Introduction to Embedded Systems

EE 186 – Fall 2026

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Today’s Topics

- Finish Wireless Topics
- Interfacing with wireless modules
  - BLE
  - LoRa
- Direct Memory Access (DMA)
- Final Project Guidelines
  - Demo Requirements
  - Poster Session Requirements

Cellular Connectivity

Cellular provides some unique advantages for wireless embedded devices (or the Internet-of-Things)

Global deployment

If the goal is deploy-today + work-anywhere, cellular is the only option

That's not to say cellular actually works *everywhere*, just generally the best available

Reuse existing telecom infrastructure

Minimal overhead (no need to deploy network infrastructure)

Allows mobility

No need to modify the destination address when moved

Reuse in-built security features

SIM card based subscriber authentication

Example: Dominion Energy Smart Meters

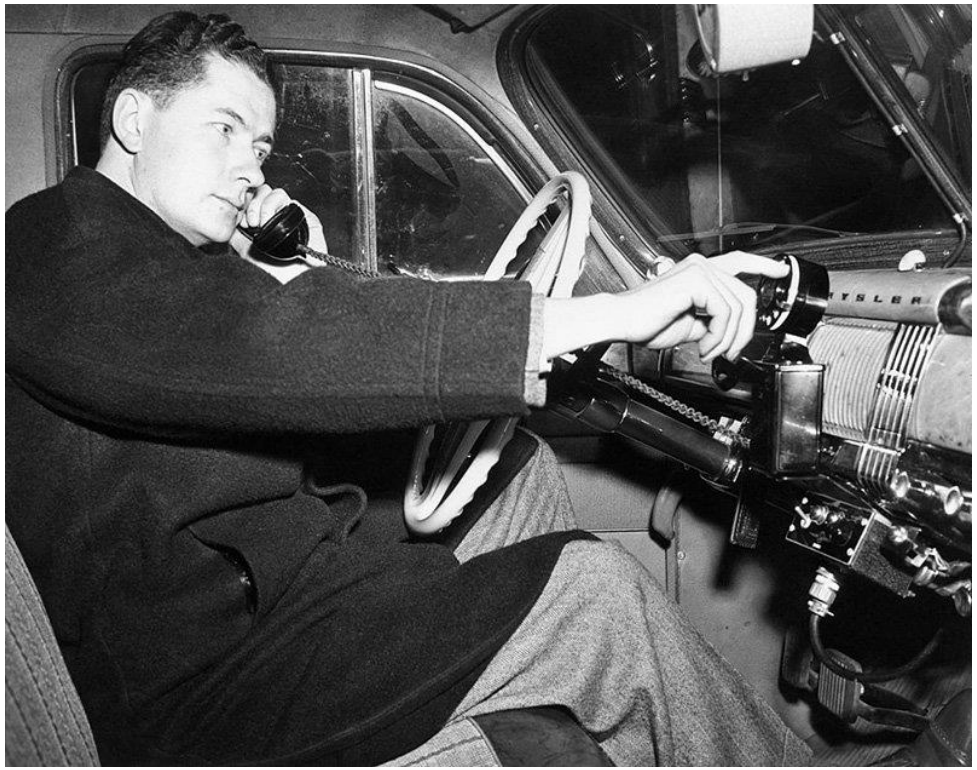
- Enables remote two-way communication between meter and Dominion Energy
- Uses RF mesh to securely gather data from the meter
- A network access point (router) collects data and send data to Dominion Energy via a secure cellular network
- Routers are strategically placed in the field





The first commercial mobile phone was in 1946!

By 1948, 5000 users placing around 30,000 calls weekly



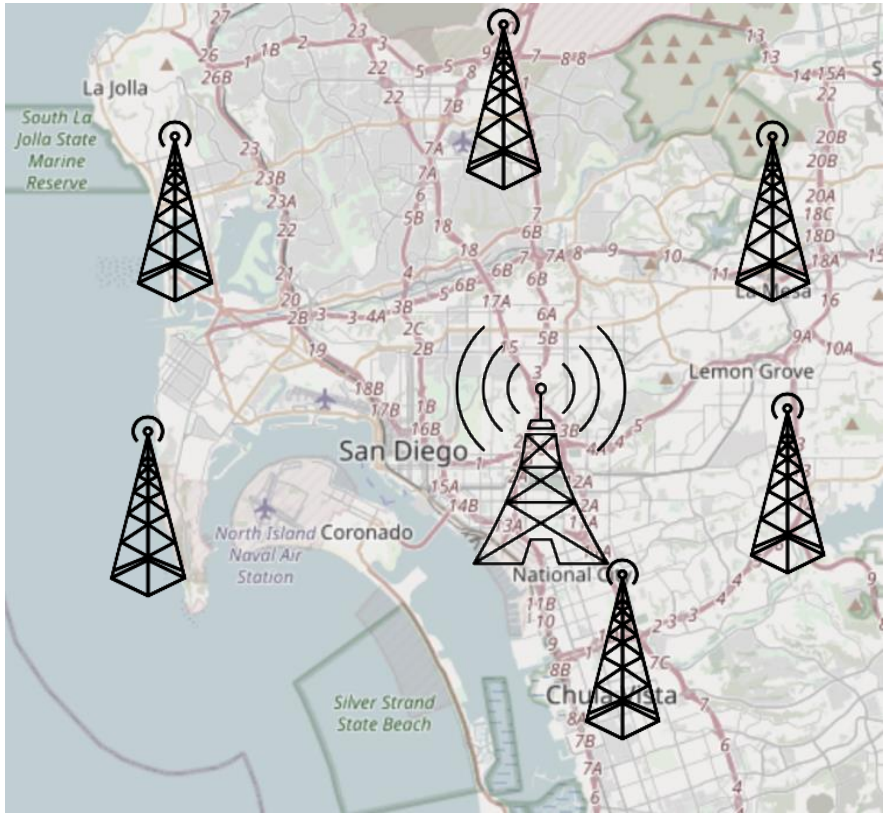
https://www.smithsonianmag.com/innovation/first-mobile-phone-call-was-made-75-years-ago-180978003/

"The equipment, of course employing vacuum tubes, **weighed eighty pounds, filled much of a vehicle's trunk and drew so much power that it would cause the headlights to dim.** Service cost $15 per month, plus thirty to forty cents per local call, equivalent to $175 2012 dollars, plus $3.50 to $4.65 per call. "

https://ethw.org/The_Foundations_of_Mobile_and_Cellular_Telephony

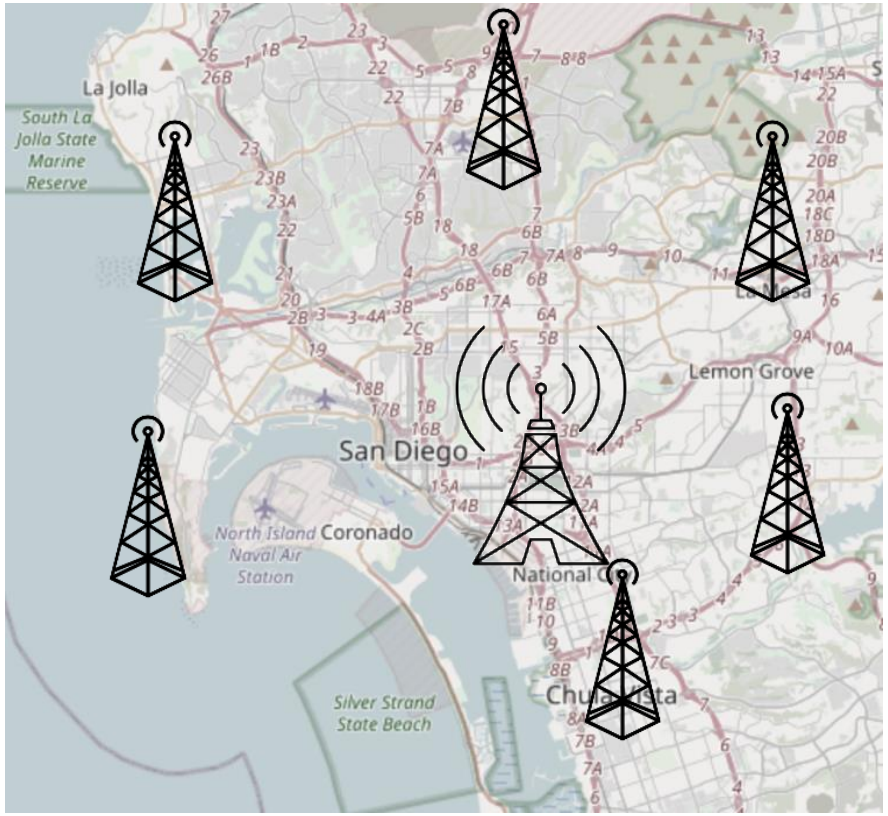
The first “mobile” network architecture

- Single transmitter tower, multiple receiver towers
  - **Why?**



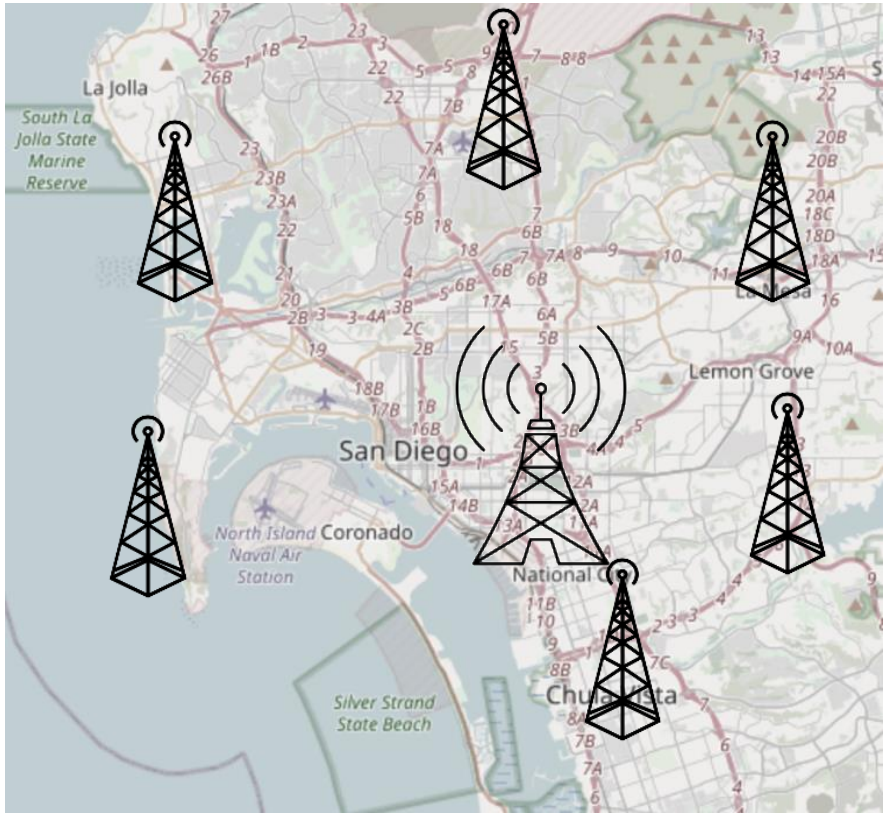
The first “mobile” network architecture

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  - **Why?** Transmission energy of phone!



