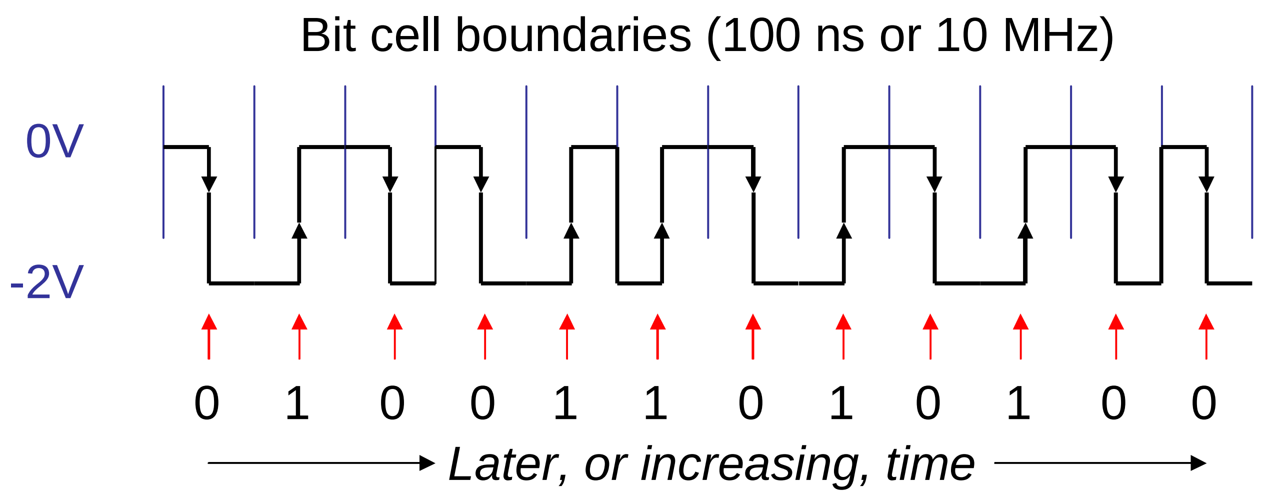
Physical Communication

- Read Chapters 1 and 2 of Shay, *Understanding Data Communications & Networks, 2nd Edition.*
  - This material is in Chapters 1 through 4 of the *3rd Edition.*
- These chapters give a good general overview of data communications.
- The detailed information is not examinable, but this reading provides 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*".
  - A digital 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.
  - For example, 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.
  - We use various multipliers, which "match up" as below, or with a "slip" of one place.
  - For example, 40 kHz has a period of 25μs, and 300 MHz a period of 3.333 ns.

Frequency	**Period**	**Example**
Kilohertz (kHz)	Millisecond (ms)	Audio: 20 Hz to 20 KHz
Megahertz (MHz)	Microsecond (μs)	Radio: 1 MHz (AM), 100 MHz (FM)
Gigahertz (GHz)	Nanosecond (ns)	Cell phones: 1 to 3 GHz

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

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

In these equations,

V_0 is the amplitude,

f is the frequency, in cycles per second

ω is the pulsatance, in radians per second

φ is the phase (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 (or two) of the following three quantities:

V_0 "*amplitude modulation*"

f *"frequency modulation"*

φ "*phase modulation*"

Fourier series

- A fundamental result is that any *periodic* signal $v(t)$ with frequency f (period $P = 1/f$; angular frequency $\omega = 2\pi f$) can be written as a sum of the *harmonic* frequencies kf with appropriate weights:

$$v(t) = a_0 + \sum_{k=1}^{\infty} a_k \cos(k\omega t) + \sum_{k=1}^{\infty} b_k \sin(k\omega t)$$

- The Fourier coefficients have the values

$$a_0 = \frac{1}{T}\int_0^T v(t)dt \quad \text{(the DC component)}$$

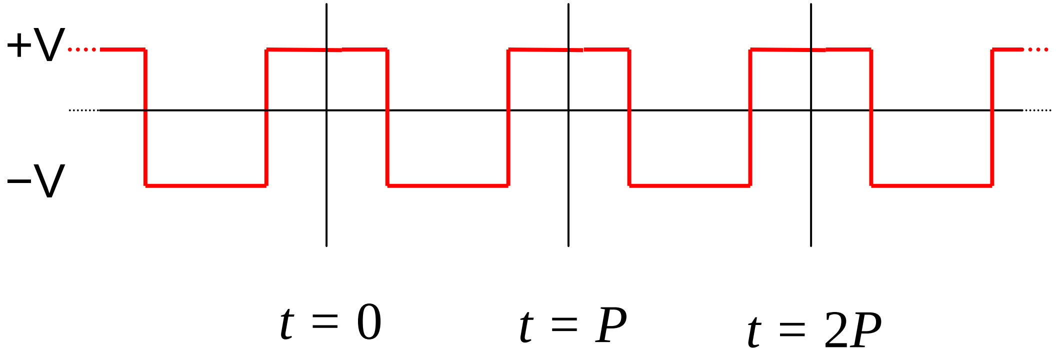
$$a_n = \frac{2}{T}\int_0^T v(t)\cos(n\omega t)dt$$

