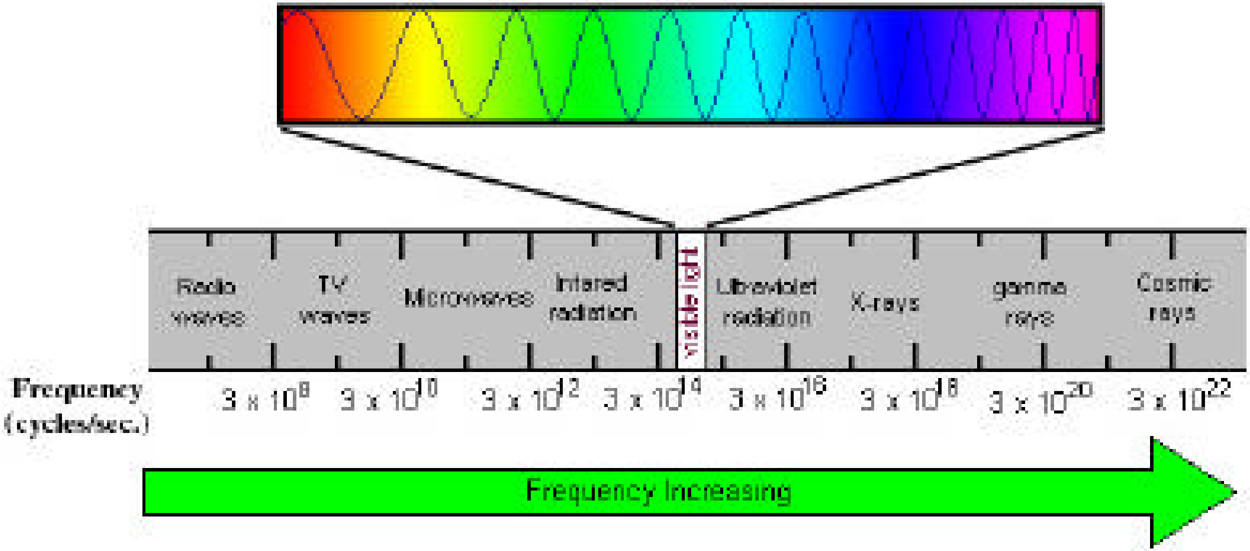
Digital television

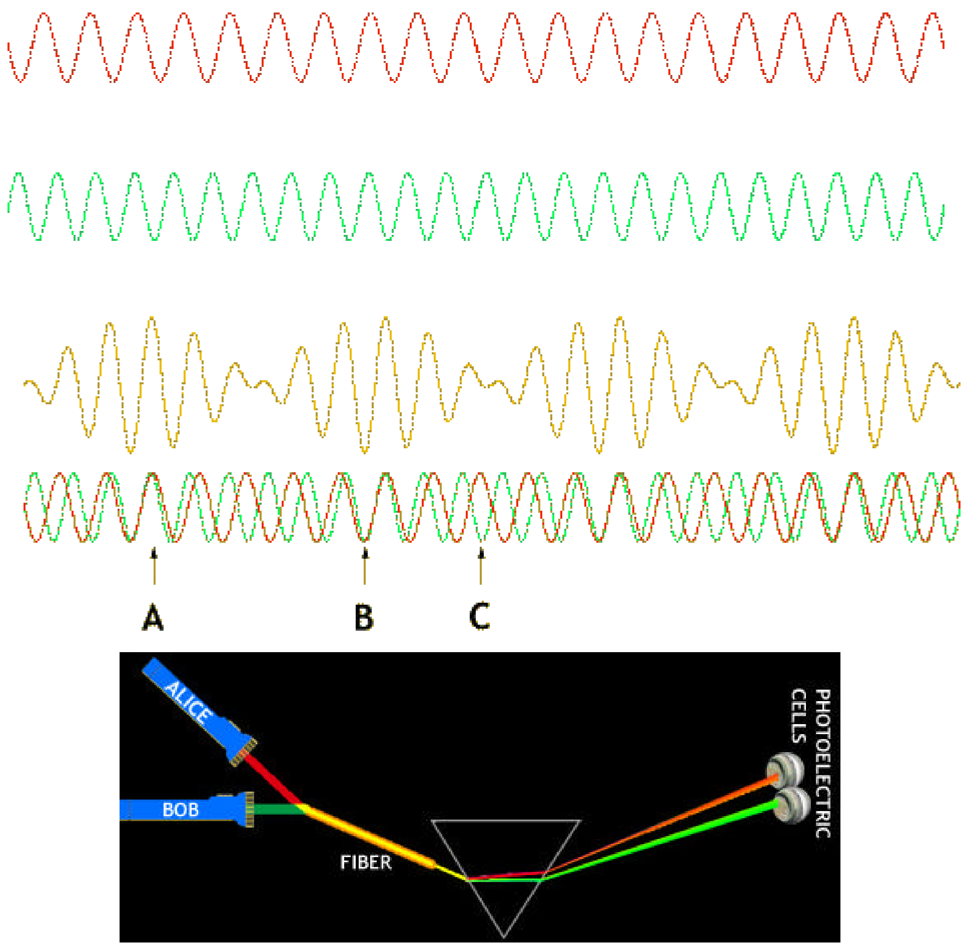
Modulation techniques

- Electromagnetic waves
- Analog modulation
    - Amplitude modulation
    - Angle modulation
        - Frequency modulation
        - Phase modulation
- Digital modulation
    - On-Off keying
    - Amplitude shift keying
    - Phase shift keying
    - Quadrature amplitude modulation

Electromagnetic waves



Electromagnetic waves



Modulation

"modulate" is "To adjust or adapt to a certain proportion."

