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

1. Early Communication
2. Simultaneously Transmitting Multiple Signals
3. Types of Modulation
4. Digital Modulation - Quantizing Data
5. Digital Modulation Techniques – CW (Constant Amplitude)
6. Quadrature Amplitude Modulation (QAM)
7. Recovering Packet Errors
8. Amplitude and Phase Shift Keying (APSK)
9. Digital Modulation - Decision Regions ~

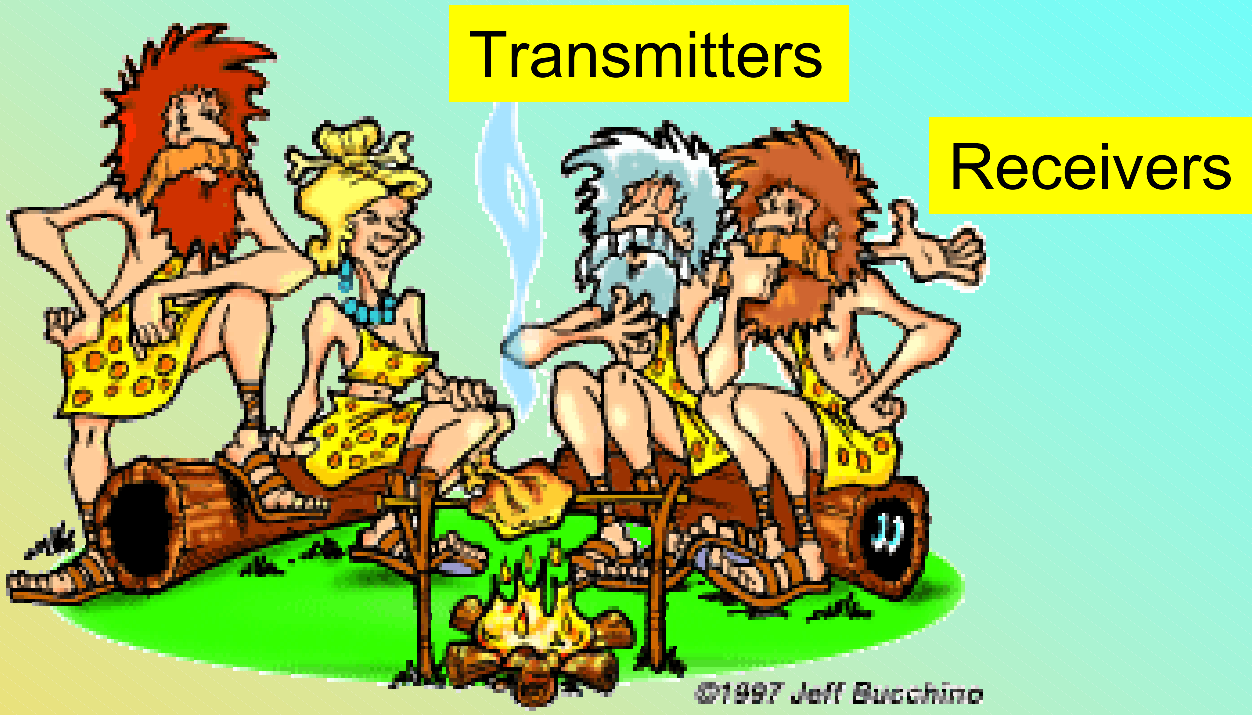
1. Early Communications

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 ~

Early Wireless Communications - Analog

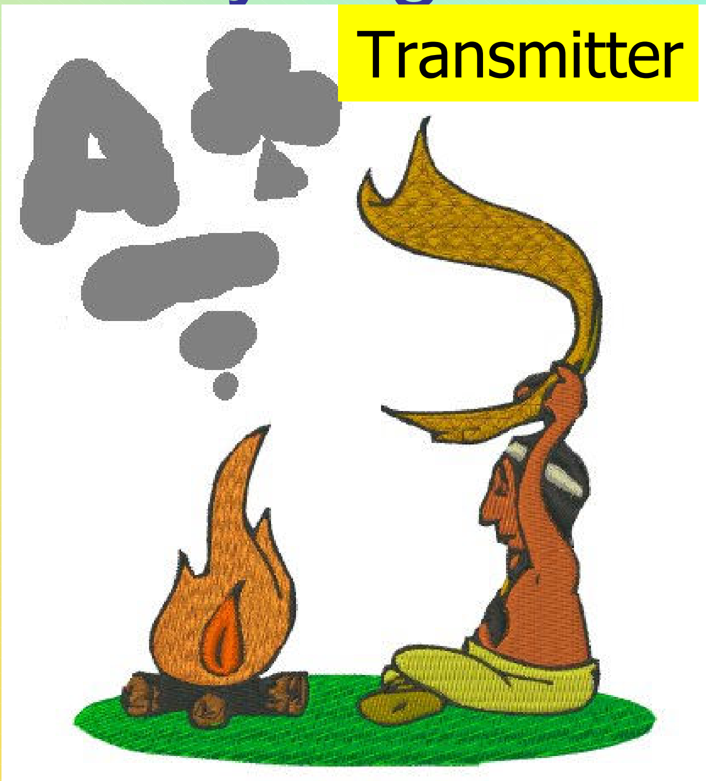


Multiple Conversations can mean a loss of information

- 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 ~

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 ~

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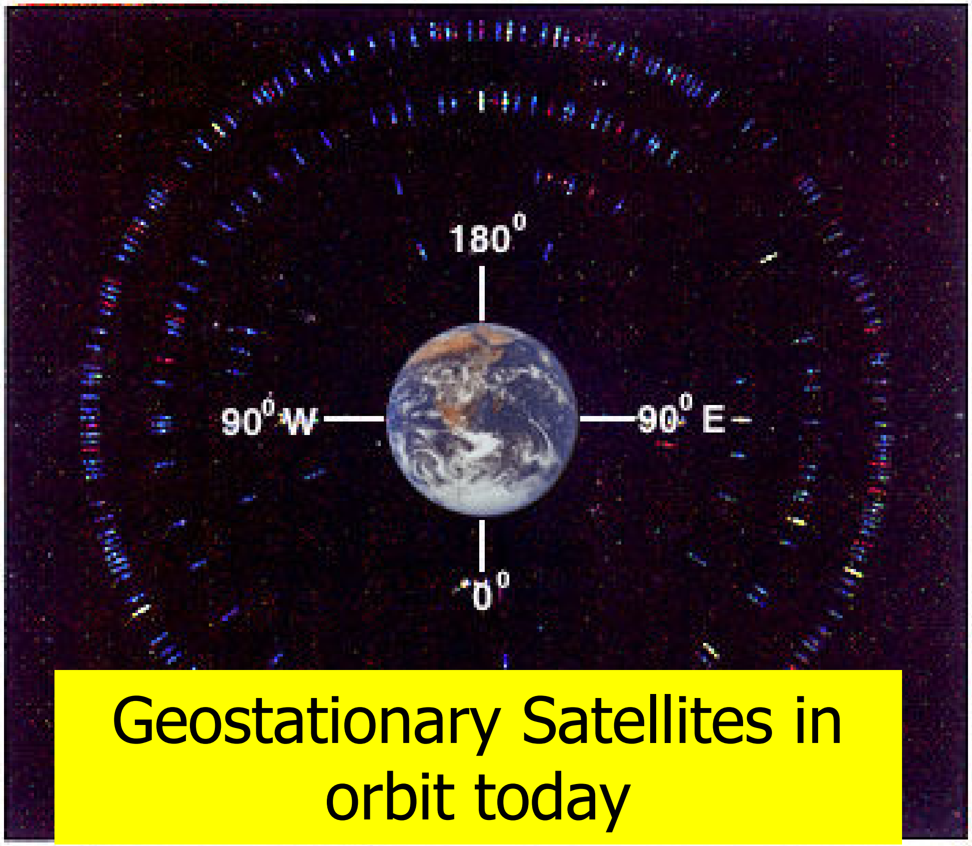
Modern Communication Satellites

- 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

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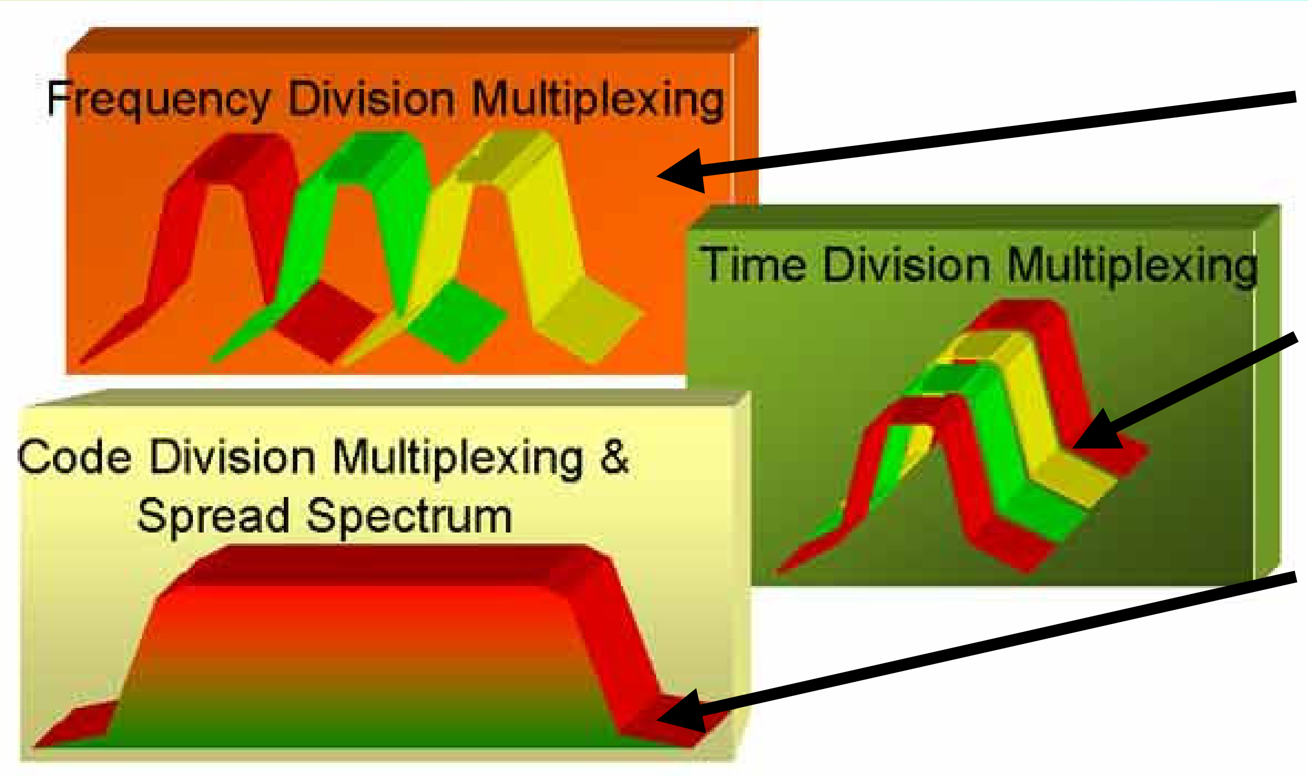
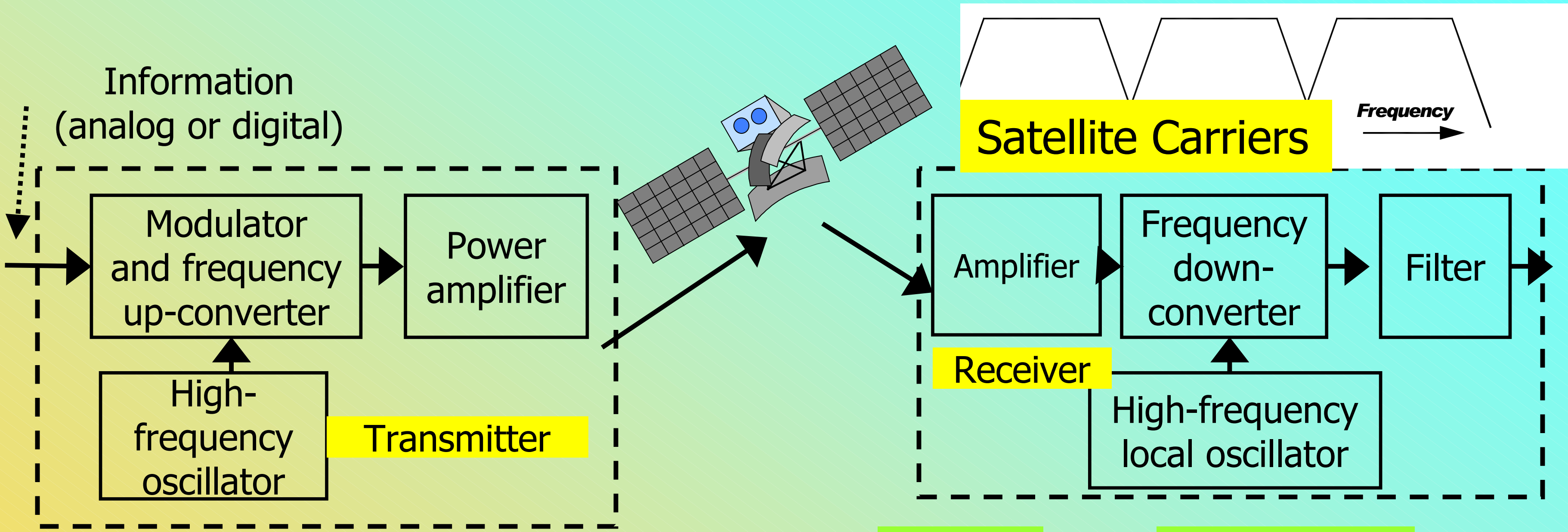
2. Simultaneously Transmitting Multiple Signals



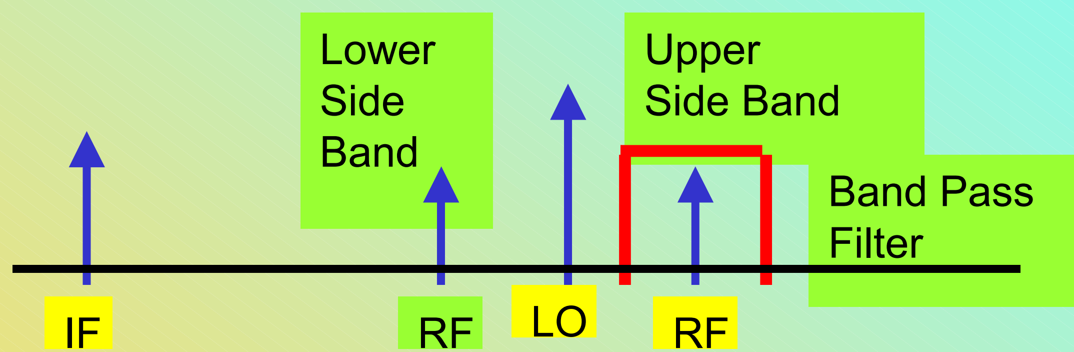
- FDM - Different Frequencies
- TDM - Different Times
- CDM - Different Codes -

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

Frequency Division Multiplexing (FDM)



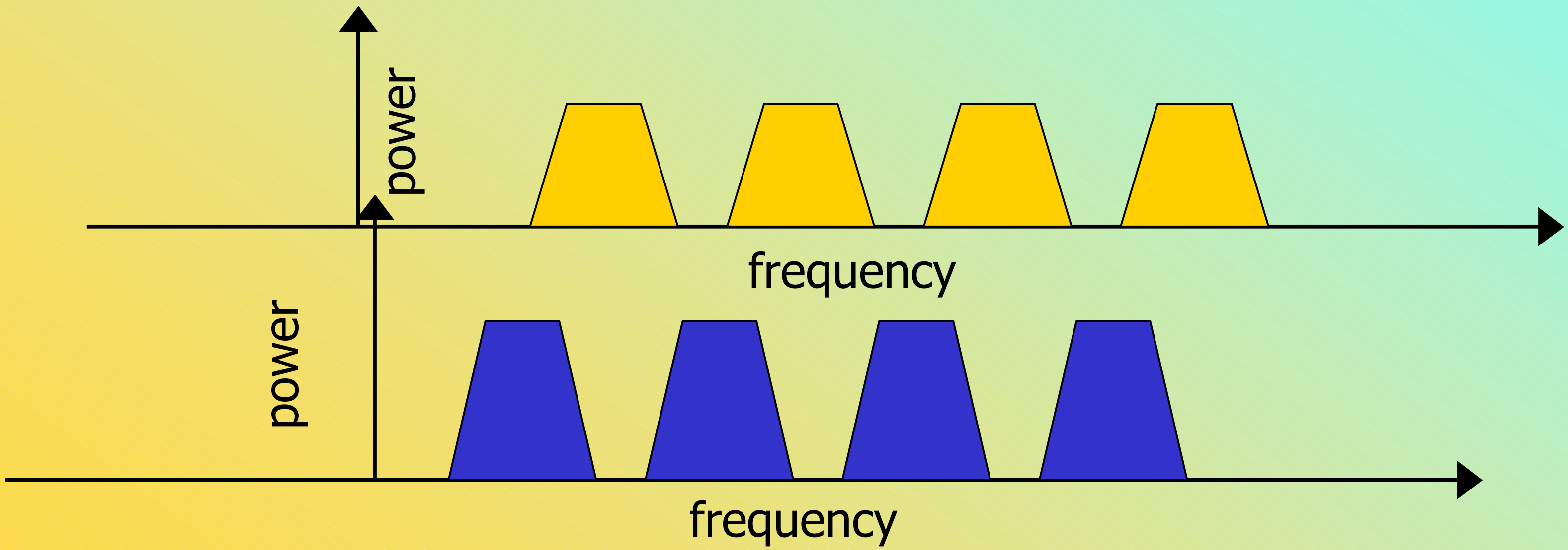
- ❑ Carriers have Assigned Frequencies and Bandwidths