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

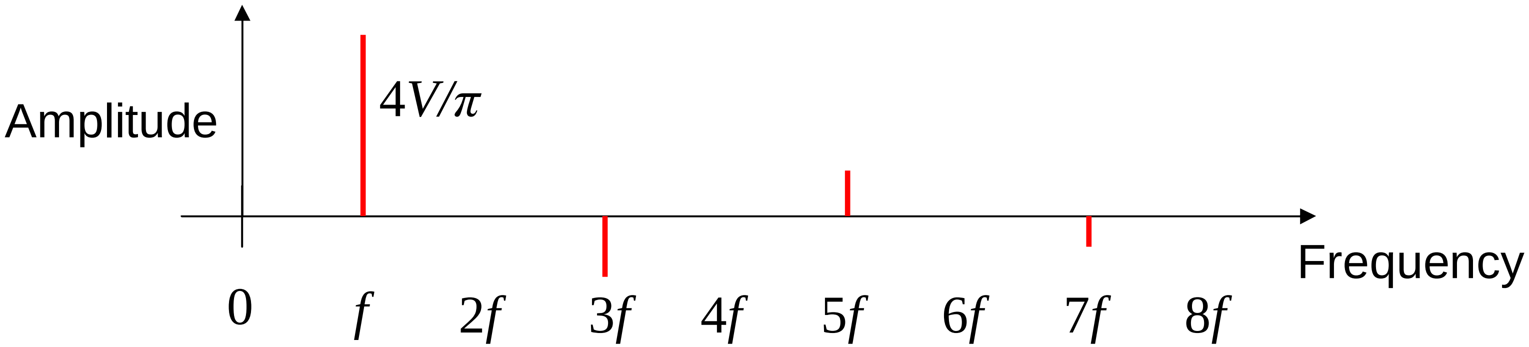
- See http://falstad.com/fourier/.

Examples of Fourier series

Square wave (infinite)

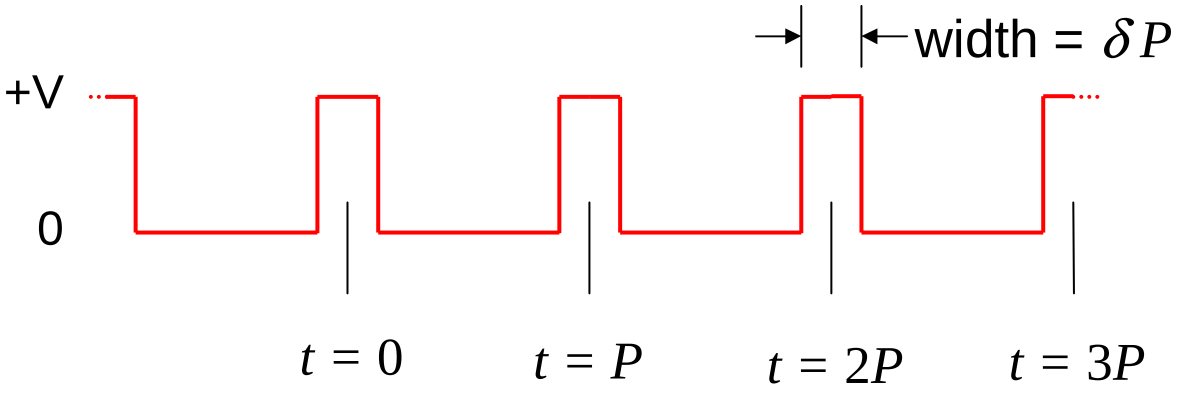


$$v(t) = \frac{4V}{\pi}\left(\cos\omega t - \frac{\cos 3\omega t}{3} + \frac{\cos 5\omega t}{5} - \frac{\cos 7\omega t}{7} + \cdots\right)$$



