

Fundamentals of Satellite Communications Part 3

Modulation Techniques used in
Satellite Communication

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Modulation Techniques used in Satellite Communication

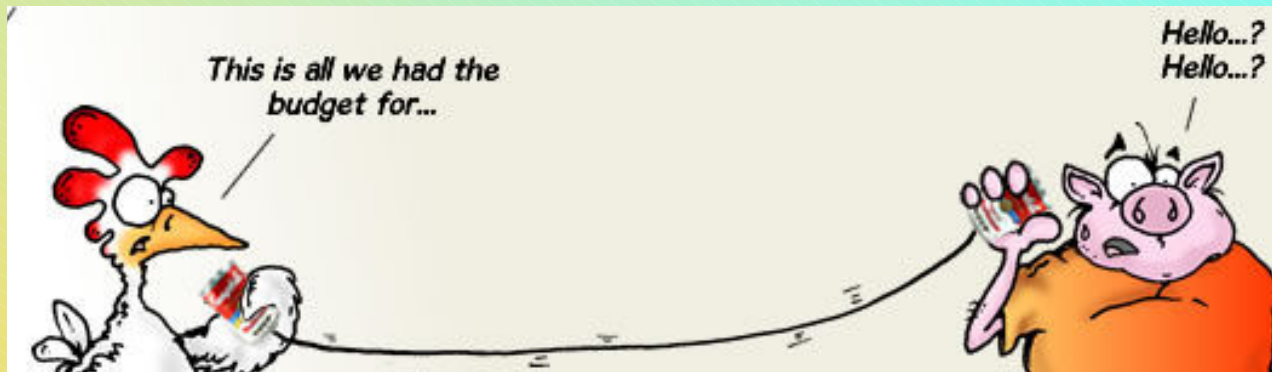
1. Early Communication
2. Simultaneously Transmitting Multiple Signals
3. Types of Modulation
4. Digital Modulation - Quantizing Data
5. Digital Modulation Techniques – CW (Constant Amplitude)
6. Quadrature Amplitude Modulation (QAM)
7. Recovering Packet Errors
8. Amplitude and Phase Shift Keying (APSK)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



1. Early Communications

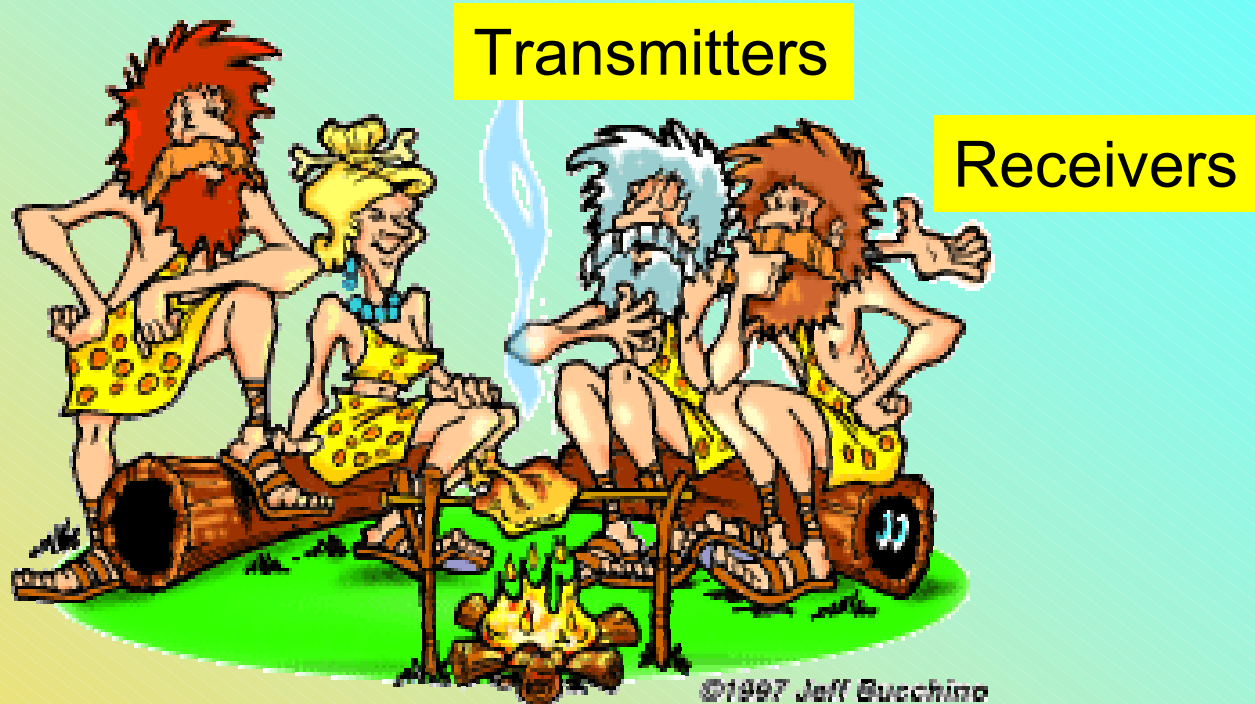
Wired Communications

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 ~

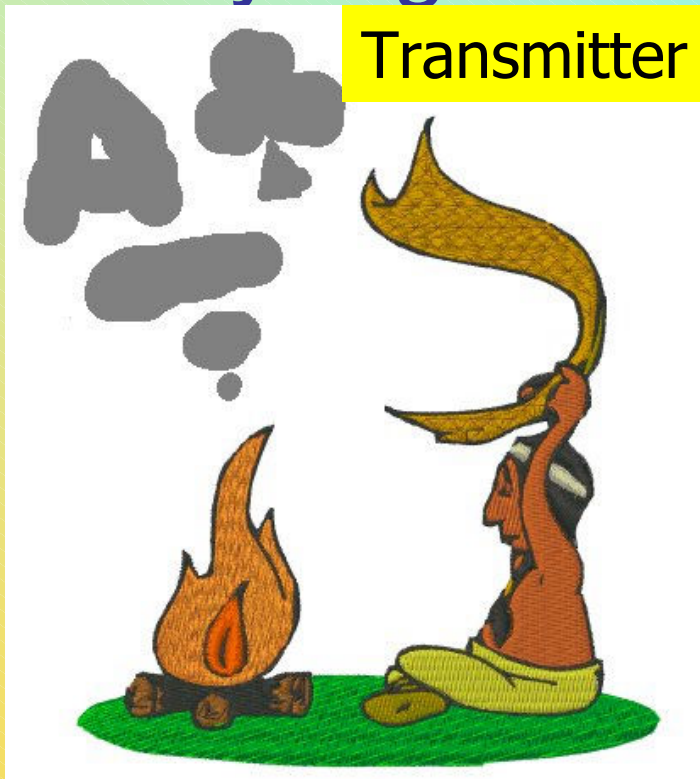
Early Wireless Communications - Analog



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



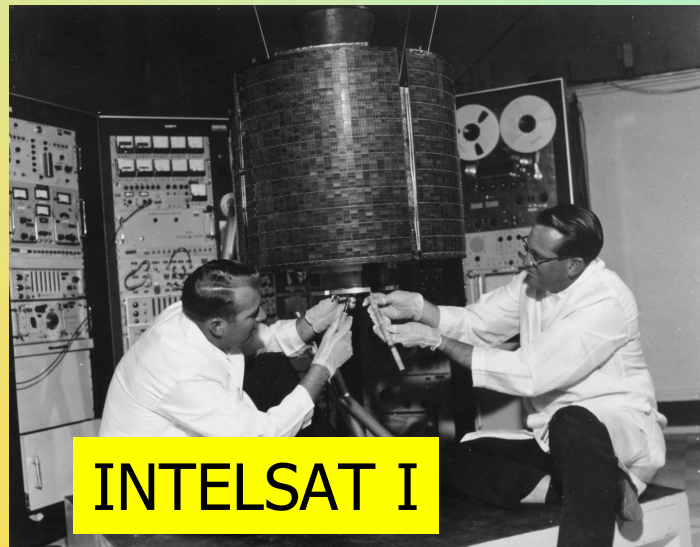
- Communication Goals
 - Speed
 - Accuracy
- Select a stable carrier - Smoke / Light / Electromagnetic Radiation
- Check the Path Loss & Distortion
- Efficiently modulate the carrier
- Prevent Interference from adjacent carriers ~

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 ~



SPUTNIK



INTELSAT I



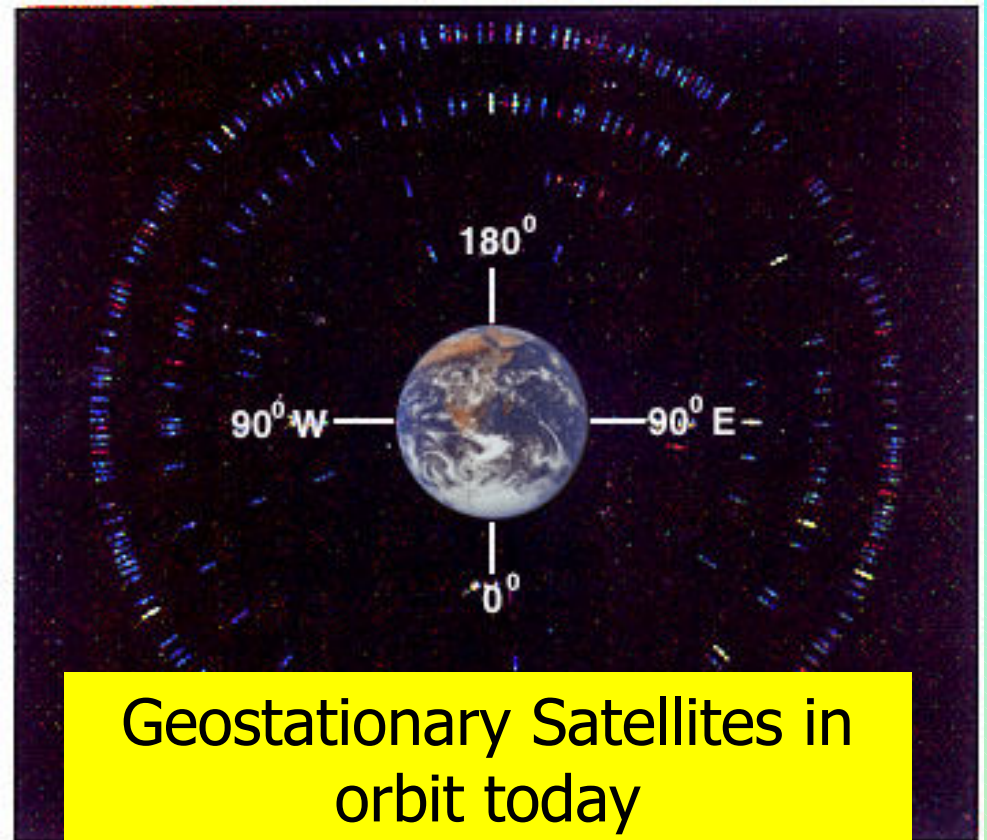
INTELSAT IVA

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 ~

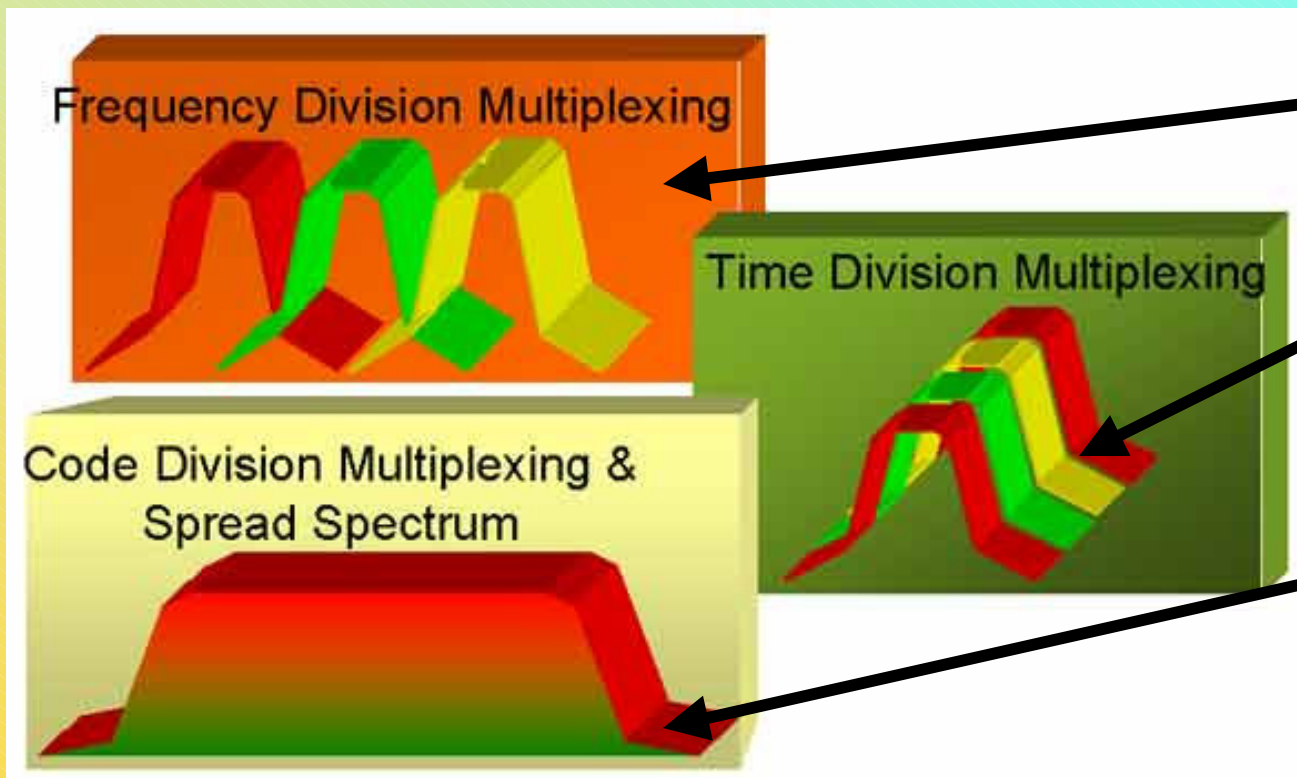


Modern Communication
Satellite



Geostationary Satellites in
orbit today

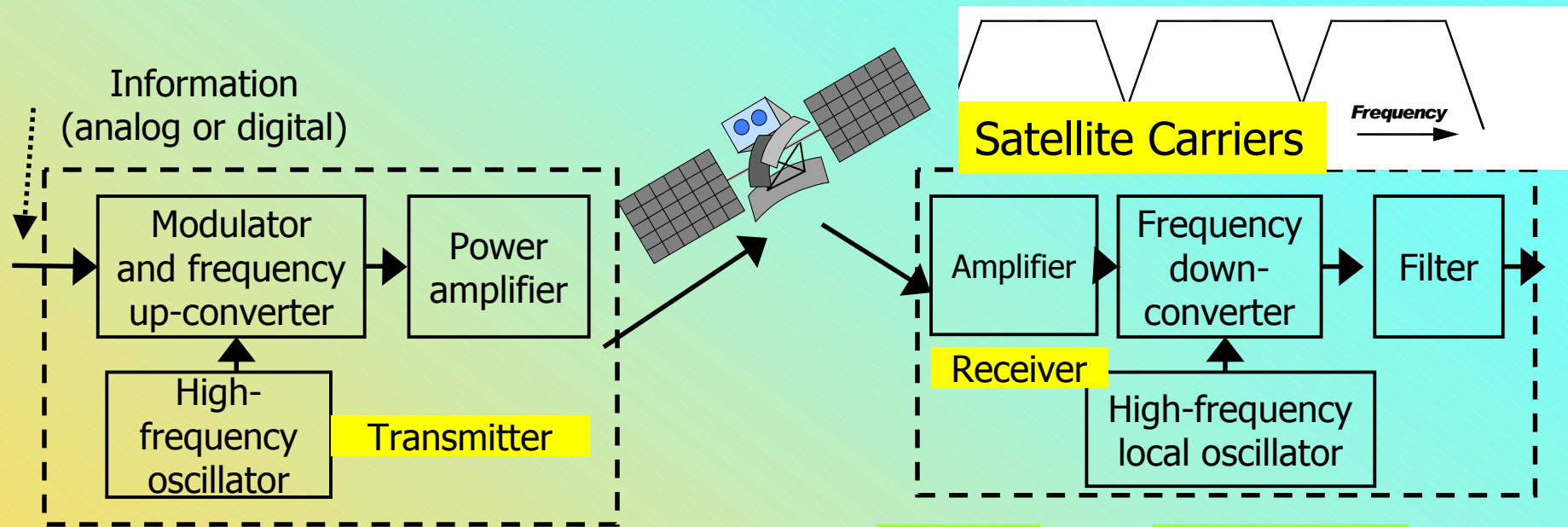
2. Simultaneously Transmitting Multiple Signals



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

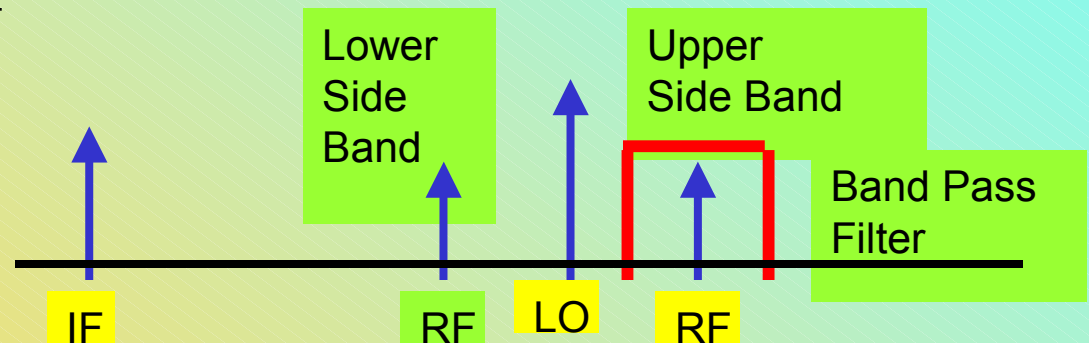
- Carriers can have multiple modulation techniques
- GSM uses FDM and TDMA ~

