Introduction to Embedded Systems

Lecture 8

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Announcements

- Project feedback has been sent out.
- **Please respond by EOD with your revisions and finalized parts list with purchase links**
- Midterm exams are being graded
- Lab 4 section tomorrow (11/5) **over Zoom**
  - Drop by Lab 058 with questions from 3-5PM
- Lab 4 and HW 4 are due November 12th
- Lab 4 document has been updated
  - Use oscilloscope to visualize the sine wave

Last lecture …

- Overview of Analog Signals in Embedded Systems
  - Sampling Signals
  - Data Conversion

- Analog to Digital Converters (ADC)

Today we are going to learn about …

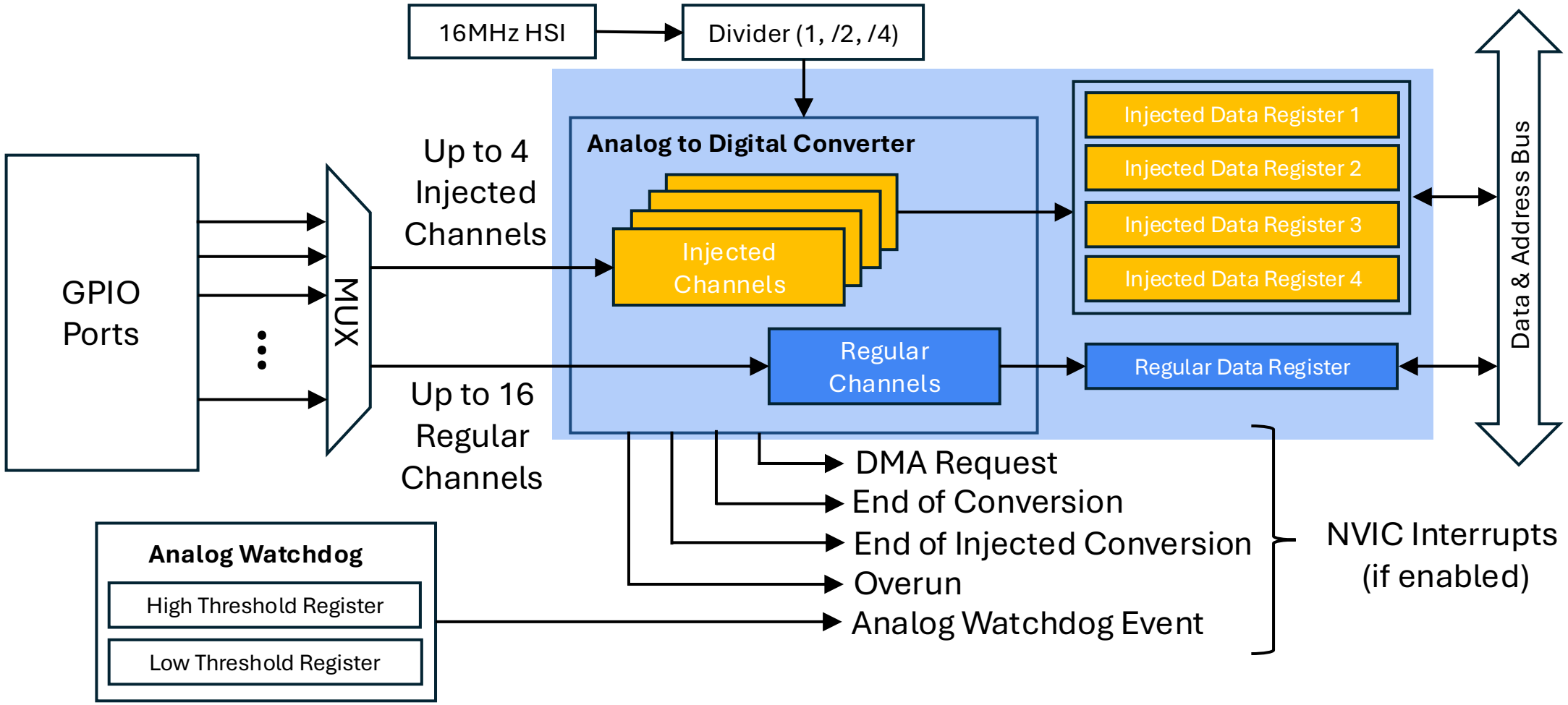
- Quick recap
- Wrap up digital-to-analog conversion (DAC)
- Wireless communication!

Reading

- **STM RM0432 Reference Manual**
  - Section 22: Digital-to-analog converter (DAC)

- **Embedded Systems with ARM Cortex-M Microcontrollers in Assembly Language and C: Third Edition**
  - Chapter 21: Digital to Analog Converters

STM32L4 ADC


16MHz HSI
Divider (1, /2, /4)
Analog to Digital Converter
Injected Data Register 1
Injected Data Register 2
Injected Data Register 3
Injected Data Register 4
Data & Address Bus
GPIO Ports
MUX
Up to 4 Injected Channels
Injected Channels
Regular Channels
Regular Data Register
Up to 16 Regular Channels
DMA Request
End of Conversion
End of Injected Conversion
Overun
Analog Watchdog Event
NVIC Interrupts (if enabled)
Analog Watchdog
High Threshold Register
Low Threshold Register

ADC Conversion Modes

The ADC module performs conversions on selected channels in either **single-conversion mode** or **continuous-conversion mode**.

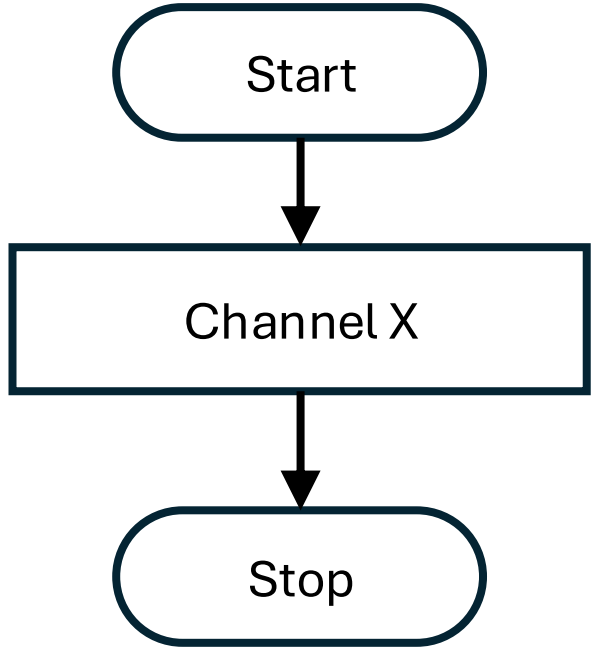
SQR = Sequence Register
EOCIE = End of Conversion Interrupt Enable
IER = Interrupt Enable Register

ADC Conversion Mode

Single Conversion On One Input Channel

(Regular Group)

1. The target channel is determined by the SQ1[4:0] bits in the SQR1 register
2. The 16-bit ADC data register (ADC_DR) holds the conversion result
3. After the conversion, the *end of regular conversion flag* (EOC) is set in the ISR register.
4. The ADC module generates an interrupt request if the EOCIE bit is set in the interrupt enable register (IER)



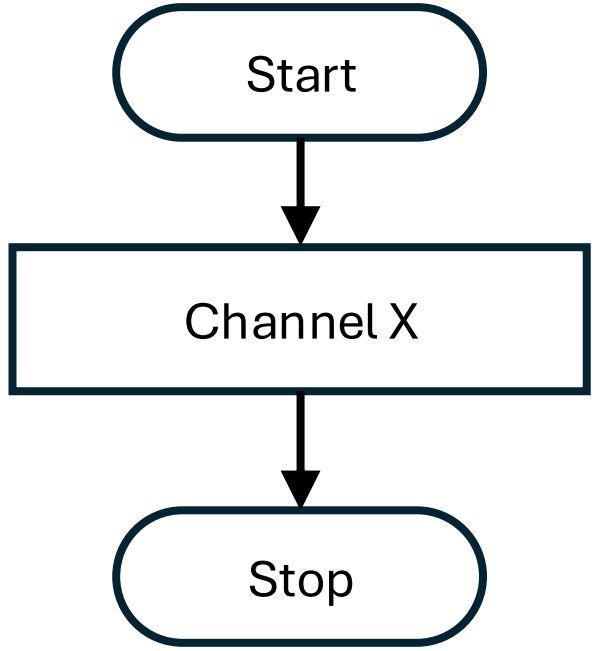
ADC Conversion Mode

J = Injected

Single Conversion On One Input Channel

(Injected Group)

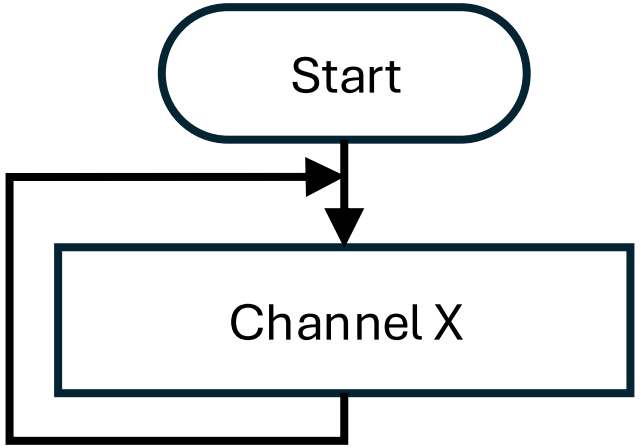
1. The JSQ1[4:0] bits in the JSQR register selects conversion channel
2. The 16-bit register (ADC_JDR1) holds the conversion result
3. After the conversion, the *end of injected conversion flag* (EOC) is set in the ISR register.
4. The ADC module generates an interrupt request if the JEOCIE bit is set in the interrupt enable register (IER)



ADC Conversion Mode

Single Channel, Continuous Conversion

- ADC module automatically starts a new conversion immediately after it finishes one.
- The last conversion result is saved in the ADC_DR register for a regular channel and in the ADC_JDR1 register for an injected channel
- CONT bit in the CFGR register enables continuous mode

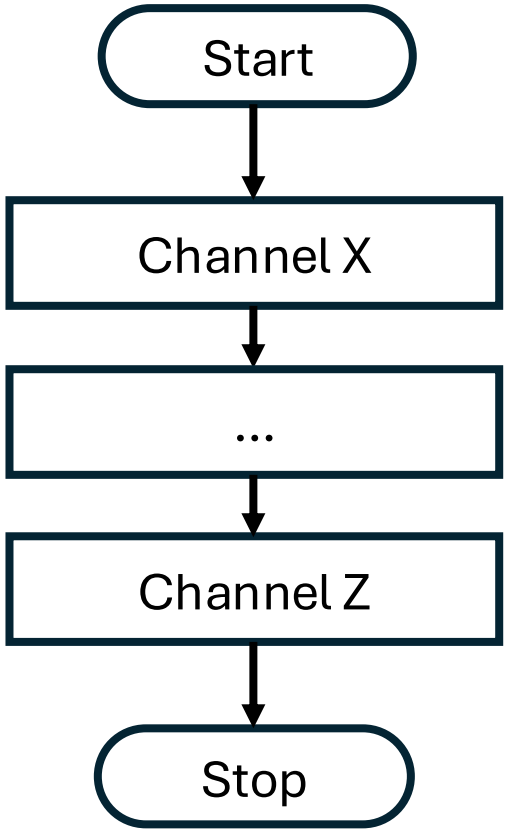


ADC Conversion Mode

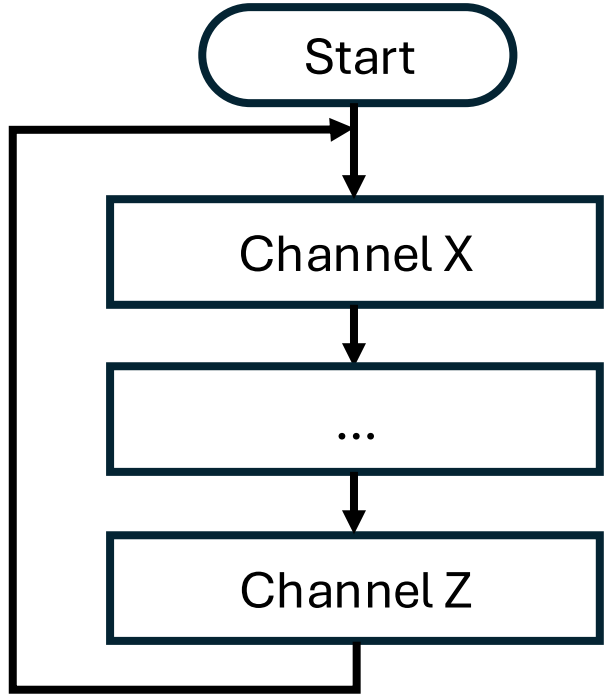
Scan Mode: The ADC module can perform sampling and conversion on a set of pre-defined input channels in a round-robin fashion.

Regular:
Channels selected by ADC_SQRx

Injected:
Channels selected by ADC_JSQR



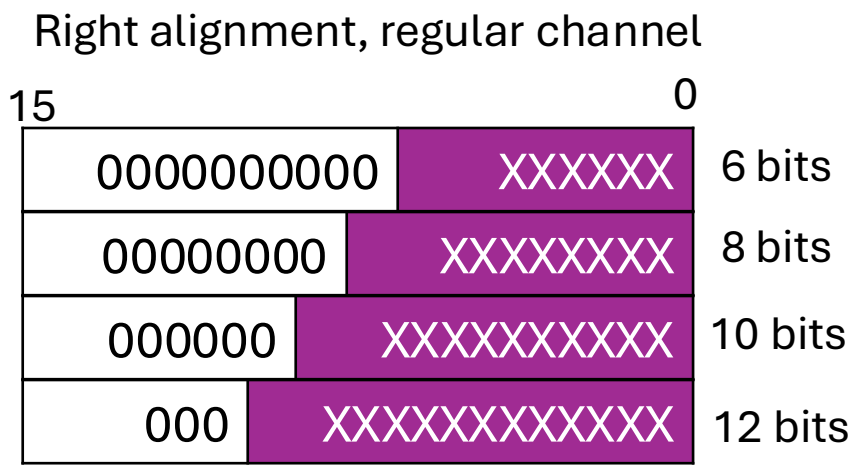
Scan with Single Conversion

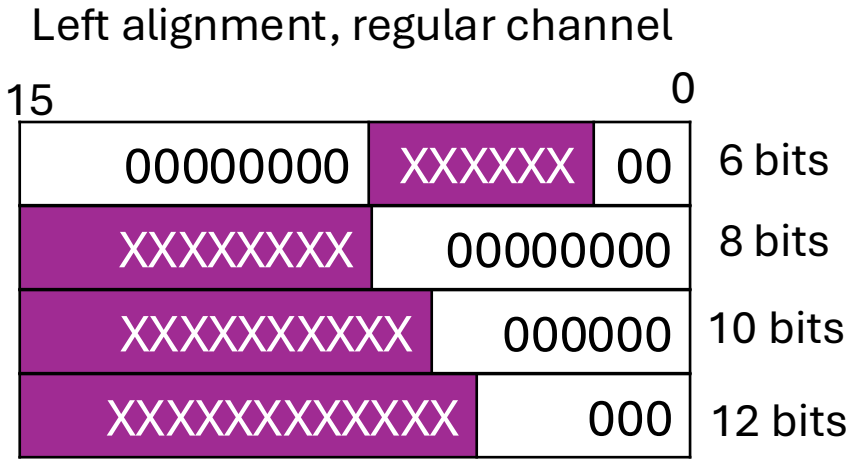


Scan with Continuous Conversion

ADC Data Alignment

- Software can change the ADC resolution (12, 10, 8, or 6 bits)
- Each ADC data register has 16 bits





Digital to Analog Conversion

What is a digital-to-analog converter (DAC)?

A digital-to-analog converter (DAC) transforms a finite-precision digital number to an analog voltage

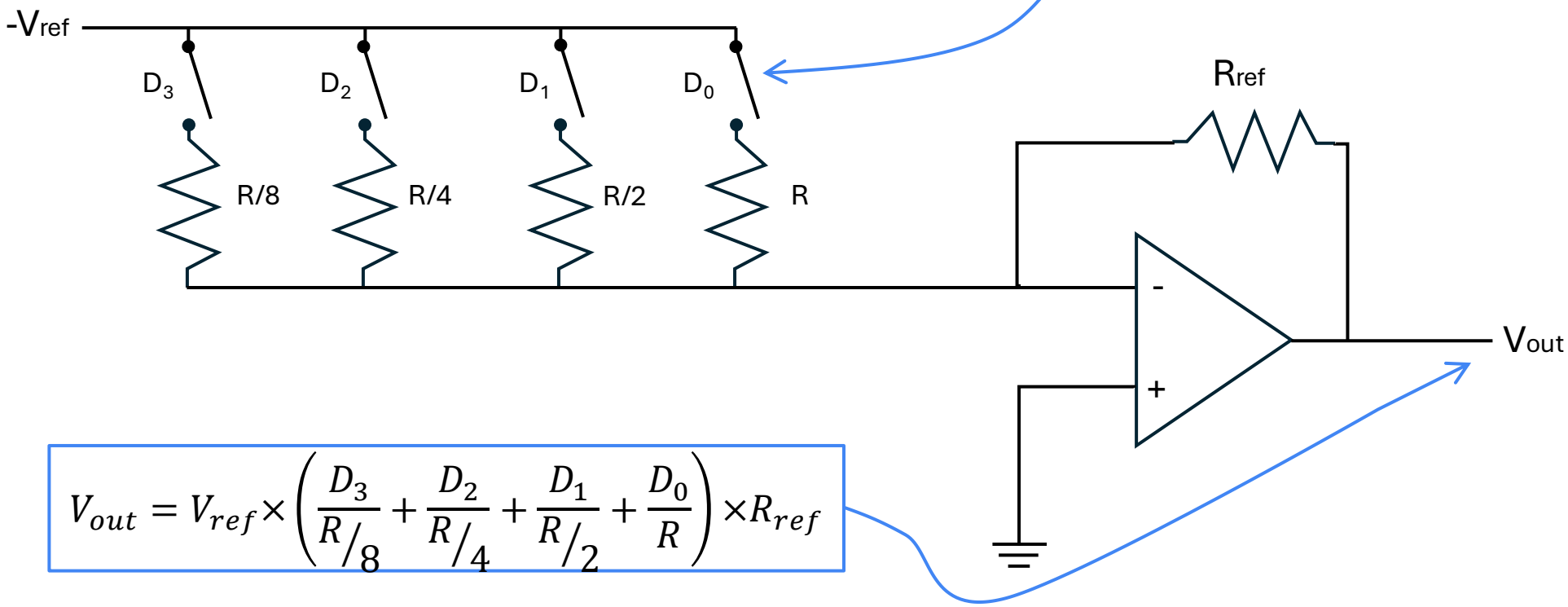
Example →



DAC Architecture

A four-bit digital-to-analog converter (DAC)

$$D_i = \begin{cases} 0, & switch\ is\ open \\ 1, & switch\ is\ closed \end{cases}$$



$$V_{out} = V_{ref} \times \left(\frac{D_3}{R/_8} + \frac{D_2}{R/_4} + \frac{D_1}{R/_2} + \frac{D_0}{R} \right) \times R_{ref}$$