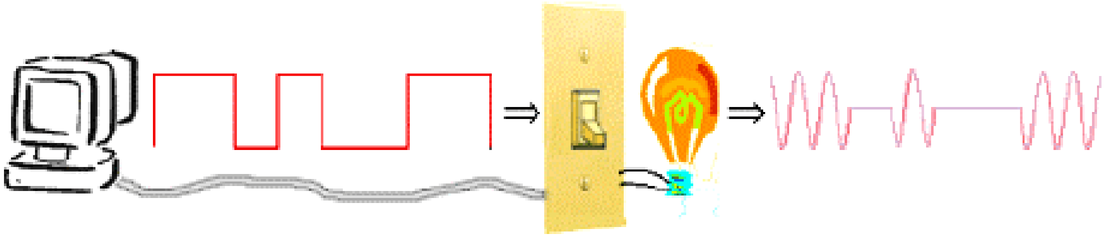
”Linear” modulation

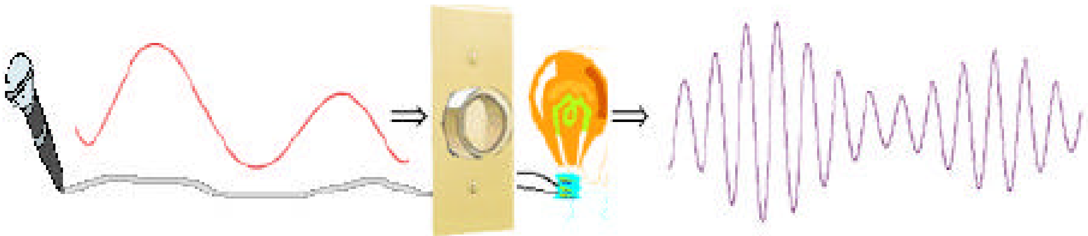
$$x_c(t) = A_c\big(1 + \mu x(t)\big)\cos\omega_c t$$

Exponential modulation

$$\begin{aligned} x_c(t) &= A_c \cos\big(\omega_c t + \phi(t)\big) \\ &= A_c \cos\Theta_c(t) = A_c \operatorname{Re}\left[e^{j\Theta_c(t)}\right] \end{aligned}$$

Amplitude modulation

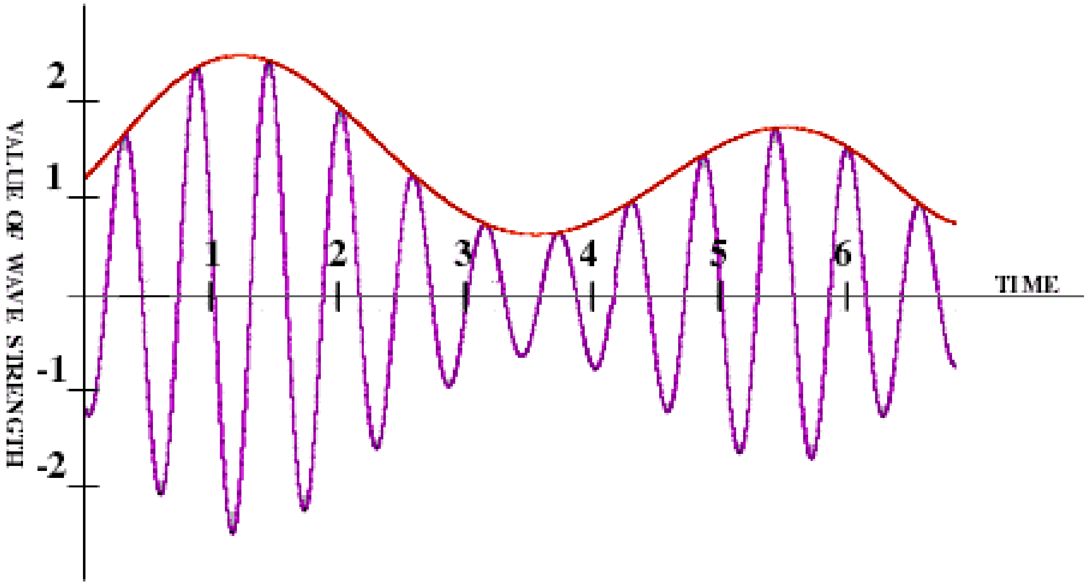




E.g..

- AM radio stations
- Analog television

Amplitude modulation



$$x_c(t) = A_c m(t) \cos 2\pi f_c t \quad (3.1)$$

$$X_c(f) = \frac{A_c}{2}\left[M(f+f_c) + M(f-f_c)\right] \quad (3.2)$$

AM: waveforms and bandwidth

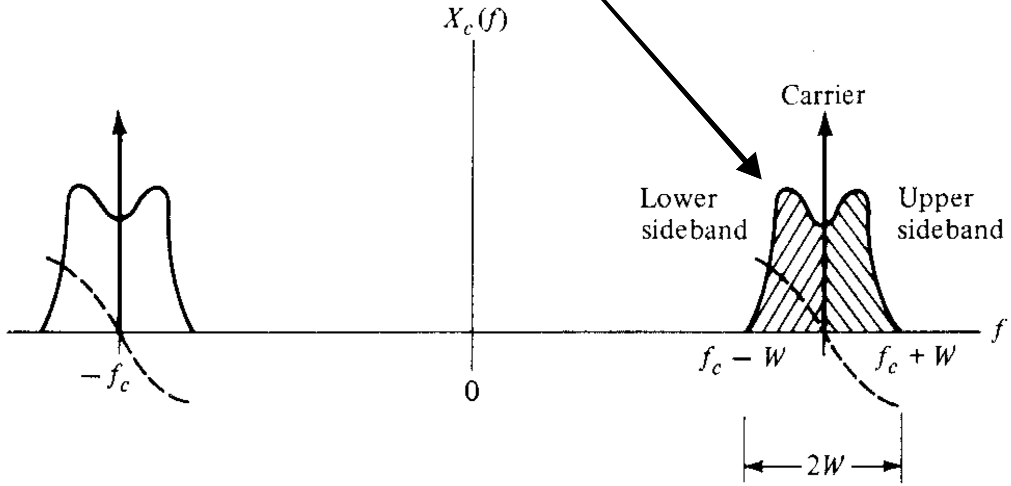
- AM in frequency domain:

$$x_C(t) = A_C[1 + m x_m(t)]\cos(w_C t)$$

$$= \underbrace{A_C \cos(w_C t)}_{\text{Carrier}} + \underbrace{m x_m(t)\cos(w_C t)}_{\text{Information carrying part}}$$

$$X_C(f) = \underbrace{A_C d(f - f_C)/2}_{\text{Carrier}} + \underbrace{m A_C X_m(f - f_C)/2}_{\text{Information carrying part}} \quad f > 0 \text{ (for brief notations)}$$

