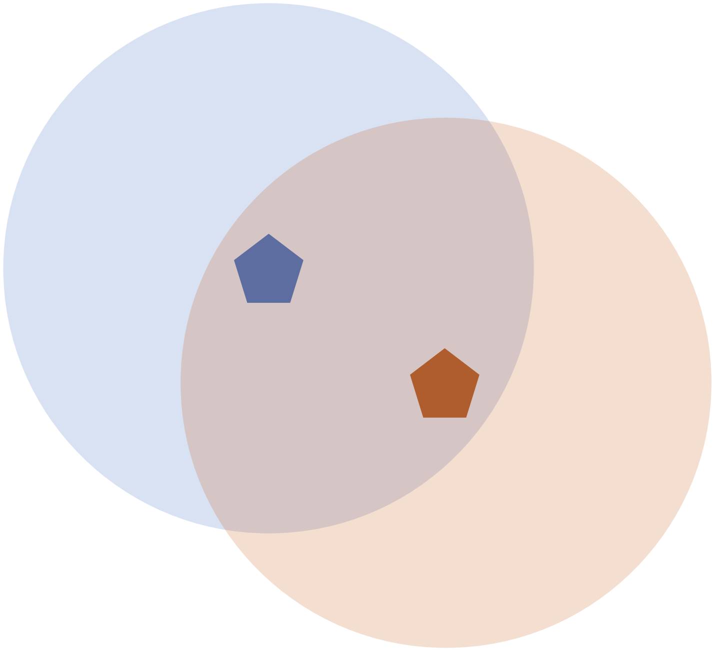
- Wired networks are constant, reliable, and physically isolated
  - Ethernet has the same throughput minute-to-minute
  - Bits sent through Ethernet or USB are (usually) received

- Wireless networks are variable, error-prone, and shared
  - WiFi throughput changes based on location and walls
  - Signals from nearby devices interfere with your signals
  - Individual bits might flip or never be heard at all

# Wireless is a shared medium

- Wired communication has signals confined to a conductor
  - Copper or fiber
  - Guides energy to destination
  - Protects signal from interference

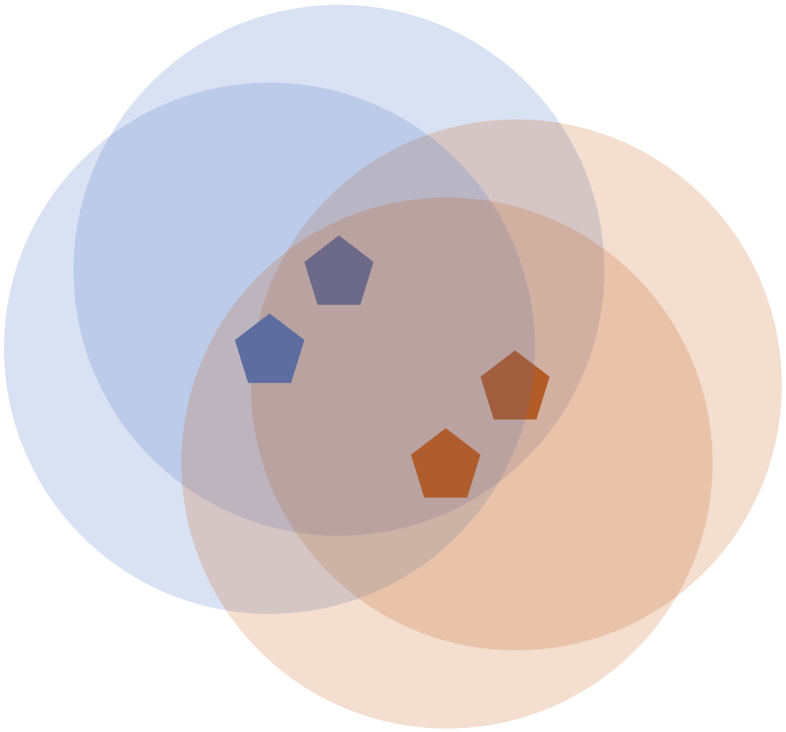
- Wireless communication is inherently broadcast
  - Energy is distributed in space
  - Signals must compete with other signals in same frequency band



