Physical Communication

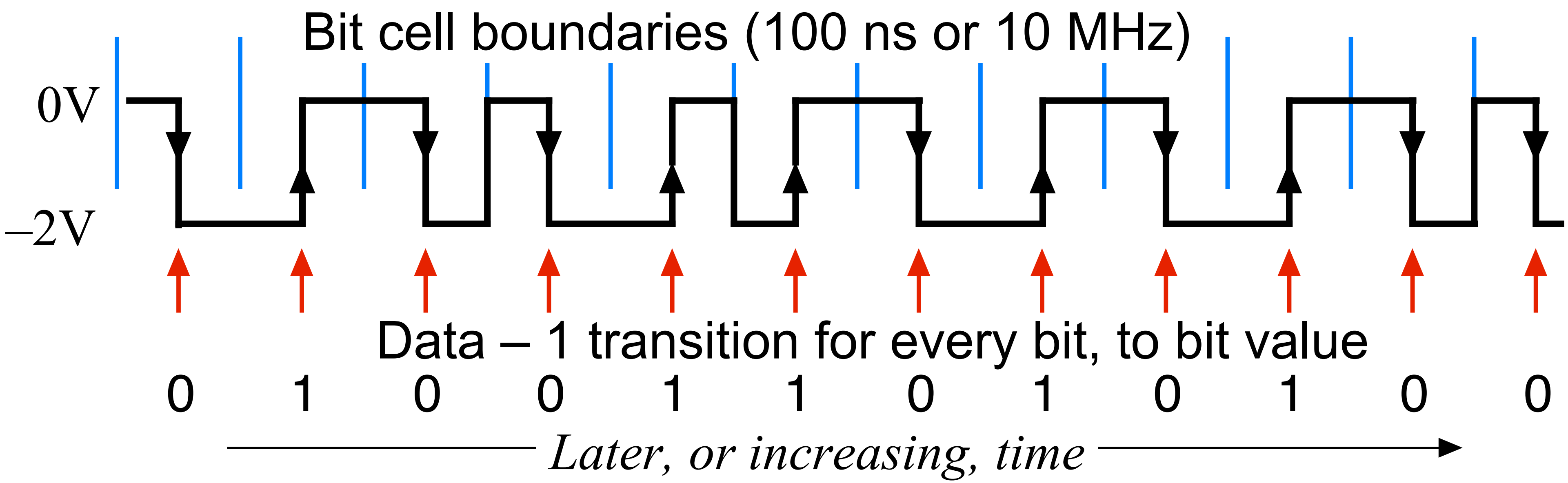
Read Chapters 1, 2 Shay *Understanding Data Communications & Networks*

- This gives a good general overview of data communications.
- It is not necessarily examinable as such, but is essential background knowledge for what is definitely examinable. (Work that one out!!)

- Almost all physical-level data communications involves electricity and magnetism, either obviously by voltages and currents in copper wires, or less obviously by electromagnetic fields such as radio (wireless, including satellite) and optical fibres.
- We start out by looking at simple voltage transmission

Voltage "Waveforms"

- We draw these as a graph of voltage as a function of time.
- The "simplest" signals are "*digital*"; the signal swings between two agreed levels, one corresponding to a logic "0" and the other to a logic "1".
- Successive bits occupy successive time periods – the bits are sent in succession, say 10 million bits per second for traditional Ethernet.
- Signal levels are typically a few Volts, or comparable to the output of small batteries (strictly cells); most cells are about 1.5V (lithium cells about 3V).



Analogue Signals

- Digital signals vary between two well-defined levels (occasionally more); it is necessary only to decode a 0 and a 1; no other values are legal.
- *Analogue signals* can vary continuously over a wide range.
- Most analogue signals are *periodic*, or repeat themselves at regular intervals.
- If a signal repeats at intervals of t seconds it has a frequency $f = {}^{1}/_{t}$ Hertz.
- Seconds and Hertz are often an inconvenient size and we use various multipliers, which "match up" as below, or with a "slip" of one place; such as 40 kHz has a period of 25µs, and 300 MHz a period of 3.333 ns.

frequency		period		
kilohertz	kHz	millisecond	ms	audio about 20 Hz to 20 kHz
megahertz	MHz	microsecond	µs	radio – 1 MHz (AM) & 100 MHz (FM)
gigahertz	GHz	nanosecond	ns	cell phones 1 – 3 GHz

A simple signal with a frequency f has an instantaneous value of the form

$$v(t) = V_0 \sin(2\pi f t + \varphi)$$

$$= V_0 \sin(\omega t + \varphi) \qquad \text{where } \omega = 2\pi f$$

In these equations,

- V_0 is the amplitude,
- f is the frequency (cycles per second)
- ω is the pulsatance (radians per second)
- φ is the phase (or ϕ is an alternative for φ)

We will see that we can use this simple "carrier" signal to carry information by varying, or *modulating* any one of the three quantities (or sometimes two together)

- V_0 *amplitude modulation,*
- f *frequency modulation*
- φ *phase modulation*

Fourier series

A fundamental result is that any periodic signal with frequency f can be written as a sum of the *harmonic* frequencies nf with appropriate weights