Frequency Division Multiplexing (FDM)



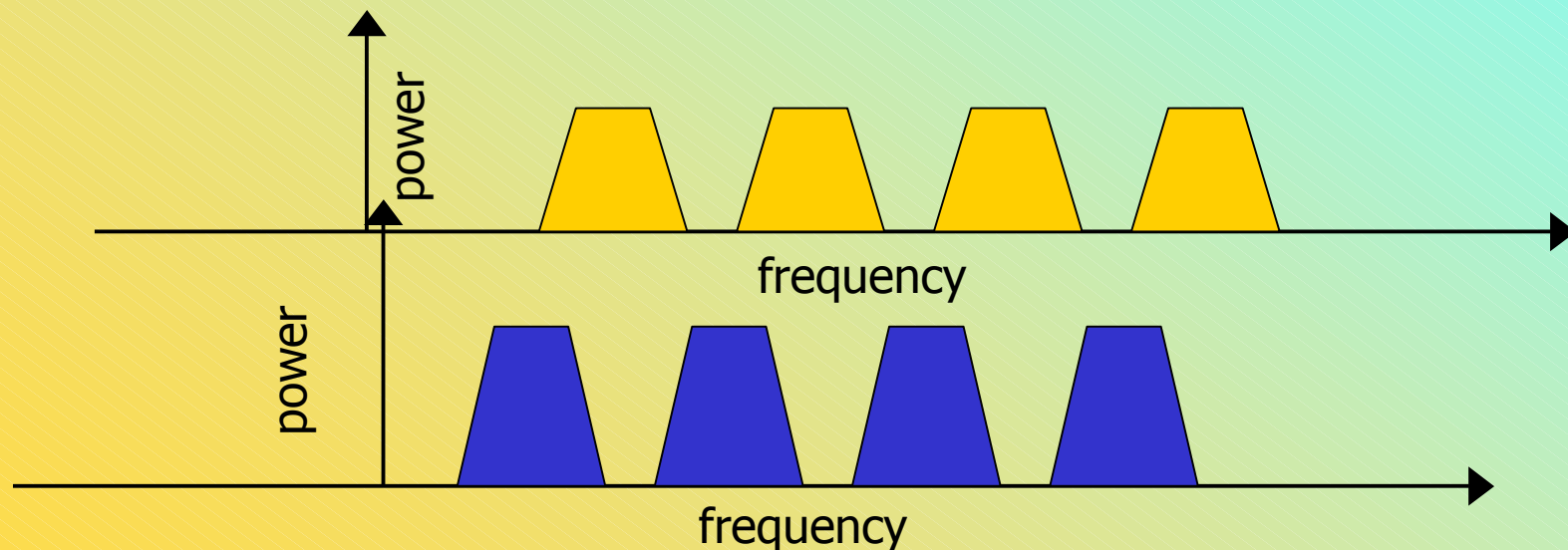
❑ Carriers have Assigned Frequencies and Bandwidths

- ❑ 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 ~



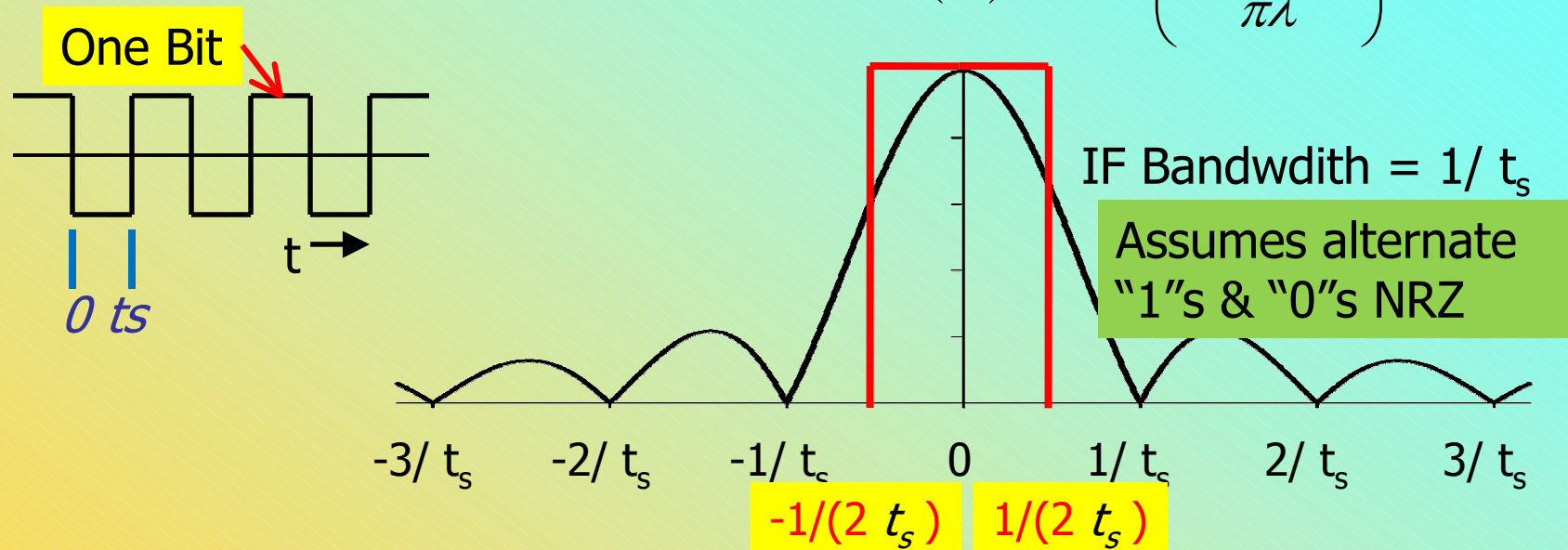
Channel Capacity

- 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 $\geq 2^{12}$, or 36 dB; typ. telephone line ~

Bandwidth Considerations

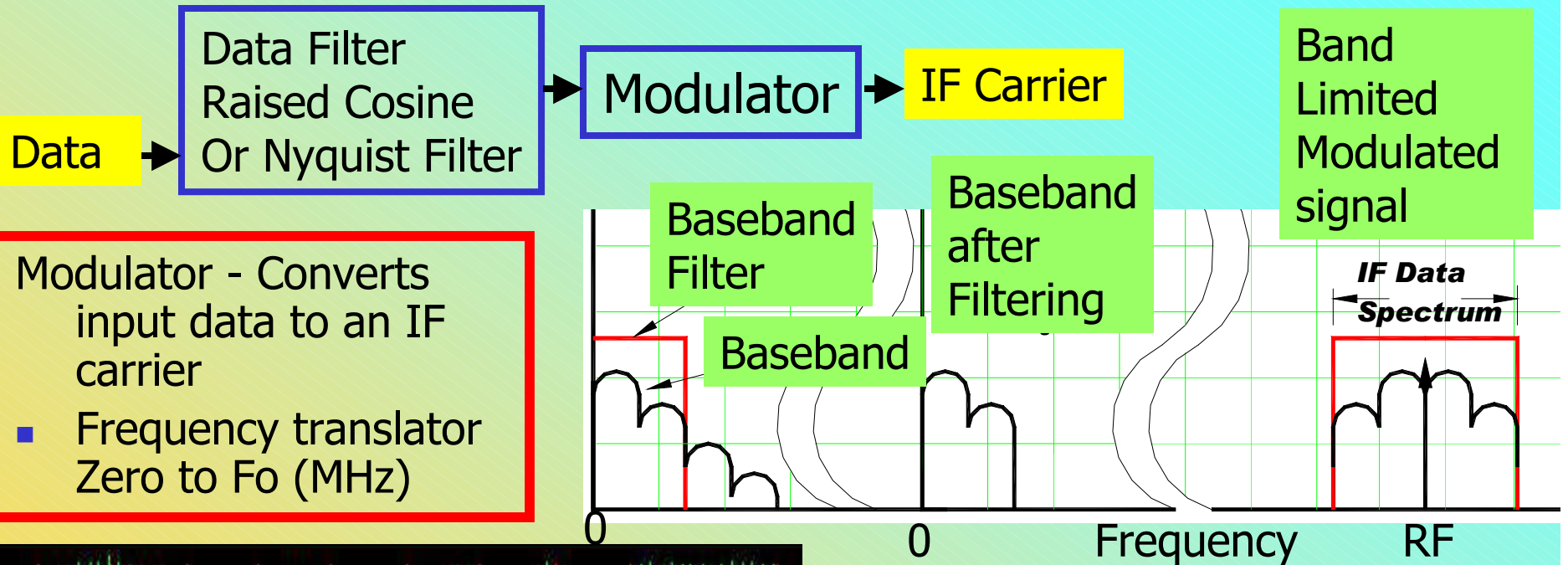
- Data in the time domain translates to the frequency domain as a $(\sin x)/x$ function

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



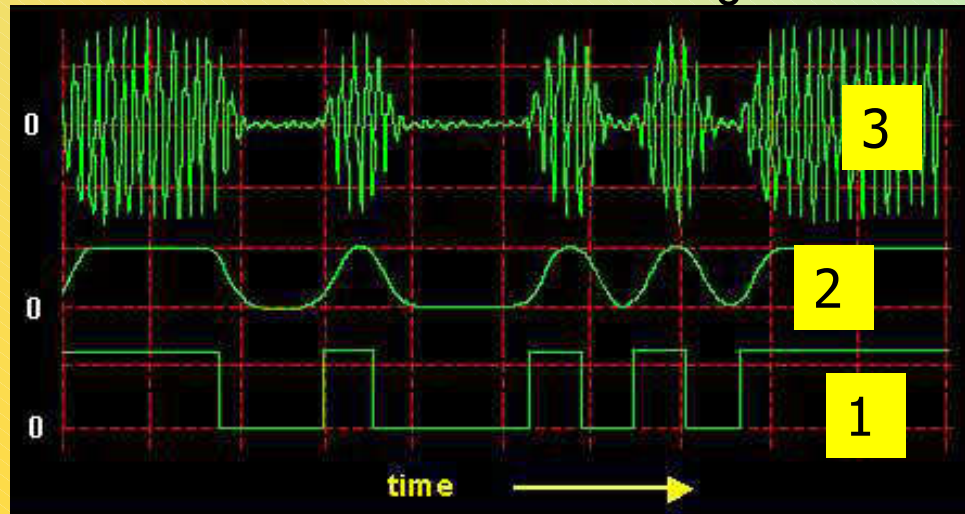
- The baseband time domain signal is filtered to minimize side lobes
 - Minimize adjacent channel interference
- Raised Cosine (Nyquist) filter best trade off of pulse distortion (time domain) and side lobe rejection (frequency domain) ~

Modulation - Preconditioning Data



Modulator - Converts input data to an IF carrier

- Frequency translator Zero to F_0 (MHz)

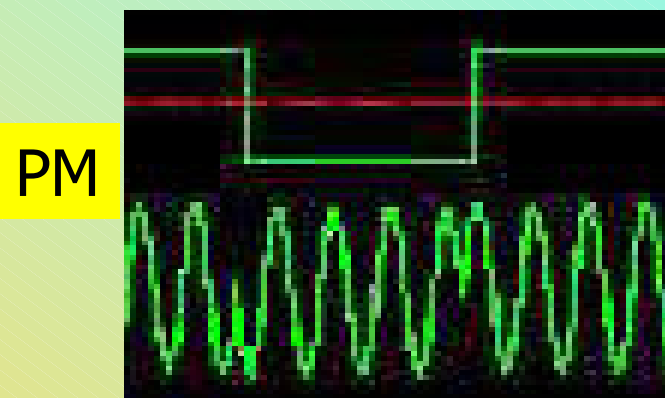
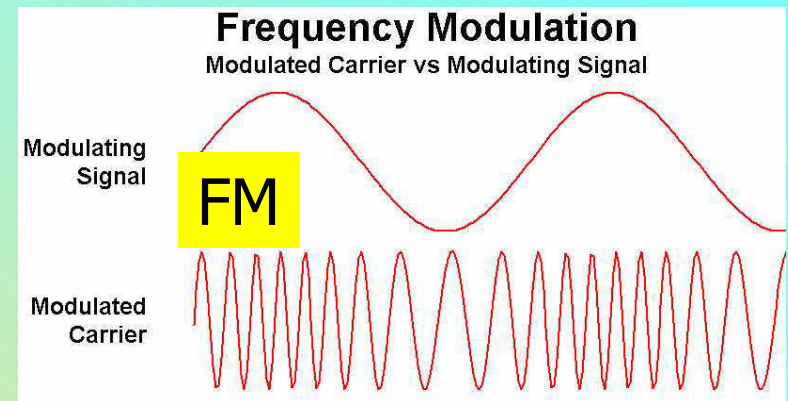
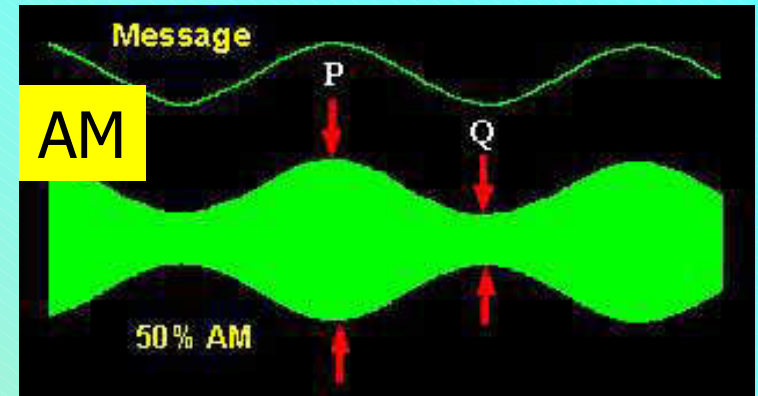


- Can't Filter at RF
 - BW is too narrow
- Pre-Modulation Filtering - Limits RF Bandwidth ~

3. Types of Modulation

- Unmodulated carrier: $V = A \cos [\omega_0 t]$.
- Modulated signals control amplitude & Phase (Frequency)
 - $V = [1 + A_c(t)] \cos [\omega_0 t + \theta(t)]$
 - $A_c(t)$ 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) ~

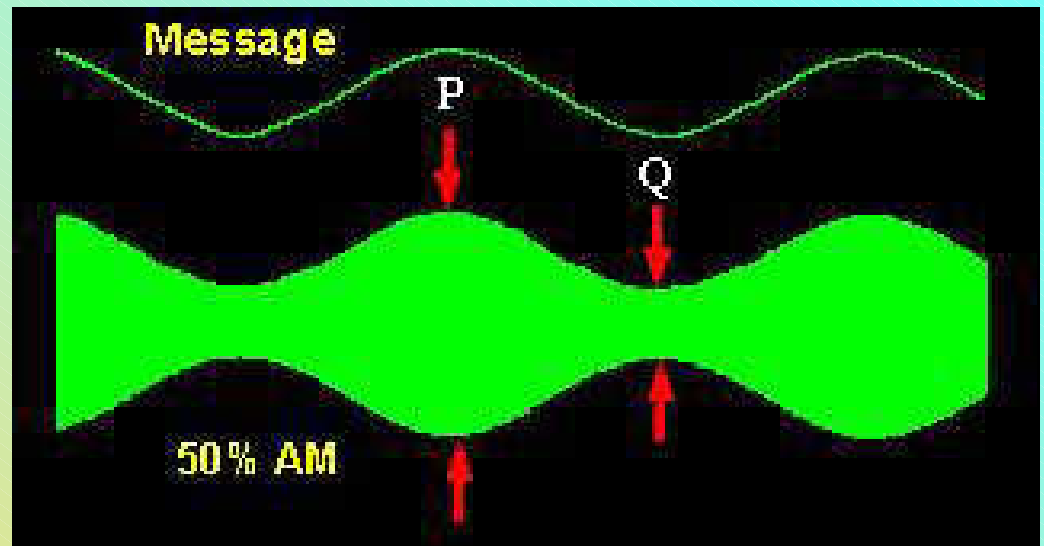


Analog Amplitude Modulation (AM)

- AM Radio
- Analog TV
- Optical Communications

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

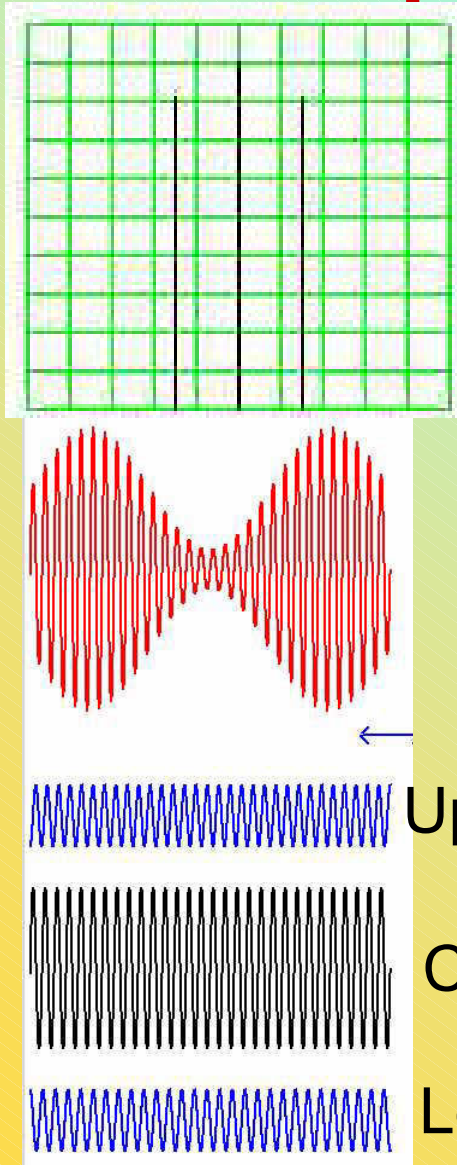
- AM Waveform
- $x(t) = A \cdot [1 + m(t)] \cdot \cos(\omega_c \cdot t)$



