INTRODUCTION TO SATELLITE COMMUNICATIONS

SATELLITE DOWNLINK AND UPLINK PATHS

GSAW 2025

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COURSE INSTRUCTOR

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COURSE INTRODUCTION

THIS COURSE INTRODUCES THE SIGNALS, DATA PATHS, AND PROTOCOLS FOR TYPICAL TELEMETRY AND COMMAND COMMUNICATION LINKS.

Prerequisite knowledge: a general understanding of satellite ground systems.

In this presentation:

- The full end-to-end picture
- Why things work the way they do

There are **many** ways to design, implement & use a ground system.

- We have tried to capture “typical” cases.
- Specific satellite programs do the same things in different ways.

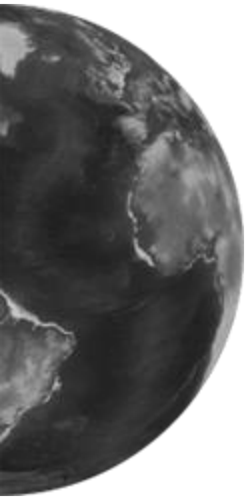
COURSE OBJECTIVES

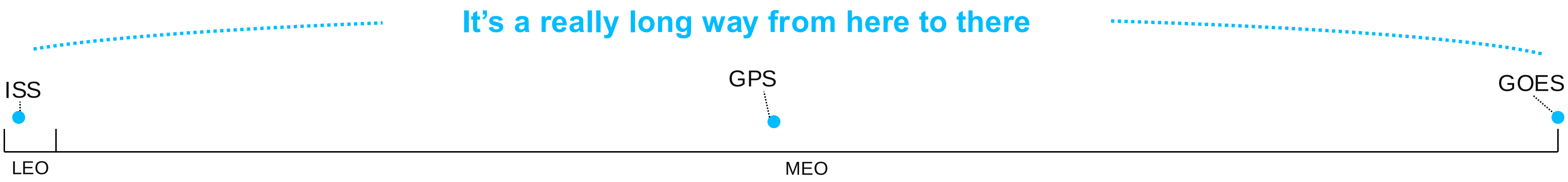
- ❑ Identify the various links and layers within a satellite communications path.
- ❑ Explain the protocols and processes by which satellite communications systems operate.
- ❑ Visualize, at a high level, how satellite ground processing systems work.

PLEASE ASK QUESTIONS

There is a lot to cover, so if you don't ask right away, the moment will be lost.

PERSPECTIVE ON SATELLITE COMMUNICATIONS





Miscommunication has a big downside

	International Space Station	Low Earth Orbit (LEO)	Medium Earth Orbit (MEO)	Geosynchronous (GEO)
Altitude	200 miles	160 – 1,200 miles	1,200 – 22,200 miles	22,200 miles
Orbit Period	92 minutes	80 – 120 minutes	120 minutes – 3 hours	24 hours
Daily Frequent Flier Miles	414,000 miles	490,000 miles	209,900 miles	164,500 miles
Signal Delay	4 msec	10 msec	< 0.2 sec	0.25 sec

There are other orbits (Cislunar, Lagrange, etc as well)

ADDITIONAL PERSPECTIVE

Satellites are relatively small and rely on solar power.

- Small receive aperture and low transmit wattage.

Signals have to travel a long distance.

- Links are designed for one-way communications.
- Signals received by a ground antenna can be very faint (<0.000000001 watt).

Low earth orbit satellites are moving fast.

- 17,000 mph.
- Requires tracking the signal Doppler.

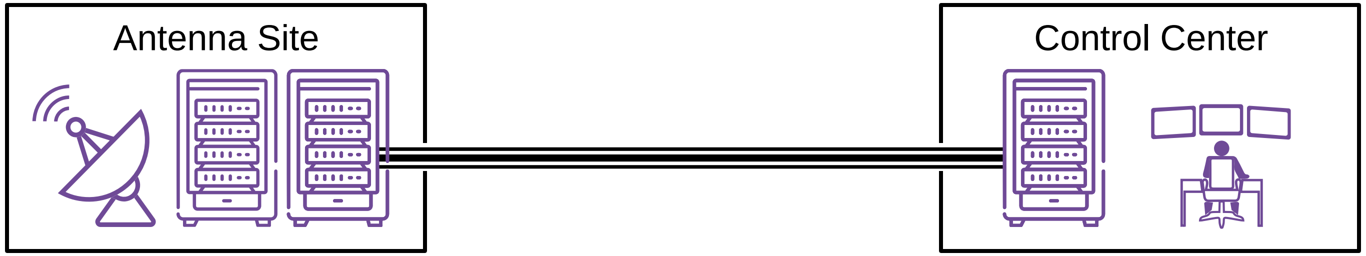
Quality of the data is really important.

- Telemetry and mission data are used to make decisions.
- Commands and uploads are something you want to get right.
- You will likely never touch your satellite again.

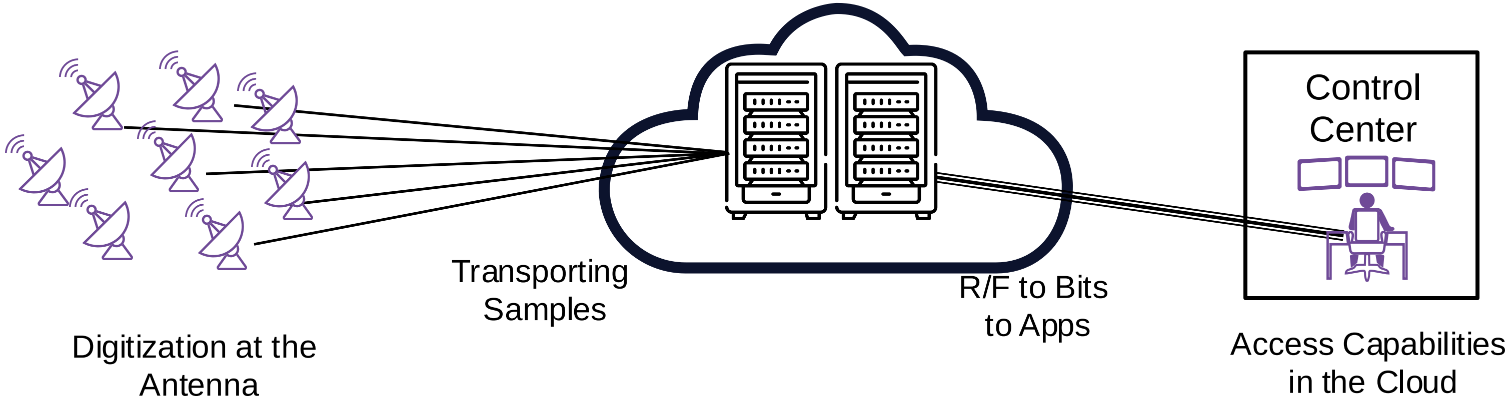
IT'S THESE AND OTHER CHALLENGES THAT MAKE IT INTERESTING.

A FUNDAMENTAL SHIFT IS HAPPENING IN THE INDUSTRY…

Traditional satellite operations…



are in the cloud!



IN THE END, ALL OF WHAT WE ARE GOING TO TALK ABOUT IS STILL NEEDED. IT'S JUST WHERE IT HAPPENS THAT CHANGES.

LINKS AND LAYERS

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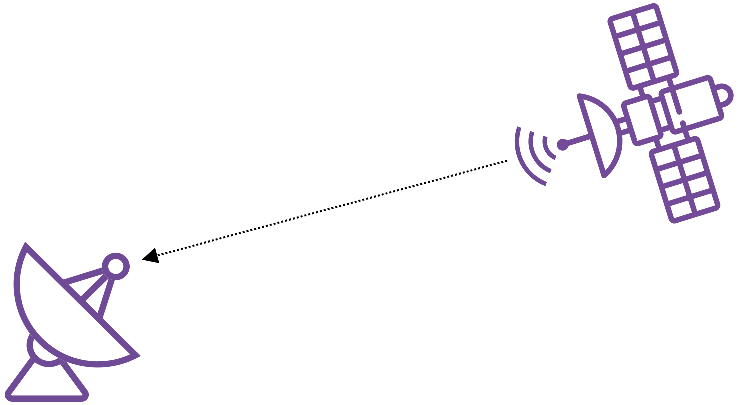
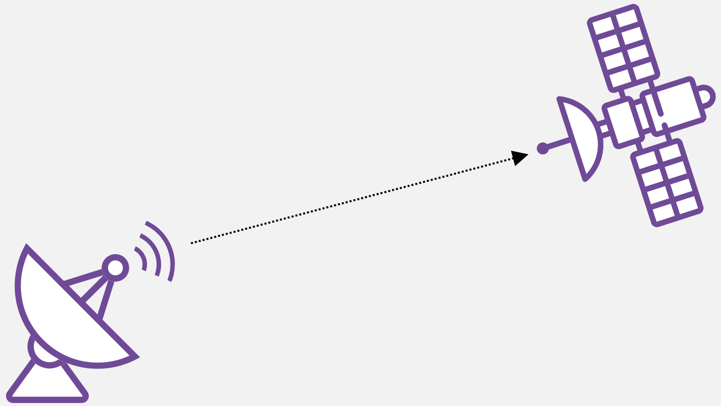
SATELLITE COMMUNICATIONS LINKS



Downlink or Return Link

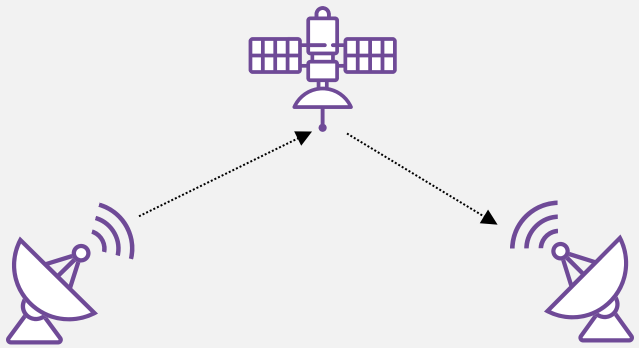
- The satellite can be the origin of the data and radiates a signal to the ground antenna.
- This can be telemetry or payload data.



Uplink or Forward Link

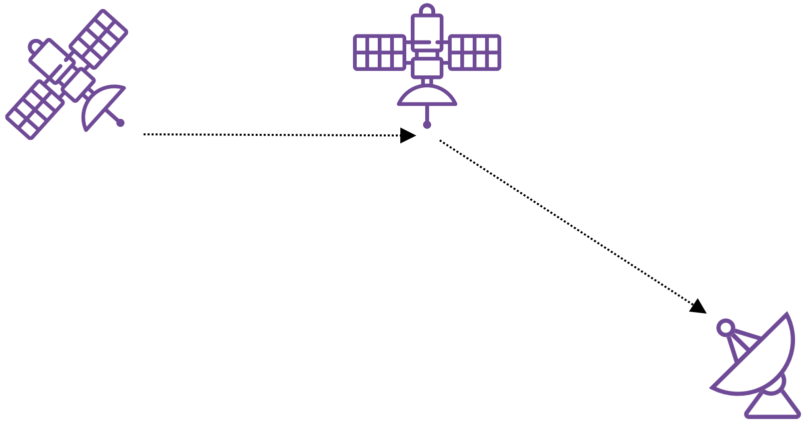
- The transmitting ground station formats data and radiates a signal to the satellite.
- In the case of commanding, the satellite consumes the signal.

SATELLITE COMMUNICATIONS LINKS



Transponded Links

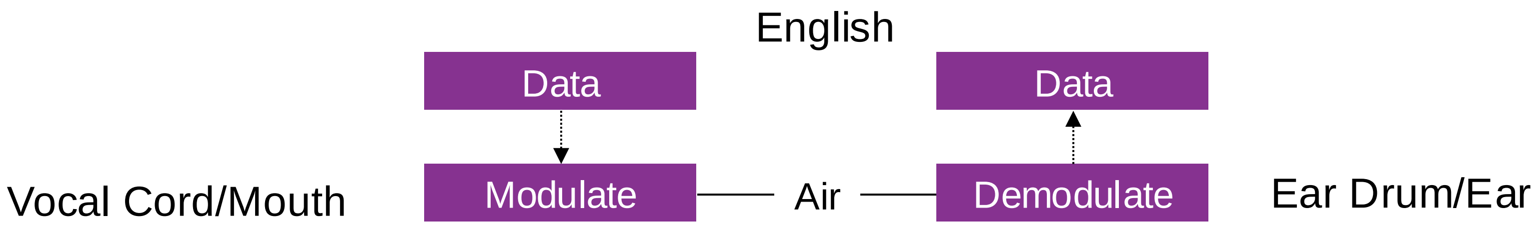
- Many communications satellites transpond (relay) the ground signal and its data.



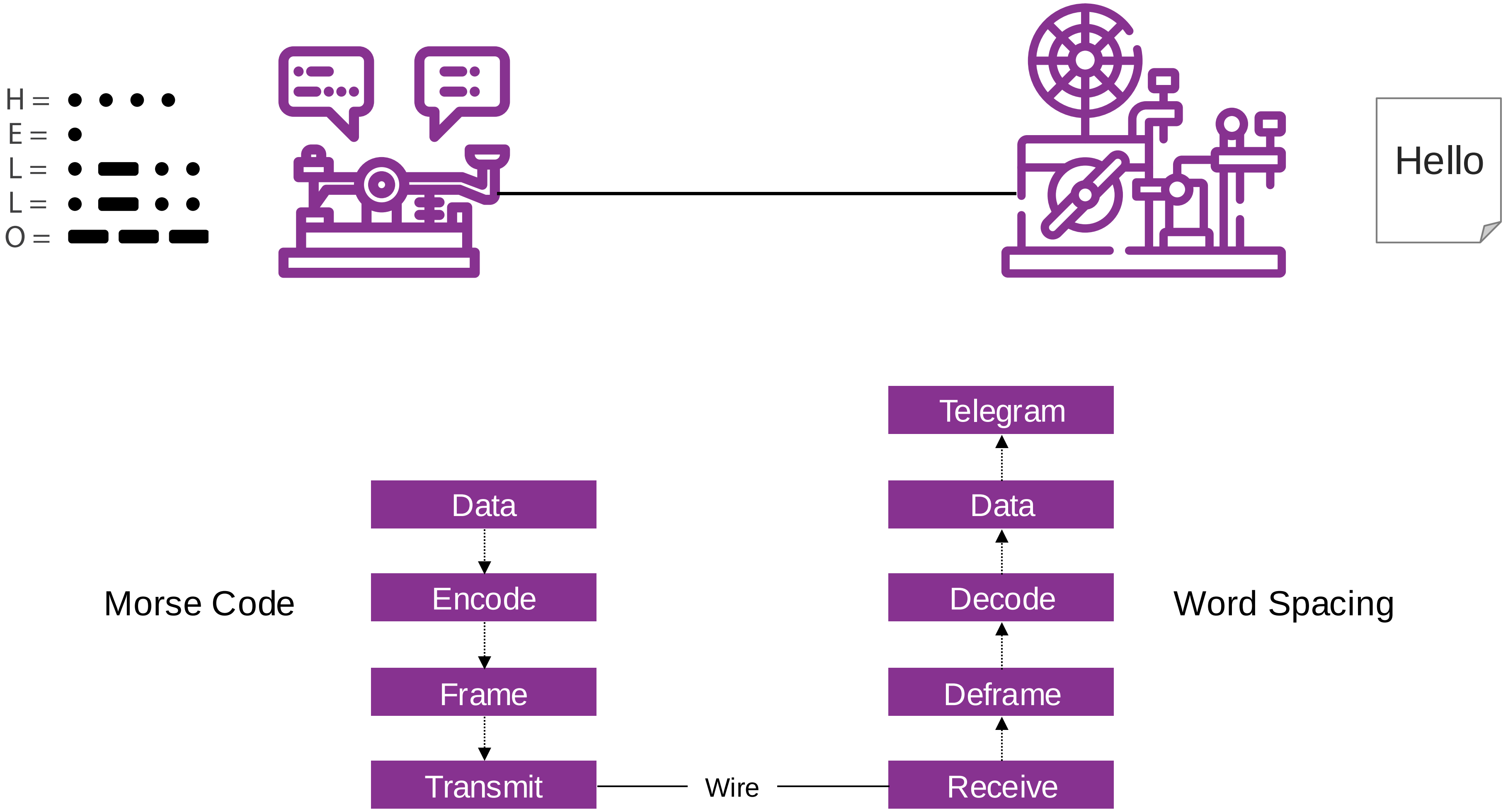
Space Relay Links

- These allow an LEO satellite to communicate without direct ground station visibility.
- NASA’s TDRSS is an example.

