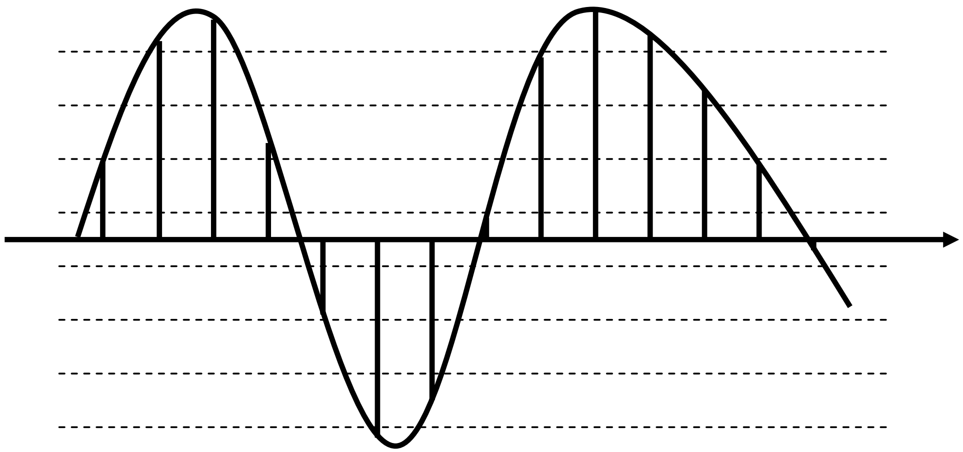
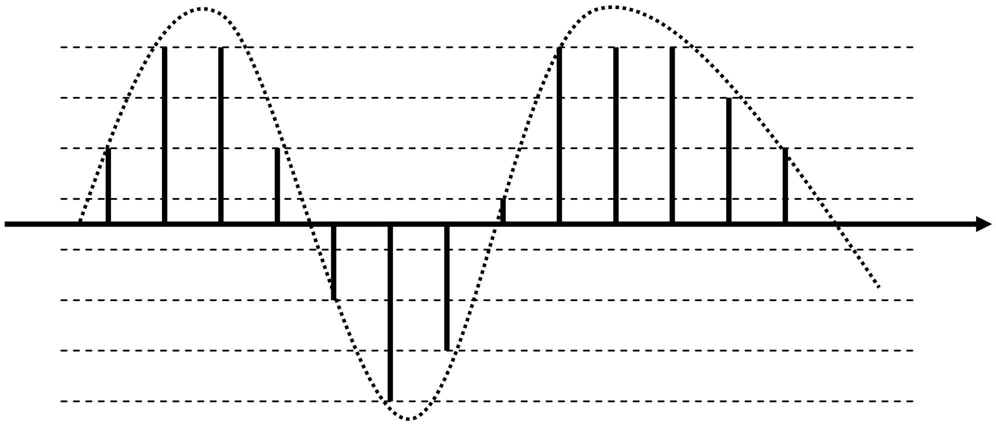
Digital Transmission Fundamentals

- Pulse Code Modulation (PCM)
  - *sampling* an analogue signal
  - *quantisation* : assigning a discrete value to each sample
    - » by *rounding* or *truncating*
    - » results in *quantisation noise* error
  - *encoding* : representing the sampled values with *n*-bit digital values
    - » higher *n* gives lower quantisation noise and *vice versa*
    - » *linear* encoding
    - » *companding* : logarithmic encoding : larger values compressed before encoding & expanded at receiver
    - » *differential* PCM : encoding difference between successive values
    - » *adaptive DPCM* : encodes difference from a prediction of next value
    - » *delta* modulation : 1-bit version of differential PCM : *a 1-bit staircase function*





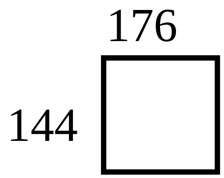
- for telephone-quality voice
  - 8000 samples per second = every 125 microsecs
  - 8 bits resolution = 64 kbps

- Compression of data
  - *compression ratio* : ratio of number of original bits to compressed bits
  - *lossless* compression : original data can be recovered exactly
    - » e.g. file compression, GIF image compression
    - » e.g. run-length encoding
    - » limited compression ratios achievable
  - *lossy* compression : only an *approximation* can be recovered
    - » e.g. JPEG image compression : can achieve 15:1 ratio still with high quality
    - » e.g. MPEG-2 for video : uses temporal coherence; MP3 for audio etc.
    - » *statistical* encoding : most frequent data sequences given shortest codes
      - e.g. Morse code, Huffman coding
    - » *transform* encoding
      - e.g. signals transformed from spatial or temporal domain to frequency domain
      - e.g. Discrete Cosine Transform of JPEG and MPEG
    - » *vector quantisation* : sequences looked up in a code-book
    - » *fractal* compression : small parts of an image compared with other parts of same image, *translated, shrunk, slanted, rotated, mirrored* etc.

Information type	Compression technique	Format	Uncompressed	Compressed	Applications
Voice	PCM	4 kHz voice	64 kbps	64 kbps	Digital telephony
Voice	ADPCM (+ silence detection)	4 kHz voice	64 kbps	32 kbps	Digital telephony, voice mail
Voice	Residual-excited linear prediction	4 kHz voice	64 kbps	8-16 kbps	Digital cellular telephony
Audio	MP3	16-24 kHz audio	512-748 kbps	32-384 kbps	MPEG audio
Video	H.261	176x144 or 352x288 @ 10-30 fps	2-36.5 Mbps	64 kbps-1.544 Mbps	Video conferencing
Video	MPEG-2	720x480 @ 30 fps	249 Mbps	2-6 Mbps	Full-motion broadcast video
Video	MPEG-2	1920x1080 @ 30 fps	1.6 Gbps	19-38 Mbps	High-definition television

- Network requirements
  - *volume of information* and *transfer rate*

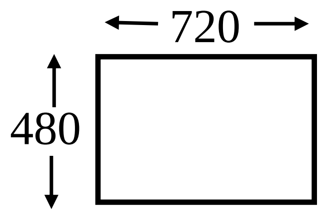
QCIF Videoconferencing



@ 30 frames/sec =

760,000 pixels/sec

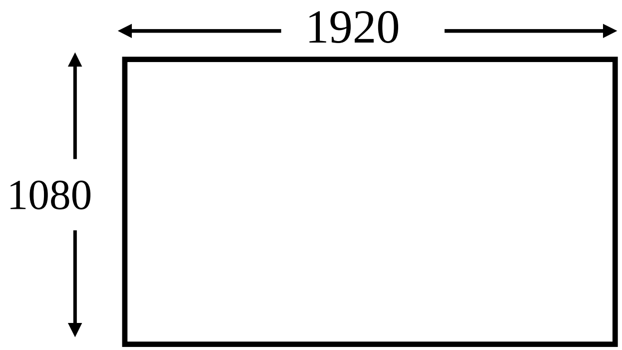
Broadcast TV



@ 30 frames/sec =

10.4×10^6 pixels/sec

HDTV



@ 30 frames/sec =

67×10^6 pixels/sec

– other possible requirements:

– *accuracy* of transmission and *tolerance* to inaccuracy

» data files cannot tolerate *any* inaccuracy

» an audio or video stream can tolerate glitches

» e.g. video conferencing : missing frames can be predicted if missing

– the higher the compression ratio, the less tolerant to transmission errors

» e.g. residual-excited linear predictive coding quite vulnerable to errors

» error detection and correction codes necessary

» like optimising traffic flows on roads : vulnerable to accident glitches

– maximum *delay* requirements

» a packet has propagation delay as well as block transmission time

» smaller packets may be necessary to limit delay (*latency*)

