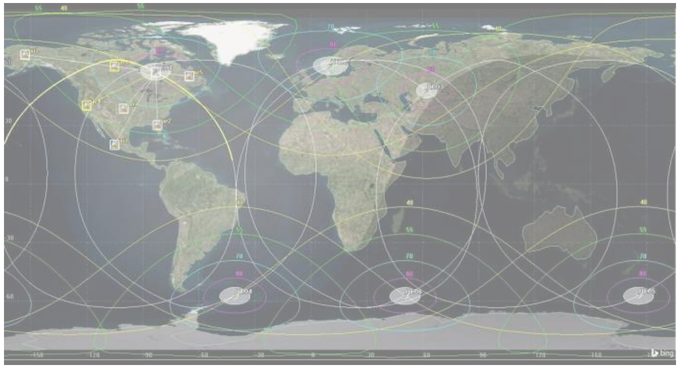

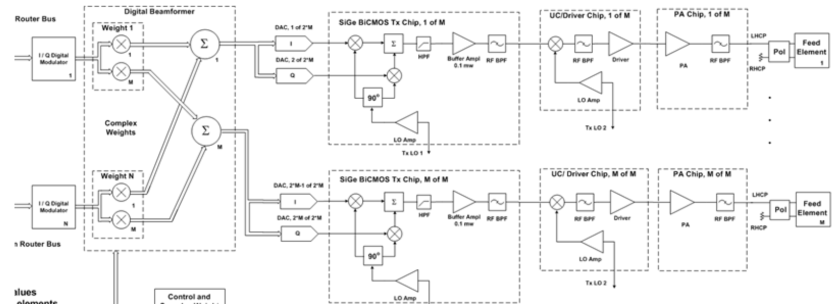

Digital Communications Theory

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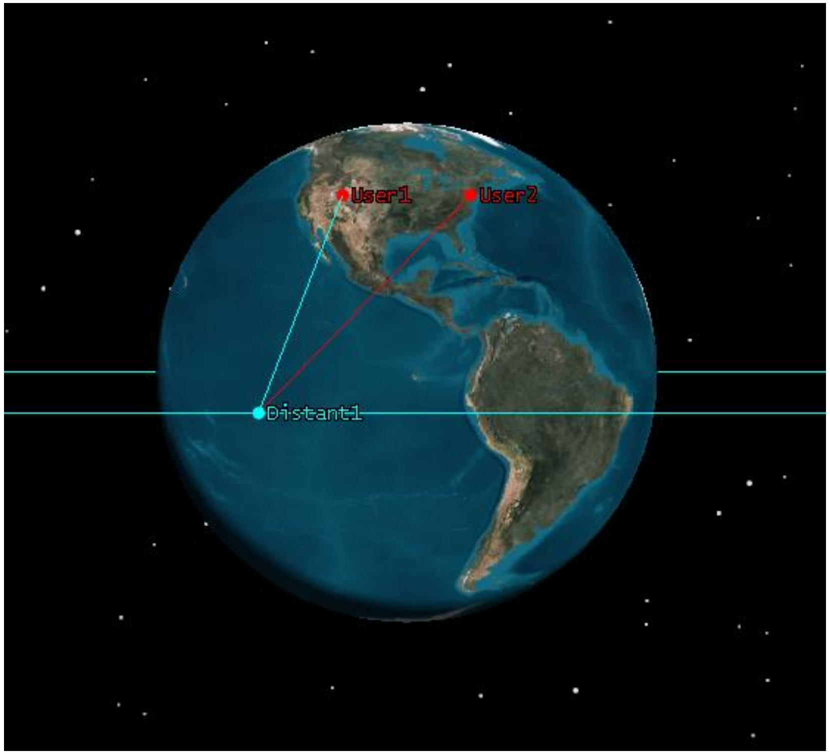
Overview