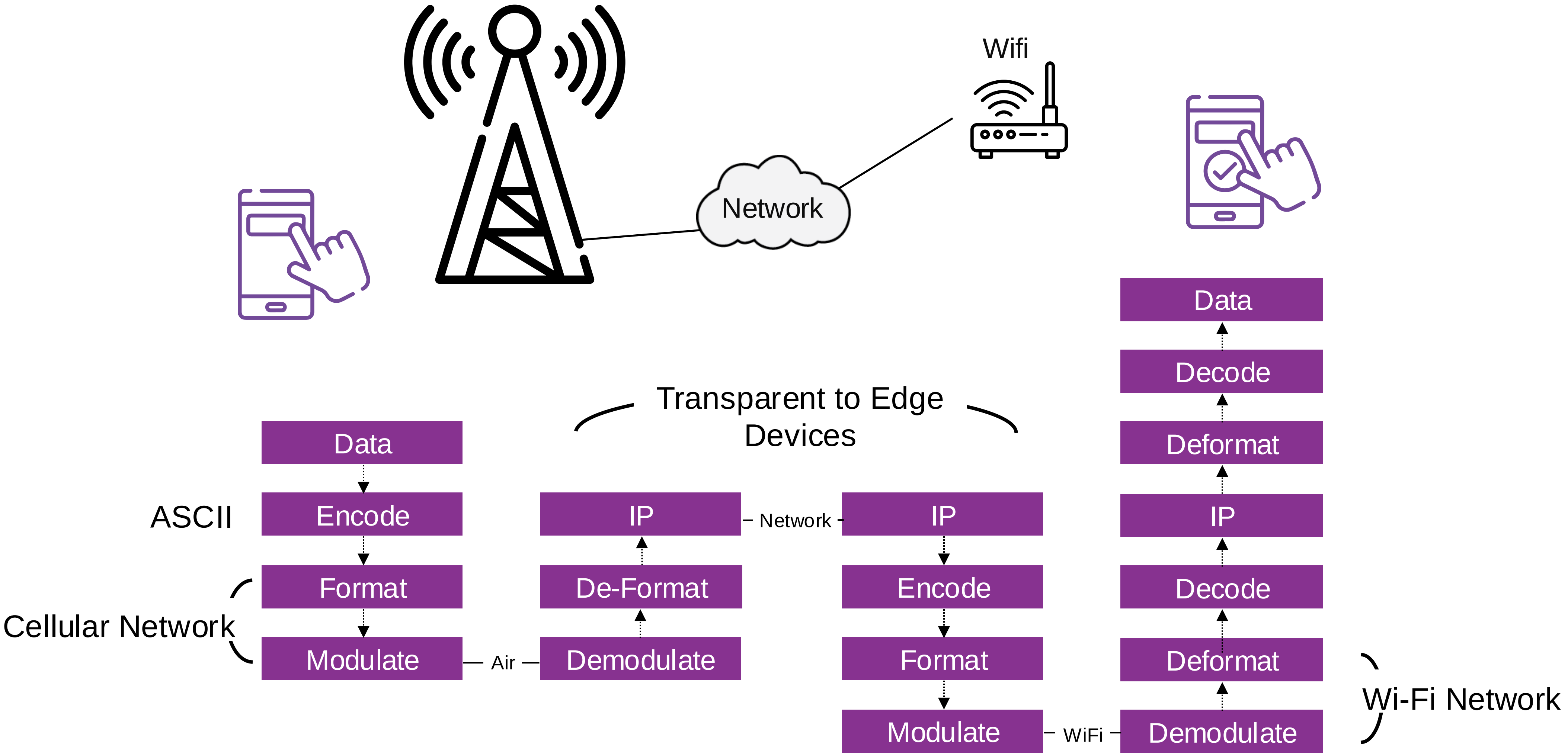
MODULATION AND DEMODULATION



ENCODING AND DECODING



NOW WE HAVE ADDED EVEN MORE!



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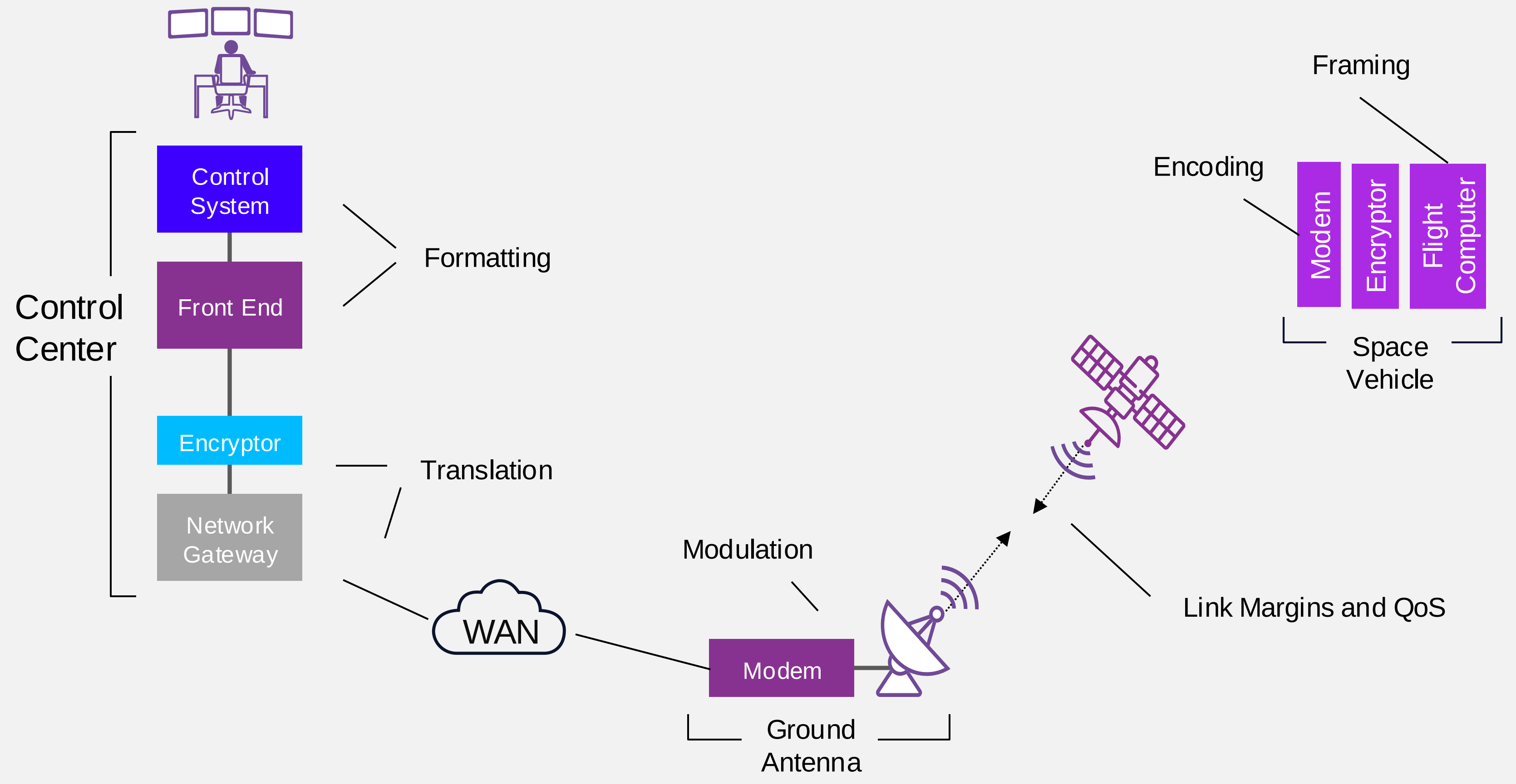
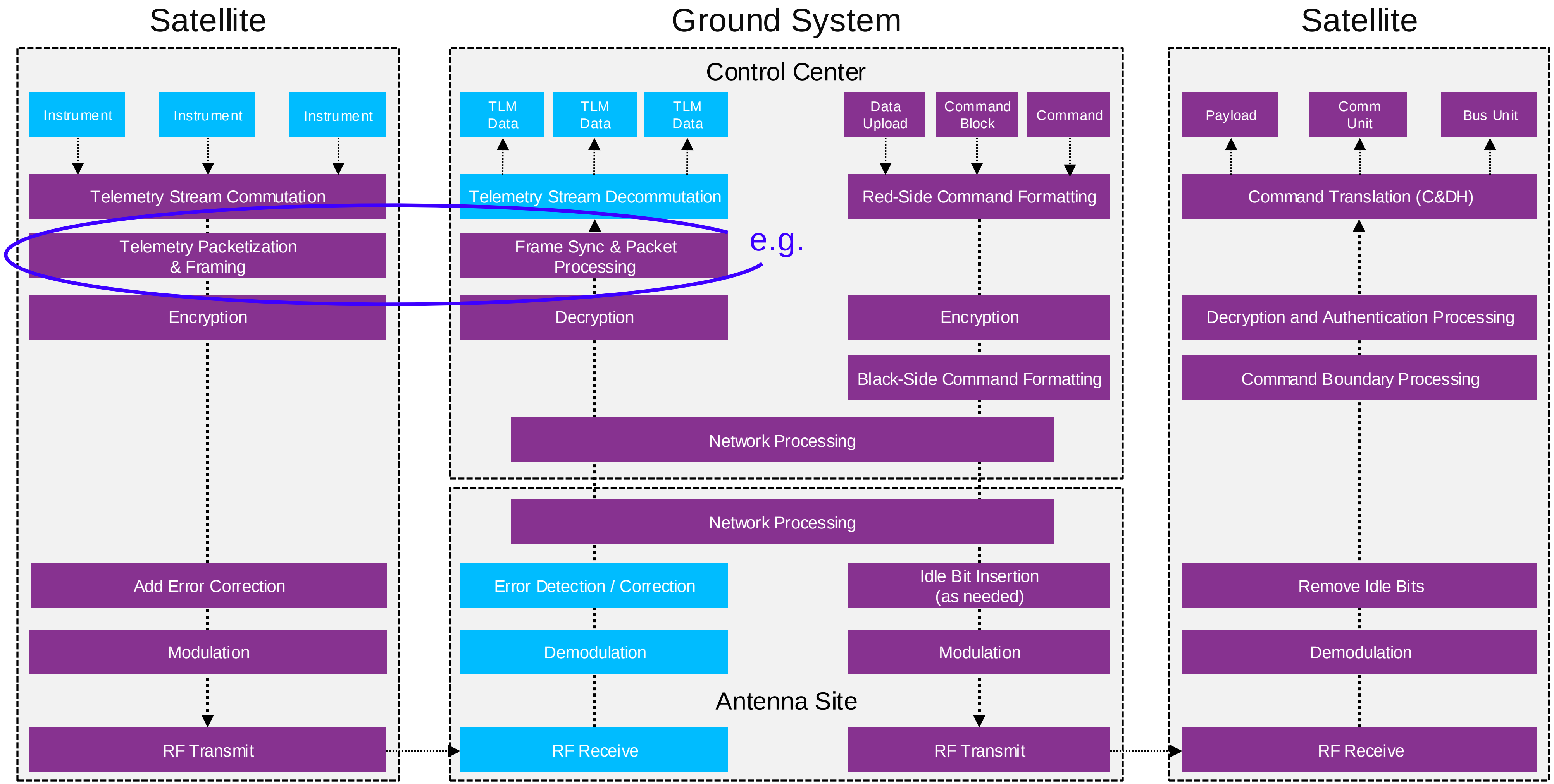
SATELLITE COMMUNICATIONS



LET'S DIVE INTO THIS CONVERSATION.

SATELLITE COMMUNICATIONS MODEL



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DOWNLINK PATH
CREATING THE TELEMETRY

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NARROWING IN ON SATELLITE TELEMETRY

Early designs were constrained by low bandwidth and data rates.

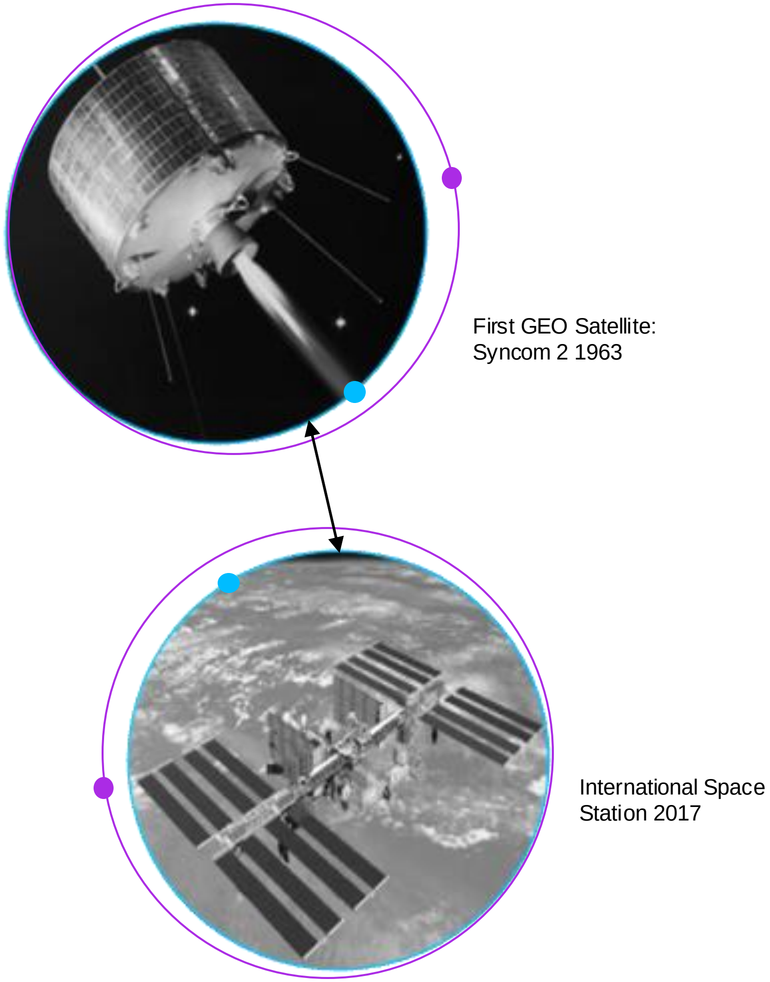
- Only a few key parameters were gathered and transmitted down the telemetry stream.

Over time, satellite telemetry has become much more complicated.

- More sophisticated space vehicles, higher data rates, encapsulated IP.

But still, many of the design choices are based on early systems.

- Piecemeal technology refreshes maintain legacy interfaces.
- “We have always done it this way” mentality.



TELEMETRY STANDARDS AND TYPES

Two primary standards exist for telemetry formats:

- IRIG 106-04: PCM Standards originated with airplanes and rockets
- CCSDS Space Data Link recommendations are space-focused

Standardized framing only solves part of the problem.

- There seems to be no limit to creativity when placing data in a frame/packet.