The first “mobile” network architecture

- Single transmitter tower, multiple receiver towers
  - **Why?** Transmission energy of phone!
- Medium Access Control?
  - Push-to-talk [half-duplex]
  - City-wide “party line”
  - Maximum of three concurrent callers



1965: The Improved Mobile Telephone Service

- More spectrum in 3 different bands for Bell System US
  - VHF Low (35-44 MHz, 9 channels)
  - VHF High (152-158 MHz, 11 channels)
  - UHF (454-460 MHz, 12 channels)



Phones fit in a briefcase now

https://en.wikipedia.org/wiki/Improved_Mobile_Telephone_Service

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  - Implemented as channel pairs (two half-duplex)



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- Full Duplex
  - Implemented as channel pairs (two half-duplex)
- More spectrum alone not enough
  - Limited to 40,000 total subscribers
  - E.g. NYC had 2,000 people on 12 channels with a typical wait of 30 mins to place a call

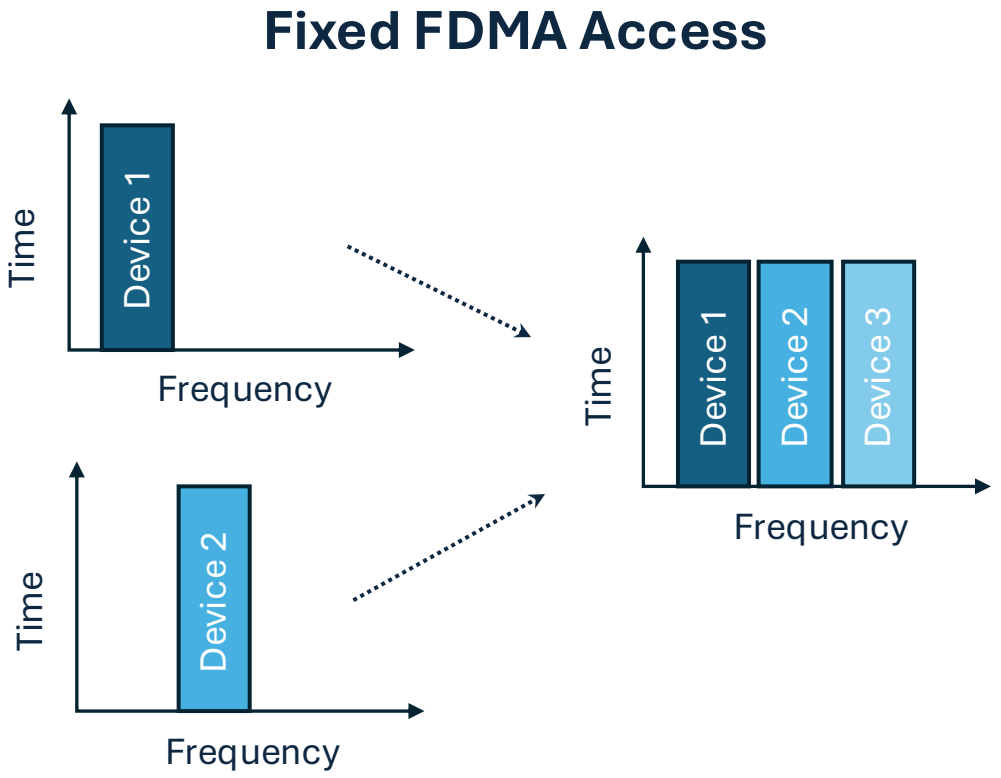


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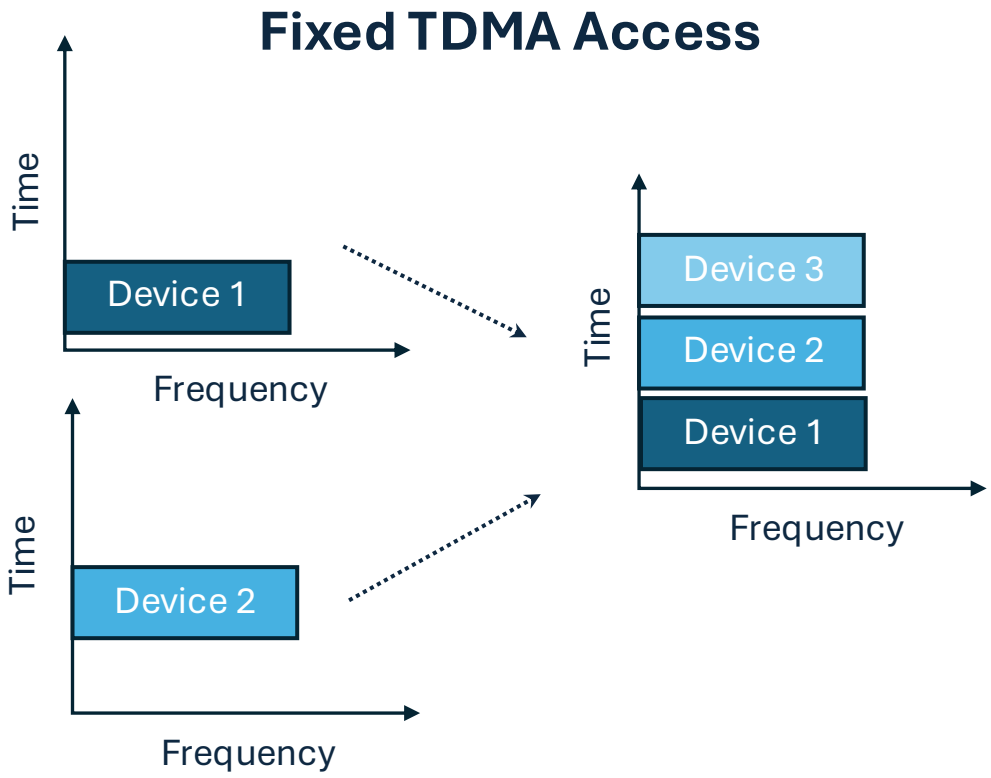
FDMA – Frequency Division Multiple Access

- Split transmissions in frequency
  - Different carrier frequencies are independent
  - Fundamentally how RF spectrum is split
- Technically, each device uses a separate, fixed frequency
  - Walkie-talkies
- Conceptually, how RF channels work
  - Wi-Fi networks pick different bands
  - 802.15.4 picks a channel to communicate on



TDMA – Time Division Multiple Access

- Split transmissions in time
  - Devices share the same channel
- Splits time into fixed-length windows
  - Each device is assigned one or more windows
  - Can build a priority system here with uneven split among devices
- Requires synchronization between devices
  - Often devices must listen periodically to resynchronize
  - Less efficient use of slots reduce synchronization
    - Large guard windows. E.g. 1.5 second slot for a 1 second transmission

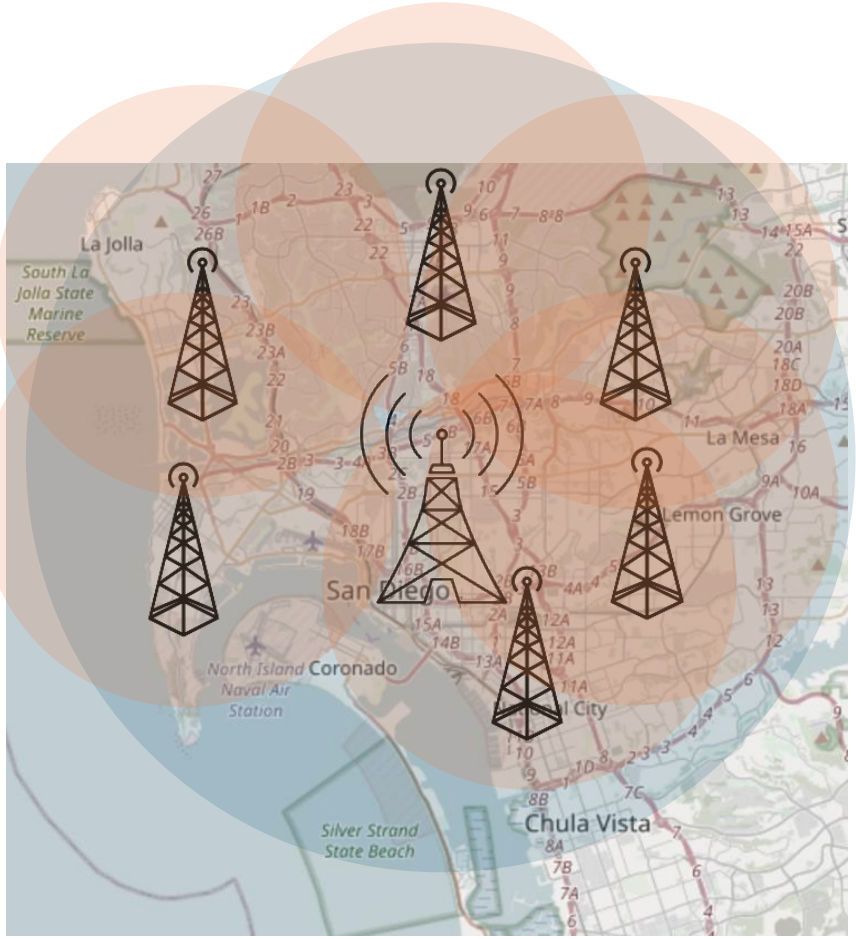


CDMA – Code Division Multiple Access

- Split transmissions in ‘codes’
  - Not new; original applications in radar and early satellite communications
- Analogy: Multiple speakers in the same room all in different languages
- Requires signal power coordination
  - [everyone needs to speak ~the same volume]
  - Can be hard in uncontrolled / dynamic environments
- Also can be more performant with highly synchronized clocks
  - i.e. if the code clock is known to both devices; intractable in mobile settings