- Sending voice or data over a constrained channel is a balancing act trading many communication parameters
  - Limited transmit power, antenna size, frequency, bandwidth, number of simultaneous users, background noise, visibility, etc.
- Some of these have limits set for us by the FCC and ITU
- Propagation has been an interesting variable we have all faced on the HF bands across the 11-year sun cycle
- Satellite communications helps resolve some of these issues but presents additional challenges
- LEO AMSATs date back to OSCAR 1 (12/61) but the challenge has been sustained access over wide geographic areas
- AMSAT Phase 4 will bring sustained access to nearly half the globe
- This talk will discuss the evolution to digital modulation schemes using the AMSAT Phase 4 Geosynchronous Satellite Application

AMSAT LEO vs. GEO

- Low Earth Orbit AMSATs have provided early satellite access to hams to extended areas using line of sight
- These typically operated on 2 meters or 70 cm
- Satellite inclination generally provided near global access however dwell times have been short with long revisit intervals
- The Phase 4 initiative will overcome both of these issues
- Figure illustrates sustained visibility and continuous dwell opportunity

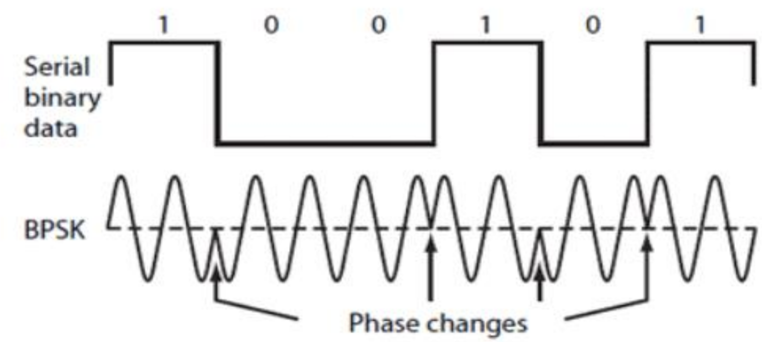


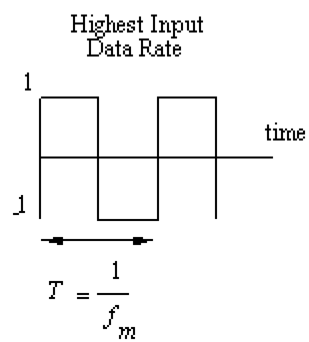
Early Modulation Systems

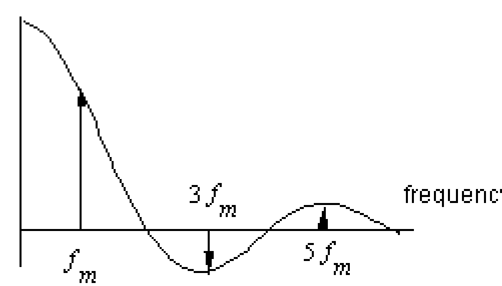
- **Many of us are familiar with the start of radio using spark-gap transmitters and CW using Morse Code**
  - **Today excellent communications using on-off keying (ASK) operates in channel bandwidths as low as 500 Hz**
- **Voice communications was first possible using amplitude modulation and later frequency modulation**
  - **AM voice bandwidths require 6 kHz and FM bandwidths of 10-15 kHz**
- **SSB achieves good voice at bandwidths of 2.8 kHz**
- **These analog modulation schemes all require high SNR for near perfect communications (think of the difference between a QSO and AM radio)**
- **Digital modulation offers near error-free communications at lower SNR**
- **Today digital modes such as PSK-31, JT65, and RTTY offer low power links that can connect over surprisingly great distance**
- **Packing more information into a given channel bandwidth has been the holy grail pushing the limits of modulation technology**

Digital Modulation Part 1

- Digital modes sample voice or data into multi-bit digital words
- Resolution in bits is related to dynamic range while sample rate is related to highest information bandwidth to be sampled
- Harry Nyquist taught us that we must sample at greater than twice the highest input frequency
  - Voice at 2.8 kHz must be sampled at greater than 5.6 ksamples/sec
- The simplest transmission scheme (BPSK) is similar to CW except rather than on-off, the carrier phase is rotated 180 degrees between a “0” and a “1” to be transmitted