- AM bandwidth is twice the message bandwidth *W*:



Phase modulation (PM)

- Carrier Wave (CW) signal: $x_C(t) = A_C \cos(\underbrace{w_C t + f(t)}_{q_C(t)})$
- In exponential modulation the modulation is “in the exponent” or “in the angle”

$$x_C(t) = A_C \cos(q_C(t)) = A_C \,\mathrm{Re}[\exp(jq_C(t))]$$

- Note that in exponential modulation superposition does not apply:

$$x_C(t) = A\cos\{w_C t + k_f\,[a_1(t) + a_2(t)]\}$$

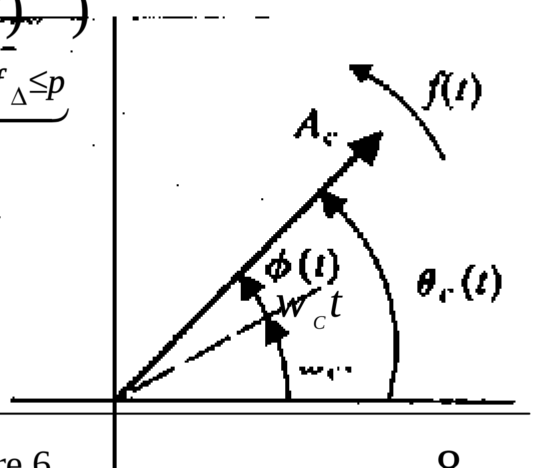
$$\neq A\cos w_C t + A\cos k_f\,[a_1(t) + a_2(t)]$$

- In **phase modulation** (PM) carrier phase is linearly proportional to the modulation amplitude:

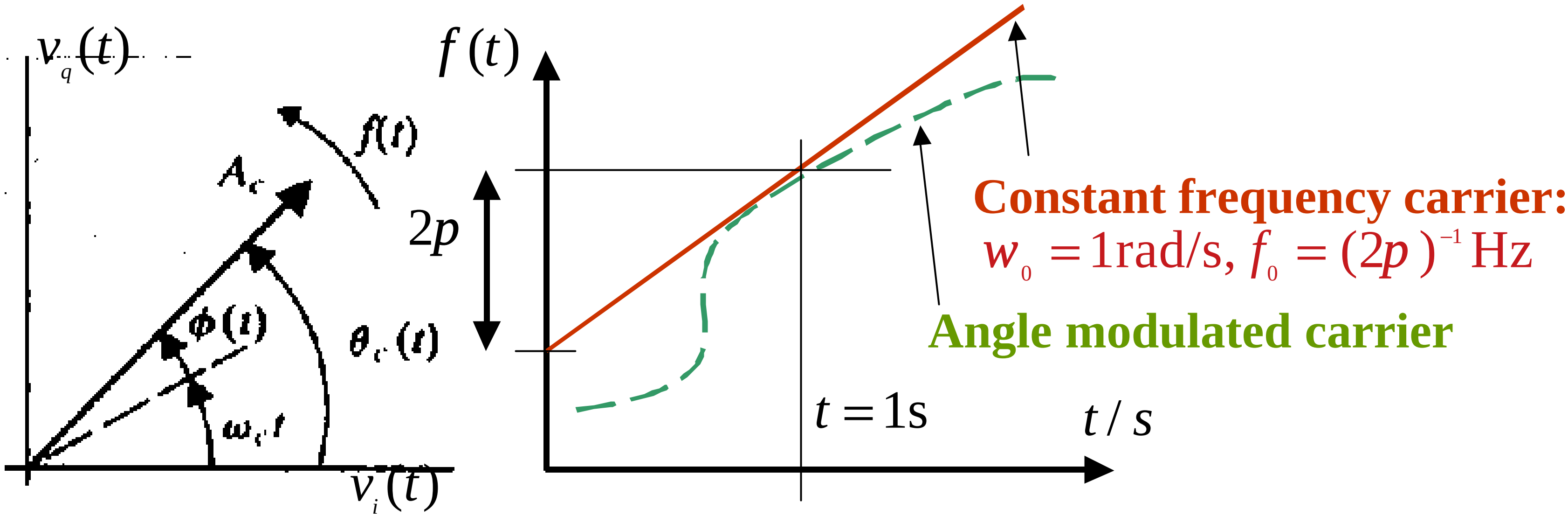
$$x_{PM}(t) = A_C \cos(\underbrace{w_C t + \overbrace{f(t)}^{f_\Delta x(t), f_\Delta \le p}}_{q_C(t)})$$

- Angular phasor has the instantaneous frequency (*phasor rate*)

$$w = 2p\, f(t)$$



Instantaneous frequency



- Angular frequency *w* (rate) is the derivative of the phase (the same way as the velocity *v(t)* is the derivative of distance *s(t)*)
- For continuously changing frequency instantaneous frequency is defined by differential changes:

$$w(t) = \frac{d f(t)}{dt} \qquad f(t) = \int_{-\infty}^{t} w(a)\,da$$

Compare to linear motion: $v(t) = \dfrac{ds(t)}{dt}\left(\approx \dfrac{s_2(t) - s_1(t)}{t_2 - t_1} \right)$

Frequency modulation (FM)

