Fundamentals of Satellite Communications
Part 3

Modulation Techniques used in Satellite Communication

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Fundamentals of Satellite Communications Part 3
Modulation Techniques used in Satellite Communication

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1. Early Communications

Wired Communications

Transfer information at Base band

- Only one link per line
- Add Modulation for multi-line communications
- Modulation
  - Altering one waveform (carrier) in accordance with the characteristics of another waveform

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Early Wireless Communications - Analog

Multiple Conversations can mean a loss of information

- Goal is too find a means of differentiating connections
- Higher pitch can be distinguished from lower pitch – multiplexing ~
  - Receiver
Early Digital Wireless Communications

- Communication Goals
  - Speed
  - Accuracy
- Select a stable carrier - Smoke / Light / Electromagnetic Radiation
- Check the Path Loss & Distortion
- Efficiently modulate the carrier
- Prevent Interference from adjacent carriers ~

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A Short History of Satellite Communication

- 1945  Arthur C. Clarke publishes an essay “Extra Terrestrial Relays”
- 1957  First satellite SPUTNIK
- 1960  First reflecting communication satellite ECHO
- 1963  First geostationary satellite SYNCOM
- 1965  First commercial geostationary satellite
  - “Early Bird” (INTELSAT I): 240 duplex telephone channels or 1 TV channel, 1.5 years lifetime ~
Modern Communication Satellites

- Galaxy 25
  - **C-Band**: 24x36 MHz
  - **Ku-Band**: 4x54 MHz, 24x27 MHz
  - 100’s of TV Stations & 100,000’s of Telephone Calls ~

Modern Communication Satellite

Geostationary Satellites in orbit today
2. Simultaneously Transmitting Multiple Signals

- Carriers can have multiple modulation techniques
- GSM uses FDM and TDMA

- FDM - Different Frequencies
- TDM - Different Times
- CDM - Different Codes
Frequency Division Multiplexing (FDM)

- Carriers have Assigned Frequencies and Bandwidths
  - Frequency Converters place the carrier in their assigned slot
  - Guard bands are necessary to prevent adjacent carrier interference

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Frequency Division Multiplexing of Satellite Carriers

- Frequency Spectrum is a limited natural resource
- Maximum utilization of the allotted Frequency is essential for a competitive communication medium
- Using Polarization diversity the useable bandwidth is doubled
- Spectrum is offset to decrease the necessary polarization isolation
- Most Satellites are Bent Pipes
  - Transmit whatever it receives
  - Receive signals come from multiple sources ~

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Channel Capacity

- Shannon’s Theorem (1950’s)
- Relates Bit Rate, Bandwidth, & Signal to Noise
- Bit Rate (Bits/Sec) = BW * log₂(1 + SNR)
  - Signal bandwidth = BW
  - SNR = Signal to Noise Ratio
- Theoretical limit, is still a goal
- Complex modulations optimize Bit Rates/BW
- Higher BR/BW require higher Signal to Noise Ratio
- Example: 28.8 Kbps modem
  - 2.4 KHz bandwidth on telephone line
  - 28 Kbps modem must send 12 bits / Symbol
  - S/N ratio must be >= 2¹², or 36 dB; typ. telephone line ~
Bandwidth Considerations

- Data in the time domain translates to the frequency domain as a \((\sin x)/x\) function

$$\varphi(f) = A^2 T \left( \frac{\sin(\pi \lambda)}{\pi \lambda} \right)^2$$

- The baseband time domain signal is filtered to minimize side lobes
  - Minimize adjacent channel interference
  - Raised Cosine (Nyquist) filter best trade off of pulse distortion (time domain) and side lobe rejection (frequency domain)

- IF Bandwidth = \(1/ t_s\)

Assumes alternate “1”s & “0”s NRZ
Modulation - Preconditioning Data

Data Filter
Raised Cosine
Or Nyquist Filter

Modulator

IF Carrier

Band Limited
Modulated signal

- Data
- Modulator - Converts input data to an IF carrier
  - Frequency translator Zero to Fo (MHz)
- IF Data Spectrum
- Can’t Filter at RF
  - BW is too narrow
- Pre-Modulation Filtering - Limits RF Bandwidth ~
3. Types of Modulation