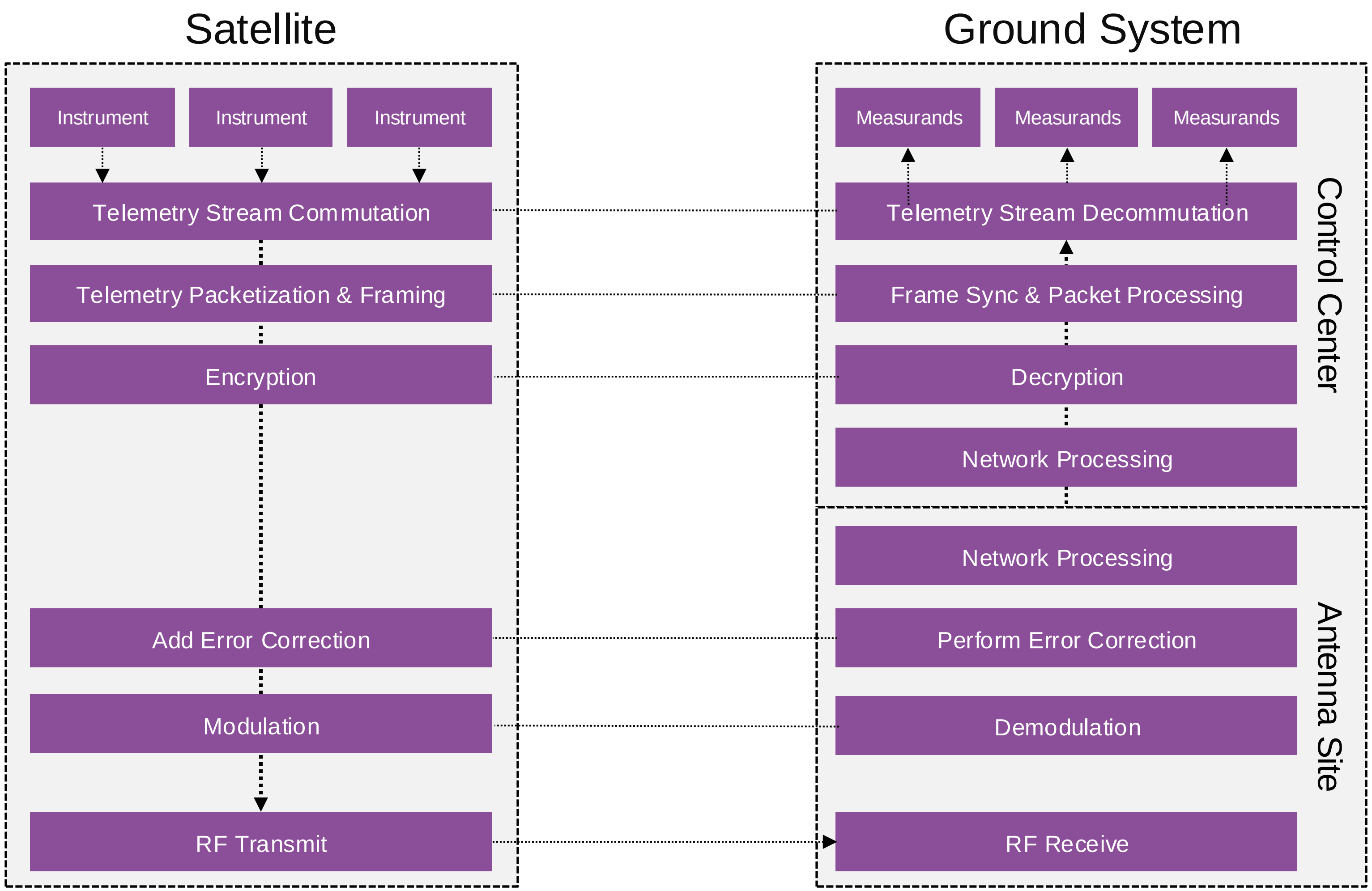
Health and Status Data

- Includes data about the state of the vehicle itself
- Typically lower rates (1 Kbps – 2Mbps)
- Modern vehicles can have 10,000 – 50,000 values

Payload

- Includes data from the sensors, cameras, etc.
- Often high rate (10 Mbps – 1 Gbps today, going to >10 Gbps)
- Multiple sensors are aggregated together

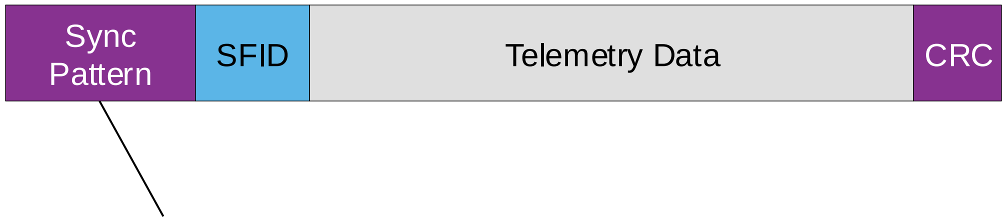
DOWNLINK SATELLITE COMMUNICATION LAYERS



TIME DIVISION MULTIPLEXING (TDM)

Minor Frames

- Well-known sync pattern
- Fixed length
- Contain a sub-frame ID
- Often have a CRC field
- Often define content per ID



Sync Patterns indicate the start of each frame

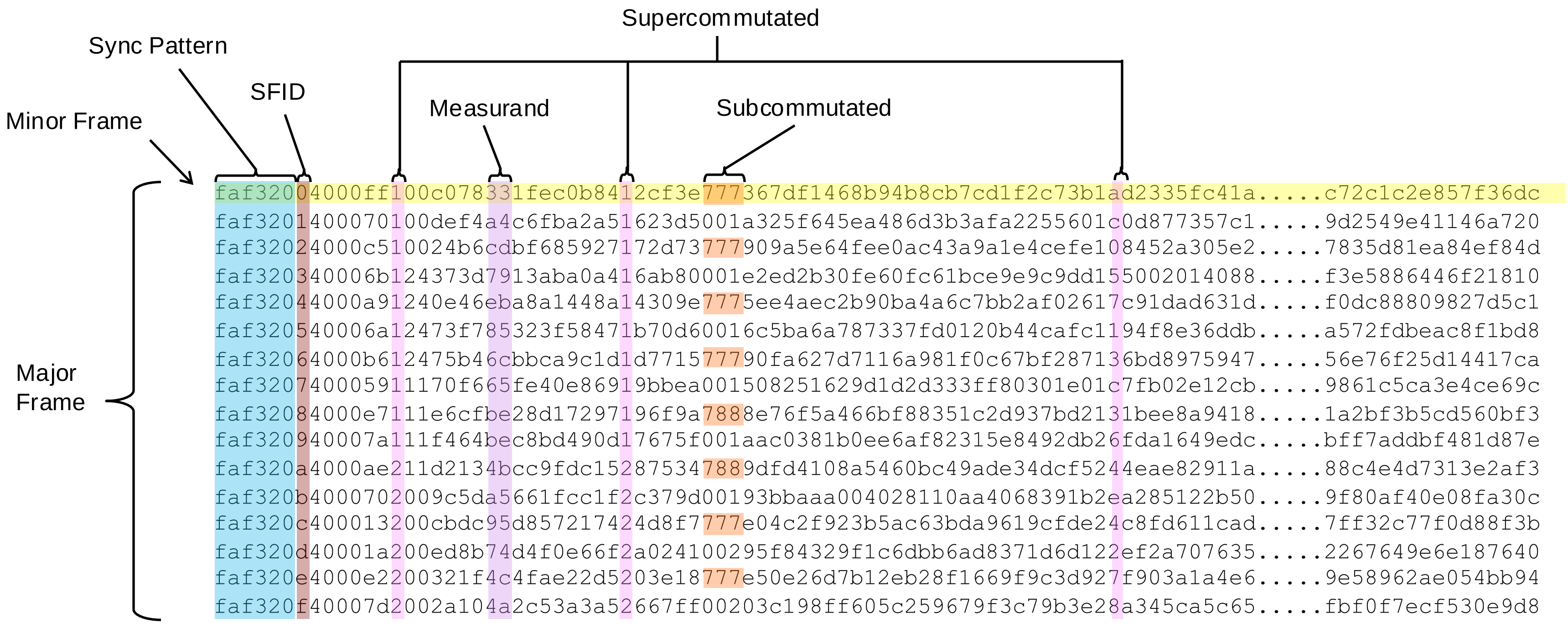
They are specifically chosen because of their low cross correlation with bit-shifted variants

<u>Common Patterns</u>: EB90, FAF320, 1ACFFC1D

TIME DIVISION MULTIPLEXING (TDM)

What does telemetry look like in a computer?

- It’s often represented as a string of hexadecimal (hex) characters.



Measurands (Values) are represented by 1 or more bits and can occur 1 or more times in a Major Frame.

Supercommutated: Occurs multiple times in a minor frame

Subcommutated: Does not occur in every minor frame

CCSDS STANDARDS FOR TELEMETRY

Consultative Committee for Space Data Systems

- Formed in 1982 by the major space agencies of the world
- Provides recommendations (standards) for Telemetry & Command data

CCSDS Telemetry Data

- Provides some consistency in data formats to enable interoperability and reuse
- Defines a common framing structure, notion of data channels, packets, etc.
- Focuses on “civil space,” e.g., encryption is only recently being addressed
- Allows dynamic allocation of data bandwidth per data channel

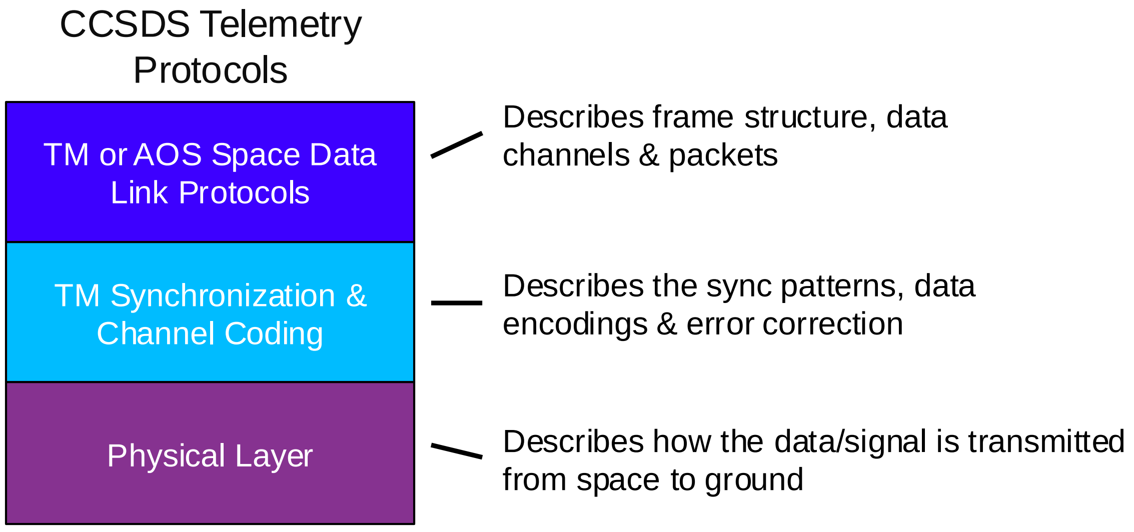
CCSDS TM SPACE DATA LINK PROTOCOL

TM Space Data Link Protocol

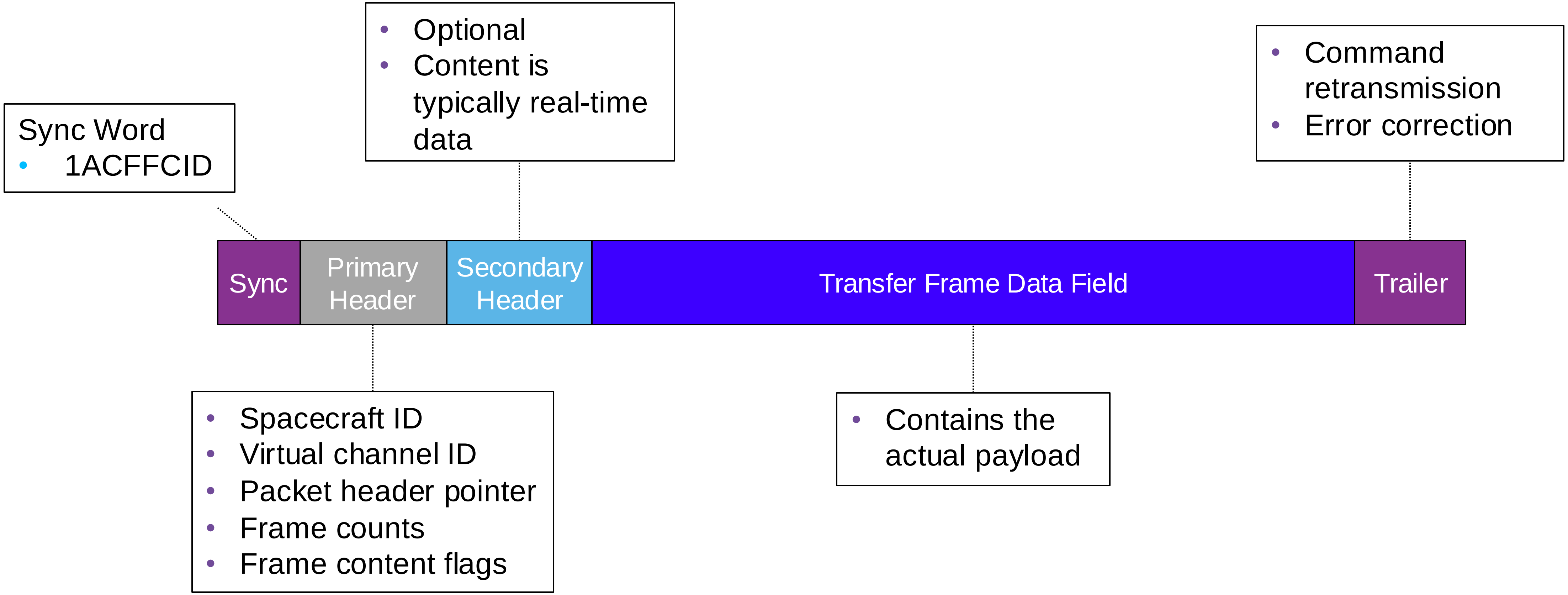
- First version of telemetry structure
- Defines virtual channels
  - Three bits in primary header (eight channels)
- Defines variable length packets
  - First header pointer in primary header

AOS (Advanced Orbiting System) Space Data Link Protocol

- Used for both Forward and Return
- Added more virtual channels (64)
- Added additional data and packet types
- Made the header more efficient



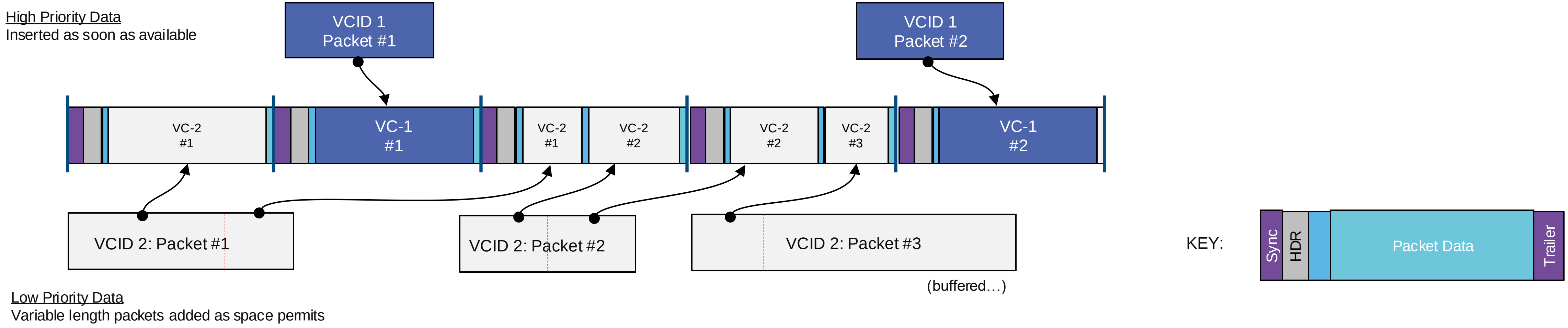
CCSDS TRANSFER FRAME



CCSDS SPACE PACKET PROTOCOL

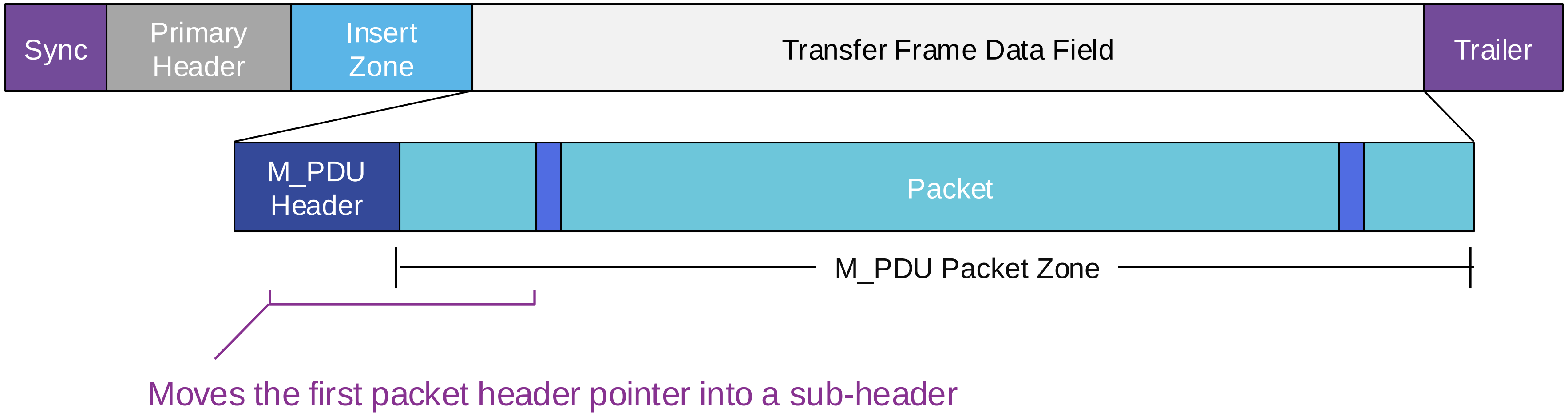
Virtual channels and packets allow multiplexing of data streams.