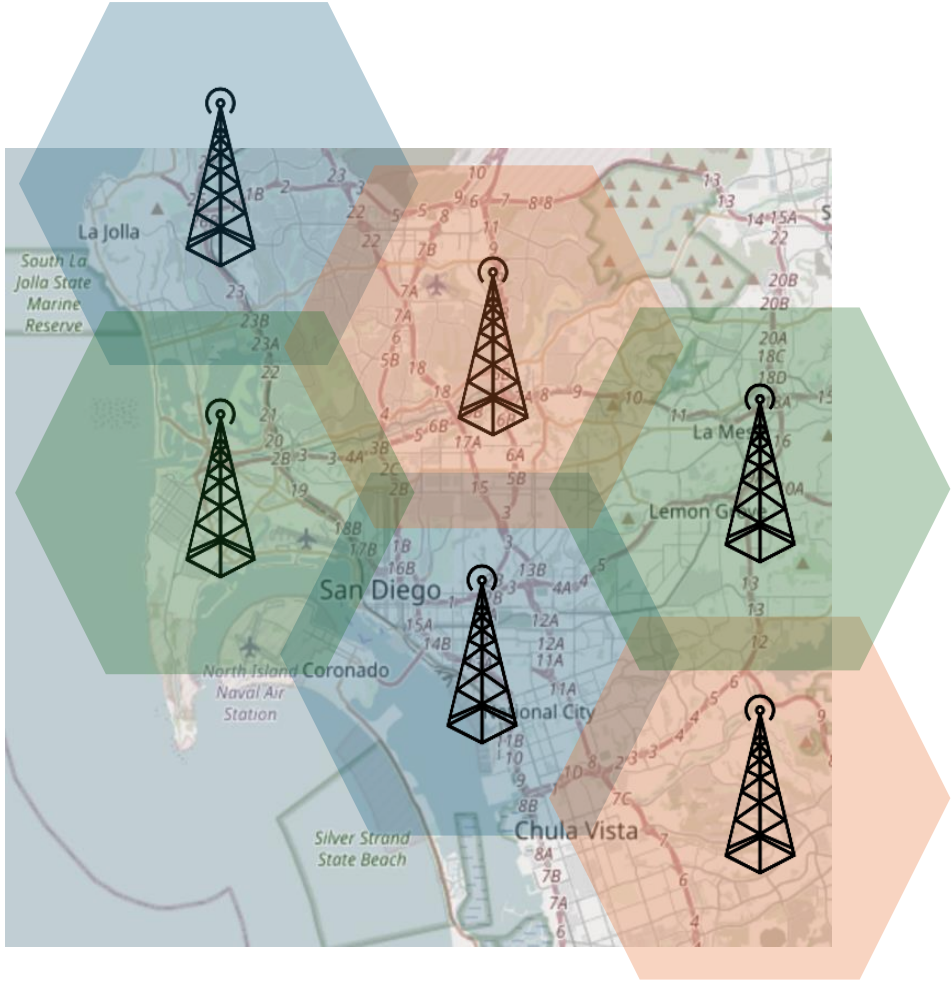
What is inefficient with this picture?

- Early mobile networks handled the mobility challenge with wide-area coverage
- The active user could be anywhere in the 40~60 mile range of the transmit tower
  - So they had exclusive access to that whole area!
- 12 frequency channels → 12 users



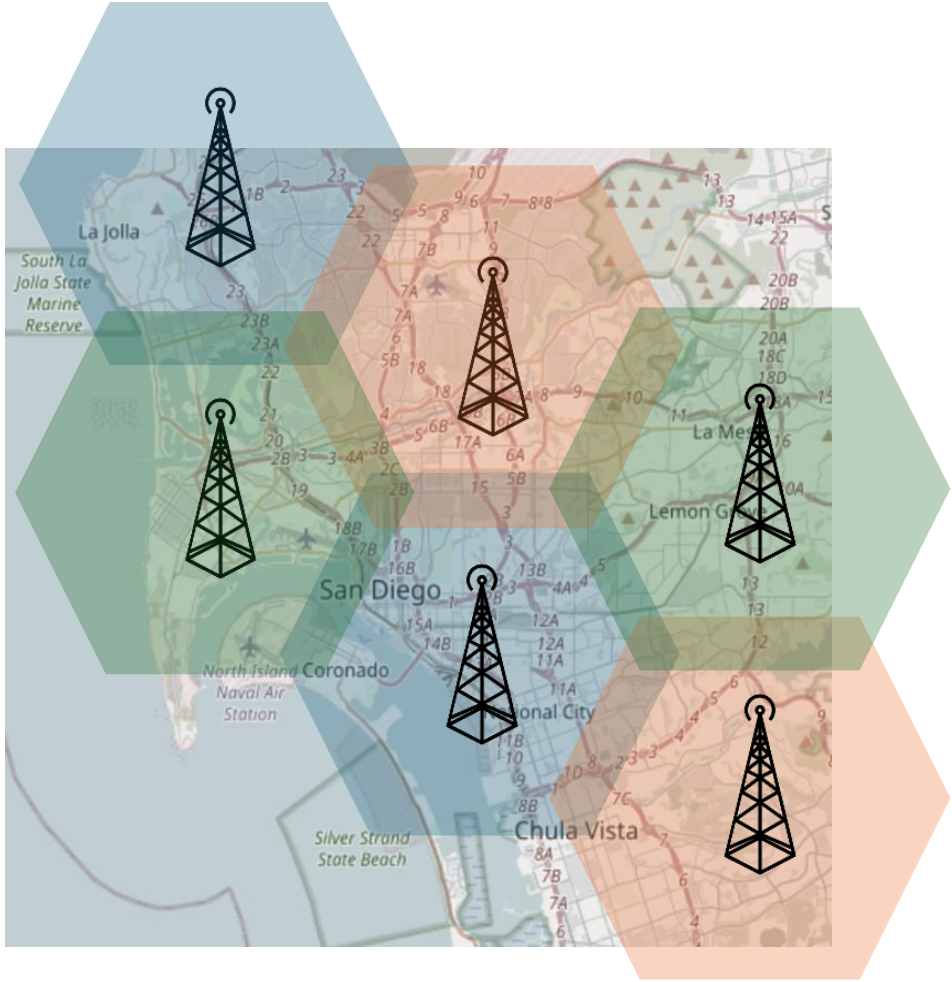
The “cell” in cellular networks

- Cell is *spatial* division
  - Reduce transmit power, smaller area



The “cell” in cellular networks

- Cell is *spatial* division
  - Reduce transmit power, smaller area
- Now…
  - 12 / 3 = 4 channels per cell
  - * 6 cells in area
  - = 24 users of same spectrum!
- And we can choose the cell size based on our expected needs



Satellite Connectivity

- Internet access can be provided through **communication satellites** which is often referred to as **satellite internet access**

- A **communication satellite** relays RF signals through a **transponder**
  - This creates a communication channel between a source **transmitter** and a **receiver** at different locations.

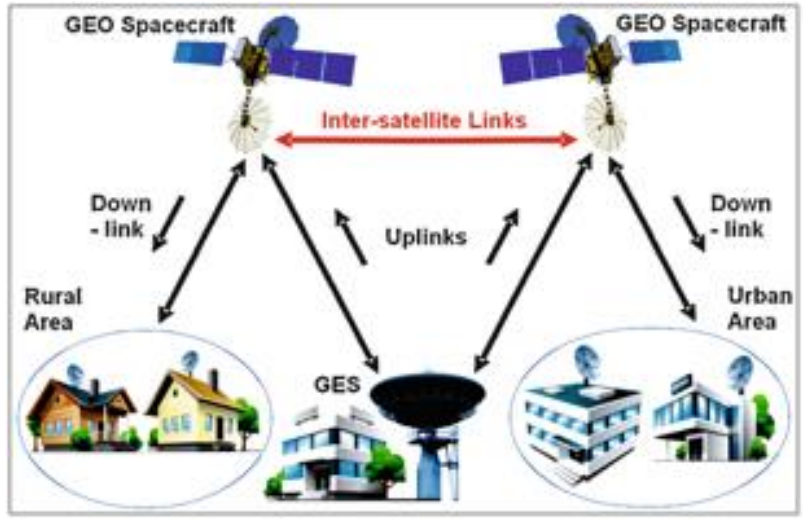


Image Source: NASA

Satellite Connectivity

A communications system consists of:

- Ground Segment – one or more ground stations located on Earth
- Space Segment – one or more spacecrafts with communication payloads
- Uplink and Downlink Transmission
  - Earth to space / Space to Earth
  - Inter-satellite links
- Two types of communication systems
  - Radio Frequency (RF)
  - Free Space Optical (FSO) or laser communications (lasercom)