DAC Characteristics

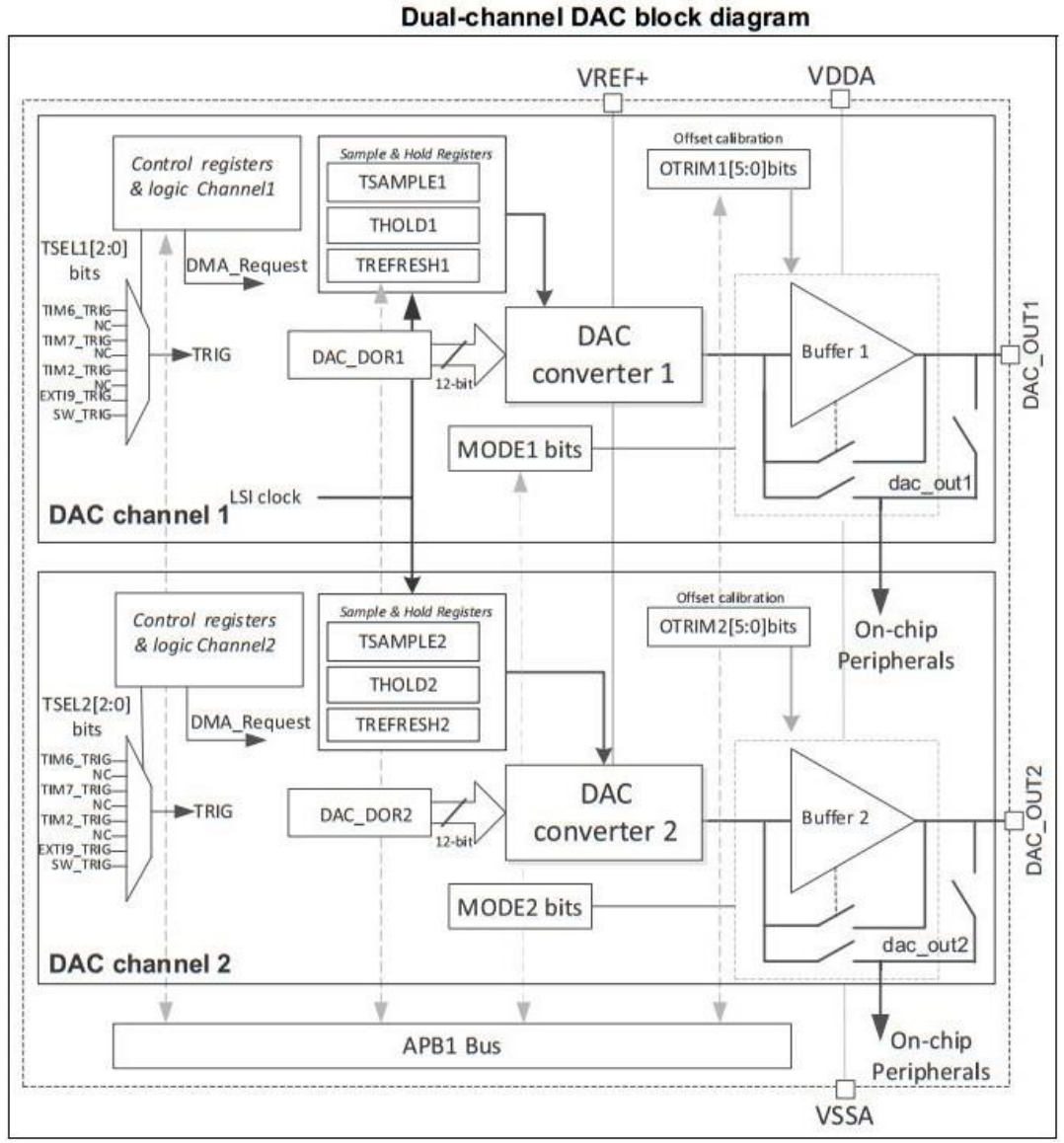
- **Precision:** the number of distinguishable DAC outputs (e.g., 1024 alternatives, 10bits)
- **Range:** the maximum and minimum DAC output
- **Setting Time:** the interval from an update of a DAC's digital input to the instant when the DAC output becomes stable within a specified percentage
- **Resolution:** the smallest change that occur in the analog output as the digital input varies (the change in output that occurs when the
- **Glitch:** the first peak transient that appears at the DAC output

DAC on the STM32L

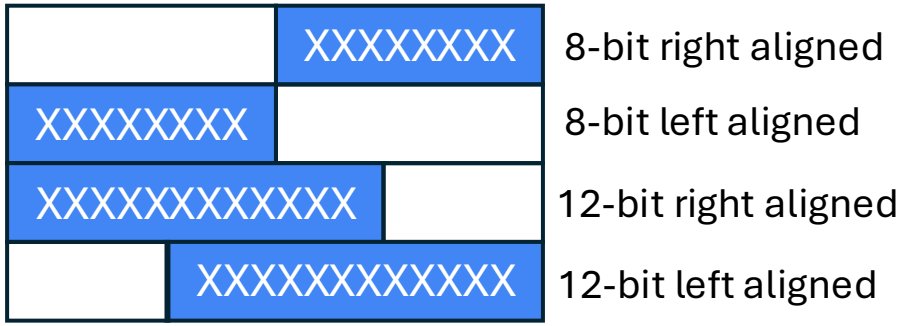
STM32L processor has two independent DAC converters, with one channel in each converter

Can be configured as a resolution of 8-bits or 12-bits

Two converters can update their output signals independently or synchronously



DAC on the STM32L



Data Holding Registers (DHR)

- 12-bit right-aligned DHR (DHR12R)
- 12-bit left-aligned DHR (DHR12L)
- 8-bit right-aligned DHR (DHR8R)
- 8-bit left-aligned DHR (DHR8L)

Control Logic

Noise generator
Triangle wave generator

Data Output Register (DOR), 12 bits

Analog Power Supply (V_{DDA})
Voltage Reference (V_{REF})
Analog Ground (V_{SSA})

Digital to Analog Converter

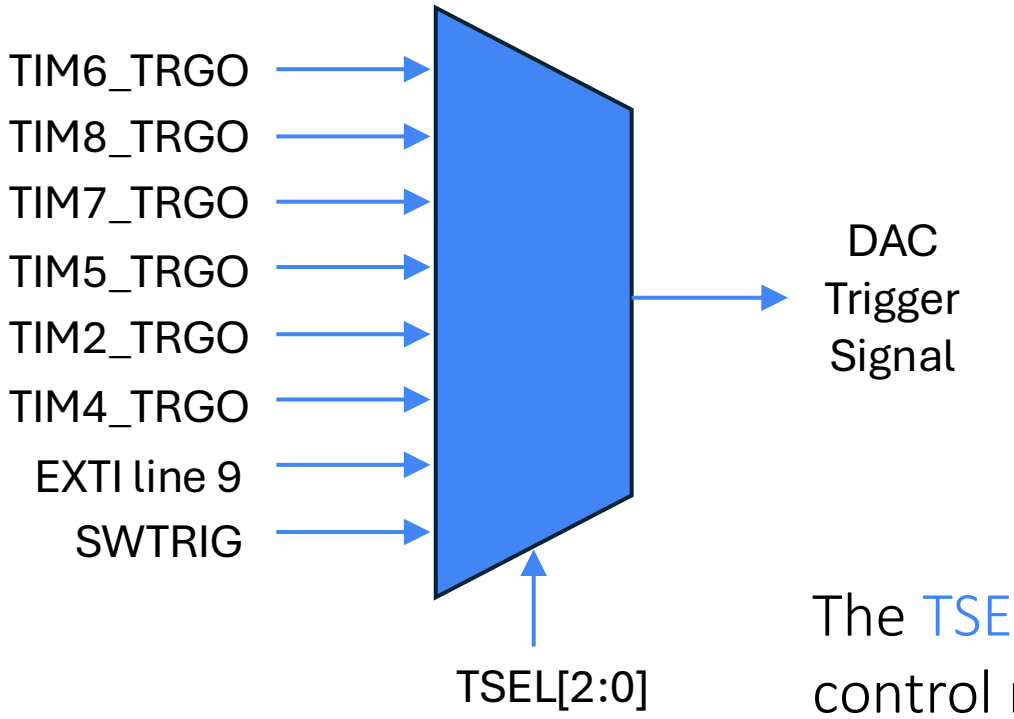
V_{OUT}

Conversion Trigger

Software triggers, external timers, and internal timers can trigger DAC conversions

Timer Trigger:
Conversion starts after detecting the rising edge of timer trigger output

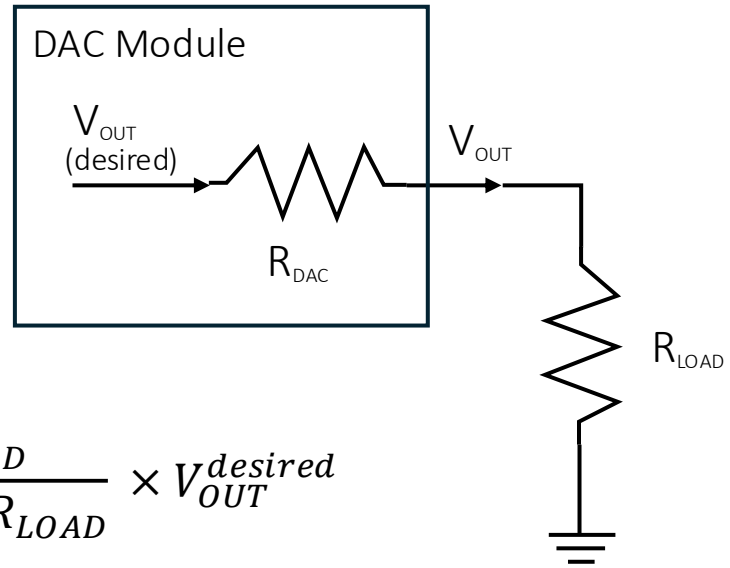
Software Trigger:
Conversions starts after the trigger bit in DAC_SWTRIGR is set by software



The TSEL bits in the control register (DAC_CR) select the DAC trigger

Loading Effects

When the DAC output is used to drive an external load (e.g., earphones) the voltage output may be lower than the desired value due to loading effects

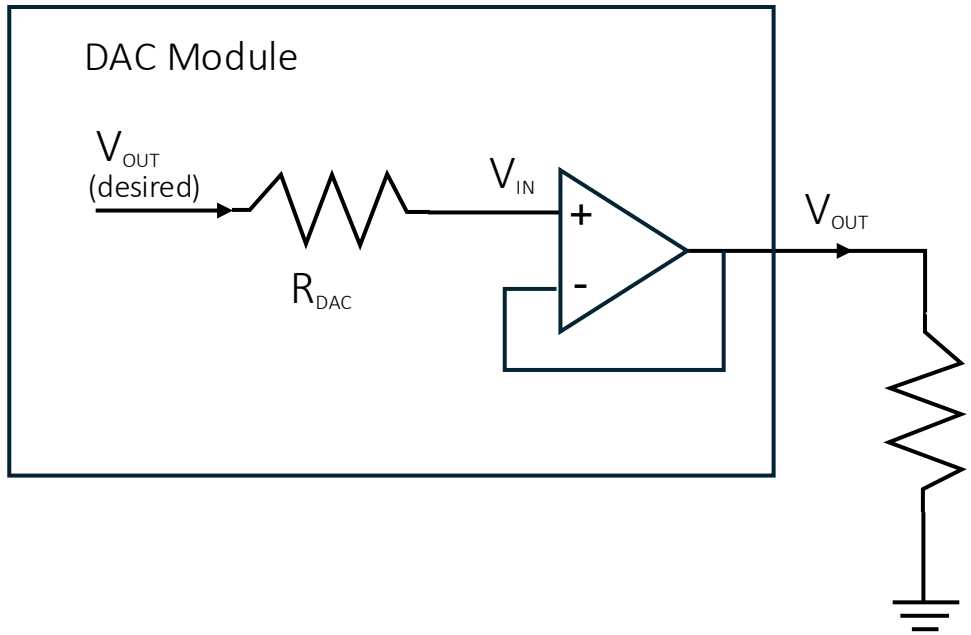


$$V_{OUT} = \frac{R_{LOAD}}{R_{DAC} + R_{LOAD}} \times V_{OUT}^{desired}$$

How do we fix this?

Buffered Output

Use an internal output buffer to avoid the load impedance problem!



Close to infinity

$$V_{IN} = \frac{R_{IN,Buffer}}{R_{DAC} + R_{IN,Buffer}} \times V_{OUT}^{desired} \approx \frac{\infty}{R_{DAC} + \infty} \times V_{OUT}^{desired} \approx V_{OUT}^{desired}$$

Close to zero

$$V_{OUT} = \frac{R_{OUT,Buffer}}{R_{LOAD} + R_{OUT,Buffer}} \times V_{IN} \approx \frac{R_{LOAD}}{R_{LOAD} + 0} \times V_{IN} \approx V_{OUT}^{desired}$$

The output buffer can be enabled or disabled by the DAC_CR_BOF bit in the control register DAC_CR

Wireless Communication

Wireless embedded systems are all around us



Smartphone



Smartwatch



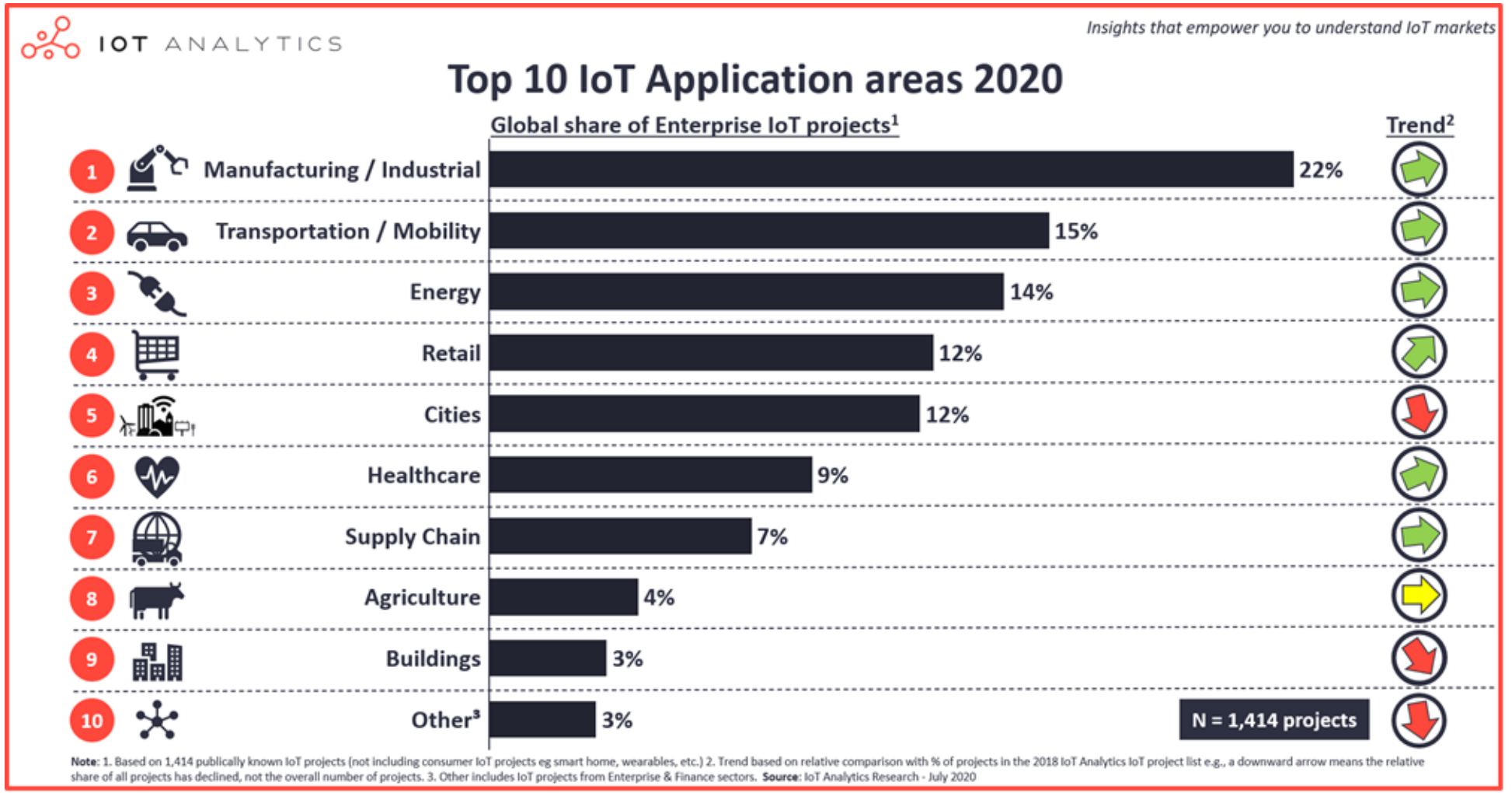
Thermostat



Environmental Sensors

How many *connected* IoT devices are there today?

Where are these technologies used today?