- Packets are fully assembled before they are processed
- Packet header format includes APID and length of the packet
- A packet can be fully contained in a transfer frame or span multiple frames
  - Fill bits are inserted if the packet does not fill the entire frame
- Virtual channels are usually "prioritized"



AOS Space Data Link Protocol

- CCSDS 732.0-B-2
- Modifies the TM Space Data Link Protocol
    - Restructures the transfer frame headers (e.g., no first header packet pointer)
    - More virtual channels (6 bits == 64 channels)
    - Adds a Multiplexing Protocol Data Unit (M_PDU) ← this is where the packets are
    - Binary Data (non-packet) transferred in a Bitstream Protocol Data Unit (B_PDU)
- Better suited for including other types of data (video, payload, etc.)



DOWNLINK PATH
TRANSMITTING THE DATA

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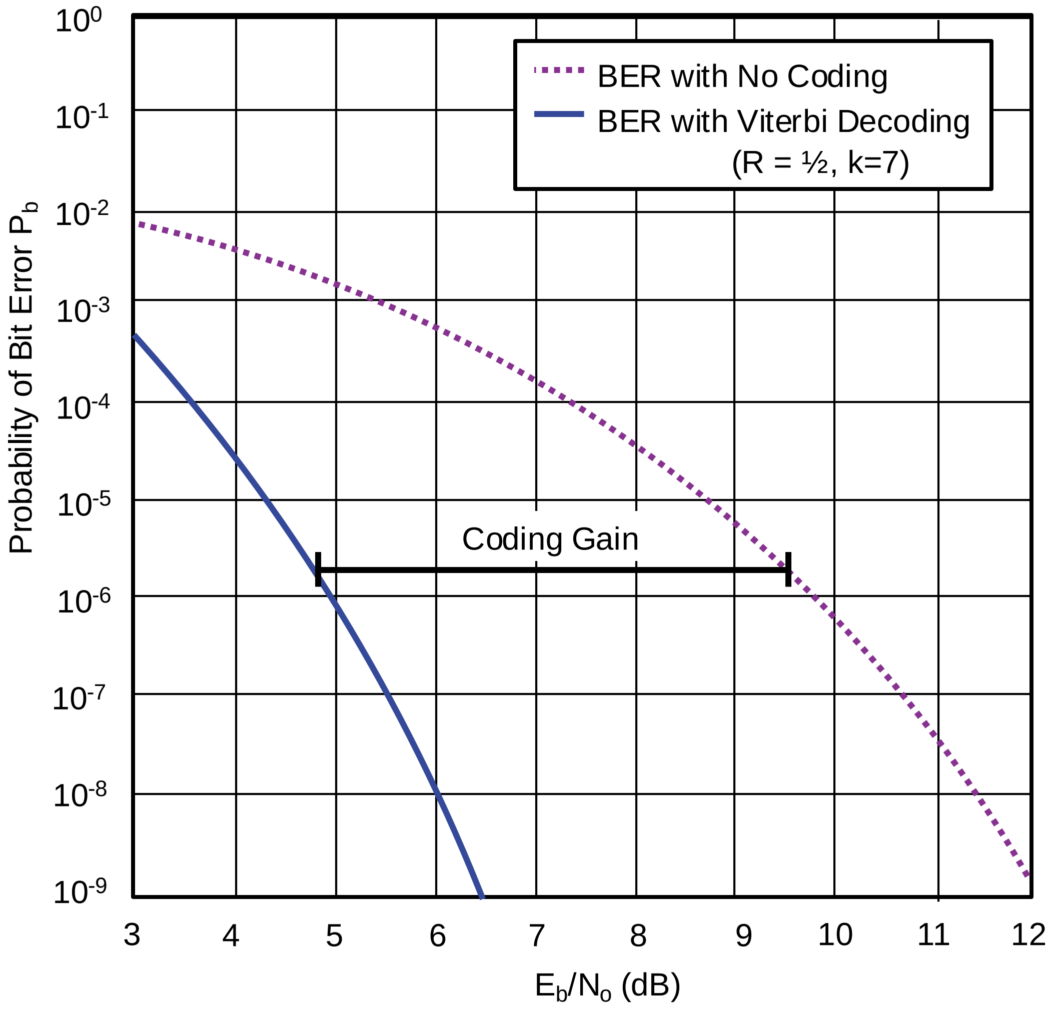
RELIABLE TRANSFER OF INFORMATION

Phonetic Alphabet

A – alpha
B – bravo
C – charlie
D – delta
E – echo
F – foxtrot
G – golf
H – hotel
I – india
J – juliet
K – kilo
L – lima
M – mike
N – november
O – oscar
P – papa
Q – quebec
R – romeo
S – sierra
T – tango
U – uniform
V – victor
W – whiskey
X – x-ray
Y – yankee
Z – zulu

CODING GAIN ILLUSTRATED



E_b: energy per bit
(how loud is it?)

N_0: noise spectral density
(how loud is everything else?)

SNR: signal-to-noise ratio

Coding Gain: the reduction in E_b/N_0 required to achieve a target BER

Coding gain adds additional information to the data stream to help ensure the data is received properly with less power and in a noisy environment.

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CHANNEL CODING

Channel coding / decoding brings complexity.

- Primarily at the decoder

Channel codes generally fall into two categories:

- Block codes
- Trellis codes

Block codes are good for burst errors.

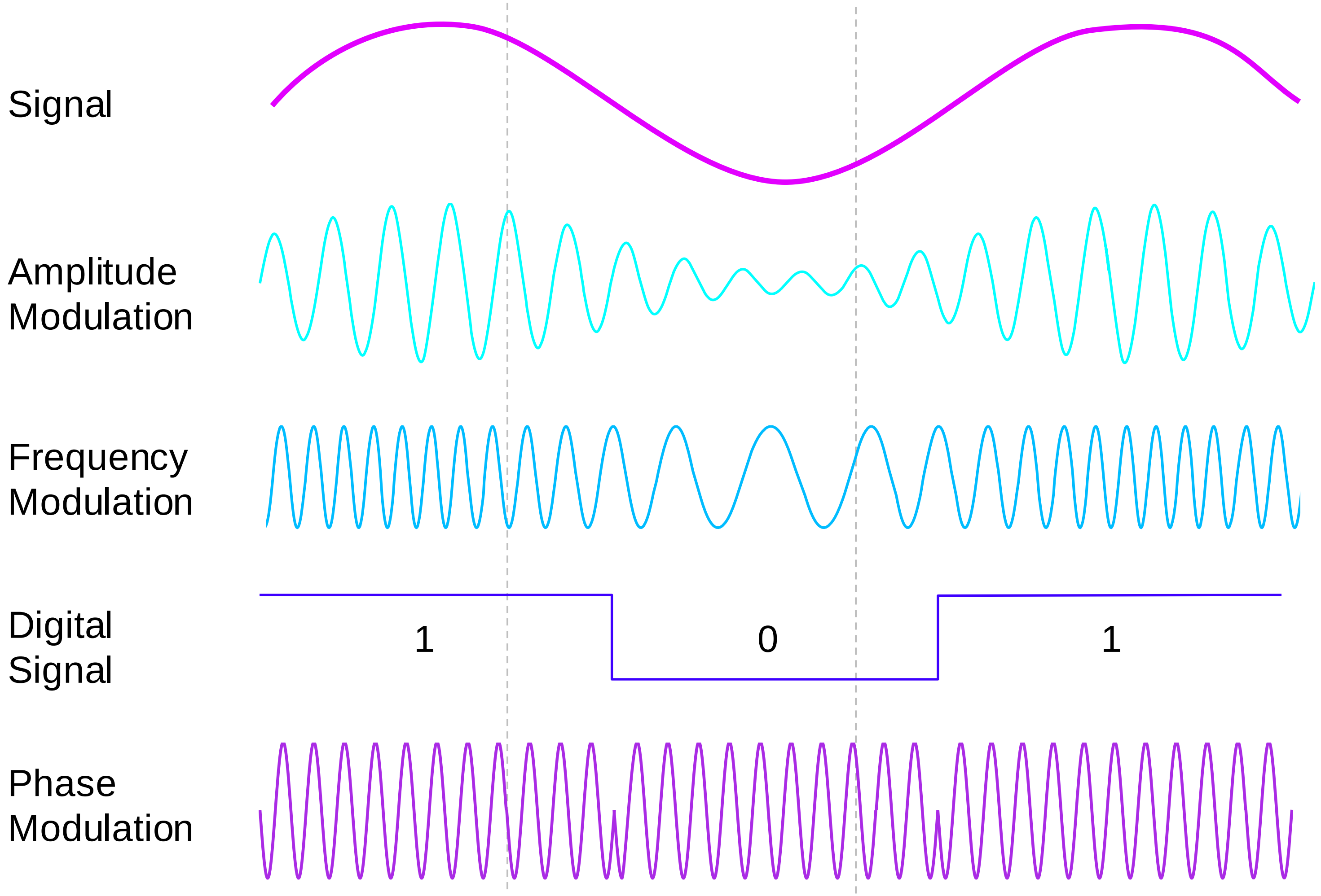
- Need to know where the code word starts and ends (block synchronization)
- Frame sync patterns (uncoded) are generally used for this process in a continuous bit stream

Trellis codes (usually called convolutional codes) continuously code arriving bits in a sliding block manner.

Reed Solomon
Turbo
LDPC
Viterbi
Convolutional
… to name a few

MODULATION ILLUSTRATED (NO MATH)

THE INFORMATION-BEARING WAVEFORM FREQUENCY MODULATES THE CARRIER.



Frequency modulation has a constant envelope waveform, is less stressful on power amplifiers.

BPSK Modulation uses 180-degree phase shifts.

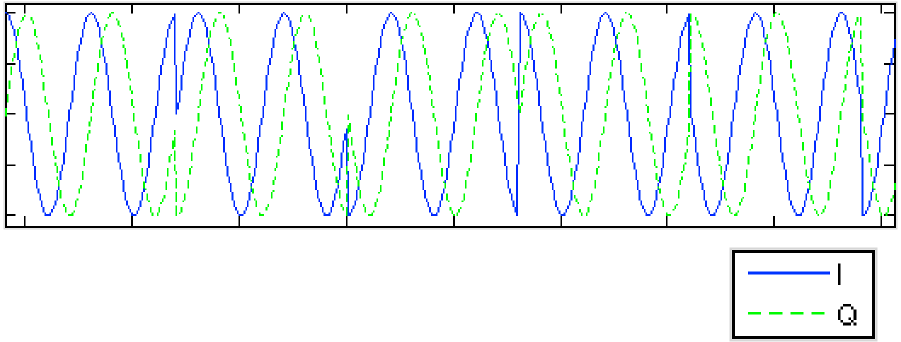
QPSK MODULATION

QPSK – Quadrature Phase Shift Keying

- Four phase states: 45^0, 135^0, -45^0, -135^0
- Each state (or symbol) represents two bits
- We've doubled the information rate!

QPSK Modulation

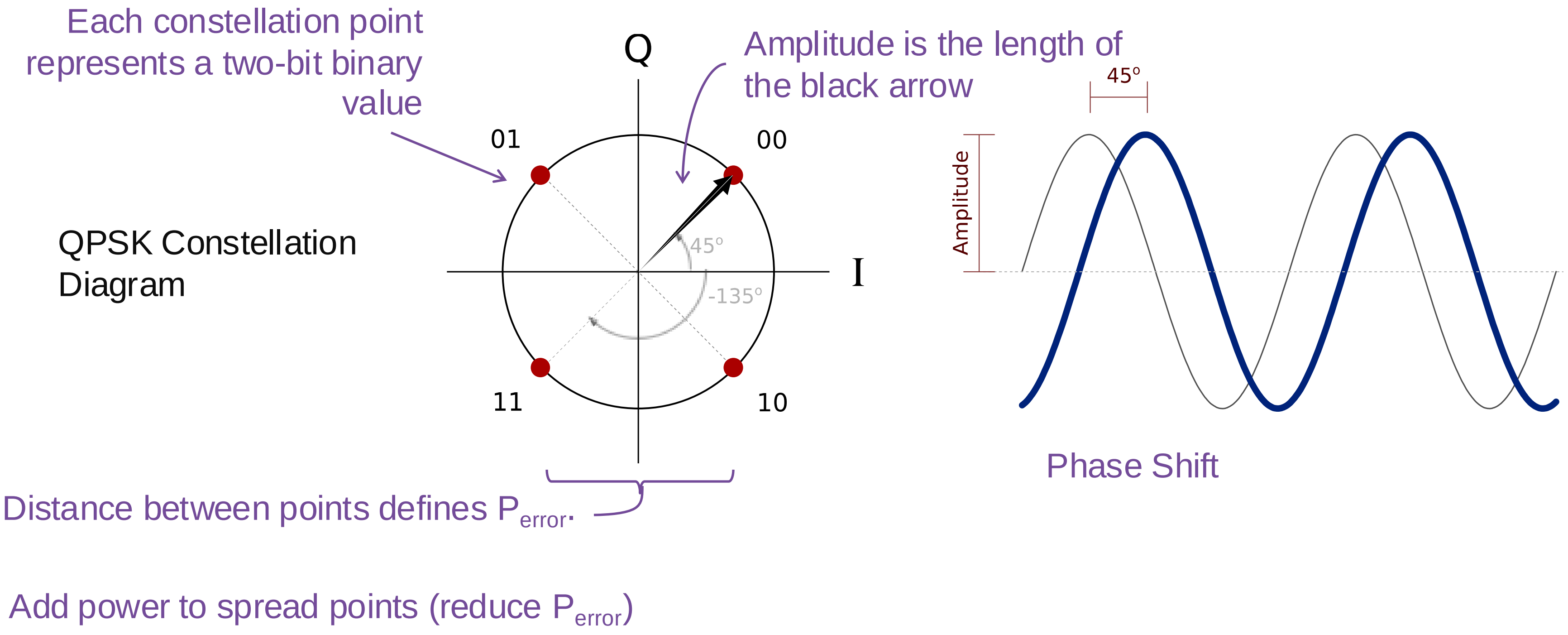
Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5
00	10	11	00	01



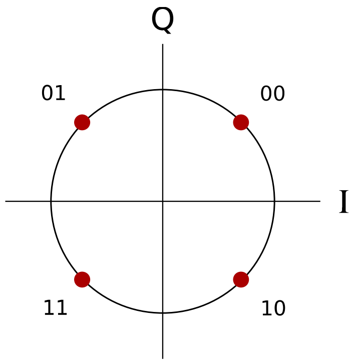
ANOTHER WAY TO REPRESENT WAVEFORMS

IQ constellations represent the possible phase/amplitude positions.

This is a mathematical representation with real and imaginary components:

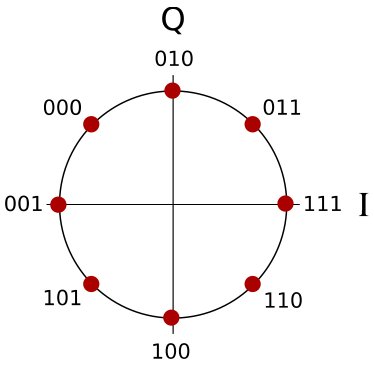


AND THEN IT GETS CRAZY!