- ❑ Frequency Converters place the carrier in their assigned slot
- ❑ Guard bands are necessary to prevent adjacent carrier interference ~

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 ~



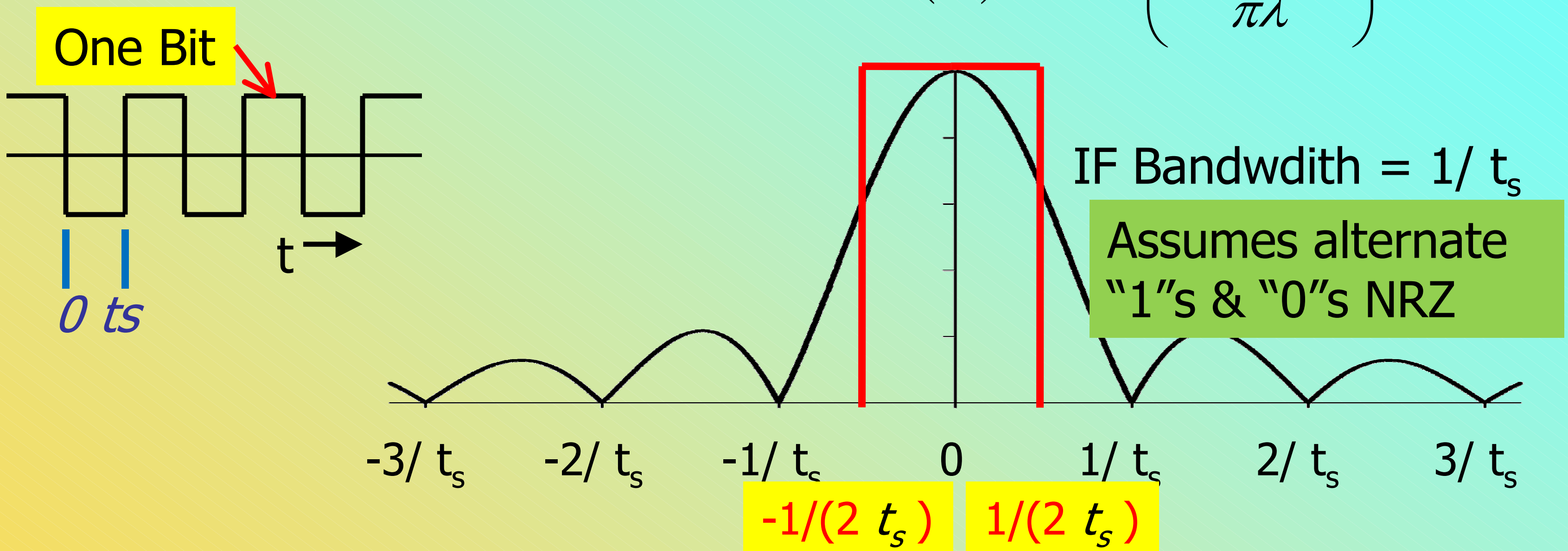
Channel Capacity

- Shannon's Theorem (1950's)
- Relates Bit Rate, Bandwidth, & Signal to Noise
- Bit Rate (Bits/Sec) = BW * $\log_2(1 + SNR)$
  - 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
- 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 >= 2^{12}, or 36 dB; typ. telephone line ~

Bandwidth Considerations

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

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

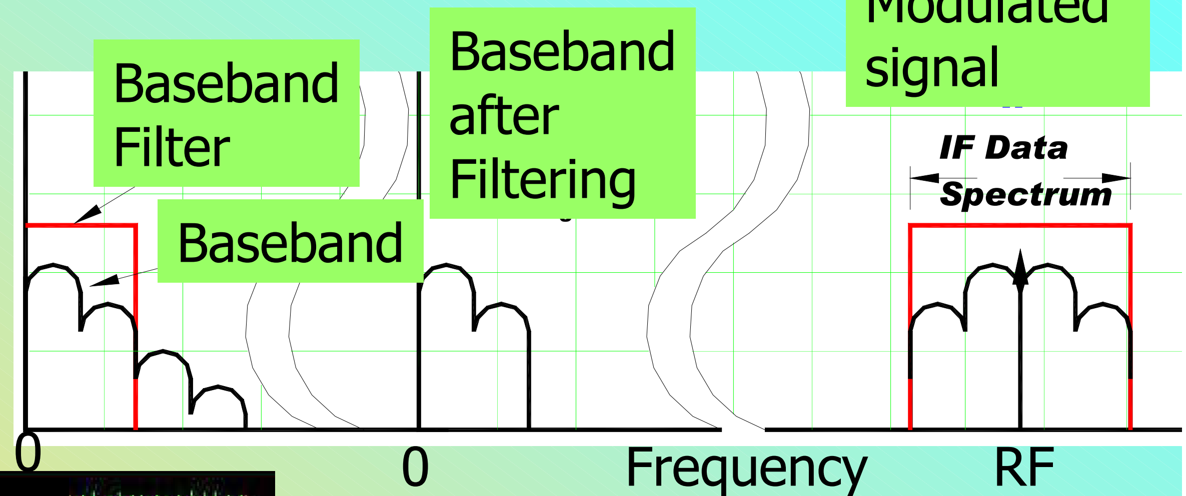


- The baseband time domain signal is filtered to minimize side lobes
  - Minimize adjacent channel interference
- Raised Cosine (Nyquist) filter best trade off of pulse distortion (time domain) and side lobe rejection (frequency domain) ~

Modulation - Preconditioning Data

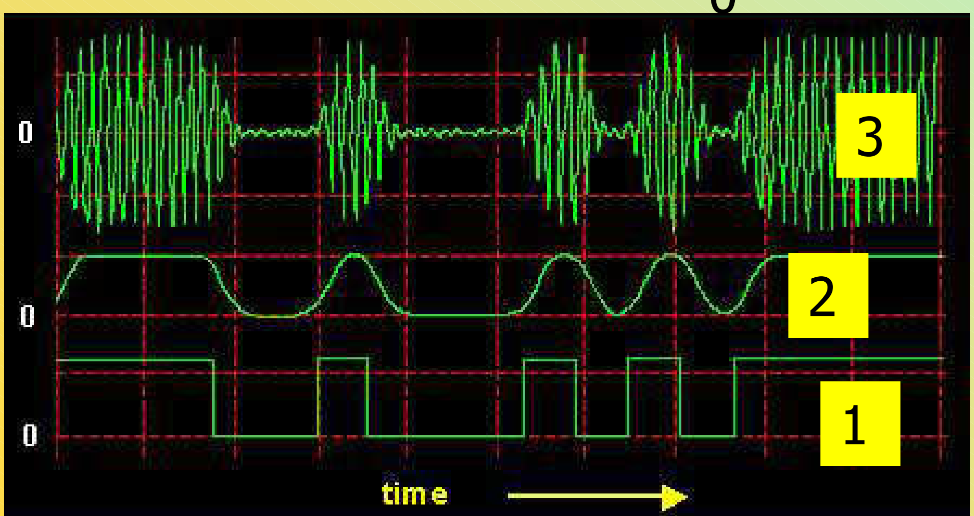
Data → Data Filter Raised Cosine Or Nyquist Filter → Modulator → IF Carrier

Band Limited Modulated signal



Modulator - Converts input data to an IF carrier

- Frequency translator Zero to Fo (MHz)

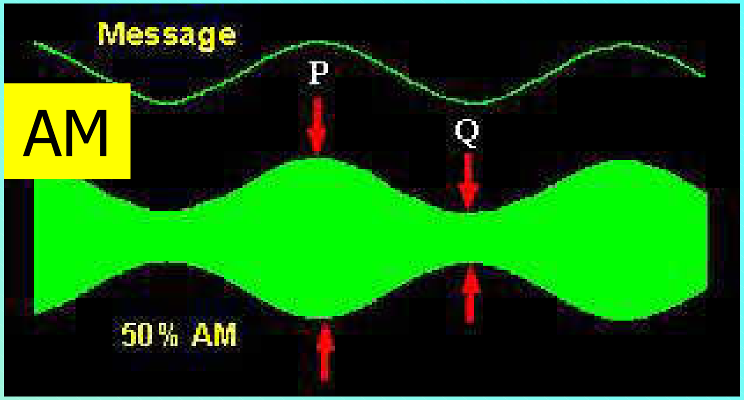


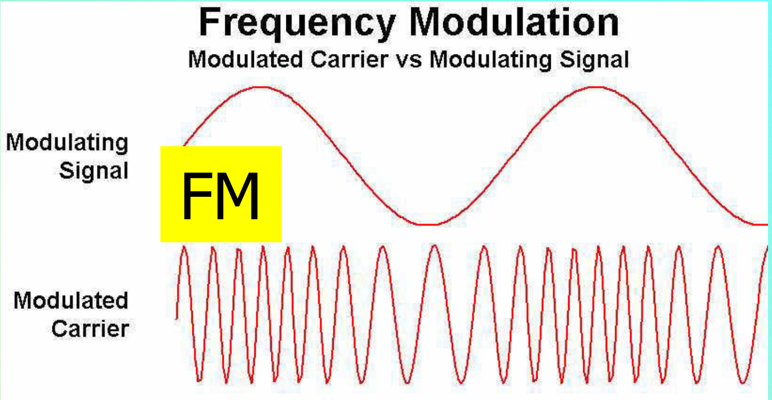
- Can't Filter at RF
  - BW is too narrow
- Pre-Modulation Filtering - Limits RF Bandwidth ~

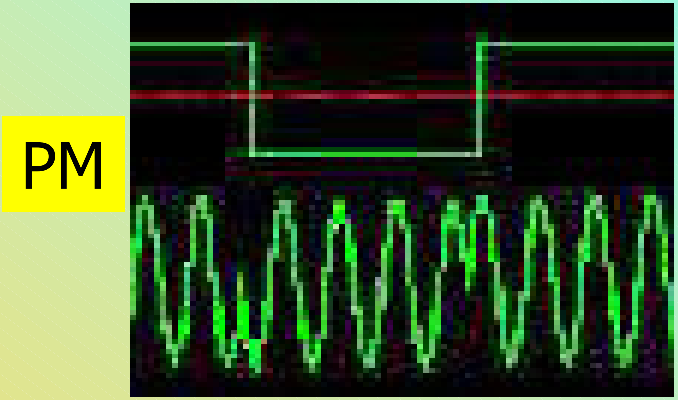
3. Types of Modulation

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

$A_c(t)$ and $\theta(t) \Rightarrow$ QAM (Digital) ~



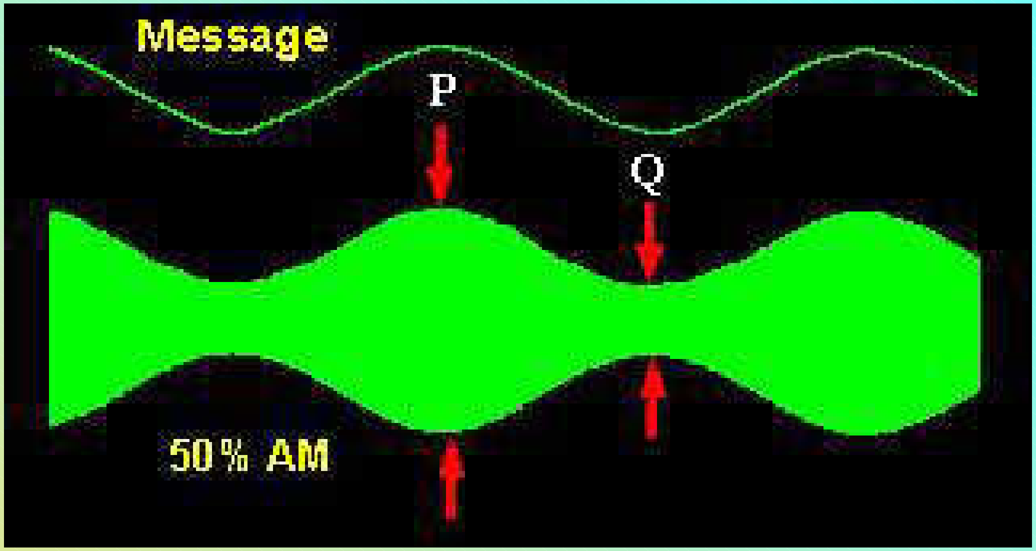




Analog Amplitude Modulation (AM)

- AM Radio
- Analog TV
- Optical Communications

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



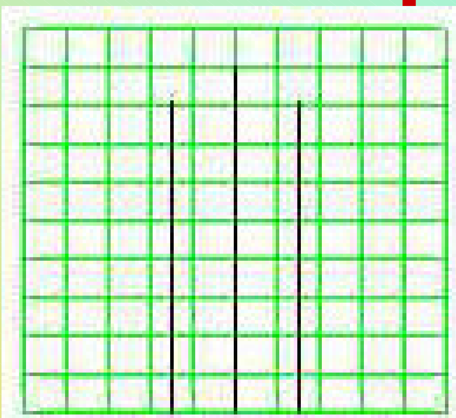
Modulation index: m=0.5

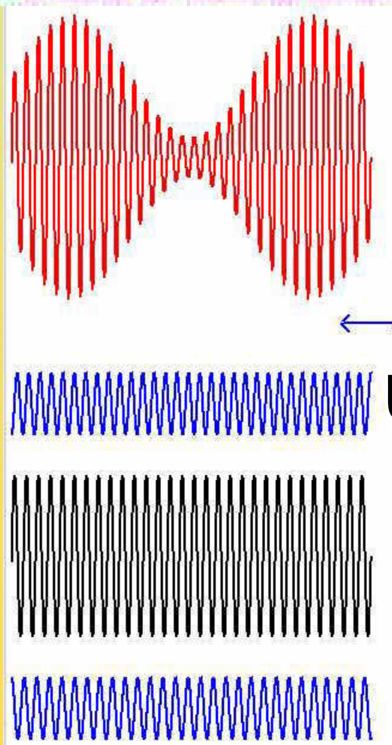
$$m = \frac{P - Q}{P + Q}$$

~

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

AM Frequency Spectrum & Power





Upper

Carrier

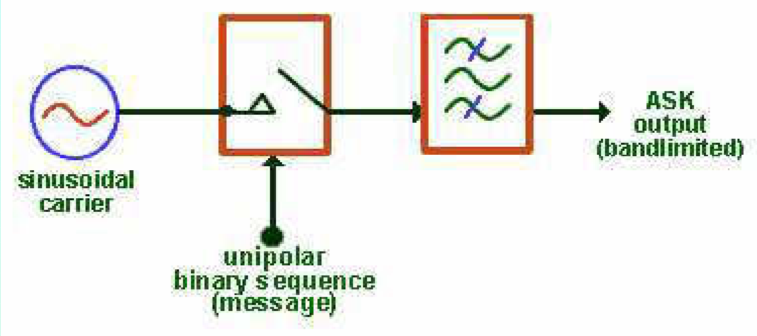
Lower

- Calculating Sideband Levels
- dBc = 20 Log_{10} m/2
  - 75% AM(m=.75)
  - Sidebands down 8.5dB from the carrier

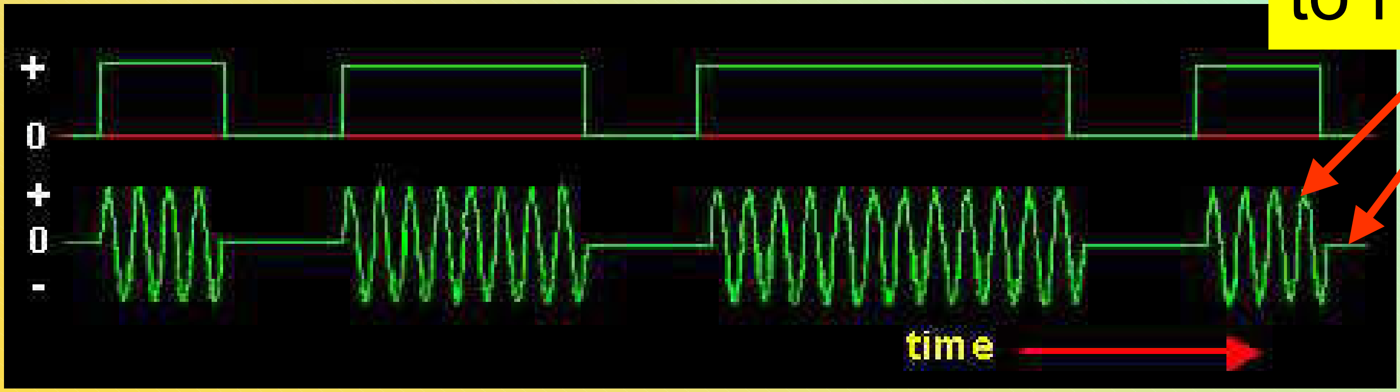
- **Required Power for AM**
- Peak level 2 x no signal (m=1)
- RF power 4 x CW Signal (m=1)
- Linear Power Amps 2 or 3 x less efficient than Non-Linear Amps
- Need more power to operate than AM than FM/PM ~