Types of Communication Systems and Connectivity Solutions

Radio and TV Broadcasting



Satellite Connectivity



Bluetooth



LoRa



Computer Networks



Cellular



Wi-Fi



RFID

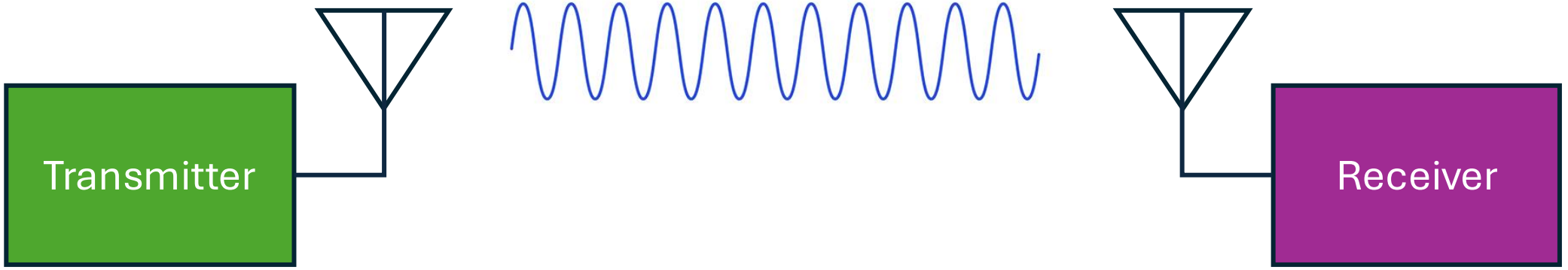


Examples of Communication Channels

- Communication systems convert information into a format appropriate for the transmission medium
- Some channels convey electromagnetic waves (signals)
  - Radio (20 kHz to 20+ GHz)
  - Optical Fiber (200 THz or 1550 nm)
  - Laser line of sight (e.g., from Mars)
- Other channels use sound, smell, pressure or chemical reactions
  - Smell: ants
  - Chemical Reactions: neuron dendrites
  - Dance: bees

Wireless Communication

- **Wireless communication** refers to the transfer of information between two or more points (that are not connected by some physical medium) using **electromagnetic waves** propagating in space



Hardware that generates radio waves is called a transmitter

Hardware that picks up radio waves is called a receiver

Electromagnetic Spectrum

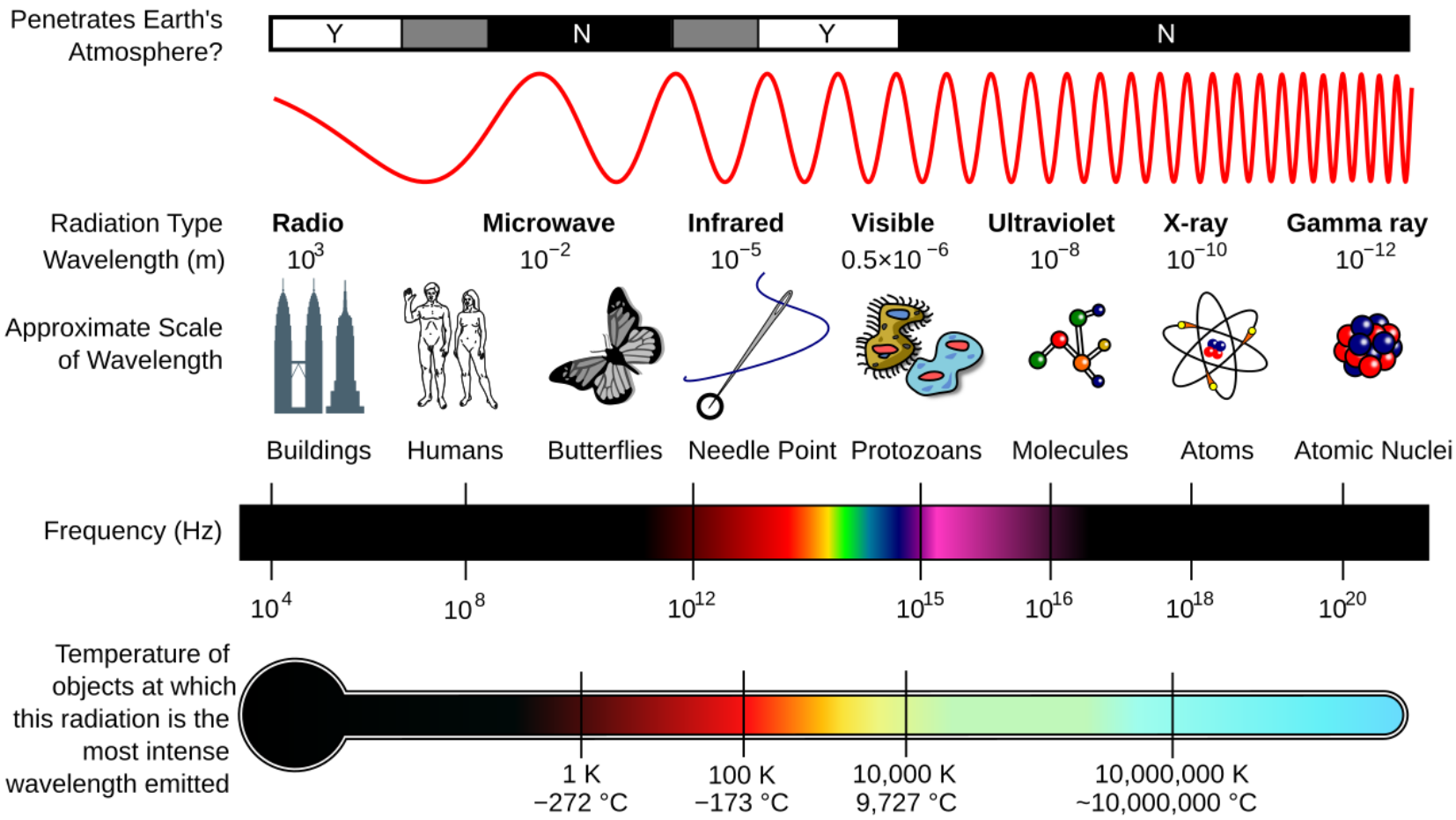
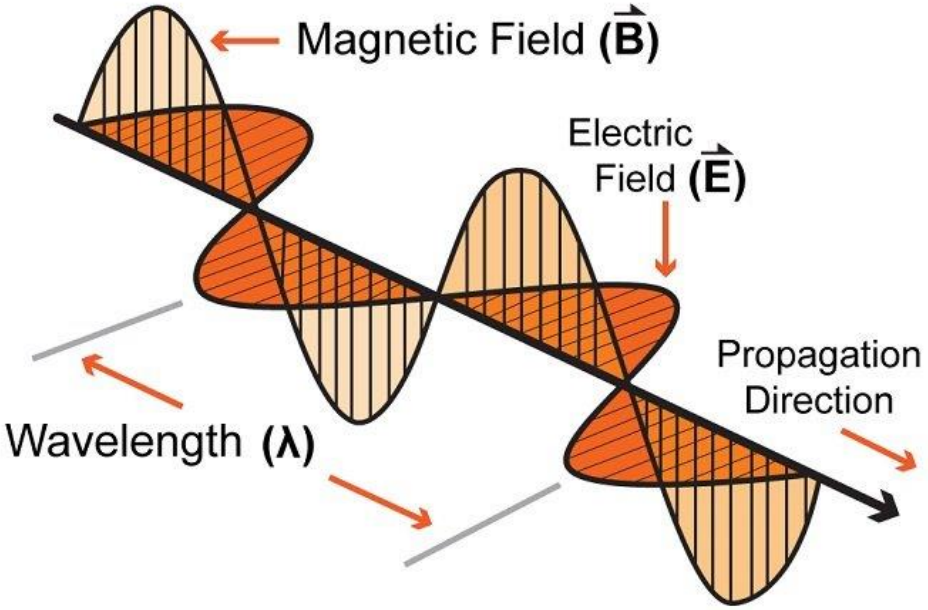


Image Source: Wikipedia

Signal Qualities

- Signal Strength
  - the amount of energy transmitted/received
- Signal frequency & bandwidth
  - Which “channel” the signal is sent on
- Signal modulation
  - How data is encoded in the signal



Signal strength is measured in decibels

- Power is measured in watts or dBw or dBm
  - $Power_{d\mathrm{Bw}} = 10 * \log_{10}(Power_{Watts})$
  - $Power_{d\mathrm{Bm}} = 10 * \log_{10}(Power_{milliwatts})$

- dBm is most relevant to the IoT domain
  - 0 dBm equals 1 mW transmit power

- Rules of thumb: +3 dB is double the power, 10 dB is 10x power

Typical Wireless Power Transmit Levels

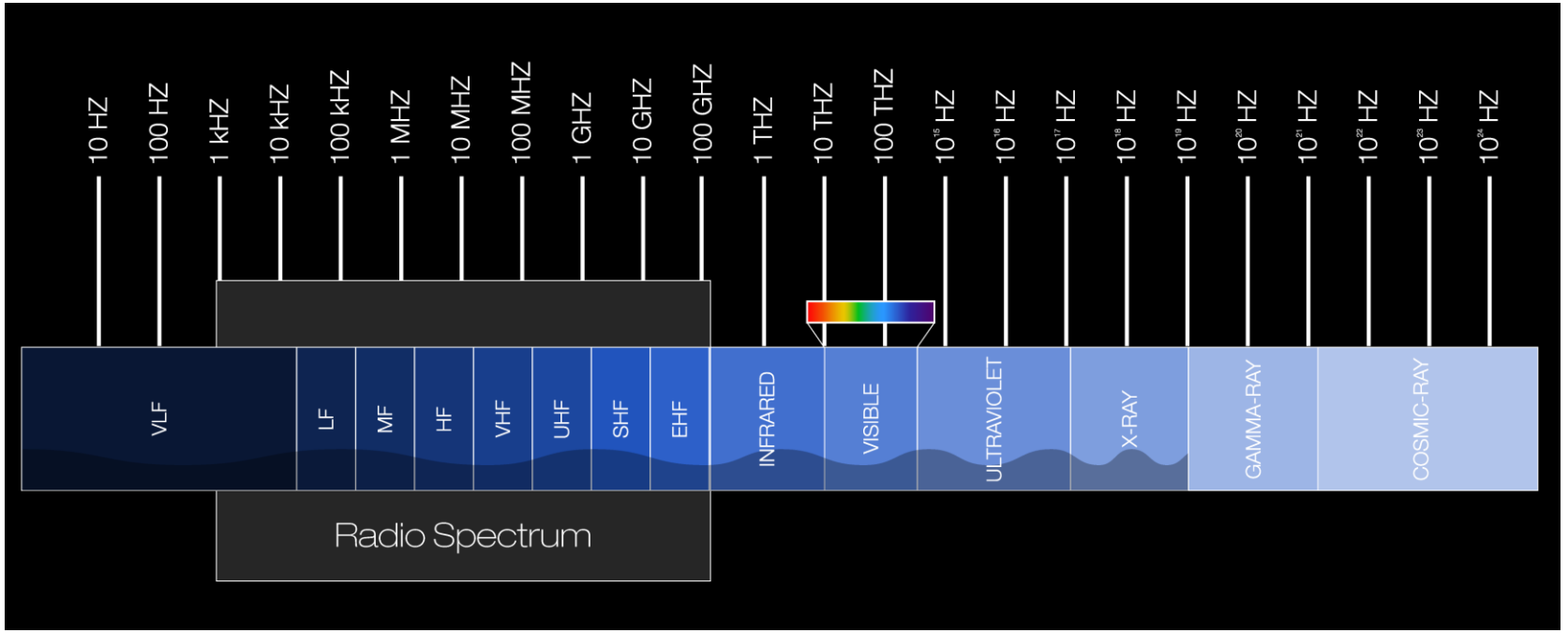
- 100kW = 80 dBm: Typical FM radio transmission with 50 km radius
- 1 kW = 60 dBm: Microwave oven element
- ~300 W = 55 dBm: Geostationary satellite
- 250 mW = 24 dBm: Cellular phone maximum power (class 2)
- 200 mW = 23 dBm: Wi-Fi access point
- 32 mW = 15 dBm: Wi-Fi transmitter in a laptop
- 4 mW = 6 dBm: Bluetooth, 10 meter range
- 1 mW = 0 dBm: Bluetooth, 1 meter range

Signal strength varies significantly across technologies

- Bluetooth Low Energy (local area)
  - nRF52840 transmit power: 8 dBm (6.31 mW)
  - nRF52840 receive sensitivity: -95 dBm (316.2 fW)

- LoRa (wide area)
  - SX127X LoRa transmit power: 20 dBm (100 mW)
  - SX127X LoRa receive sensitivity: -148 dBm (1.6 attoWatt)

Frequency separation enables different wireless technologies to operate simultaneously



LF = Low Frequencies

MF = Medium Frequencies

HF = High Frequencies

VHF = Very High Frequency

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extremely High Frequencies

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

ALLOCATION USAGE DESIGNATION

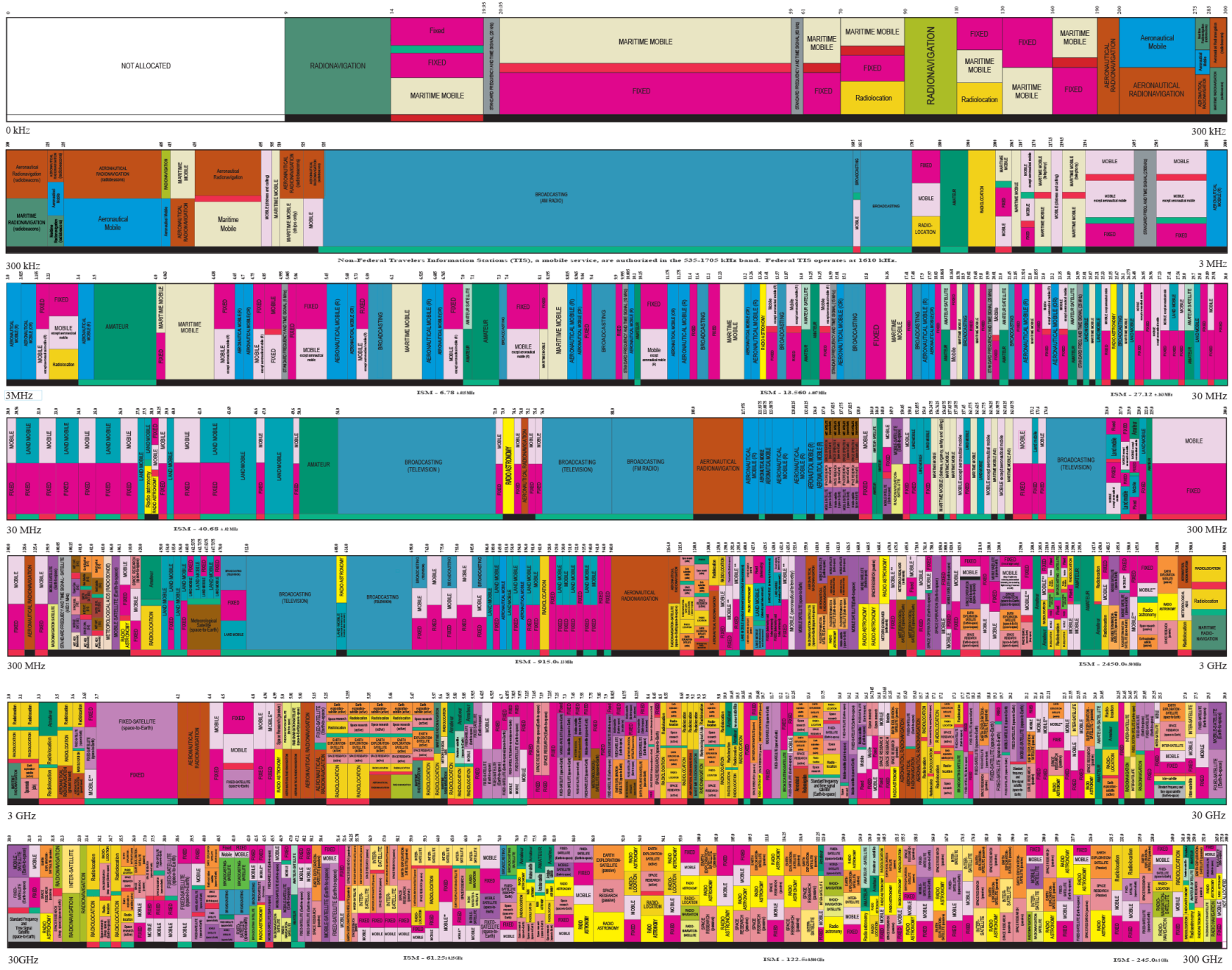
SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it may not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

JANUARY 2016

For sale by the Superintendent of Documents, U.S. Government Printing Office
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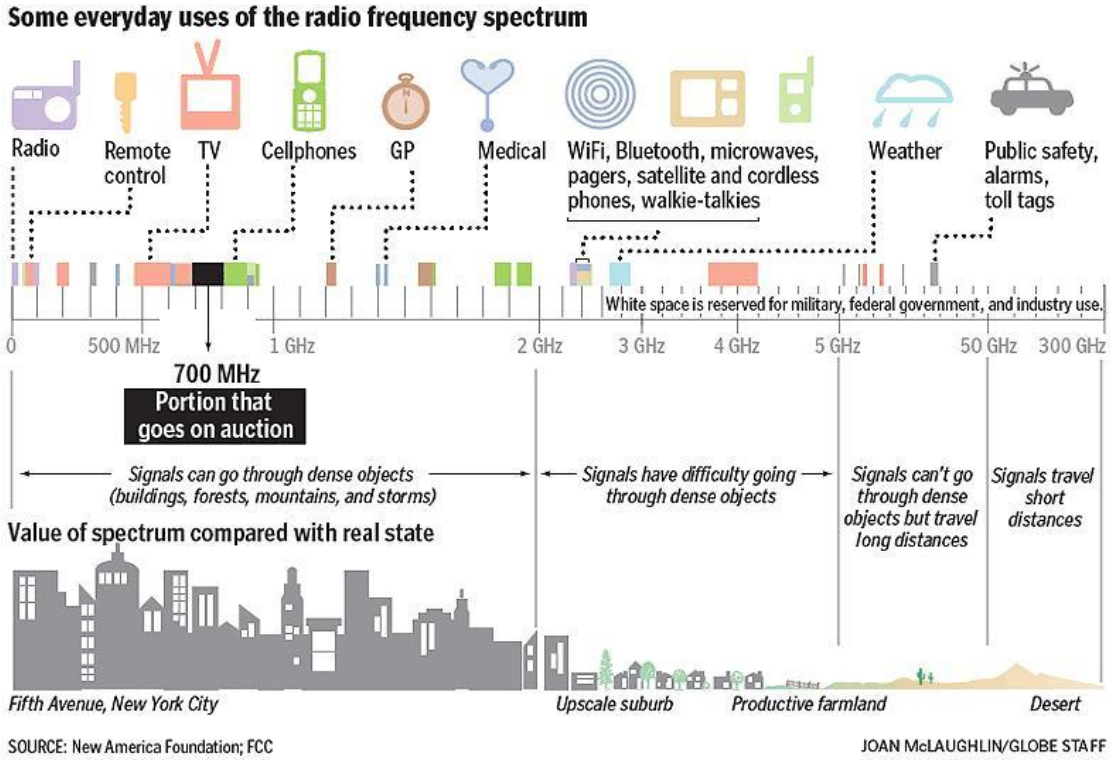
* EXCEPT AERONAUTICAL MOBILE (R)

** EXCEPT AERONAUTICAL MOBILE

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

Wireless spectrum is limited…and valuable

- FCC auctioned off 3.5 GHz spectrum in August 2020
  - 70 MHz
  - $4.6 billion
- FCC auctioned off 2.5 GHz spectrum in 2022
  - $427 million