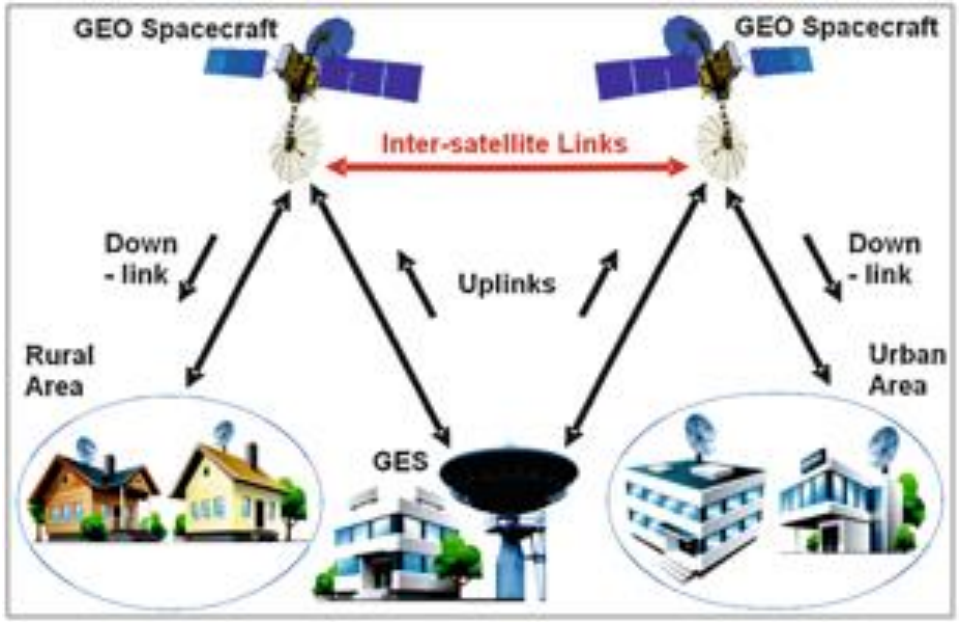


Image Source: NASA

Satellite Orbits

Three primary types of orbit

- Geostationary Orbit (GEO) – 22,236 miles from Earth's surface
  - Often appear as if they are "standing still" in the sky
  - Satellite's orbital period is the same as the rotation rate on Earth
- Medium Earth Orbit (MEO) – 1,200 to 22,400 miles above Earth
  - Similar to LEO in functionality
- Low Earth Orbit (LEO) – 99 to 1,243 miles above Earth
  - Less expensive to launch
  - Do not require high signal strength

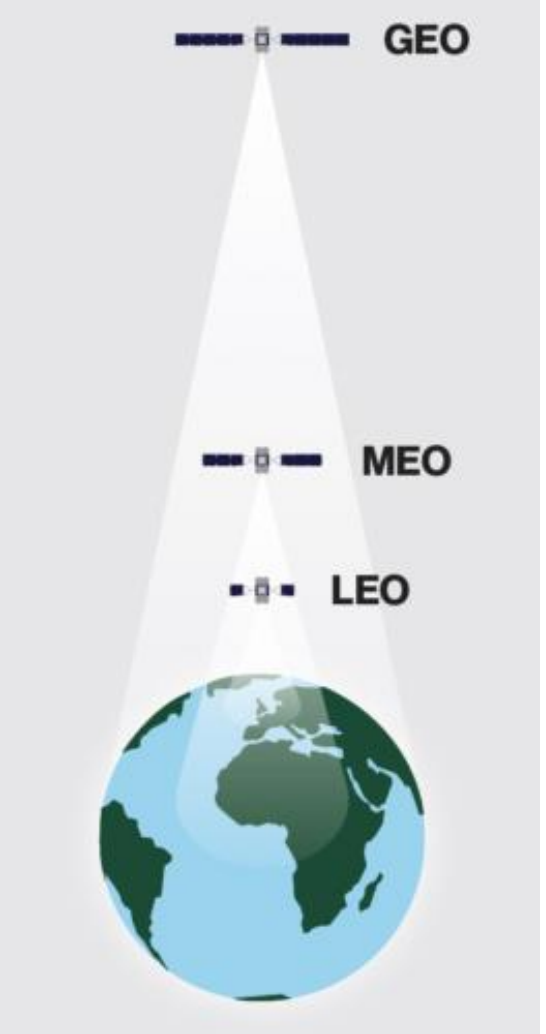


Image Source: Avanti Space

Satellite Connectivity Applications

- Telephone Communication – first and historically most important
- Television – Direct broadcast satellite (DBS) and Fixed Service Satellite (FSS)
- Amateur radio – UHF and VHF radio equipment
- Internet Access
- Military Communications
- **Data Collection –> Internet of Things**

Argos

- **Argos** is a global satellite-based system designed to collect, process and transmit environmental data
- Created by the French Space Agency (CNES), National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA)
- Has been flown on all TIROS-N family satellites of the NOAA since 1978
- Used in many global research programs:
  - Tropical Global Atmosphere Program (TOGA)
  - World Ocean Circulation Experiment (WOCE)
  - Argo

Argos Transceiver

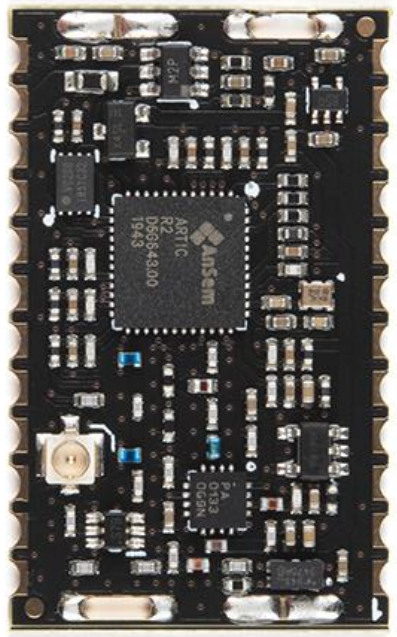


Image Source: Wikipedia

Argos

Core components

- **Platform Transmitter Terminals (PTT)** – various clients (devices) equipped with sensors to measure environmental parameters (e.g., user platforms)
- **Space Segment Data Collection System (DCS)** – receives PTT messages and retransmits data to ground stations
- **Service Provider Ground Segment** – Ground stations and Global Processing Centers (GPCs) where data is retrieved, processed and distributed to users

Artist's view of ground segment elements in the Argos DCS system

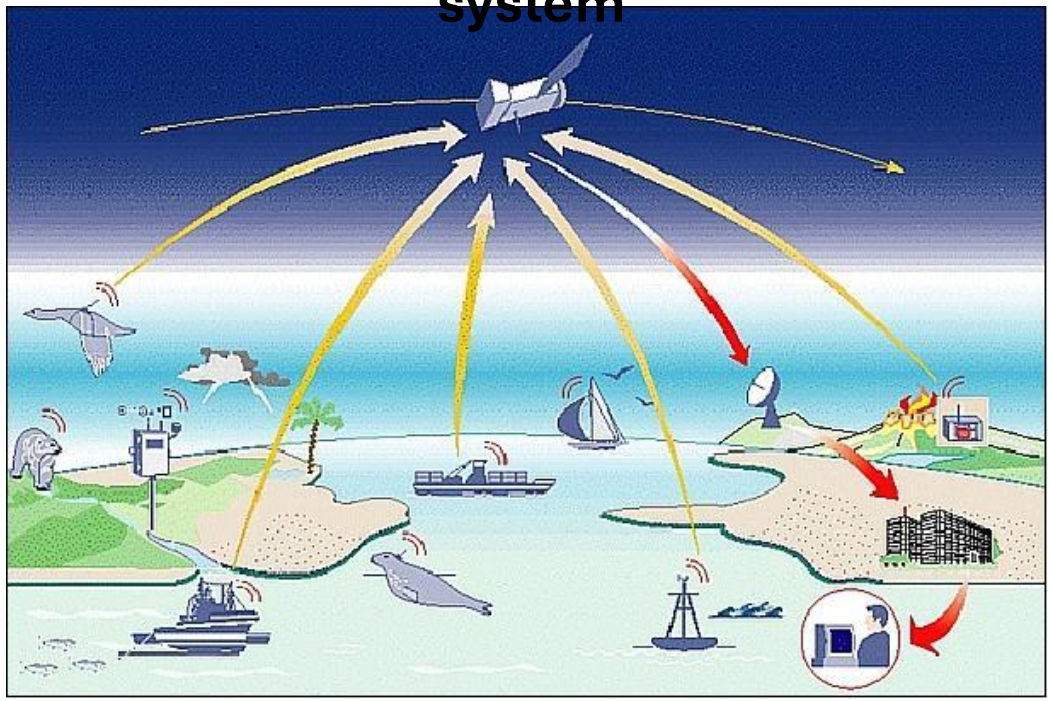


Image Source: eoPortal; Image Credit: Service Argos Inc.