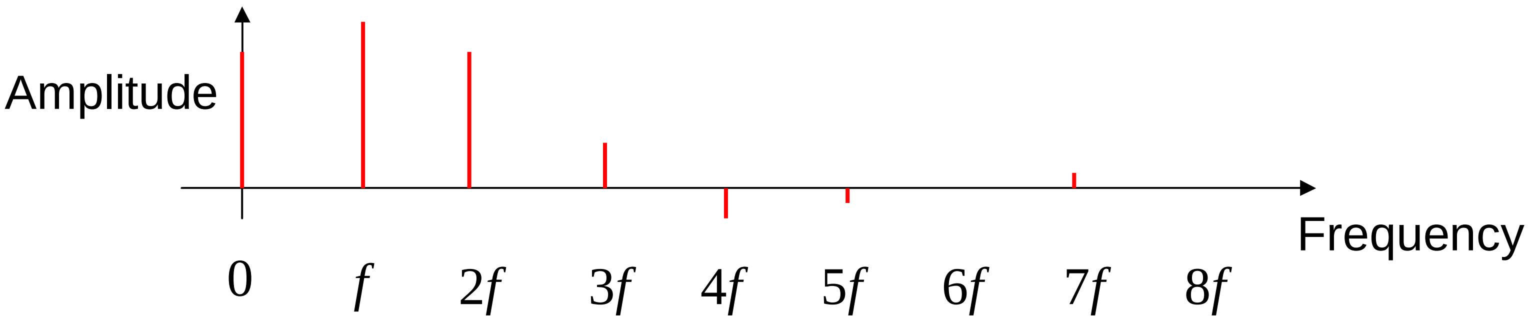
Rectangular Pulse

- Amplitude V, duty cycle $\delta \leq 1$, period P.



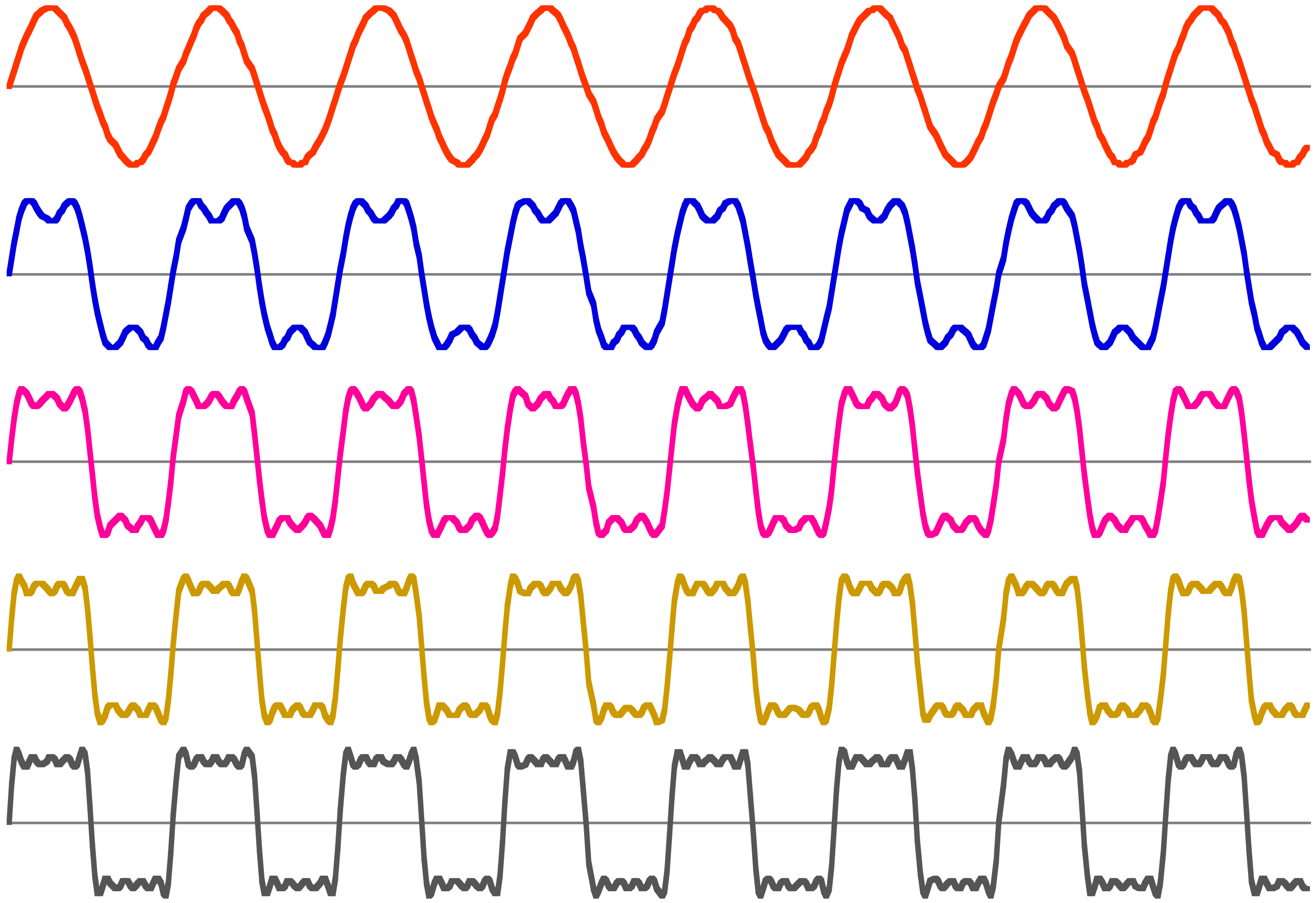
$$v(t) = V\left[\delta + \frac{2}{\pi}\left(\sin \pi\delta \cos \omega t + \frac{\sin 2\pi\delta \cos 2\omega t}{2} + \frac{\sin 3\pi\delta \cos 3\omega t}{3} + \cdots\right)\right]$$