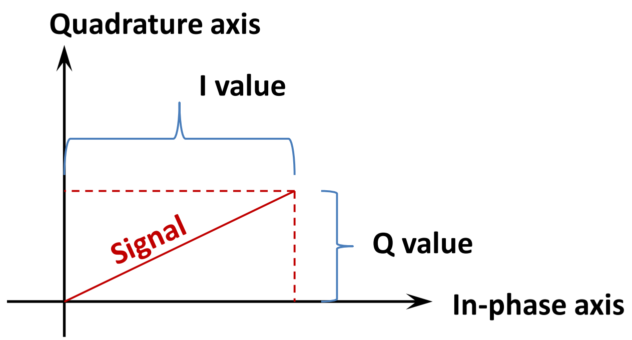




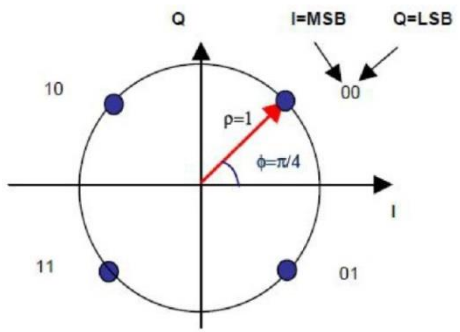


Digital Modulation Part 2

- **Increasing the data throughput with BPSK means that the bandwidth must rise with voice bandwidth or data rate**
- **Higher ordered schemes can pack more data into narrow channels by encoding multiple bits into symbols and transmitting symbols rather than bits, and transmitting their I-Q values for the symbols**



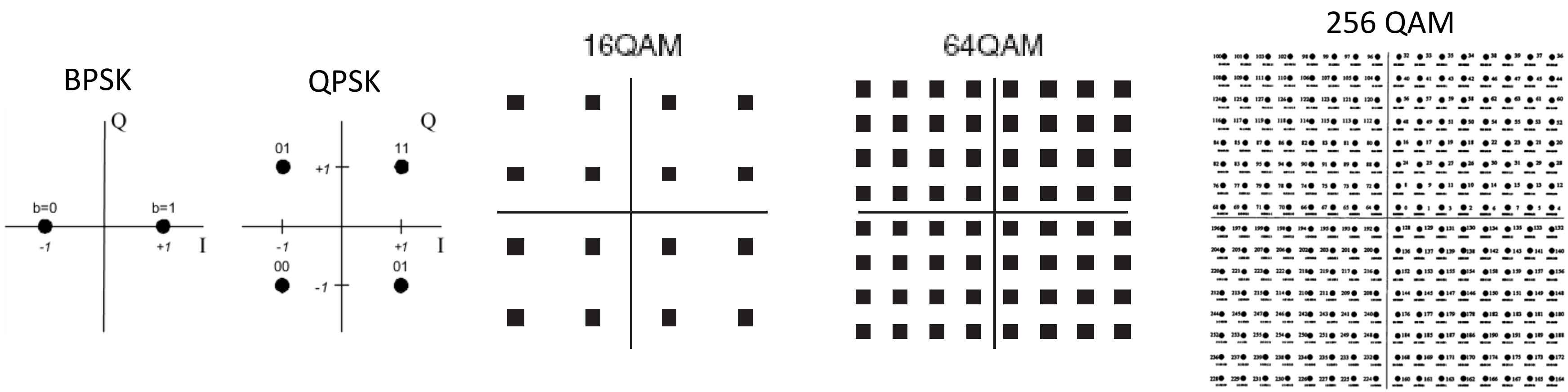
The figure to the left shows I and Q components of a signal



This figure shows how a 2-bit word is mapped to 4 possible symbol values to be transmitted based on their I and Q components

Higher Ordered Modes Increases Bits/Hz Transmitted

- **Since a symbol conveys multiple bits, higher density symbols offers greater data rate in the same bandwidth (spectrum)**
- **Common schemes range from BPSK to 1024 QAM**