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

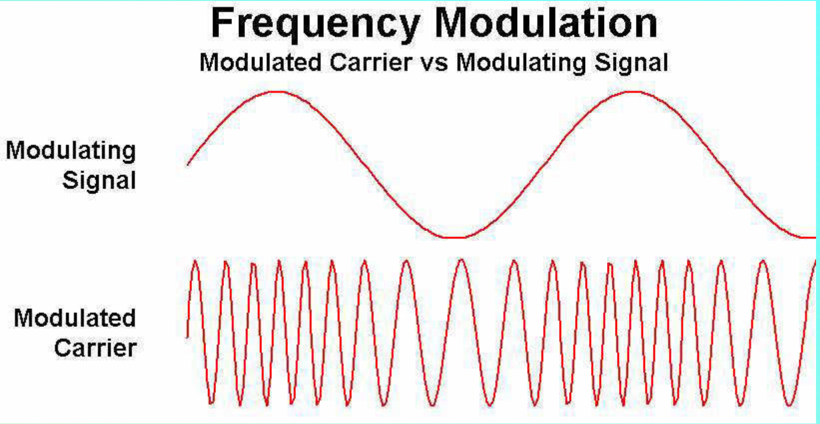
$$Xc(t) := Ac\cdot\cos(\theta c(t))$$

- Xc(t) = modulated signal
- Ac = carrier amplitude
- $\Theta c(t)$ = Instantaneous phase

$$\theta c(t) := 2\cdot\pi\cdot Fc\cdot t + \phi(t)$$

$$\theta c(t) := 2\cdot\pi\cdot Fc\cdot t + 2\cdot\pi\cdot k_f\cdot\int_{-\infty}^{t} m(\tau)\,d\tau$$

- m(t) = Information waveform
- Fc = average carrier frequency
- $\Phi(t)$ = instantaneous phase around the average frequency Fc
- Frequency = d $\Phi(t)$ / dt



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

- For m(t) sinusoidal
- $f_i = F_c + k_f m(t)$
- k_f = Gain Constant
- Frequency Deviation = Δf

$\therefore \Delta f = k_f \max|m(t)|$ ~

FM Modulation Index (β)

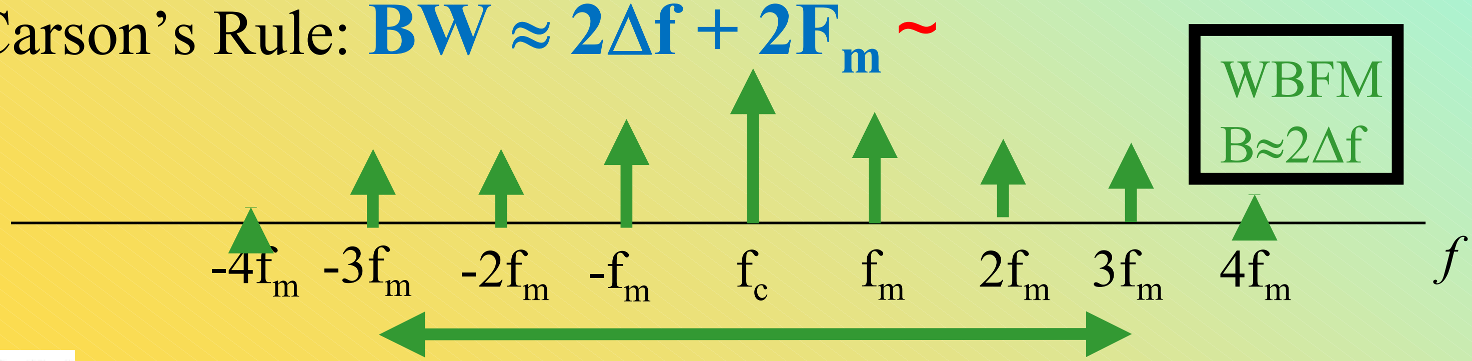
- $\Phi(t)$ = Instantaneous Phase variation around carrier Fc
- for FM signals:

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

- Kf = ΔF = the peak frequency deviation
  - m(τ) = is the normalized peak deviation
- For Sinusoidal modulation:
- m(τ) = cos(2*π*Fm *τ) where Fm is the rate of modulation
- Φ(t) = [2*π*ΔF) / (2*π*Fm] * sin (2*π*Fm *τ)
- Φ(t) = (ΔF / Fm) * sin (2*π*Fm *τ)
- β = ΔF / Fm = modulation index (Radians)
- Φ(t) = β * sin (2*π*Fm *τ)   ~

FM Spectral Analysis

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



Analog Phase Modulation (PM)

$$Xc(t) := Ac \cdot \cos\left(\theta c(t)\right)$$

$$\theta c(t) := 2 \cdot \pi \cdot Fc \cdot t + \phi(t)$$

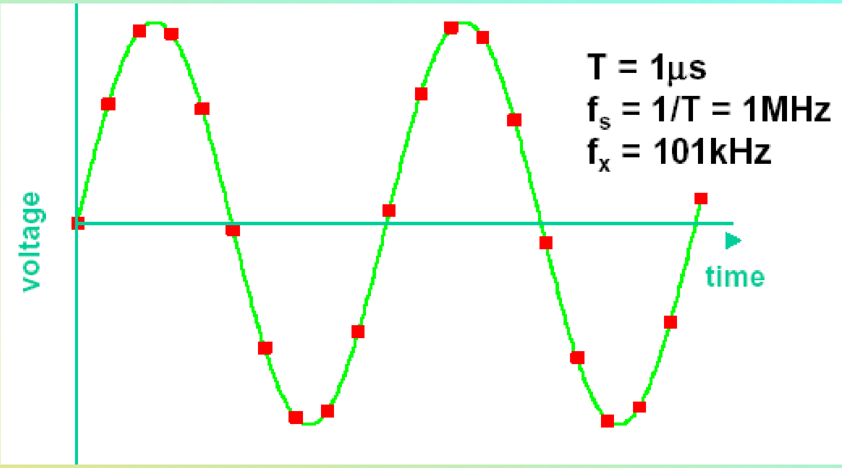
- $\Phi(t)$ = Phase Modulation
- $\Phi(t) = \beta * m(t)$: β = peak phase deviation
  - β = Modulation Index, same as FM
  - m(t) = information normalized to ± unity
- Phase Modulated Carrier is:
  - $Xc(t) = Ac*\cos[2*\pi*Fc*t + \beta * m(t)]$ ~

4. Digital Modulation - Quantizing Data

Sampled Analog Signals

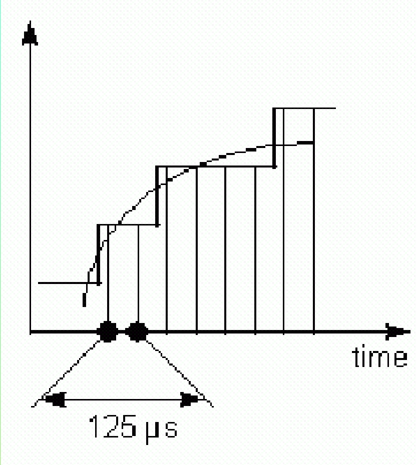
- Continuous signals are sampled at discrete times
- Samples are digitally coded & Transmitted
- Nyquist criteria for completely recovering an analog signal
  - Sampling Rate (Fs) >= 2*Maximum Information Rate (Fm)
    - No. of Samples >= 2 per period
  - Proof is in the analysis of the Fourier Transform

- 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 ~

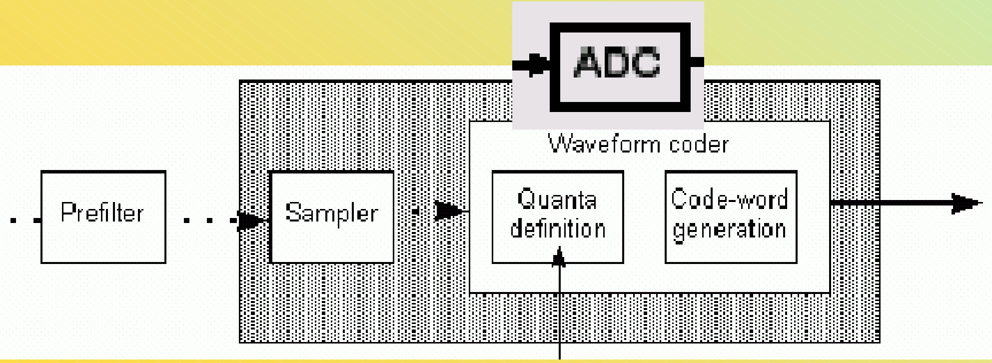


Implementation of Quantization

- 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



N Bits

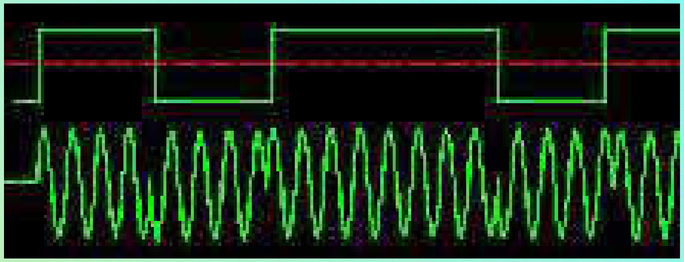


•Fm = 10 MHz
•Sample Time: 50nSec
•M = 1024 Steps
• 10 bit Binary Code
• 5nS/Bit ~

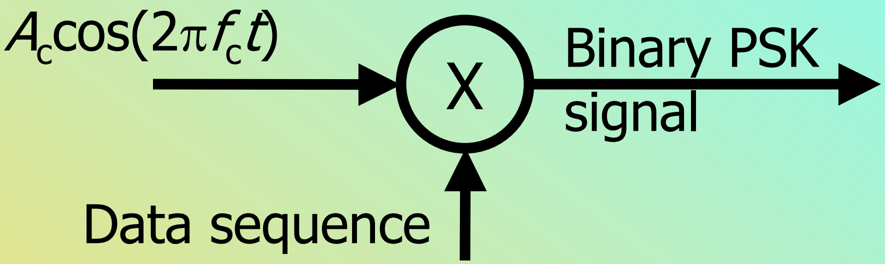
5. Digital Modulation Techniques - CW

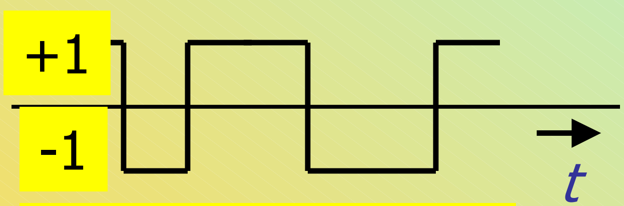
Constant Wave (CW) Modulation / Phase Shift Keying (PSK)

- 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 ~



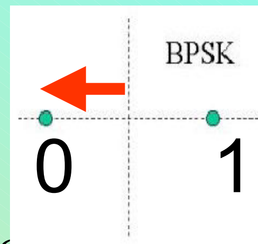
Binary Phase-Shift Keying BPSK (2-QAM)

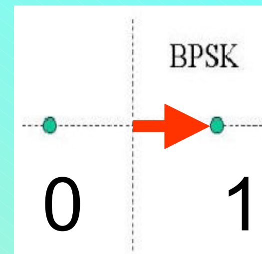




Carrier is multiplied +1(Binary 1) or –1(Binary 0)

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



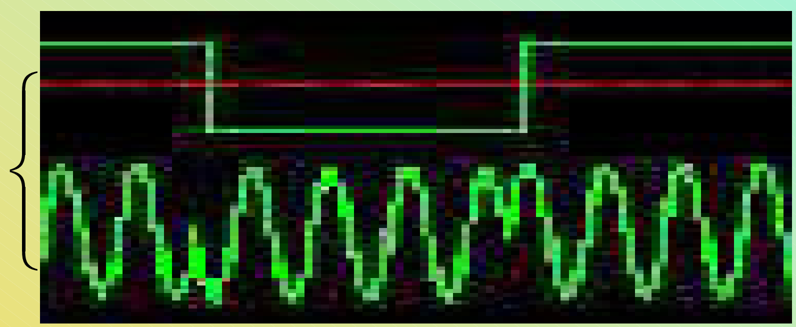


$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ A\cos(2\pi f_c t + \pi) & \text{binary } 0 \end{cases}$$

$$A\cos(2\pi f_c t) \quad \text{binary 1}$$

$$-A\cos(2\pi f_c t) \quad \text{binary 0}$$

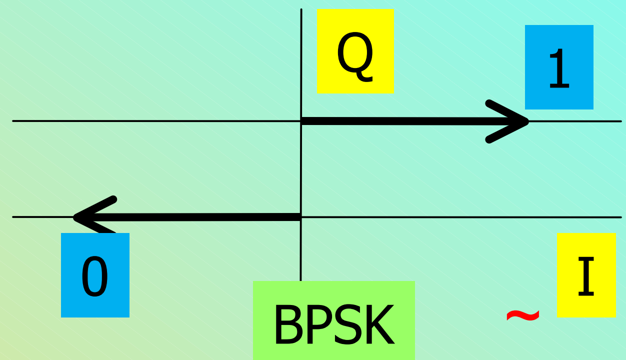
=

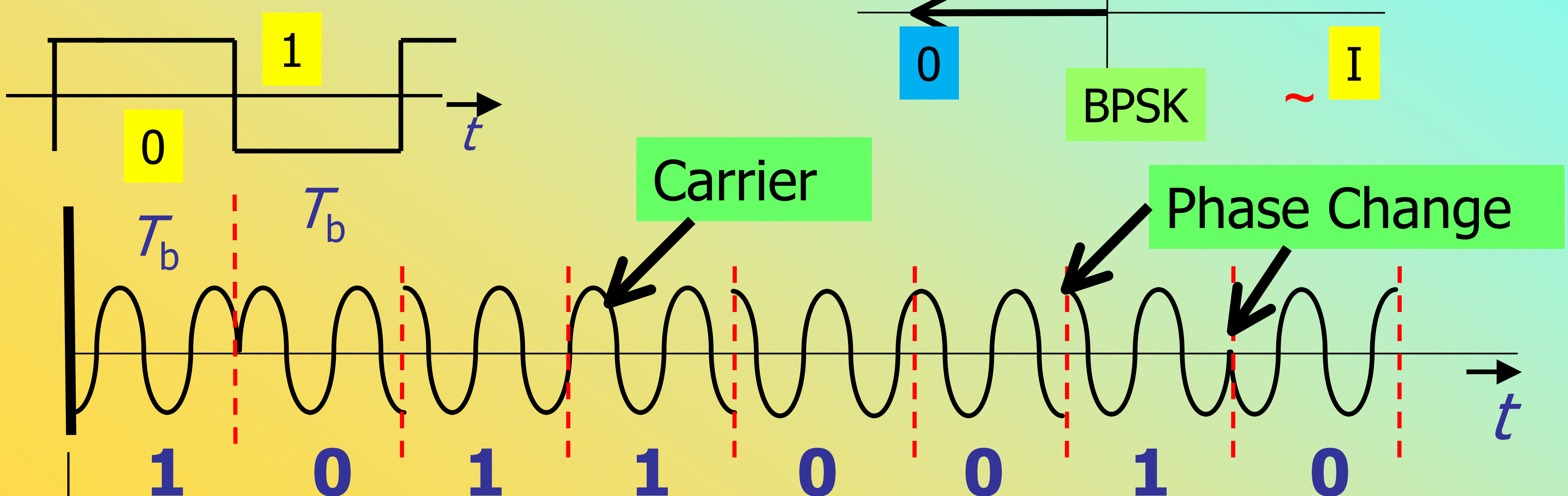


Binary Phase-Shift Keying BPSK (2-QAM)

- 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





Frequency Spectrum BPSK

- Pulsed input transforms to a (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 ½ Raised Cosine (Nyquist) filter in the transmitter for side lobe suppression
- ½ Raised Cosine filter in the Receiver for noise suppression