- In frequency modulation carrier instantaneous frequency is linearly proportional to modulation frequency:

$$w = 2p\ f(t) = dq_C(t)/dt$$
$$= 2p[f_C + f_\Delta x(t)]$$

- Hence the FM waveform can be written as

$$x_C(t) = A_C \cos(\underbrace{w_C t + 2pf_\Delta \mathbf{Z}_{t_0}^{t} x(l)\,dl}_{q_C(t)}), t \geq t_0$$

$$f(t) = \int_{-\infty}^{t} w(a)\,da$$

integrate ←

- Note that for FM

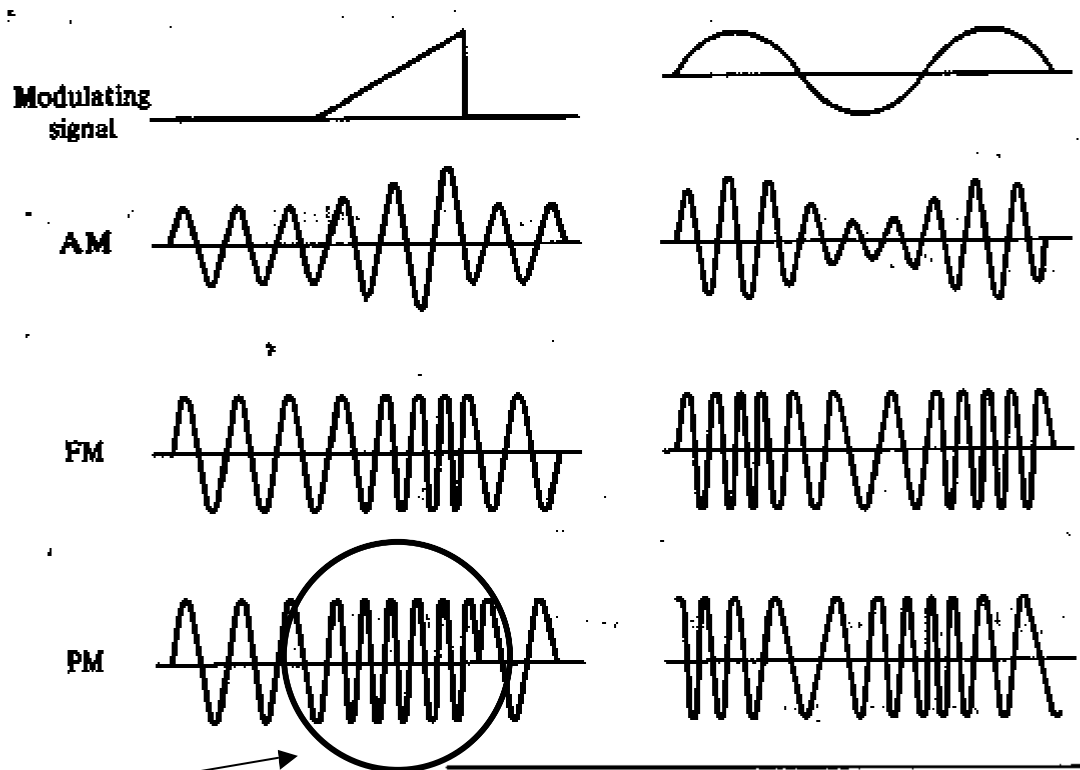
$$f(t) = f_C + f_\Delta x(t)$$

and for PM

$$f(t) = f_\Delta x(t)$$

	Instantaneous phase $\phi(t)$	Instantaneous frequency $f(t)$
PM	$\phi_\Delta x(t)$	$f_c + \frac{1}{2\pi}\phi_\Delta \dot{x}(t)$
FM	$2\pi f_\Delta \int^t x(\lambda)\,d\lambda$	$f_c + f_\Delta x(t)$

AM, FM and PM waveforms



Constant frequency follows constant modulation waveform derivative

$$x_{PM}(t) = A_C \cos(w_C t + f_\Delta x(t))$$

$$x_{FM}(t) = A_C \cos(w_C t + 2pf_\Delta \int_t x(l)\,dl)$$

	Instantaneous phase $\phi(t)$	Instantaneous frequency $f(t)$
PM	$\phi_\Delta x(t)$	$f_c + \frac{1}{2\pi}\phi_\Delta \dot{x}(t)$
FM	$2\pi f_\Delta \int^t x(\lambda)\,d\lambda$	$f_c + f_\Delta x(t)$

FM Bandwidth

Normally calculated using Carlsons rule

$B = 2\ (D + 1)W$

where W is the maximun modulation frequency and
D is the devation rato $D = f_\Delta / W$

f_Δ is the peak frequency deviation

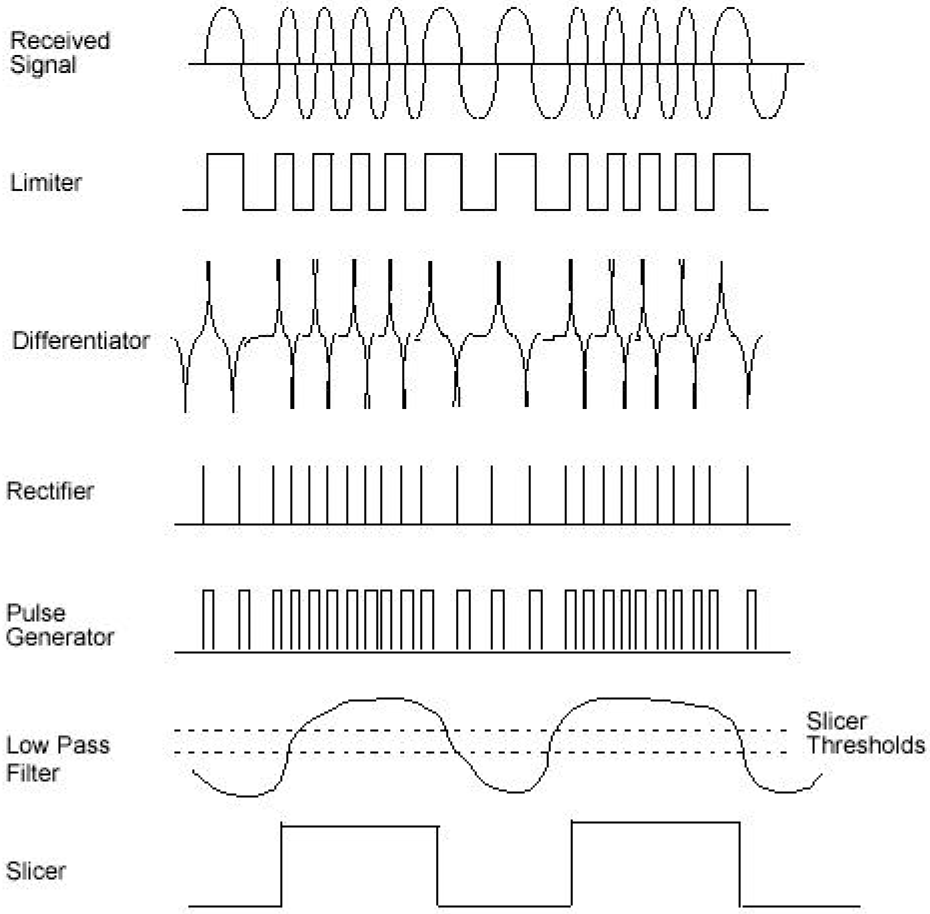
FM Radio: $f_\Delta = 75$ kHz, $W = 15$ kHz