- Spectral lines occur at harmonic frequencies $kf = k/P$.
- Line amplitudes vary as $\sin(k\delta)/k$. Some are zero if $1/\delta$ is an integer.



Fourier synthesis of a square wave

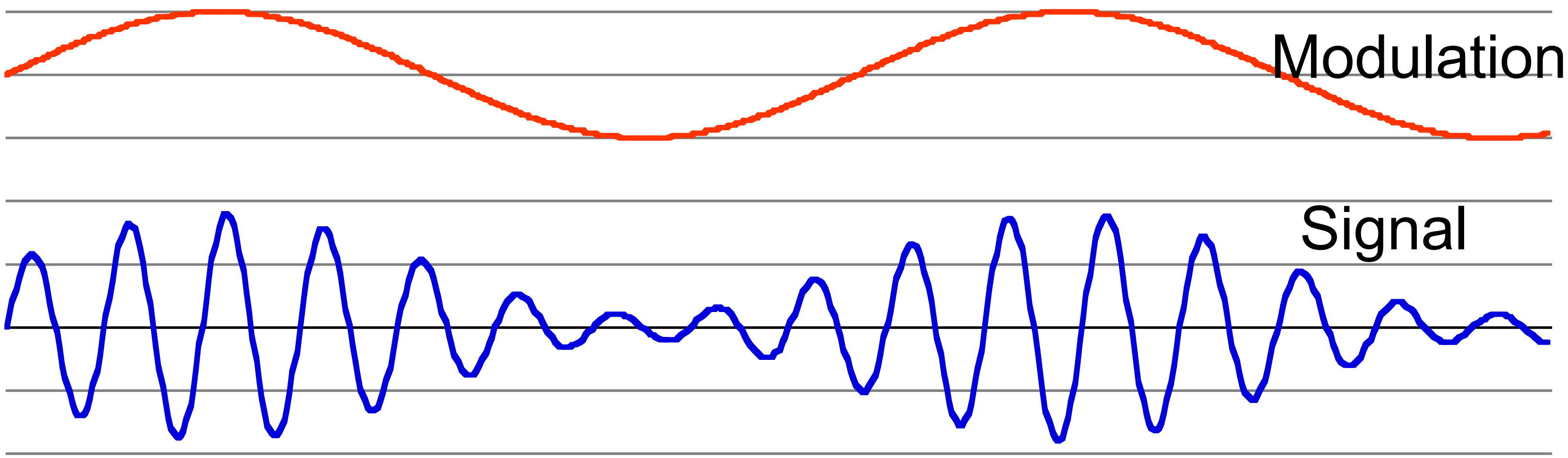
- Taking progressively more terms of the Fourier Series for the square wave gives progressively better approximations.