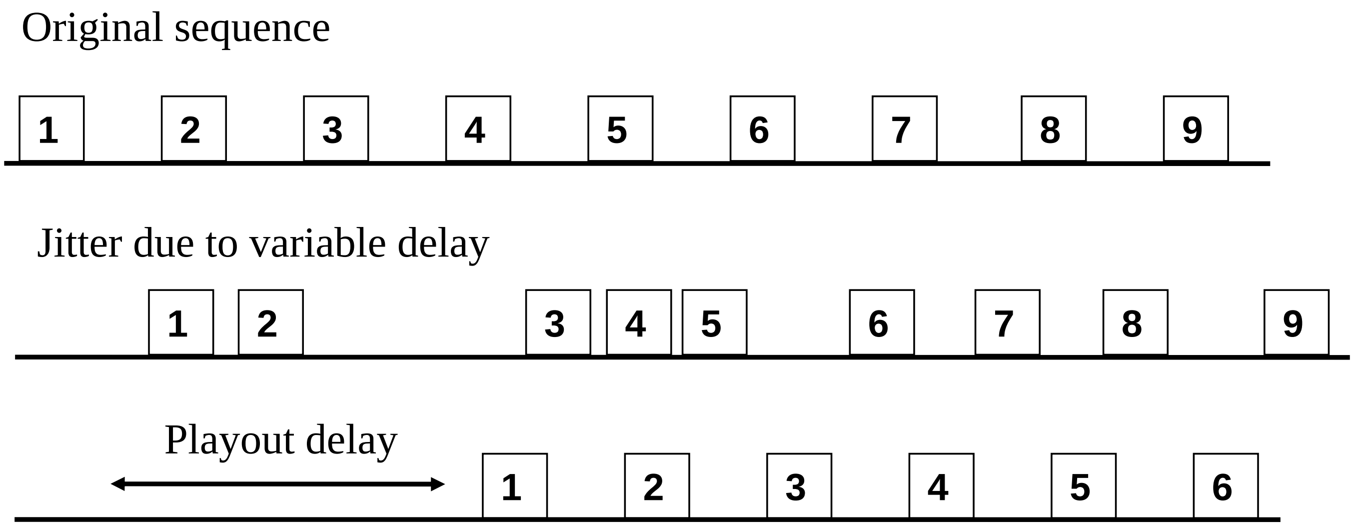
» e.g. 250ms for normal person-to-person conversation

– maximum *jitter* requirements

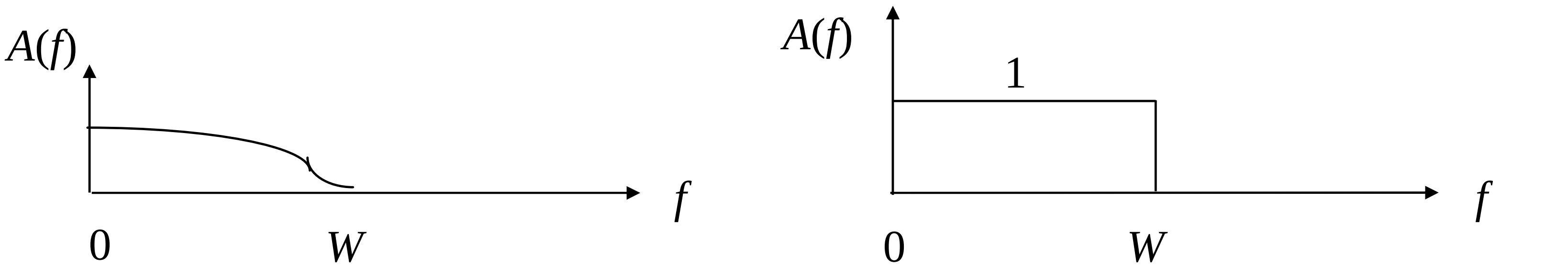
» the variation in delivery time of successive blocks

» sufficient buffering required to cope with maximum expected jitter

» e.g. RealPlayer video stream buffering

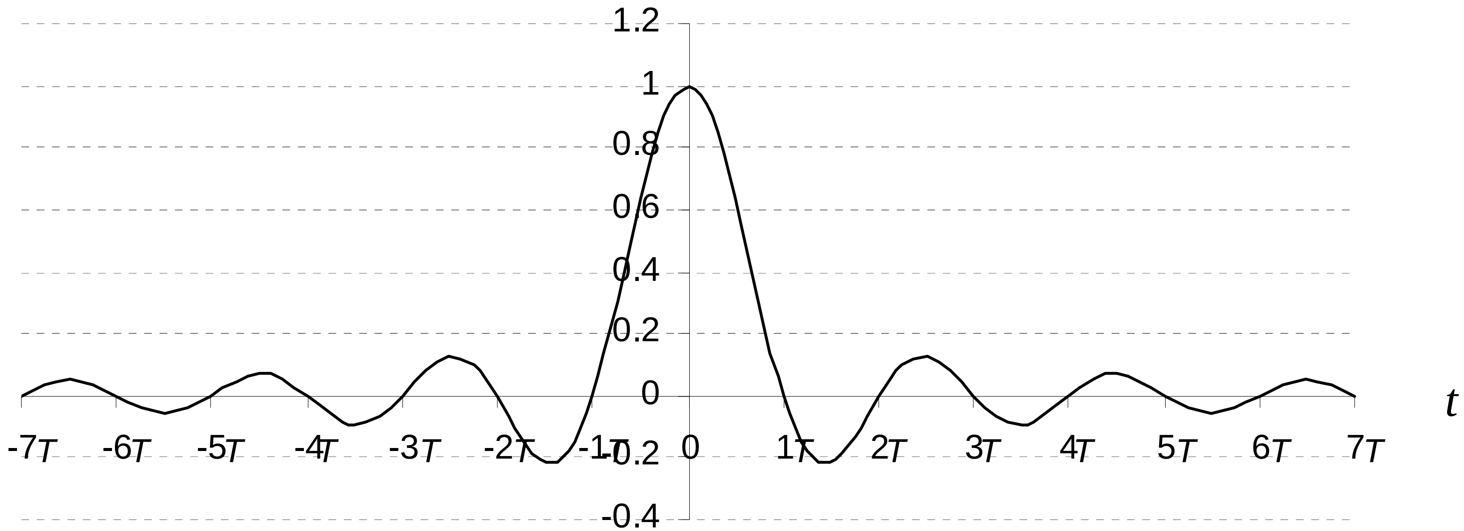


- Transmission rates
  – how fast can bits be transmitted reliably over a given medium?
  – factors include:
    » amount of *energy* put into transmitting the signal
    » the *distance* the signal has to traverse
    » the amount of *noise* introduced
    » the *bandwidth* of the transmission medium
  – a transmission channel characterised by its effect on various frequencies
    » the *amplitude-response function*, *A(f)*, defined as ratio of amplitude of the output signal to that of the input signal, at a given frequency *f*
    » a typical low-pass channel and an idealised channel of bandwidth W:



– an idealised impulse passed through a channel of bandwidth W comes out as:

$$s(t) = \sin(2\pi Wt)/\, 2\pi Wt$$



– where T = 1/2W

– most of the energy is confined to the interval between –T and T

– suggests that pulses can be sent closer together the higher the bandwidth

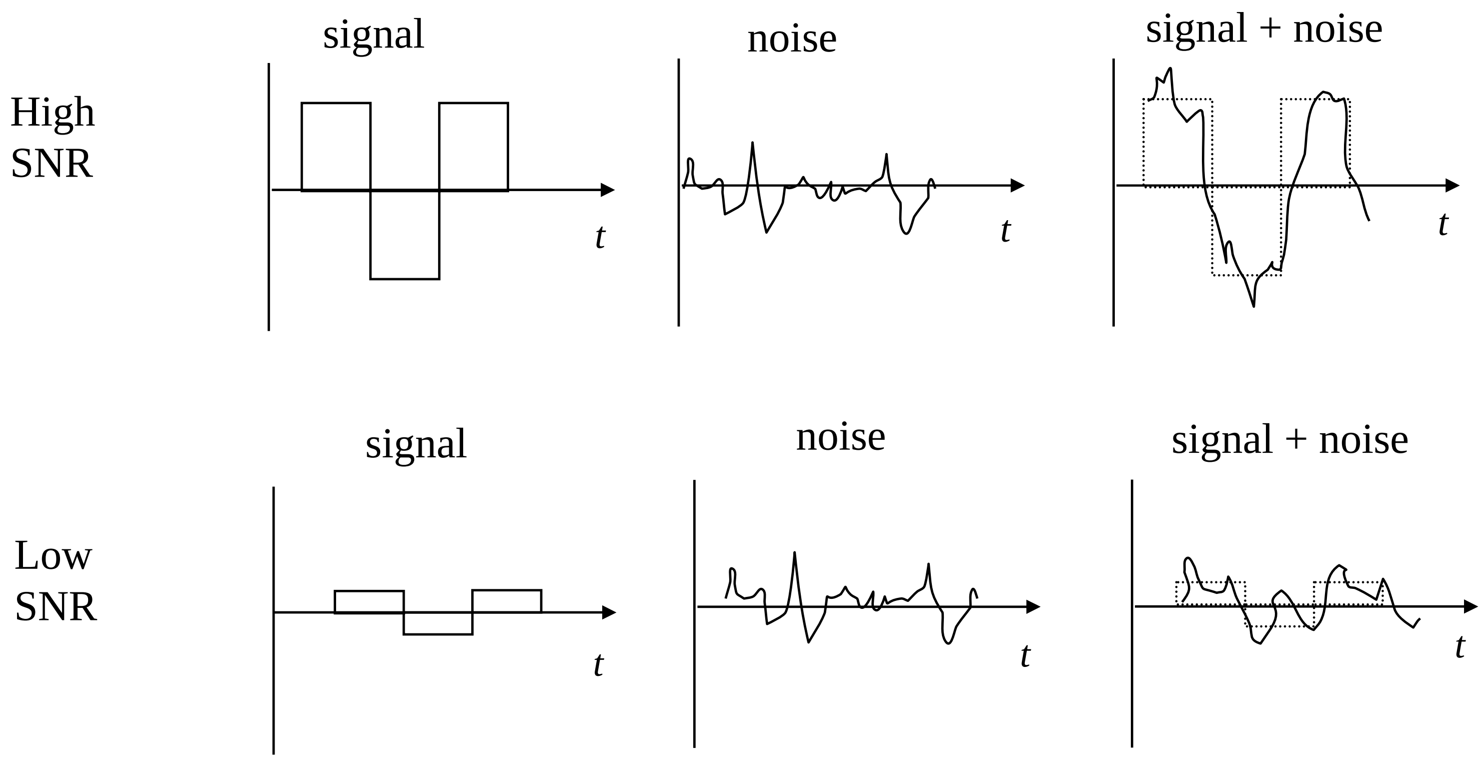
» output resulting from a stream of pulses (*symbols*) is additive

» will therefore suffer from *intersymbol interference*

– zero-crossings at multiples of T mean *zero intersymbol interference* at times *t=kT*

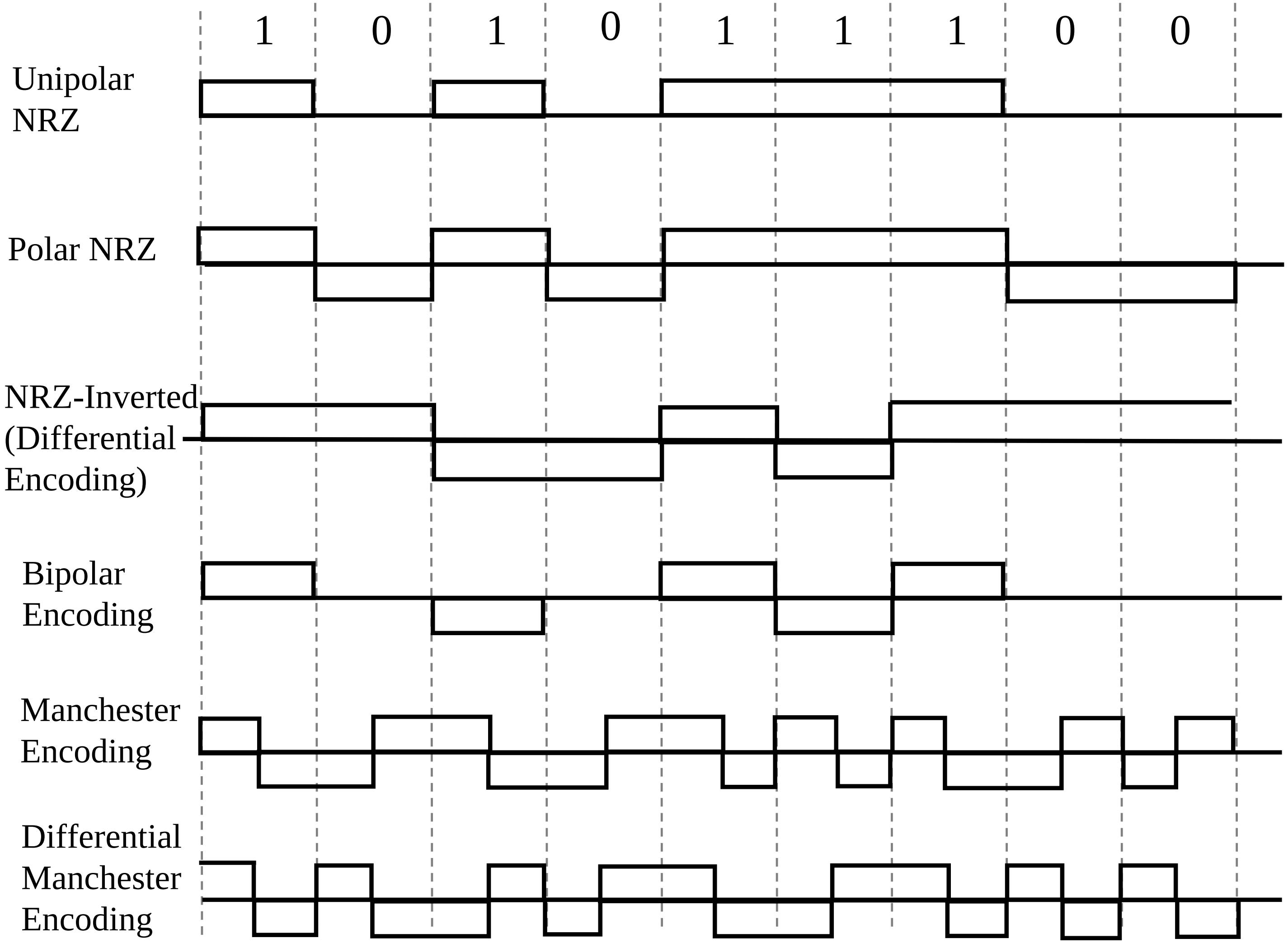
- Nyquist Signalling Rate
  - defined by : r_{max} = 2W pulses/second
  - the *maximum signalling rate* that is achievable through an *ideal* low-pass channel with *no* intersymbol interference
    - » ideal low-pass filters difficult to achieve in practice
    - » other types of pulse also have zero intersymbol interference
  - with two pulse amplitude levels
    - » transmission rate = 2W bits per second
  - *multilevel* transmission possible
    - » if signal can take 2^m amplitude levels
    - » transmission rate = 2Wm bits per second
  - in the absence of noise, bit rate can be increased without limit
    - » by increasing the number of amplitude levels
  - unfortunately, noise is always present in a channel
    - » amount of noise limits the reliability with which the receiver can correctly determine the information that was transmitted