Satellite Connectivity Providers

Iridium Satellite Constellation

- Project Stardust (2024)
- Introduced satellite-to-cellphone service
  - Messaging
  - Emergency Communications
  - **IoT Devices**



RockBlock

Replica of a first-generation Iridium Satellite

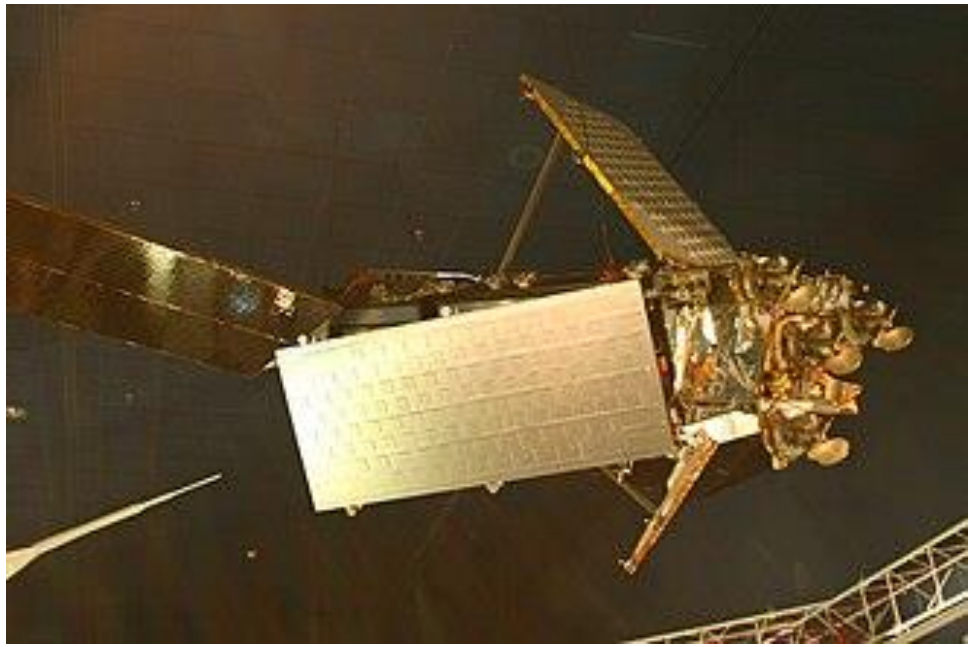


Image Source: Wikipedia

Satellite Connectivity … Recent Advancements

- Many emerging satellite IoT companies
  - EchoStar
  - FOSSA Systems
  - Swarm (acquired by StarLink)
- Satellite links using LoRaWAN
- Satellite links using BLE chips
  - Hubble Network

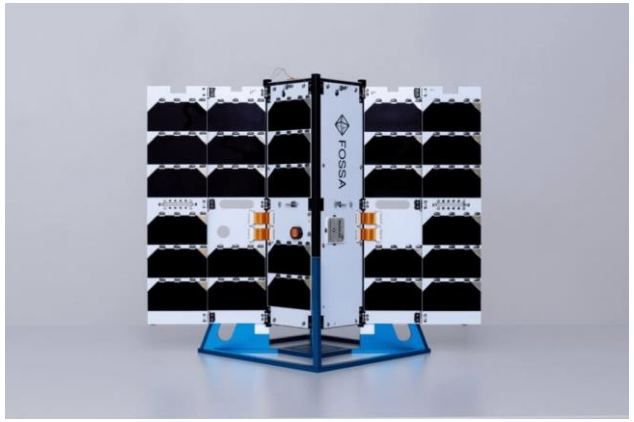
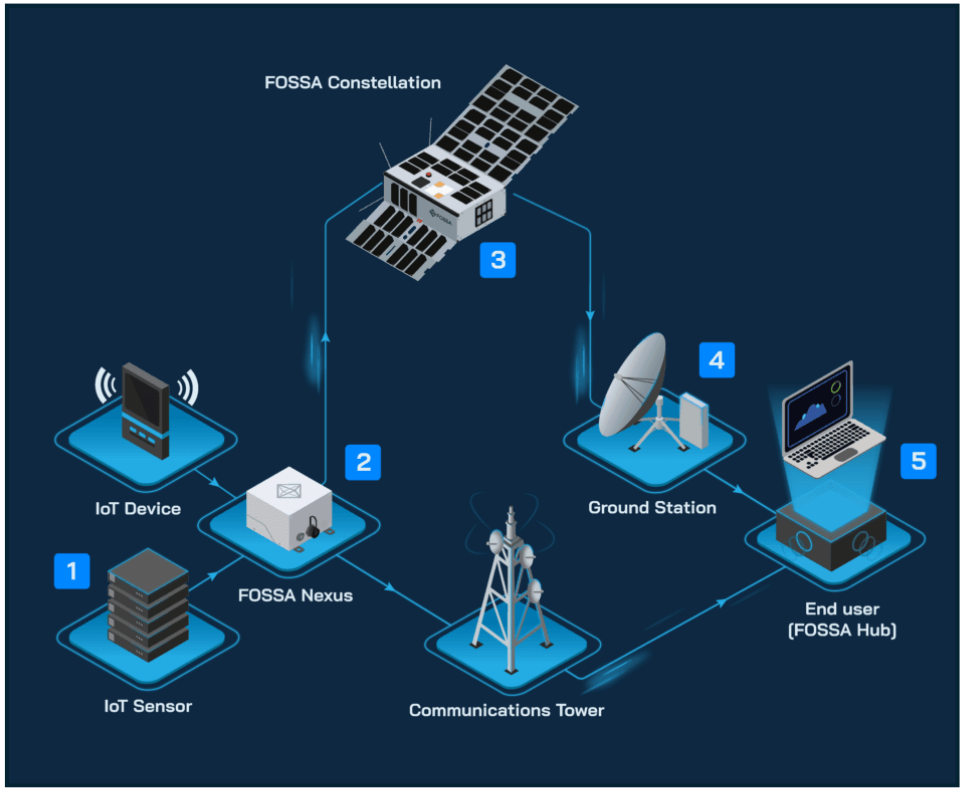


Image Source: FOSSA Systems



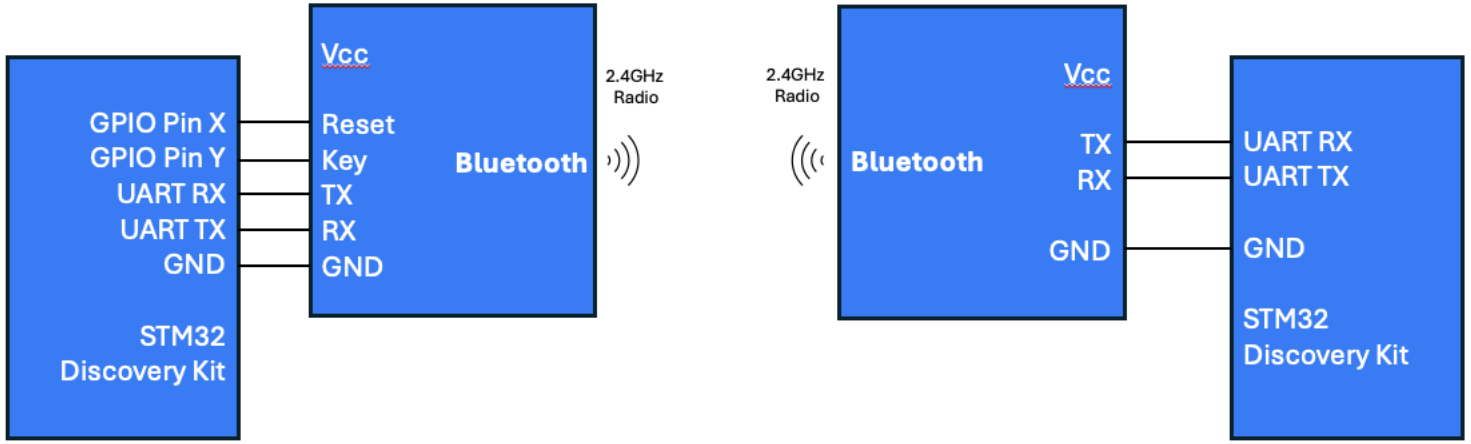
Example: FOSSA Systems

- LEO Nano and microsatellites
  - 24 satellites as of 2026
- Data Uplink
  1. Use a gateway to send data to the satellite network
  2. LoRa devices directly connect to the satellite
     - If a device is under terrestrial coverage, data is sent to a cell tower
- Data Downlink
  - Each satellite stores the information received from the terrestrial devices and relays data to ground stations