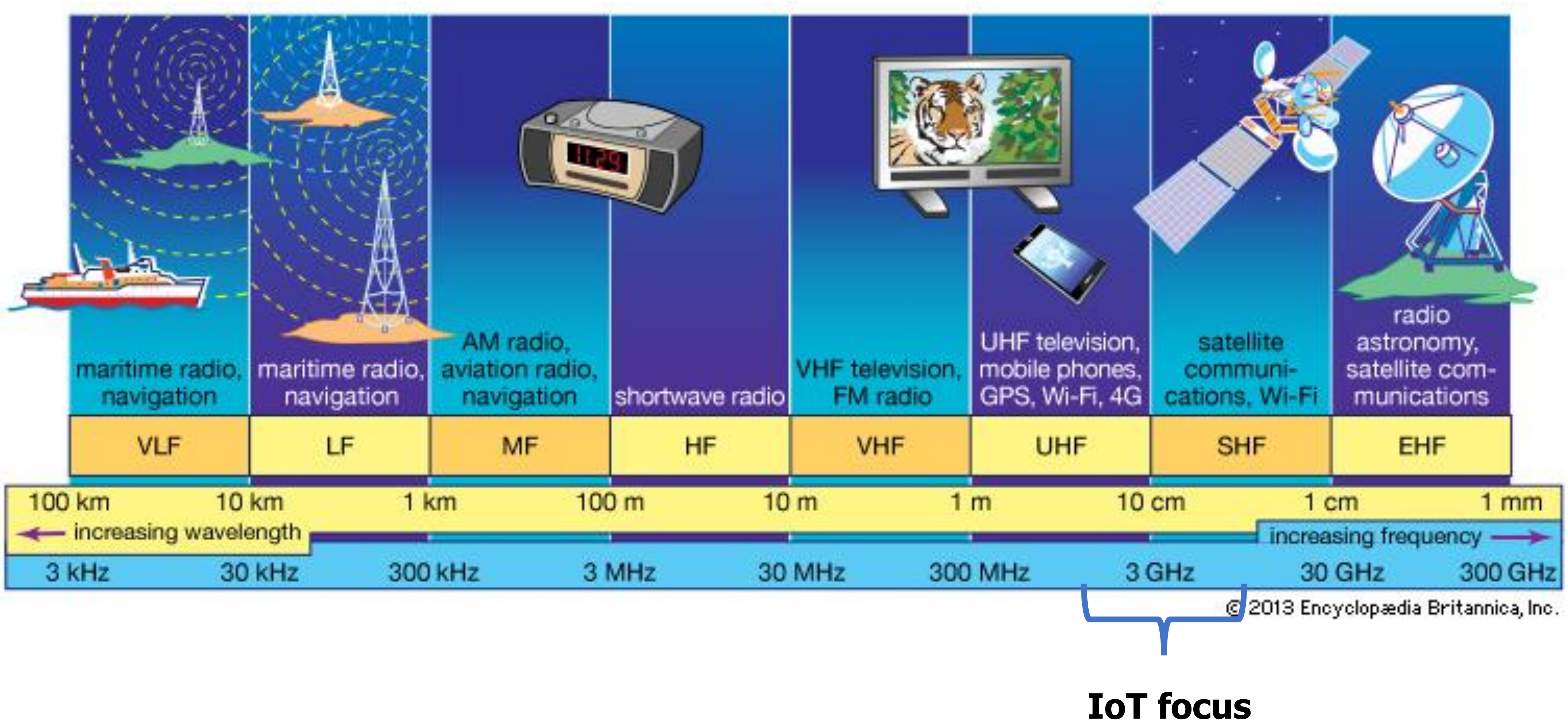
# Increasing network capacity is challenging

- Wired networks just add more wires
  - Buses are many signals in parallel to send more data