- Unmodulated carrier: \( V = A \cos [\omega_0 t] \).
- Modulated signals control amplitude & phase (Frequency)
  - \( V = \left[1 + A_c(t)\right] \cos [\omega_0 t + \theta(t)] \)
  - \( A_c(t) \) is amplitude modulation (AM)
  - \( \theta(t) \) is phase modulation (PM)
  - \( \frac{d \theta(t)}{dt} = \omega_i(t) = f_c(t) \) frequency modulation (FM)
- AM – Amplitude varies as a function of data
- FM – Frequency Shifts as a Function Data
- PM – Phase Shifts as a function of data
- QAM is a combination of Amplitude and Phase Modulation –

\[ A_c(t) \text{ and } \theta(t) \Rightarrow QAM \text{ (Digital)} \]
Analog Amplitude Modulation (AM)

- AM Radio
- Analog TV
- Optical Communications

- $\omega_c$ = carrier
- Modulation Index = $m$
- $m = \max |m(t)|$
- $m \leq 1$
- For $m(t) = m \cos(\omega_m * t)$
- Modulation Index determined graphically

AM Waveform

$x(t) = A \times [1 + m(t)] \times \cos(\omega_c * t)$

Modulation index: $m = 0.5$

$$m = \frac{P - Q}{P + Q}$$
AM Frequency Spectrum & Power

- Calculating Sideband Levels
  - $\text{dBc} = 20 \log_{10} \frac{m}{2}$
  - 75% AM ($m=0.75$)
  - Sidebands down 8.5dB from the carrier

- Required Power for AM
  - Peak level 2 x no signal ($m=1$)
  - RF power 4 x CW Signal ($m=1$)
  - Linear Power Amps 2 or 3 x less efficient than Non-Linear Amps
  - Need more power to operate than AM than FM/PM
ASK - AMPLITUDE SHIFT KEYING

- Two or more discrete amplitude levels
- Used in optical communications
- For a binary message sequence
  - two levels, one of which is typically zero
  - Modulated waveform consists of bursts of a sinusoidal carrier.

Extinction Ratio
Max. Light to no light ~

Laser Output
Frequency Modulation

\[ X_c(t) := A_c \cdot \cos \left( \theta_c(t) \right) \]

- \( X_c(t) \) = modulated signal
- \( A_c \) = carrier amplitude
- \( \theta_c(t) \) = Instantaneous phase

\[ \theta_c(t) := 2 \cdot \pi \cdot F_c \cdot t + \phi(t) \]

\[ \theta_c(t) := 2 \cdot \pi \cdot F_c \cdot t + 2 \cdot \pi \cdot k_f \cdot \int_{-\infty}^{t} m(\tau) \, d\tau \]

- \( m(t) \) = Information waveform
- \( F_c \) = average carrier frequency
- \( \Phi(t) \) = instantaneous phase around the average frequency \( F_c \)
- Frequency = \( \frac{d \Phi(t)}{dt} \)

\[ \phi(t) := 2 \cdot \pi \cdot k_f \cdot \int_{-\infty}^{t} m(\tau) \, d\tau \]

- For \( m(t) \) sinusoidal
- \( f_i = F_c + k_f \cdot m(t) \)
- \( k_f \) = Gain Constant
- Frequency Deviation = \( \Delta f \)

\[ \therefore \Delta f = k_f \max |m(t)| \sim \]
FM Modulation Index ($\beta$)

- $\Phi(t) = \text{Instantaneous Phase variation around carrier } F_c$
- For FM signals:
  
  $\phi(t) := 2 \cdot \pi \cdot k_f \cdot \int_{-\infty}^{t} m(\tau) \, d\tau$

- $K_f = \Delta F = \text{the peak frequency deviation}$
  - $m(\tau) = \text{is the normalized peak deviation}$
- For Sinusoidal modulation:
  - $m(\tau) = \cos(2\cdot\pi\cdot Fm \cdot \tau)$ where $Fm$ is the rate of modulation
  - $\Phi(t) = \frac{2\cdot\pi\cdot\Delta F}{(2\cdot\pi\cdot Fm)} \cdot \sin(2\cdot\pi\cdot Fm \cdot \tau)$
  - $\Phi(t) = \frac{\Delta F}{Fm} \cdot \sin(2\cdot\pi\cdot Fm \cdot \tau)$
  - $\beta = \Delta F / Fm = \text{modulation index (Radians)}$
  - $\Phi(t) = \beta \cdot \sin(2\cdot\pi\cdot Fm \cdot \tau)$