$B = 2 * (75 / 15 + 1) * 15$ kHz $= 180$ kHz

FM demodulation - Example

Zero-crossing based demodulation

Other:
PLL



Comparison of carrier wave modulation systems

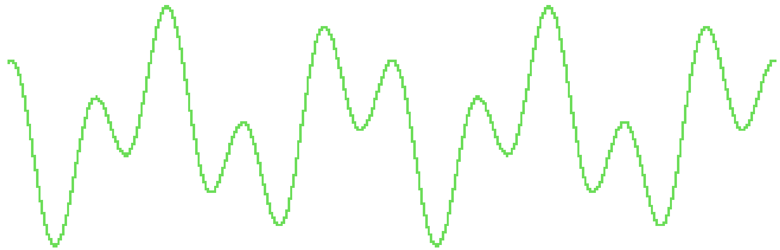
Type	$b = B_T/W$	$(S/N)_D/\gamma$	γ_{th}	DC	Complexity	Comments	Typical applications
Baseband	1	1	...	No†	Minor	No modulation	Short-haul links
AM	2	$\frac{\mu^2 S_x}{1+\mu^2 S_x}$	20	No	Minor	Envelope detection $\mu \leq 1$	Broadcast ratio
DSB	2	1	...	Yes	Major	Synchronous detection	Analog data, multiplexing
SSB	1	1	...	No	Moderate	Synchronous detection	Point-to-point voice, multiplexing
VSB	1+	1	...	Yes	Major	Synchronous detection	Digital data
VSB + C	1+	$\frac{\mu^2 S_x}{1+\mu^2 S_x}$	20	Yes‡	Moderate	Envelope detection $\mu < 1$	Television video
PM§	$2M(\phi_\Delta)$	$\phi_\Delta^2 S_x$	$10b$	Yes	Moderate	Phase detection $\phi_\Delta \leq \pi$	Digital data
FM§¶	$2M(D)$	$3D^2 S_x$	$10b$	Yes	Moderate	Frequency detection	Broadcast radio, microwave relay, satellite systems

Unless direct-coupled.
With electronic DC restoration.
$b \geq 2$.

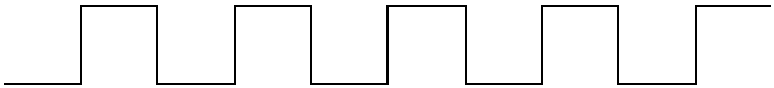
Digital modulation

On-off keying (Binary Amplitude Key Shifting) bandwidth?

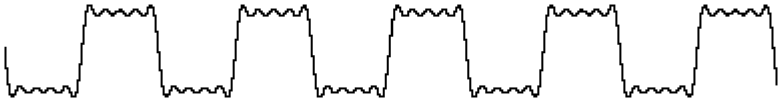
2 analog signals



digital signal (010101...)



digital signal approximated
using 5 sinus waveforms



$$\left[\sin \pi f x + \frac{\sin 3\pi f x}{3} + \frac{\sin 5\pi f x}{5} + \frac{\sin 7\pi f x}{7} + \frac{\sin 9\pi f x}{9}\right]$$ e.g. keeping 5 components -> B = 18 f_m

Shannon's theorem

The capacity *C* of a channel is

$$C = B \log_2 \left(1 + \frac{S}{N} \right).$$

where *B* is the bandwidth and S/N is the signal to noise ratio (given in watts/watts)

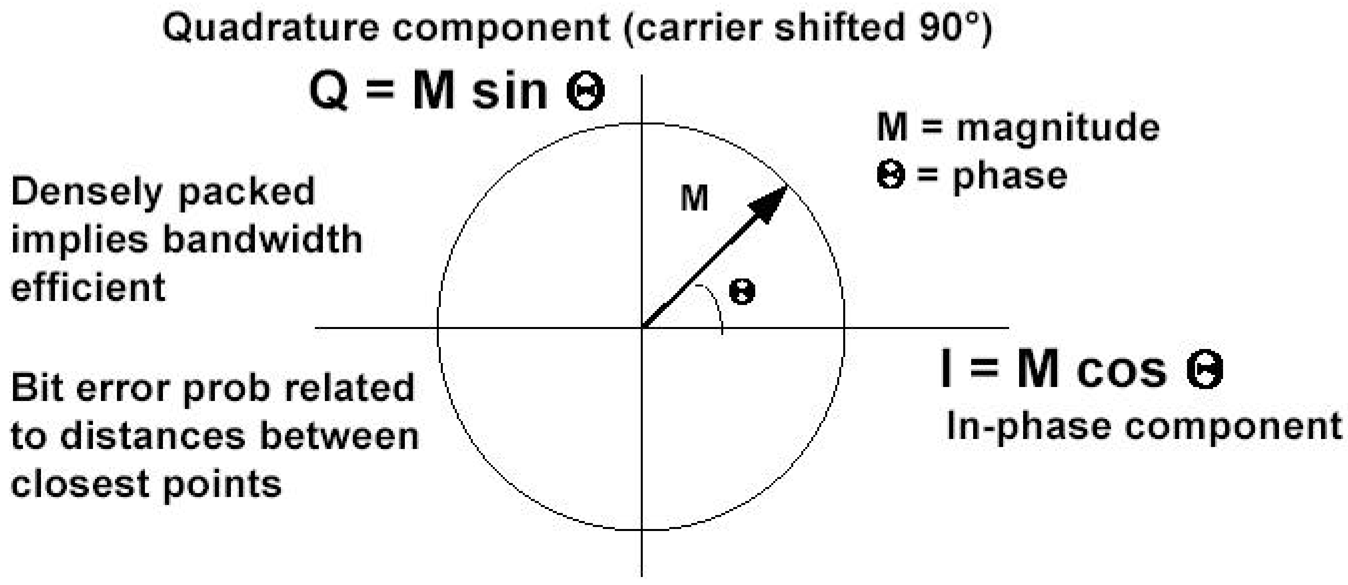
PAL analog 6MHz studio eq. S/N = 65 dB -> 129 Mbit/s
PAL analog 6MHz broadcast S/N = 21 dB -> 42 Mbit/s