Modulation index: $m=0.5$

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

AM Frequency Spectrum & Power



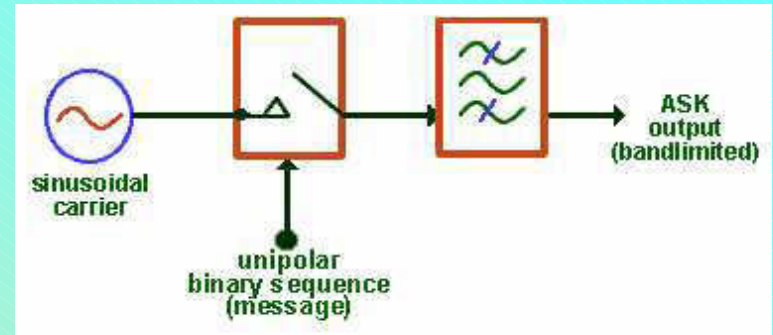
- Calculating Sideband Levels
- $\text{dBc} = 20 \text{ Log}_{10} m/2$
 - 75% AM ($m=.75$)
 - Sidebands down 8.5dB from the carrier

• Required Power for AM

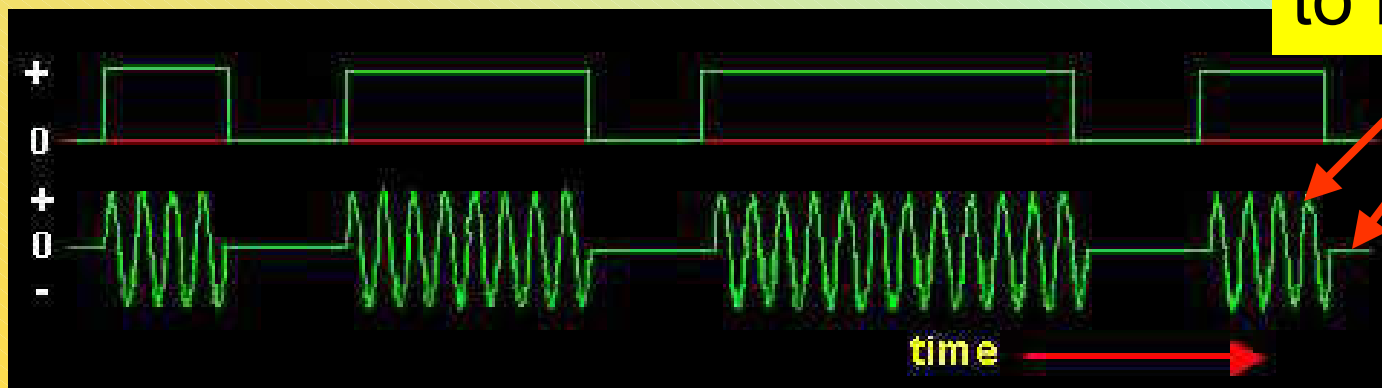
- Peak level 2 x no signal ($m=1$)
- RF power 4 x CW Signal ($m=1$)
- Linear Power Amps 2 or 3 x less efficient than Non-Linear Amps
- Need more power to operate than AM than FM/PM ~

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 ~



Frequency Modulation

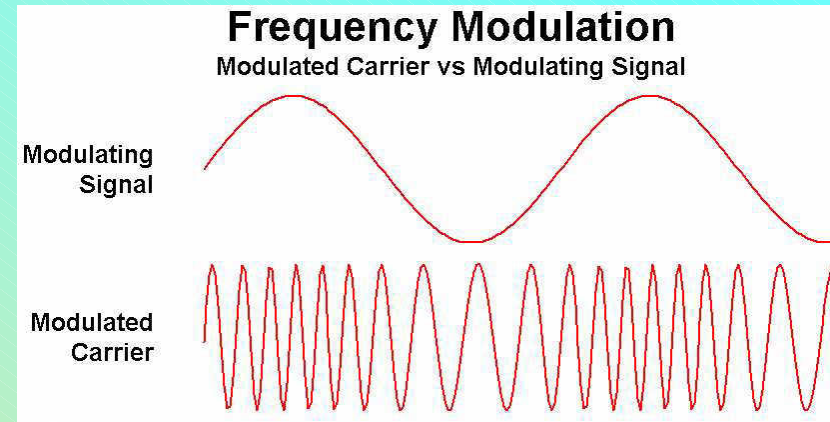
$$X_c(t) := A_c \cdot \cos(\theta_c(t))$$

- $X_c(t)$ = 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 = $d \Phi(t) / dt$



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

- For $m(t)$ sinusoidal
- $f_i = F_c + k_f m(t)$
- k_f = Gain Constant
- Frequency Deviation = Δf
 $\therefore \Delta f = k_f \max |m(t)| \sim$

FM Modulation Index (β)

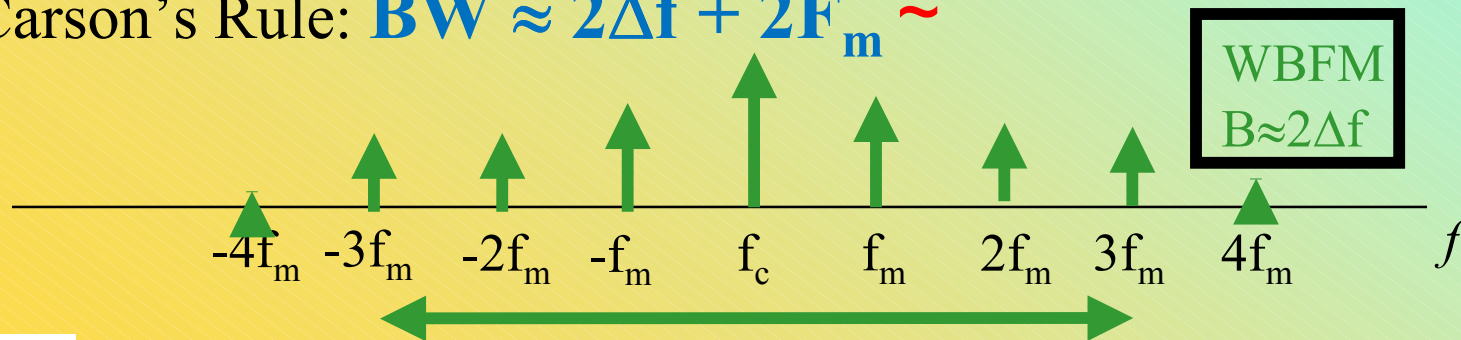
- $\Phi(t)$ = Instantaneous Phase variation around carrier F_c
- for FM signals:

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

- $K_f = \Delta F$ = the peak frequency deviation
 - $m(\tau)$ = is the normalized peak deviation
- For Sinusoidal modulation:
 - $m(\tau) = \cos(2 \cdot \pi \cdot F_m \cdot \tau)$ where F_m is the rate of modulation
 - $\Phi(t) = [2 \cdot \pi \cdot \Delta F] / (2 \cdot \pi \cdot F_m) \cdot \sin(2 \cdot \pi \cdot F_m \cdot \tau)$
 - $\Phi(t) = (\Delta F / F_m) \cdot \sin(2 \cdot \pi \cdot F_m \cdot \tau)$
 - $\beta = \Delta F / F_m$ = modulation index (Radians)
 - $\Phi(t) = \beta \cdot \sin(2 \cdot \pi \cdot F_m \cdot \tau)$ ~

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 (δ functions) are at \pm integral multiples of F_m , from the carrier (F_c)
 - 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)

$$X_c(t) := A_c \cdot \cos(\theta_c(t))$$

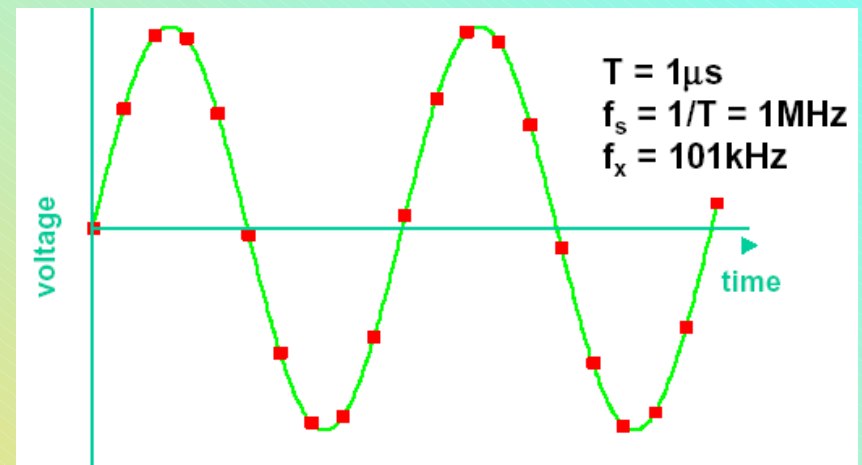
$$\theta_c(t) := 2 \cdot \pi \cdot F_c \cdot t + \phi(t)$$

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

4. Digital Modulation - Quantizing Data

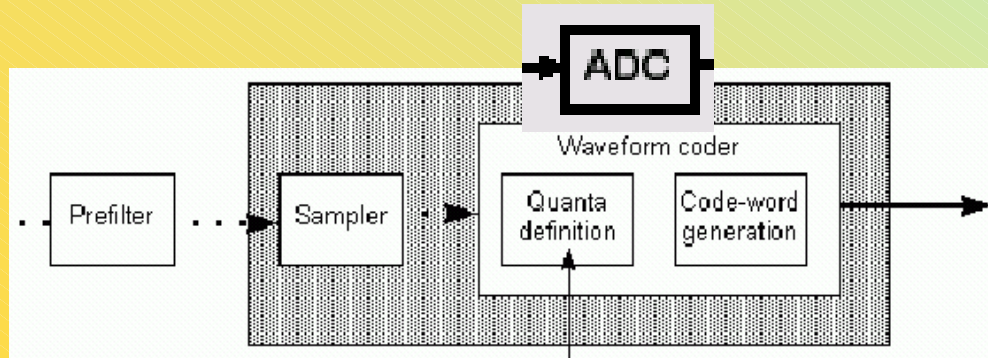
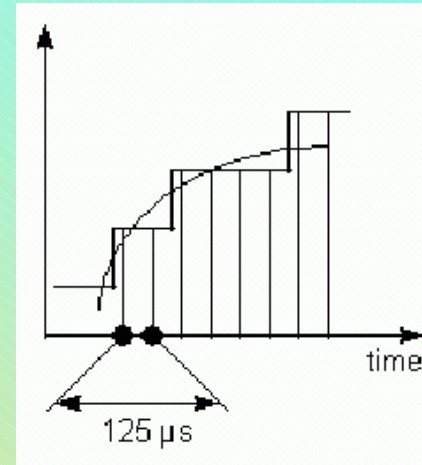
Sampled Analog Signals

- Continuous signals are sampled at discrete times
- Samples are digitally coded & Transmitted
- Nyquist criteria for completely recovering an analog signal
 - Sampling Rate (F_s) $\geq 2 \times$ Maximum Information Rate (F_m)
 - 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 (F_m)
- All frequency components $> F_m$ are suppressed
- The Nyquist Criteria will solve all of the unknowns sampling at a rate of $2F_m$
- 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



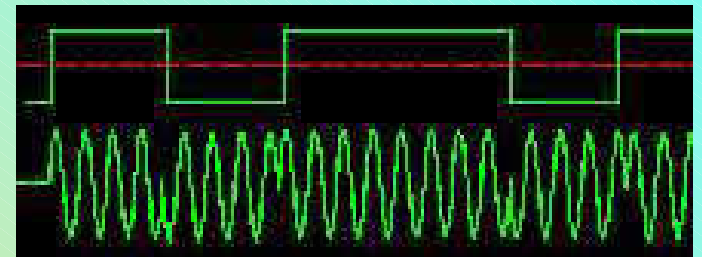
N Bits

- $F_m = 10 \text{ MHz}$
- Sample Time: 50nSec
- $M = 1024 \text{ Steps}$
- 10 bit Binary Code
- 5nS/Bit

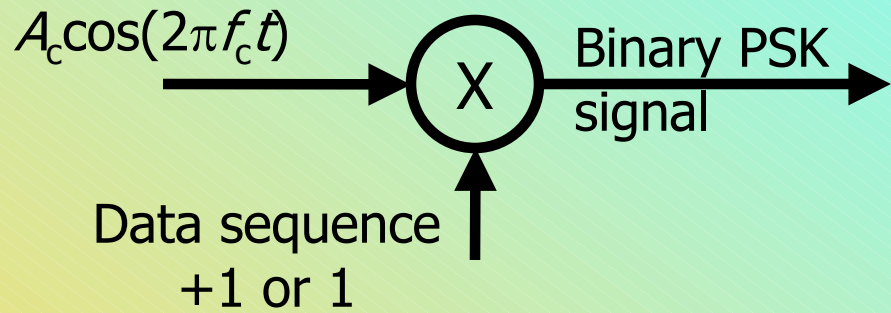
5. Digital Modulation Techniques - CW

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

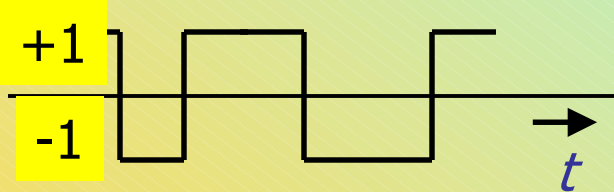
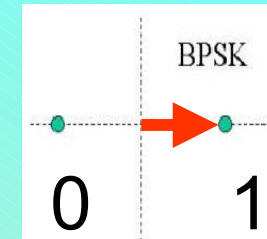
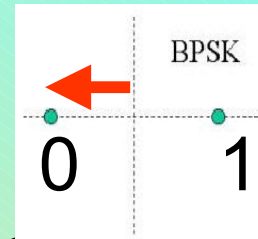
- Modulated Phase (or Frequency)
- Highly Efficient Power Amps
 - More resilient to amplitude distortion
- Recovery by Simple Phase Detection
- Bi-Phase Shift Keying
 - BPSK: Low Data Rates
- Quadrature Phase Shift Keying
 - QPSK (OQPSK): Medium Data Rates
- Eight Level Phase Shift Keying
 - 8PSK: High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



Binary Phase-Shift Keying BPSK (2-QAM)

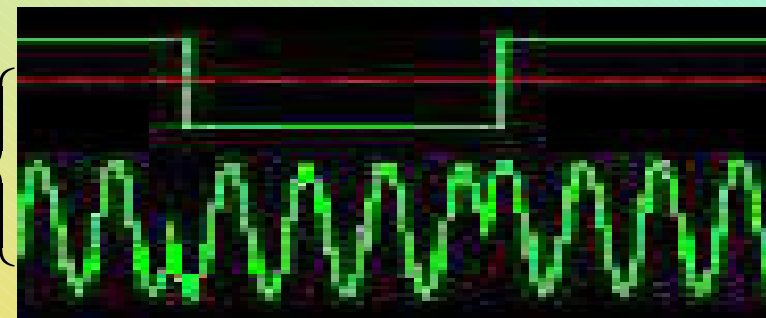


- Signal is represented as a vector
- A change in phase (180°) is a change in Binary code ~



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

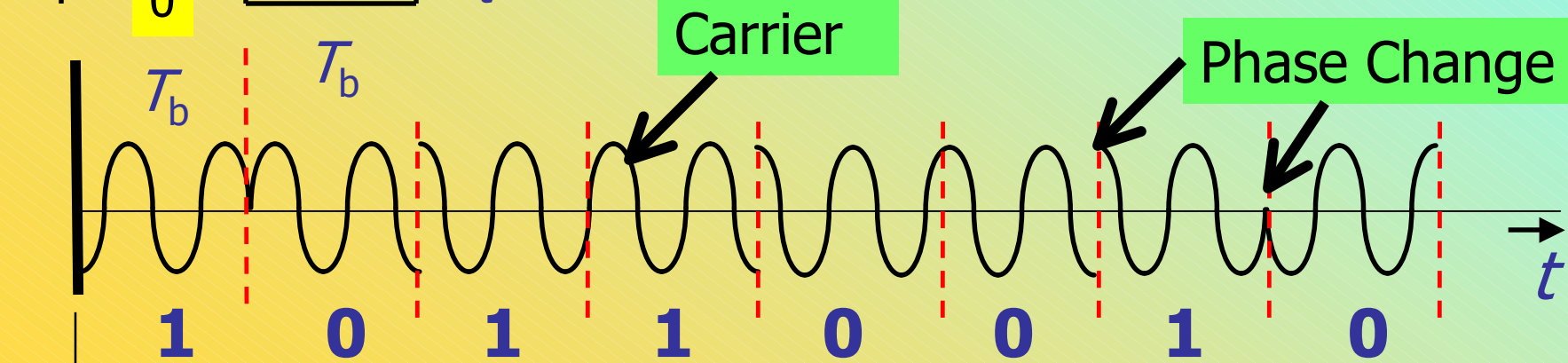
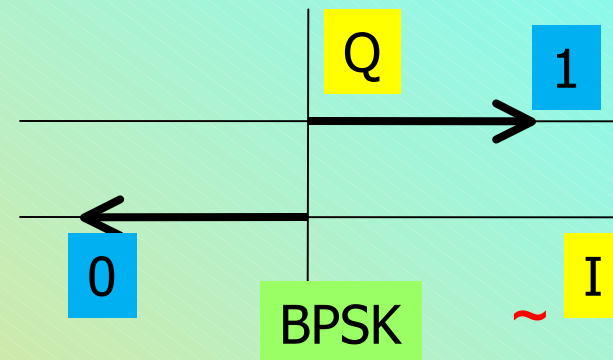
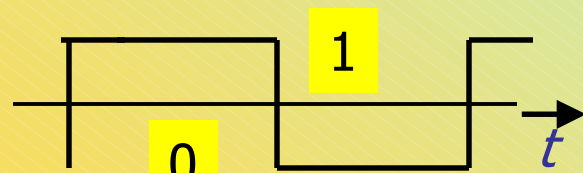
$$s(t) = \begin{cases} A \cos(2\pi f_c t) & \text{binary 1} \\ A \cos(2\pi f_c t + \pi) & \text{binary 0} \\ A \cos(2\pi f_c t) & \text{binary 1} \\ -A \cos(2\pi f_c t) & \text{binary 0} \end{cases}$$