FCC NEWS from the Federal Communications Commission

Media Contact:
Will Wiquist, (202) 418-0509
will.wiquist@fcc.gov

For Immediate Release

FCC CONCLUDES FIRST 5G MID-BAND SPECTRUM AUCTION

3.5 GHz Spectrum Will Promote Innovation and Advance U.S. Leadership in 5G

WIRELESS

T-Mobile pays $304M to fill in holes in its 2.5 GHz spectrum

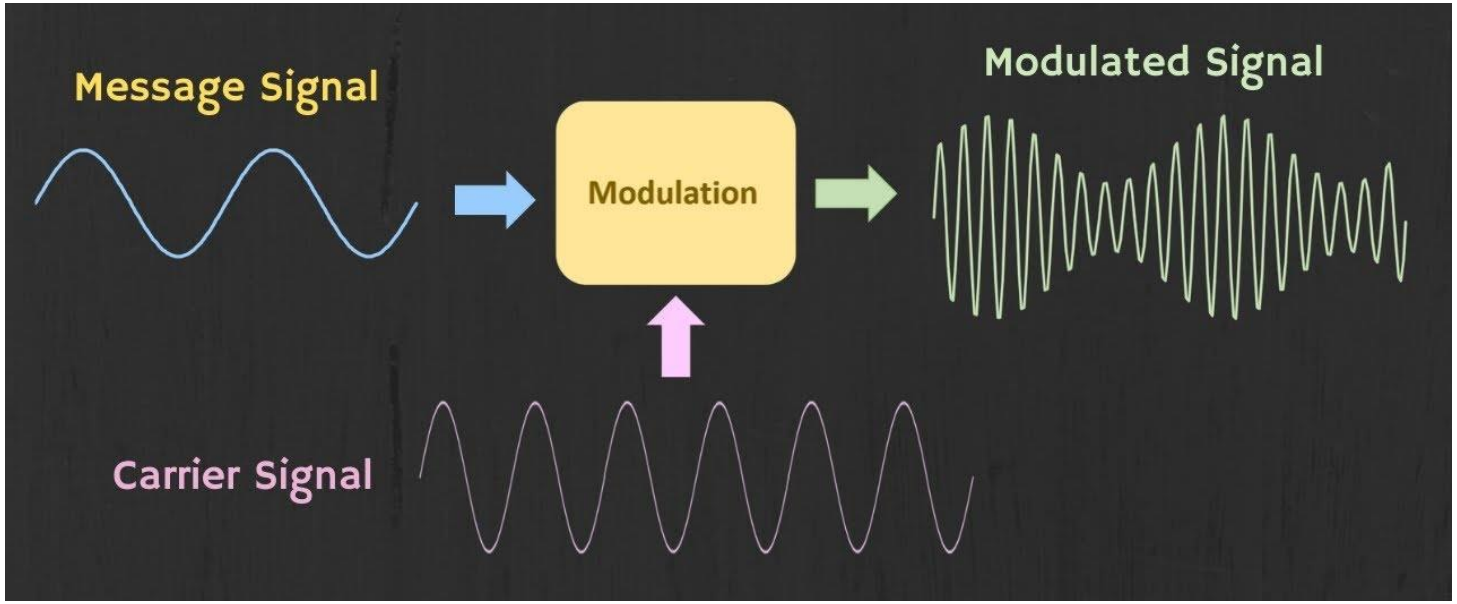
By **Linda Hardesty** · Sep 1, 2022 5:39pm

T-Mobile | 2.5 GHz | spectrum auction

https://www.fiercewireless.com/wireless/t-mobile-pays-304m-fill-holes-its-25-ghz-spectrum

Modulation

- Encoding signal data in an analog “carrier” signal
  - Carrier signal defines the frequency
  - Modulation scheme + data define bandwidth required

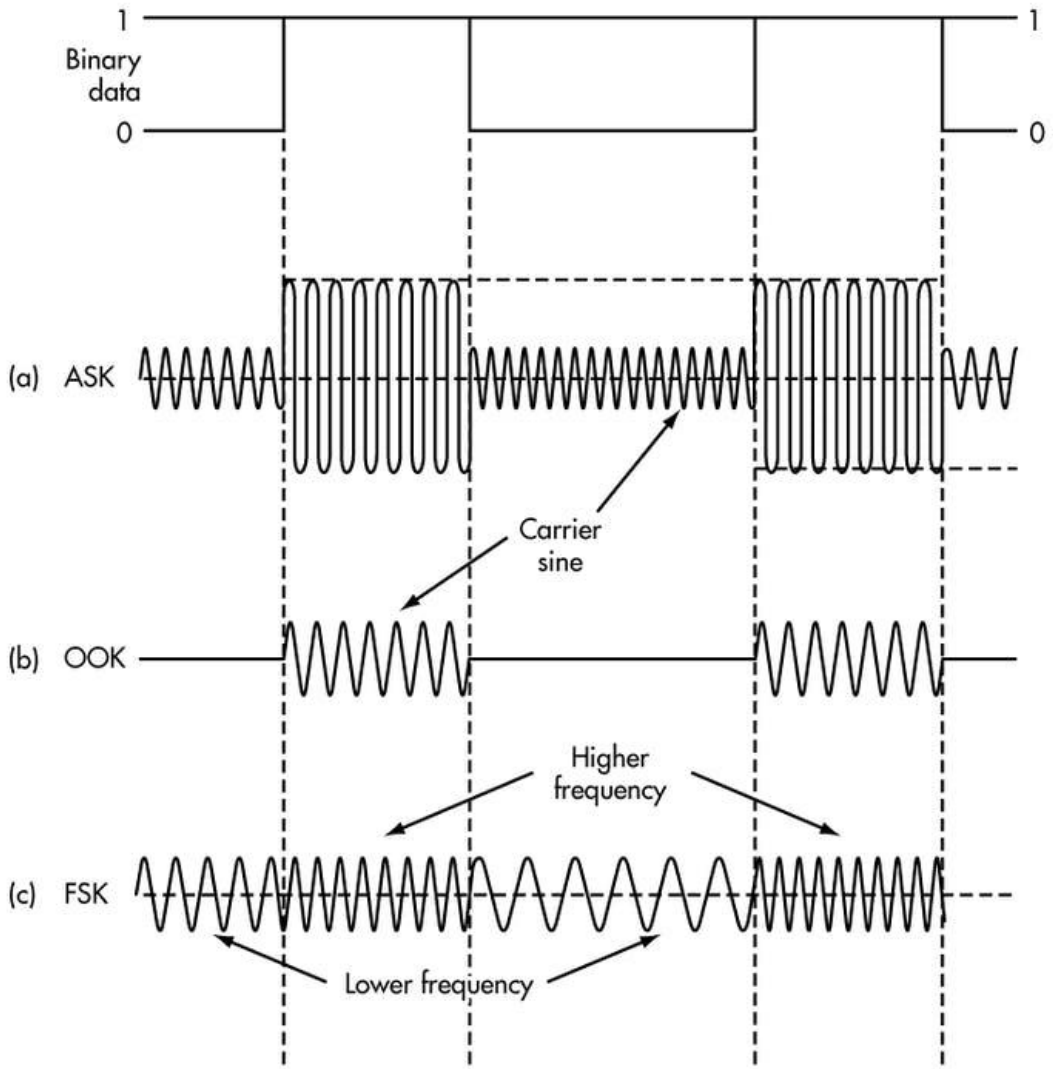


Modulation types

- Encoding binary data on a signal

- Amplitude-shift Keying (ASK)
  - Modify amplitude of carrier signal
  - On-Off Keying (OOK) is an extreme example

- Frequency-shift Keying (FSK)
  - Modify frequency of carrier signal

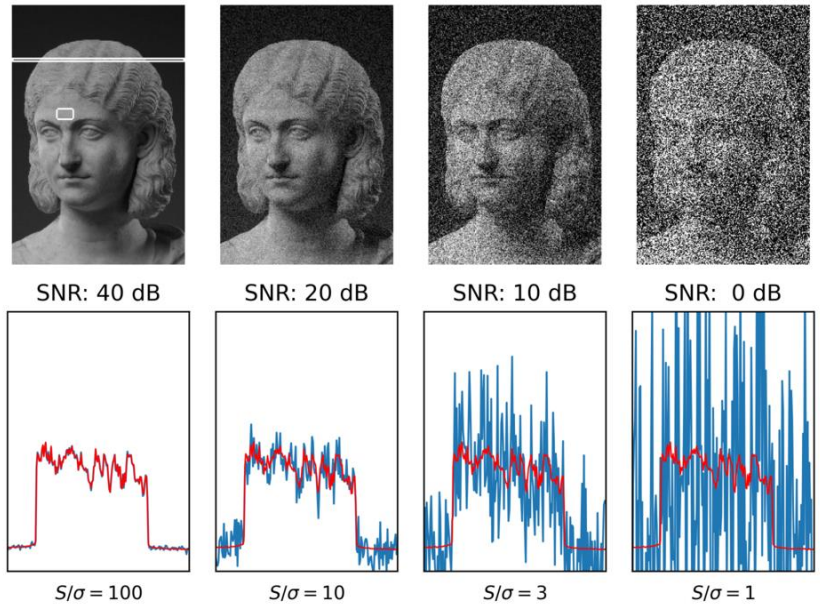


Modulation tradeoffs

- Various tradeoffs between different modulation schemes
  - Bandwidth requirements, transceiver hardware, immunity to noise, etc.
- ASK (amplitude) is simple but susceptible to noise
  - Noise exists in the real world
- FSK (frequency) is relatively simple and robust to noise, but uses more bandwidth
  - Bandwidth is limited, but still commonly used
- PSK (phase) energy efficient and robust, but more complex hardware
  - More expensive hardware, but very commonly used

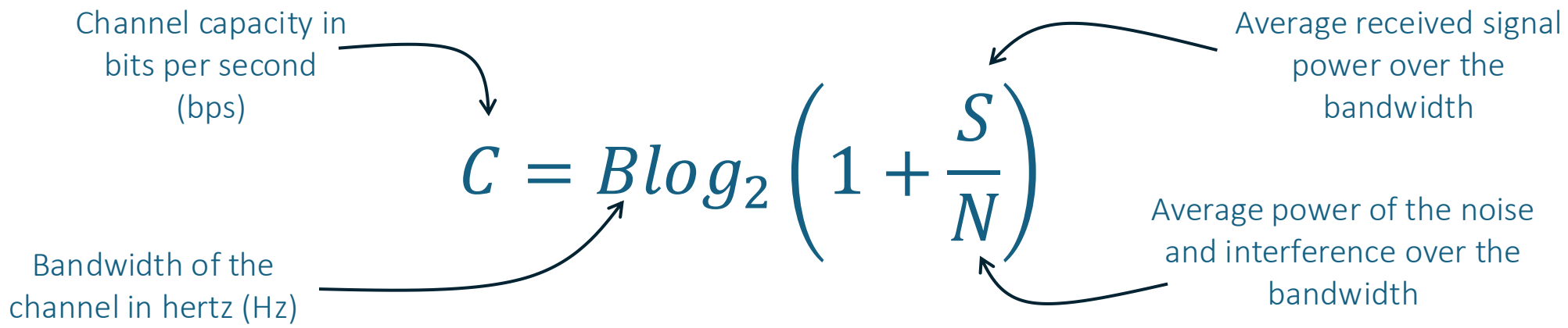
Signal to Noise Ratio

- The signal-to-noise ratio (SNR) compares the signal level to the background level noise.
- It is the ratio of signal power to noise power
- Often expressed in decibels (dB)
  - Greater than 0dB (ratio higher than 1:1) means more signal than noise
- Has an impact on performance and signal reception



Performance Metrics

- **Data rate**, R, is limited by signal power, noise power, and distortion
- In an ideal case (no noise or distortion), data can be transmitted at a rate of $R = \infty$ and have a probability error of 0
- The **Shannon-Hartley theorem** tells us the maximum rate at which information can be transmitted over a communication channel with a specific ***bandwidth*** in the presence of ***noise***.
- For an additive white Gaussian noise (AWGN) channel the Shannon capacity is given as,



Link Budget

- **Link Budget** is analysis of a radio link accounting for all power gains and loss that a signal will experience going from TX to RX
  - Transmitter Power
  - Receiver Power
  - Propagation Loss
  - Antenna Gains

- **Link margin** is a safety margin between RX power and minimum power needed to correctly detect the signal

Link Budget

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} + G_{RX} - L_{RX}$$

P_{RX} = received power (dBm)

P_{TX} = transmit power (dBm)

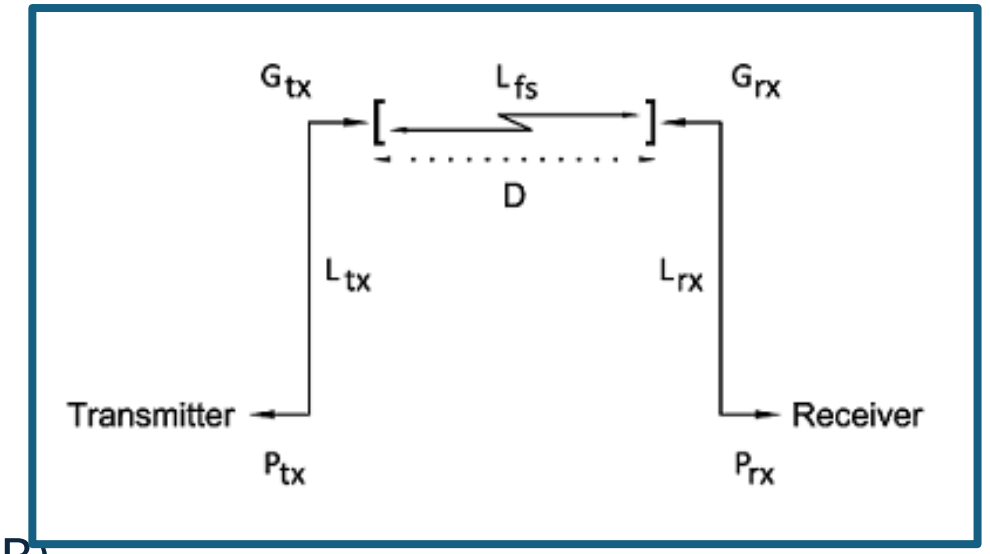
G_{TX} = transmit antenna gain (dBi)

G_{RX} = receiver antenna gain (dBi)

L_{RX} = receiver losses (coax, connectors, …) (dB)

L_{TX} = transmitter losses (coax, connectors, …) (dB)

L_{FS} = path loss (dB)



>> 60 second brainstorm <<

1. Why do we have so many different wireless protocols?

2. Why do we have different protocols for indoor and outdoor applications?

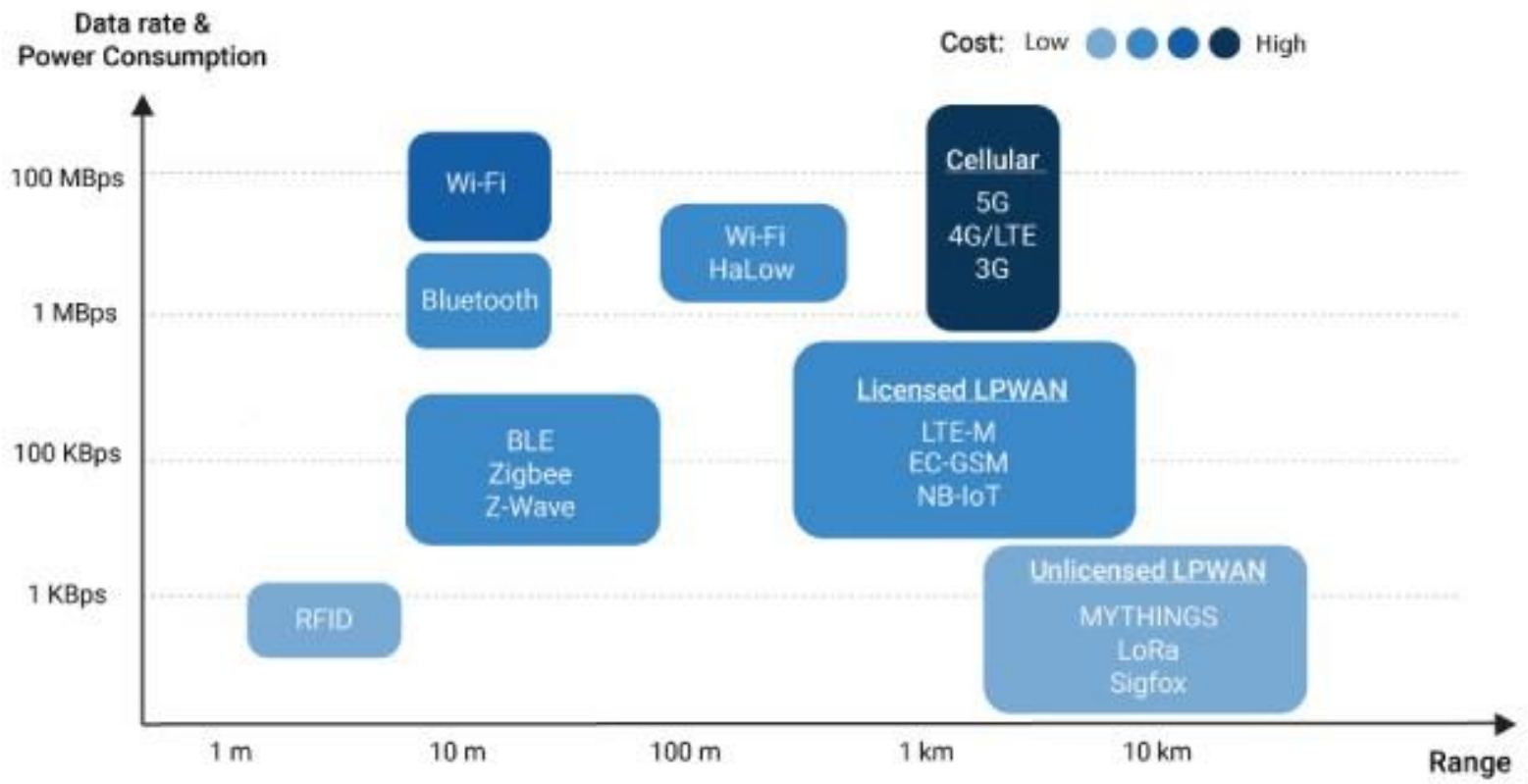
1. What are the tradeoffs?

Tradeoffs

All radios have to make tradeoffs

- Short vs. long distance
- High vs. low power/energy
- High vs. low seeds
- Large vs. small number of devices
- Indoor vs. outdoor usage
- Device-to-device, device-to-infrastructure

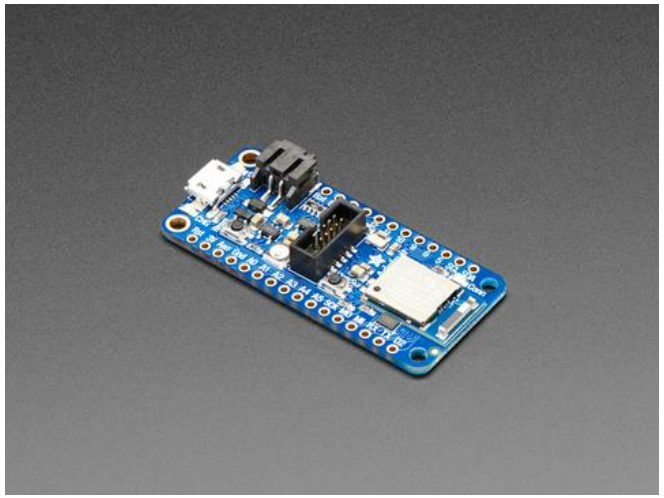
Range vs. Data Rate vs. Cost

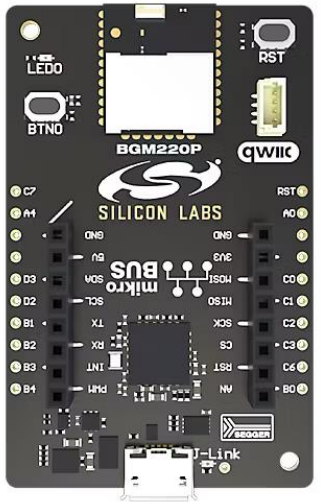


https://behrtech.com/blog/6-leading-types-of-iot-wireless-tech-and-their-best-use-cases/

Bluetooth

- Radio band: 2.4-2.48GHz
- Average 1 Mbps and up to 3Mbps
- Supports point-to-point and point-to-multipoint
  - Creates personal area networks
  - Connects up to 8 devices simultaneously
- 3 class of transmit power
- Frequency hopping communication





Bluetooth: Some History

Invented in 1989 at Ericsson Mobile



Named after a Viking King from the 10th Century

Managed by the Bluetooth Special Interest Group

- Started as IEEE 802.15.1



First consumer device was a Bluetooth headset in 1999

Fun Fact: Frequency hopping communication was invented by actress Hedy Lamarr

UNITED STATES PATENT OFFICE

2,292,387

SECRET COMMUNICATION SYSTEM

Hedy Kiesler Markey, Los Angeles, and George Antheil, Manhattan Beach, Calif.