Practical for digital applications 15 dB -> 30 Mbit/s

Normal digital applications: 6 bps / Hz

Digital modulation

- Modify carriers amplitude and/or phase (and frequency)
- Constellation: Vector notation / polar coordinates



Modulation scheme - considerations

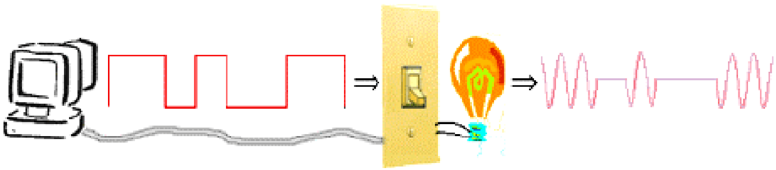
- High spectral efficiency
- High power efficiency
- Robust to multipath effects
- Low cost and ease of implementation
- Low carrier-to-cochannel interference ratio
- Low out of band radiation
- Constant or near constant envelope
  - Constant: Only phase is modulated
  - Non-constant: phase and amplitude is modulated

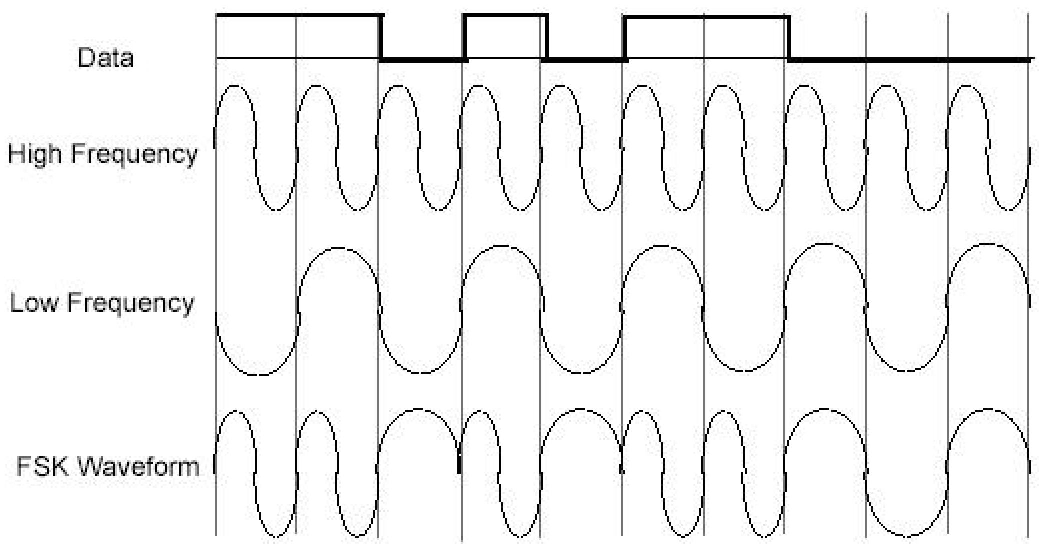
Binary modulations

•Amplitude shift keying (ASK)

Transmission on-off

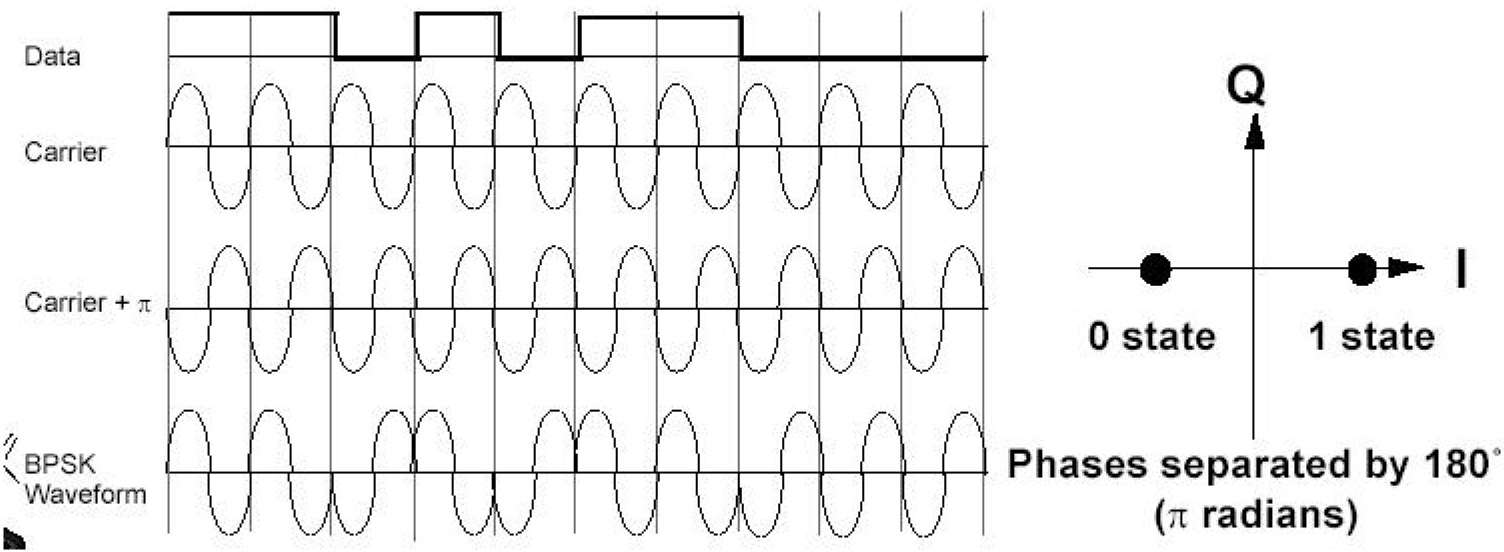
•Frequency shift keying (FSK)