- Signal-to-Noise Ratio
  - defined as: $$\text{SNR} = \frac{\text{Average Signal Power}}{\text{Average Noise Power}}$$
  - $$\text{SNR (db)} = 10 \log_{10} \text{SNR}$$



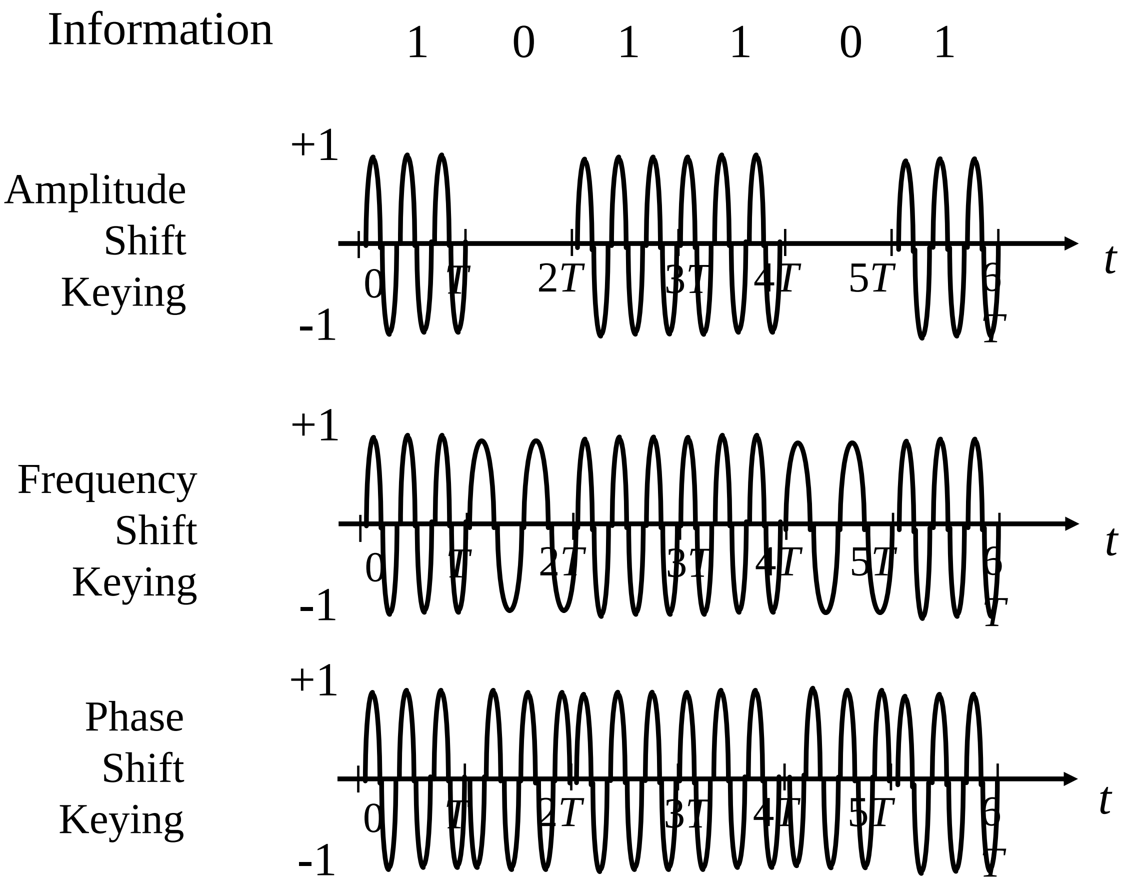
- Shannon Channel Capacity:
  - $$C = W \log_2(1 + SNR) \text{ bits/second}$$
  - reliable communication only possible up to this rate
  - e.g. ordinary telephone line V.90 56kbps modem
    - » useful bandwidth of telephone line ≈ 3400 Hz
      - purely because of added filters!
    - » assume SNR = 40 db (somewhat optimistic)
    - » C = 44.8 kbps !
    - » in practice, only 33.6 kbps possible inbound into network
      - quantisation noise decreases SNR because of A-D conversion from telephone line into the network
    - » outbound from ISP, signals are already digital
      - no extra quantisation noise through the D-A from the network onto the telephone line
    - » a higher SNR therefore possible
      - speeds approaching 56 kbps can be achieved

- Line Coding:



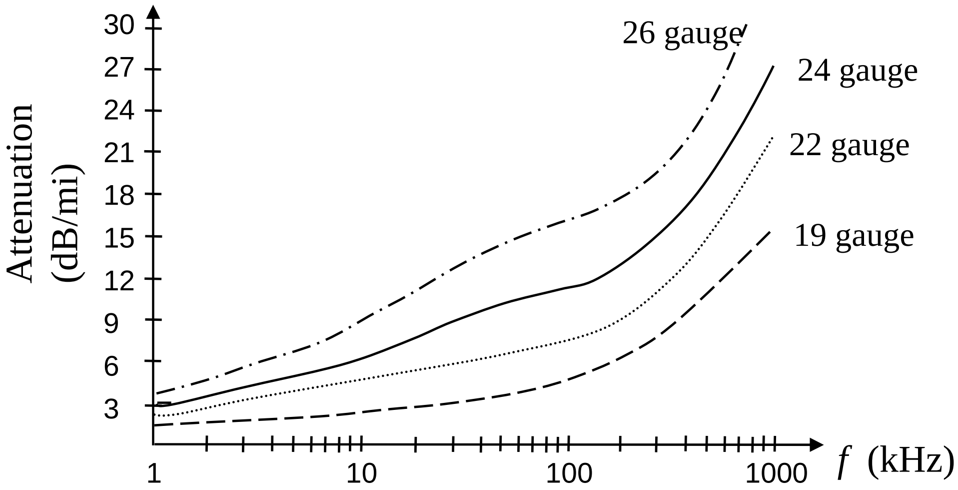
  – considerations:
    » average power, spectrum produced, timing recovery etc.