Application June 10, 1941, Serial No. 397,412

6 Claims. (Cl. 250—2)

This invention relates broadly to secret communication systems involving the use of carrier waves of different frequencies, and is especially useful in the remote control of dirigible craft.

Fig. 2 is a schematic diagram of the apparatus at a receiving station;

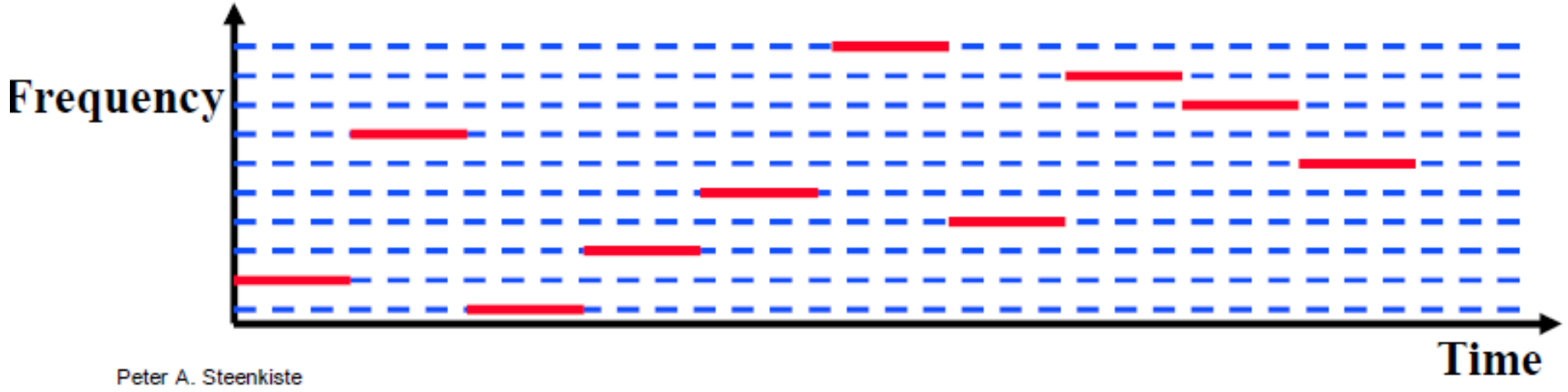
Fig. 3 is a schematic diagram illustrating a starting circuit for starting the motors at the



One Example / Bluetooth Preview: Frequency Hopping Spread Spectrum (FHSS)

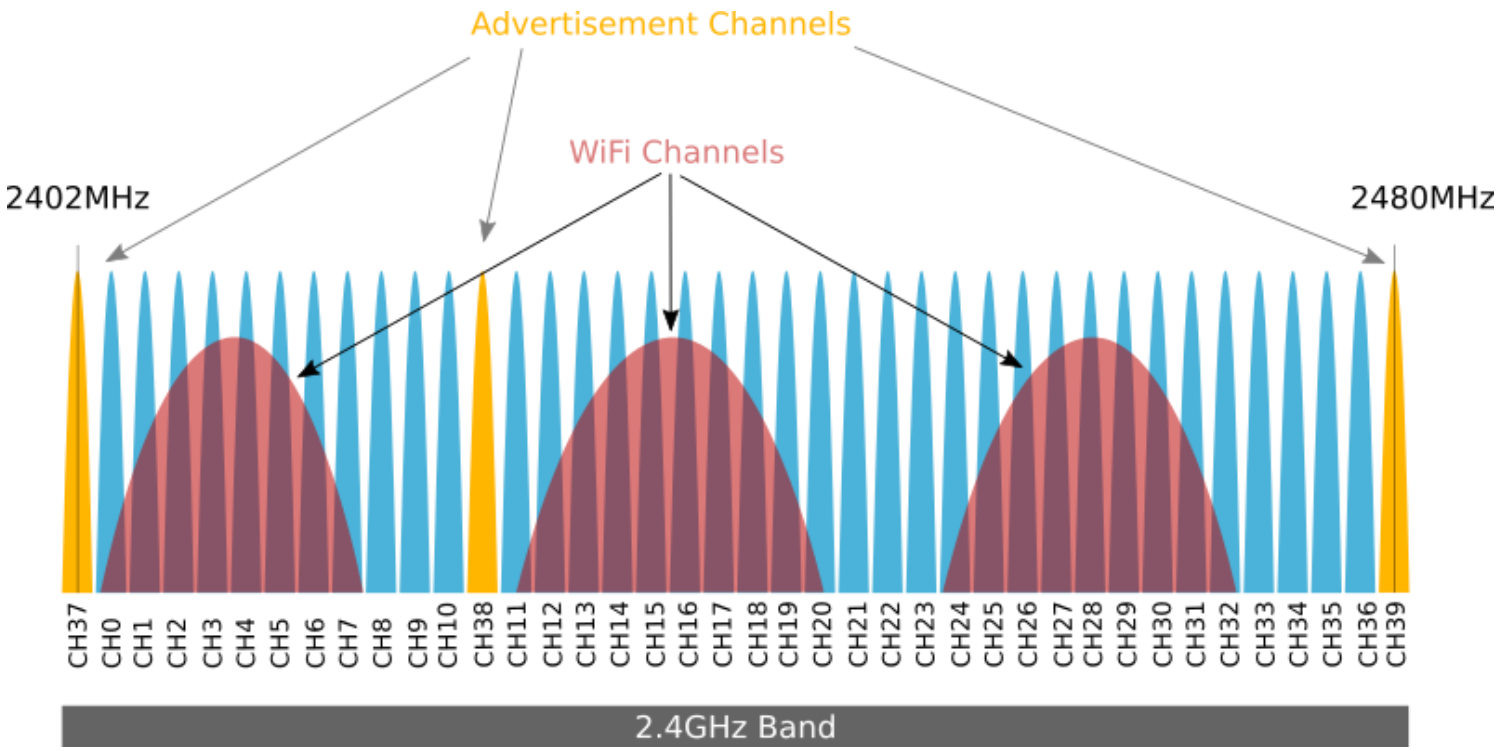
- Transmitter hops through a sequence of transmit channels
  - Spend some “dwell time” on each channel before hopping again
  - Receiver must know the hopping pattern

- Avoid causing or receiving prolonged interference



BLE Physical Layer

- 2.4 GHz Carrier
- 40 channels (2 MHz)
- 1 Mbps data rate
- Channels 37, 38, and 39 for advertising



Bluetooth Applications

- Wireless communication between devices
  - Mobile phones, laptops, cameras, gaming controllers, computer peripherals…
- Short range sensor transmission
- Share multimedia
  - Pictures, video music
- A2DP – Advanced Audio Distribution Profile
  - Stream audio wirelessly

Bluetooth Low Energy

From 2001 – 2006 Nokia asked:

How do we design a radio that can transmit short burst of data for months or years ***only being powered by a coin cell battery*** ?

Keep the radio in sleep mode most of the time!

1. Advertise on only one of the three channels (less frequency hopping)
2. Transmit quickly at 1Mbps
3. Make the minimum time to send data only 3ms
4. Make a very predictable time when the device accepts connections
5. Limit the max transmit power to 10mW
6. However, don’t sacrifice security: AES 128-bit

LoRA (Long RAnge)

- A long-range wireless communication protocol based on spread spectrum modulation
- Used a physical layer for LoRaWAN a low-power wide-area network (LPWAN) protocol
- Very popular for outdoor IoT
- Frequency
  - 868 MHz (Europe), 915MHz (North America), 433 MHz (Asia)

Example application: air quality monitoring

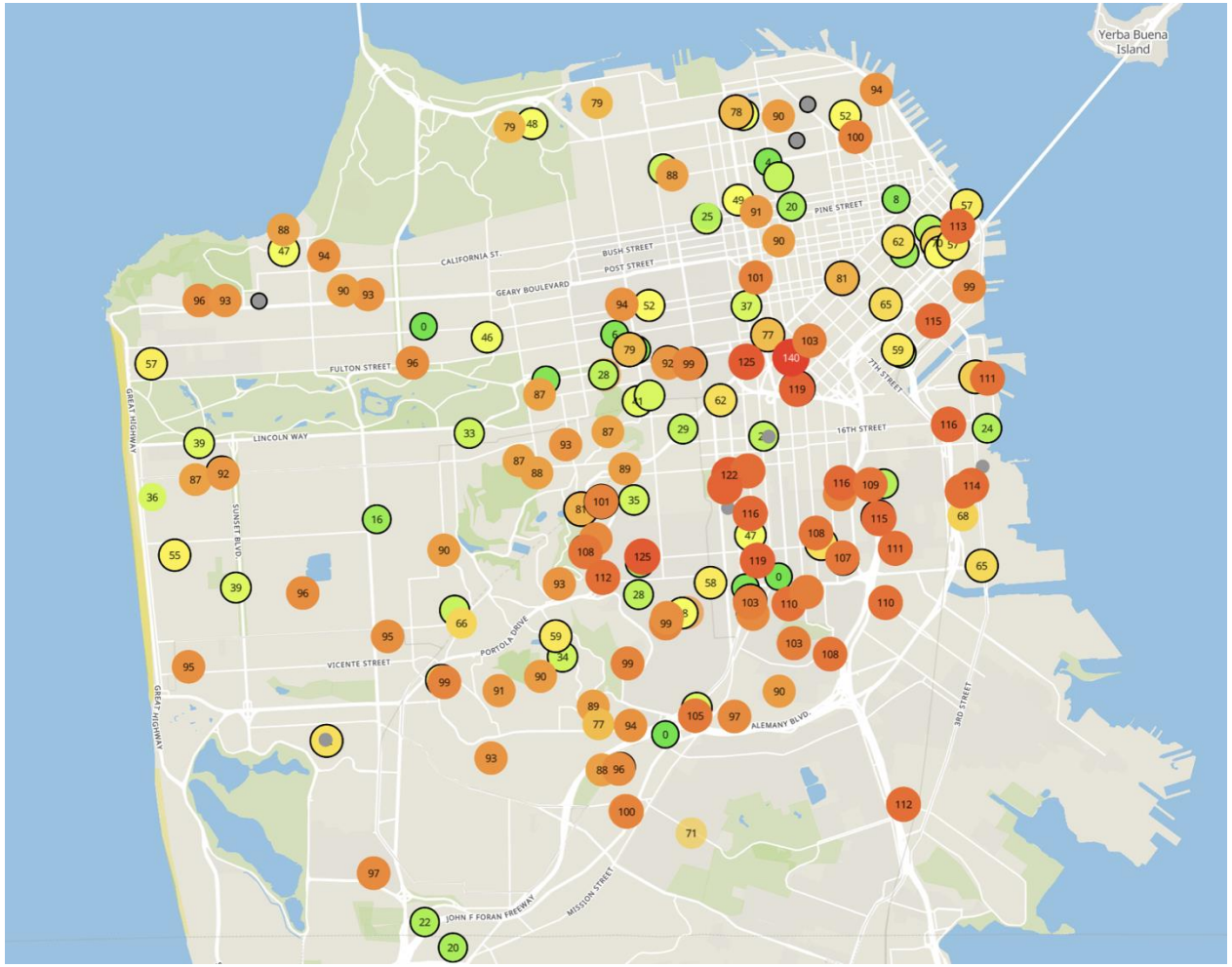


[1]

[2]



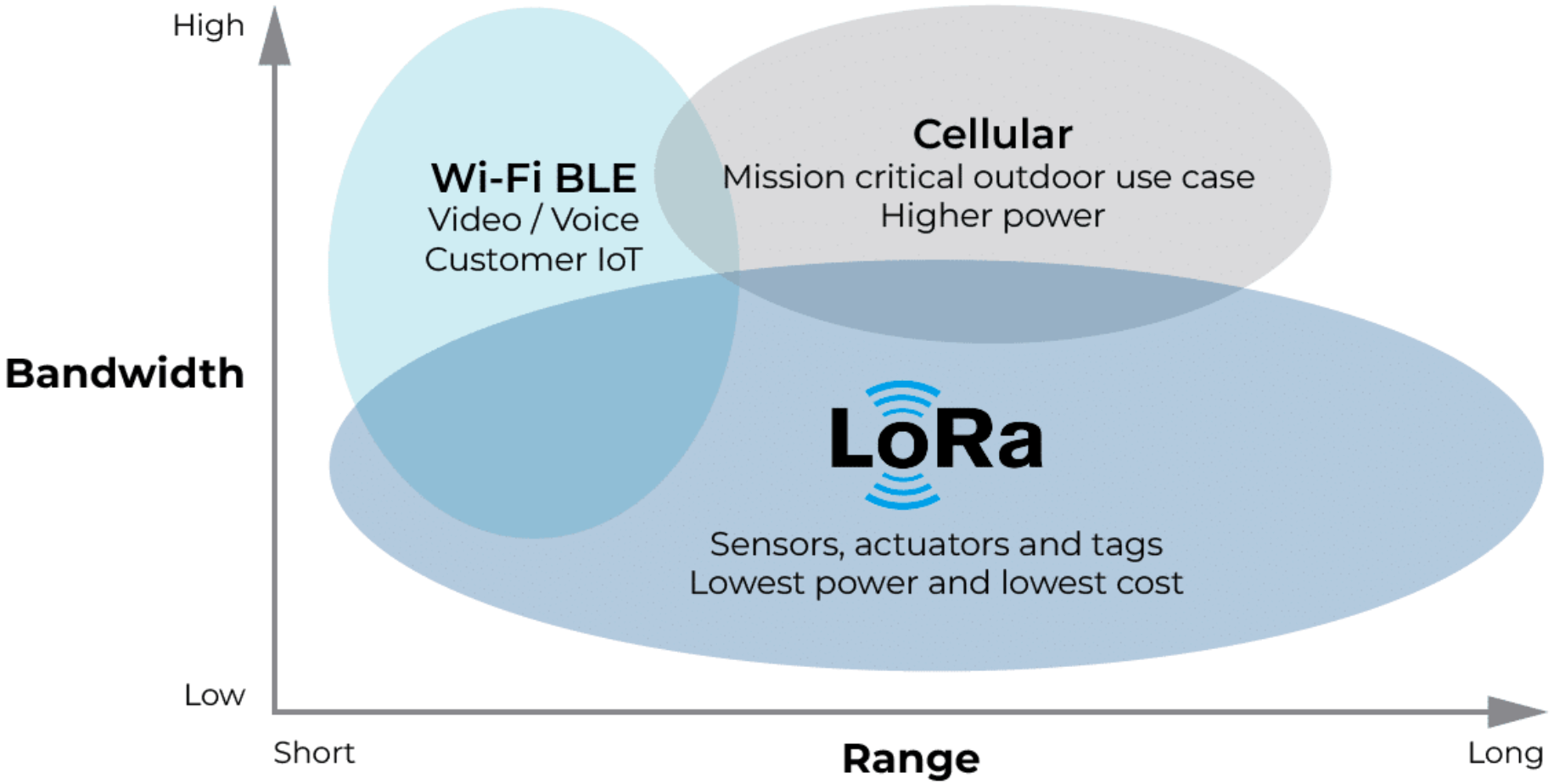
[2]



[1] Cheng et al. AirCloud: a cloud-based air-quality monitoring system for everyone. 2014.

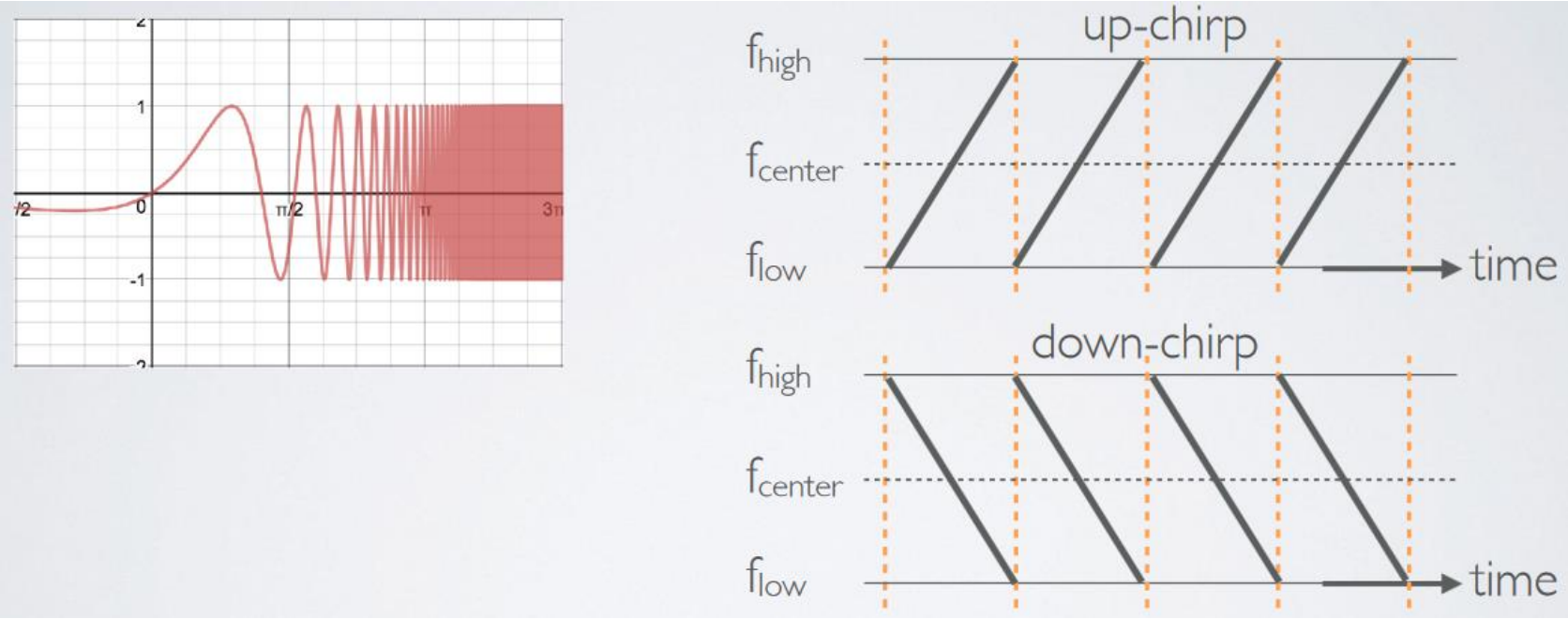
[2] Purple Air. 2019.