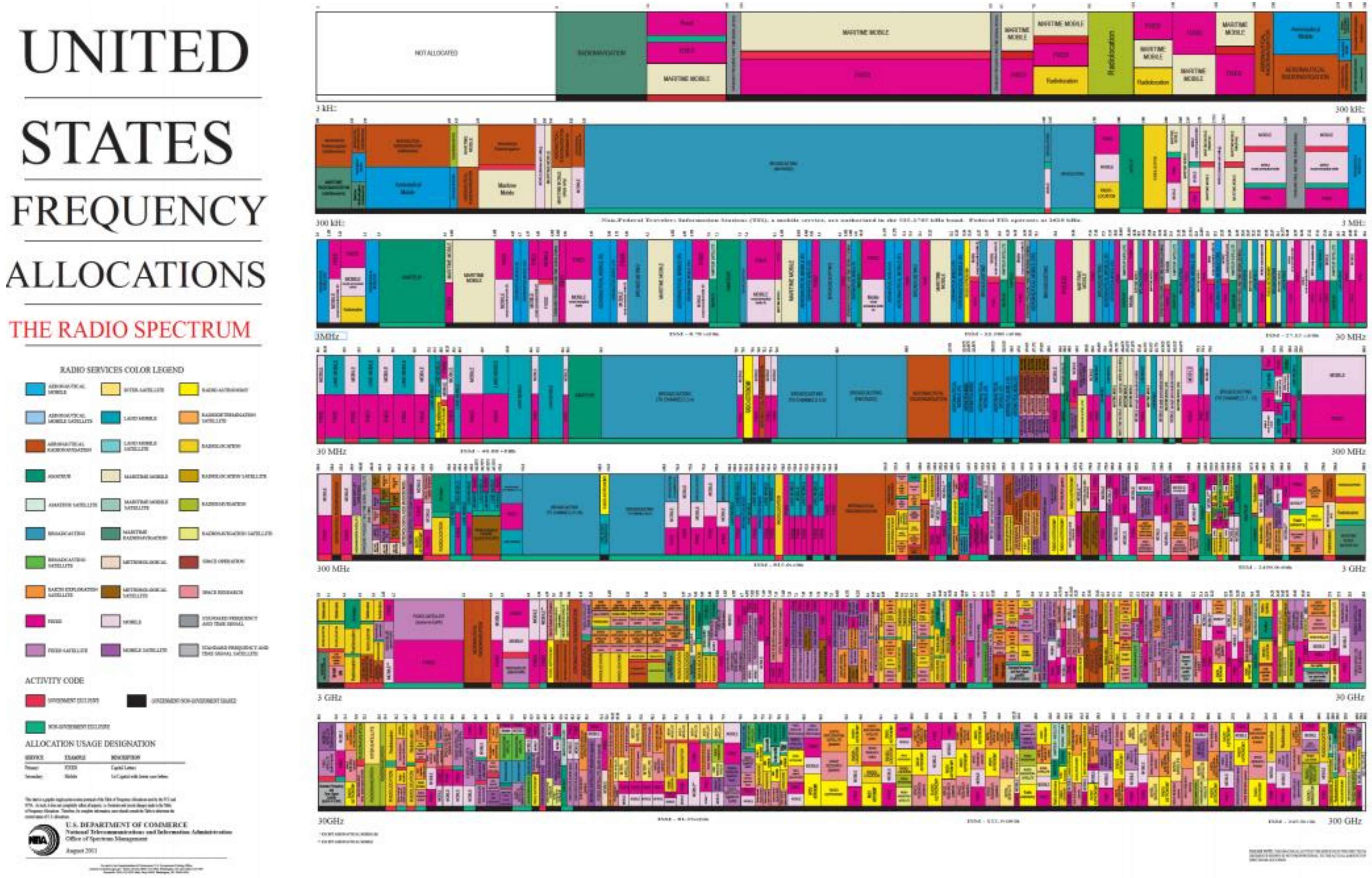
- Wireless networks are harder
  - Adding more links just increases interference
  - Need to expand to different frequencies