(again, put $\omega = 2\pi f$ and $\omega_0 = 2\pi f_0$, where f_0 is the *fundamental* frequency)

$$v(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t$$

where

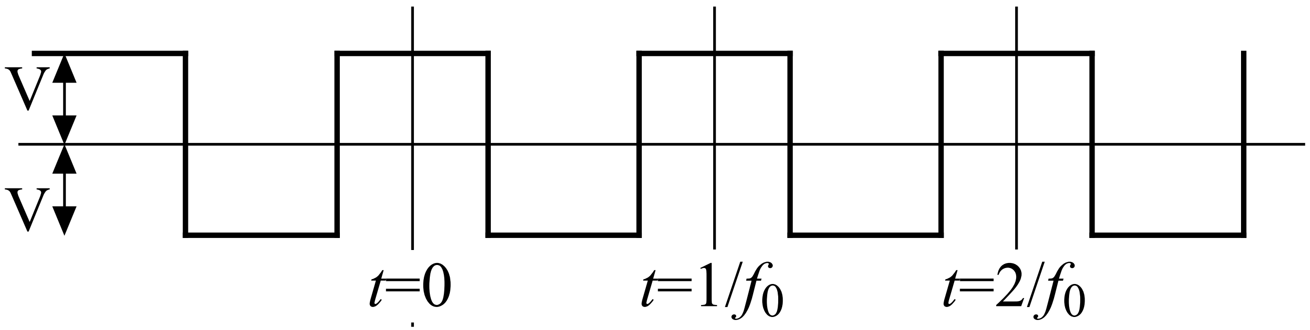
$$a_0 = \frac{1}{T}\int_0^T v(t)\,dt \qquad \text{where } T = \frac{2\pi}{\omega_0} \qquad a_0 \text{ is the DC component}$$

$$a_n = \frac{2}{T}\int_0^T v(t)\cos(n\omega_0 t)\,dt$$

$$b_n = \frac{2}{T}\int_0^T v(t)\sin(n\omega_0 t)\,dt$$

Examples of Fourier series

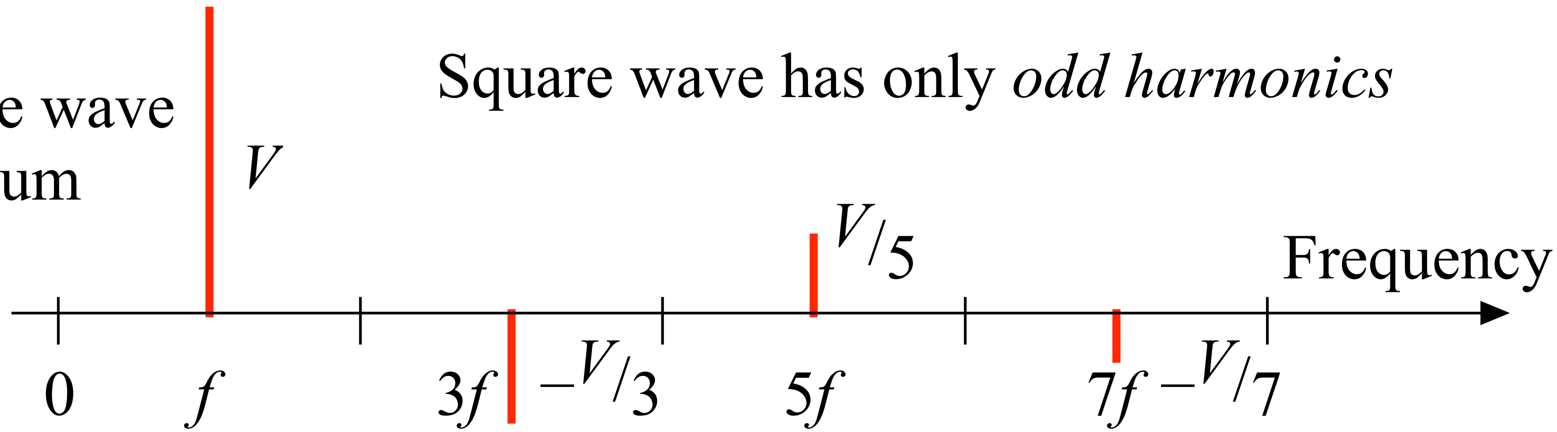
Square wave



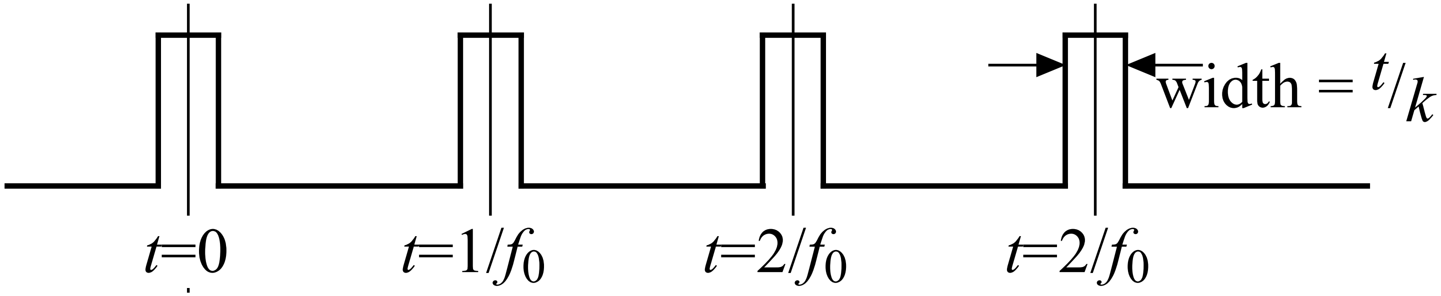
$$v(t) = \frac{4V}{\pi}\left(\cos\omega_0 t - \frac{\cos 3\omega_0 t}{3} + \frac{\cos 5\omega_0 t}{5} - \frac{\cos 7\omega_0 t}{7} + \ldots\right)$$