Binary Phase-Shift Keying BPSK (2-QAM)

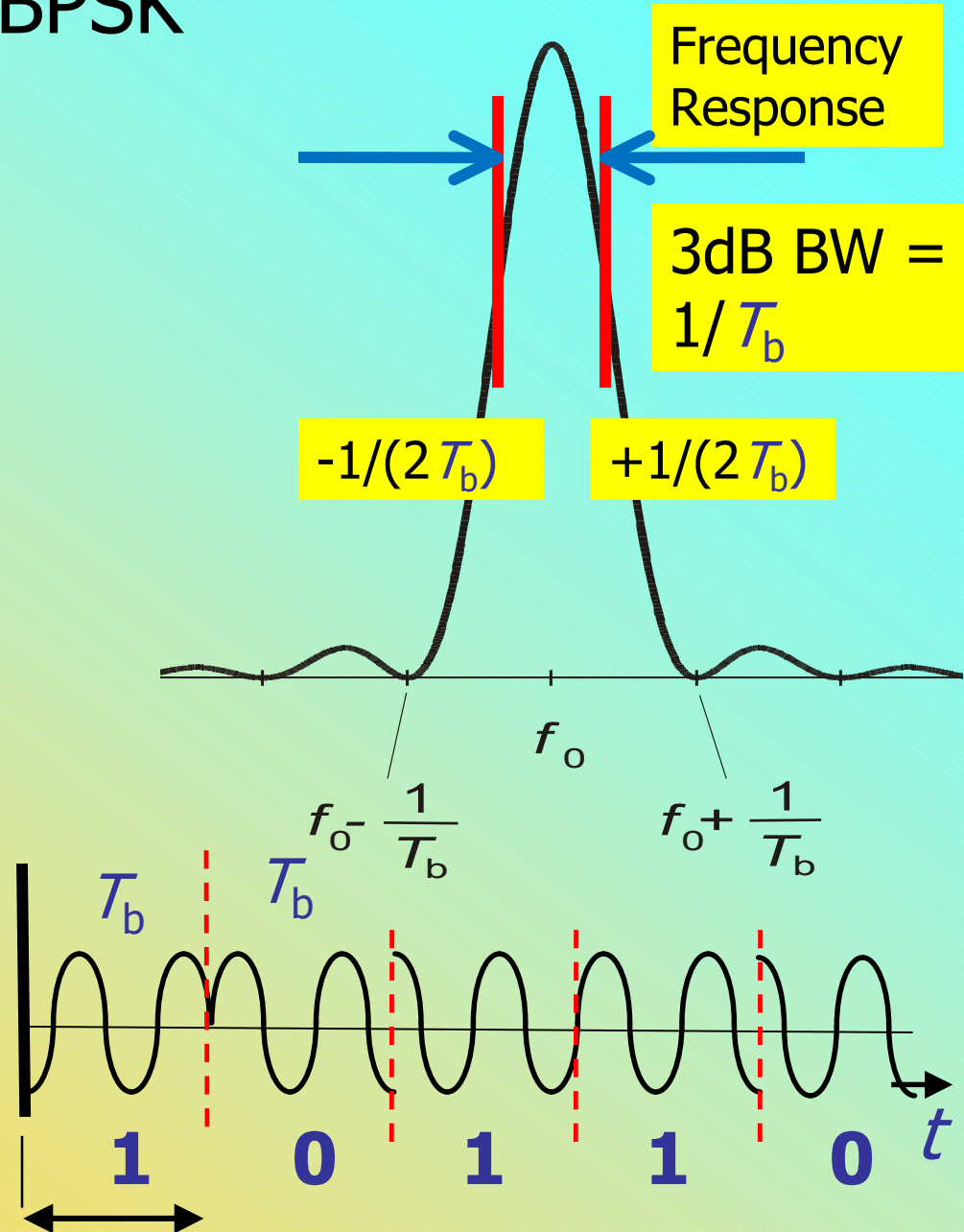
- T_b is the duration of 1 Bit
- Bit Rate = $1/T_b$
- Symbol Rate = $1/T_b$
- IF BW = Symbol Rate = $1/T_b$

- Absolute phase is determined by a known synchronization pattern



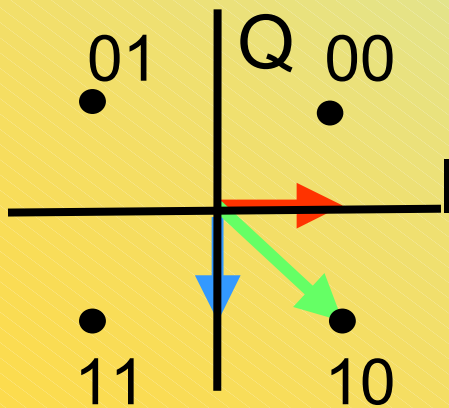
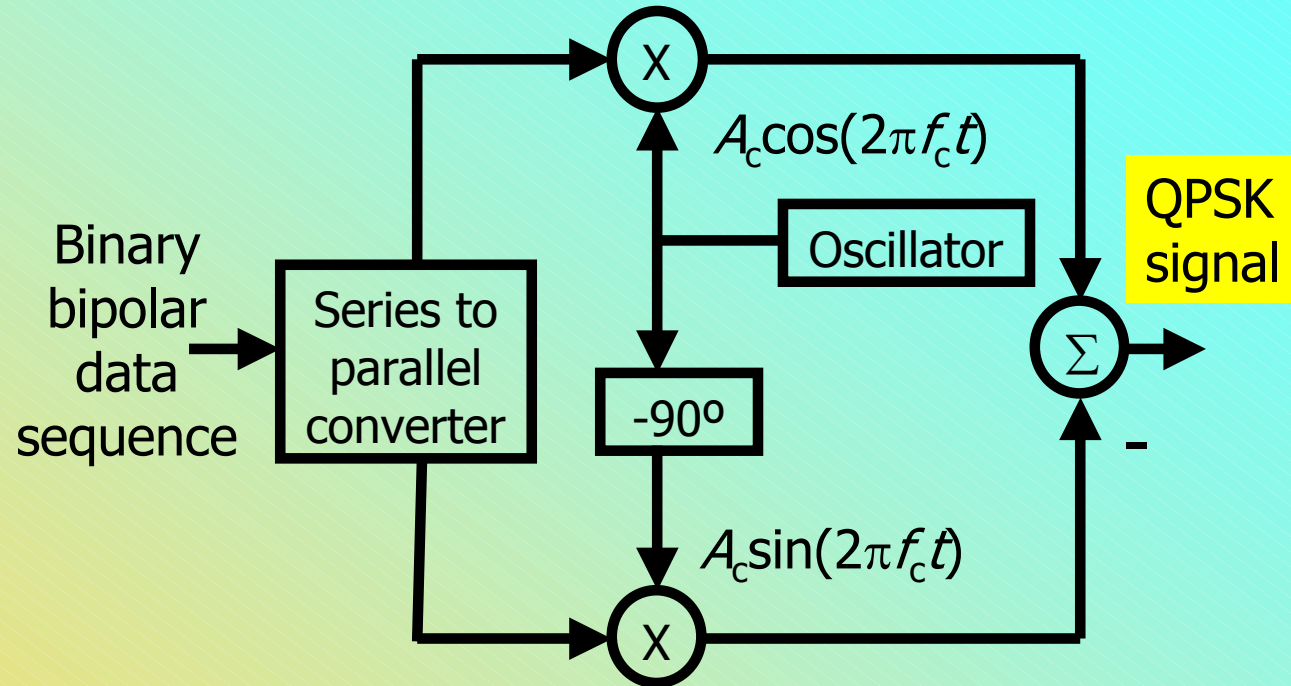
Frequency Spectrum BPSK

- Pulsed input transforms to a $(\text{Sin } x)/x$ 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 $1/2$ Raised Cosine (Nyquist) filter in the transmitter for side lobe suppression
- $1/2$ Raised Cosine filter in the Receiver for noise suppression



Quadrature Phase-Shift Keying (QPSK)

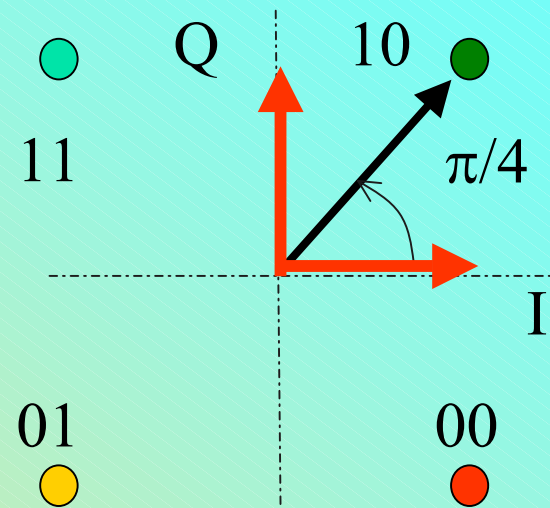
- Successive bits are transferred to alternate channels
- Bits are stretched x2
- 2 Bits per symbol ~



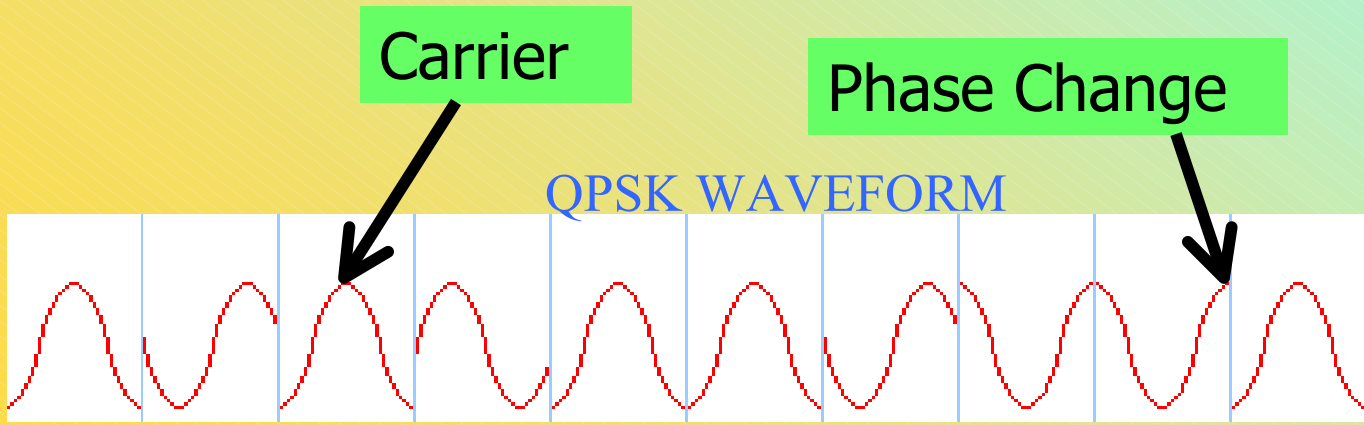
- 2 BPSK modulators
- Carriers are 90° Out of Phase (I & Q)
- Σ 2 vectors 90° out of phase

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.

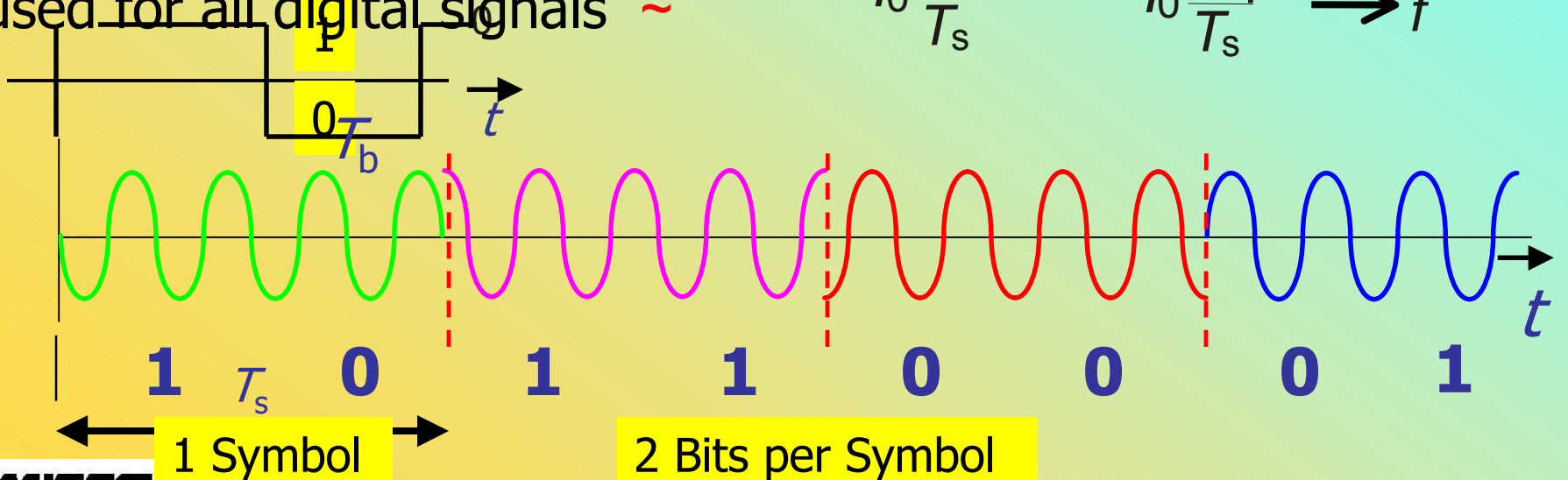
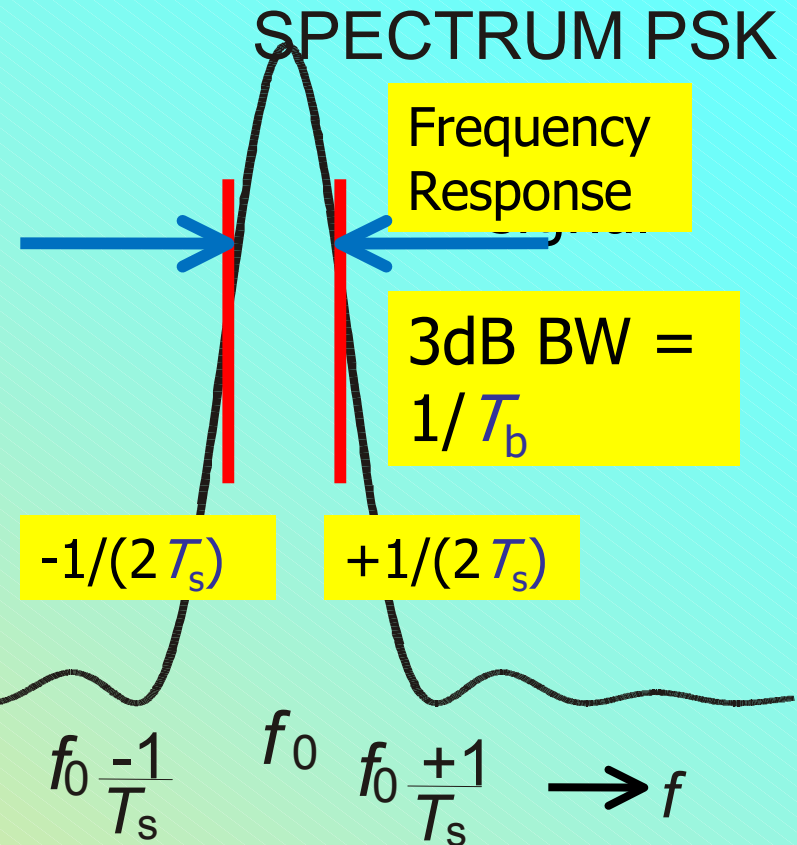


I(+)	Q(+)	=	10
I(-)	Q(+)	=	11
I(-)	Q(-)	=	01
I(+)	Q(-)	=	00



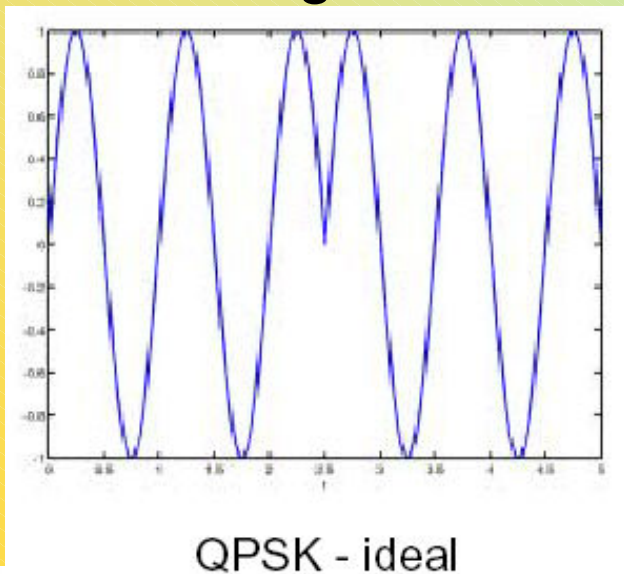
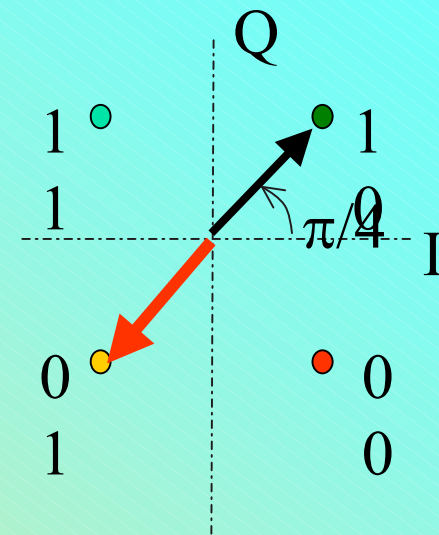
QPSK Bandwidth