Amplitude Modulation

- The simplest form of modulation involves transmitting a *carrier*, with frequency f_c and amplitude A_{c}..
  - We send information by varying (*modulating*) the amplitude of the carrier in proportion to a message-bearing signal $m(t)$.
  - Remember that $\omega_c = 2\pi f_c$.
- If the modulation $m(t)$ is periodic at frequency f_m and amplitude A_m, then the "Signal" (or modulated carrier) is given by

$$\begin{aligned} A(t) &= (1 + m(t))A_c \sin \omega_c t \\ &= A_c \sin \omega_c t + A_m A_c \sin \omega_m t \sin \omega_c t \end{aligned}$$



Sidebands

- From basic trigonometry,

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

- Substituting into $A(t) = A_c \sin(\omega_c t) + A_m A_c \sin(\omega_m t)\sin(\omega_c t)$ we obtain

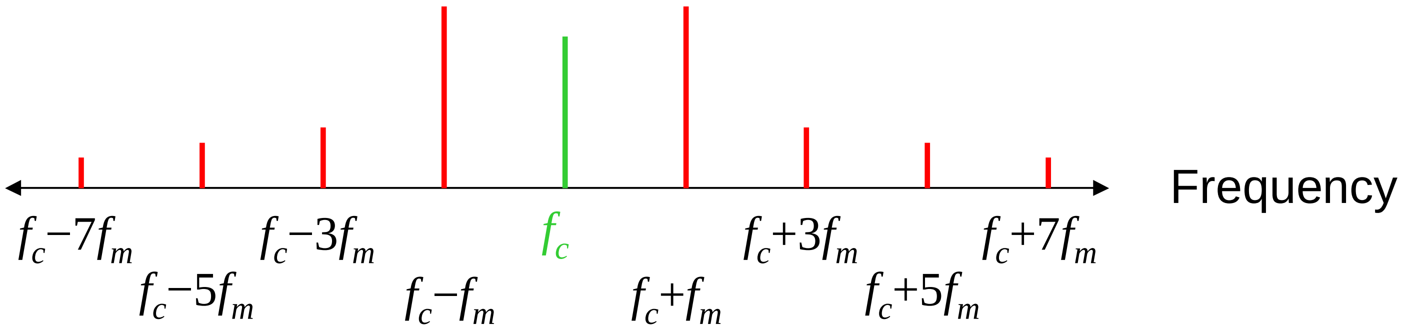
$$A(t) = A_c\sin(\omega_c t) + (A_m A_c/2)[\cos(\omega_c t - \omega_m t) - \cos(\omega_c t + \omega_m t)]$$

carrier *lower sideband* *upper sideband*

- Our AM signal therefore has three frequency components:
  - The original carrier, which is unchanged at f_c
  - A lower sideband at frequency $f_l = f_c - f_m$
  - An upper sideband at frequency $f_u = f_c + f_m$
- Each sideband carries a copy of the information.
  - By filtering out the carrier and lower sideband, we can shift our signal to a higher frequency.