Square wave has only *odd harmonics*

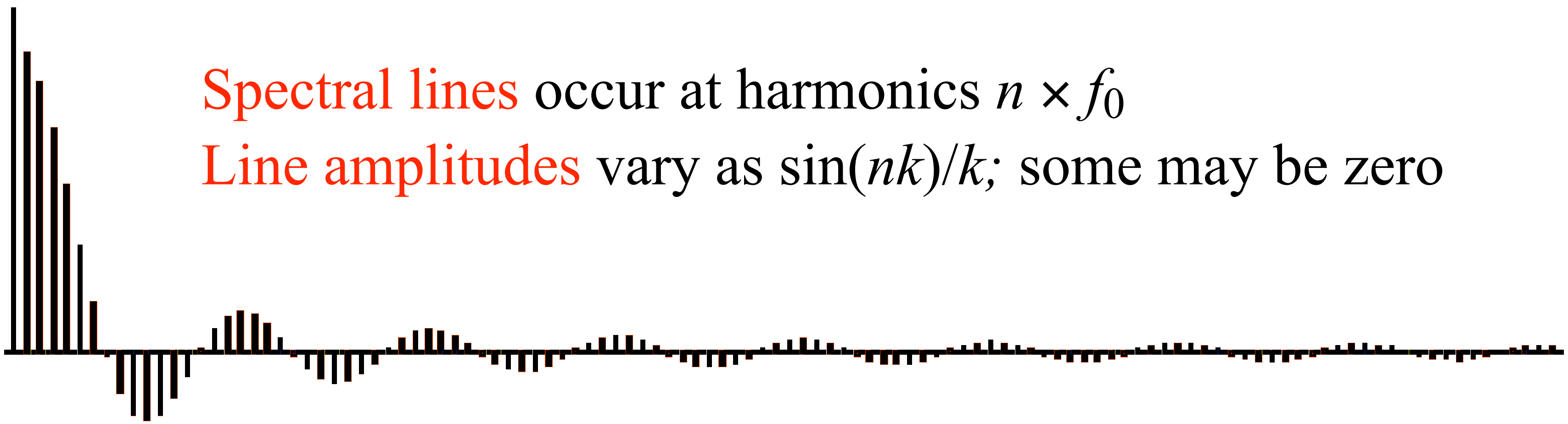
Square wave spectrum



Rectangular pulse, amplitude V, duration $^1/_k$ of period



$$v(t) = V\left[k + \frac{2}{\pi}\left(\sin k\pi \cos \omega t + \frac{\sin 2k\pi \cos 2\omega t}{2} + \frac{\sin 3k\pi \cos 3\omega t}{3} + \frac{\sin 4k\pi \cos 4\omega t}{4} + \frac{\sin 5k\pi \cos 5\omega t}{5} + \ldots\right)\right]$$