- Modulation:



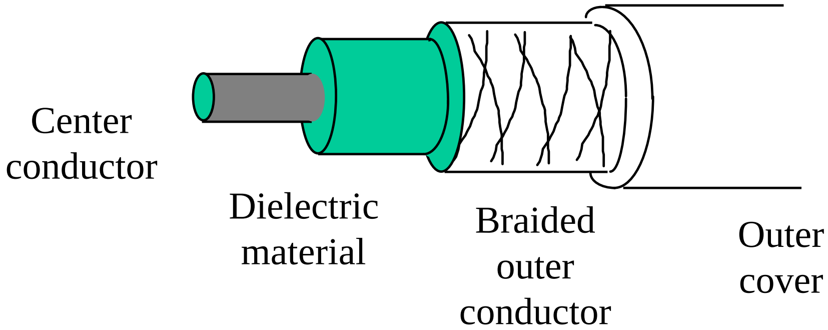
  - other types:
    - » Quadrature Amplitude Modulation (QAM)
    - » Trellis modulation, Gaussian Minimum Shift Keying, etc. etc.

- Properties of media: Copper wire pairs
  - » twisting reduces susceptibility to crosstalk and interference
    - shielded (STP) or unshielded (UTP)
  - » can pass a relatively large range of frequencies:



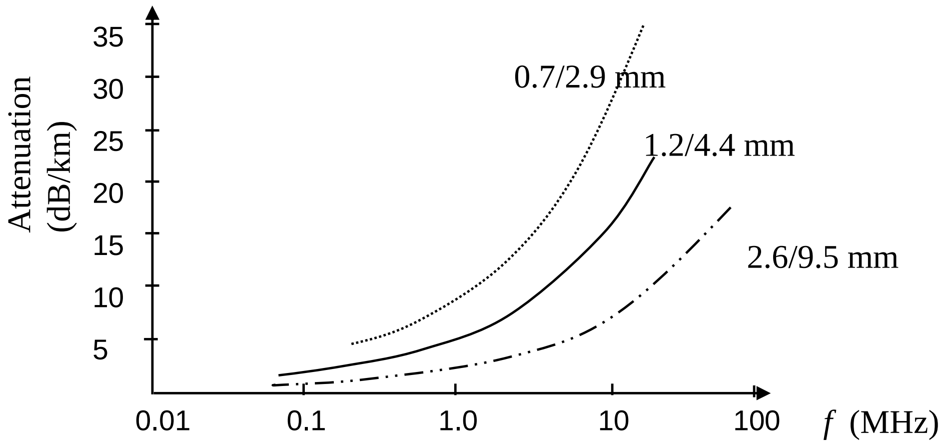
  - » still constitutes overwhelming proportion of access network wiring
  - » *Category 5* cable specified for transmission up to 100MHz
    - possibly even up to 1GHz in Gigabit Ethernet
  - » 4kHz bandwidth on telephone lines due to inserted filters
    - *loading coils* added to provide flatter response and better fidelity

- Coaxial cable



  » much better immunity to interference and crosstalk than twisted wire pair

  » and much higher bandwidths:



  » used in original Ethernet at 10Mbps

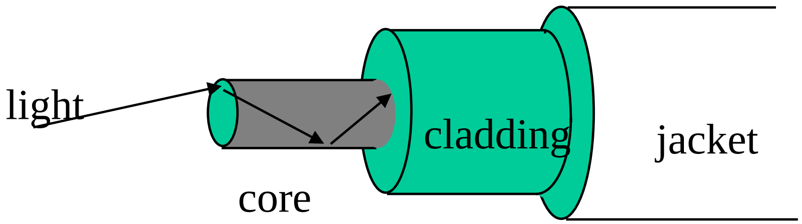
  » 8MHz to 565MHz in telephone networks

    - but superseded by optical fibre

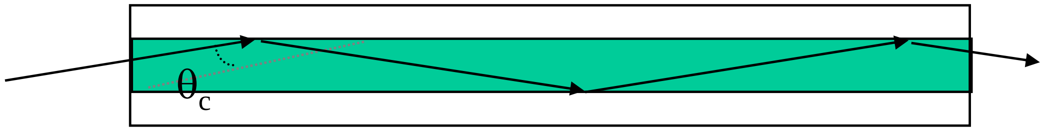
  » used in cable TV distribution

    - tree-structured distribution networks with branches at road ends

- Optical fibre



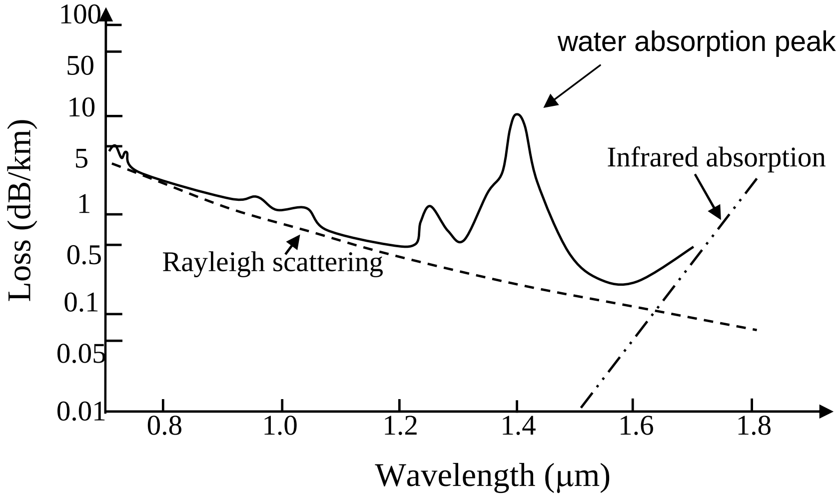
» relies on *total internal reflection* of light waves:



» core and cladding have different refractive indices: $n_{\text{core}} > n_{cladding}$

» first developed by Corning Glass in 1970

- demands extremely pure glass - now approaching theoretical limits
- originally 20 db per km, now 0.25 db per km
- signals can be transmitted more than 100 km without amplification