- 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
- 1/2 Raised Cosine filters are used for all digital signals ~

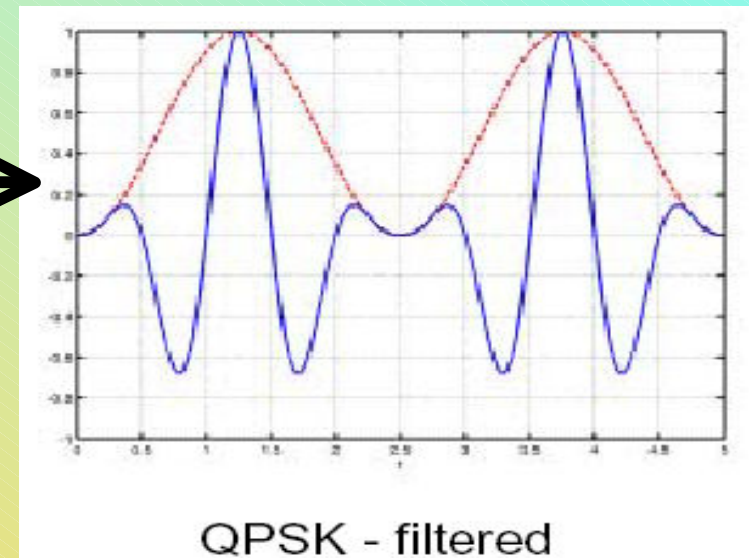


Amplitude Variations of QPSK

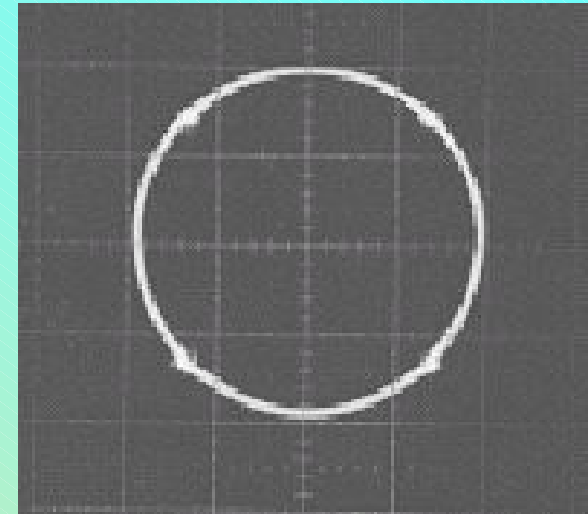
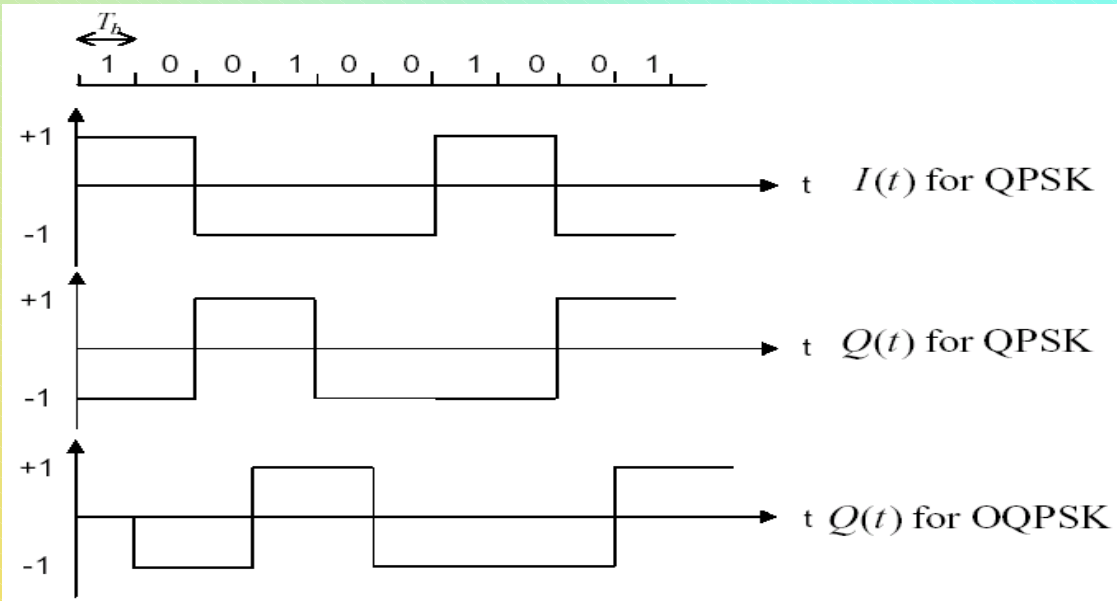
- If I & Q bits change at the same time vector goes through zero
- Power changes abruptly
- Non-constant envelope after filtering
- Peak to Average Ratio increases with zero crossings
- Causes signal distortions ~



Many
Zero
crossings

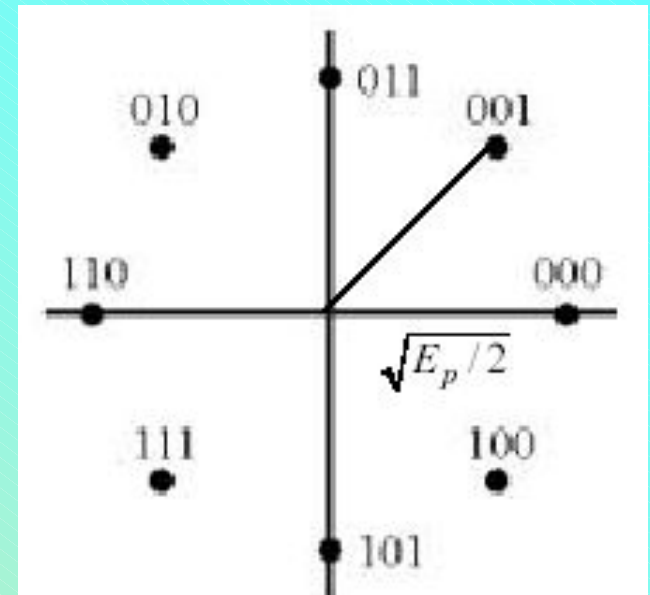
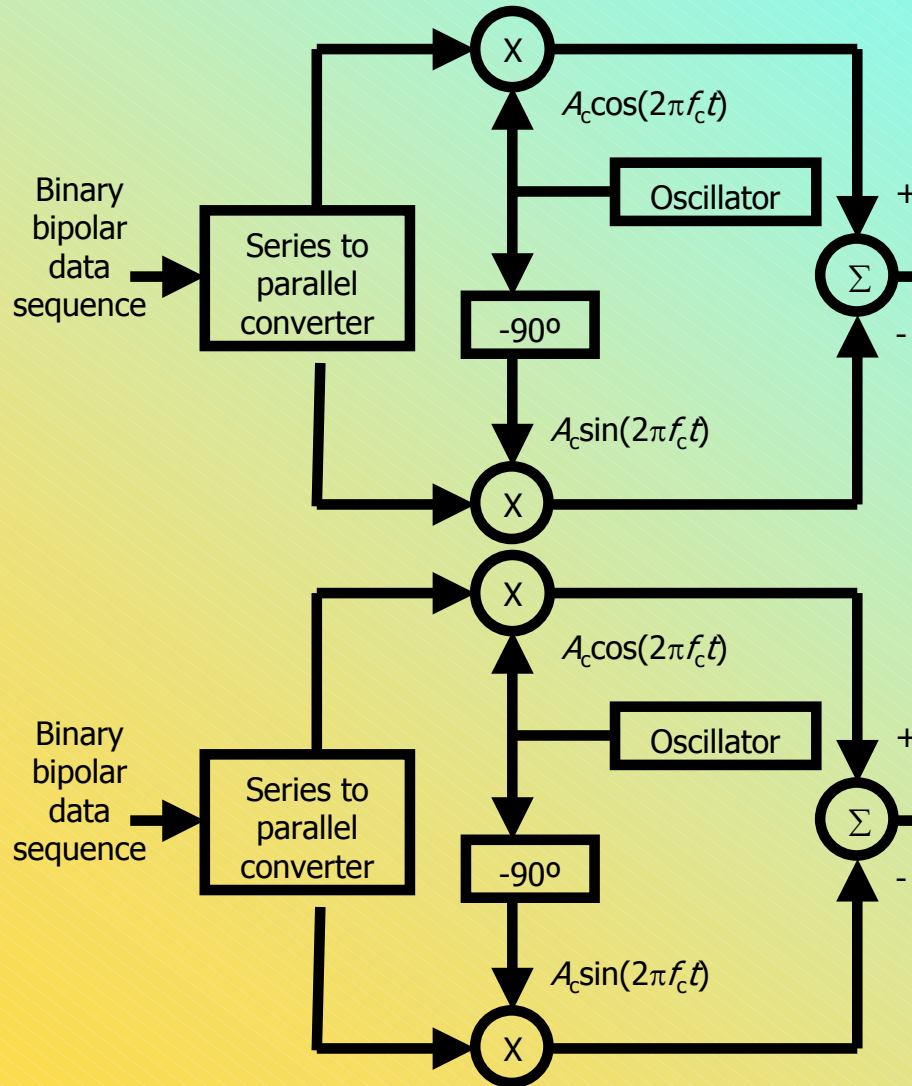


Offset QPSK (OQPSK)



- 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



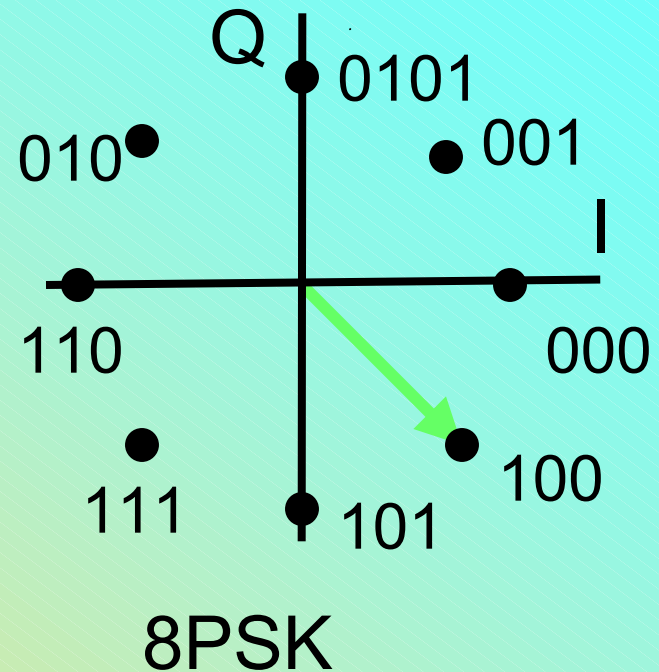
Offset 45 degrees

8PSK

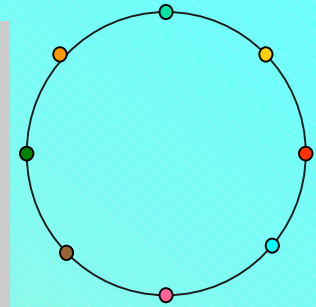
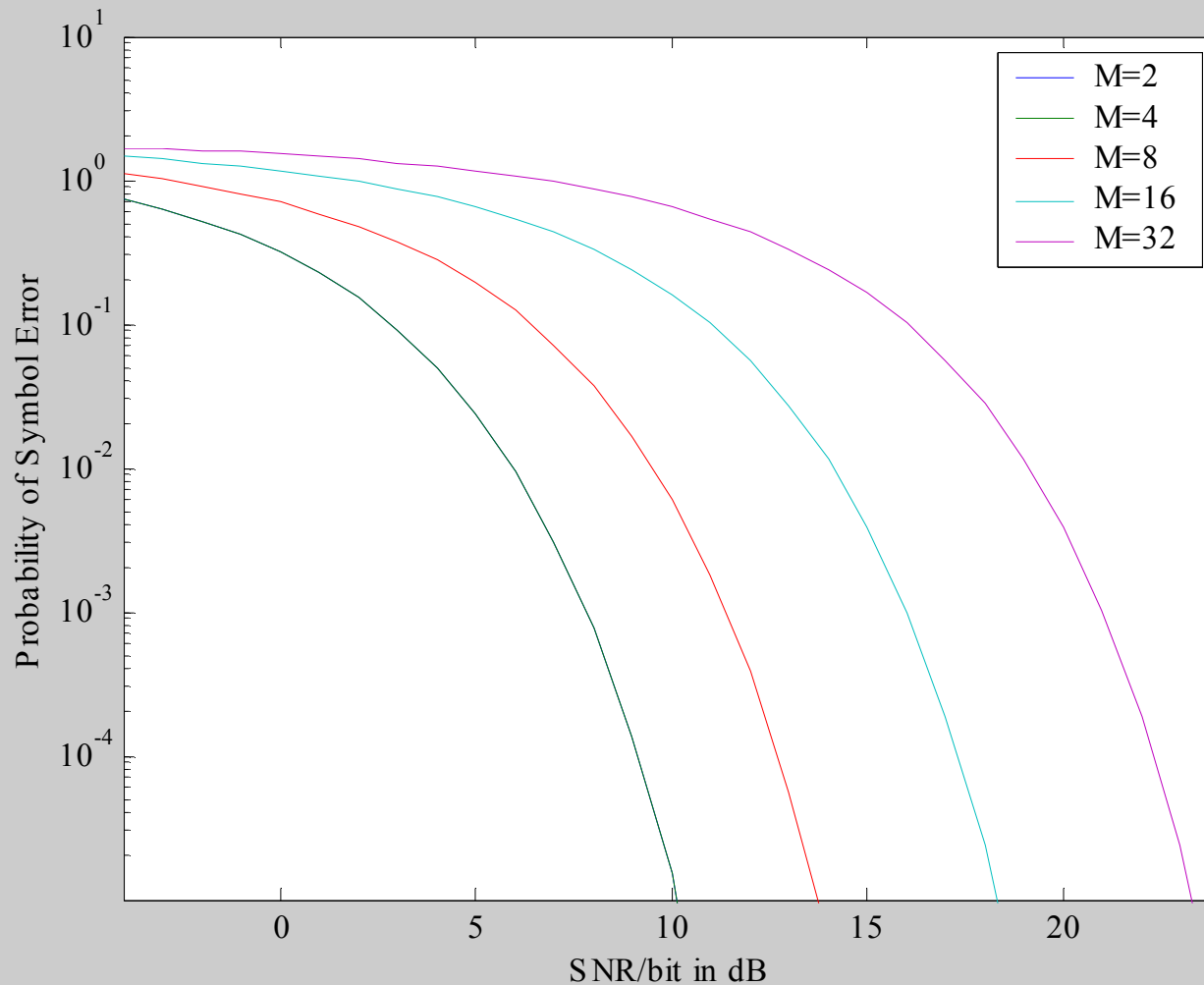
- 8PSK, Two QPSK modulators offset by 0° or 45°
- Output switches between QPSK modulators ~

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 ~



Symbol Error in M-ary PSK Systems

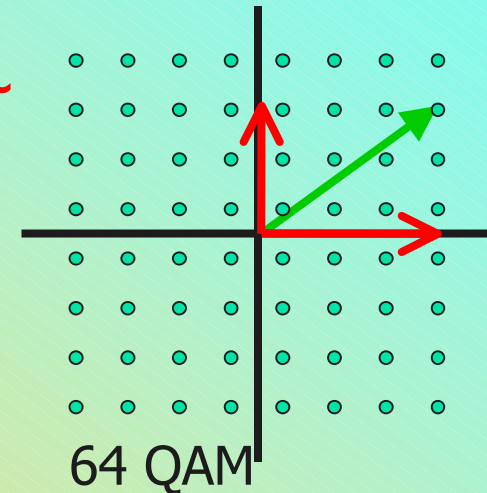
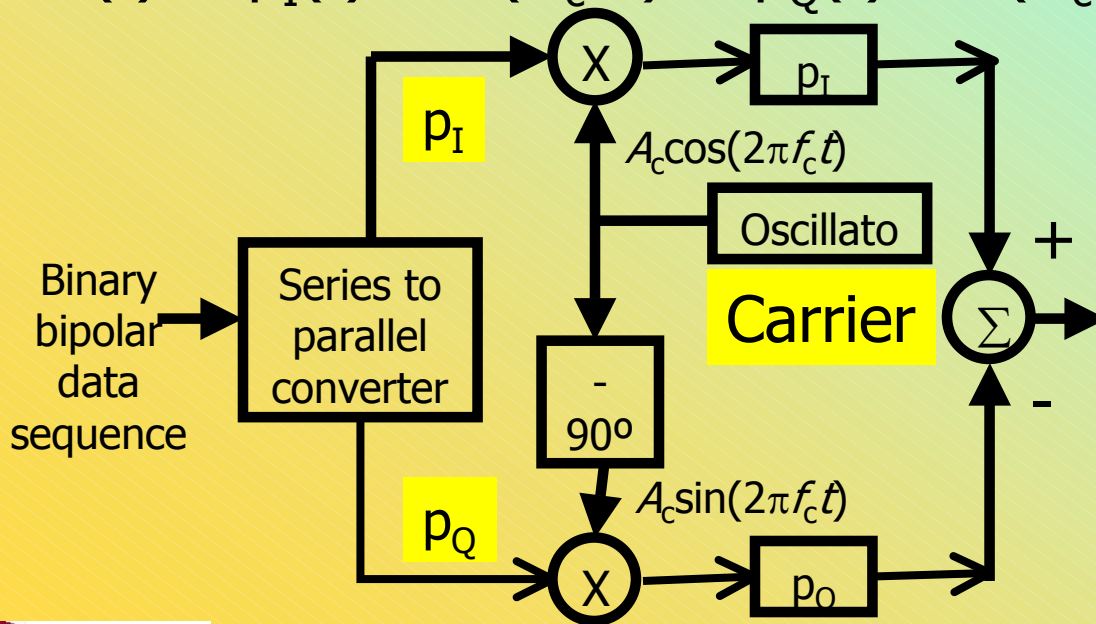