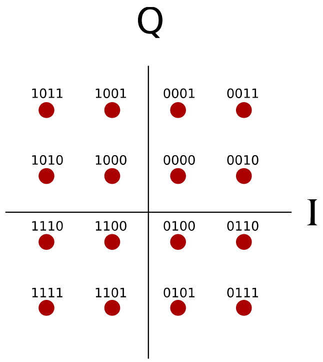
QPSK
Constellation

Constant amplitude



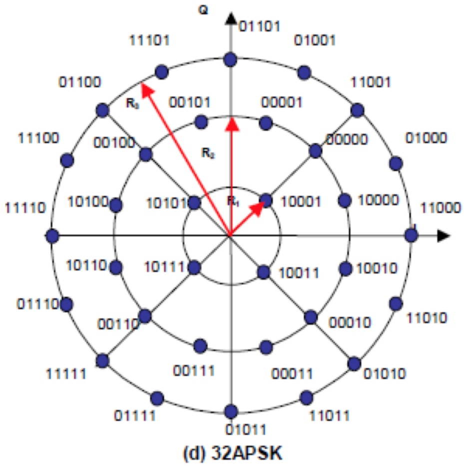
8PSK
Constellation

Constant amplitude
(3 bits per symbol)



16QAM
Constellation

Variable amplitude
for more states



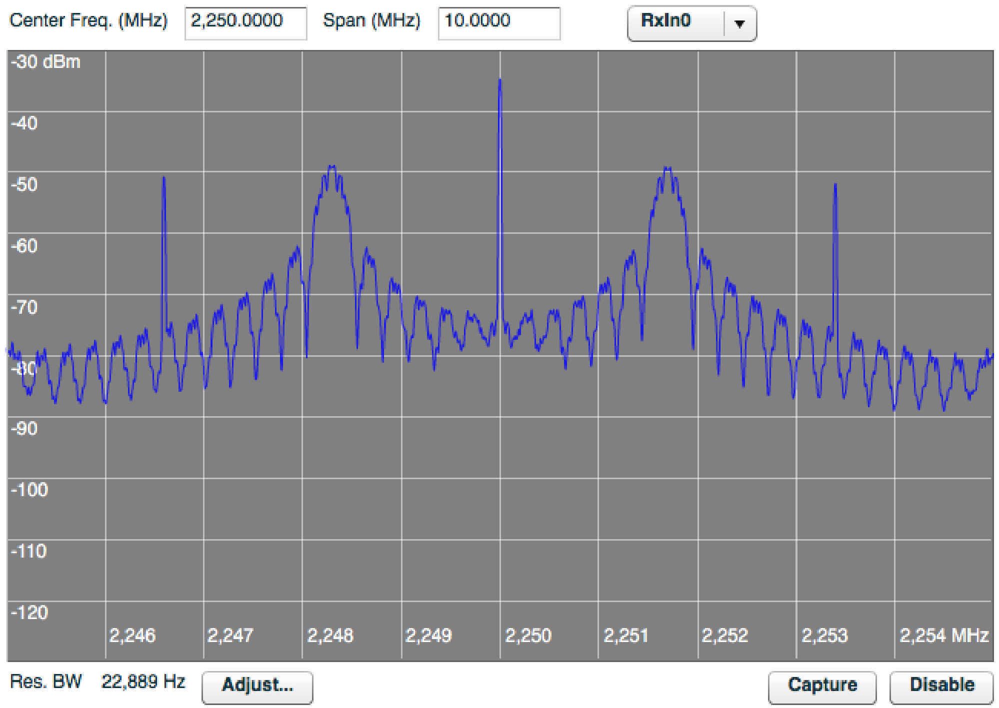
32 APSK
Constellation

Concentric rings of
amplitude, evenly
divided phase

SPECTRUM ANALYZER = REAL WORLD

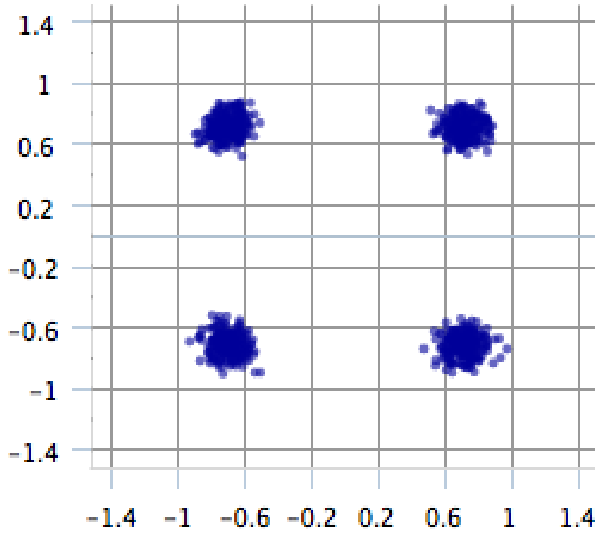
BPSK Subcarrier Modulation

- Carrier at 2,250 MHz
- 1.75 MHz subcarrier, 256 ksps



QPSK Modulation

- Constellation diagram



WHY SO MANY WAVEFORMS?

Spectral Efficiency
Maximize data / hertz

Power Efficiency
Minimize transmit power / data

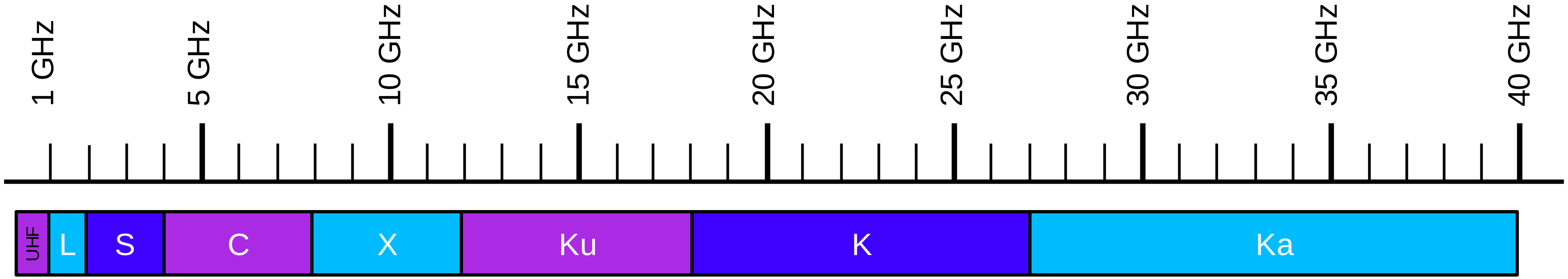
Ease of Acquisition and Tracking
Find signal quickly and easily in degraded or high-signal environment (high Doppler)

Low Probability of Detection / Intercept
Hide in the noise

Ease of Implementation
Size, weight, and power constraints drive simple waveform processing for space transceivers

RF BANDS

RF BANDS USED FOR SATELLITE COMMUNICATIONS:



- **UHF**: licensed for experimental use, narrow band for commercial
- **L-Band/S-Band**: TT&C, GPS
- **C-Band, Ku-Band**: satellite communications
- **X-Band**: MilSat communications, DSN, payloads
- **Ka Band**: broadcast

Spectrum must be licensed via the International Telecommunication Union (ITU) and is in high demand.

S-Band is being sold off for cellular applications.

DOWNLINK PATH
THE GROUND PROCESSING

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The received modulated carrier is corrupt.

- We're not making a moral judgment here…
- Noise, interference, distortion (analog effects), fading, timing alignment

Received signal changes due to satellite motion.

- Doppler is the change in frequency due to motion
- The demodulator must track these changes

The demodulator must recover the modulating waveform, and hence the information bits, with an expected reliability.

Demodulation is the most challenging aspect of modem design.

PROCESSING ON THE GROUND

Reverses the process performed on the space vehicle, while often adding in a network or two

Remote Ground Facility (RGF):

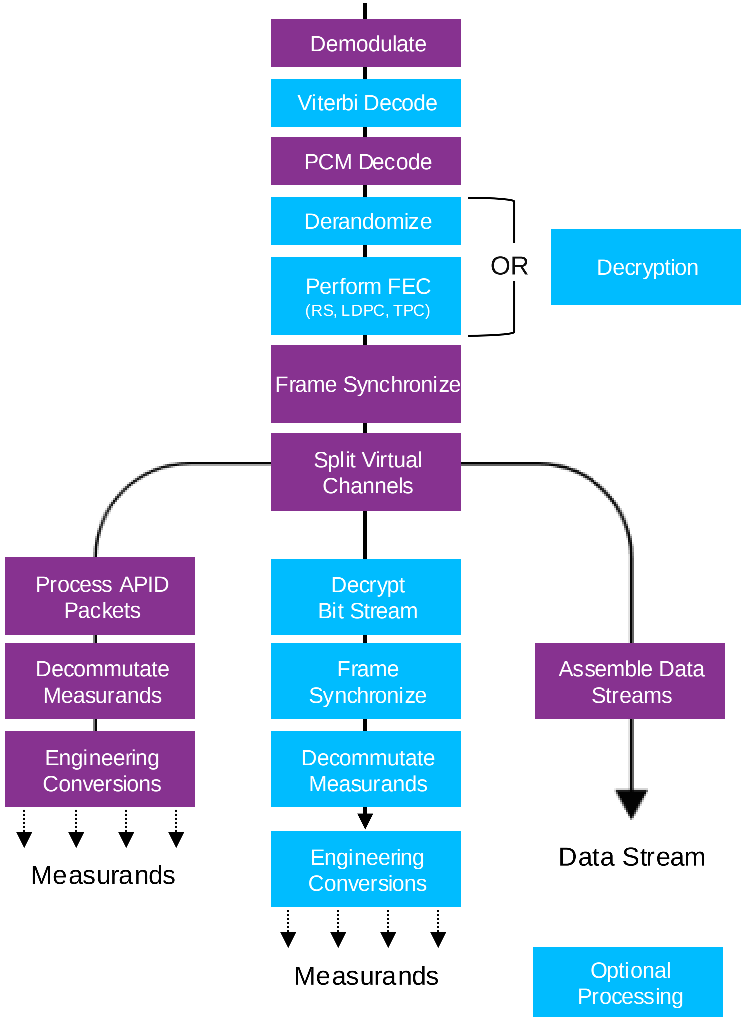
- Performs the RF-to-digital processing
- Adds formatting for transfer across the network

Control Center:

- Removes network formatting
- Performs and necessary decryption
- Performs frame and packet processing
- Extracts (decommutates) each measurand
- Displays measurands to the satellite operators
- Might perform automated telemetry processing and anomaly resolution

Location of functionality (site vs. SOC) varies

- One key factor can be encryption



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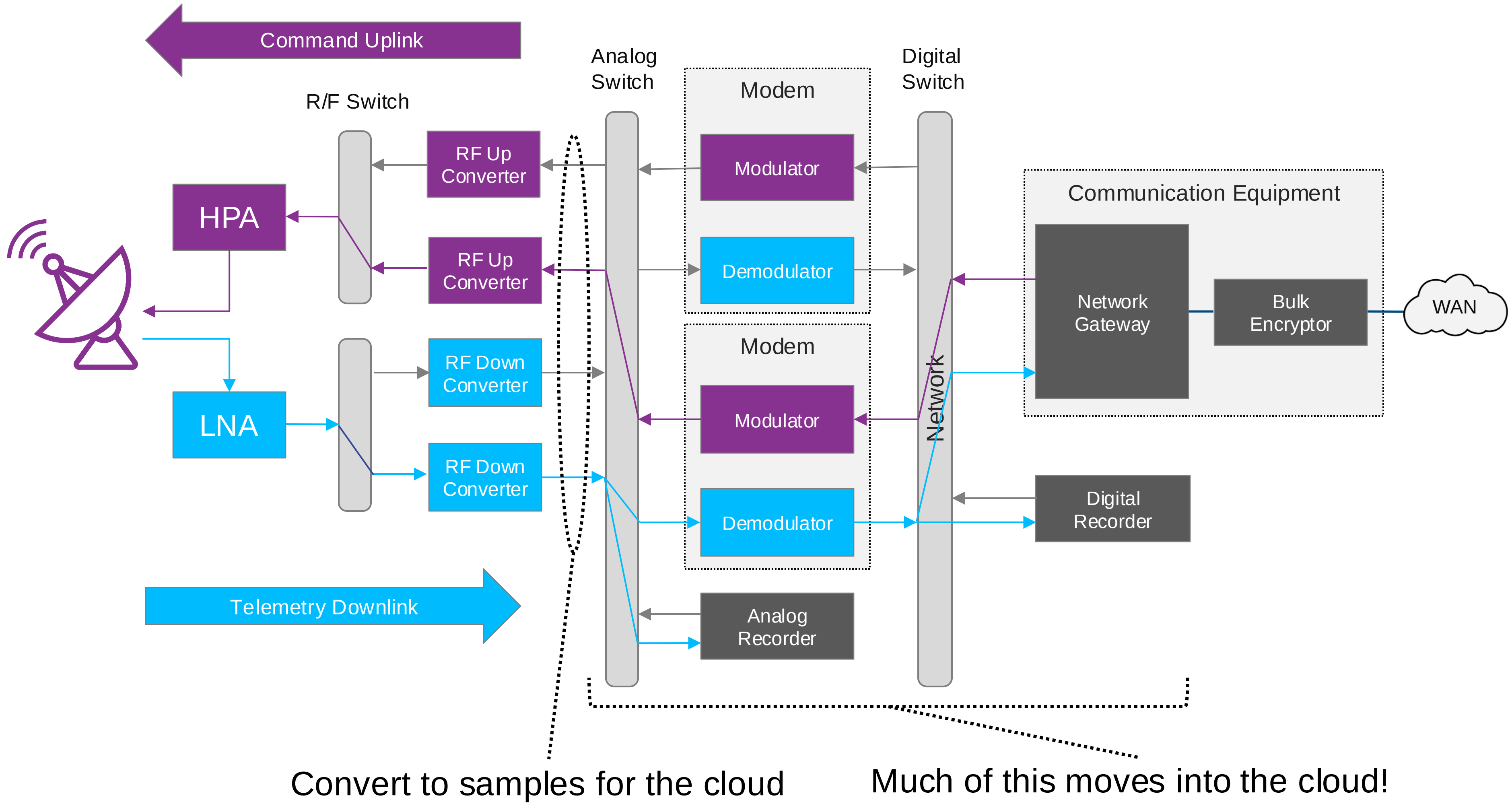
ANTENNA SITE OVERVIEW

THE ANTENNA SITE EQUIPMENT CONVERTS RF SIGNALS TO NETWORK PACKETS.



ANTENNA SITE OVERVIEW

Antenna

Specialized Antennas

HPA

Higher Power Amplifier (uplink)

LNA

Low Noise Amplifier (downlink)

RF Down Converters

Convert RD frequencies to intermediate frequency (IF)

Demodulators

Extract digital data from analog signals

Modulators

Generate uplink analog signals

Switches

Route analog and digital signals over redundant paths

Comm. Equipment

Encapsulate data in network protocols

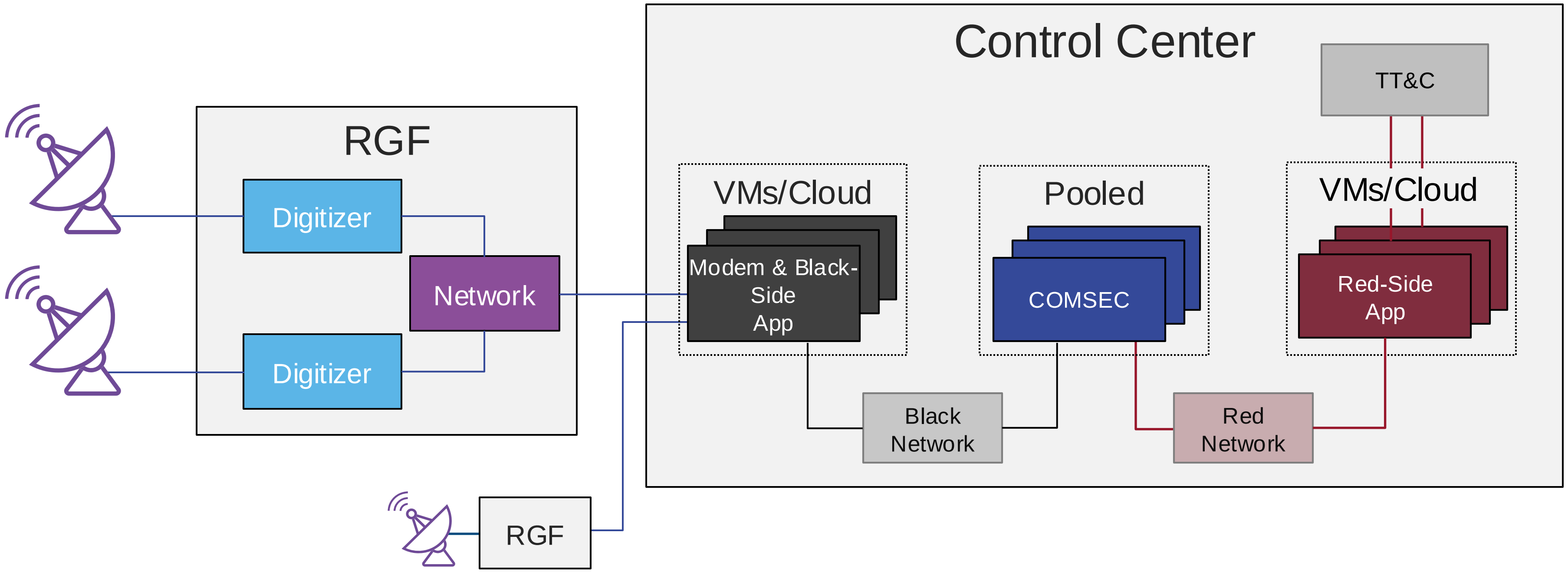
Recorders

Record and playback analog and digital signals

NETWORK-CENTRIC ARCHITECTURE

Today's ground systems are computers on a network.