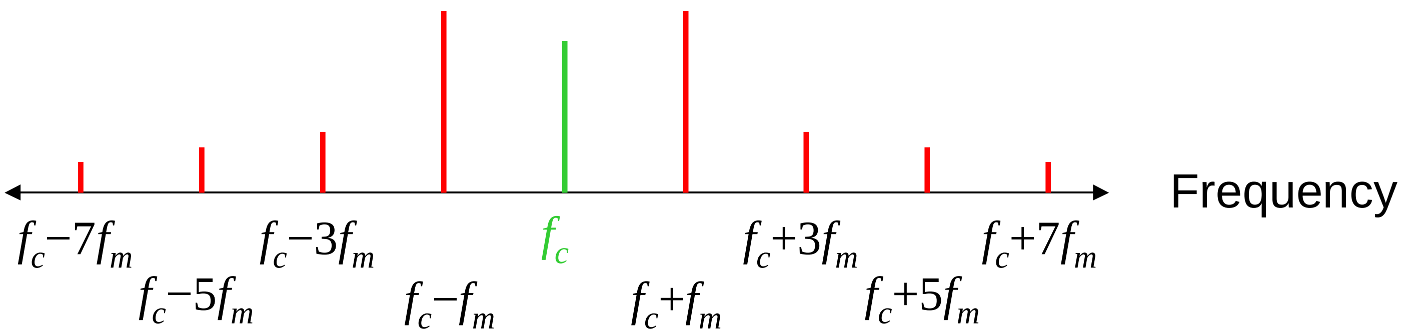
Complex waveforms

- Complex waveforms are a linear combination of sine waves (and cosine waves): Fourier!
  - Decompose a complex modulation into its Fourier components.
  - Components can be added easily in the "transform space" (a.k.a. the "frequency domain"): this is the *principle of linearity*.
  - We can inverse-transform to discover what the modulated carrier looks like in the "time domain".
- For example, modulating a carrier f_c with a square wave produces sidebands at $\pm k f_m$ for odd k.
  - The diagram below shows a total bandwidth of $14 f_m$.
  - Signals with sharp changes, such as square waves, require a lot of bandwidth.
  - We can filter the modulated signal to restrict the bandwidth.
  - We can remove one complete set of sidebands, 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.
  - The pattern of sidebands (and the amplitude of the carrier) changes at each bit-transition, to reflect the modulation.
- Let’s look first at a square wave modulation.
  - When sending a “1”, the square-wave sidebands appear.
  - When sending a “0”, there are no sidebands (and only a weak carrier).
  - The receiver can be tuned to f_c+f_m (or to f_c-f_m).
  - The receiver should use f_c as a reference frequency, for tuning.
- Periodic bit patterns give rise to other frequency components.
  - Modulating with signal 001100110011… gives an $f_m/4$ component.



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_{power}.
- In communications systems, power ratios are usually measured in decibels

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

- We often measure *voltage ratios*, rather than *power ratios*; the formula becomes

$$S/N = 20 \log_{10} (S/N_{voltage})$$

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	1000	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 power ratio (S/N_{power}) and bandwidth (W Hz) is due to Shannon:

$$C = W \log_2 \left(1 + S/N_{power} \right)$$

- 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)

$$C/W = 56{,}000/3100 = 18.1$$

$$1 + S/N_{power} = 2^{18.1} = 274{,}133$$

$$S/N = 10(\log_{10} 274{,}132) = 54 \text{ dB.}$$

S/N vs. data rates

- Most modem communications use the standard audio bandwidth W = 3,100 Hz, established many years ago for telephone communication.
- What signal/noise ratios are required for various “standard” speeds?

Speed (bps)	S/N (dB)
2400	-1.5
4800	2.8
9600	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.
- A signal at –2 dB has about 60% of the power of the accompanying noise (remember, dB are *logarithmic*).
- Most of our calculations need not be very precise. You may use

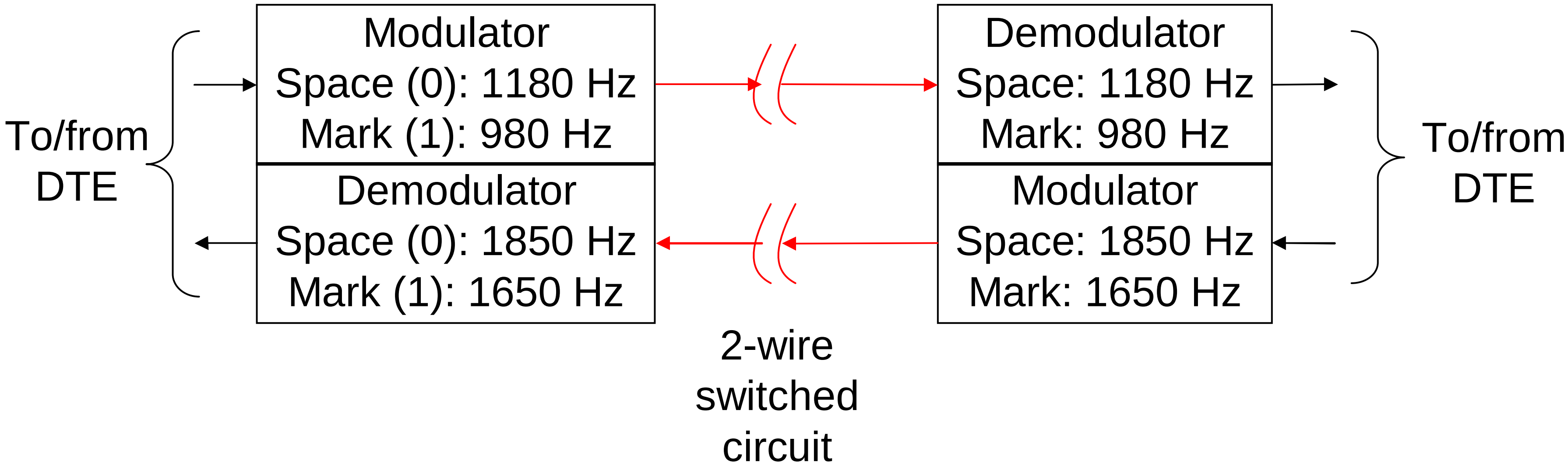
$$\log(3) \approx 0.5 \qquad \log(2) \approx 0.3$$

Frequency modulation

- A consequence of Shannon's theorem is that if noise is a problem (and all systems are noisy), we can reduce the noise if we use more bandwidth.
- Usually we need a 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 $A(t) = A_c \sin(1 + k \sin \omega_m t)\, \omega_c t$
  - 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 radio broadcasting.
  - FM radio bandwidth is typically 150 kHz.
  - AM radio bandwidth is typically 9 kHz.
  - An FM signal usually has fewer decoding errors than an AM signal.
  - In FM, 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: the 300 bit/s ITU-T V.21 standard, still used for initial communication between modems.
- V.21 uses a low-band (780–1380 Hz) to signal in one direction, and a high-band (1450–2150 Hz) for the other direction.