Note:
More
Complex
Modulations
Require
higher S/N
for the same
Error ~

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

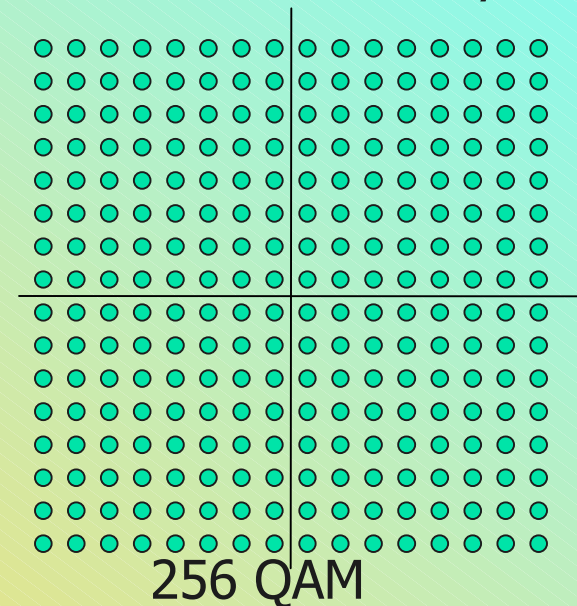
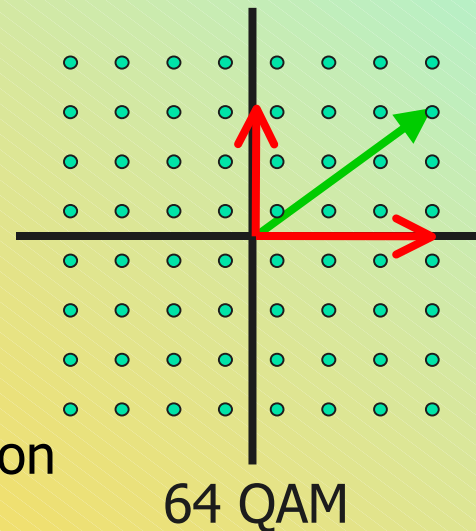
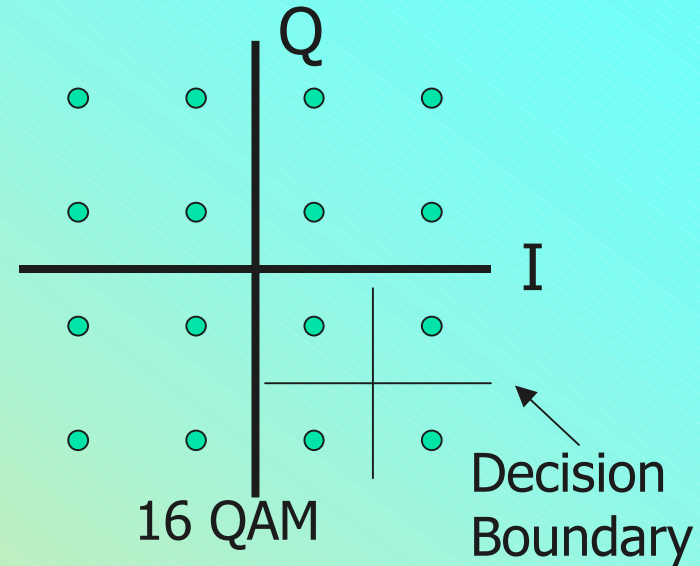
$$S(t) = p_I(t) * \cos(\omega_c * t) + p_Q(t) * \sin(\omega_c * t) \sim$$



Carrier Vector is the summation of the I & Q vectors

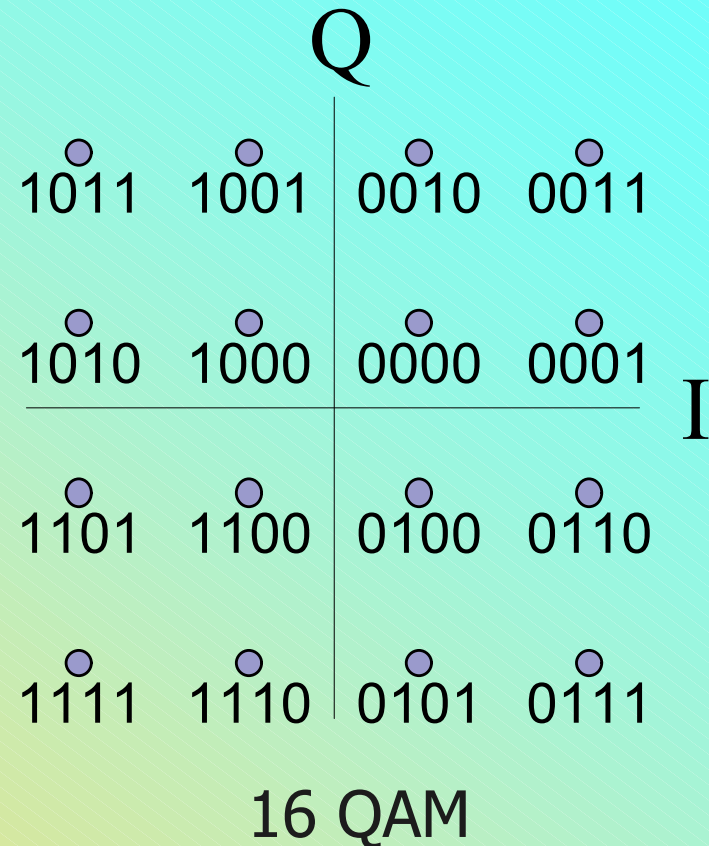
Typical Constellations

- 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



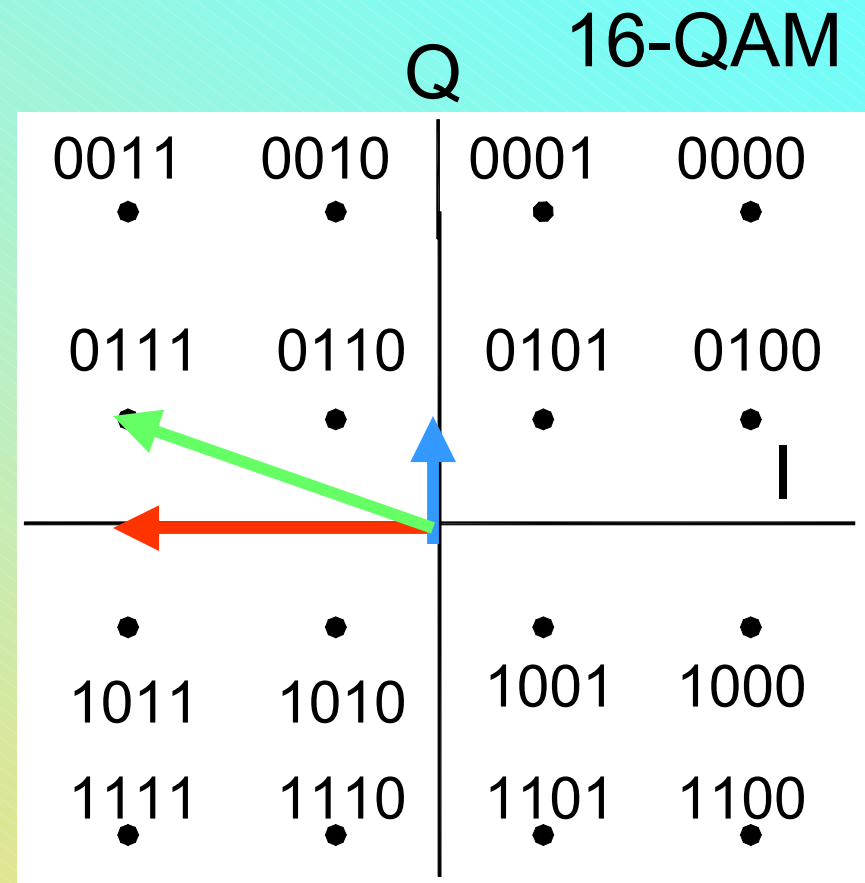
Constellation Characteristics: 16QAM Example

- 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 ~



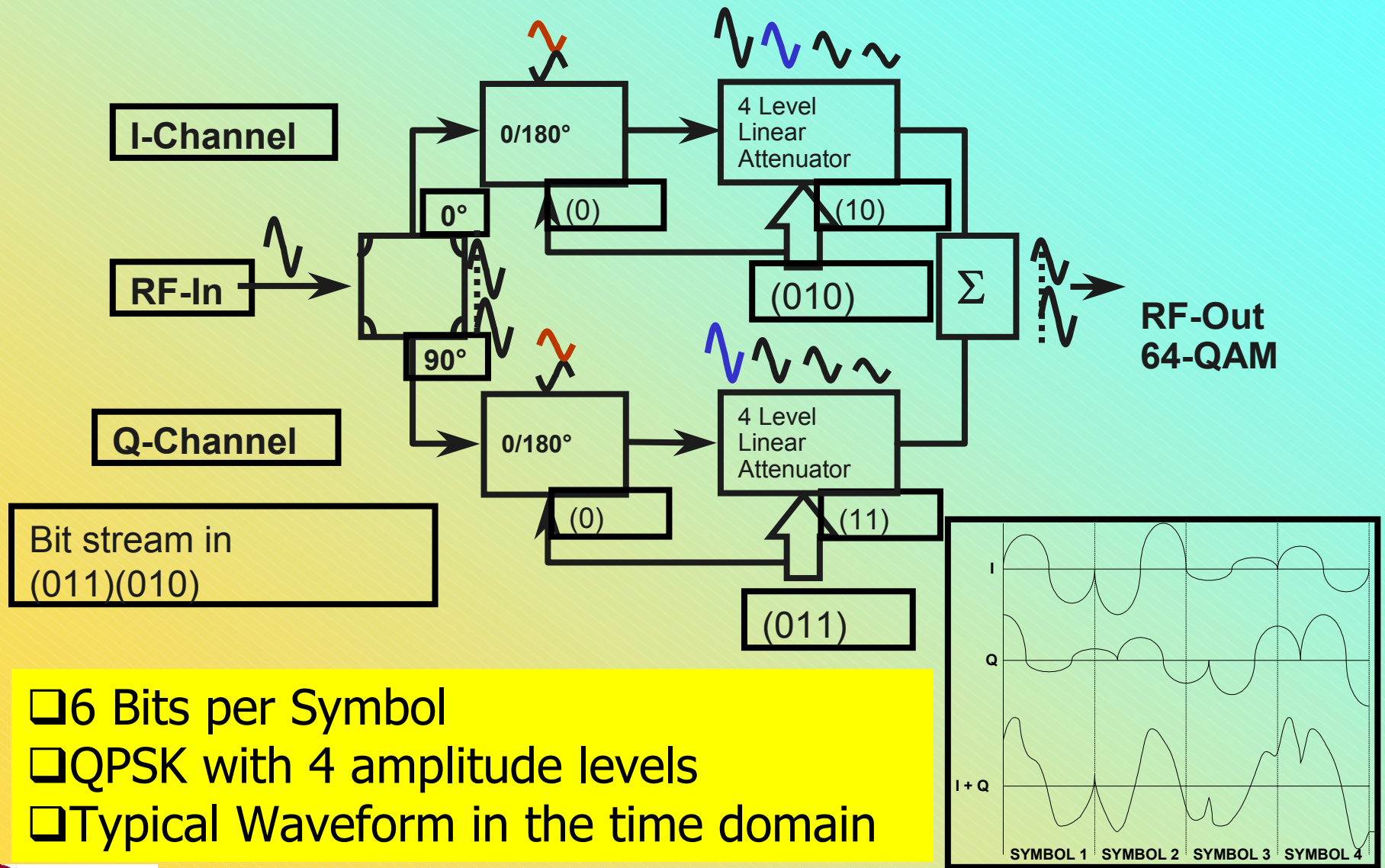
16-QAM Modulation (4 Bits / Symbol)

- 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

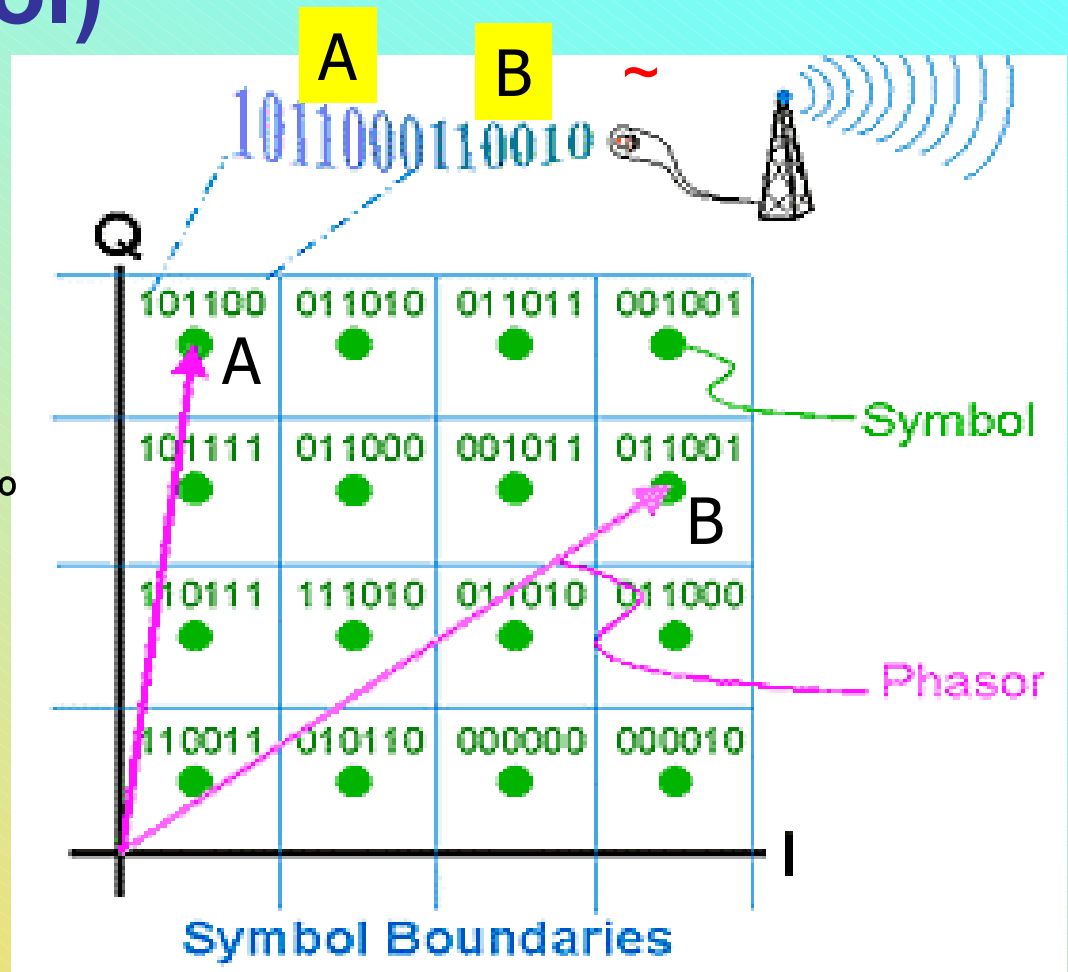
64-Quadrature Amplitude Modulation



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

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)
- $M = \text{No. of States}$
 - $M = 2^N * 2^A$
 - $M = 2^2 * 2^4 = 64$