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FM Spectral Analysis

- FM Modulated Carrier: $X_c(t) = A_c \cos(2\pi f_c t + 2\pi k_f \int m(\tau) \, d\tau)$
- Sinusoidal signals: $m(\tau) = \cos(2\pi F_m \tau)$
  - Note: Non-sinusoidal signals are handled by taking the Fourier Transform of $m(t)$ and applying the resultant sinusoidal infinite series using superposition
- $\beta = \Delta F / F_m =$ modulation index (Radians)
- All frequency components ($\delta$ functions) are at $\pm$ integral multiples of $F_m$, from the carrier ($F_c$)
  - $\delta$ functions at $f_c \pm nf_m$ have an amplitude $= J_n(\beta)$
  - $J_n(\beta)$ are Bessel Coefficients of the first kind, order $n$ and argument $\beta$
- Carson’s Rule: $BW \approx 2\Delta f + 2F_m$
Phase Modulation (PM)

\[ X_c(t) := A_c \cdot \cos \left( \theta_c(t) \right) \]

\[ \theta_c(t) := 2 \cdot \pi \cdot F_c \cdot t + \phi(t) \]

- \( \Phi(t) \) = Phase Modulation
- \( \Phi(t) = \beta \cdot m(t) \): \( \beta \) = peak phase deviation
  - \( \beta \) = Modulation Index, same as FM
- \( m(t) \) = information normalized to \( \pm \) unity
- Phase Modulated Carrier is:
  - \( X_c(t) = A_c \cdot \cos \left( 2 \cdot \pi \cdot F_c \cdot t + \beta \cdot m(t) \right) \)
Sampled Analog Signals

- Continuous signals are sampled at discrete times
- Samples are digitally coded & Transmitted
- Nyquist criteria for completely recovering an analog signal
  - Sampling Rate (Fs) \( \geq 2 \times \) Maximum Information Rate (Fm)
  - No. of Samples \( \geq 2 \) per period
  - Proof is in the analysis of the Fourier Transform

- Take the Fourier Transform of a complex analog waveform
- Limit the bandwidth to the maximum frequency rate (Fm)
- All frequency components > Fm are suppressed
- The Nyquist Criteria will solve all of the unknowns sampling at a rate of 2Fm
- Add one sample to calculated the DC component ~
Implementation of Quantization

- Analog to digital converter (ADC)
- Approximates analog signal by discrete $M$ levels.
- Small step size, signals can appear continuous (e.g. Movies)
- Quantization level to a sequence of $N$ binary bits
  - No. of Levels = $M = 2^N$
  - No. of Bits = $N = \log_2 M$
- Nyquist Criteria
  - $N$ Bits per sample

$F_m = 10$ MHz
- Sample Time: 50nSec
- $M = 1024$ Steps
- 10 bit Binary Code
- $5nS/Bit$
5. Digital Modulation Techniques - CW

Constant Wave (CW) Modulation / Phase Shift Keying (PSK)

- Modulated Phase (or Frequency)
- Highly Efficient Power Amps
  - More resilient to amplitude distortion
- Recovery by Simple Phase Detection
- Bi-Phase Shift Keying
  - BPSK: Low Data Rates
- Quadrature Phase Shift Keying
  - QPSK (OQPSK): Medium Data Rates
- Eight Level Phase Shift Keying
  - 8PSK: High Speed Data
- Higher Levels are use less often

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Binary Phase-Shift Keying BPSK (2-QAM)

- Signal is represented as a vector
- A change in phase (180°) is a change in Binary code

\[ s(t) = \begin{cases} 
A \cos(2\pi f_c t) & \text{binary 1} \\
A \cos(2\pi f_c t + \pi) & \text{binary 0}
\end{cases} \]

Carrier is multiplied +1(Binary 1) or –1(Binary 0)

Data sequence +1 or 1

\[ A_c \cos(2\pi f_c t) \]

Binary PSK signal

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Binary Phase-Shift Keying BPSK (2-QAM)

- $T_b$ is the duration of 1 Bit
- Bit Rate = $1/T_b$
- Symbol Rate = $1/T_b$
- IF BW = Symbol Rate = $1/T_b$

- Absolute phase is determined by a known synchronization pattern

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Frequency Spectrum BPSK

- Pulsed input transforms to a \(\frac{\sin x}{x}\) frequency spectrum
- 3dB bandwidth is \(1/T_b\)
- 1st null is \(1/T_b\) (1 symbol rate) away from the carrier
- Side lobes interfere with adjacent carriers
- Baseband is filtered to minimize the height of the nulls
- Optimize between frequency response and pulse response
- Use \(\frac{1}{2}\) Raised Cosine (Nyquist) filter in the transmitter for side lobe suppression
- \(\frac{1}{2}\) Raised Cosine filter in the Receiver for noise suppression
Quadrature Phase-Shift Keying (QPSK)