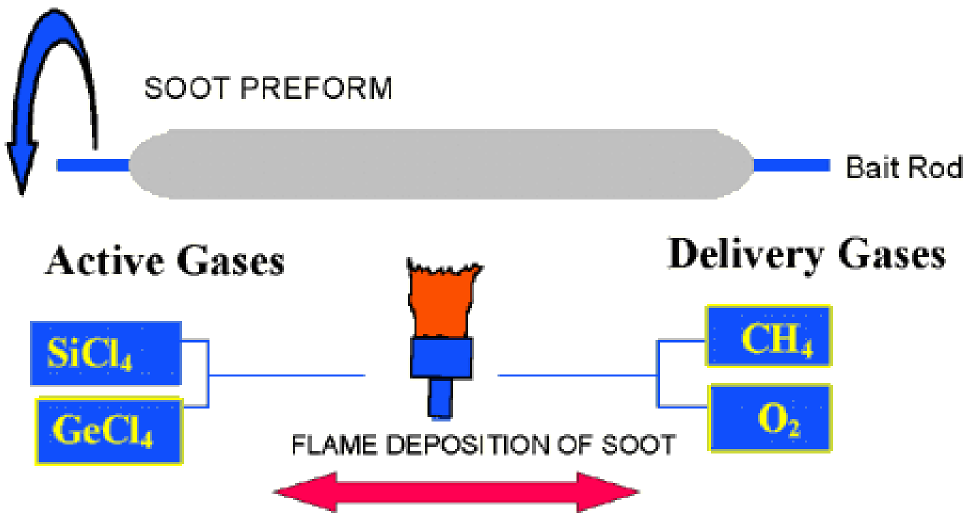


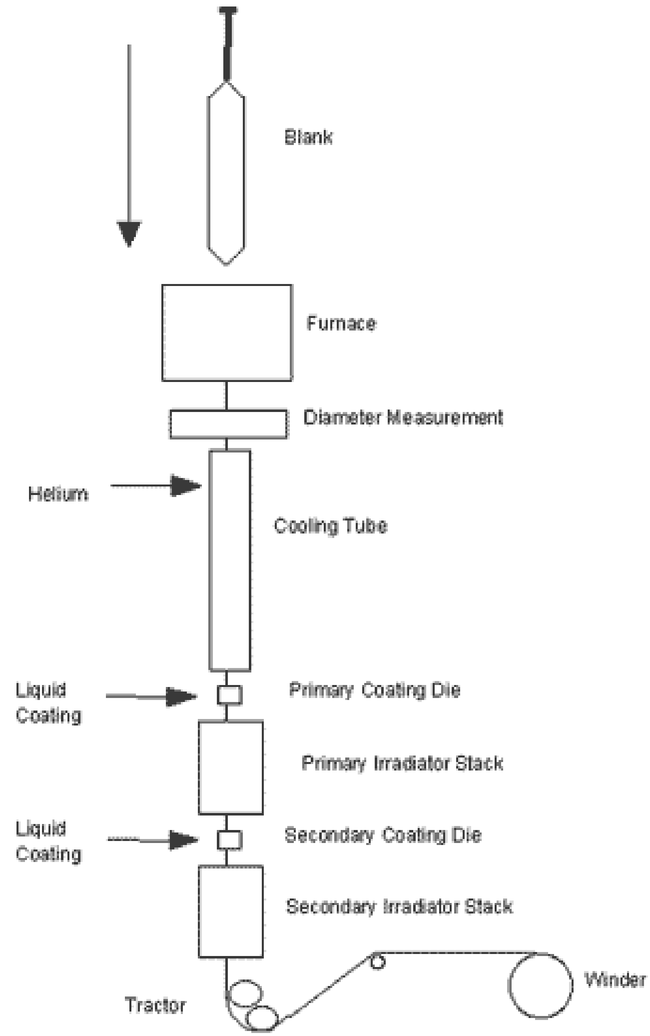
– manufacture:

» *preform* created by *Outside Vapour Deposition* (OVD) of ultrapure silica

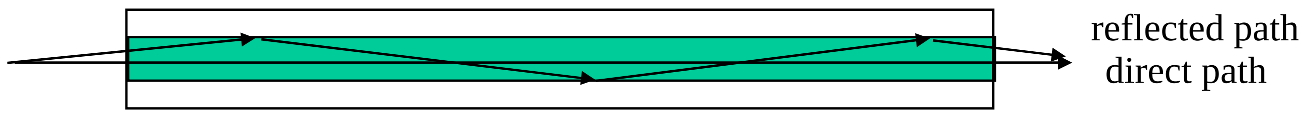
» then *consolidated* in a furnace to remove water vapour

» then *drawn* through a furnace into fine fibres

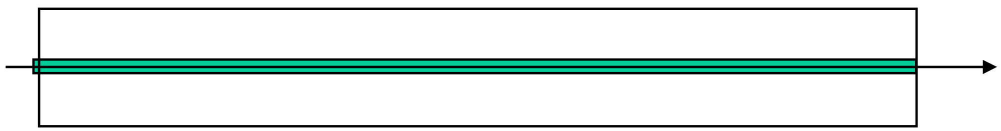




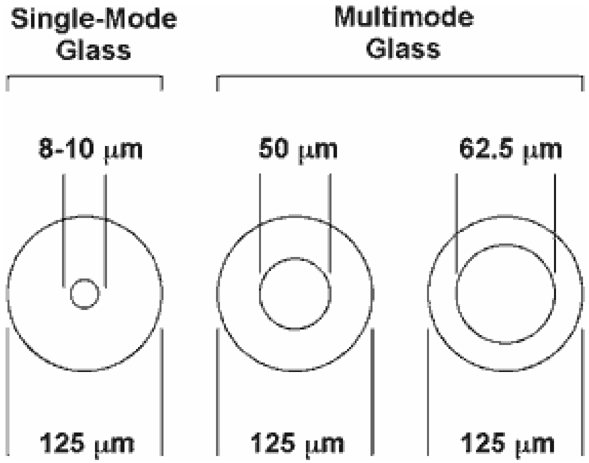
» multimode fibre - multiple rays follow different paths:



» single-mode fibre - all rays follow a single path:



» diameters:



» larger core of multimode fibre allows use of lower-cost LED and VCSEL optical transmitters

» single-mode fibre designed to maintain spatial and spectral integrity of optical signals over longer distances

- and have much higher transmission capacity

– maximum capacity at *zero-dispersion* wavelength

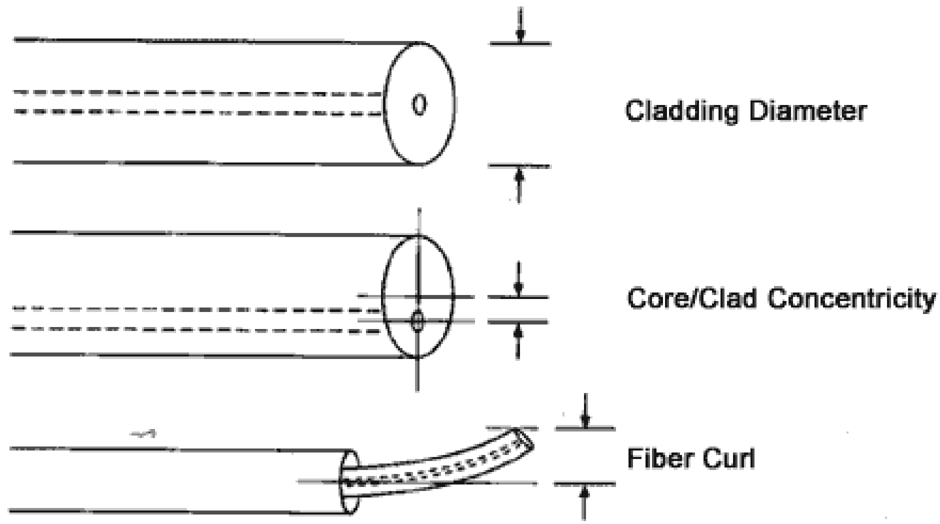
» typically in region of 1320nm for single-modes fibres