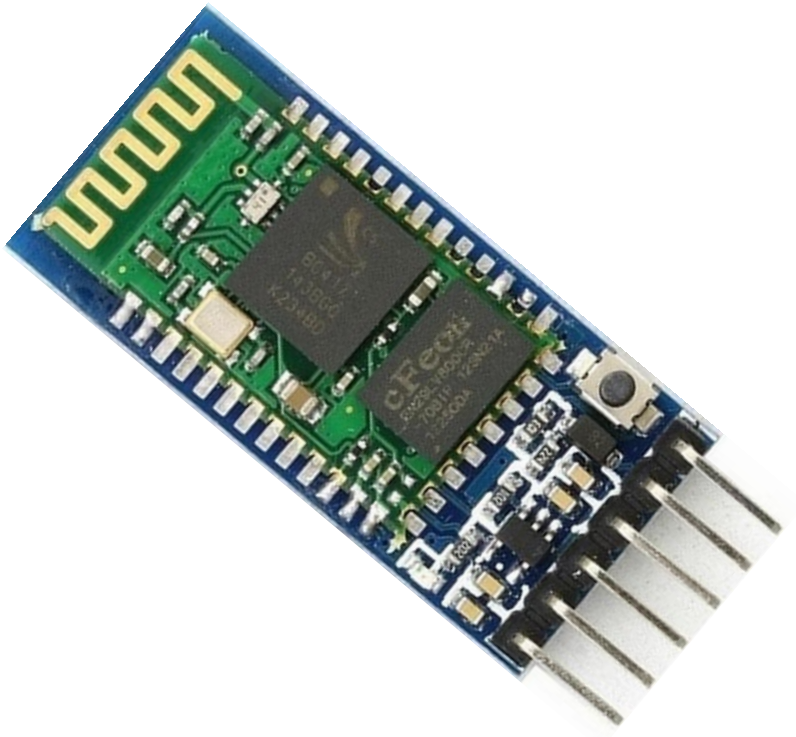


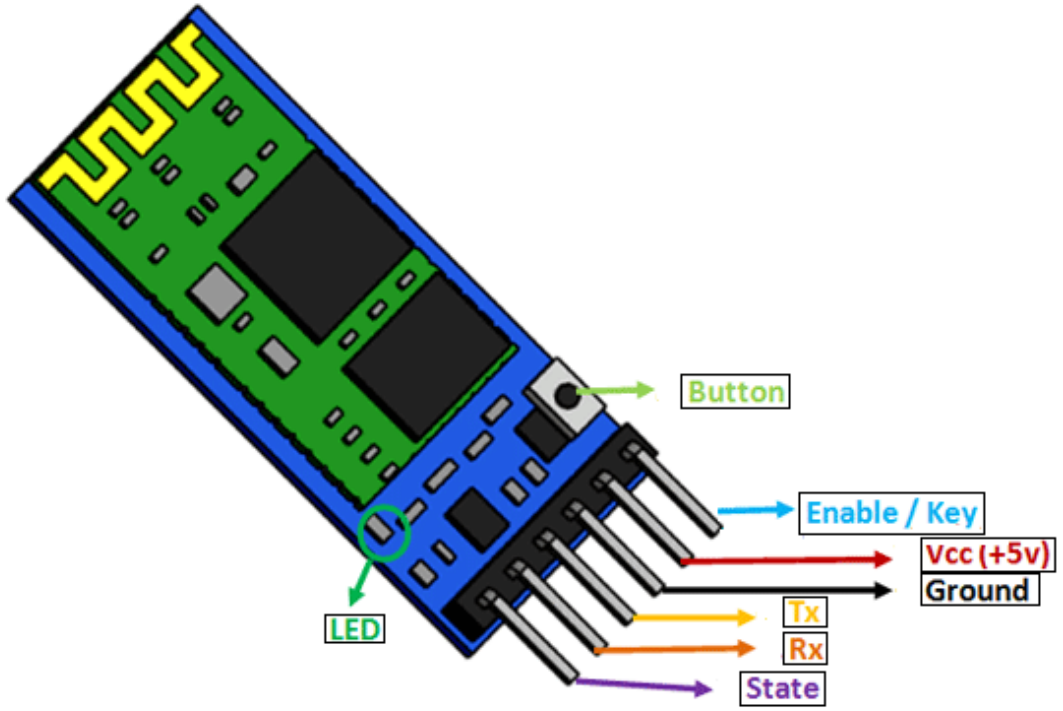
Serial Communication to Bluetooth Module

- There are many low-cost Bluetooth modules that you can interface with using serial communication
  - HC-05, HC-06
- RFCOMM (radio frequency communication) is a Bluetooth device profile that emulates the serial cable line
  - UART interface for serial communication between the Bluetooth module and microprocessors
  - Bluetooth interface for wireless communication between two Bluetooth modules



HC-05/06



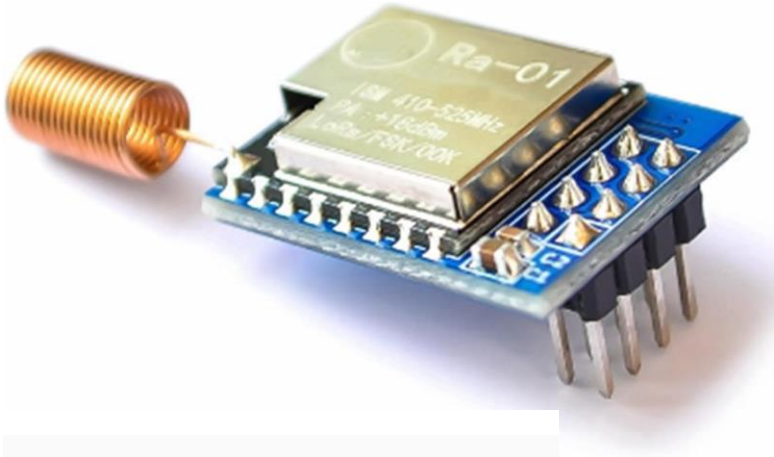


Pairing Bluetooth Modules

- Bluetooth modules need to be “paired” before they can exchange data
- A *primary* device must know the address of the *secondary* device and the pairing password is set by the *secondary* device
- The MCU sends commands via the serial interface to the Bluetooth *primary* device to complete the pairing process
- Commands start with “AT” (attention) and end with a terminator “return”
  - ASCII values

Interfacing with LoRa Modules

- EXAMPLE: Ra-01SH LoRa
  - Designed around the SX1262
    - 803-930MHz
    - Up to 300kbps
  - Serial Peripheral Interface (SPI)
- What do you need to configure?
  - Frequency (TX/RX must match)
  - Data rate
  - Data packet
  - Transmit power



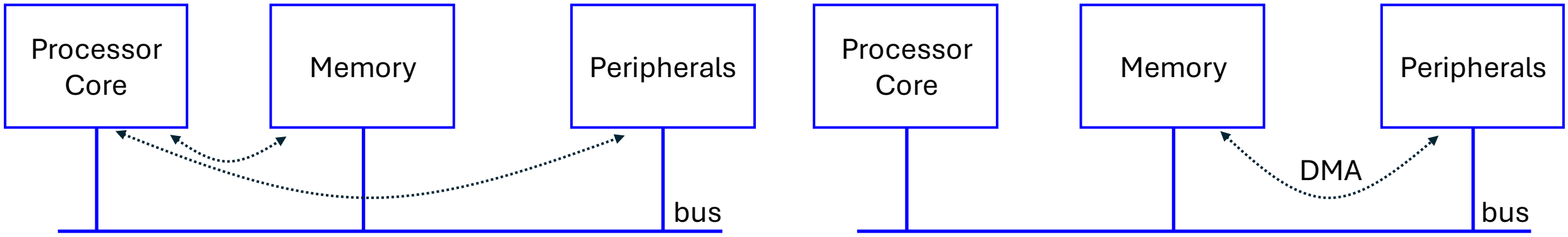


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- Finish Wireless Topics
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  - LoRa
- **Direct Memory Access (DMA)**
- Final Project Guidelines
  - Demo Requirements
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Direct Memory Access (DMA)

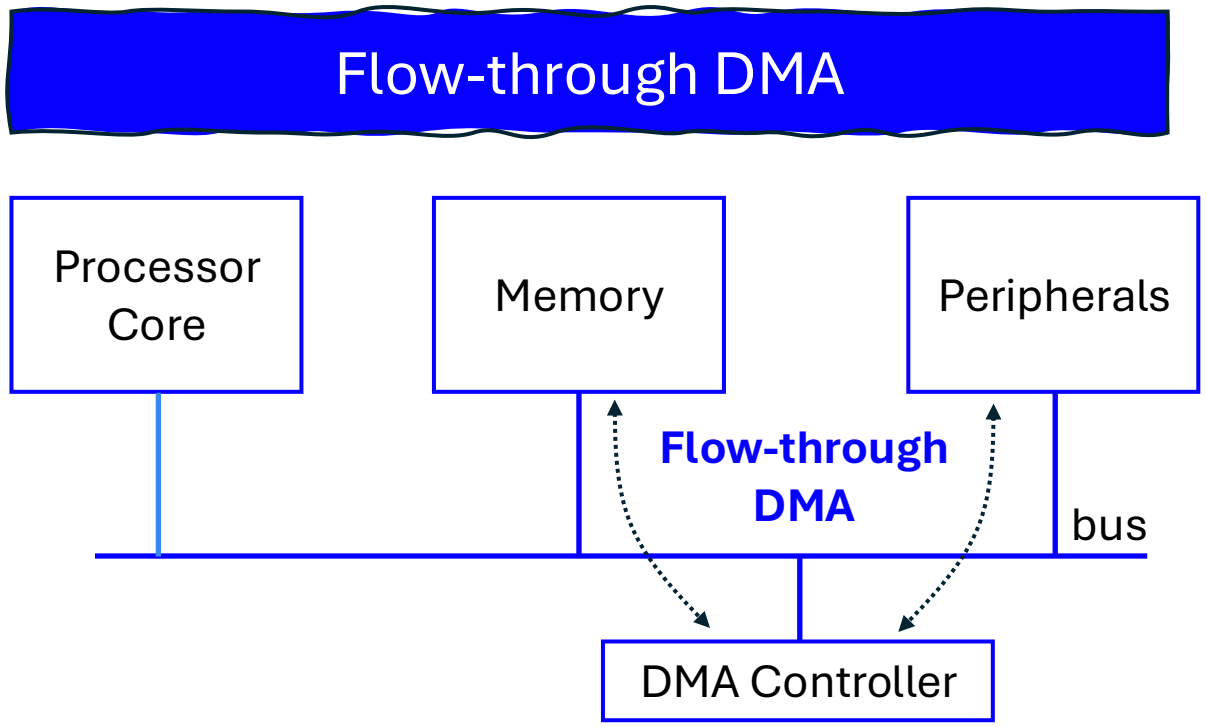
A useful technique for transferring data between **peripherals and memory**, or between **memory and memory**, without using many processor cycles