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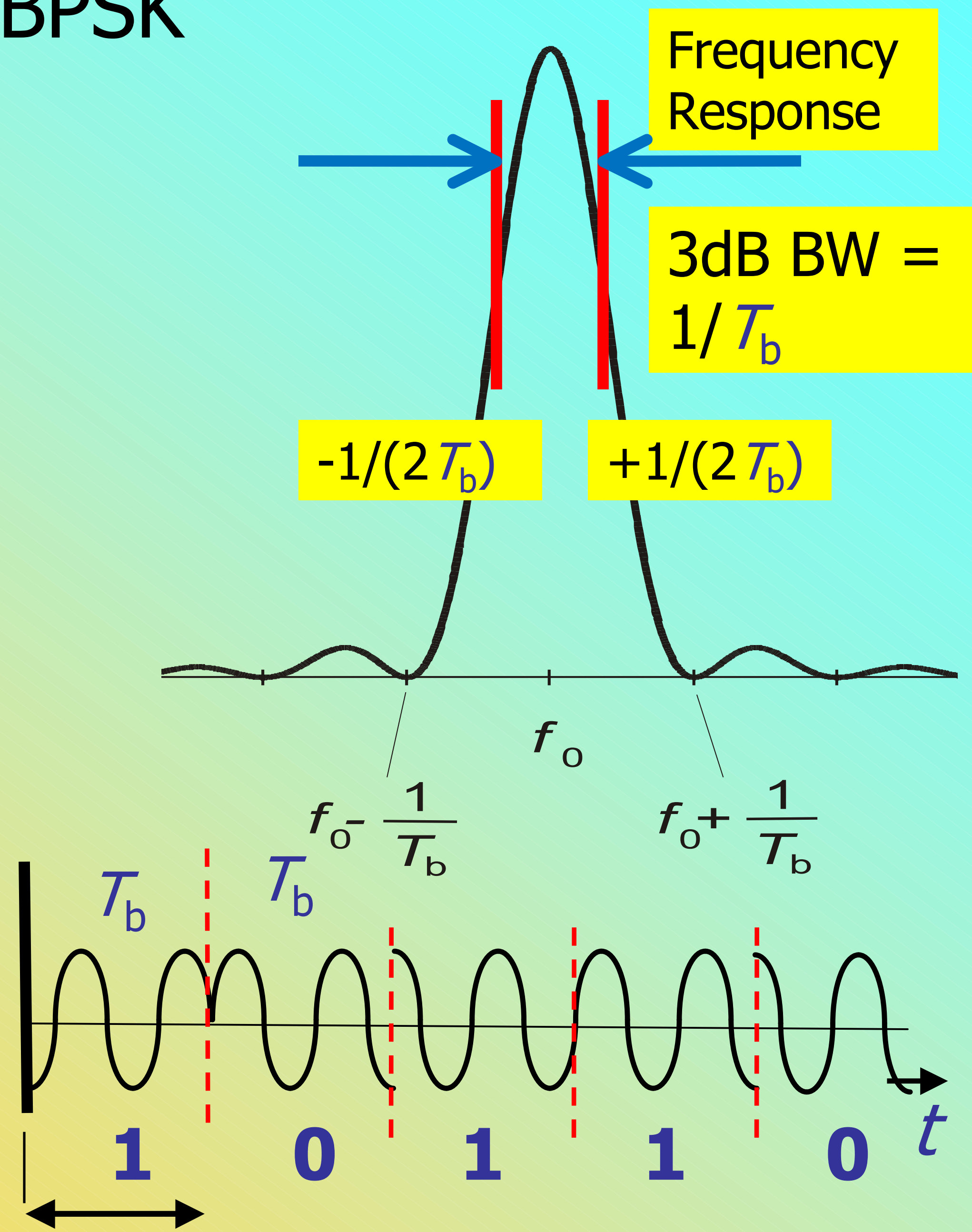
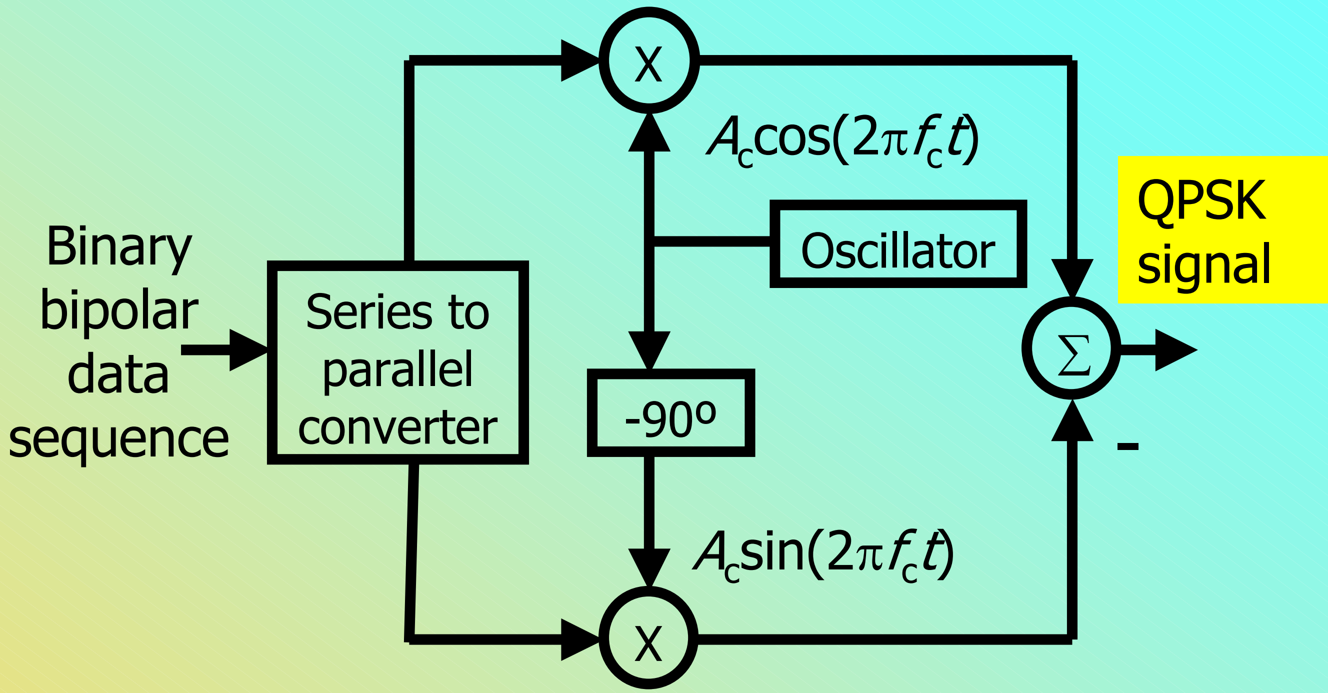
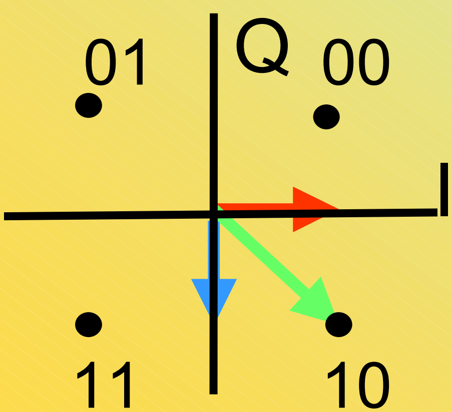


Quadrature Phase-Shift Keying (QPSK)

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

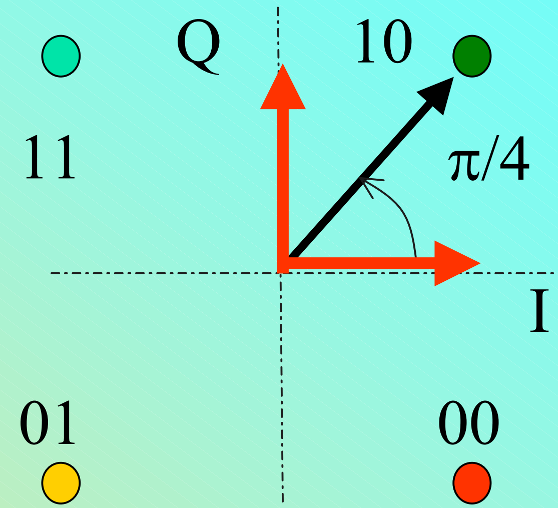




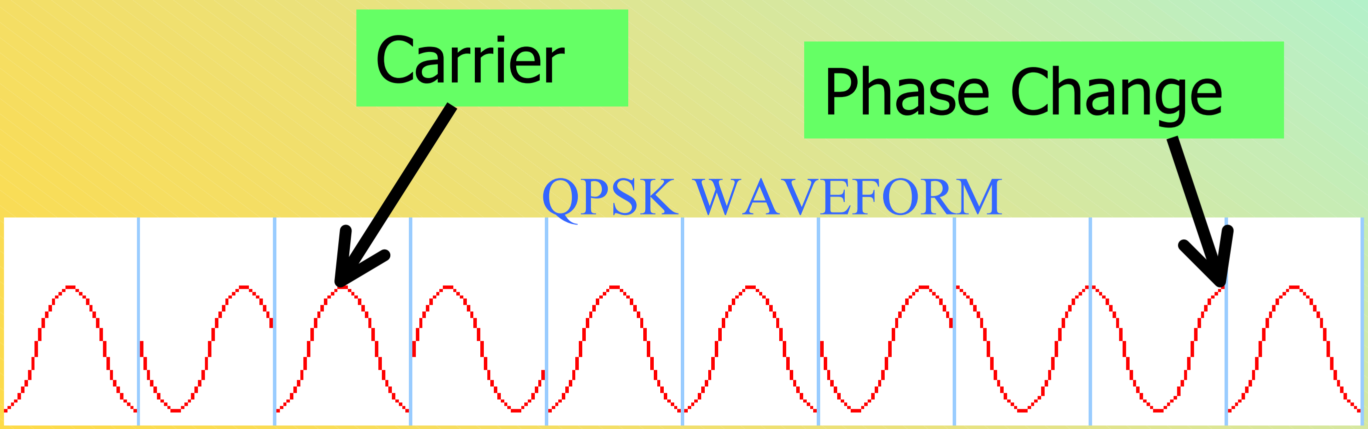
- 2 BPSK modulators
- Carriers are 90º Out of Phase (I & Q)
- Σ 2 vectors 90º out of phase

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.

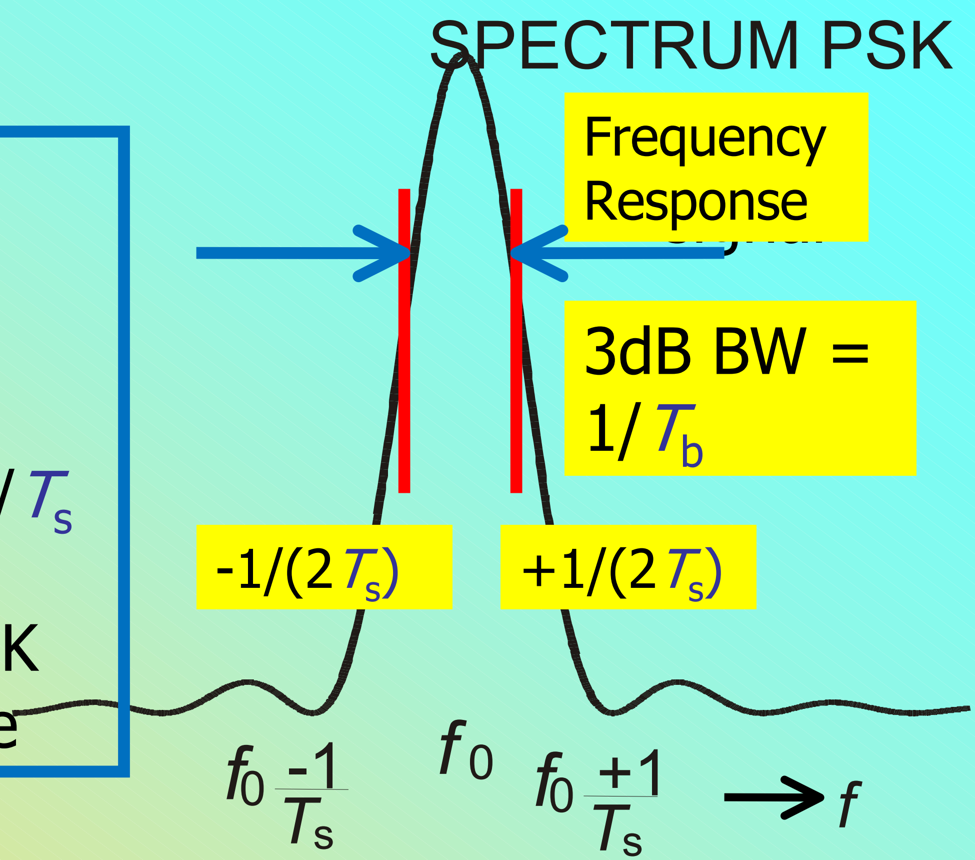


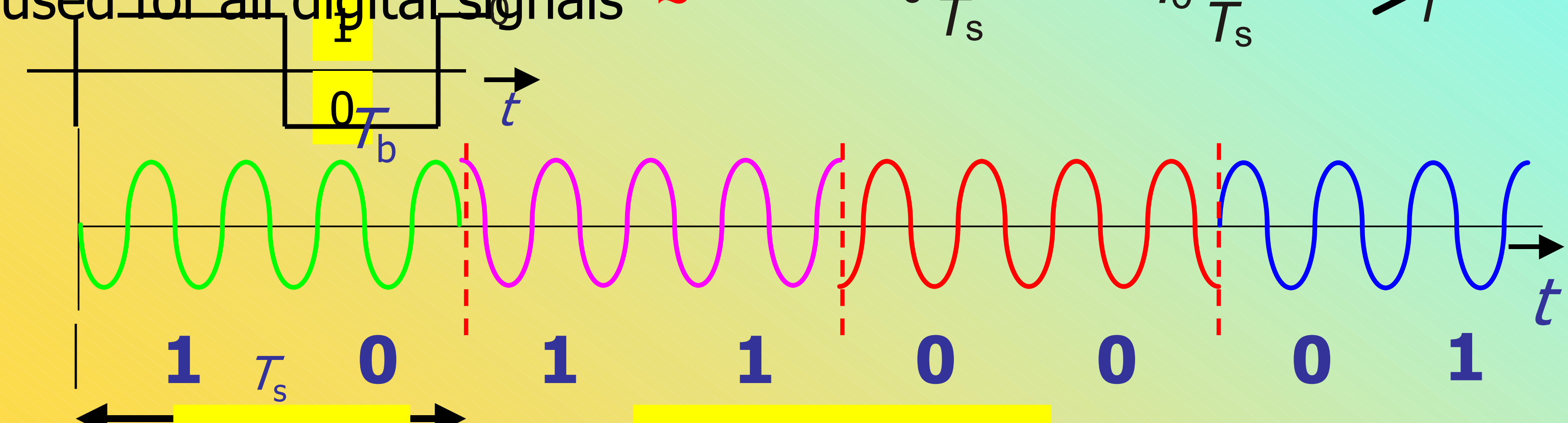
I(+) Q(+) = 10
I(-) Q(+) = 11
I(-) Q(-) = 01
I(+) Q(-) = 00



QPSK Bandwidth

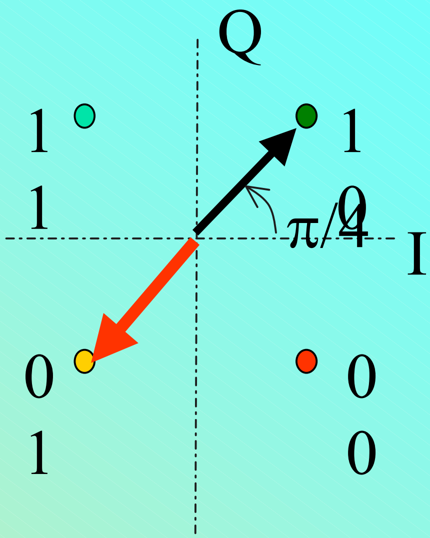
- Bit Rate =1/ T_b
- 2 Bits per Symbol
- Symbol Rate =1/(2 T_b) = 1/ T_s
- IF BW = Symbol Rate = 1/ T_s
- 1st Null is at Symbol Rate
- 2 times as efficient as BPSK
- ½ Raised Cosine filters are used for all digital signals

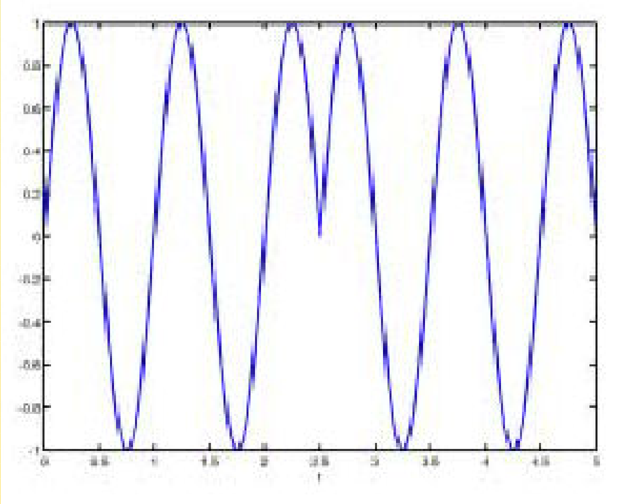




Amplitude Variations of QPSK

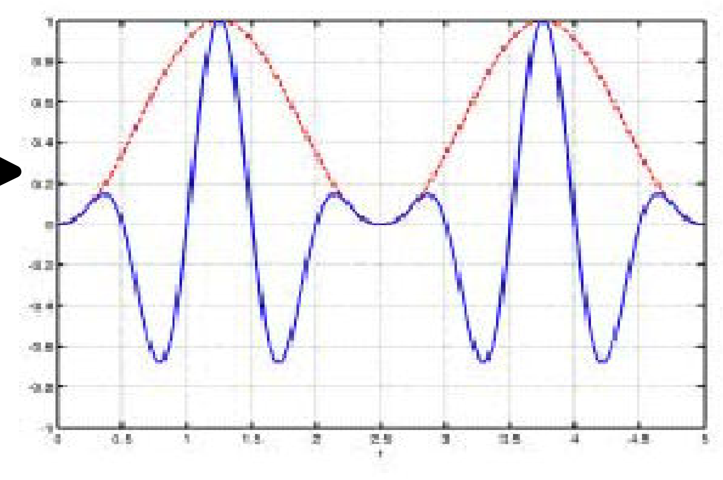
- If I & Q bits change at the same time vector goes through zero
- Power changes abruptly
- Non-constant envelope after filtering
- Peak to Average Ratio increases with zero crossings
- Causes signal distortions ~