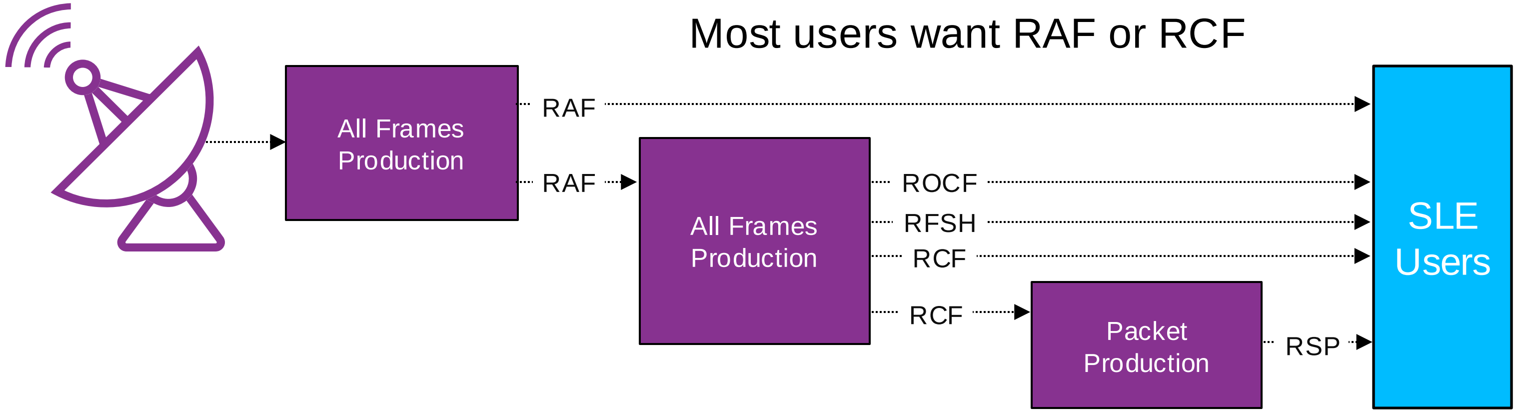
- Pooled resources rather than strings
- Software-defined equipment does the signal and data processing
- Virtual Machines (VMs) or cloud environments run applications



CCSDS SLE (USING A REAL NETWORK)

Part of the CCSDS cross support services

- Used to transfer telemetry and command data between the control center and antenna site
- Designed to work well with CCSDS-formatted data
- Supports multiple, geographically separated users



SLE Telemetry Services

- Return All Frames (RAF)
- Return Channel Frames (RCF)
- Return Frame Secondary Header (RFSH)
- Return Operational Control Field (ROCF)
- Return Space Packet (RSP)

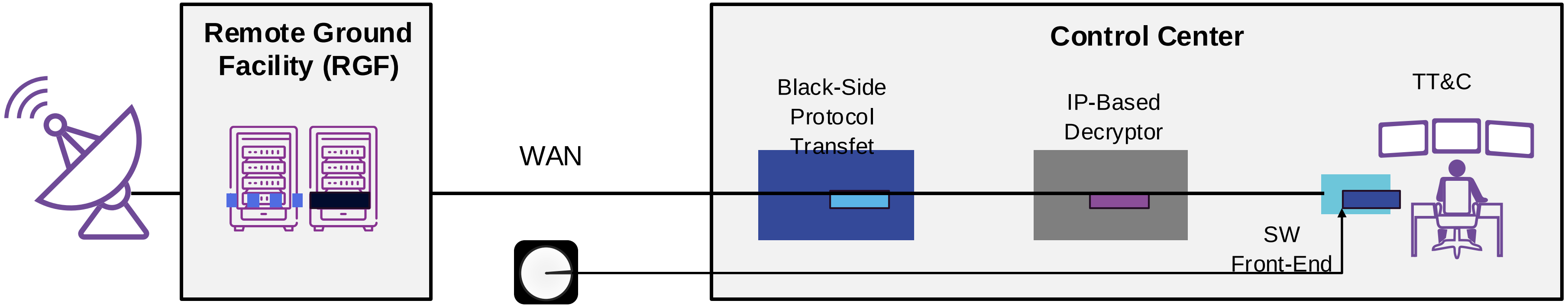
TLM/CMD requirements allocated to front-ends still exist.

- Synchronization, barker codes, command spacing, etc.
- Modern IP cryptos pass timestamps through with the packets

We must also consider the impact of the network.

- WAN jitter varies packet delivery time
- The new crypto uses raw UDP packets for data transfer

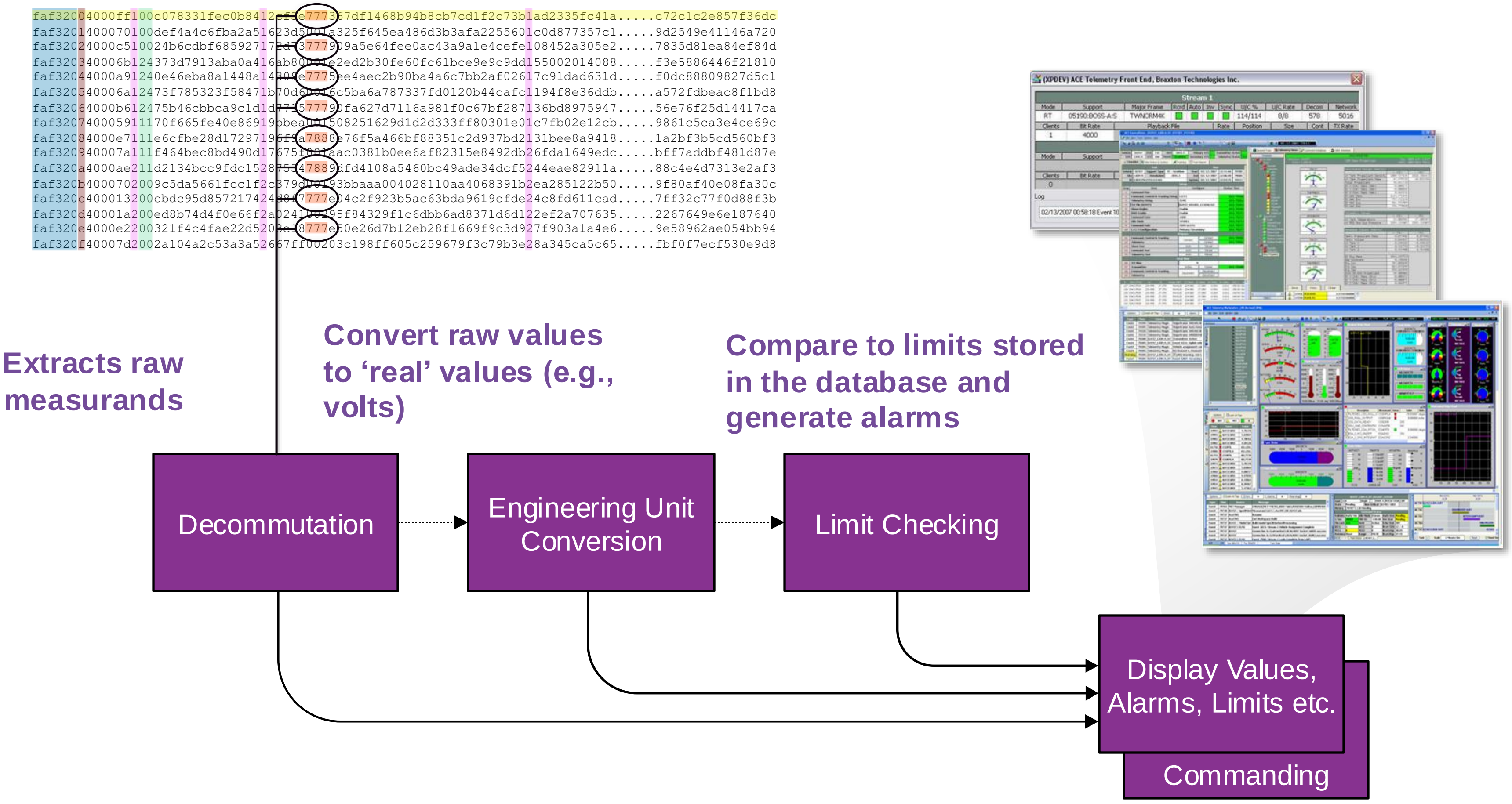
As a result, some red/black front-end capabilities are still required.



TELEMETRY DECOMMUTATION

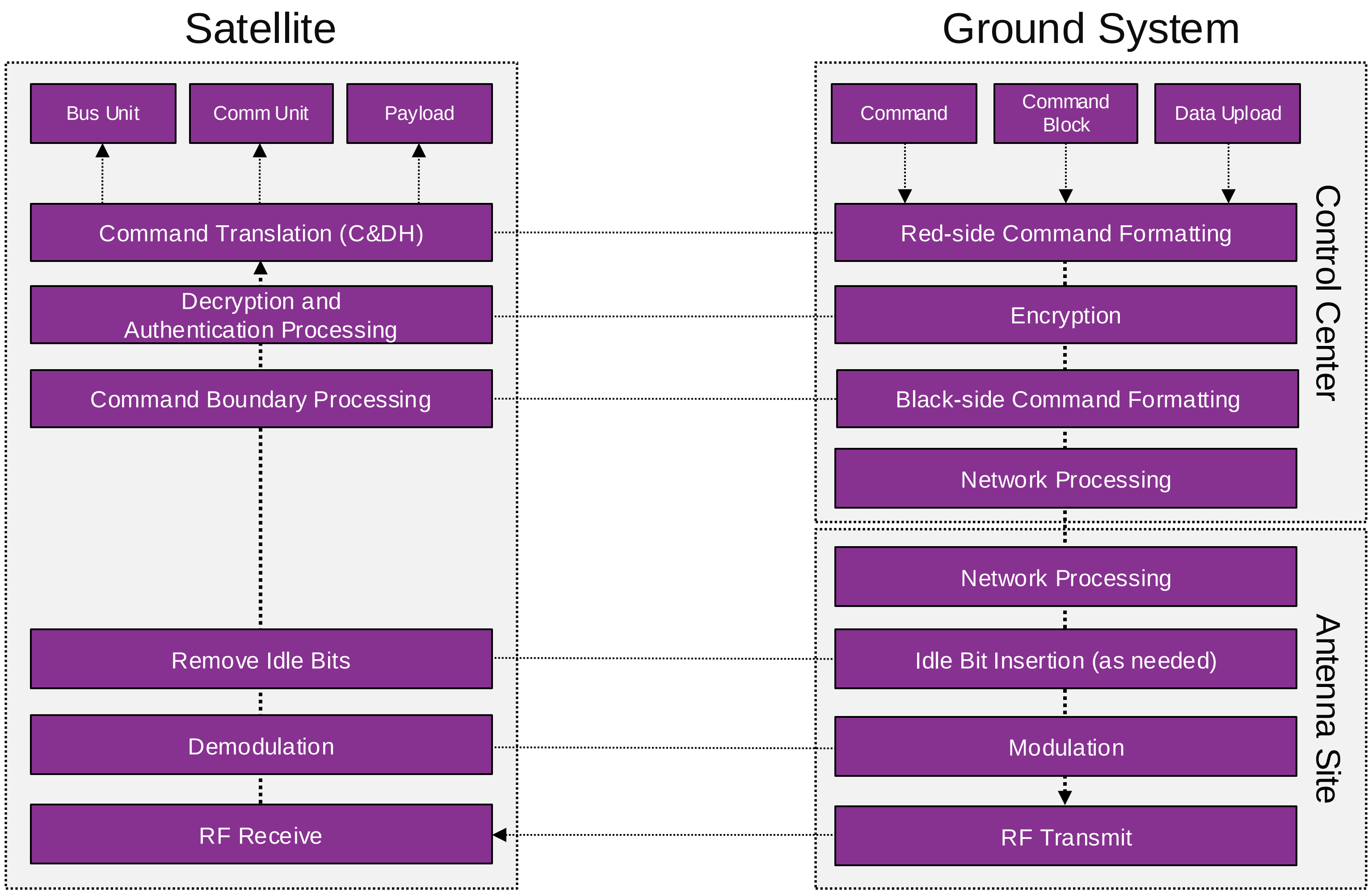
At this point, the telemetry is just a “bunch of bits.”

- Need to extract the raw bits and convert them to something meaningful
- The bit locations, conversion equations, and limits are all stored in the database



UPLINK PATH
COMMANDING THE SPACECRAFT

UPLINK COMMUNICATIONS



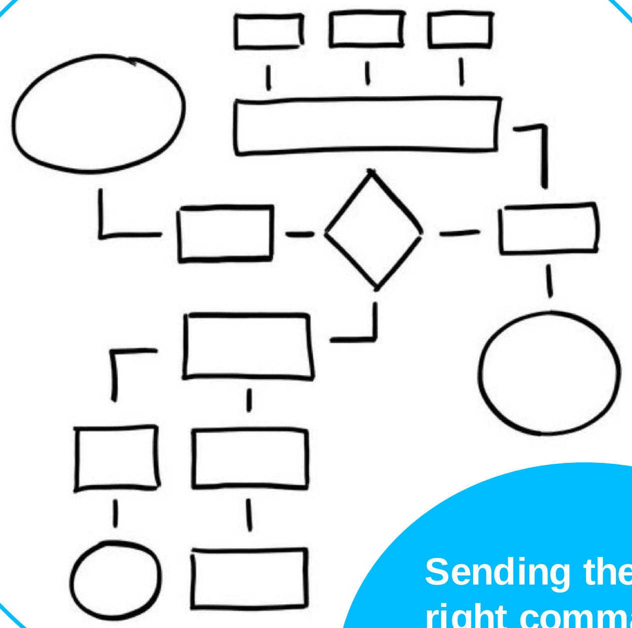
COMMANDING IS NEVER AD HOC

Much of the commanding infrastructure is geared around ensuring that only valid commands are processed at the spacecraft.

- Verification of commanding procedures
- Command echo processing
- Command authentication
- Command encryption
- VCC verification in telemetry
- Store and Execute protocol

The nature of satellite problems:

- Tumbling satellites make constant uplink streams difficult/impossible
- Anomaly resolution



Sending the right commands at the right time may be critical to getting your satellite back.