Comparison to other techniques

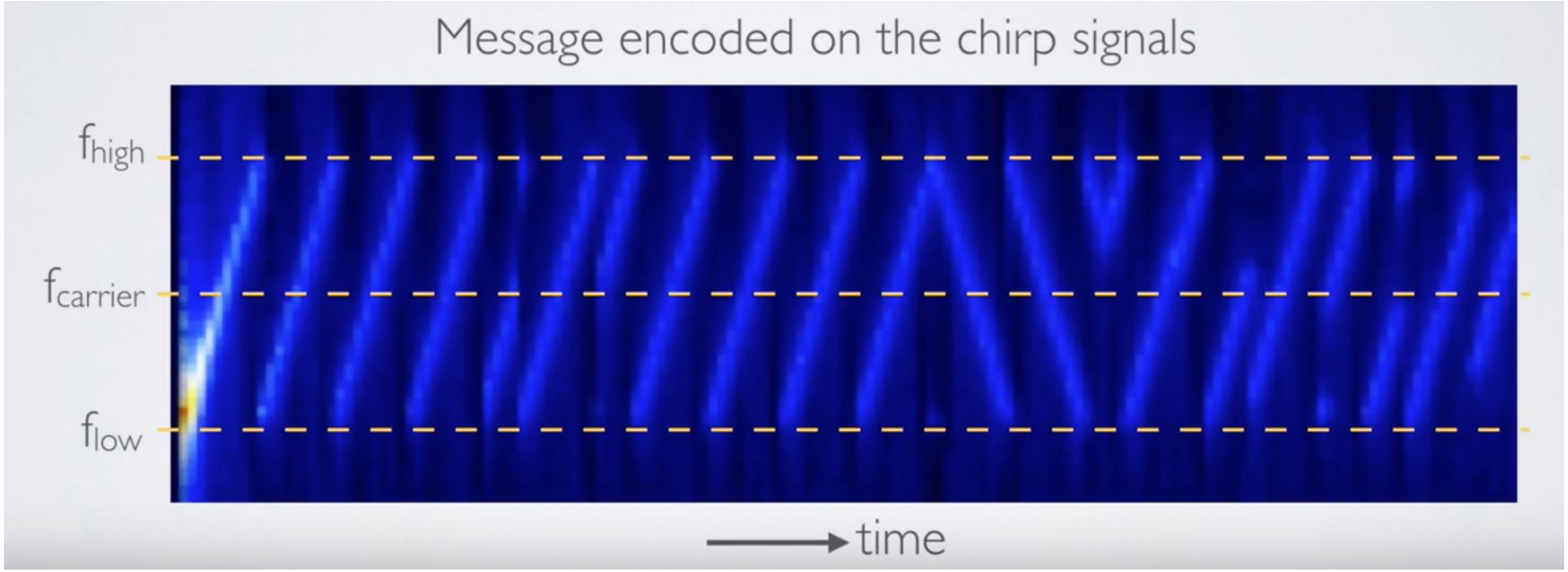


LoRa PHY uses a spread spectrum modulation technique

- Chirp Spread Spectrum (CSS)
  - Modulation technique where frequency is varied linearly from (to) lowest to (from) highest within a channel



LoRa Modulated Signal



Source: https://youtu.be/lg0eZWZFKiE

Backscatter Communication

Motivation: we'd like to make **very very** low power, battery-free sensors

Problem: Regular radios consume a lot of power when they transmit since they have to make their own radio waves

Backscatter is a method used in RFID tags to perform low power communication…it can also be used for more general purpose communication

Radio **F**requency **ID**entification (RFID)





Inventory Control

Marketing





Access Control

Tolling



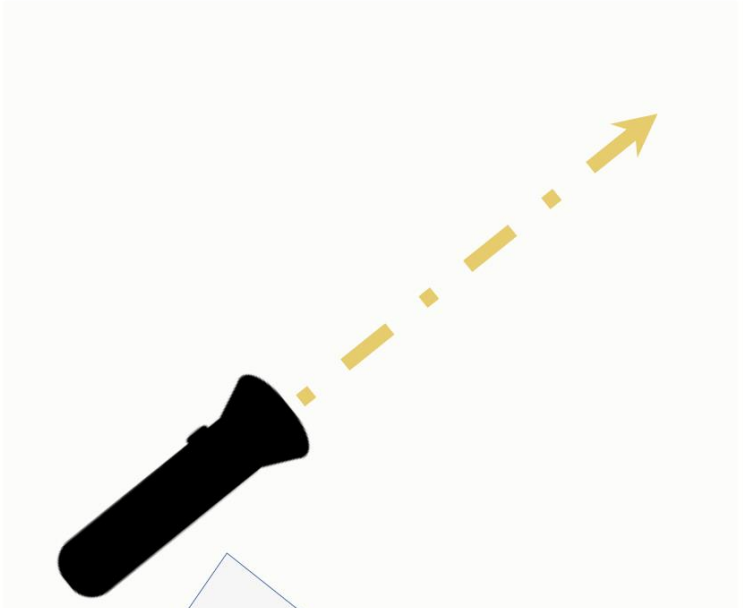


Tracking and Localization

https://www.atlasrfidstore.com/rfid-insider/how-is-rfid-used-in-the-real-world/?srsltid=AfmBOopO4VG-WVjR3BQyMr52NasJQDJQF05gEc5XmIiK8h3u3vHgKID5

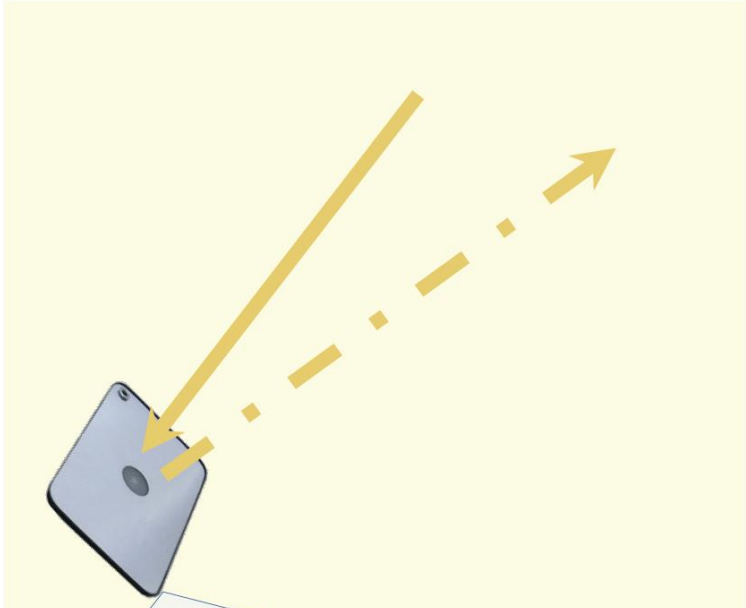
How does backscatter work?

Conventional radio



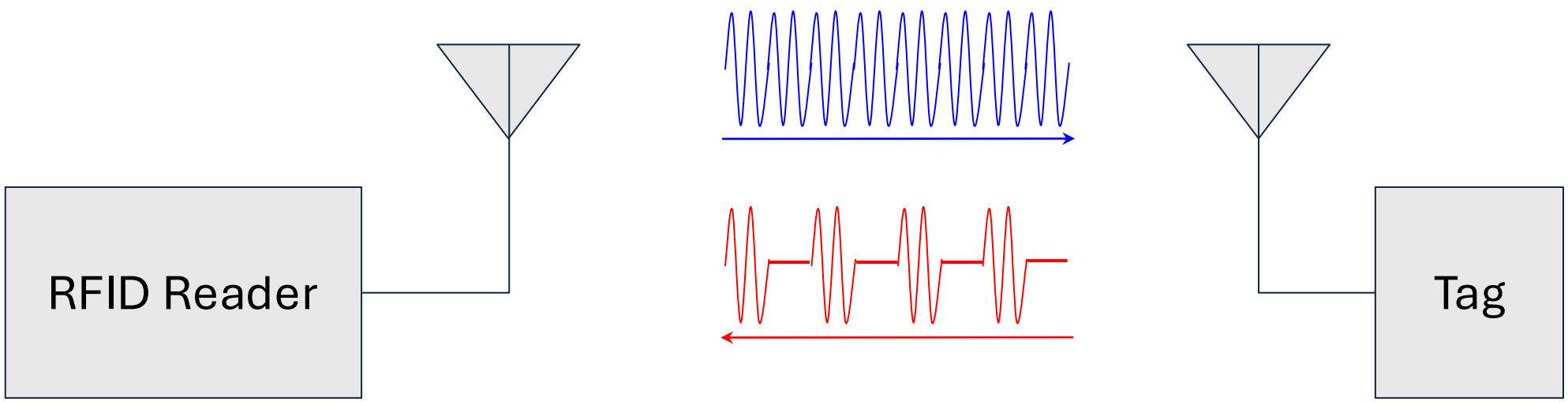
Generates and emits signals. **Uses lots of energy.**

Backscatter passive radio



Reflects existing signals. **1000x-10000x less energy per bit**

Basic Principle of Operation



Tag reflects the RF signal using ON-OFF keying (OOK)

How many RFID tags are out there?

Approximately 39.3 billion sold in 2023…



https://www.idtechex.com/en/research-article/rfid-market-trends-for-2023-and-the-next-five-years/28940

Types of RFID Solutions



	Passive	Semi Passive	Active
Power	Energy Harvesting (RFID Reader Signal)	Battery/Energy Harvesting	Battery/Energy Harvesting
Communication Scheme	Backscatter	Backscatter	Conventional
Power Consumption	<20 meters	< 40 meters	> 50 meters
Cost	$0.05	$2	>$2

Types of RFID Solutions

- 120 - 150 kHz – **Low Frequency (LF)**
- 13.56 MHz – **High Frequency (HF) & Near-Field Communication (NFC)**
- 865 - 960 MHz – **Ultra High Frequency (UHF)** read range.



Photo Credit: AtlasRFIDStore

The “Thing”

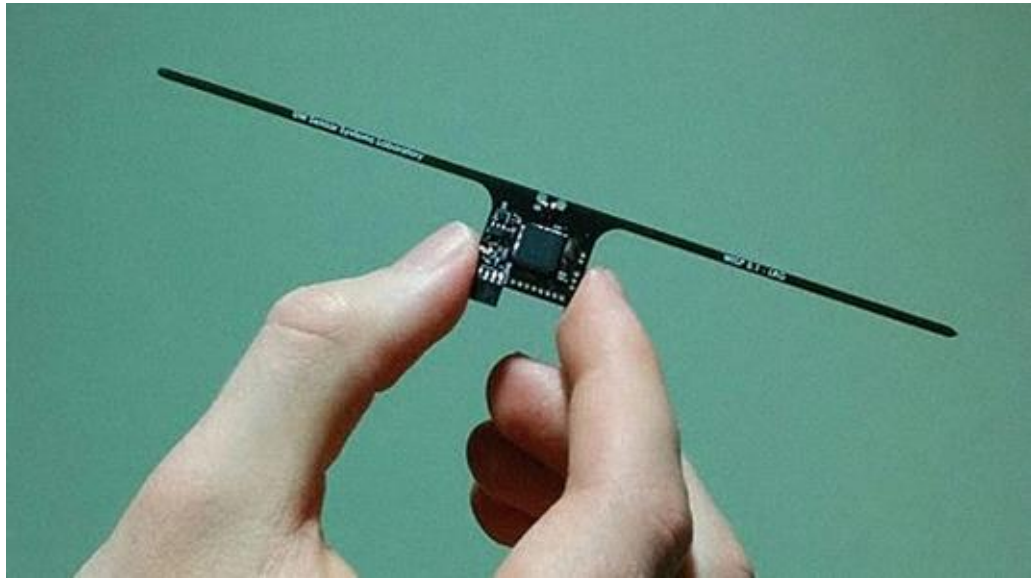
- The Thing or the Great Seal Bug, invented by Leon Theremin in 1945
- Considered to be a predecessor to RFID





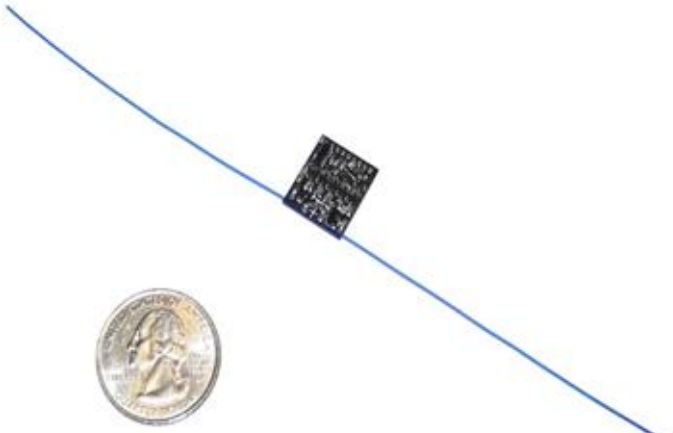
Wireless Identification and Sensing Platform (WISP)





Evolution of the WISP

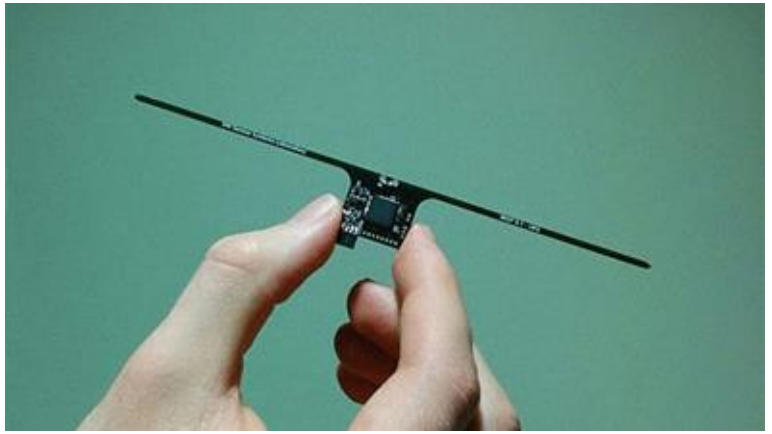
WISP



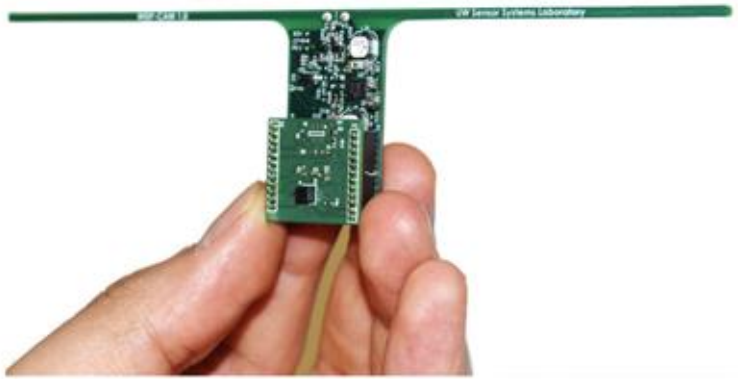


WISP 4.0

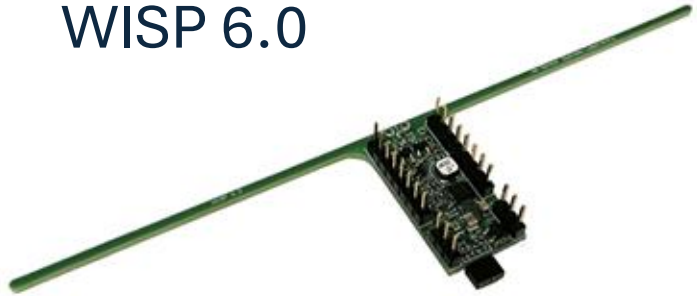
WISP 5.0



WISPCam



WISP 6.0



(a) Basic Sensor Node



(b) Basic Sensor Node

(c) Camera



(d) Microphone

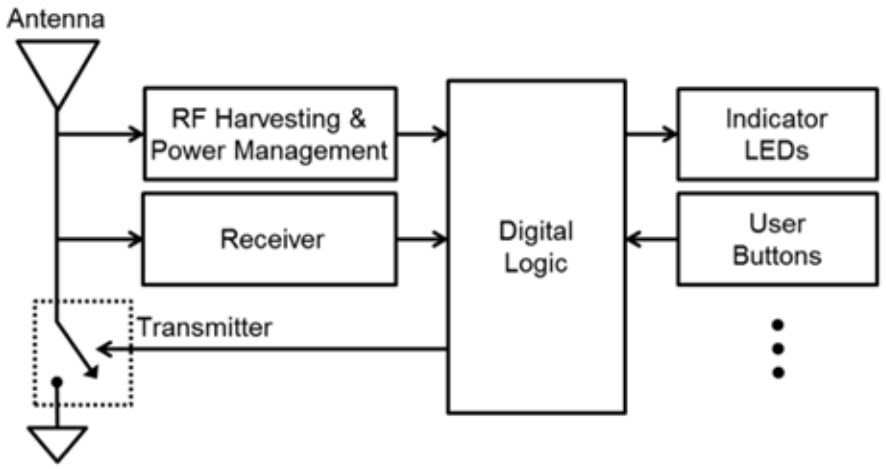
(e) Accelerometer

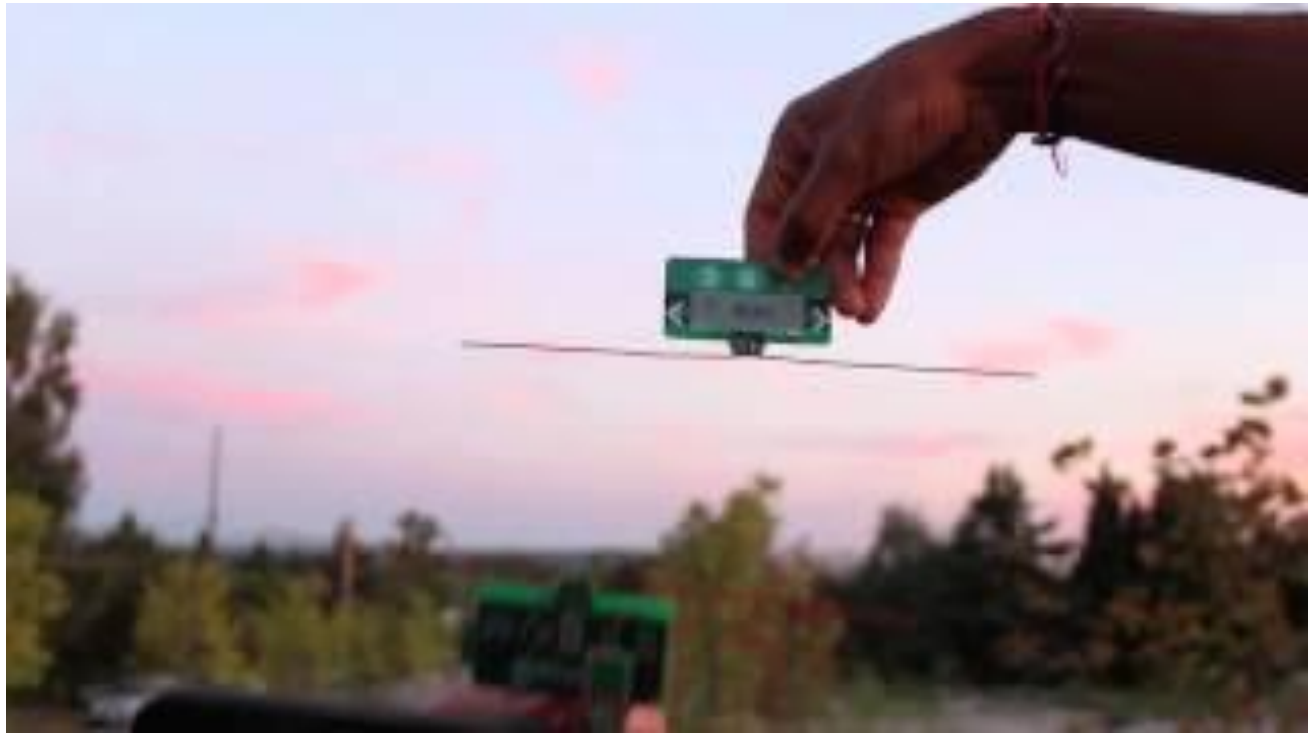
(f) Ambient Light Energy Harvester + Camera