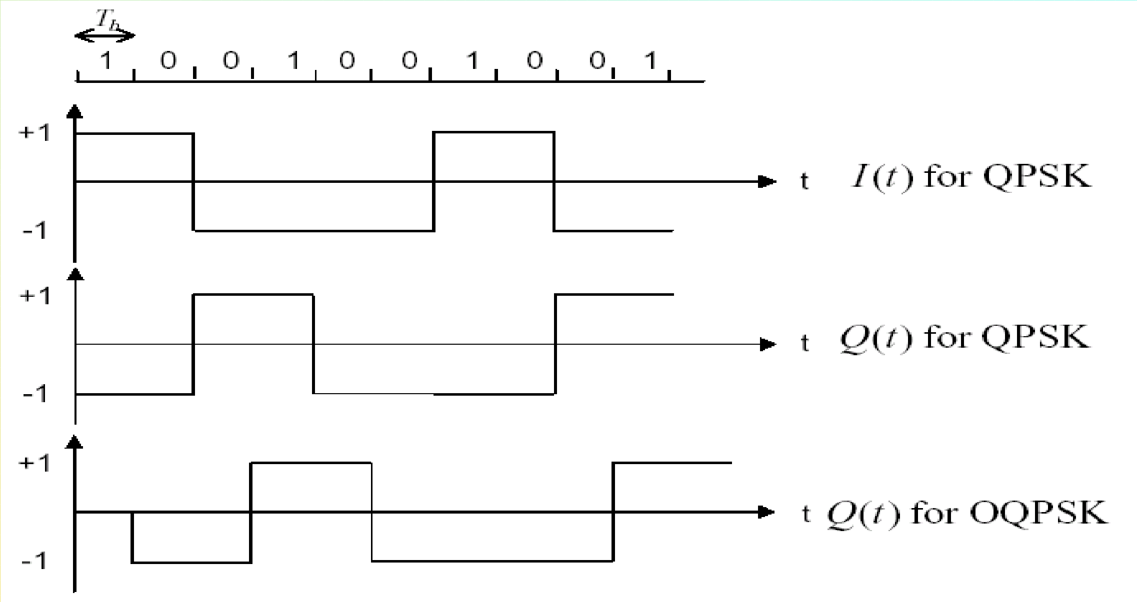
QPSK - ideal

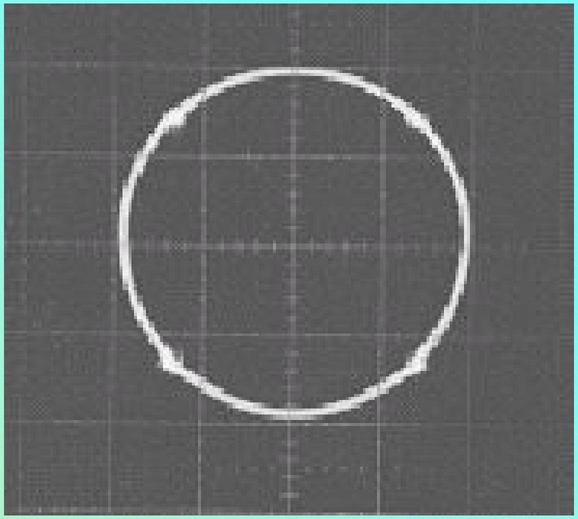
Many Zero crossings →



QPSK - filtered

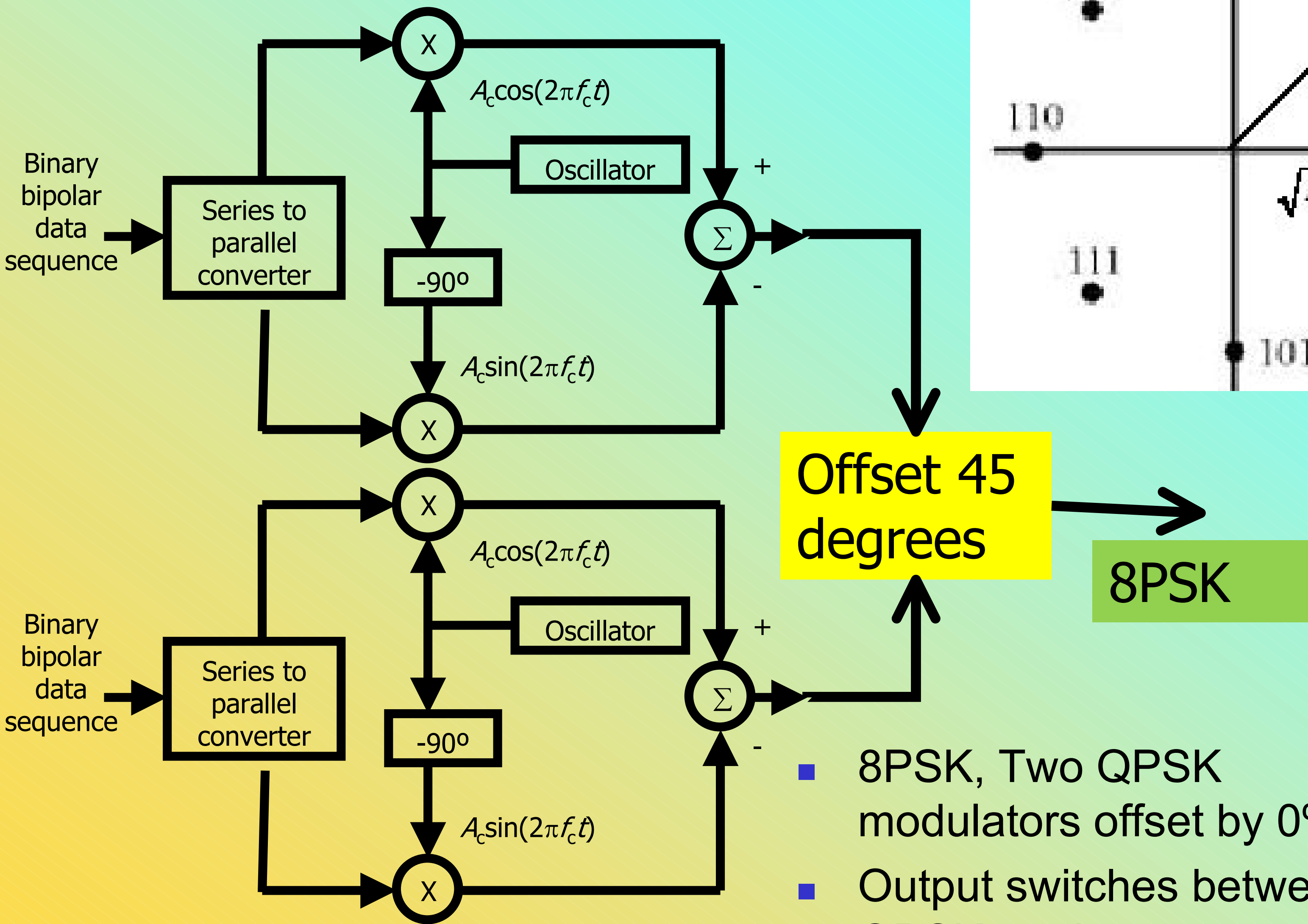
Offset QPSK (OQPSK)

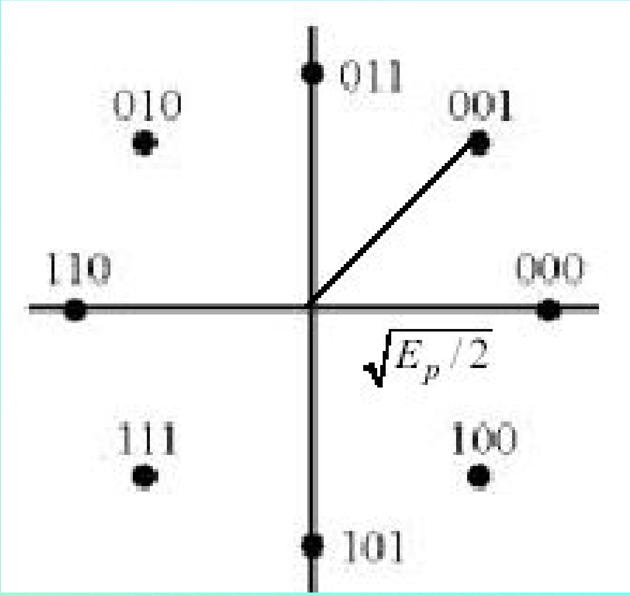




- Offset the I & Q bits so they don't change at the same time
- Instead of signals going through zero they go around the circle
- The receiver corrects the offset to recover the signal
- OQPSK does not have a distinct null in the frequency domain ~

8 PSK Modulation

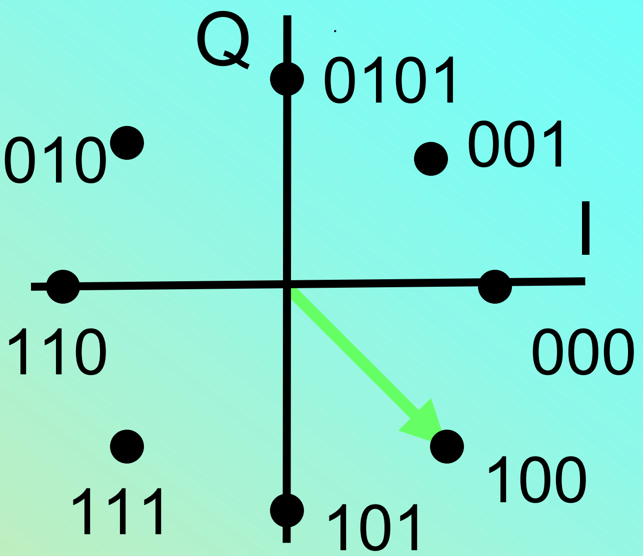




- 8PSK, Two QPSK modulators offset by 0º or 45º
- Output switches between QPSK modulators ~

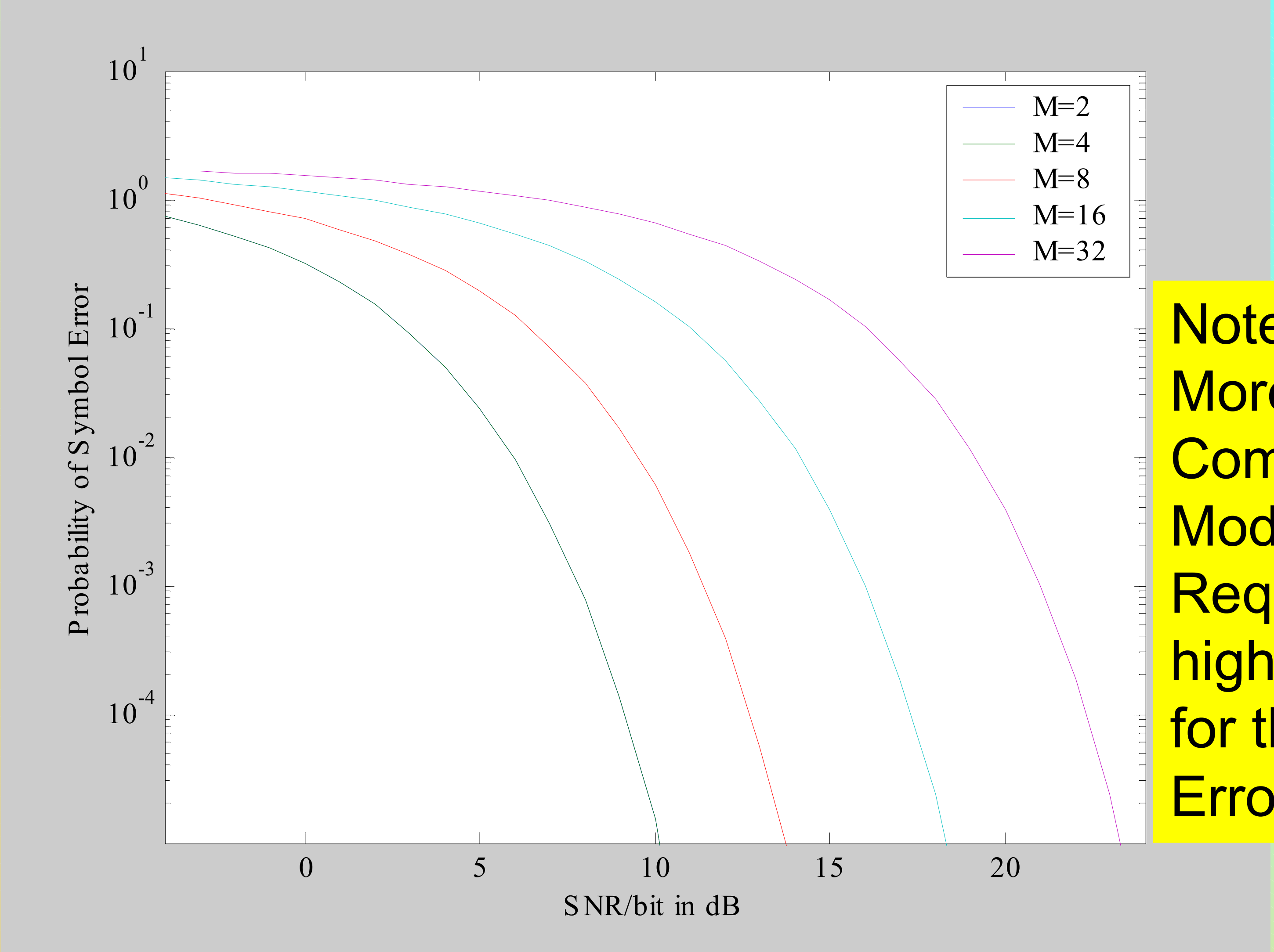
8PSK Vector

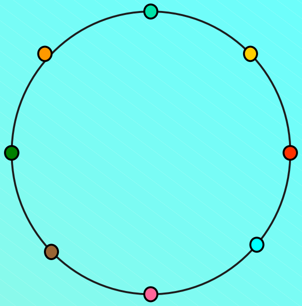
- Used for High Data Rate Constant Amplitude Modulation
- 3 Bits/Symbol
  - Bit Rate = 3 x Symbol Rate
- Required Bandwidth is based on symbol rate (Bit Rate/3)
- Higher values than 8 are rarely used
  - Phase Increment is too small
  - Phase Noise is the limiting factor ~



8PSK

Symbol Error in M-ary PSK Systems



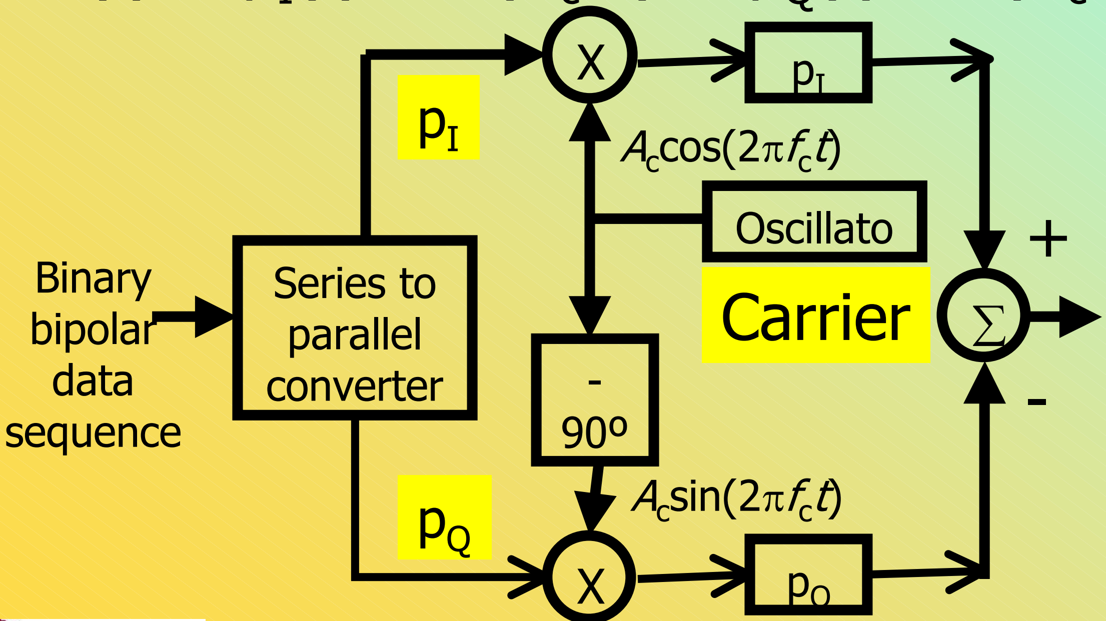


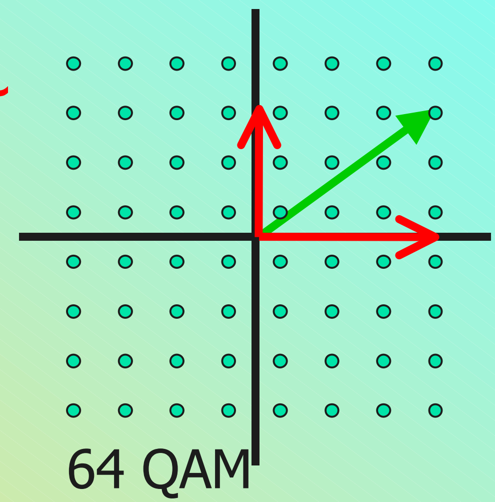
Note:
More Complex Modulations Require higher S/N for the same Error ~