TT&C SYSTEM

Maintains a database of all the available commands

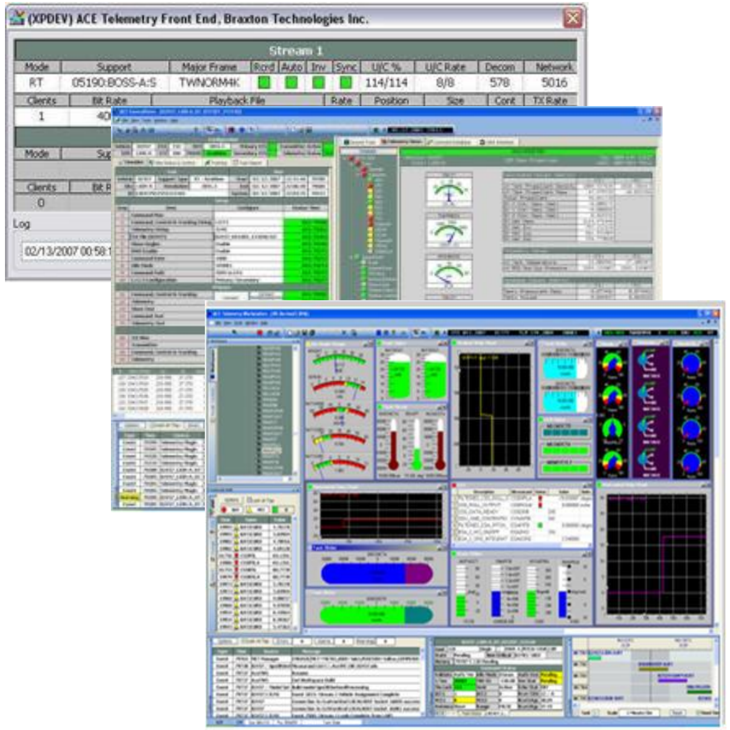
- This database can be quite large and complex
- Often links commands to telemetry values for validation

Block Commands

- Large number of commands uplinked as a group
- Example: memory uploads that reprogram on-board functionality

Command Procedures

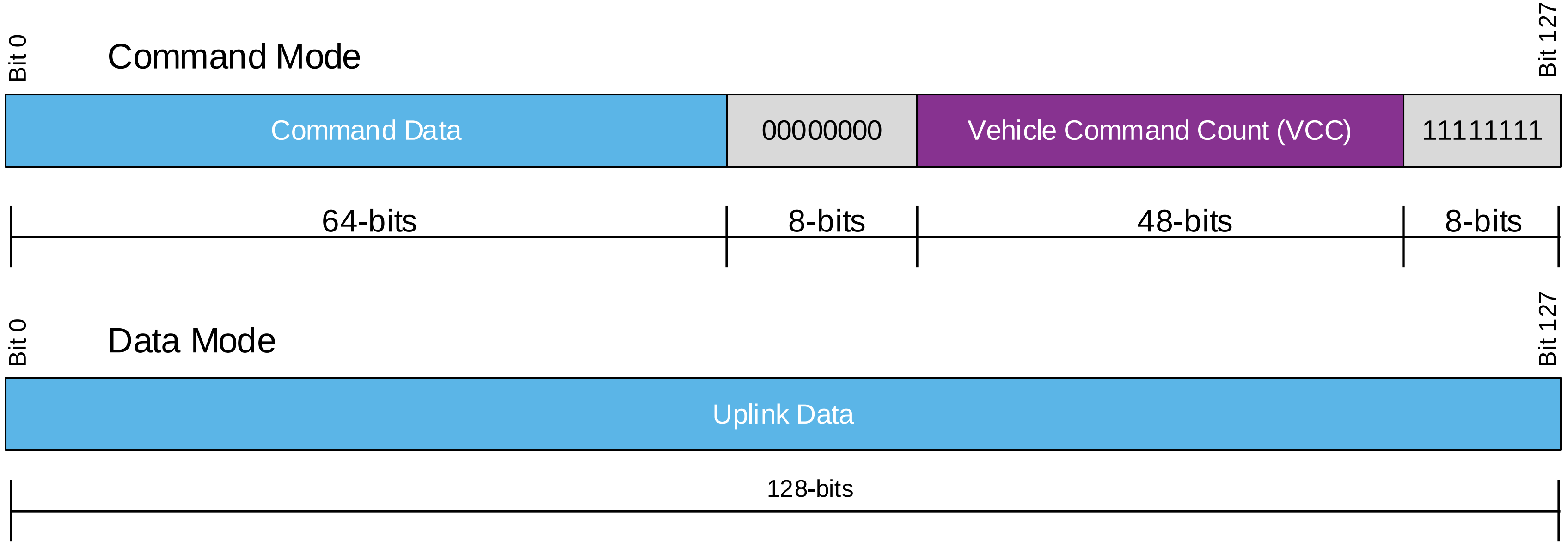
- A sequence of commands
  - Routine operations, anomaly resolution, etc.
- Scripting languages
  - A wide variety of purpose-built, unique, and often proprietary languages exist
  - Often lack common logic structures found in more typical programming languages
- OMG's Spacecraft Operations Language Meta-model (SOLM)
  - Emerging specification for transfer of procedures from one language to another



THE CRYPTO FORMAT DRIVES COMMANDING

Command Structure (e.g., CARIBOU)

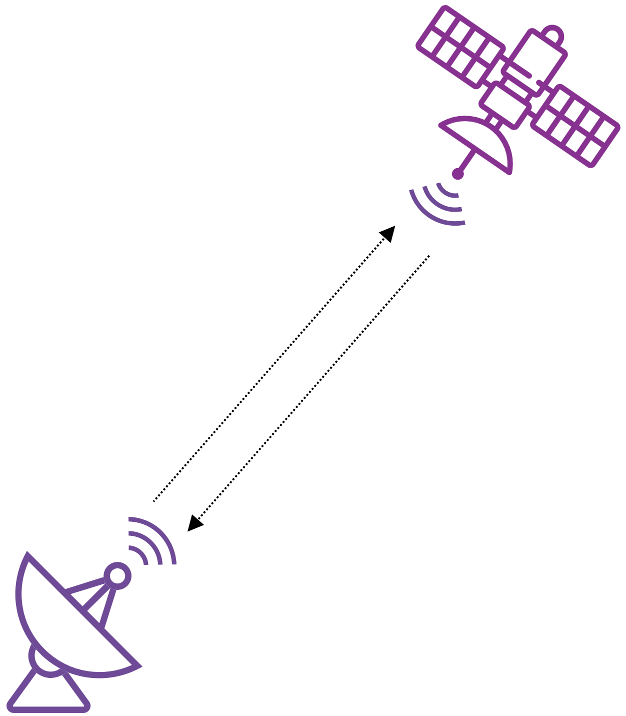
- Unique modes and data formats for commands and data
- The 64-bit command field is commands and their operands
- Special commands to flip in and out of data mode



GROUND – VEHICLE SYNCHRONIZATION

The Ground Command Counter (GCC) and Vehicle Command Counter (VCC) ensure the ground stays in sync with the vehicle.

- The GCC is incremented when the ground sends a command to the spacecraft.
- The VCC is incremented when the spacecraft receives a command – the spacecraft always sends its VCC down to the ground to verify the two are in sync.



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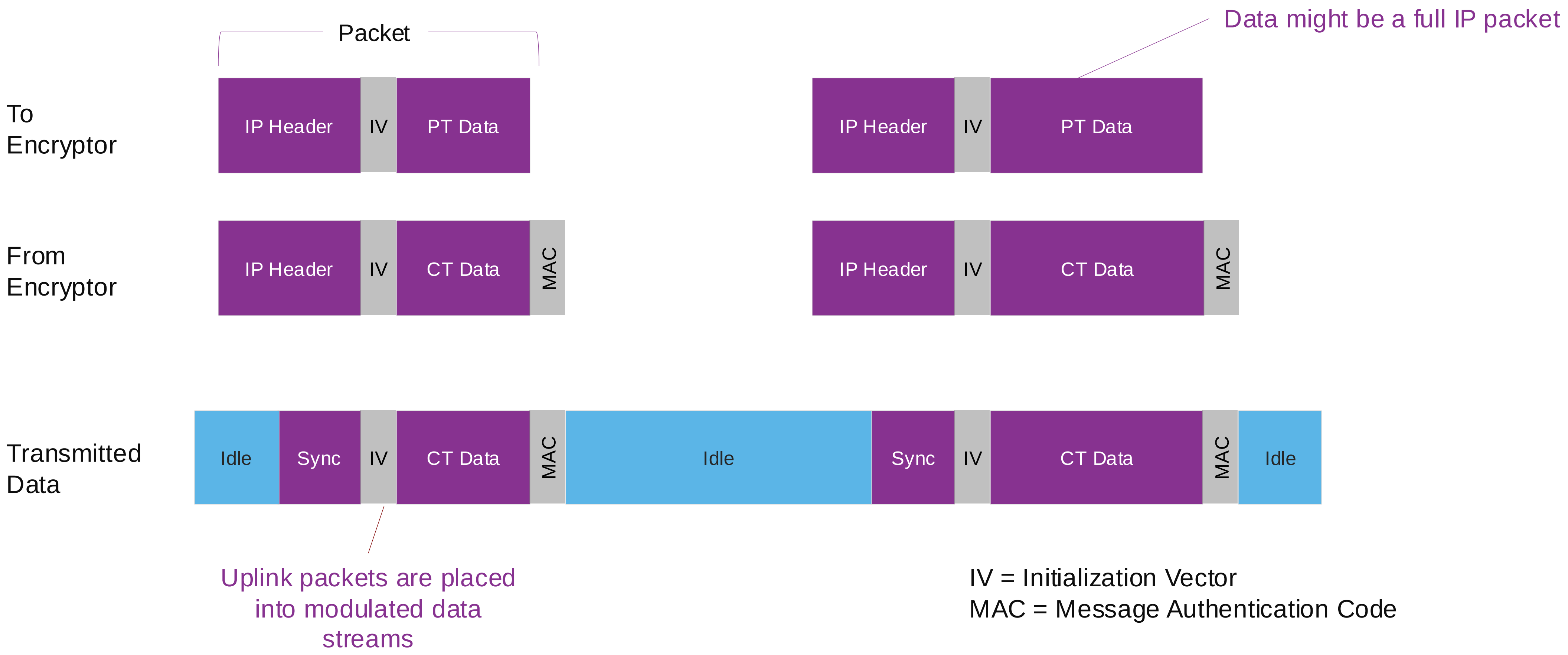
AES COMMAND ENCRYPTION

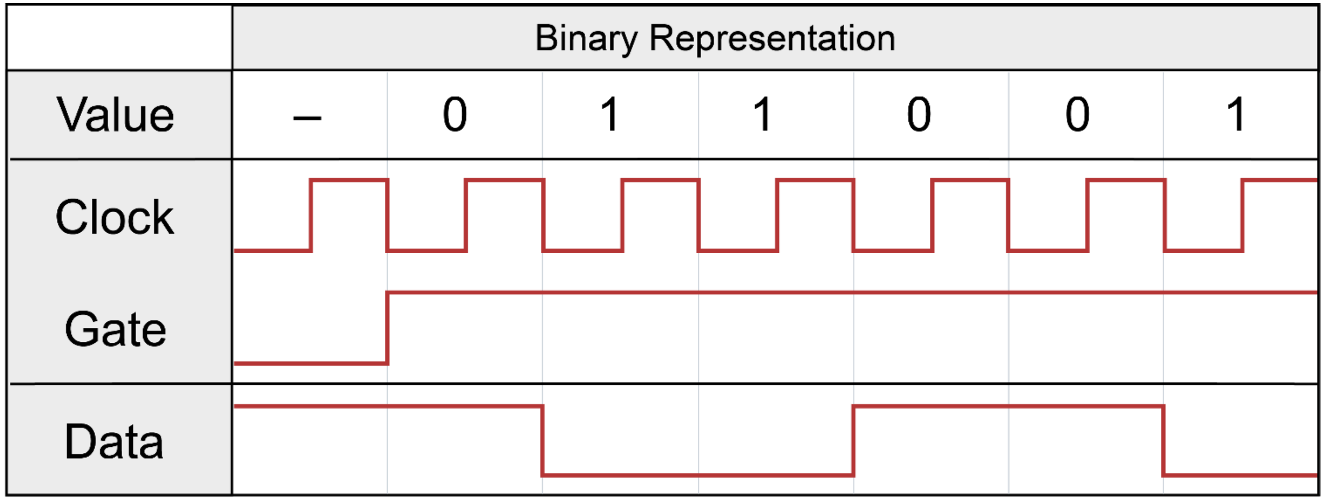
AES encryptors are typically network hardware security modules (HSMs).

The AES algorithm encrypts variable sized blocks of data.

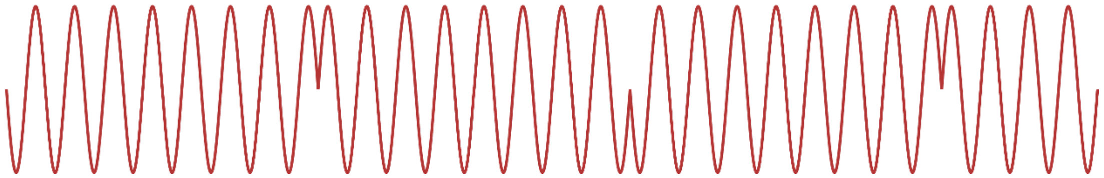


Binary Phase Shift Keying

- Data transitions reflected with a 180-degree phase shift in the carrier



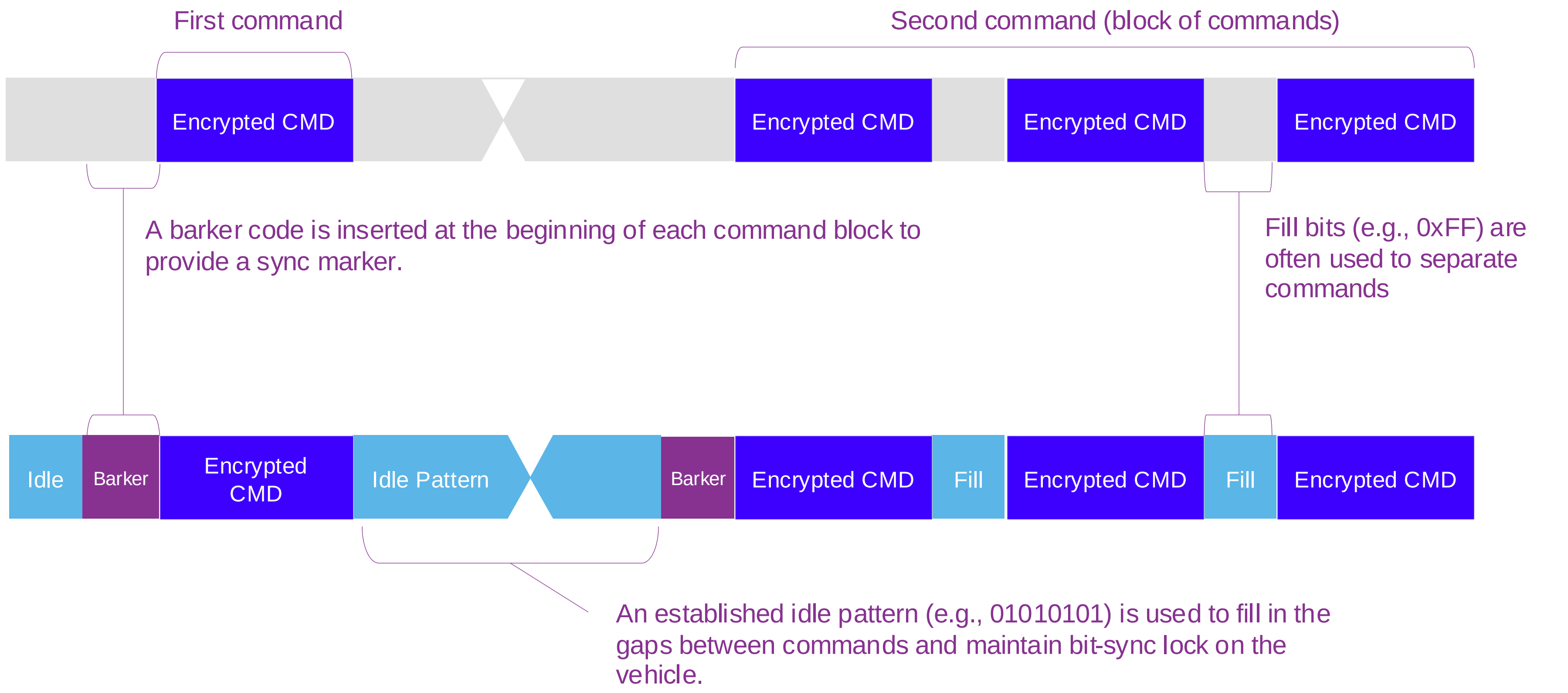
BPSK Modulation



UPLINK PATH COMMANDING PROTOCOLS

BINARY COMMANDS ON THE WIRE

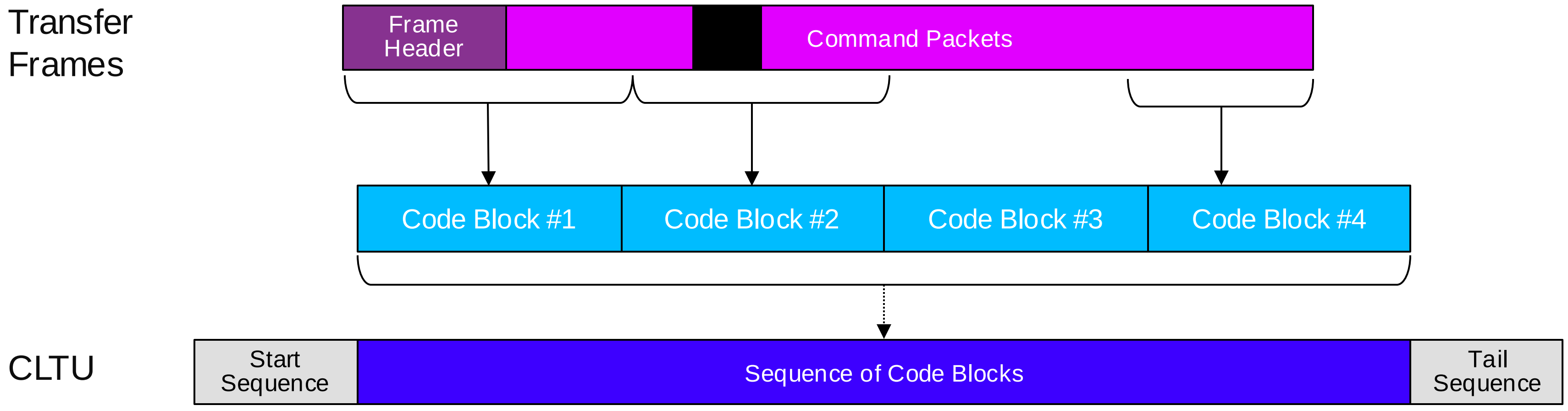
Insertion of plain-text barker code, fill bits, and idle sequences are used to indicate command boundaries.