- Successive bits are transferred to alternate channels
- Bits are stretched x2
- 2 Bits per symbol

- 2 BPSK modulators
- Carriers are 90° Out of Phase (I & Q)
- ∑ 2 vectors 90° out of phase
QPSK Vector

- "Quadrature": 1 of 4 phases (4-PSK) of the carrier
- 0, 90, 180, 270° (00, 01, 10, 11)
- 2 Bits per symbol. The bit rate for QPSK is twice the symbol rate.

\[
\begin{align*}
&I(+) Q(+) = 10 \\
&I(-) Q(+) = 11 \\
&I(-) Q(-) = 01 \\
&I(+) Q(-) = 00
\end{align*}
\]
QPSK Bandwidth

- Bit Rate = \(1/ T_b\)
- 2 Bits per Symbol
- Symbol Rate = \(1/(2 \cdot T_b) = 1/ T_s\)
- IF BW = Symbol Rate = \(1/ T_s\)
- 1st Null is at Symbol Rate
- 2 times as efficient as BPSK
- 1/2 Raised Cosine filters are used for all digital signals

IF BW = Symbol Rate = \(1/ T_s\)

Frequency Response

3dB BW = \(1/ T_b\)

\(-1/(2 \cdot T_s)\) to \(+1/(2 \cdot T_s)\)

\(f_0\) to \(f_0\)

\(f_0 - 1/ T_s\) to \(f_0 + 1/ T_s\)

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Amplitude Variations of QPSK

- If I & Q bits change at the same time vector goes through zero
- Power changes abruptly
- Non-constant envelope after filtering
- Peak to Average Ratio increases with zero crossings
- Causes signal distortions

Many Zero crossings

QPSK - ideal

QPSK - filtered
Offset QPSK (OQPSK)

- Offset the I & Q bits so they don’t change at the same time
- Instead of signals going through zero they go around the circle
- The receiver corrects the offset to recover the signal
- OQPSK does not have a distinct null in the frequency domain ~

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8 PSK Modulation

- 8PSK, Two QPSK modulators offset by 0° or 45°
- Output switches between QPSK modulators

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8PSK Vector

- Used for High Data Rate Constant Amplitude Modulation
- 3 Bits/Symbol
  - Bit Rate = 3 x Symbol Rate
- Required Bandwidth is based on symbol rate (Bit Rate/3)
- Higher values than 8 are rarely used
  - Phase Increment is too small
  - Phase Noise is the limiting factor ~
Symbol Error in M-ary PSK Systems

Note: More Complex Modulations Require higher S/N for the same Error

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6. Quadrature Amplitude Modulation (QAM)

- (QAM) A Combination of ASK & PSK
- M-QAM is QPSK with variable Amplitude vectors
- Varying Vector Amplitude and Phase
- I & Q Vector Phase (0° / 180° & 90° / 270°)
- \( p_I(t) \) & \( p_Q(t) \) = Discrete (Binary) Amplitude Steps
- Sum = Vector with discrete Amplitude and Phase positions

\[
S(t) = p_I(t) \cos(\omega_c t) + p_Q(t) \sin(\omega_c t) \quad \sim
\]

Carrier Vector is the summation of the I & Q vectors
- Constellation Diagrams
  - Contains all possible vector locations
- Points defined by the Quantized I & Q vector amplitudes
- Primary QAM Configurations
  - 16-QAM
  - 64 QAM
  - 256 QAM
- Less Efficient
  - Requires Linear Power Amplifiers
- Peak compression causes distortion
- Receiver requires complex Phase & Amplitude Detection
16QAM modulations is a constellation of discrete Phase & Amplitude positions.

Each position (Symbol) represents 4 bits of data.

4:1 efficiency of transmission over BPSK.