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 (0º / 180 º & 90º / 270 º)
- $p_I(t)$ & $p_Q(t)$ = Discrete (Binary) Amplitude Steps
- Sum = Vector with discrete Amplitude and Phase positions

$$S(t) = p_I(t)*\cos(\omega_c*t) + p_Q(t)*\sin(\omega_c*t) \sim$$



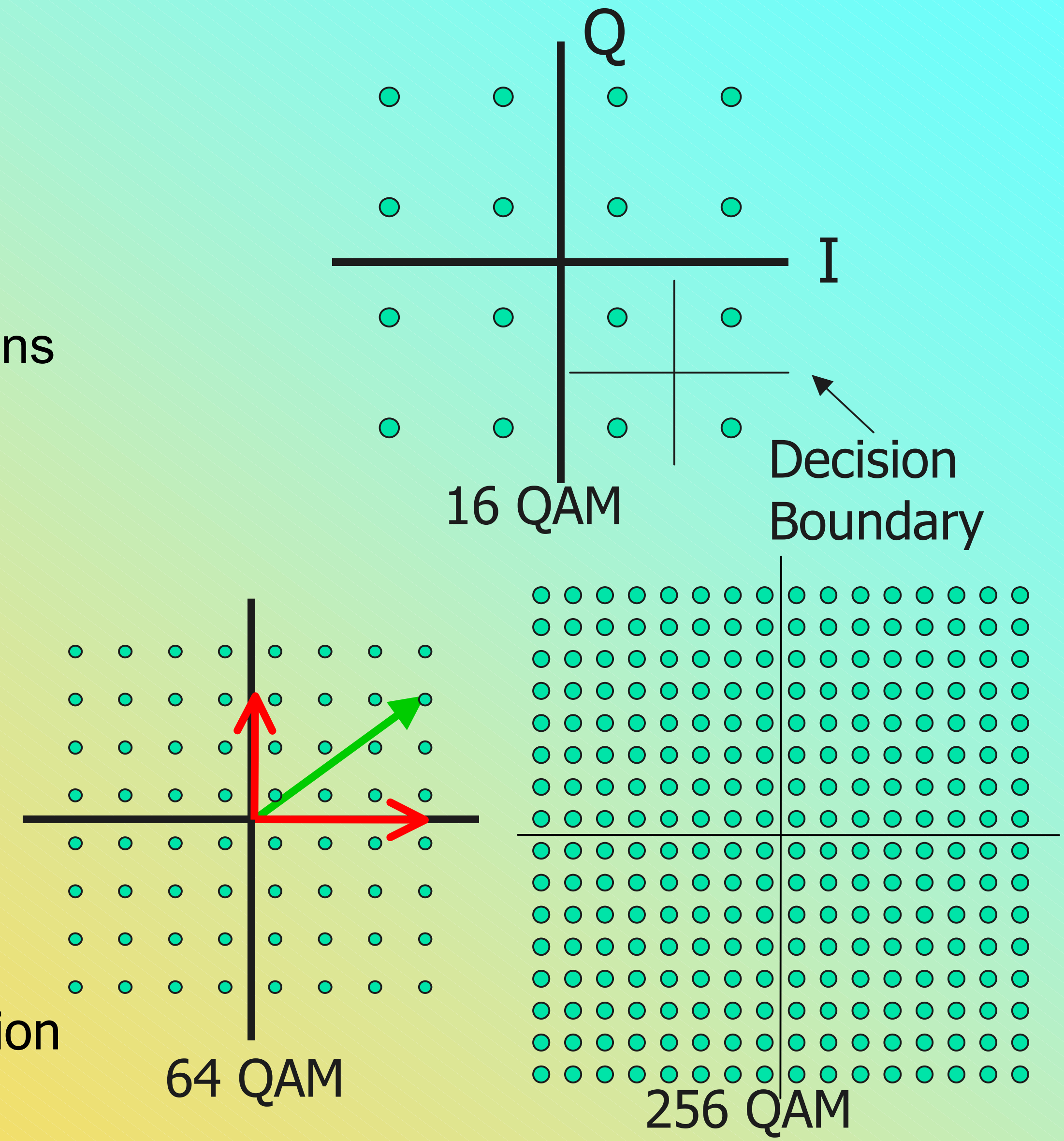


Carrier Vector is the summation of the I & Q vectors

Typical Constellations

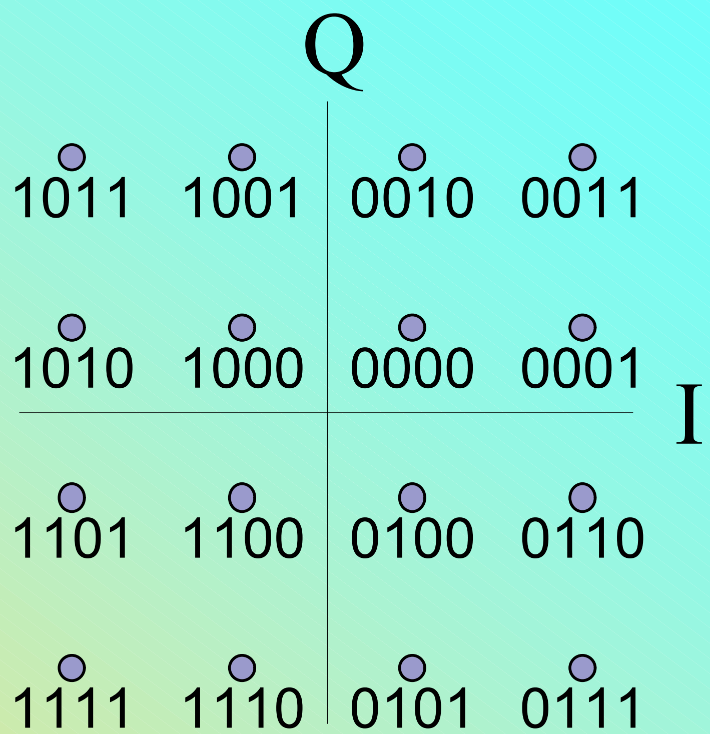
- Constellation Diagrams
  - Contains all possible vector locations
- Points defined by the Quantized I & Q vector amplitudes
- Primary QAM Configurations
  - 16-QAM
  - 64 QAM
  - 256 QAM
- Less Efficient
  - Requires Linear Power Amplifiers
- Peak compression causes distortion
- Receiver requires complex Phase & Amplitude Detection

~



Constellation Characteristics: 16QAM Example

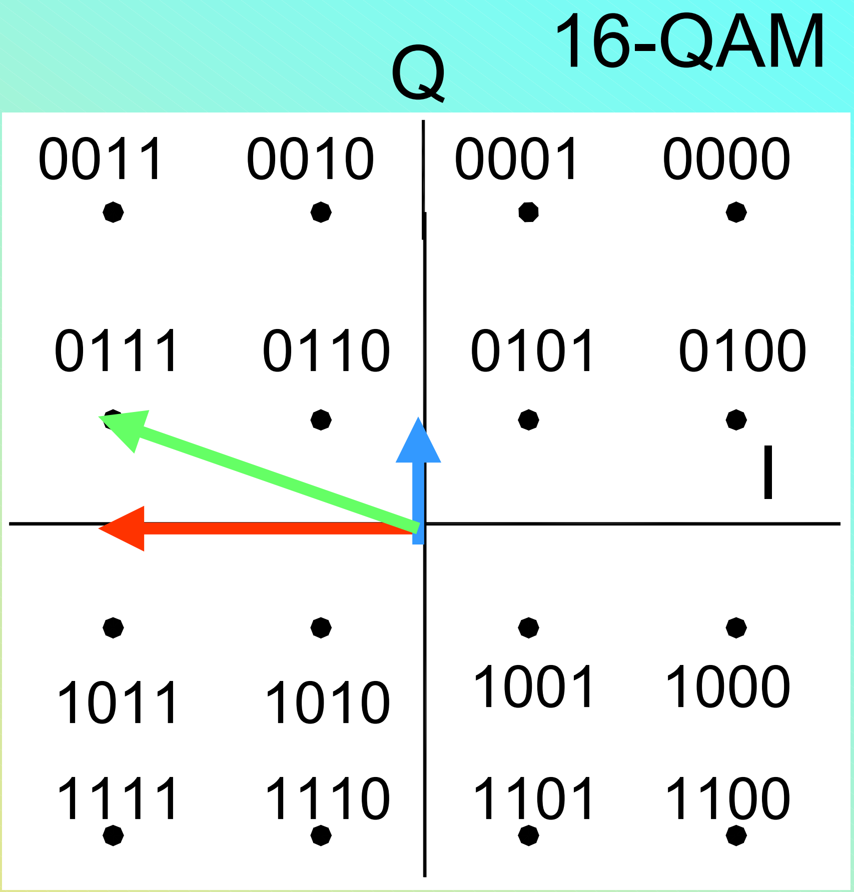
- 16QAM modulation is a constellation of discrete Phase & Amplitude positions
- Each position (Symbol) represents 4 bits of data
- 4:1 efficiency of transmission over BPSK
- Down side: Less allowable vector distortion for correct data reception ~



16 QAM

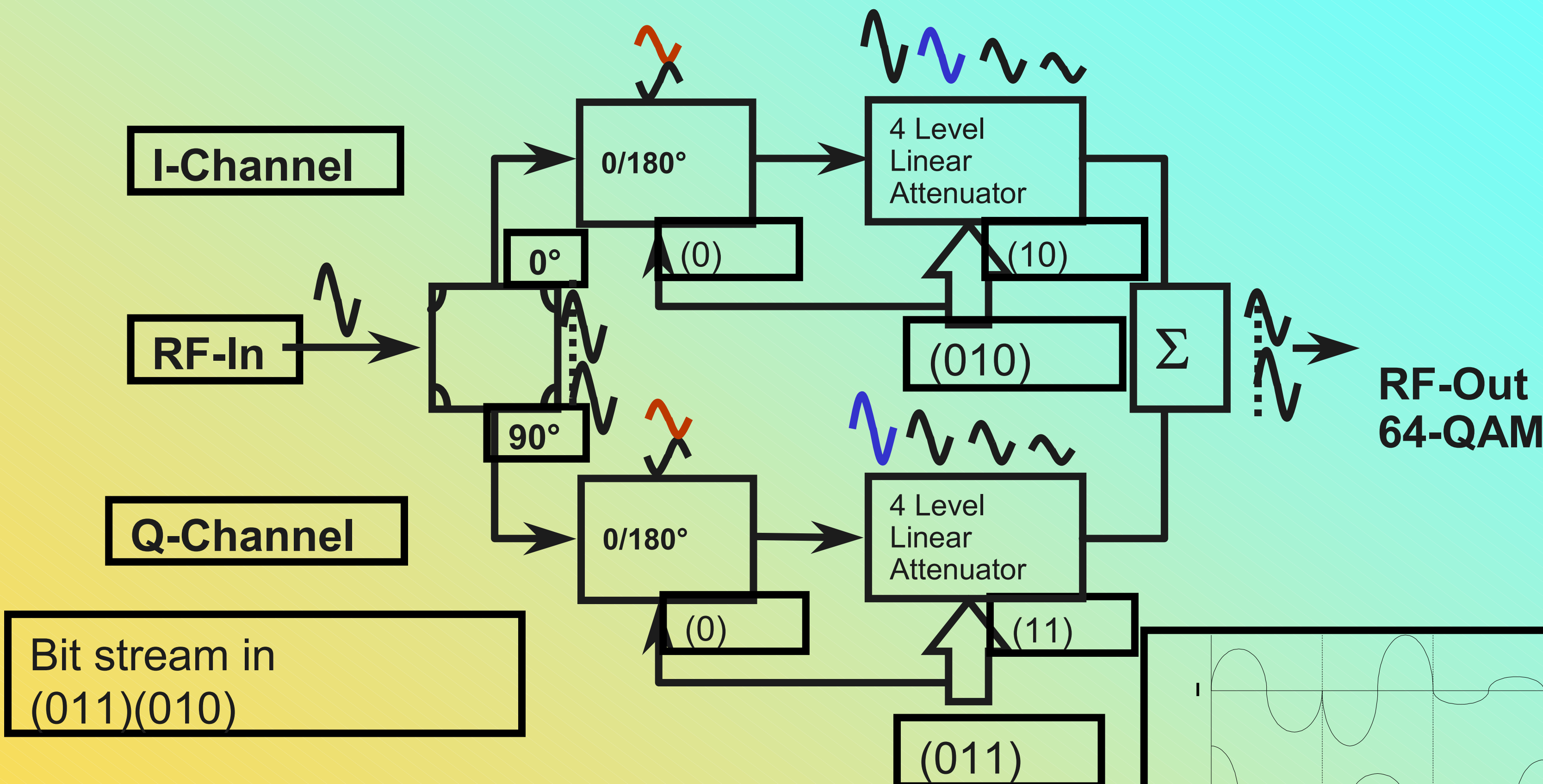
16-QAM Modulation (4 Bits / Symbol)

- 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) ~

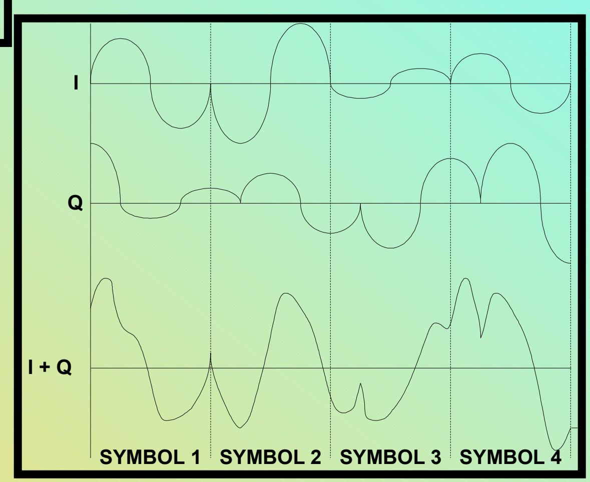


Transmitted 16-QAM Data, 4 bits/symbol

64-Quadrature Amplitude Modulation



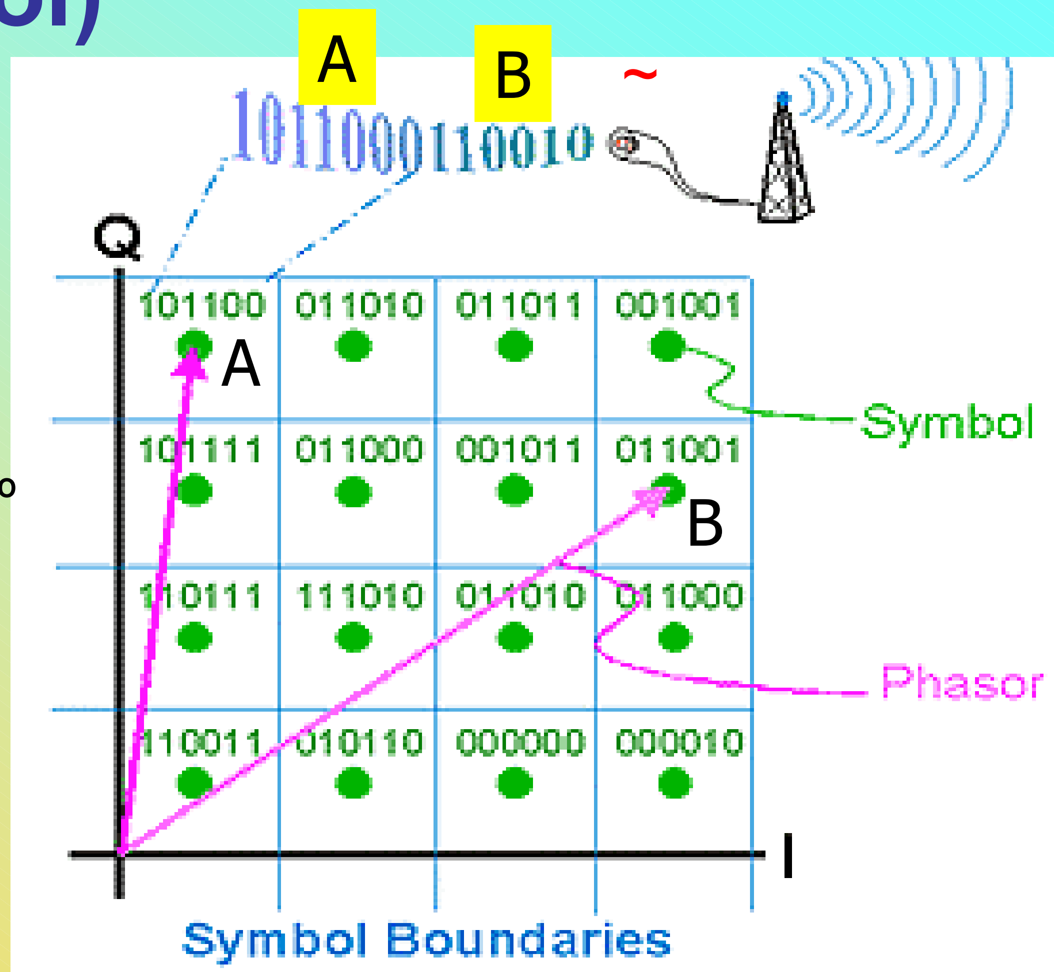
- ❑6 Bits per Symbol
- ❑QPSK with 4 amplitude levels
- ❑Typical Waveform in the time domain



MITEQ

64-QAM Modulation (6 Bits / Symbol)

- 2 Vectors (I & Q)
- Phase States 4 = 2^N: (N=2) (BPSK N=1)
  - 0° / 180° & 90° / 270°
- Amplitude Levels = 16= 2^A (A = 4), (A=0 for Constant Amplitude)
- M = No. of States
  - $M = 2^N * 2^A$
  - $M = 2^2 * 2^4 = 64$