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 $nd/2k$.

FSK spectrum

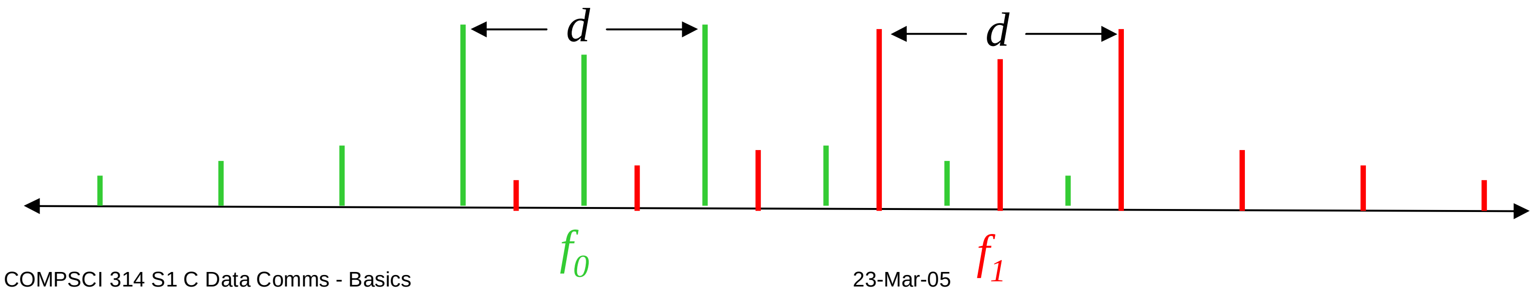
- Combining the normal and complement spectra gives us the FSK spectrum.
  - Its bandwidth is the sum of the two ASK bandwidths.
- With just the first harmonics present, the bandwidth is

$$(f_1 - f_0) + d$$

- With the third harmonics, the bandwidth is

$$(f_1 - f_0) + 3d$$

- If we keep just the first sidebands, each carrier has a bandwidth of d.
  - 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.