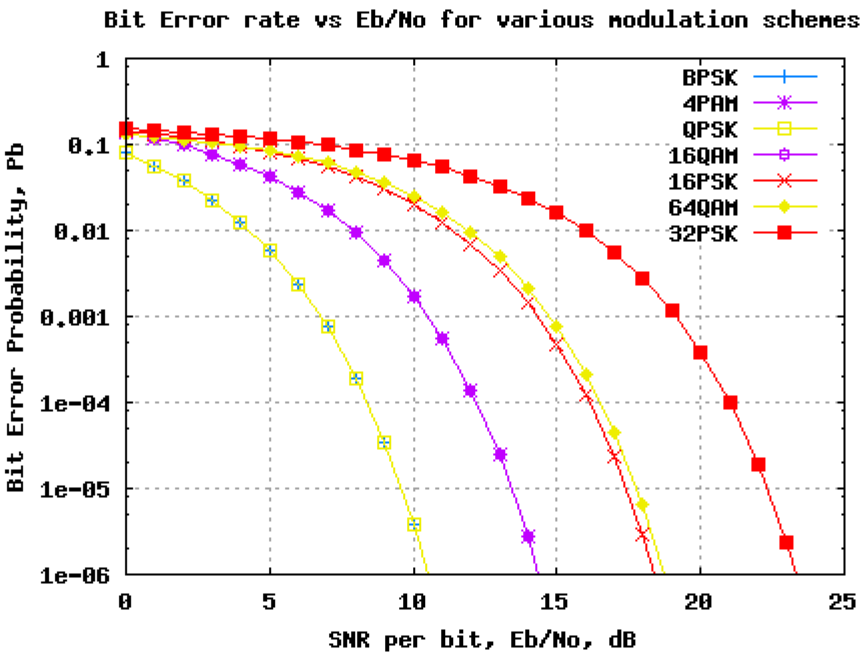


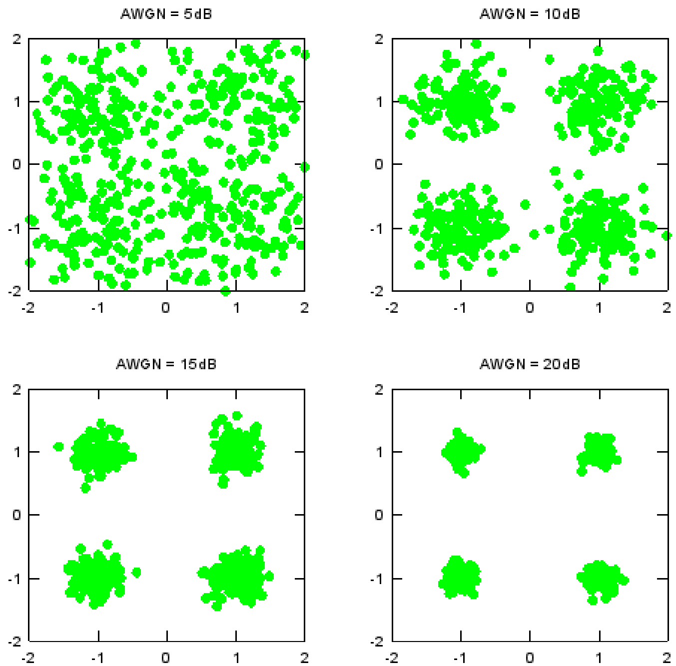
1 bits/symbol **2 bits/symbol** **4 bits/symbol** **6 bits/symbol** **8 bits/symbol**

- **Is this a free lunch, e.g. infinite data in a narrow channel without bound?**
- **Increasing the modulation density requires increasing energy per bit (power) and becomes more susceptible to noise in the demodulation process**