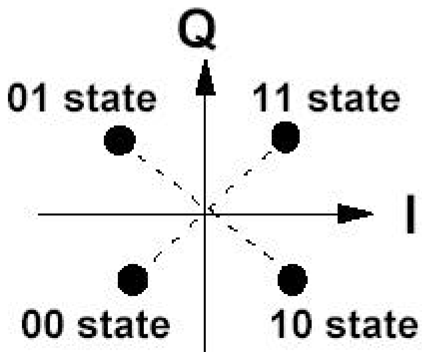
Binary modulations

- Binary phase shift keying (BPSK)
  - Simple to implement, inefficient use of bandwidth
  - Very robust, used in satellite communications



Phase key shifting

- Quadrature Phase Shift Keying (QPSK)
  - Multilevel modulation technique: 2 bits per symbol
  - More spectral efficiency, more complex receiver

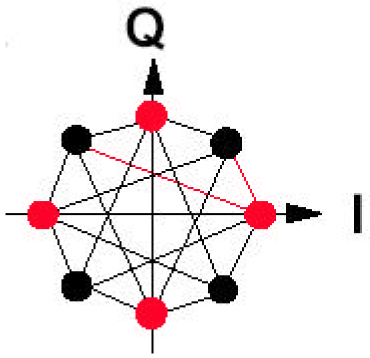


Phase of carrier:
$\pi/4$, $3\pi/4$, $5\pi/4$, $7\pi/4$

Output waveform is sum of modulated ± Cosine and ±Sine wave

π / 4 – Shifted QPSK

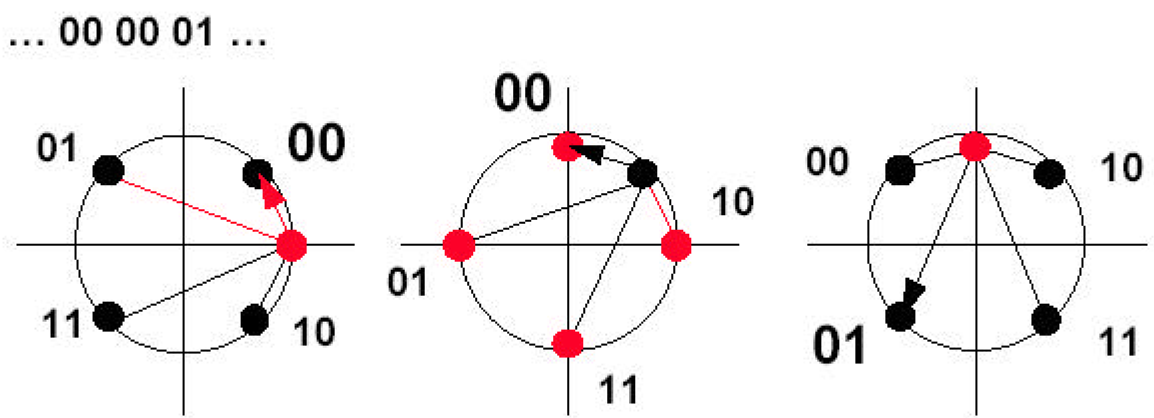
- Variation of QPSK
  - Restricted carrier phase transitions to +/- $\pi/4$ and +/- $3\pi/4$
  - Signalling elements selected in turn from two QPSK constellations each shifted by $\pi/4$
- Popular in Second Generation Systems
  - North American Digital Cellular (1.62 bps / Hz)
  - Japanese Digital Cellular System (1.68 bps / Hz)



π / 4 – Shifted QPSK

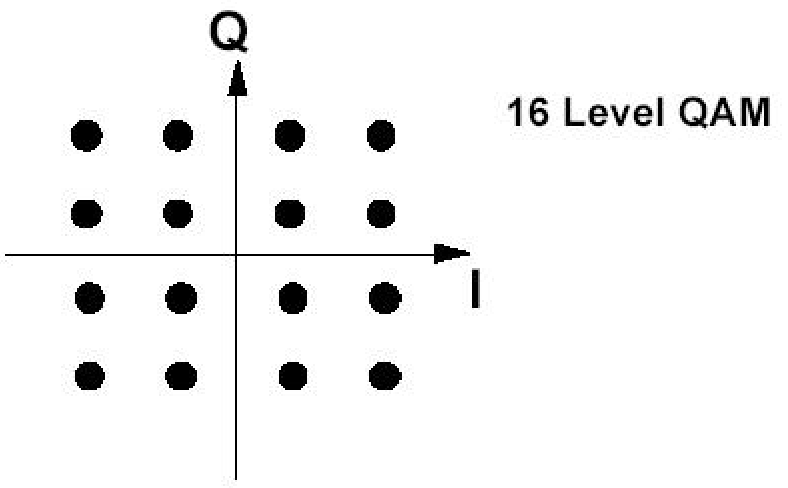
- Advantages
  - Two bits per symbol
  - Phase transitions avoid center of diagram, remove som design constraints on receiver
  - Always a phase change between symbols, leading to self-clocking