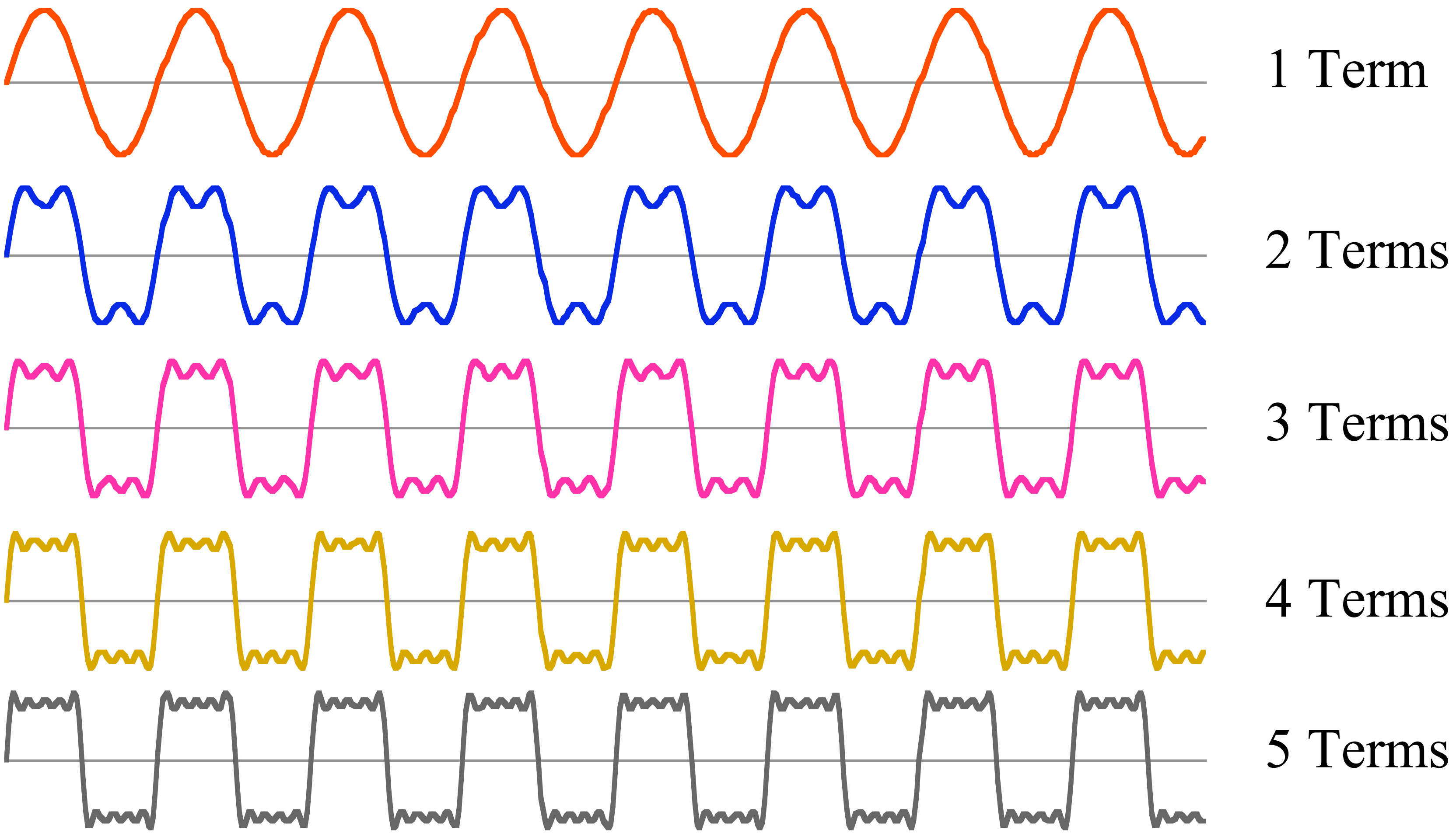


Spectral lines occur at harmonics $n \times f_0$

Line amplitudes vary as $\sin(nk)/k$; some may be zero

Fourier synthesis of a square wave

Taking progressively more terms of the Fourier Series for the square wave gets progressively better approximations.

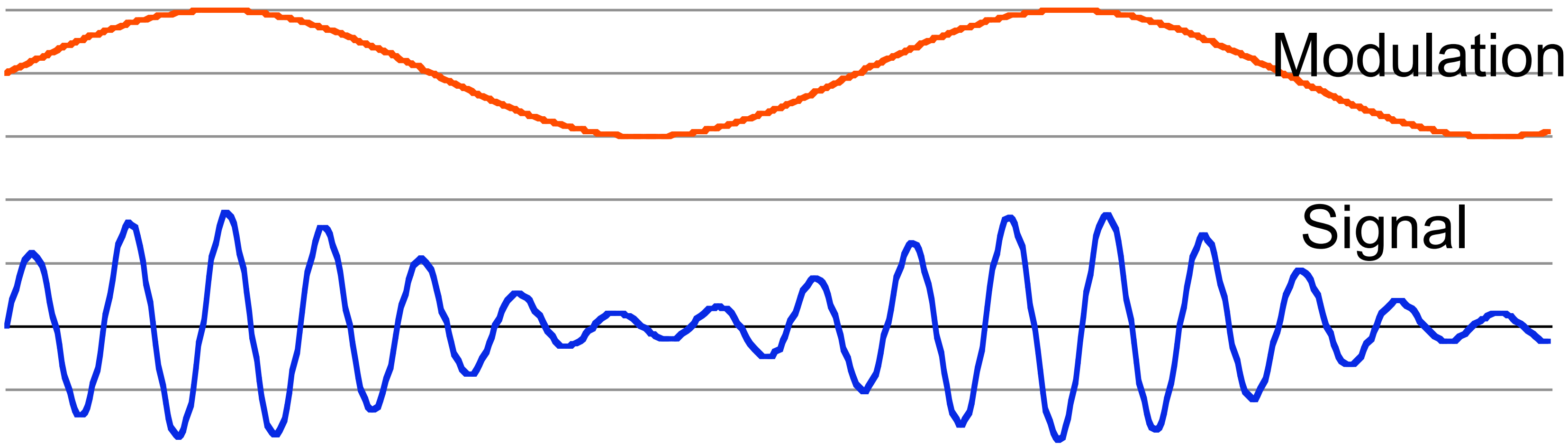


Amplitude Modulation

The simplest form of modulation involves transmitting a *carrier*, with frequency f_c, (or $\omega_c = 2\pi f_c$), amplitude A_c, and varying its amplitude.

With a single modulation frequency f_m (or $\omega_m = 2\pi f_m$) and amplitude A_m, we have that the instantaneous amplitude A is

$$A = (1+A_m \sin \omega_m t)A_c \sin \omega_c t = A_c \sin \omega_c t + A_m \sin \omega_m t A_c \sin \omega_c t$$



But from basic trigonometry

$$\cos(A+B) = \cos A \cos B - \sin A \sin B$$

and $$\cos(A-B) = \cos A \cos B + \sin A \sin B$$

giving $$2 \sin A \sin B = \cos(A-B) - \cos(A+B)$$

From earlier $$A = A_c \sin \omega_c t + A_m A_c \sin \omega_m t \sin \omega_c t$$

substituting $$A = \underbrace{A_c \sin \omega_c t}_{\text{carrier}} + A_m A_c/2 \left[\underbrace{\cos(\omega_c - \omega_m)t}_{\text{lower sideband}} - \underbrace{\cos(\omega_c + \omega_m)t}_{\text{upper sideband}}\right]$$