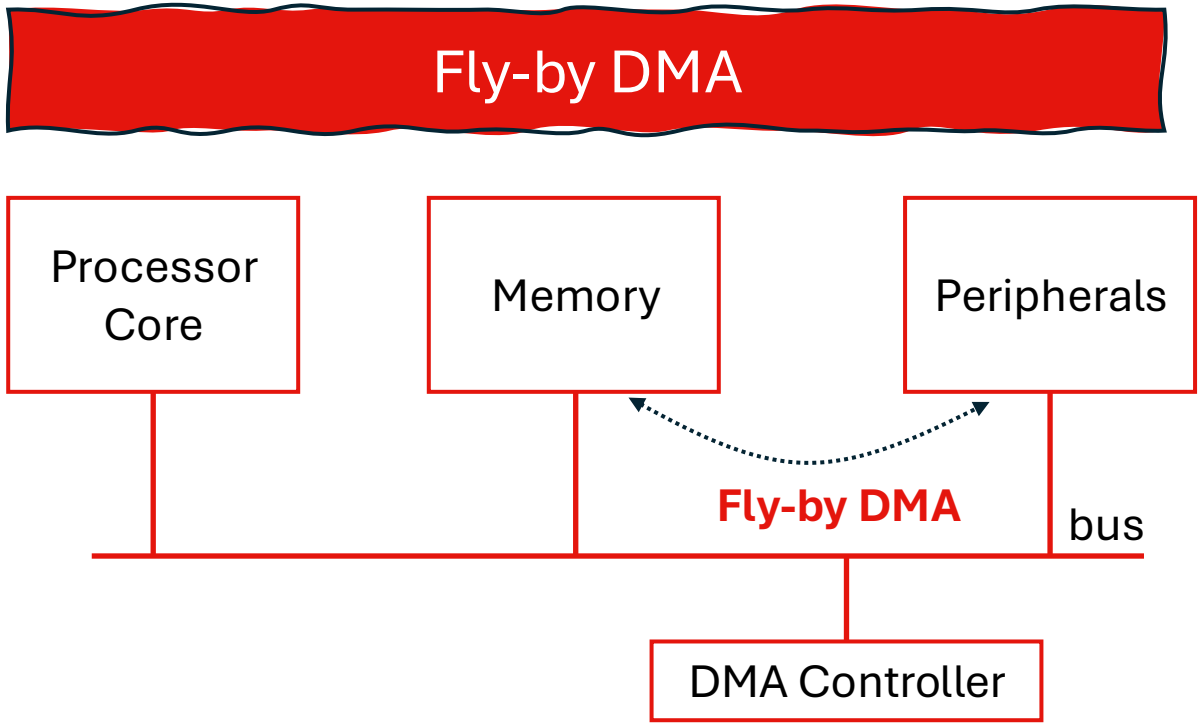


Without DMA

With DMA

DMA: Flow-through vs Fly-by





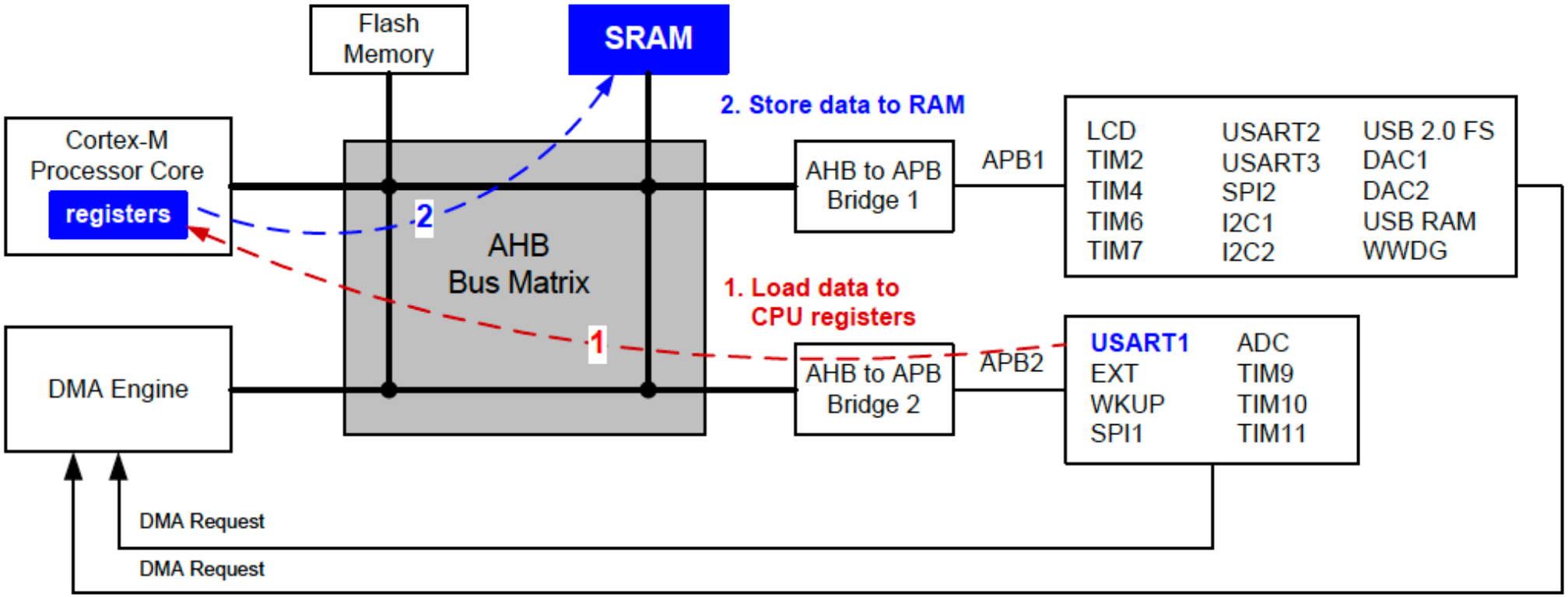
Flow-through DMA transfer involves two steps:

(1) Data are read one at a time from the source into a register in the DMA controller
(2) Data are written to the destination

Fly-by DMA transfer only requires one bus transfer:

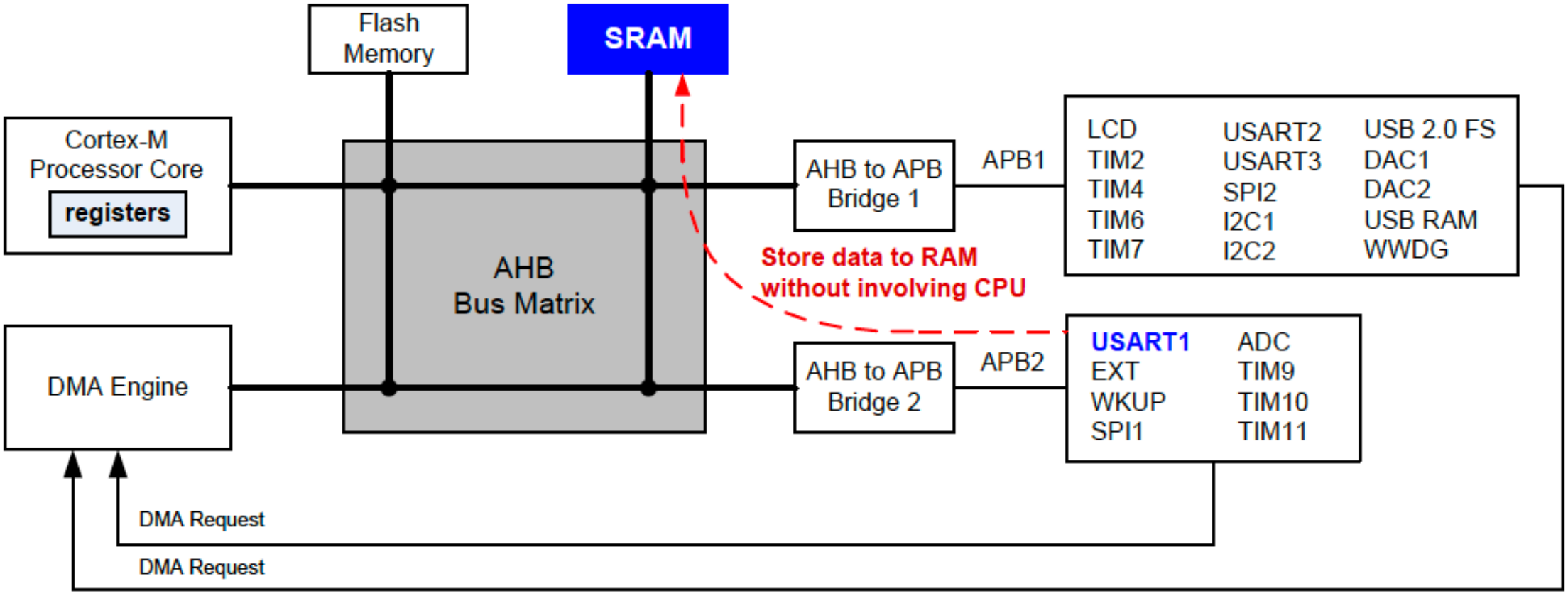
Data are directly transferred from the source to the destination without being read into the DMA controller

Interfacing a peripheral ***without*** DMA



- Processor executes **many** loads/stores to move data
- High overhead and slow

Interfacing a peripheral ***with*** DMA



- CPU delegates read/writes to DMA controller
- Low overhead and fast

DMA on the STM32L4

STM32L4 has two DMA controllers, with seven channels each

Each channel can perform DMA transfers independently

Each channel has its own source, destination, transfer direction, transfer width, data amount, and trigger