Down side: Less allowable vector distortion for correct data reception.
16-QAM Modulation (4 Bits / Symbol)

- I & Q vectors with variable discrete amplitudes define the vector position
- Initial phase is determined by a header code transmitted before actual data
- Note: Adjacent symbol positions differ by only one Bit
- Enhances the ability to correct data without retransmission (FEC)

Transmitted 16-QAM Data, 4 bits/symbol
64-Quadrature Amplitude Modulation

- I-Channel
- Q-Channel
- RF-In
- RF-Out

Bit stream in (011)(010)

- 6 Bits per Symbol
- QPSK with 4 amplitude levels
- Typical Waveform in the time domain
64-QAM Modulation (6 Bits / Symbol)

- 2 Vectors (I & Q)
- Phase States \(4 = 2^N\): 
  \((N=2)\) (BPSK \(N=1\))
  - \(0^\circ / 180^\circ \) & \(90^\circ / 270^\circ\)
- Amplitude Levels = \(16 = 2^A\) (\(A = 4\)), (\(A=0\) for Constant Amplitude)
- \(M = \text{No. of States}\)
  - \(M = 2^N \times 2^A\)
  - \(M = 2^2 \times 2^4 = 64\)

\(1/4\) 64 QAM Constellation

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QAM Modulation Summary

- Number of States = \( M = 2^N * 2^A \) Bits/Symbol
- 2-QAM (BPSK) \( N=1, A=0, M = 2^1 * 2^0 = 2 \) (1 Bit)
- 4-QAM (QPSK) \( N=2, A=0, M = 2^2 * 2^0 = 4 \) (2 Bit)
- 8PSK \( N=3, A=0, M = 2^2 * 2^1 = 8 \) (3 Bit)
- 16-QAM \( N=2, A=2, M = 2^2 * 2^2 = 16 \) (4 Bit)
- 32-QAM \( N=2, A=3, M = 2^2 * 2^3 = 32 \) (5 Bit)
- 64-QAM \( N=2, A=4, M = 2^2 * 2^4 = 64 \) (6 Bit)
- 128-QAM \( N=2, A=5, M = 2^2 * 2^5 = 128 \) (7 Bit)
- 256-QAM \( N=2, A=6, M = 2^2 * 2^6 = 256 \) (8 Bit)
- 256-QAM transfers 56kBits/sec on a 3kHz telephone line
- Faster transmission over a standard telephone line is not possible because the noise on the line is too high (Shannon’s Theorem) ~
Carrier to Noise vs. Bit Error Rates (BER)

More Complex Modulations Require higher S/N for the same Error

Bit Errors based on Average Signal Power

Number of Standard Deviations to Threshold
7. Recovering Packet Errors

- **Error detection - Parity Check**
  - Effective when probability of multiple bit errors is low
  - Only one extra bit
  - If any bit is distorted, parity will come out to be wrong

- **Two ways of recovering packets:**
  - Forward Error Correction (FEC)
    - Recipient recovers data bits using additional bits
  - Automatic Repeat Request (ARQ)
    - Recipient requests the retransmission of lost packets.

- **Observations:**
  - Most corrupted packets have single or double bit errors.
  - ARQ is not suitable for broadcast communication pattern.
    - Retransmissions cause severe performance degradation.
  - Long delays, especially in Satellite Communication ~
Forward Error Correcting (FEC) Codes

- A system of error control for data transmission
  - Sender adds redundant data to its messages
- Reduces need to retransmit data
- Forward Error Correction (FEC) or Error Correcting Codes (ECC)
  - Goal: Include enough redundant bits to permit the correction of errors at the destination.
  - Avoid retransmission of data.
- Extra bits are added to the transmitted word
- Can find the error bit and correct it
- More extra bits – the more bit errors that can be corrected

Diagram:
- Transmitter
  - User information
    - Encoder
    - Path
  - Receiver
    - Pattern Checking
    - Deliver user information
Types of Error-Correcting Codes

- Two basic types: block and convolution codes
- Block codes
  - All code words have same length
  - Encoding for each data message can statistically be defined
  - Reed-Solomon is a subset of Block Codes
- Convolution codes
  - Code word depends on data message and a given number of previously encoded messages
  - Encoder changes its state with processing of each message
  - Length of the code words is usually constant
- Other categorization of types of codes: linear, cyclic, and systematic codes
Forward Error Correcting Codes

- R=3/4 means 4 bits are sent for every three data bits.
- More extra bits – the more errors that can be corrected.
- More extra bits – lower Eb/No for the same BER.
Example - Correcting 1-bit Errors

- Simple extensions of parity check per code word
  - Longitudinal Redundancy Check (LRC):
    - Additional parity bit with a sequence of 7 bits \(\rightarrow\) new code word – 8 bits
  - Vertical Redundancy Check (VRC)
    - An extra sequence of 8 bits after a series of \(n\) code words
    - Each bit in this sequence works as parity for bits that occupy same position in \(n\) code words