After modulation there are now three frequencies —

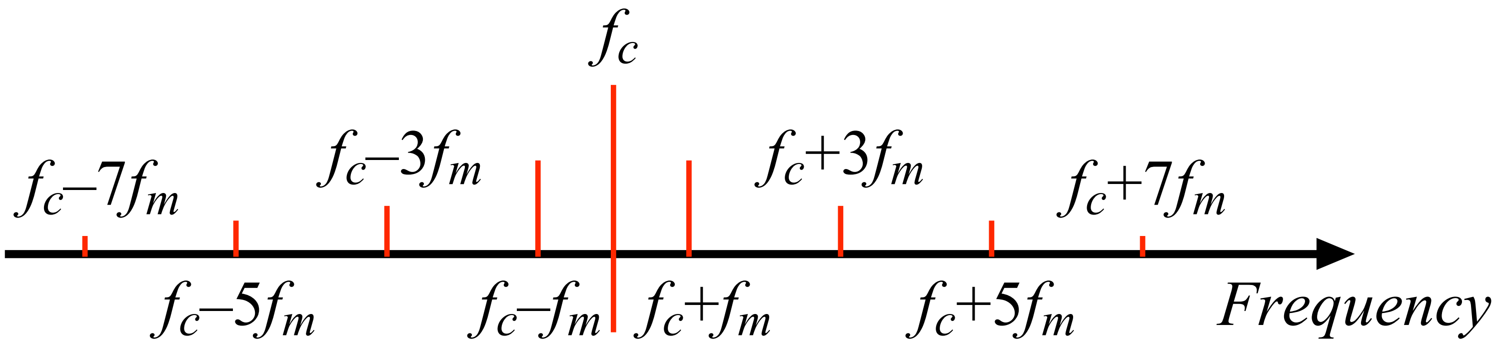
1. The original carrier, which is unchanged
2. A lower sideband at frequency $f_l = f_c - f_m$
3. An upper sideband at frequency $f_u = f_c + f_m$

Each sideband carries all of the information.

By filtering out the carrier and lower sideband we can move a band of frequencies to a higher or lower frequency.

Complex waveforms

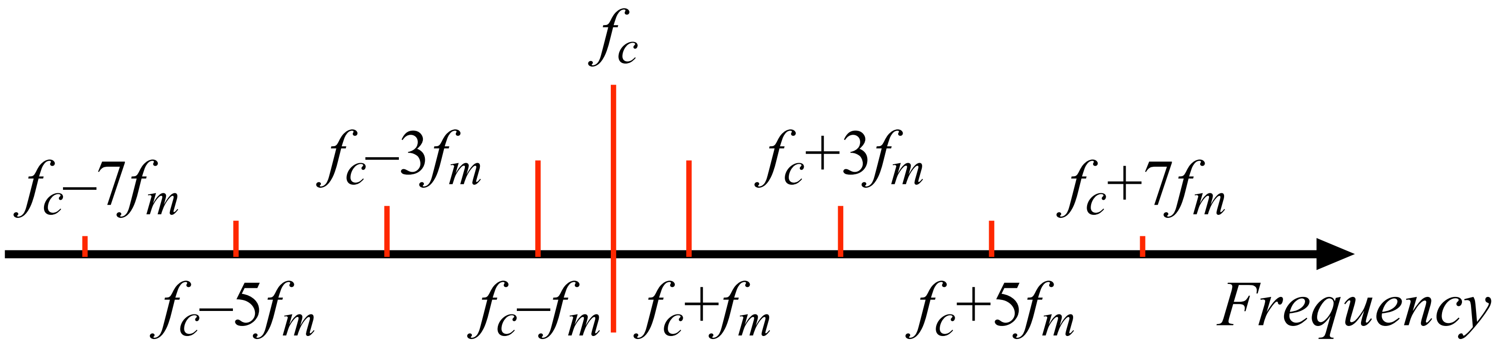
- If we modulate a carrier with a complex waveform, we can decompose the modulation into its Fourier components, treat them individually and then recombine. (This follows from the *principle of linearity*.)
- So, modulating the carrier with a square wave gives the central carrier and a whole series of sidebands above and below the carrier.
  The diagram shows a total bandwidth of 14 f_m. (Signals with sharp changes, such as square waves may need a lot of bandwidth.)



- Often we filter the modulated signal to restrict the bandwidth, or remove one complete set of sidebands, or even say lower sideband plus carrier.

Amplitude Shift Keying (ASK)

- One of the simplest methods of modulating a digital signal onto a carrier is to turn the carrier on for a 1 and off for a 0. (Sometimes it is better to use a small, non-zero, amplitude for a 0 so there is always *some* carrier.)
- Look first at modulation by a square wave. The square wave sidebands are copied around the carrier frequency, both above and below.
- This modulation gives a frequency spectrum as before (repeated here), with sidebands at multiples of the basic bit rate around the carrier.



- A realistic bit pattern contains frequencies at sub-multiples of f_m (a pattern 0011001100… is obviously like $f_m/4$), so the instantaneous pattern of sidebands changes to reflect the modulation.