Errors and Energy per Bit and Noise Effects

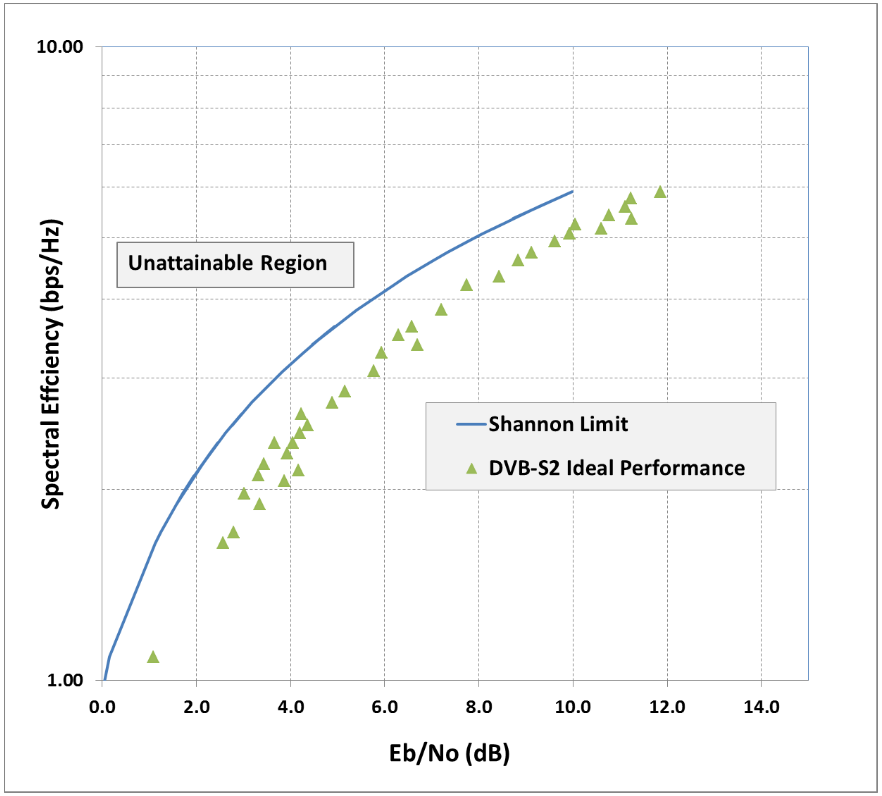
- Plots shows uncoded performance for increasing modulation density; note the y-axis log scale; extra 2 dB reduces errors ~10X
- Detection requires sensing I and Q values and making a decision
- How does noise impact this





Demodulation Issues

- As the modulation density increases, the space between symbol decision points gets closer together, increasing errors
- Claude Shannon described the limit on channel capacity (bits/Hz per Eb/No)
- The DVB-S2 modem standard is becoming common and will be used for AMSAT Phase 4
- Performance is less than 2 dB away from the Shannon limit on channel capacity
- Not all users must use the same modulation format or FEC, e.g. QPSK, 64-QAM, rate 11/20, called MODCODs

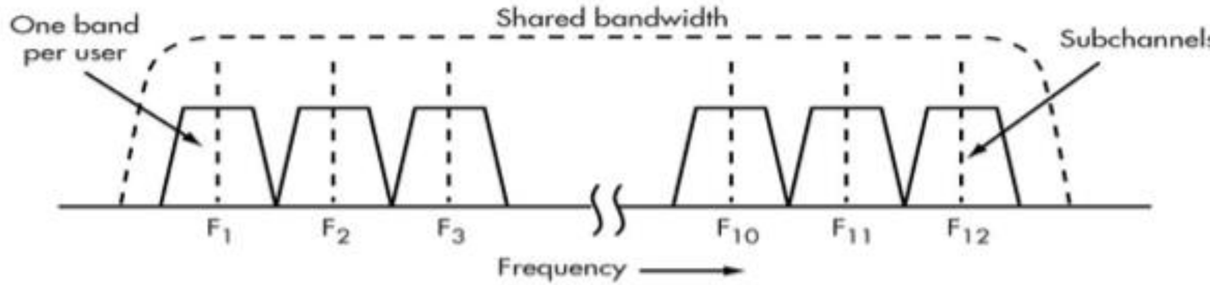


Communications Challenges

- Satellite provides wideband channel on both uplink and downlink
  - Equivalent throughput greatly exceeds capabilities of most users
- Therefore channel must be shared by all simultaneous users
- Goal is to minimize communications burden on users
  - Satellite transponder is expensive
  - System must be architected to simplify user equipment
- Some users may have greater capability than others
  - Larger antennas, higher power
  - Users with lesser capabilities are referred to as disadvantaged users
- User data throughput is small compared to transponder aggregate
- Techniques must enable both low and high rate users to be served
- A combination of techniques has been used by other systems to address this dilemma