# RF communication

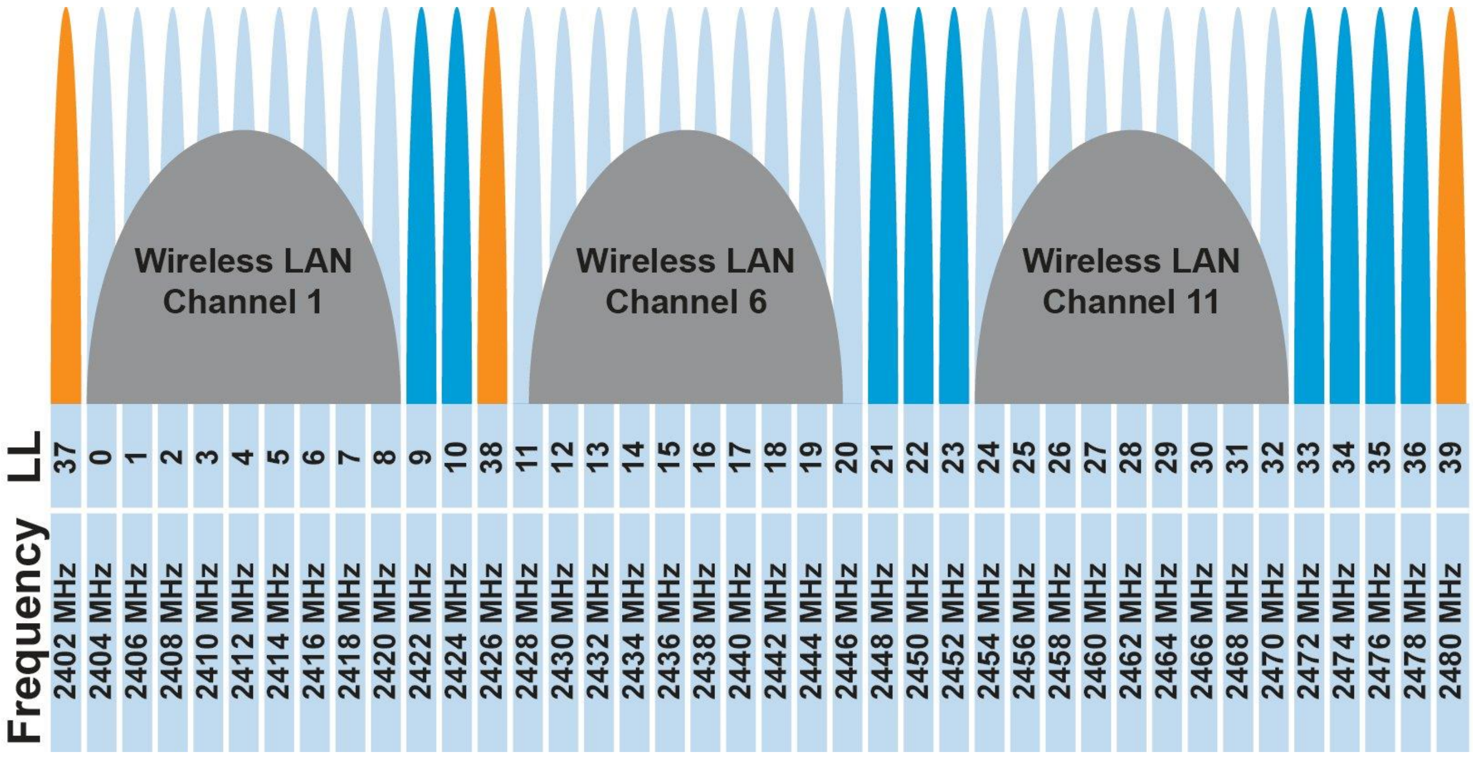


# Wireless spectrum is allocated to specific uses



# Unlicensed bands are where IoT thrives

- 902 MHz – 928 MHz
  - LPWANs
- 2.4 GHz to 2.5 GHz
  - WiFi, BLE, Thread
- 5 GHz
  - Faster WiFi
- Cellular uses licensed bands

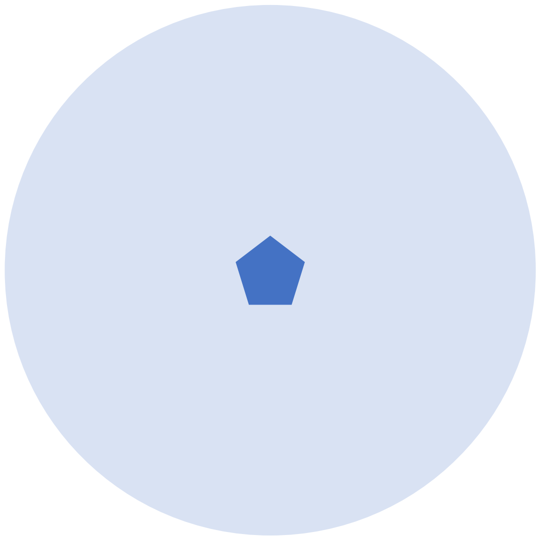


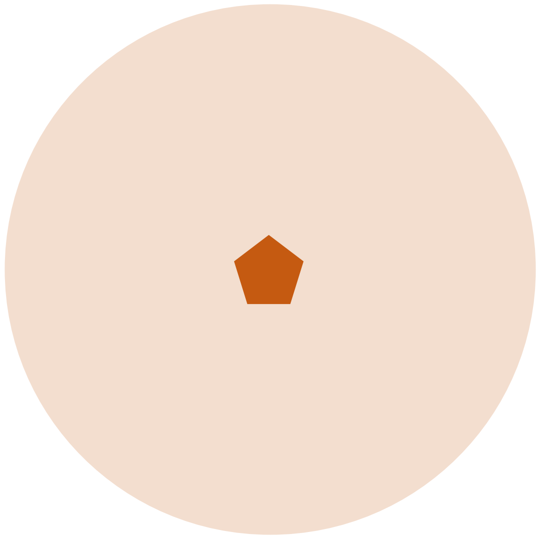
# Model of RF communication

- Energy that radiates spherically from an antenna

- Attenuation with distance
  - Density of energy reduces over time, distance
  - Signal strength reduced, errors go up

- Two key features
  - Error rates depend on distance
  - Spatial reuse of frequencies





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