Noise and Capacity

- How many bits per second can be sent over a certain bandwidth?
- Before looking at this we must consider *noise*, which is anything undesirable mixing into the signal we want. The more noise, the harder it is to detect fine details and the fewer bits can be detected.
- Examples of noise include —
  - Any other user's signal mixed with ours
  - Noise from bad connectors, cross-talk from other circuits
  - "White noise" from warm or hot components.
- We measure noise by the ratio of the *signal power* to the *noise power*, S/N.
- In communications systems power ratios are usually measured in decibels

$$S/Ndecibels = 10 \log_{10} (S/N_{power})$$

- We often measure *voltage ratios*, rather than *power ratios*; the formula becomes $S/Ndecibels = 20 \log_{10} (S/N_{voltage})$

Some typical S/N values

Voltage Ratio	Power Ratio	decibel ratio (dB)
1	1	0
2	4	6
3	9	10
4	16	12
5	25	14
10	100	20
20	400	26
32	1,000	30
100	10,000	40
316	100,000	50
1000	1,000,000	60

- A power change of 1 dB is barely audible to most people; some audio systems use 2 dB steps.

Shannon's Channel capacity

The fundamental formula relating channel capacity (*C* bits per second) to signal/noise ratio (*S*/*N*) and bandwidth (*W* Hz) is due to Shannon

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

- It shows that while we can "trade off" bandwidth against noise, it takes a lot of signal/noise to counter a small change in bandwidth.

Example: what signal/noise ratio is needed to get 56,000 bits/second through a bandwidth of 3,100 Hz? (Modern fast modem)

C/W = 56,000/3100 = 18.1.

Then $1+S/N = 2^{18.1} = 274{,}133 = 54$ dB.

Now most modem communications use the standard audio bandwidth of 3,100 Hz, established many years ago for telephone communication.

What signal/noise ratios are required for various "standard" speeds?

speed bit/s	S/N (dB)
2,400	-1.5
4,800	2.8
9,600	8.8
14,400	13.8
33,000	32.0
56,000	54.4

A negative S/N ratio means that the signal is less than the noise, about 60% of the noise power for –2 dB (remember it is *logarithmic*).

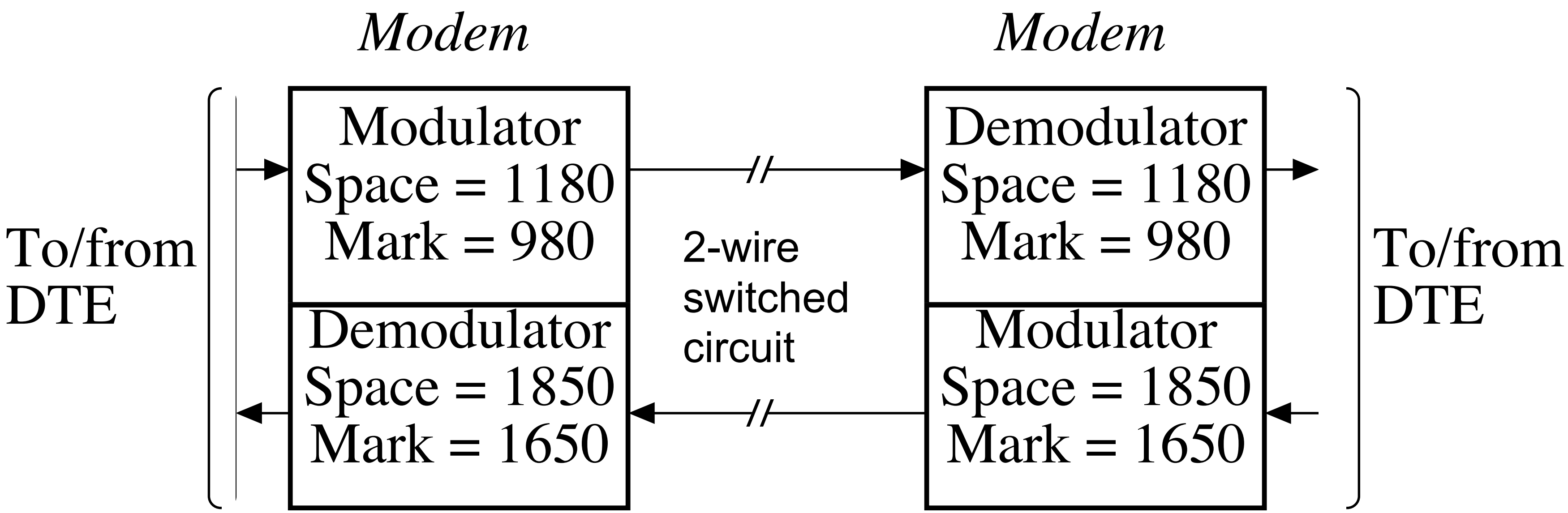
For most of our work calculations need not be very precise.
For example log(3) ≈ 0.5, and log(2) ≈ 0.3) is usually quite adequate.

Frequency modulation.

- A consequence of Shannon's theorem is that given some noise (and all systems are noisy) we can use wider bandwidth for lower noise.
- Usually we need a more complex modulation system so that the available bandwidth is full of sidebands ……
- The simplest of these more complex schemes is *frequency modulation*.
- In analogue terms $A = A_c \sin(1+k \sin \omega_m t)\, \omega_c t$
- This is not a nice function at all; its solution involves Bessel functions and we don't touch it.
- Frequency modulation is used in FM broadcasting and usually has a bandwidth of 150 kHz, compared with the 9 kHz of normal AM broadcast.
- It gives a much less noisy signal, but as the received noise level increases the demodulated noise level suddenly increases from low to much higher.
- This "threshold" effect is usual in complex modulation systems; with increasing noise the performance suddenly collapses.