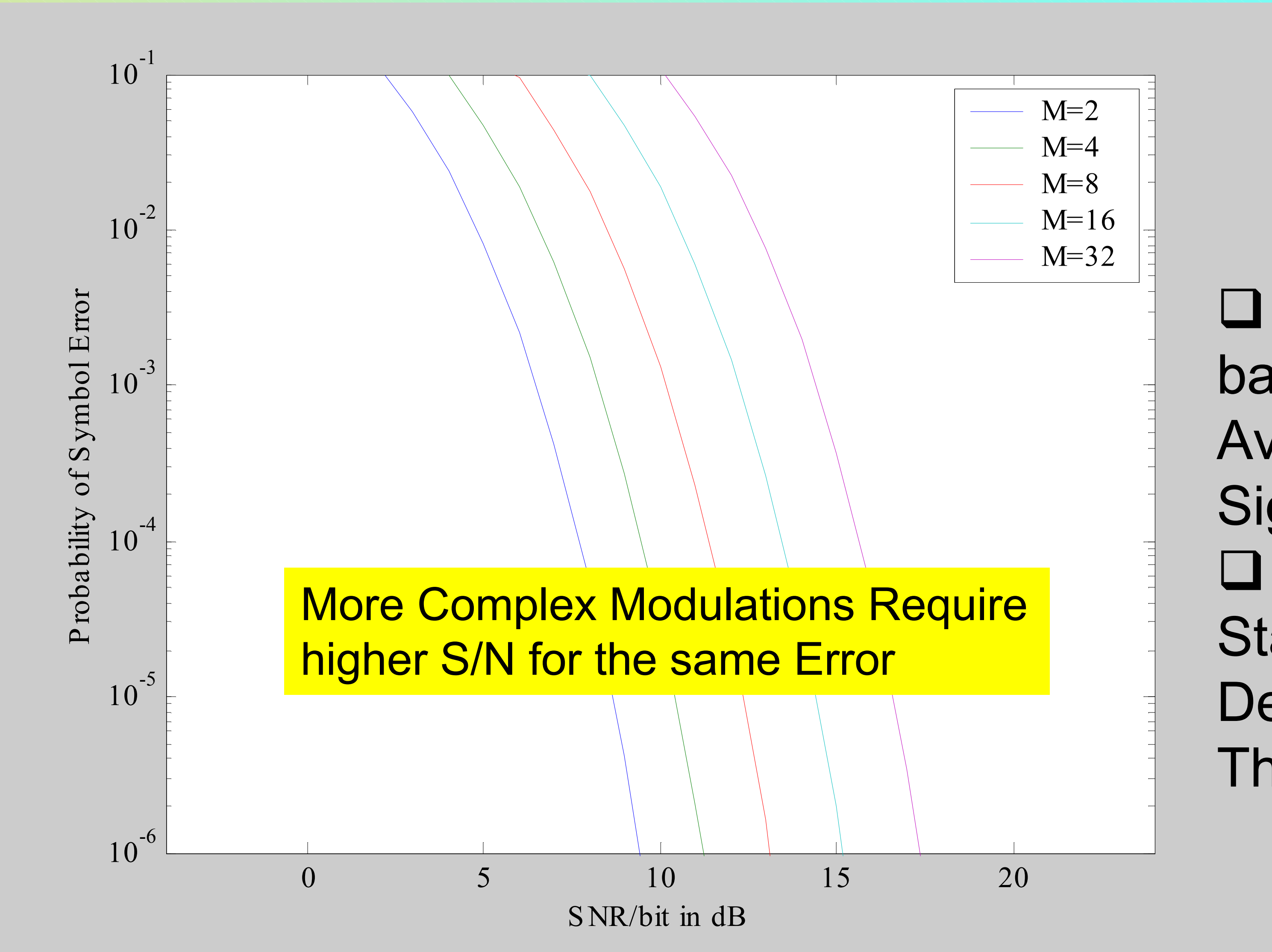


1/4 64 QAM Constellation

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)



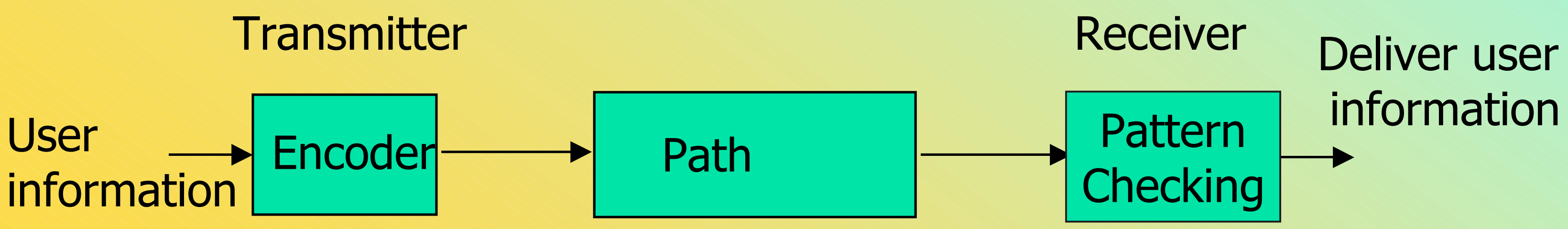
- ❑ Bit Errors based on Average Signal Power
- ❑ Number of Standard Deviations to Threshold ~

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 ~

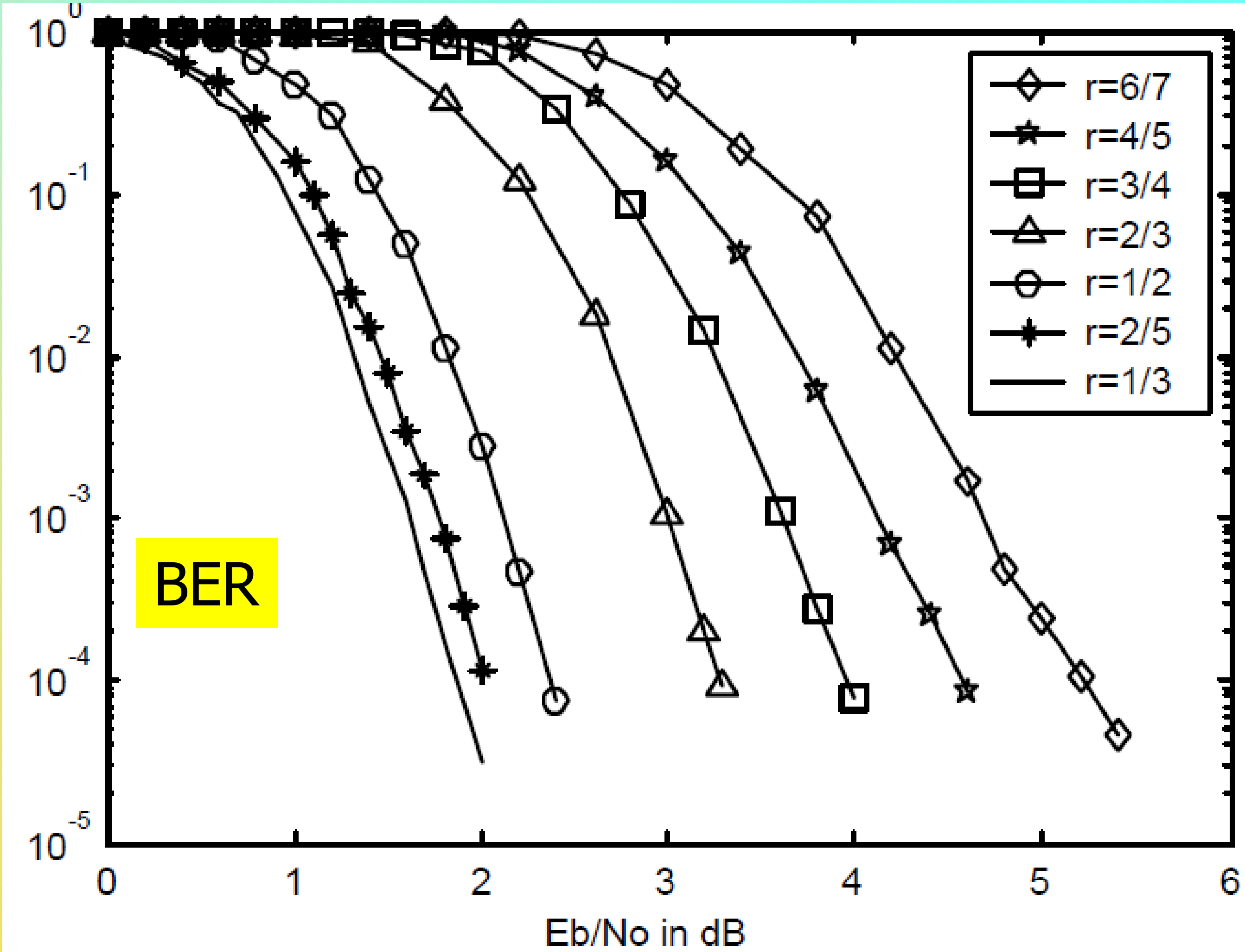


Types of Error-Correcting Codes

- 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 ~

MITEQ

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 → 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 ➔ 4 bits
  - 1 parity word ➔ 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

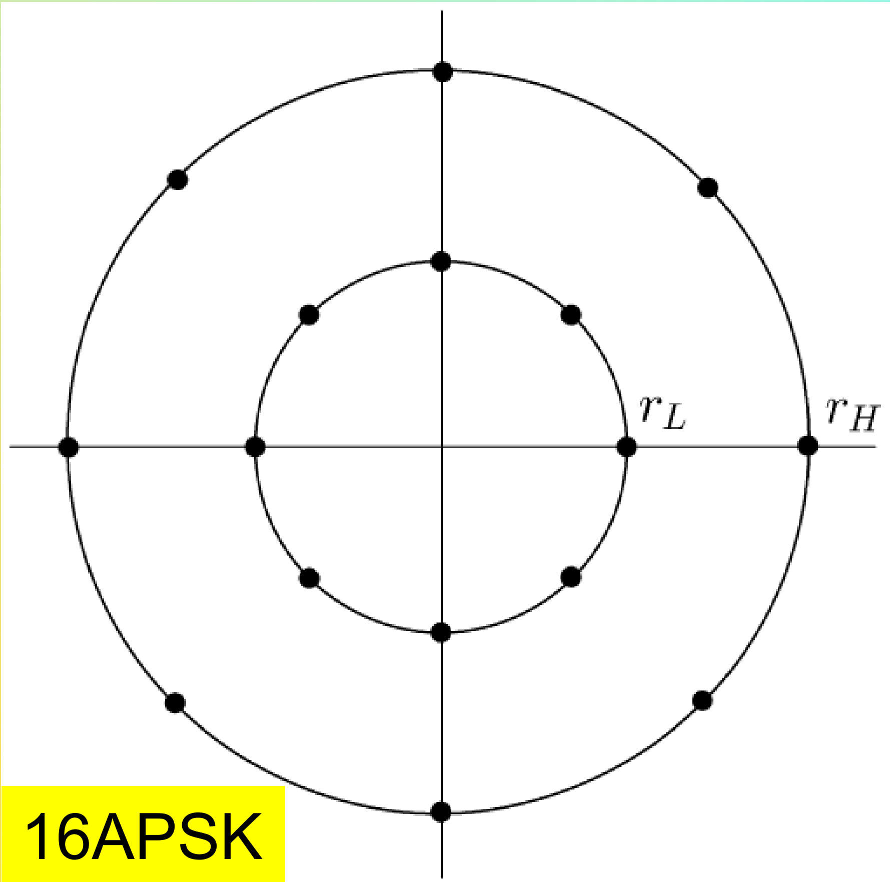
1	1	0	0	1	1	1	1
1	0	1	1	1	0	1	1
0	1	1	1	0	0	1	0
0	1	0	1	0	0	1	1
0	1	0	1	0	1	0	1

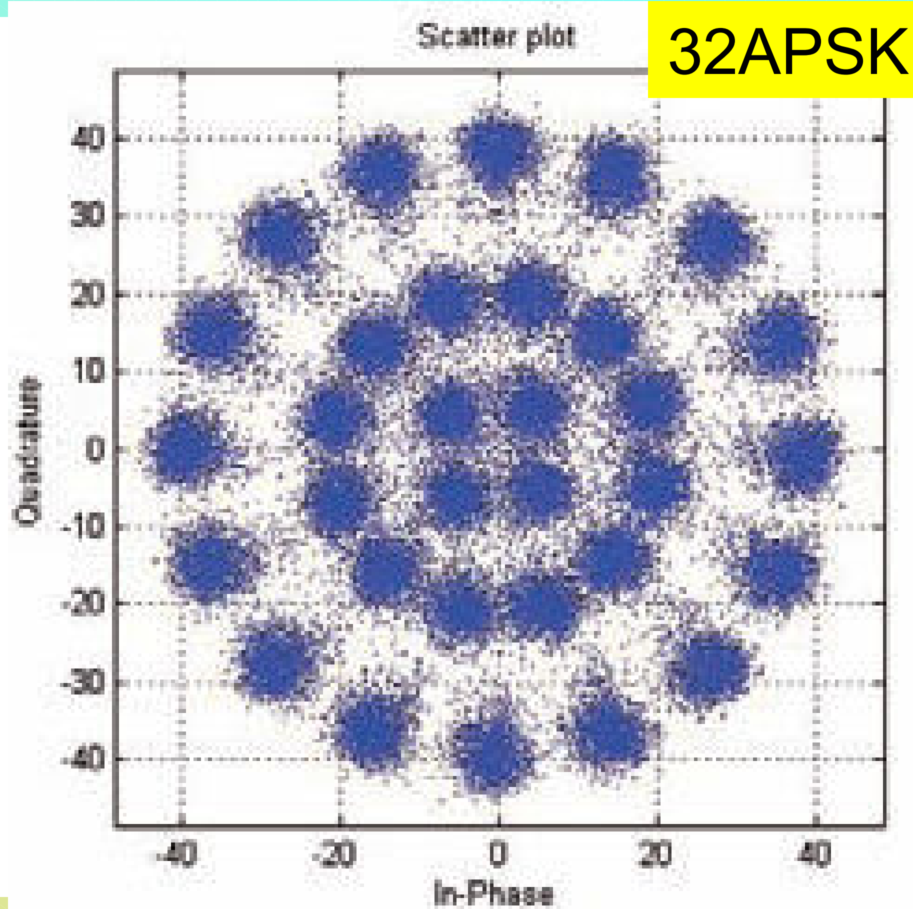
8. Amplitude and Phase Shift Keying (APSK)

Digital Video Modulator

- DVB-S2 is a new Video modulation standard for Digital Video Broadcasting
- Second-generation specification for satellite broad-band applications
- Uses QPSK, 8PSK, 16APSK, or 32APSK
- 16APSK or 32APSK is a new digital modulation scheme
    - Changing, both amplitude and phase ~

16APSK & 32APSK

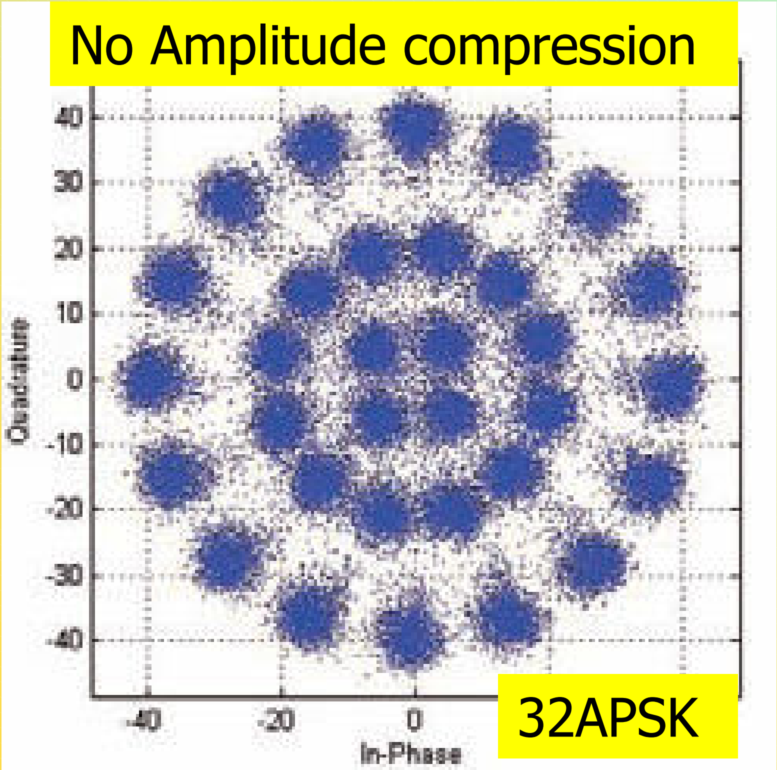


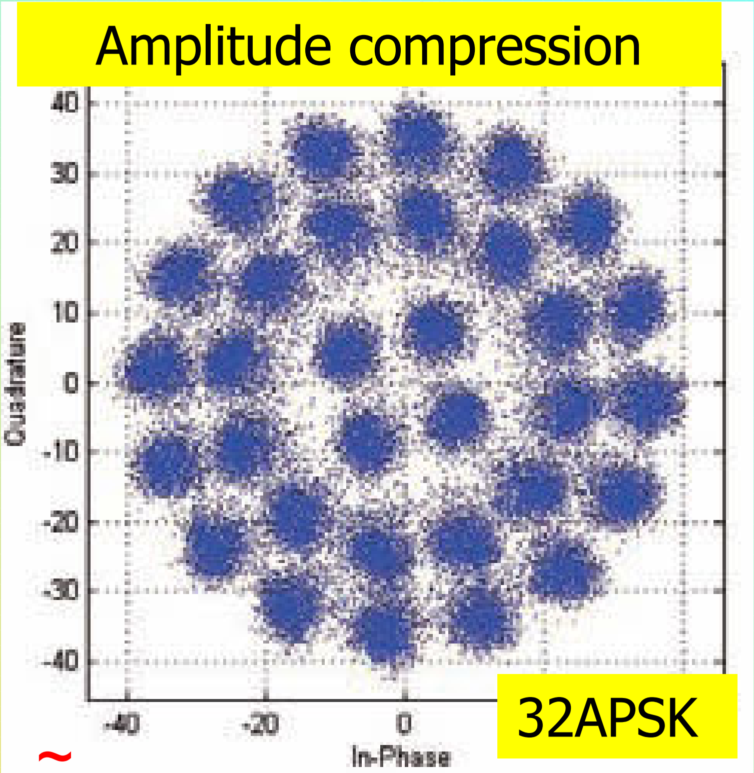


- QAM modulators can place signals at any vector location
- 16APSK more immune to Phase Noise than 16QAM
- 32APSK symmetrical means of doubling bits/symbol
  - Emphasis on Phase Noise immunity ~