CCSDS TO SPACE DATA LINK PROTOCOL

CCSDS uplinks utilize a binary, frame-based structure known as a "command link transfer unit."

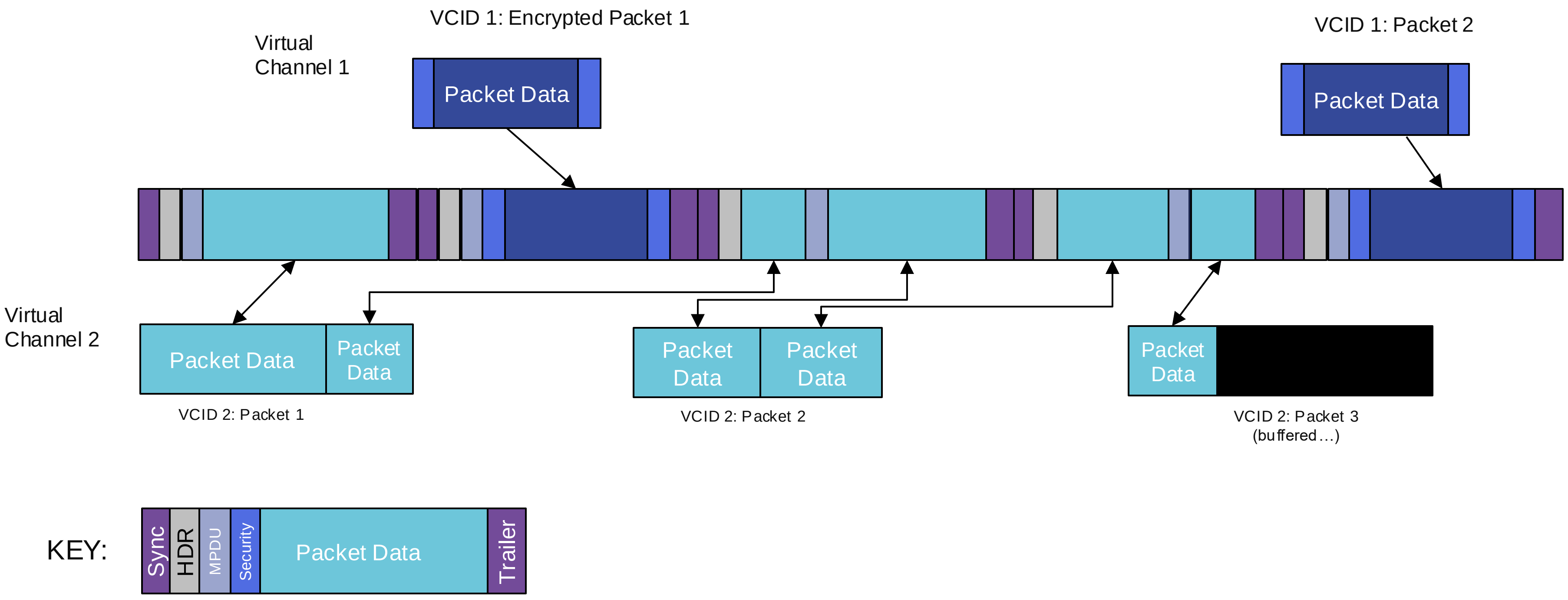
- A start sequence (0xEB90) is used to establish bit lock
- A sequence of 64-bit code blocks follows
  - CCSDS specifies 56 bits of data + 7 parity & 1 fill, and this is a useful size for the crypto
- Transfer frames span code blocks and contain virtual channels, etc.
  - Transfer frame header identifies vehicle, virtual channel, sequence number, etc.
- CCSDS 231.0-B-2 (channel coding), CCSDS 232.0-B-2 (data link)



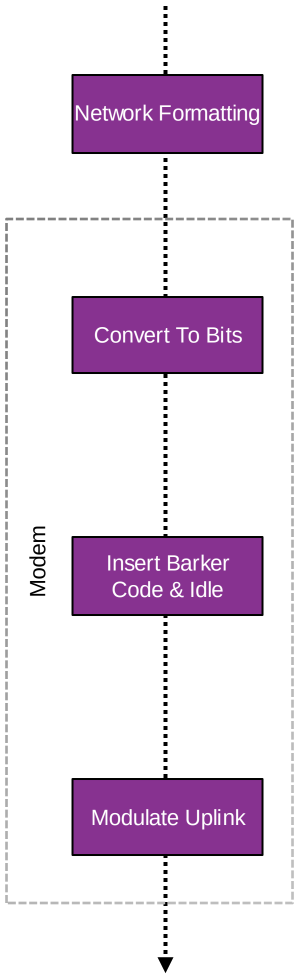
CCSDS AND TELECOMMANDING

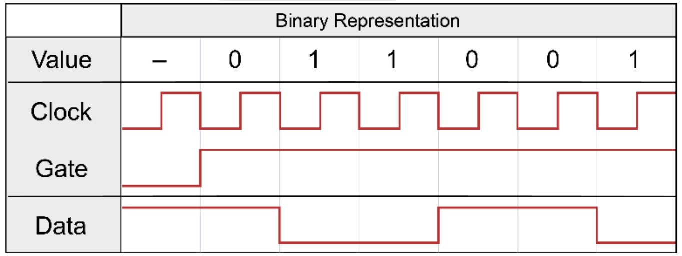
Provides for multiplexed virtual channels and packetized uplink

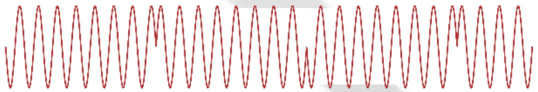
- Basically the same as the AOS telemetry structure
- Provides for fill and idle data
- Foundation for encapsulation and newer security specifications

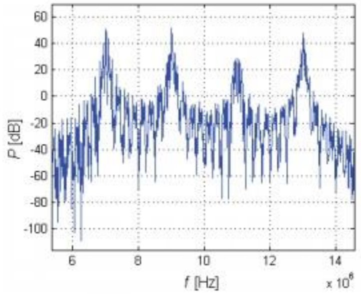


COMMAND PROCESSING (MODEM)





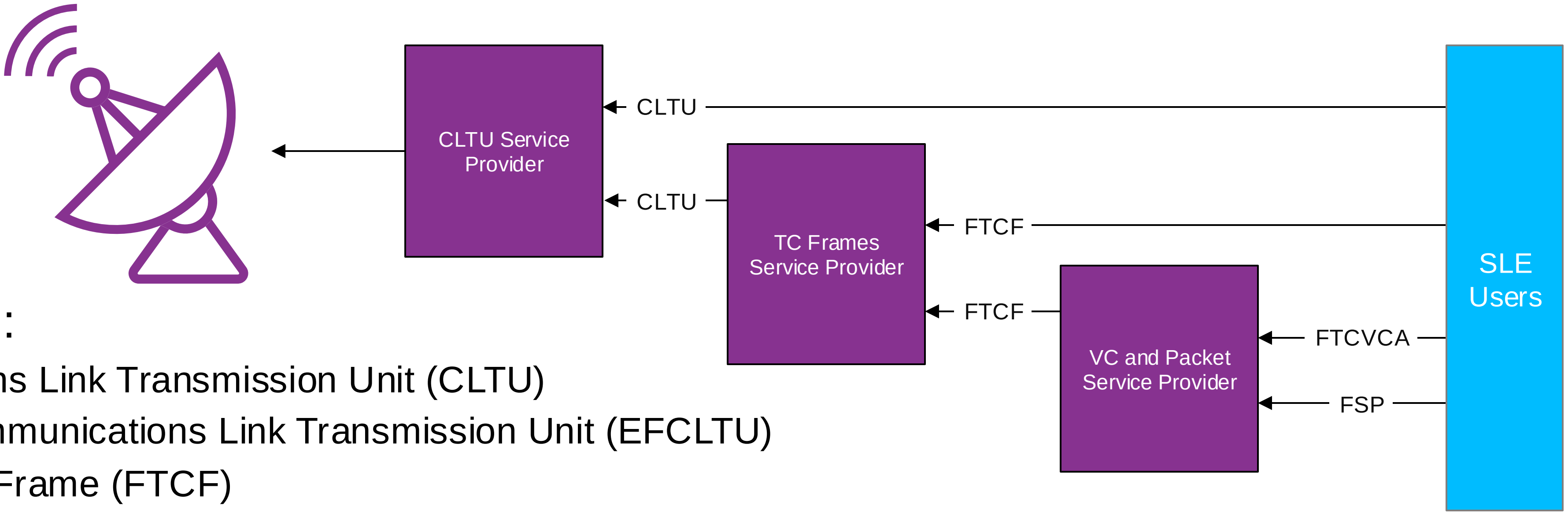




CCSDS SLE (TELECOMMANDING)

Part of the cross-support services

- Used for the transfer of command data between the control center and the antenna site
- Works well with CCSDS-formatted data



- Telecommand Services:
  - Forward Communications Link Transmission Unit (CLTU)
  - Enhanced Forward Communications Link Transmission Unit (EFCLTU)
  - Forward Telecommand Frame (FTCF)
  - Forward Telecommand Virtual Channel Access (FTCVCA)
  - Forward Space Packet (FSP)

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WRAP-UP

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MOVING TO NETWORK PROTOCOLS

Many satellites are now using network protocols on the space link.

- The satellite becomes just another computer on your network
- Eliminates the need for a lot of the things we just covered
- Ternary commanding, framed telemetry, etc.
- Enables the use of standard networking protocols such as UDP, TCP, HTML5, etc.

BUT!
You still need to account for a lot:

- The physical transport over the space link
- Encryption
- Overhead

Encapsulation Schemes

- CCSDS provides a standard for encapsulating IP packets
  - Builds on AOS telecommanding, can be multiplexed with other non-IP data streams
- Framing, such as HDLC, optionally combined with FEC, is sometimes used for smaller commercial satellites

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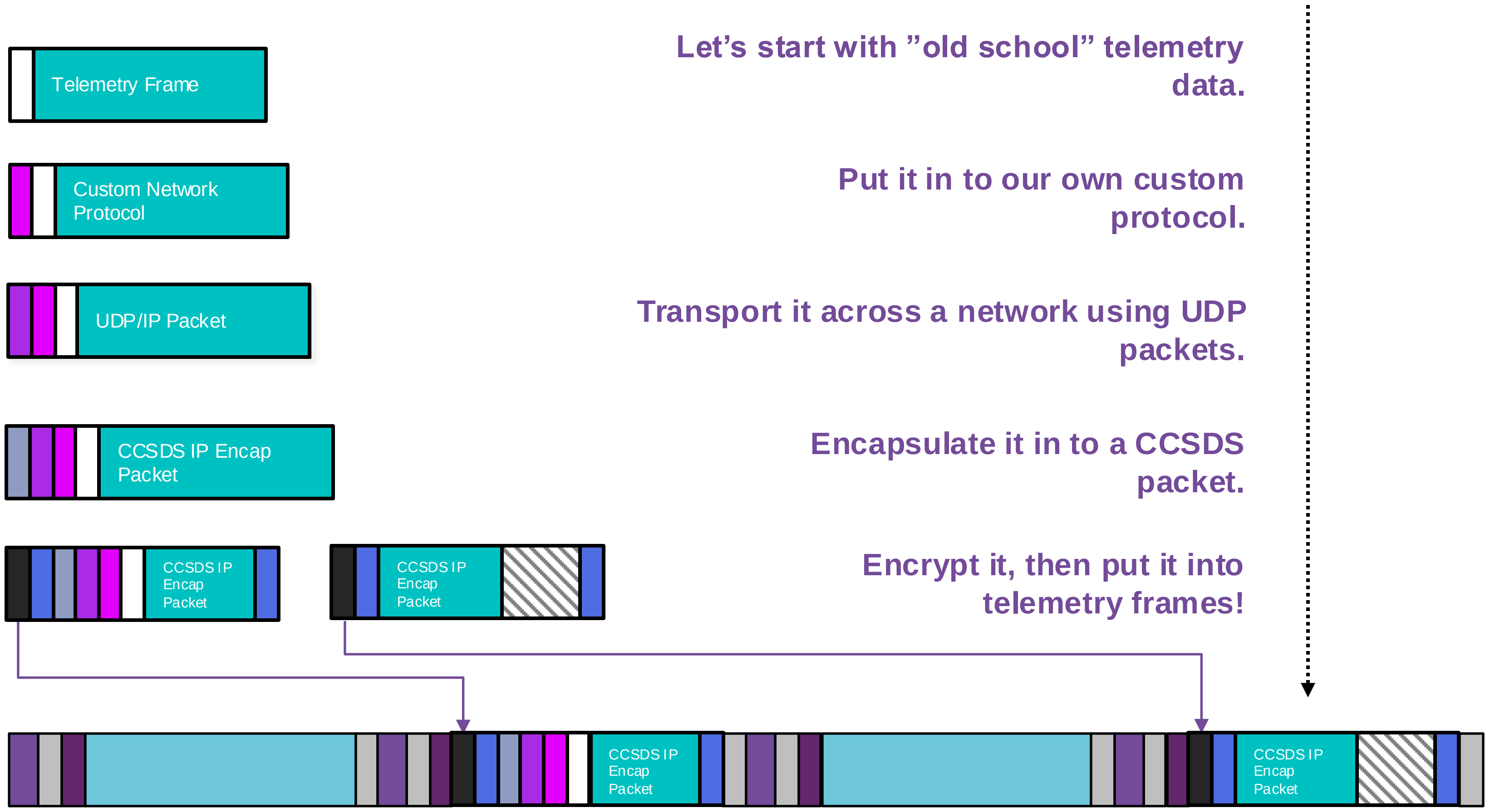
THE LAYERS CAN GET OUT OF HAND

Don't add layers blindly just because you "have to."

Consider restructuring your original data to take advantage of IP.



WE TOOK A LOOK AT:

- data paths
- communications links
- satellite telemetry standards and protocols
- satellite commanding processes and protocols

Each step is important and understandable; it's only when you put it all together that it appears complex.

There are many ways to design, implement, and use a ground system.
Don't fall into the trap of "we have always done it this way."
In many cases, better, more cost-effective solutions exist and are being used today.

Understanding the technical reasons and the history behind the requirements is important!

CLOSING Q&A SESSION

THANK YOU.