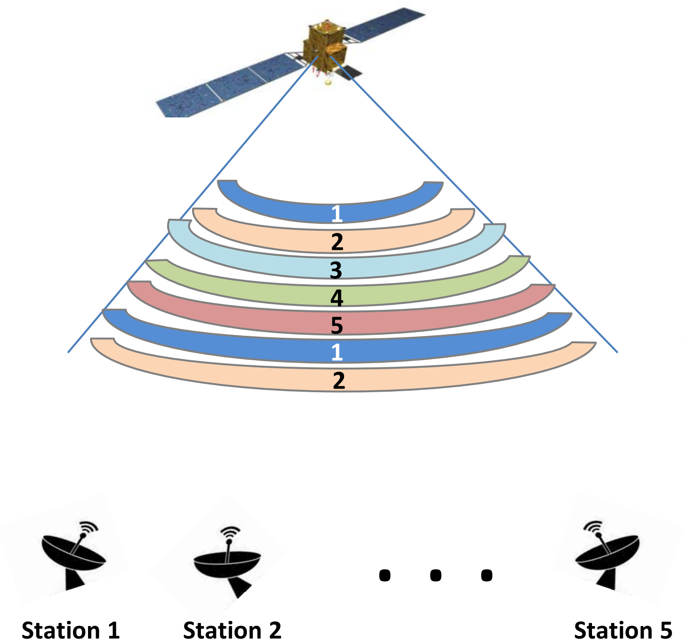
Channel Access Approach

- FDMA uplink – each ground station transmits on a different channel.



- TDMA downlink – traffic destined for each ground station on a different time slot.

- All ground stations can hear all downlink timeslots (broadcast).