Data	Phase Change
00	45°
01	135°
10	-45°
11	-135°



Quadrature Amplitude Modulation

- Quadrature Amplitude Modulation (QAM)
  - Amplitude modulation on both quadrature carriers
  - 2^n discrete levels, if n=2 -> same as QPSK
- Extensively used in microwave links
- DVB-T uses QAM



Quadrature Amplitude Modulation

4 bits / symbol

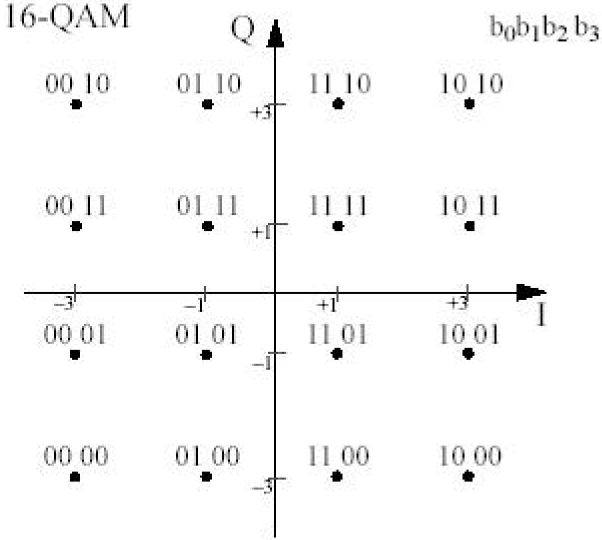


Table 84—16-QAM encoding table

Input bits (b_0 b_1)	I-out
00	–3
01	–1
11	1
10	3

Input bits (b_2 b_3)	Q-out
00	–3
01	–1
11	1
10	3

Quadrature Amplitude Modulation

6 bits / symbol

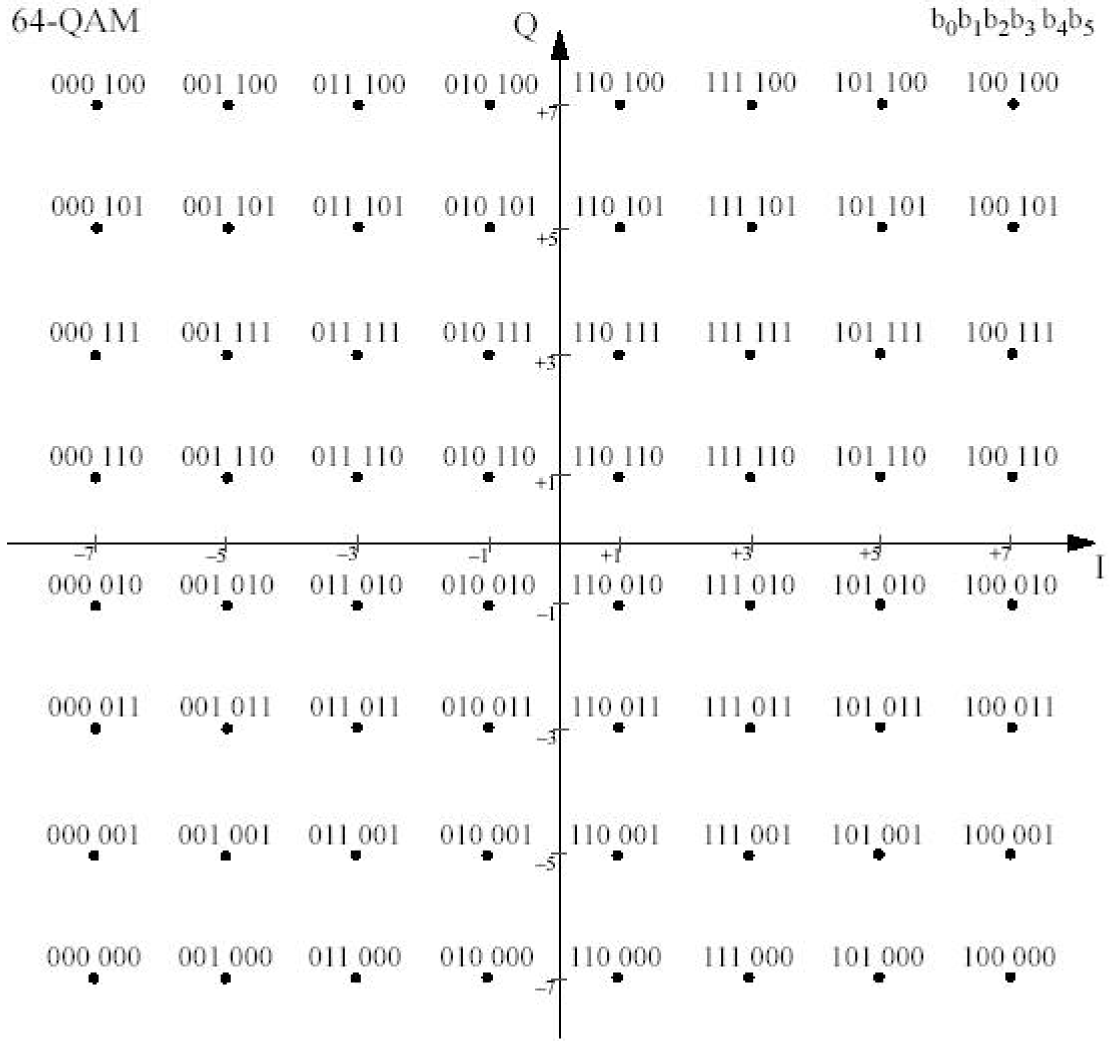


Table 85—64-QAM encoding table

Input bits (b_0 b_1 b_2)	I-out
000	–7
001	–5
011	–3
010	–1
110	1
111	3
101	5
100	7

Input bits (b_3 b_4 b_5)	Q-out
000	–7
001	–5
011	–3
010	–1
110	1
111	3
101	5
100	7