Frequency Shift Keying (FSK)

- FSK switches the carrier between two frequencies, one for 0 and one for 1.
- Example is 300 bit/s ITU-T V.21 standard, now used for initial communication between modems.



Mark = 1, Space = 0

- Use a *low-band* (780–1380 Hz) in one direction and *high-band* (1450–2150 Hz) in the other.

Bandwidth of Frequency Shift Keying

Frequency Shift Keying (FSK) between two frequencies f_0 and f_1 with a bit rate d can be regarded as the sum of two amplitude modulations —

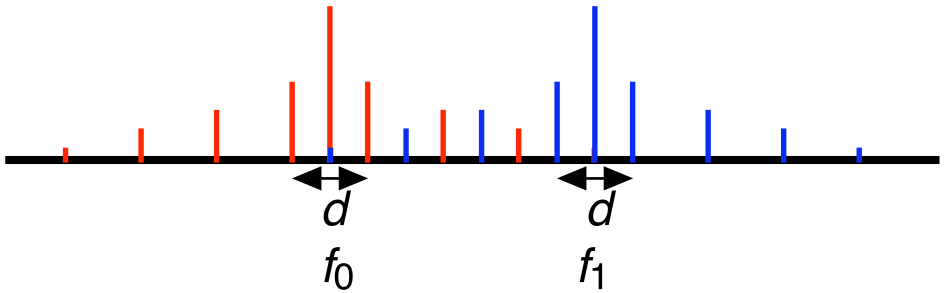
- a "normal" modulation turns the f_1 frequency on for a 1 and off for a 0.
- a "complement" modulation turns the f_0 frequency on for a 0 and off for a 1.

The two spectra have similar sideband structure, but different centre frequency, phases and possibly carrier amplitude.

With a bit rate d, the highest modulation frequency is $d/2$, with alternating 0s and 1s, giving "primary" sidebands at $d/2$, $3d/2$, $5d/2$, $7d/2$, etc.

Longer sequences of 0s and 1s resemble bit rates of d/k, giving "secondary" sidebands at frequencies $nd/2k$.

Combining the two spectra gives the FSK spectrum. Its bandwidth is just the sum of the two ASK spectra. With just the first harmonics present, the bandwidth is $\left(f_1 - f_0\right) + d$, and with the third harmonics $\left(f_1 - f_0\right) + 3d$.



If we keep just the first sidebands, each carrier has a bandwidth of d and we can in principle use a carrier spacing of d while still maintaining the identity of the sidebands. The total bandwidth is then $2d$, just as with ASK.

Phase-Shift Keying (PSK)

- Remember back – $v(t) = V_0 \sin(2\pi f t + \varphi)$

  $= V_0 \sin(\omega t + \varphi)$ where $\omega = 2 \pi f$

- Apart from *amplitude* (V_0) and *frequency* (f or ω), we can also modulate the *phase* (φ in the equation), or usually *phase changes*, for *Differential PSK*. (NOTE that this is a more subtle change, for even better performance).

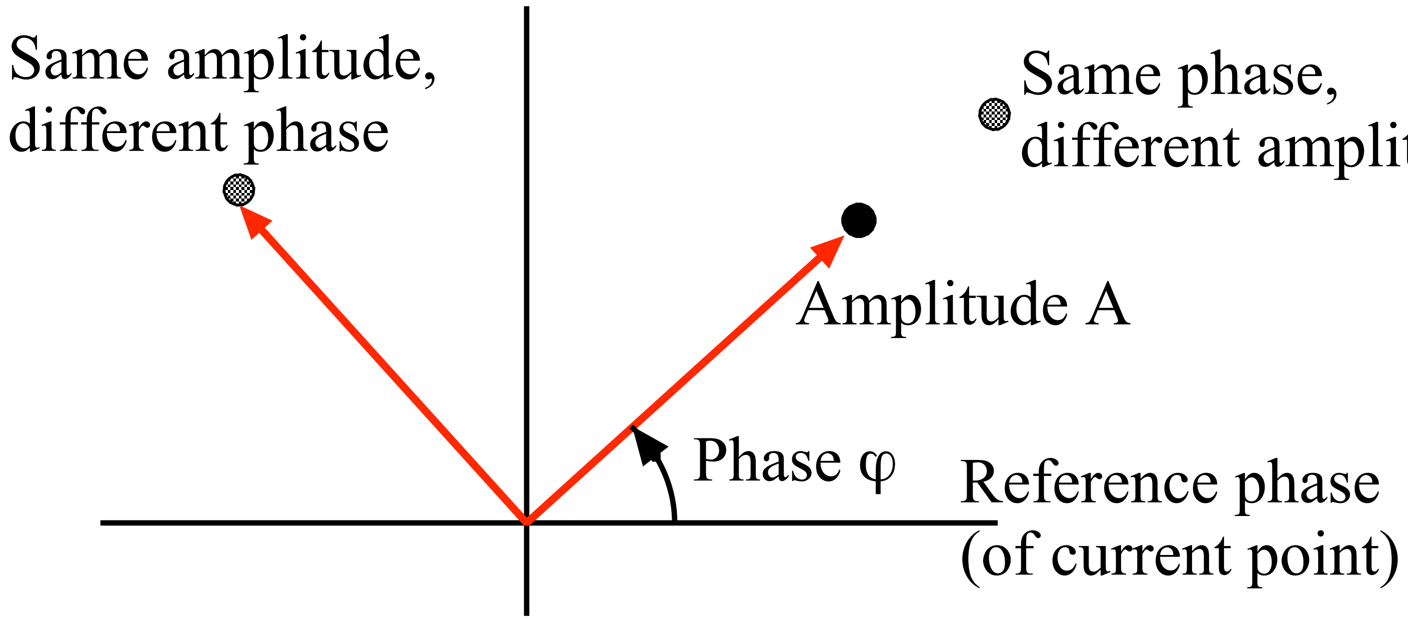
- A given signalling interval might have possible phase changes of 0°, 90°, 180° and 270° relative to the previous interval. The four possible changes can represent 2 possible bits, say 0° = 00, 90°=01, 180°=10 and 270°=11 OR 45° = 00, 135°=01, 225°=10 and 315°=11 (always have a shift).