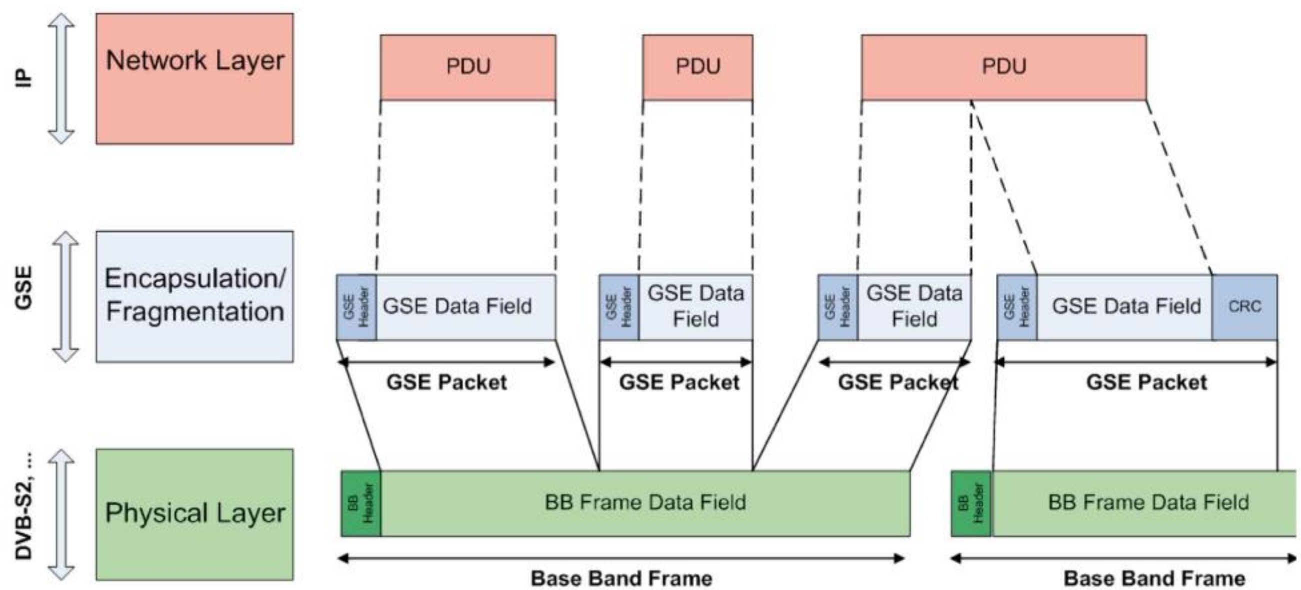
SEA PAC

Network Formats

- User data must be fragmented into packets called Protocol Data Units (PDUs) before transmission on the uplink
- These PDUs are sent from source (user 1) to the satellite where it is turned around in a regenerative link to the destination (user 2)
- Both uplink and downlink messages must contain information to identify source and destination (users) for transmitted packets
- Satellite is not a bent pipe, that is the uplink data stream is not mirrored to the ground as with terrestrial VHF/UHF repeaters
- The FDMA uplink must be recrafted into the TDMA downlink
- This means that while uplink signals are narrowband compared to the transponder the downlink sends much higher data rate signals to all users
- Special attention in the downlink supports disadvantaged users

GSE Packets

- **Generic Stream Encapsulation (GSE) is used to support bi-directional communications while enabling disadvantaged users to participate equally on the links**
- **Each GSE packet has unique header attached to PDU**
  - **GSE data fields may be transmitted at different modulation format and coding but headers all transmitted at the lowest common rate**