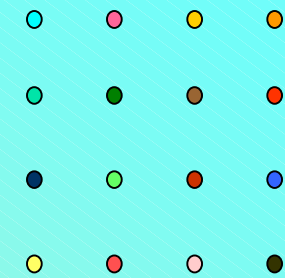
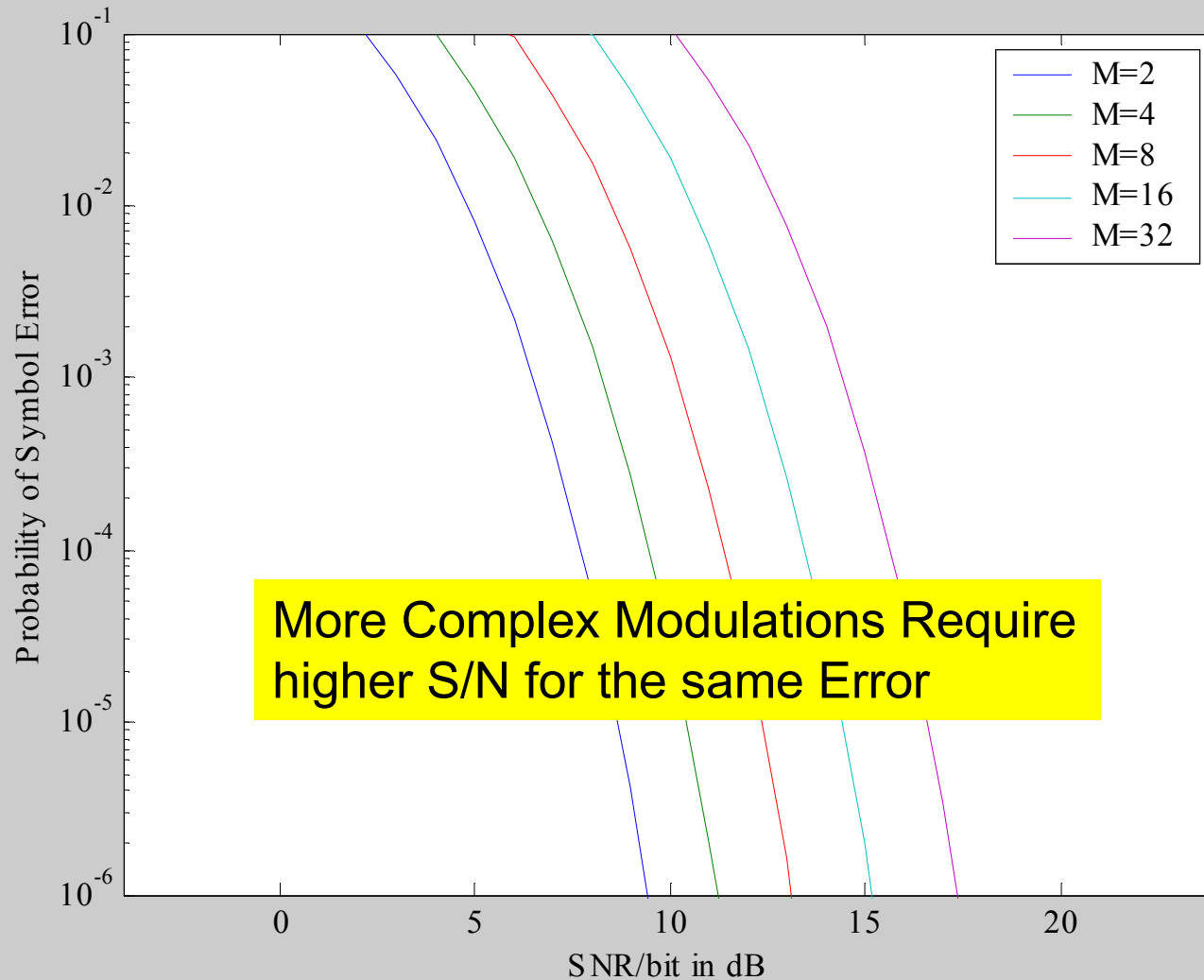


1/4 64 QAM Constellation

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

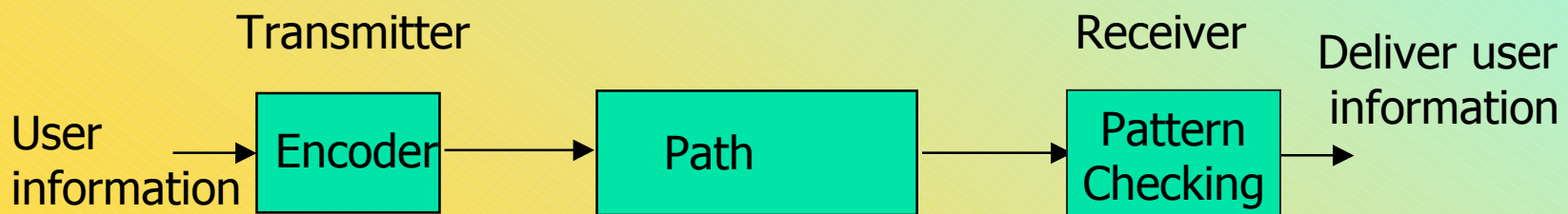
□ Number of Standard Deviations to Threshold ~

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 ~

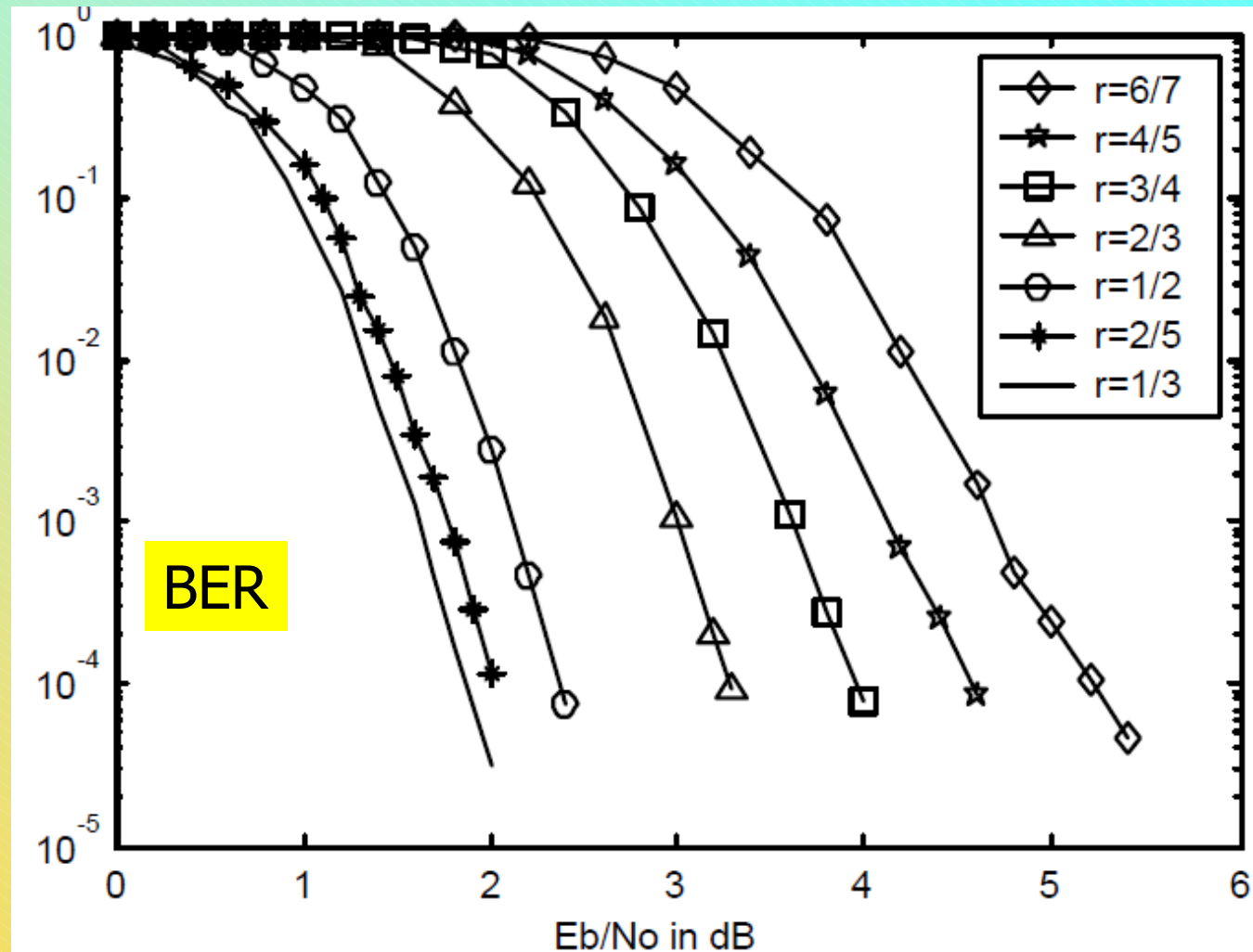


Types of Error-Correcting Codes

- 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

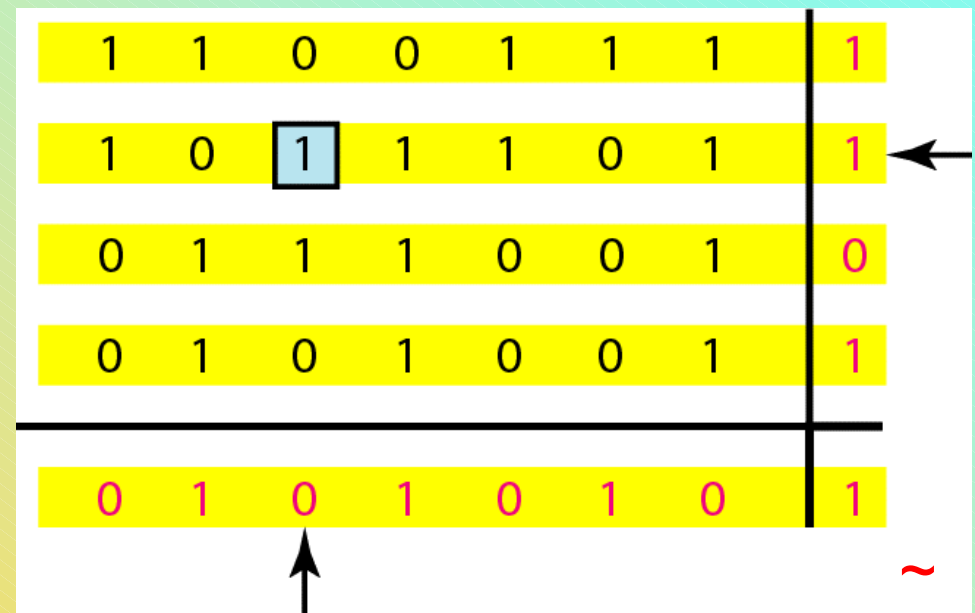
- $R=3/4$ means 4 bits are sent for every three data bits
- More extra bits – the more errors that can be corrected



- More extra bits – lower E_b/N_0 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 → 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
- $R=7/10$

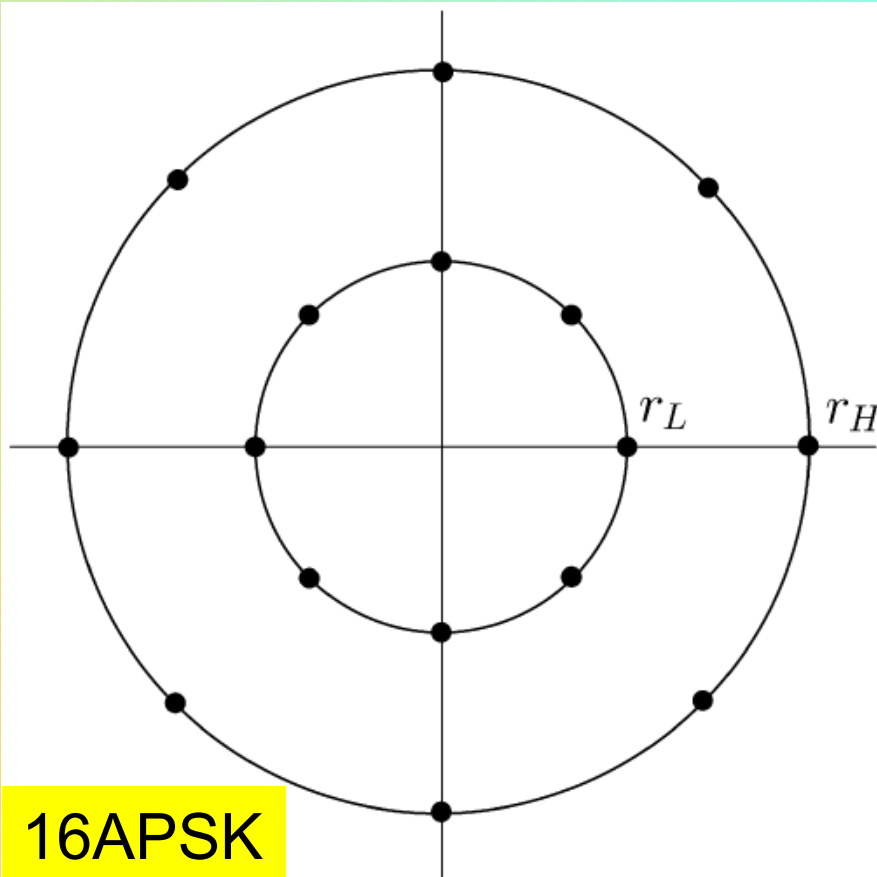


8. Amplitude and Phase Shift Keying (APSK)

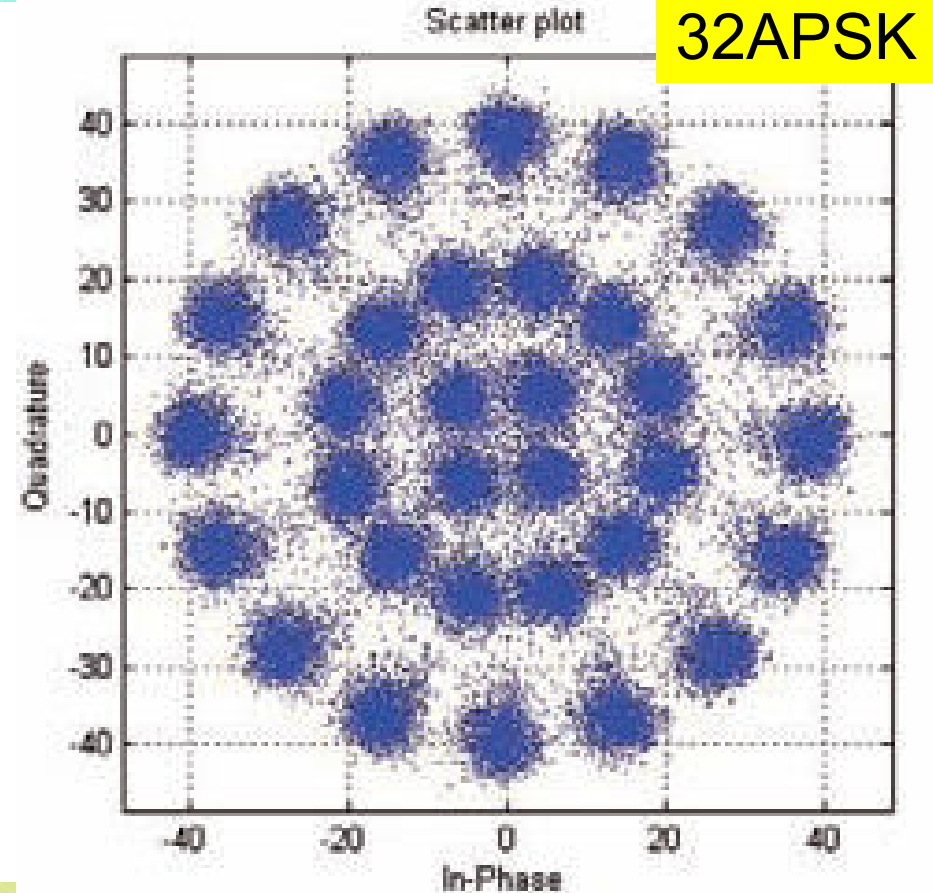
Digital Video Modulator

- 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 ~

16APSK & 32APSK



16APSK

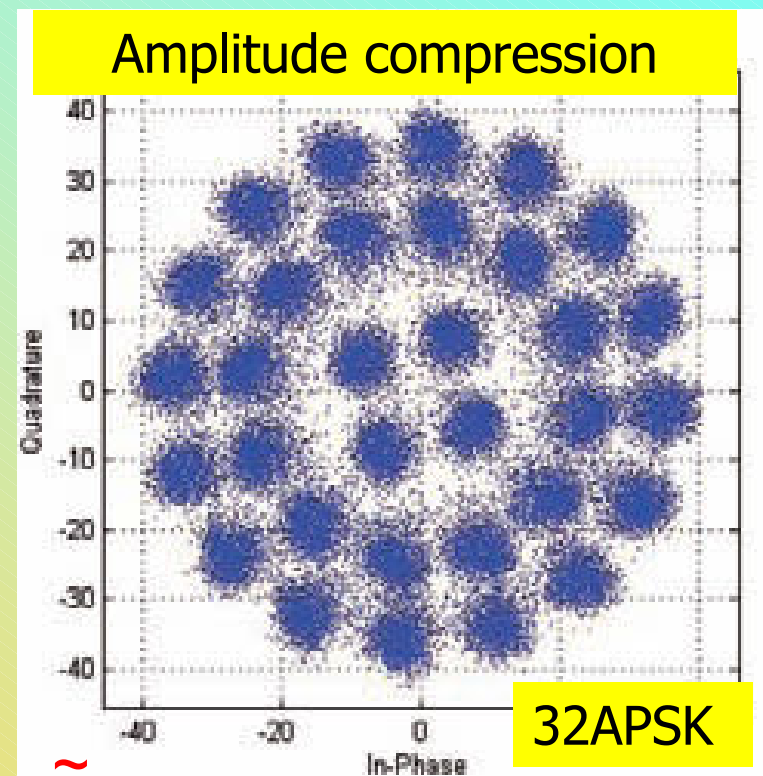
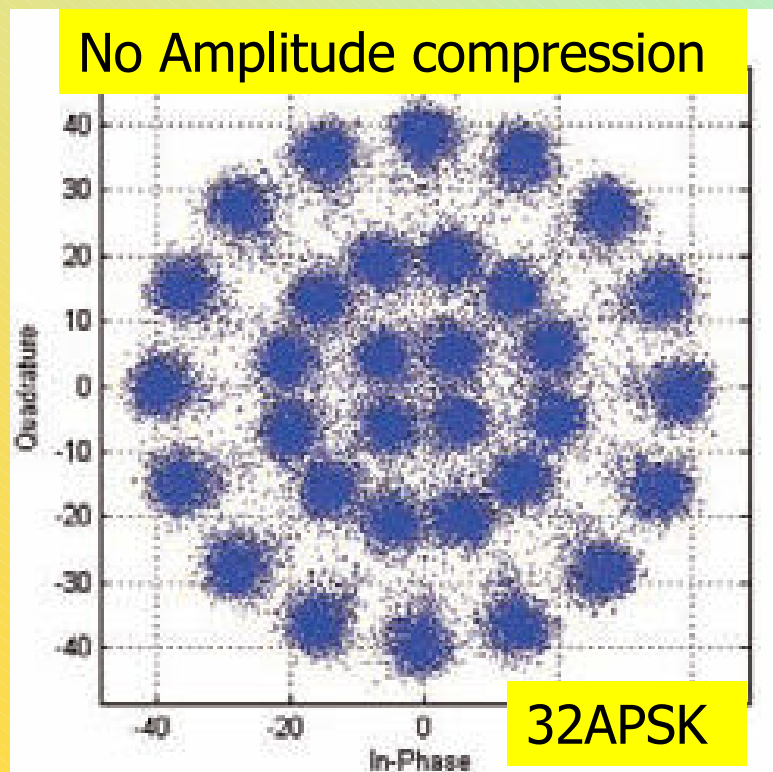