Ambient Backscatter

Backscatter existing RF signals

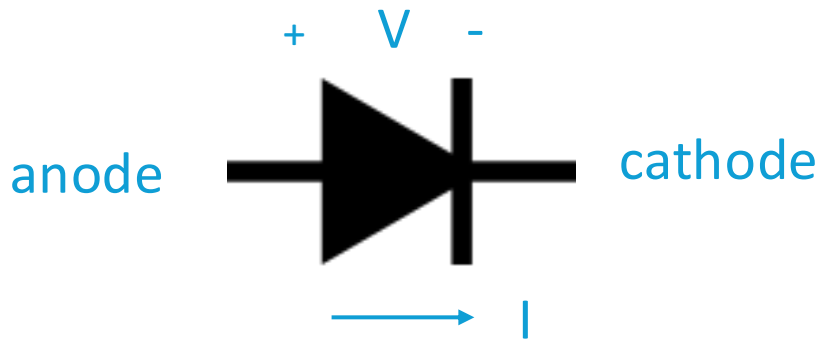
- TV
- FM
- Wi-Fi
- LoRa

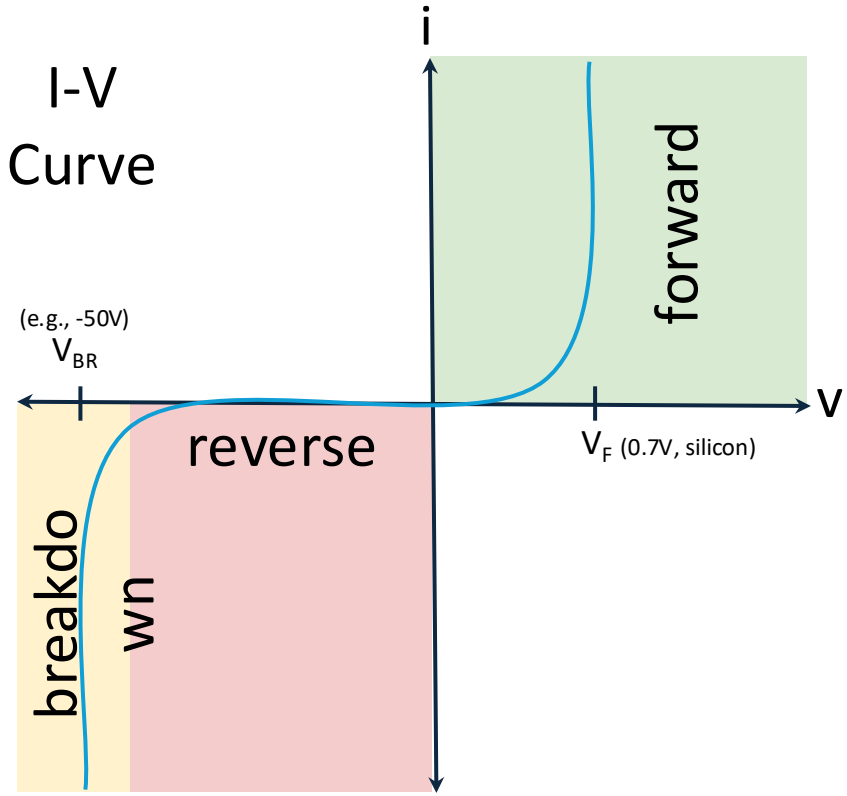




Voltage Rectification

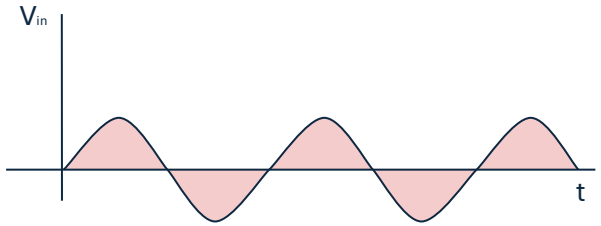
Diodes allow current to flow in one direction

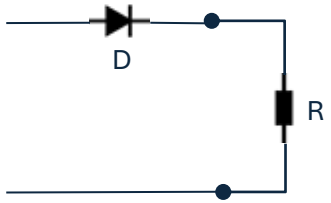


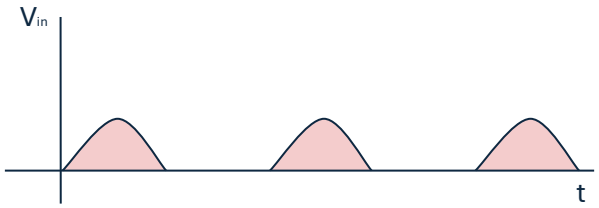


Voltage Rectification

What is a rectifier?

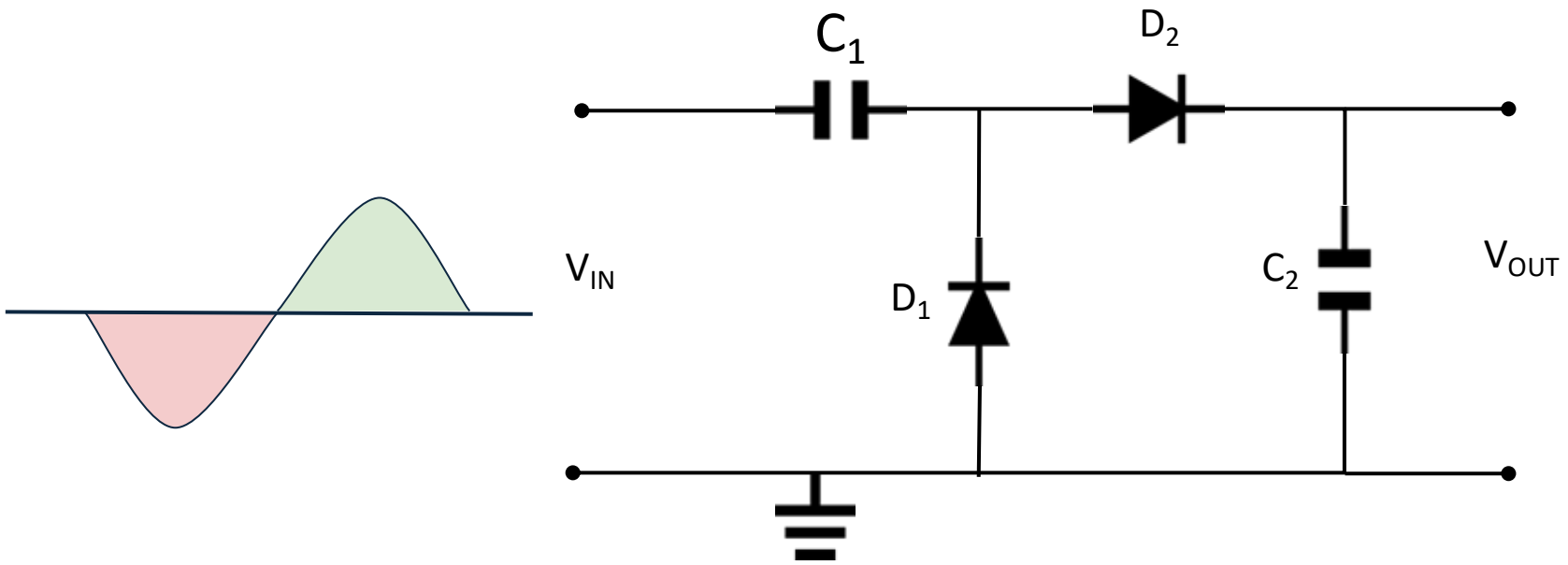






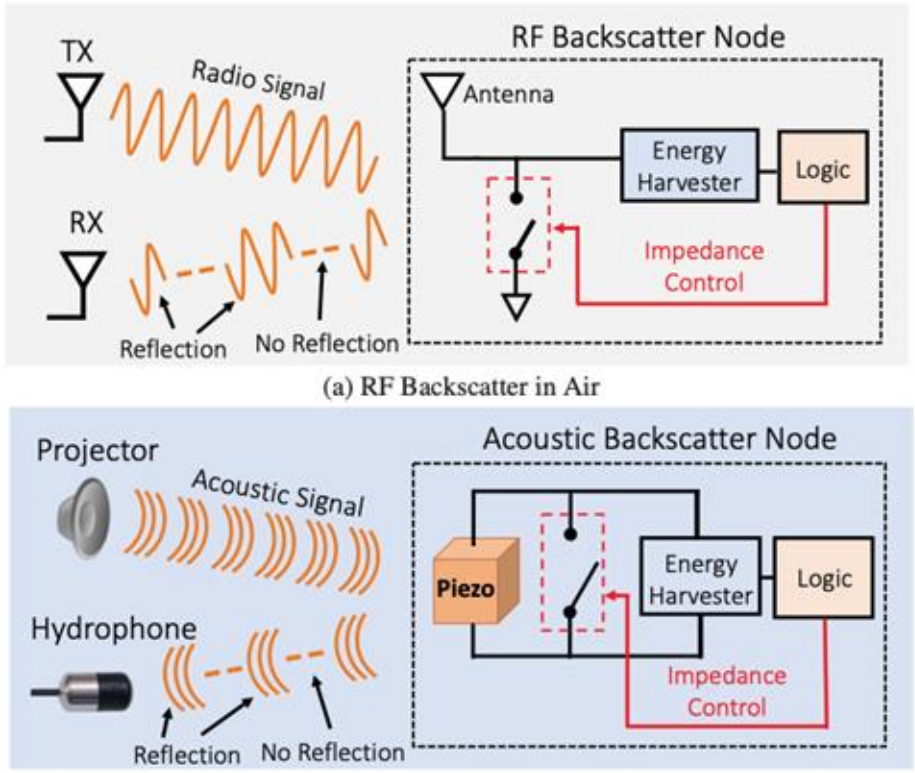
half-wave rectifier

What is going on in this circuit?



Other Forms of Backscatter Communication

Underwater Backscatter Networking

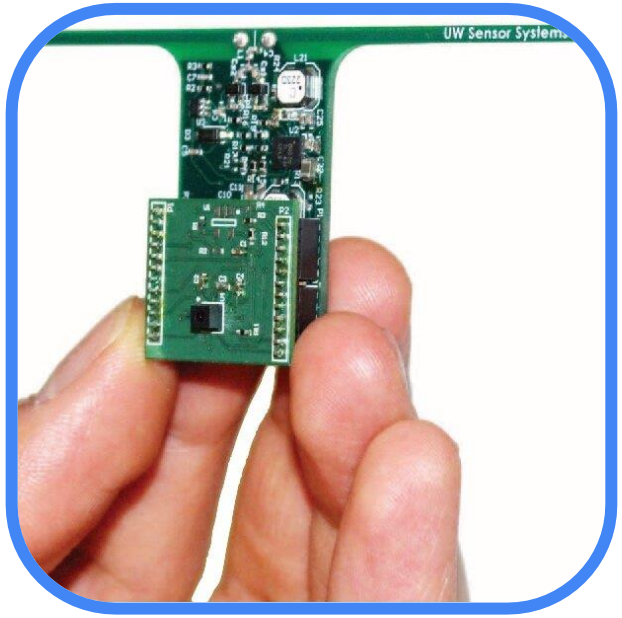


(a) RF Backscatter in Air

(b) Piezo-Acoustic Backscatter in Water



Battery-free sensing



Battery-free Camera[1]



Battery-free phone[2]



Battery-free Underwater Sensing[3]

[1]WISPCam: A battery-free RFID camera. S. Naderparizi, A. Parks, Z. Kapetanovic, B. Ransford, J. Smith. IEEE RFID 2015
[2]Battery-free Cellphone. V. Talla, B. Kellogg, S. Gollakota, J. Smith ACM IMWUT 2017
[3]Ultra-Wideband Underwater Backscatter via Piezoelectric Metamaterials. R. Ghaffarivardavagh, S. Saad Afzal, O. Rodriguez, F. Adib. ACM SIGCOMM 2020

Some limitations

Traditional backscatter techniques require you to be nearby an RF signal source

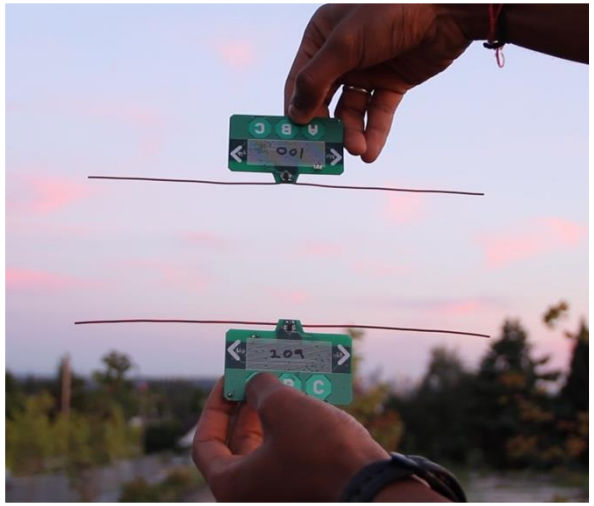


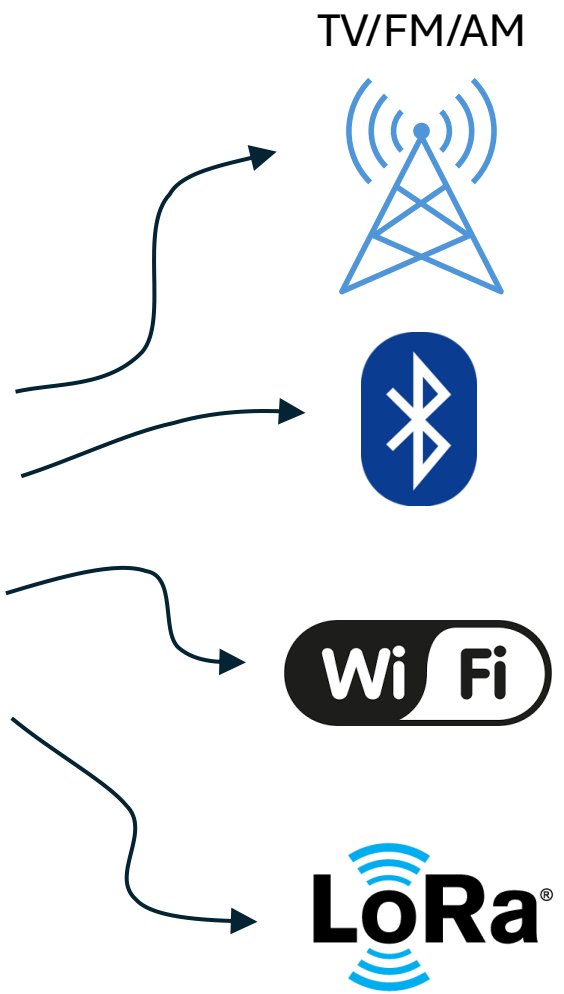
Photo Credit: Ericson



Photo Credit: Impinj

Ambient Backscatter[1]





[1]Liu, Vincent, et al. "Ambient backscatter: Wireless communication out of thin air." *ACM SIGCOMM computer communication review* 43.4 (2013): 39-50.

Is there a signal source that is **always** available?