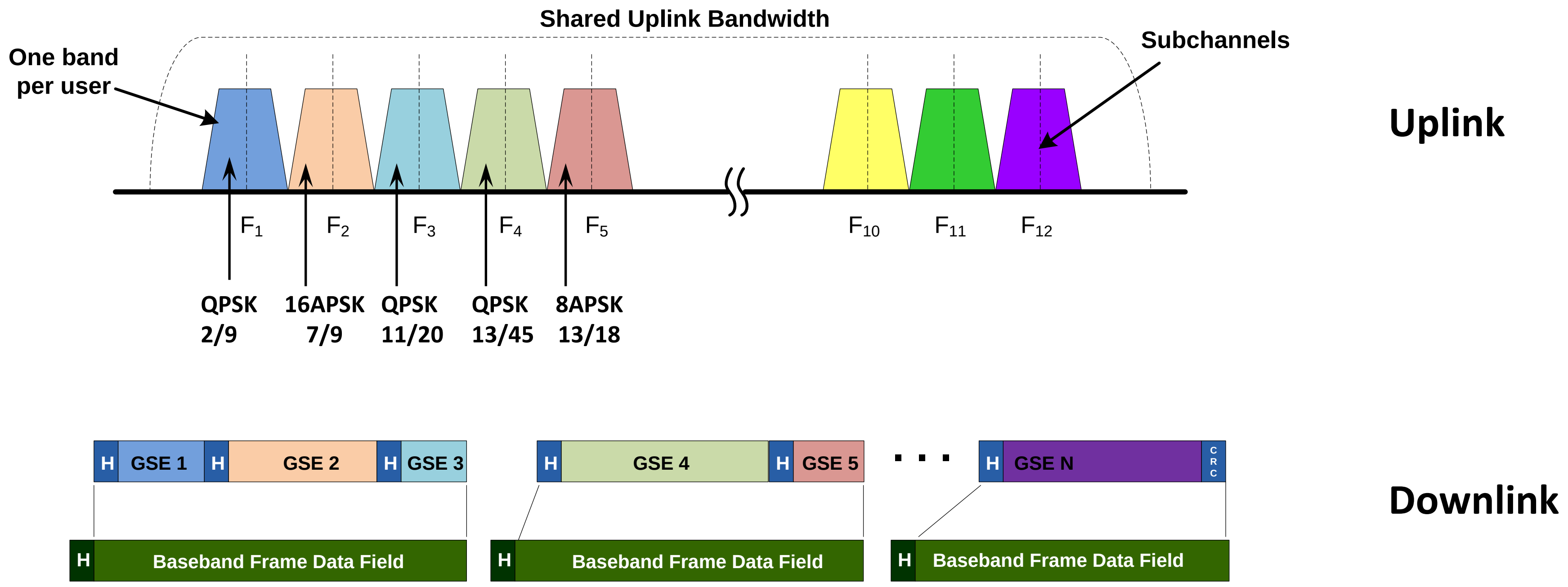
User Link Rates

- Each user uplinks in a subchannel of the shared transponder BW
  - Frequency division multiple access permits many simultaneous users to transmit in the shared bandwidth
  - Collisions are possible and network protocols such as Slotted Aloha can be used to mitigate through features such as random back-off
- Rates depend on many factors but using an uplink symbol rate of 640 kilo-Symbols per second, a subset of possible user rates are shown in the table
- Downlink rates to 2.4 meter dish using 8PSK FEC rate 13/18 achieves 18 Mbps
- If shared amongst 12 users, this amounts to 1.5 Mbps each less some small overhead for frame headers and matches uplink rates

Canonical MODCOD Name	Spectral Effciency (bits/sym)	Effective User Throughput, kbps
QPSK 2/9	0.43	279
QPSK 13/45	0.57	364
QPSK 9/20	0.89	570
QPSK 11/20	1.09	698
8APSK 5/9-L	1.65	1056
8APSK 26/45-L	1.71	1098
8PSK 23/36	1.90	1215
16APSK 1/2-L	1.97	1264
8PSK 25/36	2.06	1322
16APSK 8/15-L	2.10	1349
8PSK 13/18	2.15	1375

Hybrid FDMA Uplink and TDMA Downlink Example

- Uplink users may have different MODCODs but have common header mode
- Downlink may be the same per user or can adaptively be varied



Sample Downlink Budget

- **The data is for simplified for this presentation using a 2.4 meter dish**
- **Each user gets nearly 1.5 Mbps on both the uplink and downlink**

System Parameters

Frequency, Hz	1.045E+10
Wavelength, meters	0.03
Symbol Rate, sps	8.333E+06
Range, km	38000
Modulation Description	8-PSK
Modulation Order, {sqrt(M-ary states)}	3
FEC Code Rate, Rc	0.7222
Link Rate, Mbps	18.05

Satellite Transmitter

Gain, dBi	20.00
Transmitter Power, dBm	46.00
EIRP, dBm	66.00

User Receiver

Antenna Temperature, K	50
Gain, dBi	45.80
Receiver Noise Bandwidth, Hz	1.000E+07
Noise Figure, dB	0.70
Net Receiver gain at antenna, dB	45.80

Noise Computations

Boltzmann's Constant (k), J/K	1.38E-23
Line Loss Ratio	1.00
Ant temp	50.00
line temp ref to ant	0.00
Receiver Temp ref to ant	50.72
sys temp	100.72
Thermal Noise Power in Receiver, dBm	-108.57
Receiver G/T	25.77

Link

EIRP, dBm	66.00
Space loss, dB	-204.42
Net Receiver gain at antenna port, dB	45.80
Power Received, dBm	-92.62
Interference Received, dBm	-192.62
Noise plus Interference Power, dBm	-108.57
Propagation Losses, dB	0.00
Carrier to Interference + Noise (CINR), dB	15.95
Implementaton Loss, dB	0
Eb/No, dB	13.39
Required Eb/No, dB	4.18

Margin, dB 9.21

Summary

- Digital modulation formats are being adopted quickly in the amateur community for low data rate but long range communications
- As amateur satellites take their place in the GEO arc, we will benefit from reliable long range communications that do not depend upon ionospheric skip conditions and the solar cycle
- An understanding of digital communications will enable the ham to further experiment with these modes and develop new applications
- I expect hybrid networks to form using both terrestrial and satellite-based communications to extend our reach with APRS and other data-based services

Questions