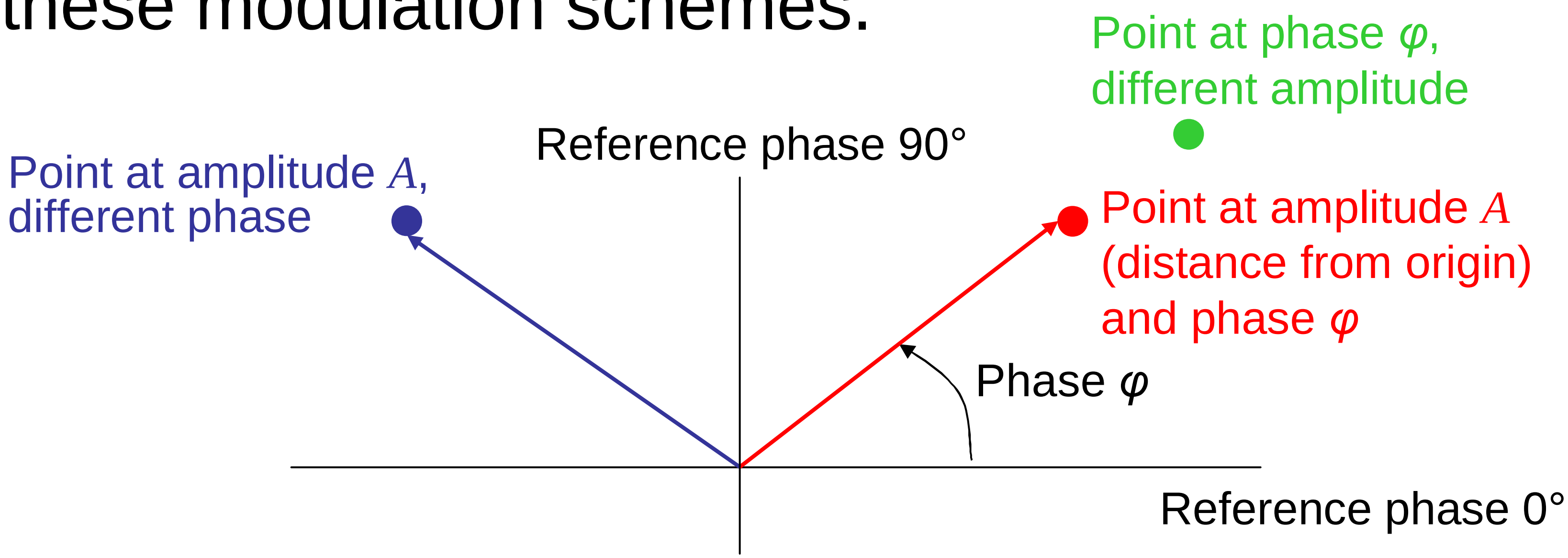


Phase-Shift Keying (PSK)

- Remember back: $v(t) = V_0 \sin(2\pi ft + \varphi)$
  $= V_0 \sin(\omega t + \varphi)$ where $\omega = 2\pi f$
- Apart from *amplitude* (V_0) and *frequency* (f or ω), we can also modulate the *phase* (φ) in this equation.
  - *Differential PSK* uses *phase changes*.
  - NOTE that this is a 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 (we 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.*
  - Even fast (19,200 or 56,000 bit/s) modems have *baud_rate* < 3,100.

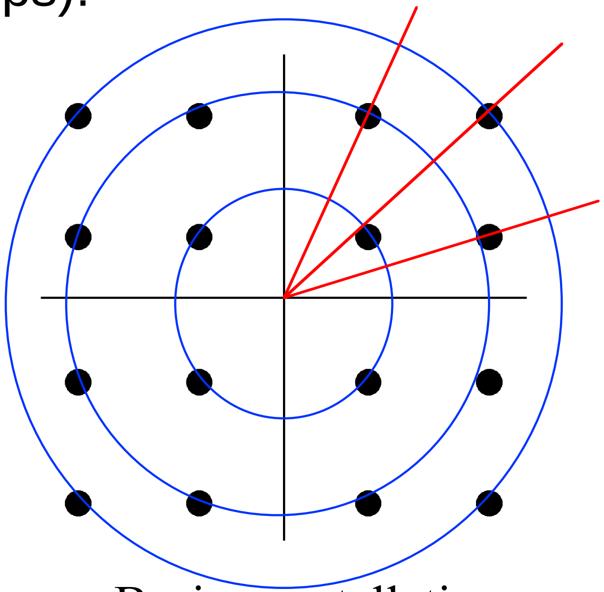
Quadrature Amplitude Modulation

- Most modems use a combination of AM and DPSK.
  - Say: 4 amplitudes, and 8 possible phase shifts (but not all combinations)
- We use a phase/amplitude diagram, with polar coordinates, to describe signals as “points” in these modulation schemes.

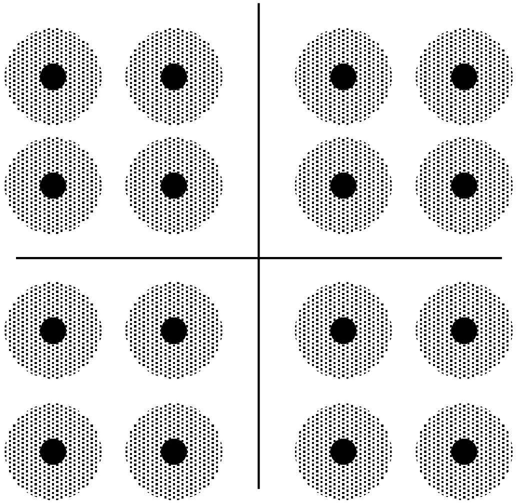


V.22bis standard

- A V.22bis modem signals at 600 baud on a 16-point constellation (2400 bps):



Basic constellation
3 amplitudes, 12 phases



Constellation, points
blurred by noise

- Noise blurs the points.
  - If points don't overlap, the nearest point to the received signal is "correct".
- To optimise noise immunity, we want our points to be as widely separated as possible.
- To maximise bandwidth, we want as many points as possible.

Examples of analogue modulation

- Note that there is very little observable difference -- in the time domain -- between Frequency Modulation (FM) and Phase Modulation (PM).
- With PM, the instantaneous frequency is proportional to the *rate of change* of the modulation.