Thermal Noise Sources

Resistors



Sun

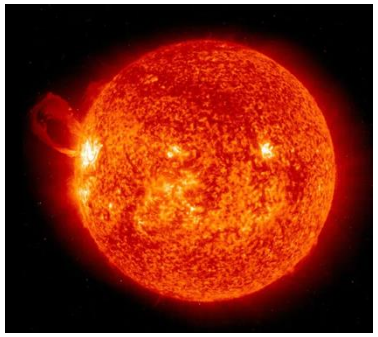


Photo Credit: NASA

Moon



Photo Credit: NASA

Earth



Photo Credit: NASA

Cosmic Background Radiation

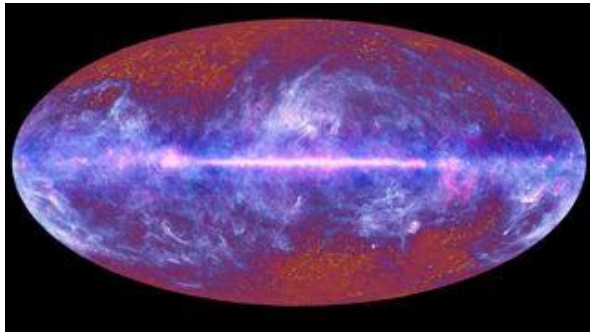
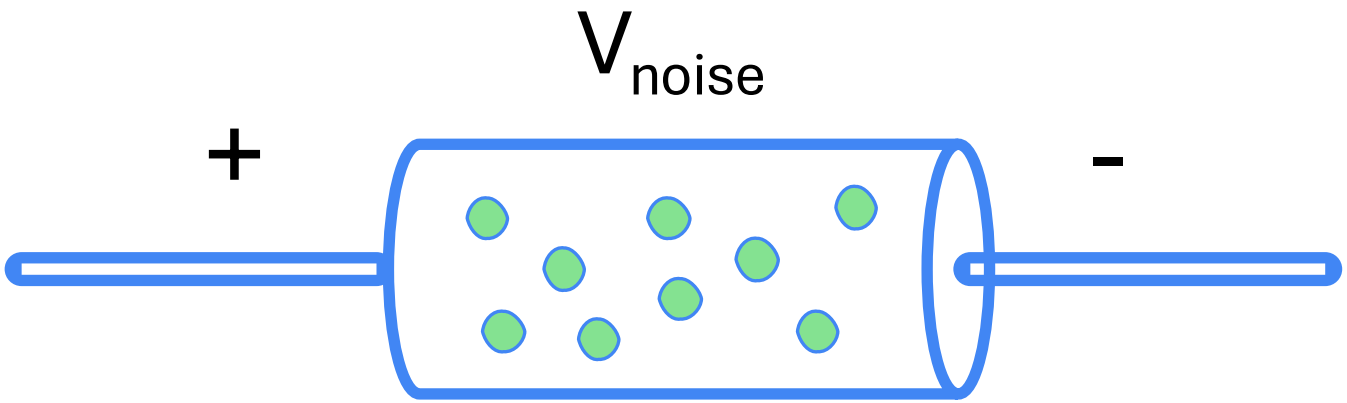


Photo Credit: ESA/ LFI & HFI Consortia

An unpowered resistor generates Johnson (thermal) Noise

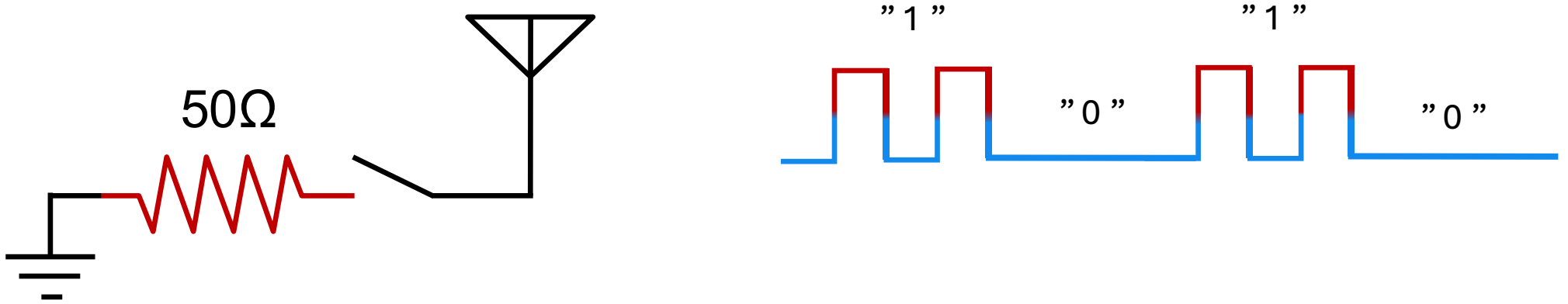


$$V_n^2 = 4kTBRe(Z)$$

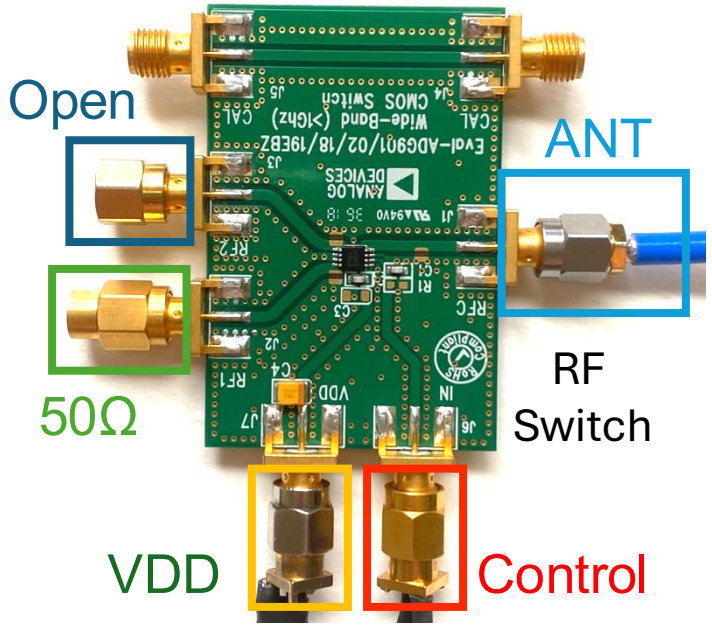
$$P_n = \frac{V_n^2}{4\mathrm{R}} = \mathrm{kTB}$$

How do we transmit data?

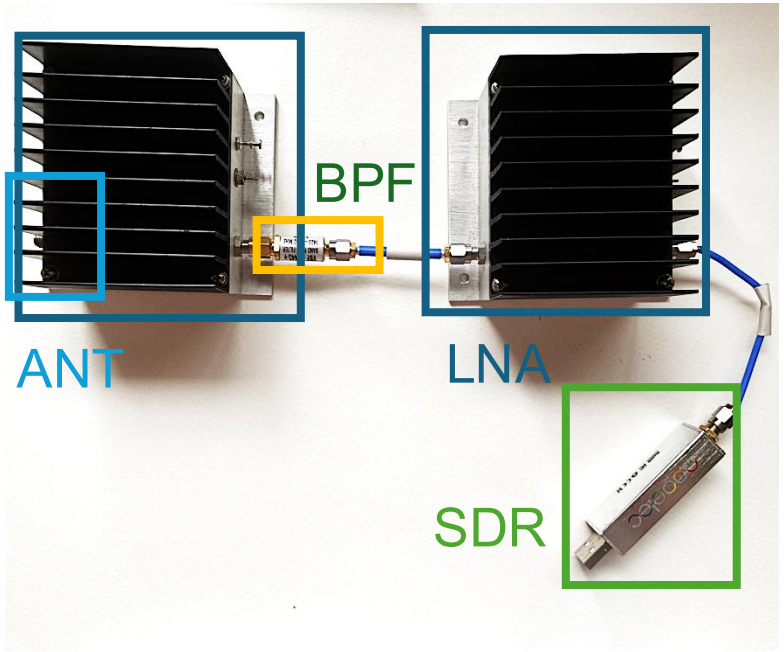
- Modulate data using ON-OFF keying



Prototype Implementation



Transmitter



Receiver



Antennas

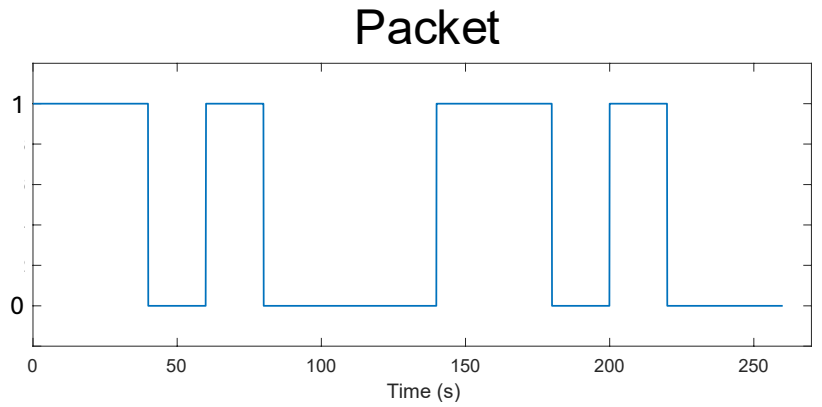
How to transmit data

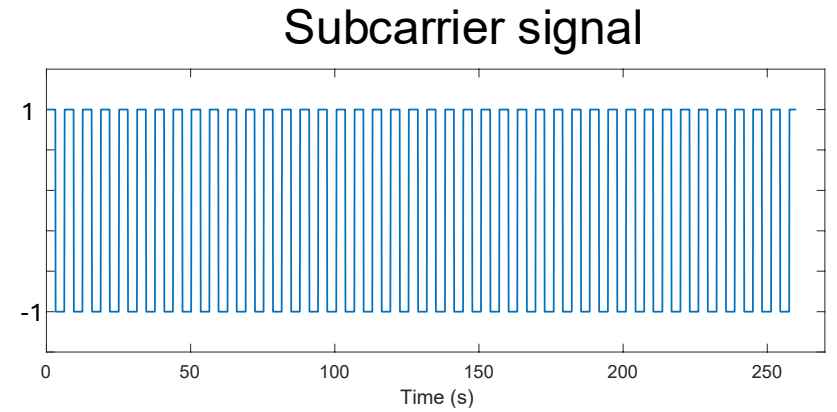
1. Modulate data using ON-OFF keying

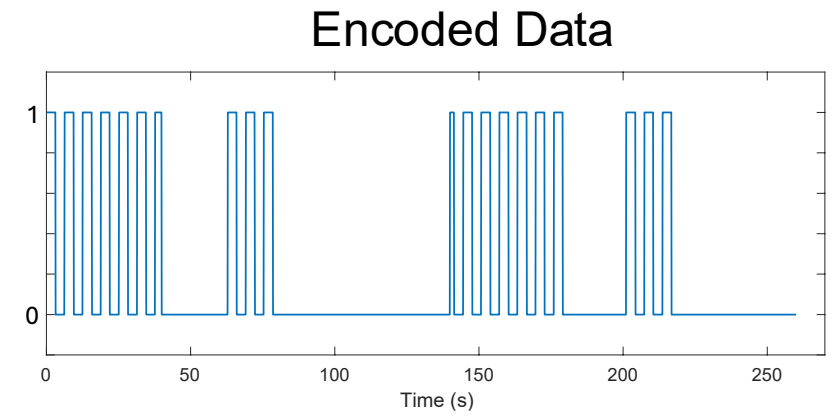
$$s(t) = m \cdot sgn(\cos 2\pi f_{sc} t)$$

f_{sc} = subcarrier frequency

m = bit value (1 or 0)





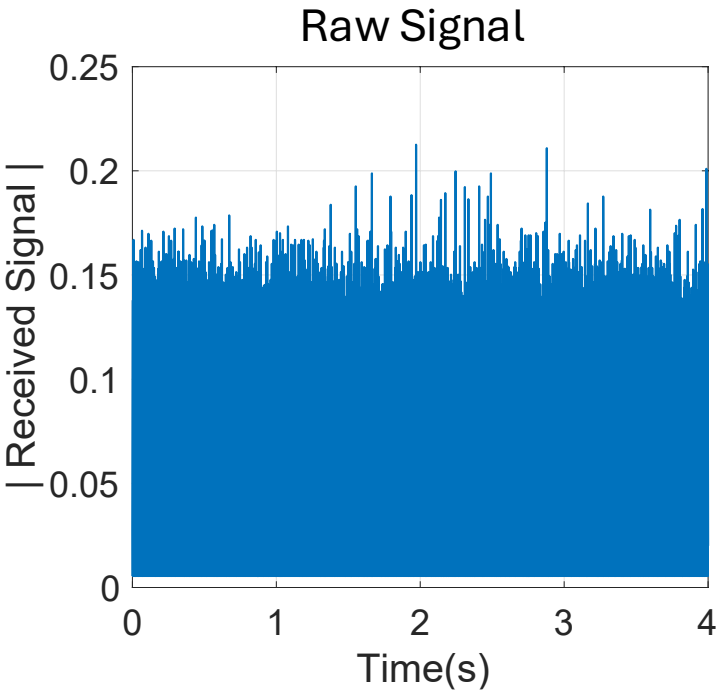


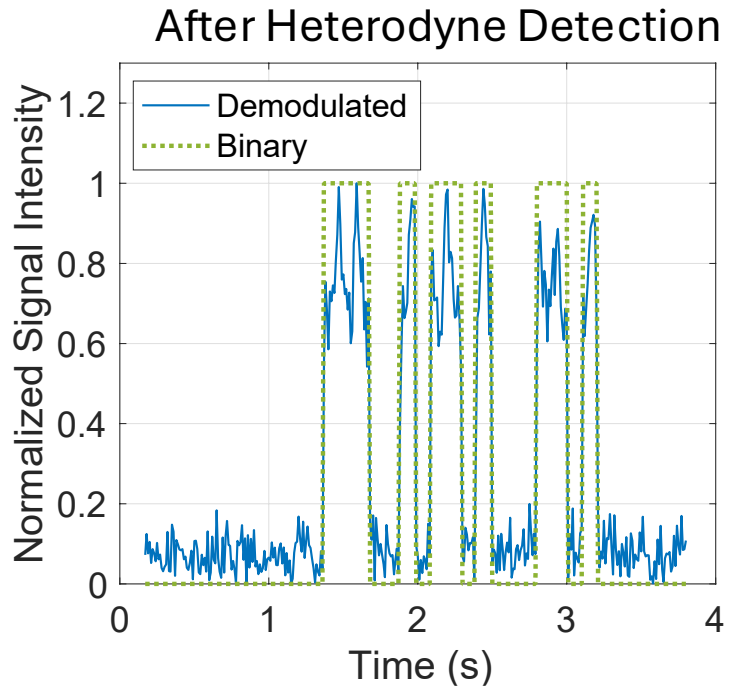
How to receive data

2 Decode using heterodyne detection

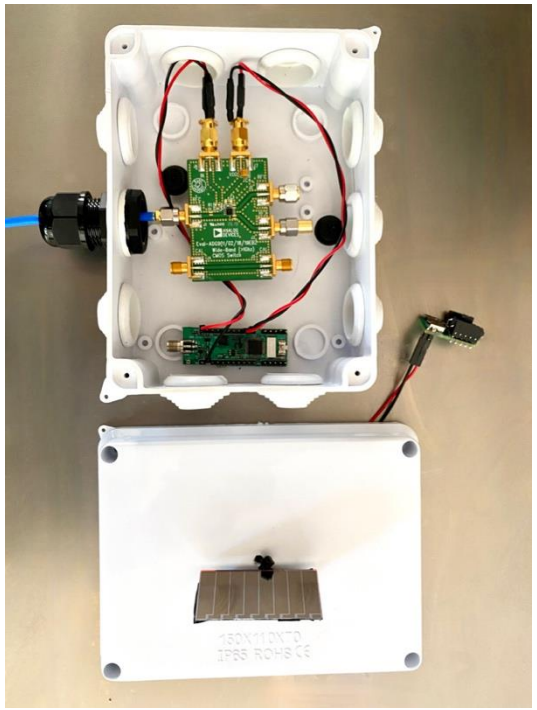
- Generate a square-wave subcarrier with frequency f_{sc} and amplitude values of ± 1
- Multiply the received signal with the receive-side subcarrier
- Accumulate (integrate) the product values

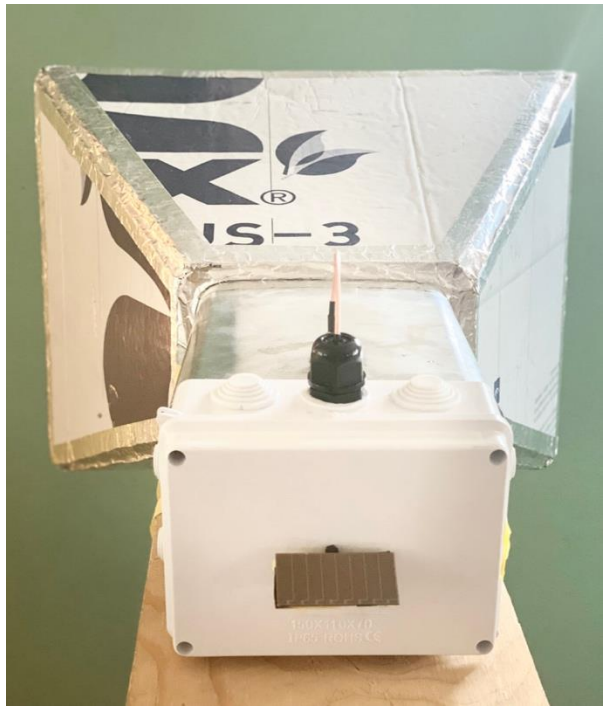
$$\langle s_{rx}, s_{sc} \rangle = \int_0^{t_i} s_{rx}(t_i) s_{sc}(t_i) dt$$



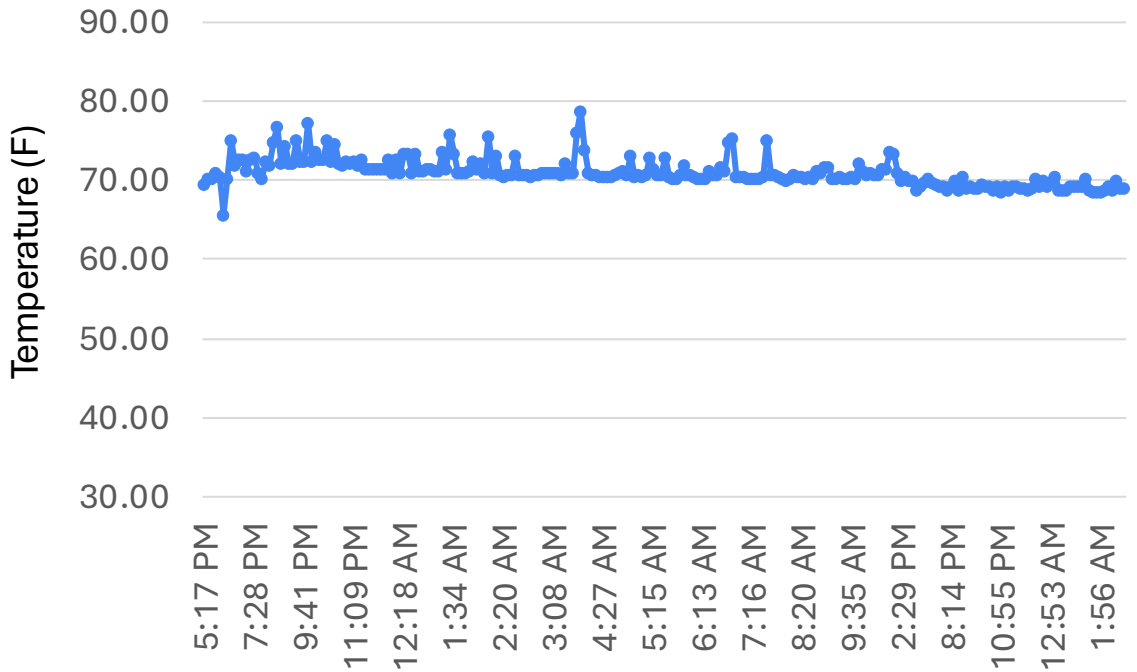


Battery-free Transmitter using Modulated Thermal Noise





Battery-free Transmitter



Acknowledgements

- These lecture slides were adapted from:
  - University of Michigan's EECS 373 course
  - UC San Diego's CSE 190 course
  - University of Virginia's ECE4501 course

- These lecture slides also leverage materials from the following books:
  - Embedded Systems with ARM Cortex-M Microcontrollers in Assembly Language and C
    - Yifeng Zhu
  - The Definitive Guide to ARM Cortex – M3 and Cortex – M4 Processors
    - Joseph Yiu
  - Introduction to ARM Cortex – M Microcontrollers, Embedded Systems
    - Jonathan W. Valvano