- The rate of *signal changing* is the *baud rate*;
  the rate of *data bits* is the *bit rate*.

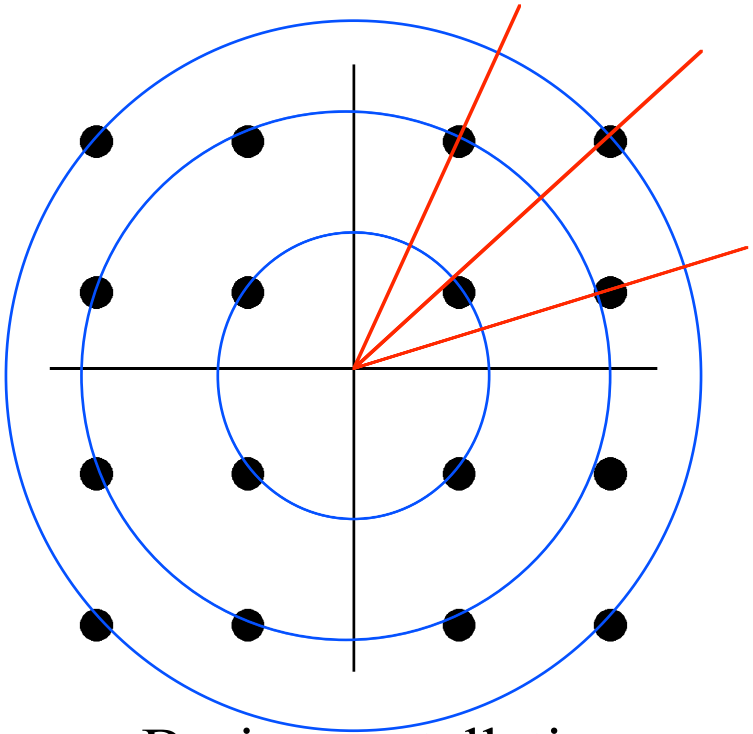
- Almost always *bit_rate > baud_rate*,
  and *baud_rate* < 3,100 even for say 19,200 or 56,000 bit/s modems.

Quadrature Amplitude Modulation

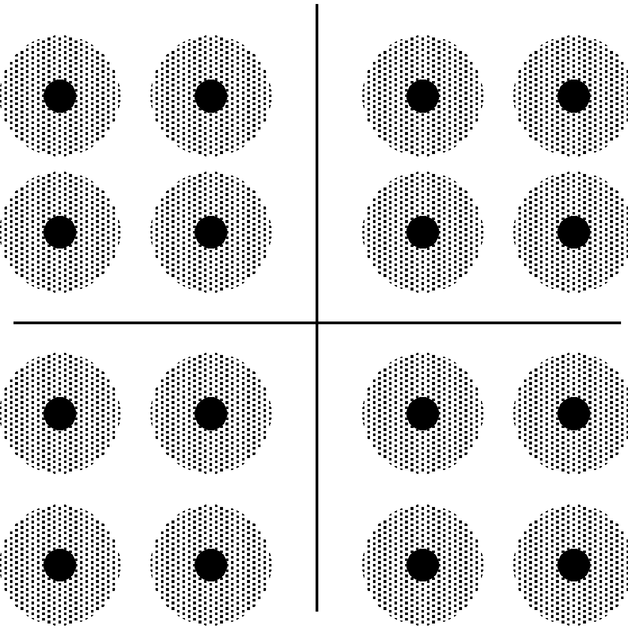
- Most modems use a combination of AM, say 4 amplitudes, and DPSK, say 8 possible phase shifts (but not all combinations)
- But firstly describe the point positions on a phase/amplitude diagram (using polar coordinates)



- The V.22bis standard, 2400 bps, signalling at 600 baud has the constellation



Basic constellation
3 amplitudes, 12 phases



Constellation, points
blurred by noise

- Noise blurs the points; if there is no overlap we can choose the nearest point.
- Use only selected combinations of phase and amplitude for greatest distance between points.

Examples of analogue modulation

Note that there is very little difference here between Frequency Modulation and Phase Modulation; with PM the instantaneous frequency is proportional to *rate of change* of the modulation.