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 ~





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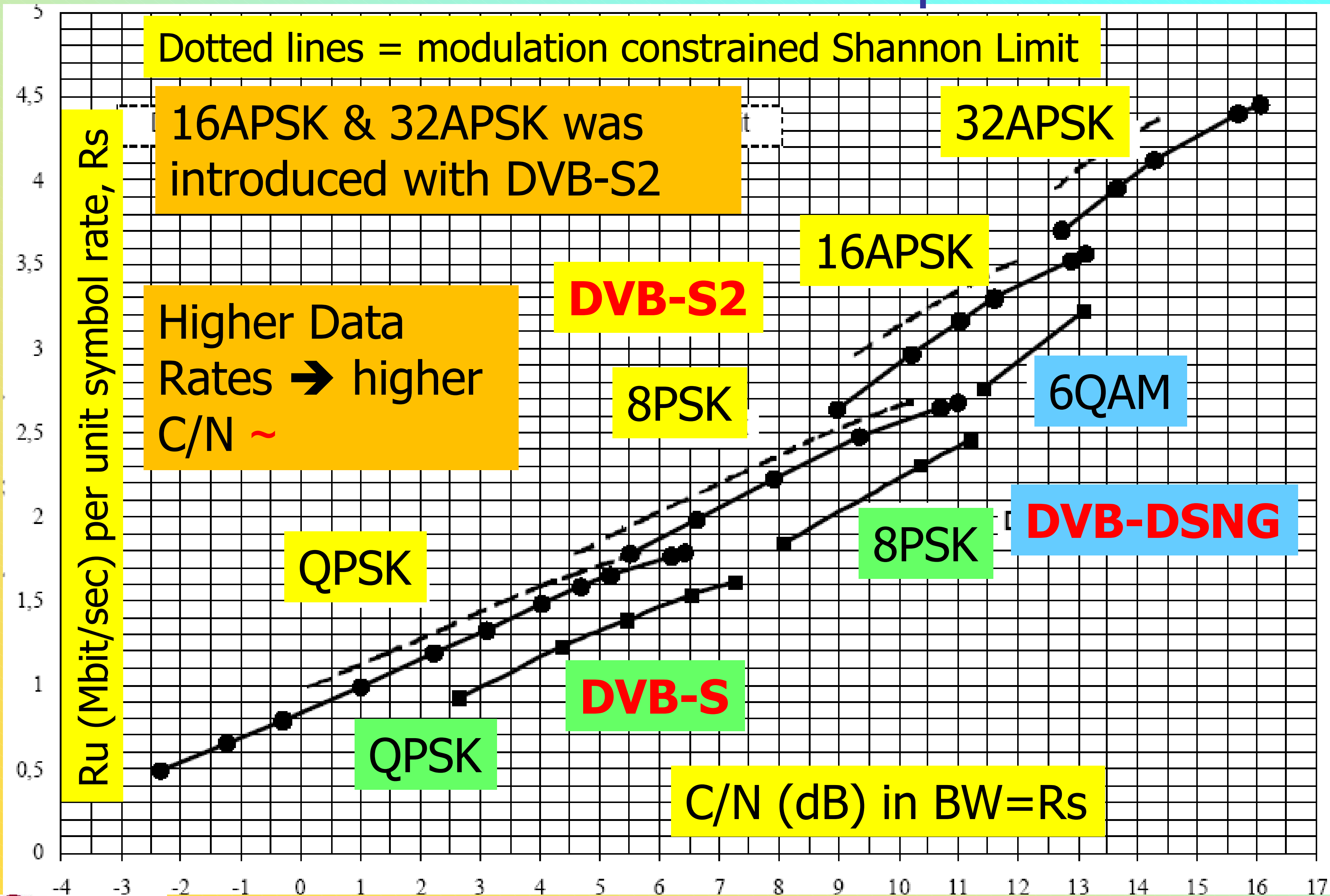
DVB-S2 Carrier to Noise Requirements

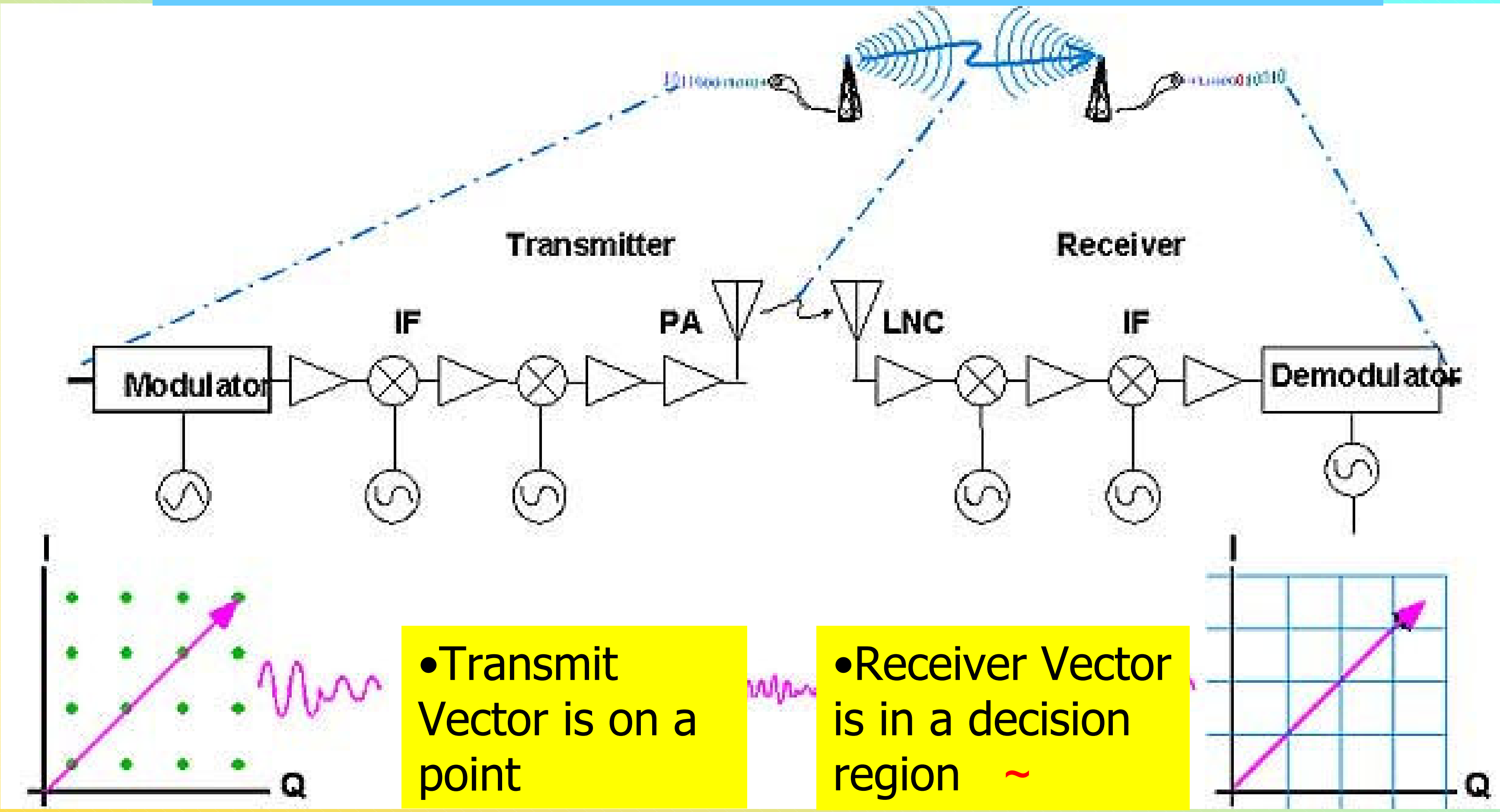


MITEQ

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 → 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

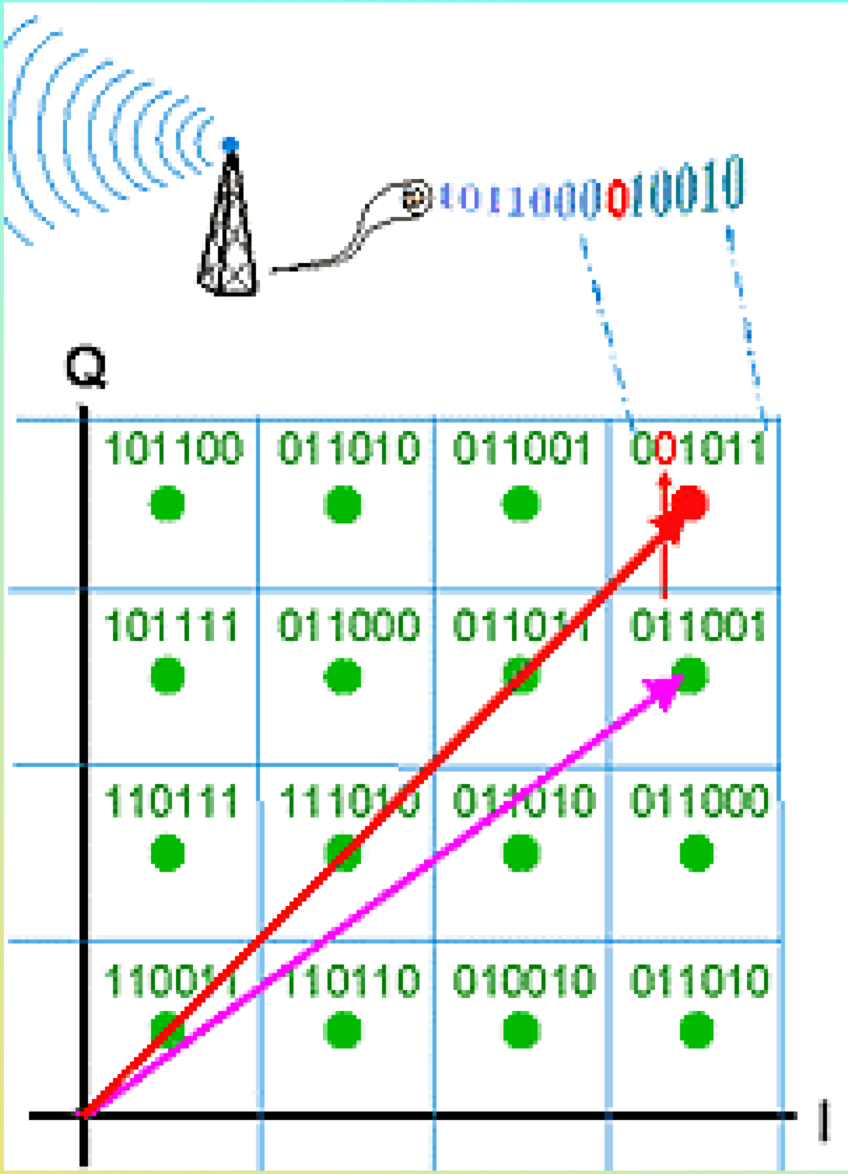


- Transmit Vector is on a point
- Receiver Vector is in a decision region ~

QAM Decision Region

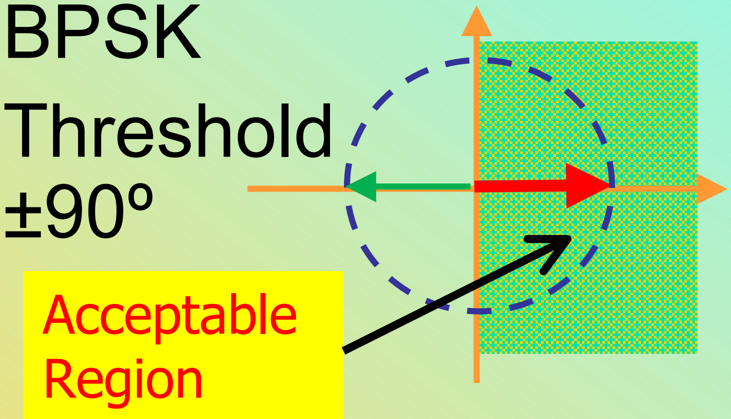
❑ Lines between the constellation points are the threshold levels

❑ Signals residing in the square are assume to reside at the discrete vector location. ~

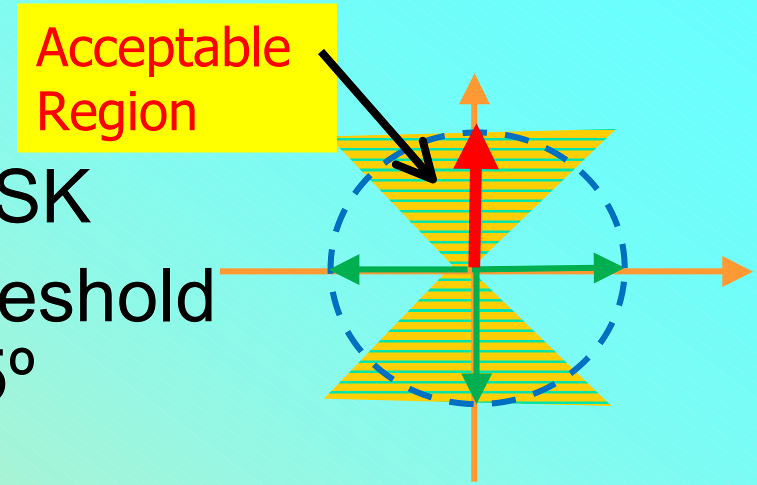


Threshold Spacing

- BPSK
- Threshold ±90º



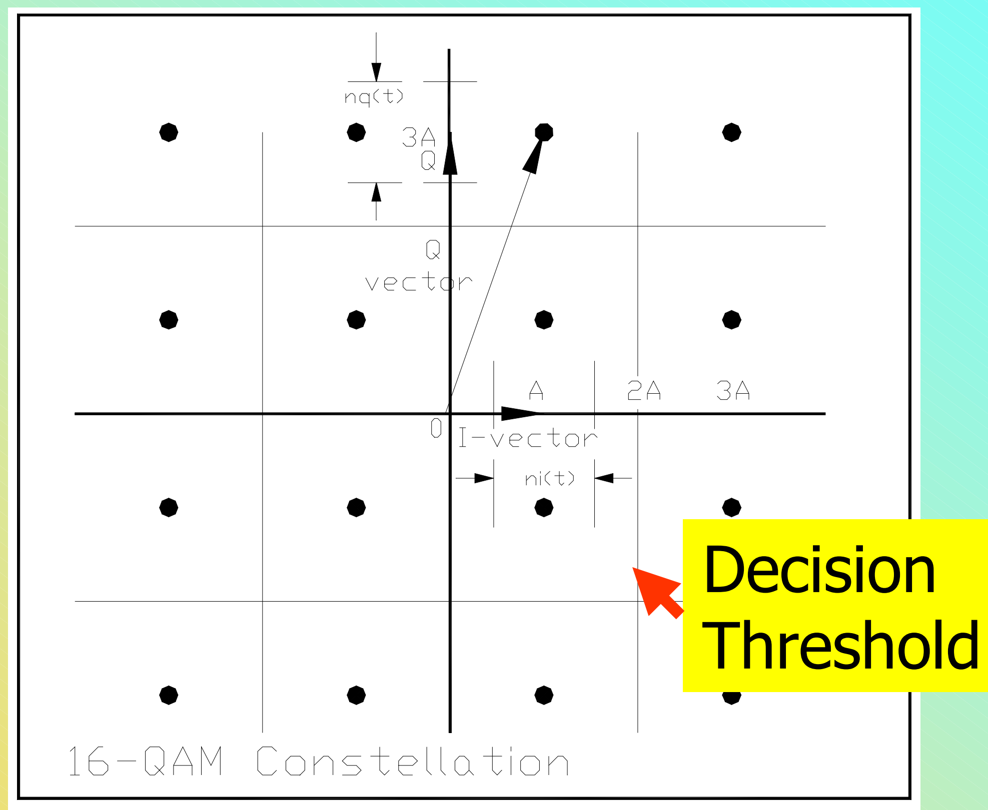
- QPSK
- Threshold ±45º



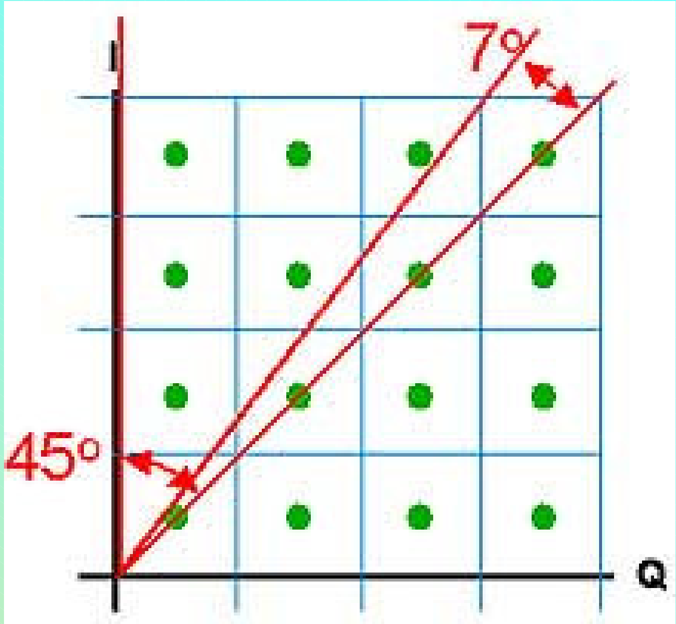
- **16-QAM Amplitude steps**
  - **A or 3A**
- **Separation – 2A**
- **Amplitude Noise:**

Decision region must have Equal Area

•Phase Noise: Vector Angles must be equal ~



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** ~

Modulation	Error
•2QAM	90.0°
•4QAM	45.0°
•16QAM	16.9°
•32AM	10.9°
•64QAM	7.7°
•128QAM	5.1°

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 ~