- Example: ASCII coding (7 bit word) for \(n=4\) (4 words)
- Add bits
  - 1 parity bit / word \(\Rightarrow\) 4 bits
  - 1 parity word \(\Rightarrow\) 8 bits
  - Total additional = 12 bits
- Code rate = \(28/(12+28) = 0.7\)
- 3 correction bits for every 7 data bits sent
- \(R=7/10\)
8. Amplitude and Phase Shift Keying (APSK)

Digital Video Modulator

- DVB-S2 is a new Video modulation standard for Digital Video Broadcasting
- Second-generation specification for satellite broadband applications
- Uses QPSK, 8PSK, 16APSK, or 32APSK
- 16APSK or 32APSK is a new digital modulation scheme
  - Changing, both amplitude and phase ~
QAM modulators can place signals at any vector location
16APSK more immune to Phase Noise than 16QAM
32APSK symmetrical means of doubling bits/symbol
Emphasis on Phase Noise immunity ~

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Amplitude Compression - APSK

- 16APSK and 32APSK are not widely adopted
- Requires Higher power amplifiers than CW modulation
  - Note the effect of amplitude compression
- Note the Threshold region is still similar to the inner circle

No Amplitude compression

Amplitude compression

32APSK

32APSK
DVB-S2 Carrier to Noise Requirements

Dotted lines = modulation constrained Shannon Limit

16APSK & 32APSK was introduced with DVB-S2

Higher Data Rates ➞ higher C/N ~

DVB-S2

16APSK

32APSK

16APSK & 32APSK was introduced with DVB-S2

DVB-DSNG

6QAM

8PSK

QPSK

DVB-S

QPSK

C/N (dB) in BW=Rs

Ru (Mbit/sec) per unit symbol rate, Rs

-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Modulation Standards are driven by HDTV

- Standard Analog TV bandwidth is 6MHz
- HDTV with twice the resolution is 12MHz
- If the analog signal is digitized with 8 bits that \( \Rightarrow \) 96MHz of baseband signal (192MHz RF Bandwidth)
- Even with 16APSK (32APSK is not currently in use) bandwidth compresses to 24MHz baseband & 48MHz RF
- HDTV uses less than 6MHz of bandwidth: **It’s a miracle**
  - Scene are only updated as necessary
    - Only scene changes are transmitted
  - High speed movement has many errors, No one notices
    - This is a calculated effect
- Networks want to minimize Bandwidth, it’s expensive
  - They utilize the eyes of the viewer as a Forward Error Correcting code
- We can live with a large number of errors in TV, this doesn’t work for our financial transactions ~
9. Decision Regions - System Diagram

- Transmit Vector is on a point
- Receiver Vector is in a decision region

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- Lines between the constellation points are the threshold levels
- Signals residing in the square are assume to reside at the discrete vector location.
Threshold Spacing

- **BPSK**
- Threshold ±90°

- **QPSK**
- Threshold ±45°

- 16-QAM Amplitude steps
  - A or 3A
  - Separation – 2A
  - Amplitude Noise: Decision region must have Equal Area
  - Phase Noise: Vector Angles must be equal ~

Acceptable Region

Decision Threshold

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QAM Geometric Effects

- Maximum angle error is dependent on Symbol Location
- Outer Symbols Tolerate the least angle error
- Allowable Error Window is smaller for More Complex Modulation

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>2QAM</td>
<td>90.0°</td>
</tr>
<tr>
<td>4QAM</td>
<td>45.0°</td>
</tr>
<tr>
<td>16QAM</td>
<td>16.9°</td>
</tr>
<tr>
<td>32AM</td>
<td>10.9°</td>
</tr>
<tr>
<td>64QAM</td>
<td>7.7°</td>
</tr>
<tr>
<td>128QAM</td>
<td>5.1°</td>
</tr>
</tbody>
</table>
Part 4 Signal Distortions & Errors

- Error Vector Measurements (EVM)
  - Thermal Noise Effects
  - Phase Noise Effects
  - Group Delay Distortion (Deterministic)
  - AM-AM Distortion (Deterministic)
  - AM-PM Distortion (Deterministic)
  - Modulated Power Levels
  - Total Noise Effects

- Eye Diagrams
  - Amplitude & Phase Distortion
  - Thermal Noise
  - Timing Errors ~