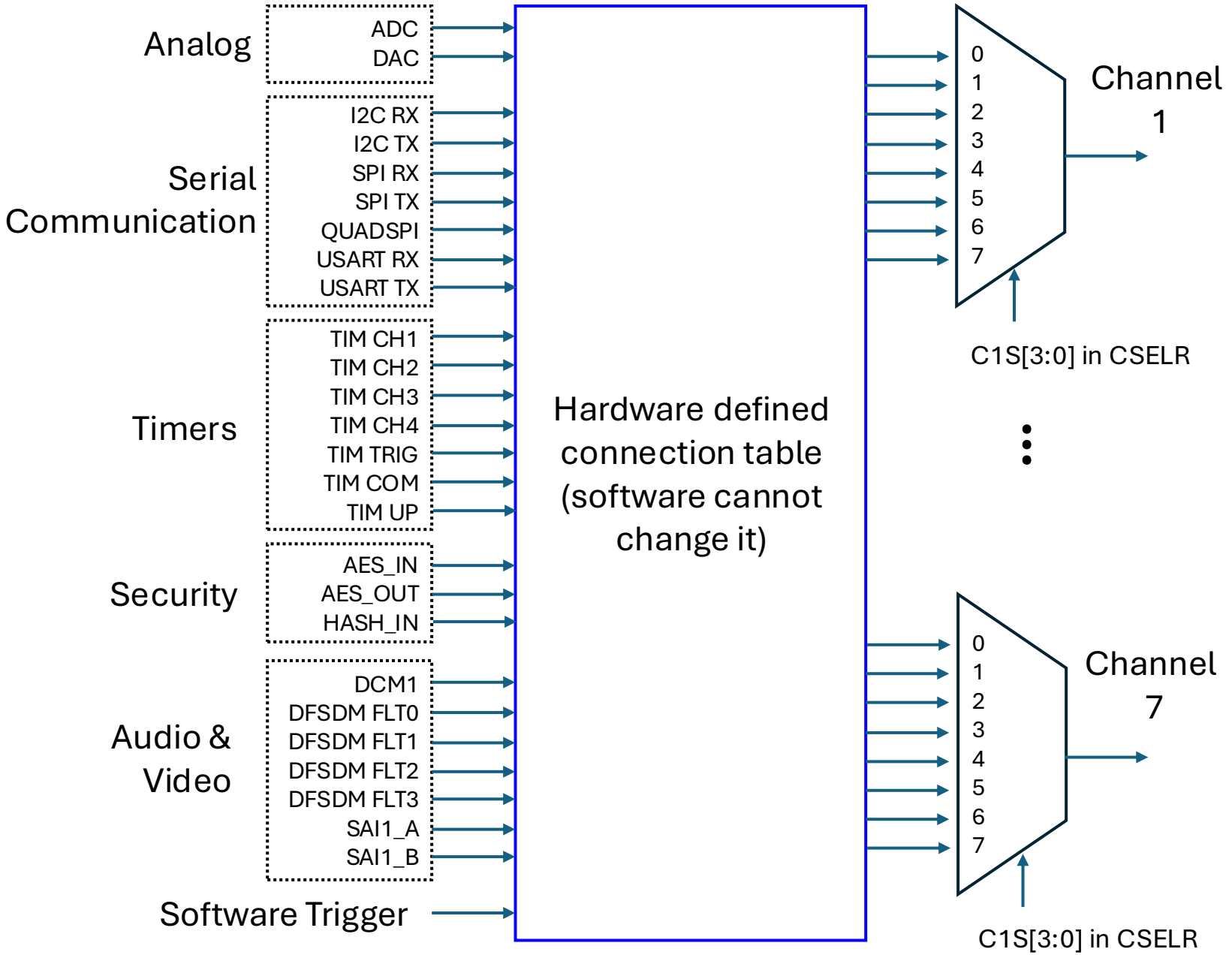
If a DMA channel is enabled, it performs a DMA transfer automatically for each trigger received

Each channel can be programmed to be triggered by one event selected (achieved by programming the DMA's controller CSELR register)

DMA Channels

Selecting one trigger signal for each DMA channel

Programs can configure the software priority for each channel



DMA Channels

Trigger	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7
0	ADC1	ADC2	ADC3	DFSMD1_FLT0	DFSMD1_FLT1	DFSMD1_FLT2	DFSMD1_FLT3
1	-	SPI1_RX	SPI1_TX	SPI2_RX	SPI2_TX	SAI2_A	SAI2_B
2	-	USART3_TX	USART3_RX	USART1_TX	USART1_RX	USART2_TX	USART2_RX
3	-	I2C3_TX	I2C3_RX	I2C2_TX	I2C2_RX	I2C1_TX	I2C1_RX
4	TIM2_CH3	TIM2_UP	TIM16_CH1 TIM16_UP	-	TIME2_CH1	TIM16_CH1 TIM16_UP	TIM2_CH2 TIM2_CH4
5	TIM17_CH1 TIM17_UP	TIM3_CH3	TIM3_CH4 TIM3_UP	TIM7_UP DAC2	QUADSPI	TIM3_CH1 TIM3_TRIG	TIM17_CH1 TIM17_UP
6	TIM4_CH1	-	TIM6_UP DAC1	TIM4_CH2	TIM4_CH3	-	TIM4_UP
7	-	TIM1_CH1	TIM1_CH2	TIM1_CH4 TIM_TRIG TIM1_COM	TIM15_CH1 TIM15_UP TIM15_TRIG TIM15_COM	TIM1_UP	TIM1_CH3

DMA Chanel Registers

- Channel Memory Address Register (CMAR)
- Channel Peripheral Address Register (CPAR)
- Channel Number of Data Register (CNDTR)
- Channel Configuration Register (CCR)

Specifies the starting address of data memory

Specifies the starting address of the peripheral

Software must specify the total number of data transfers in the CNDTR register

Specifies data transfer direction, increment mode, circular mode, channel priority

CMAR = Channel Memory Address Register
CPAR = Channel Peripheral Address Register

Increment Mode

Increment mode determines whether CPAR or CMAR increments after each DMA transfer

Can be programmed separately for CPAR and CMAR

EXAMPLE: If increment mode for CMAR is enabled and MSIZE is four bytes, then memory address stored in CMAR is automatically incremented by four after each DMA transfer

Channel **M**emory **A**ddress **R**egister (CMAR)
Channel **P**eripheral **A**ddress **R**egister (CPAR)
Channel **N**umber of **D**ata **R**egister (CNDTR)
Channel **C**onfiguration **R**egister (CCR)

DMA Circular Mode

The DMA channel can run in ***circular mode*** or ***normal mode***

Normal mode (CIRC bit in the CCR register is cleared)

- For each DMA transfer, hardware decrements the CNDTR register by 1
- The DMA channel is disabled once CNDTR reaches 0

Circular mode (CIRC bit in the CCR is set)

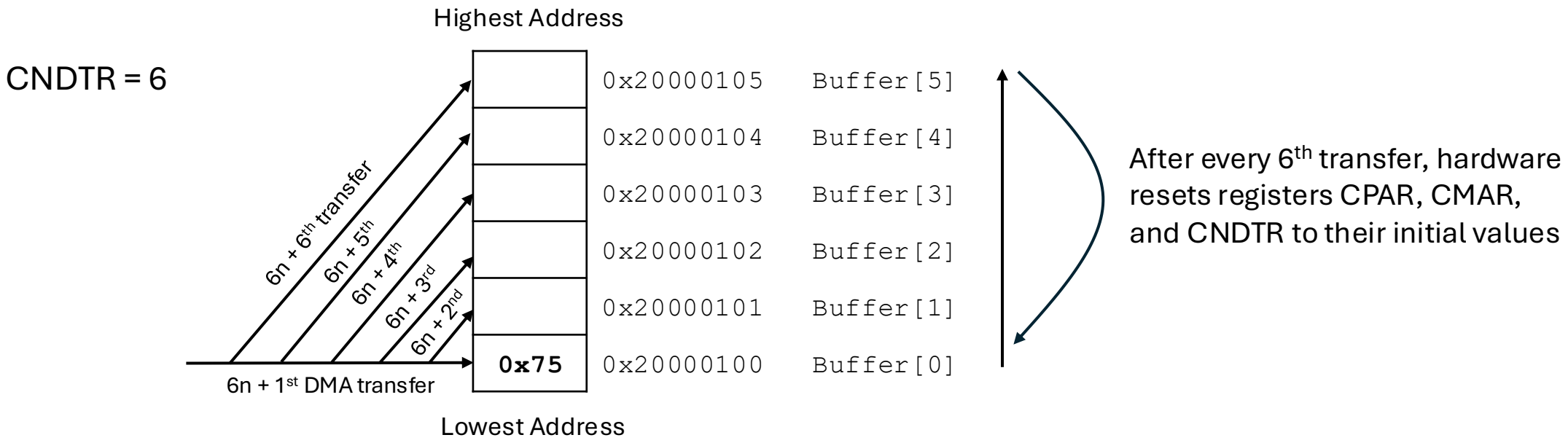
- often used for memory to implement a circular buffer
- After CNDTR reaches 0, CPAR, CMAR, and CNDTR are automatically reset to the value originally programmed.
- DMA can start the next round of DMA transfers
- Useful for DMA transfers for continuous data streams.

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DMA Circular Mode

Circular mode (CIRC bit in the CCR is set)

- often used for memory to implement a circular buffer
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- Useful for DMA transfers for continuous data streams.



DMA Summary

- Without DMA, CPU has to execute many load and store instructions, leading to slower performance
- DMA automatically initiates data transfer when it receives a DMA request without involving the CPU
- Accelerates overall performance

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  - LoRa
- Direct Memory Access (DMA)
- **Final Project Guidelines**
  - Demo Requirements
  - Poster Session Requirements

Final Project Demos and Poster Session

- Each group must sign up to demo their final project to the course staff
  - We will share a sign-up sheet

- Poster session is on December 11th , 12:15PM – 3:15PM

Demos

- Demonstrate a fully functioning system that meets the design requirements listed in your final project proposal
- Explain the core functionalities and how you implemented them
- Explain and justify your design decisions
- 20 Minute Sessions
- Each group member is expected to participate

Poster Session

- **Each group must prepare a poster to present their final project**
  - Intro / Motivation
  - Block diagram of your system
  - Key features
  - Results
- **Formatting**
  - 36 x 48”
  - How to design a good poster
    - https://icme.stanford.edu/sites/g/files/sbiybj17116/files/media/file/designing_excellent_engineering_posters-workshop_0.pdf
  - Poster Example
    - https://icme.stanford.edu/sites/g/files/sbiybj17116/files/media/file/icme_fyliu_0.pdf

A Title

Team Member Names

Intro and motivation

What is the system your building and why

System Design

What components did you use?
How do they work?
What is your end-to-end system design?

Key Features

What are your key features?
Example:
Digital Alarm Clock

- Clap to snooze

Results

Images of your system/solution
Oscilloscope/logic analyzer outputs
Code snippets
Etc.

Logistics

- Poster Session will be in the Packard EE Atrium
- Tables will be set up to display your project and to support live demos
- Let us know if you require a power outlet!
- December 11th , 12:15 – 3:15PM
  - Setup from 12:15-1PM
  - Poster session 1PM-2:30PM
  - Tear down 2:30 – 3:15PM