32APSK

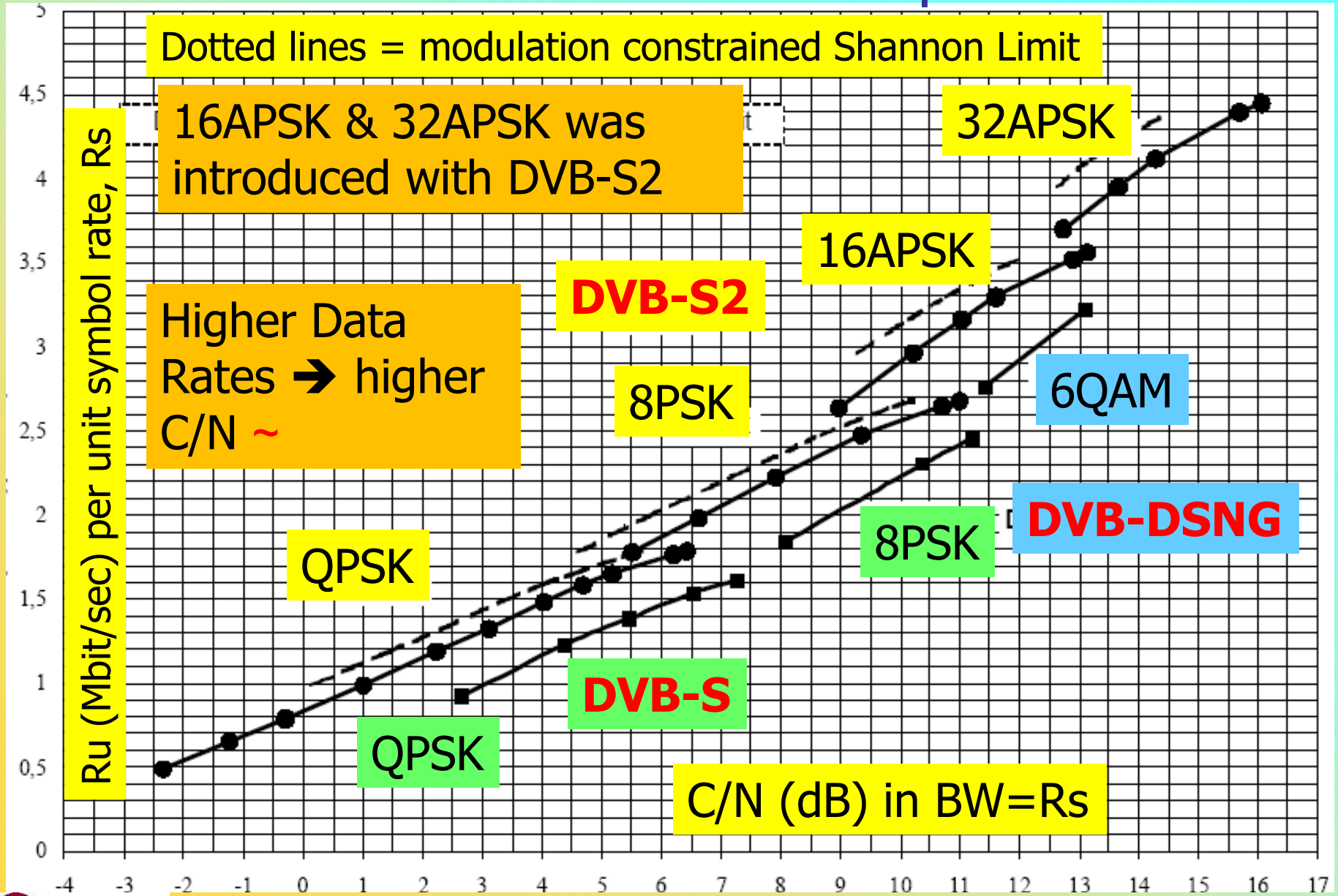
- QAM modulators can place signals at any vector location
- 16APSK more immune to Phase Noise than 16QAM
- 32APSK symmetrical means of doubling bits/symbol
 - Emphasis on Phase Noise immunity ~

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 ~



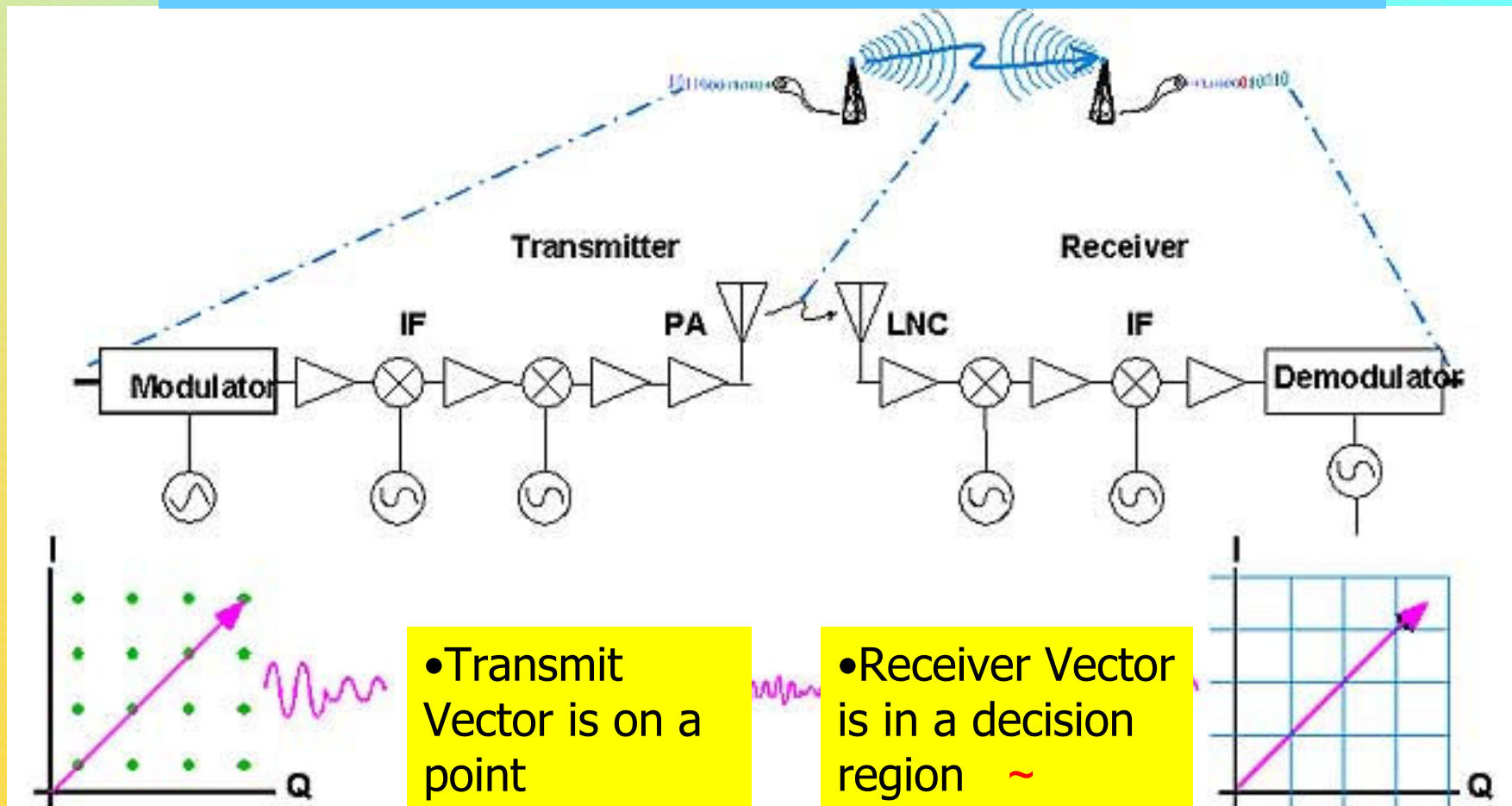
DVB-S2 Carrier to Noise Requirements



Modulation Standards are driven by HDTV

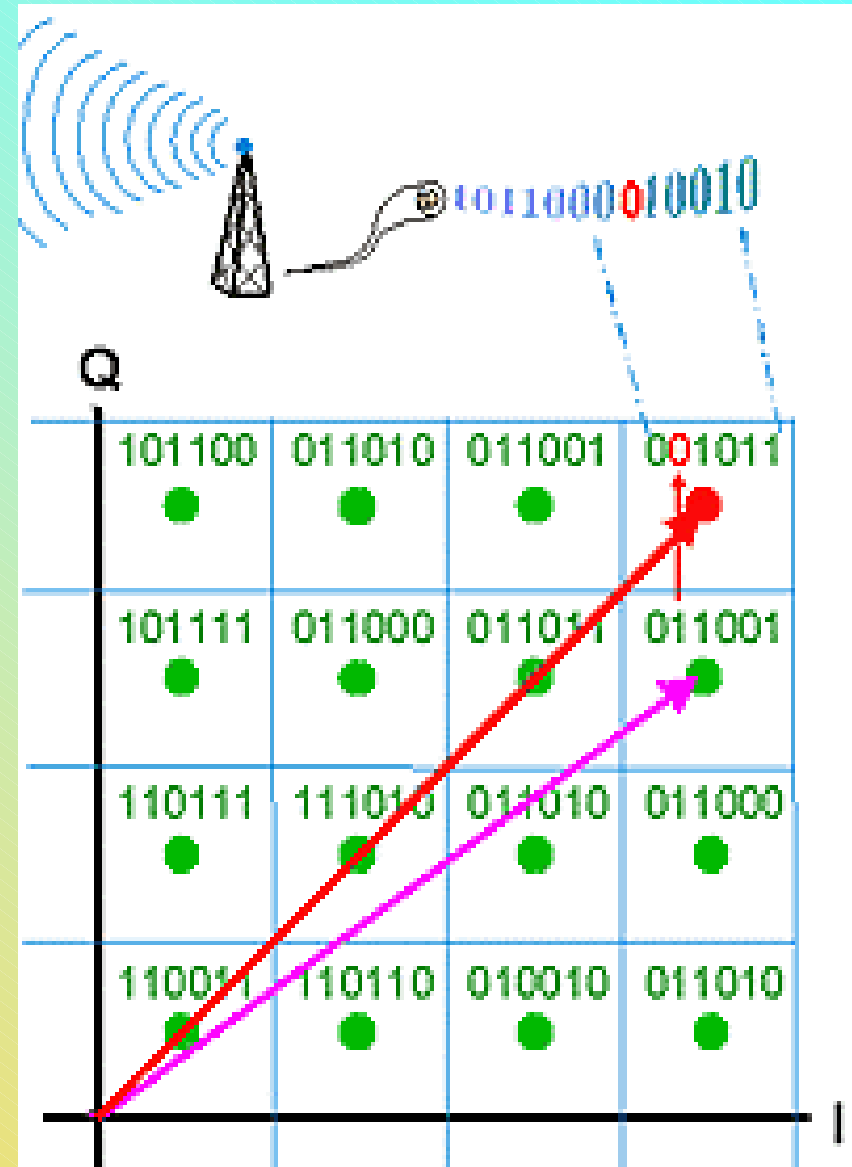
- Standard Analog TV bandwidth is 6MHz
- HDTV with twice the resolution is 12MHz
- If the analog signal is digitized with 8 bits that → 96MHz of baseband signal (192MHz RF Bandwidth)
- Even with 16APSK (32APSK is not currently in use) bandwidth compresses to 24MHz baseband & 48MHz RF
- HDTV uses less 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



QAM Decision Region

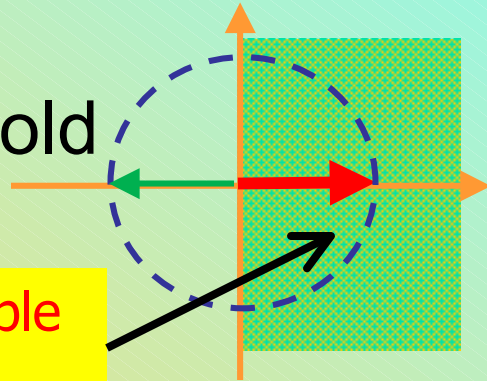
- ❑ Lines between the constellation points are the threshold levels
- ❑ Signals residing in the square are assumed to reside at the discrete vector location. ~



Threshold Spacing

- BPSK
- Threshold $\pm 90^\circ$

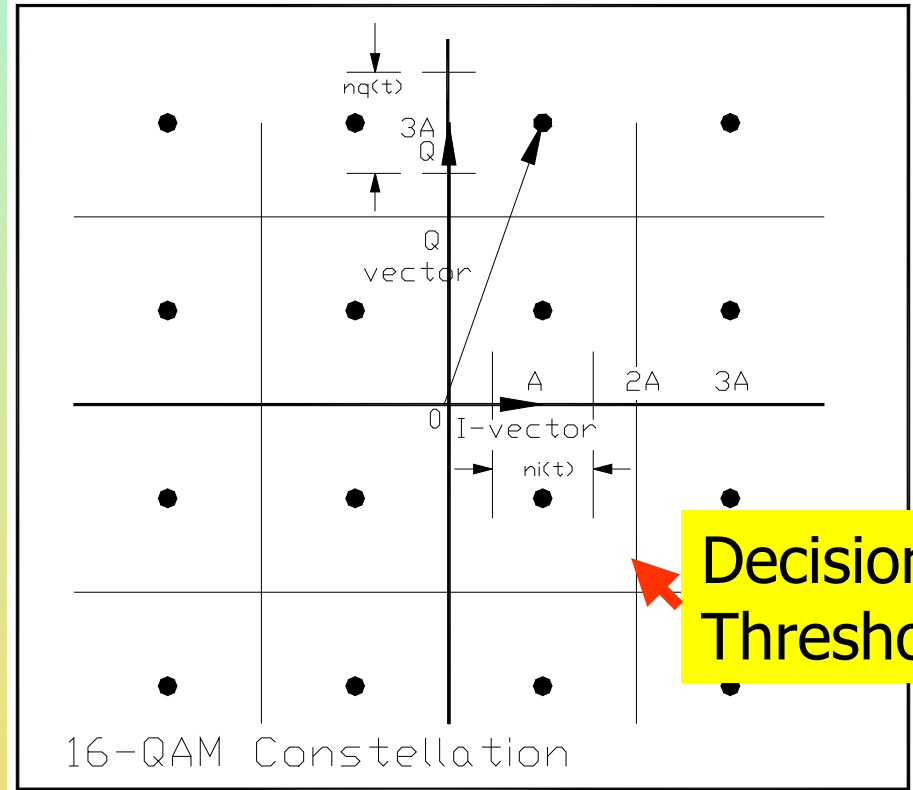
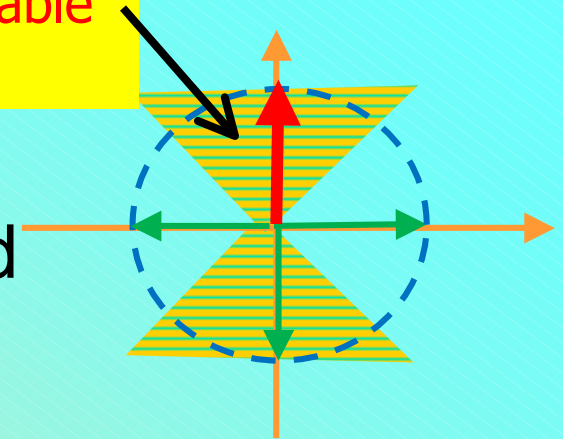
Acceptable Region



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

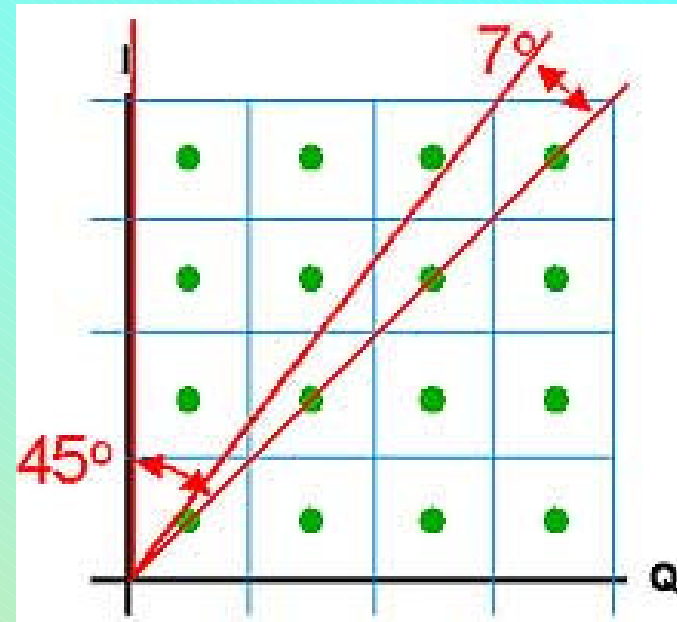
- QPSK
- Threshold $\pm 45^\circ$

Acceptable Region



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 ~