» but can be tailored to anywhere between 1310nm and 1650nm

– optical fibre splicing difficult

» demands tight control of fibre during manufacture

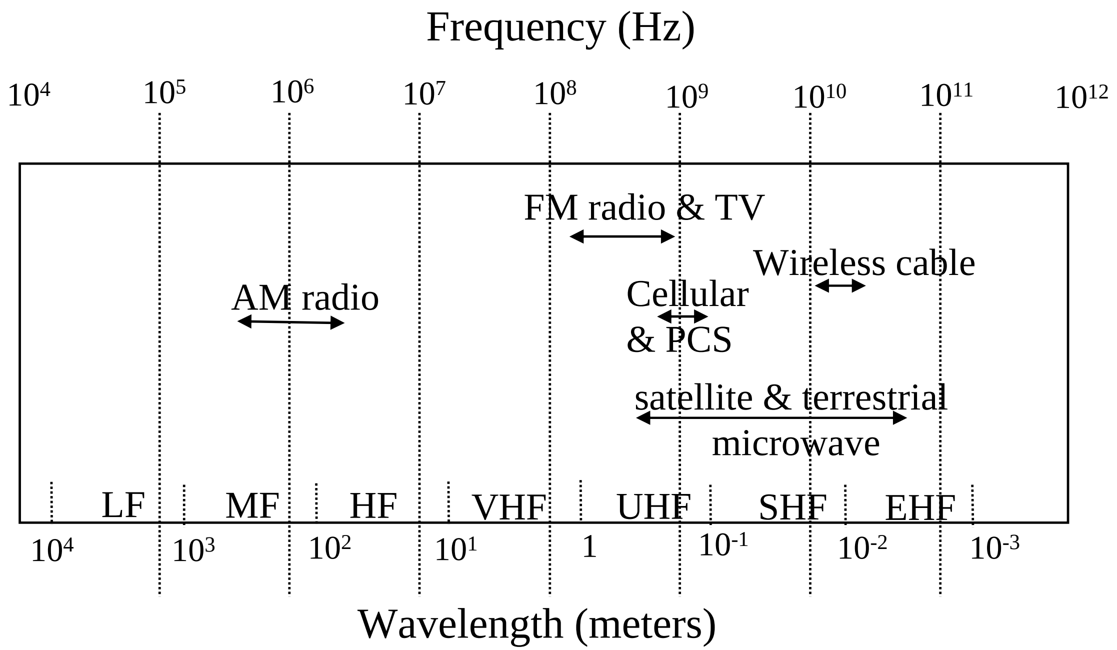
- cladding diameter
- concentricity
- curl



– widely deployed in backbone networks

» but still too expensive for the *last mile* to individual consumers

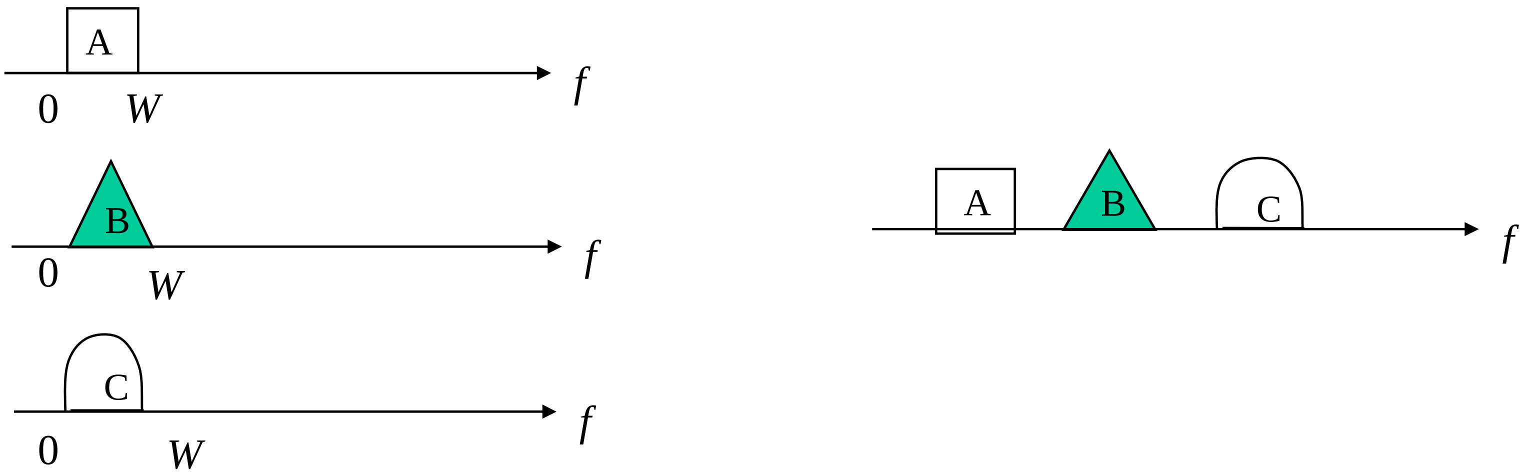
- Radio transmission
  - » 3 kHz to 300 GHz



  - » attenuation varies logarithmically with distance
    - varies with frequency and with rainfall
  - » subject to interference and multipath fading
    - interference the main reason for tight regulatory controls on radiated power
  - » VLF, LF and MF band radio waves follow surface of earth
    - VLF at anything up to 1000km; LF and AM less
  - » HF bands reflected by ionosphere (Appleton Layer etc.)
  - » VHF and above only detectable within line-of-sight
  - » applications: Bluetooth, 802.11, Satellite etc.

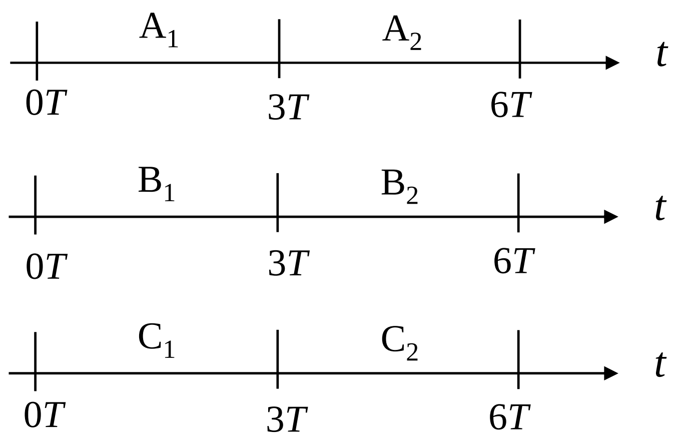
- Error Detection and Correction (CS3 Comms)
  - – automatic retransmission request (ARQ) versus forward error correction (FEC)
  - – detection:
    - » parity checks, 1-dimensional and 2-dimensional in rows and columns
    - » checksums on blocks of words
      - extra word added to block to make sum = 0
      - e.g. IP protocol blocks – uses 1’s complement arithmetic
    - » polynomial codes
      - checkbits in the form of a *cyclic redundancy check*
      - standard generator polynomials
        - ¤ CRC-8 : x^8+x^2+x+1 : used in ATM header error control
        - ¤ CCITT-16 : $x^{16}+x^{12}+x^5+1$: HDLC, etc.
  - – correction
    - » Hamming codes, Reed-Solomon codes, Convolutional codes etc.
  - – all require *redundancy*
    - » i.e. extra information must also be transmitted

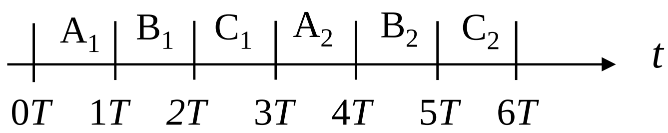
- Multiplexing:
  - – sharing expensive resources between several information flows
- Frequency-division multiplexing:
  - – used when the bandwidth of the transmission line is greater than that required by a single information flow
  - – multiplexer modulates signals into appropriate frequency slot and transmits the combined signal:



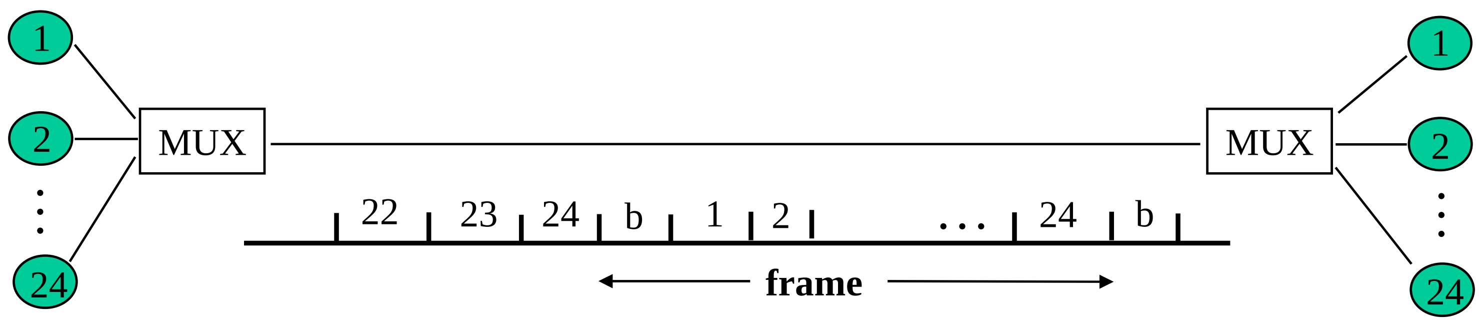
  - – e.g. telephone *groups* (12 voice channels), *supergroups* (5 groups = 60 voice channels) and *mastergroups* (10 supergroups = 600 voice channels)
  - – e.g. broadcast radio and television - each station assigned a frequency band

- Time-division multiplexing:
  - – transmission line organised into equal-sized time-slots
  - – an individual signal assigned to time-slots at successive fixed intervals





  - – e.g. a T-1 carrier time-division multiplexes 24 channels onto a 1.544Mbps line

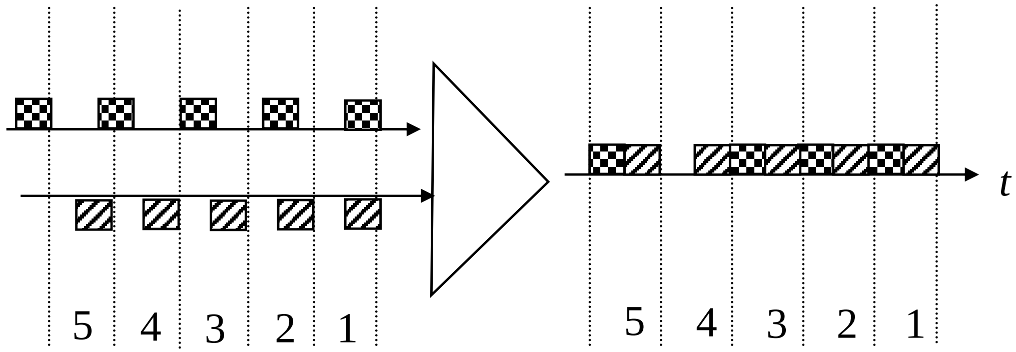


– tricky problems can arise with the synchronisation of input streams

– e.g. two streams of data both nominally at 1 bit every T secs

– what happens if one stream is *slow* ?

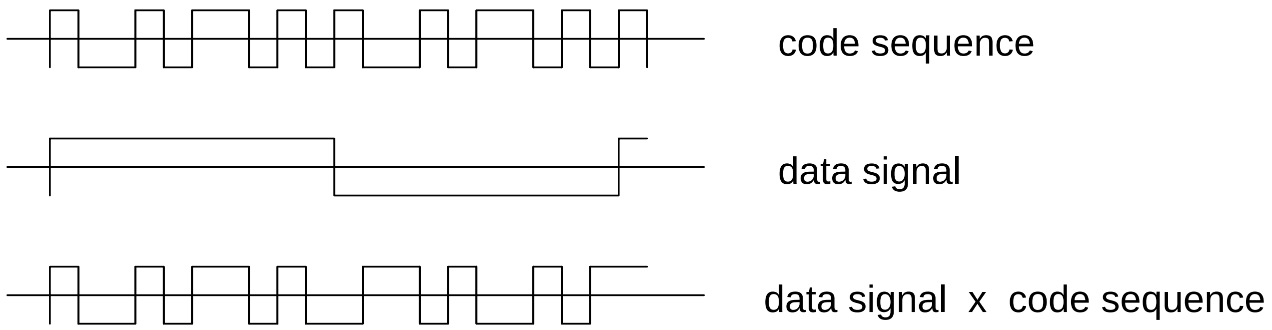
– eventually the slow stream will *miss* a slot – *bit-slip* :



– dealt with by running multiplexer slightly faster than combined speed of inputs

– signal bits to indicate that a bit-slip has occurred

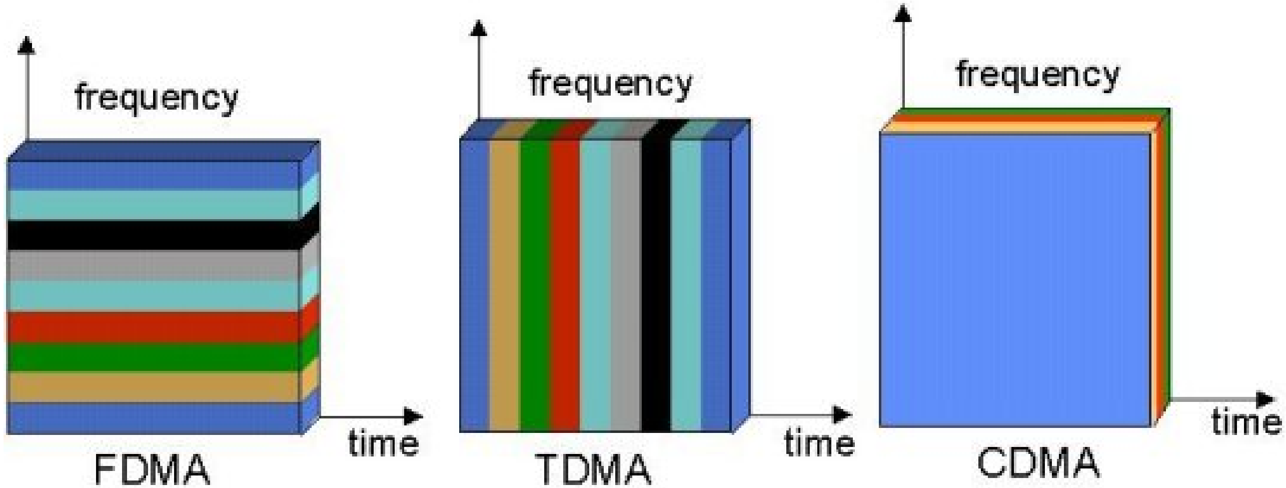
- Code-division multiplexing:
  - – primarily a *spread-spectrum* radio transmission system
    - » 3G mobile phones, GPS, etc. but also in cable transmission systems
  - – transmissions from different stations simultaneously use *same* frequency band
  - – individual transmissions separated by individual *codes* for each transmitter
    - » a long pseudorandom sequence that repeats after a very long period
    - » receivers need the specific code to recover the desired signal
  - – each bit from a signal is transformed into *G* bits by multiplying the signal bits by the successive *G* code bits (using -1 in place of 0 and +1 in place of 1)

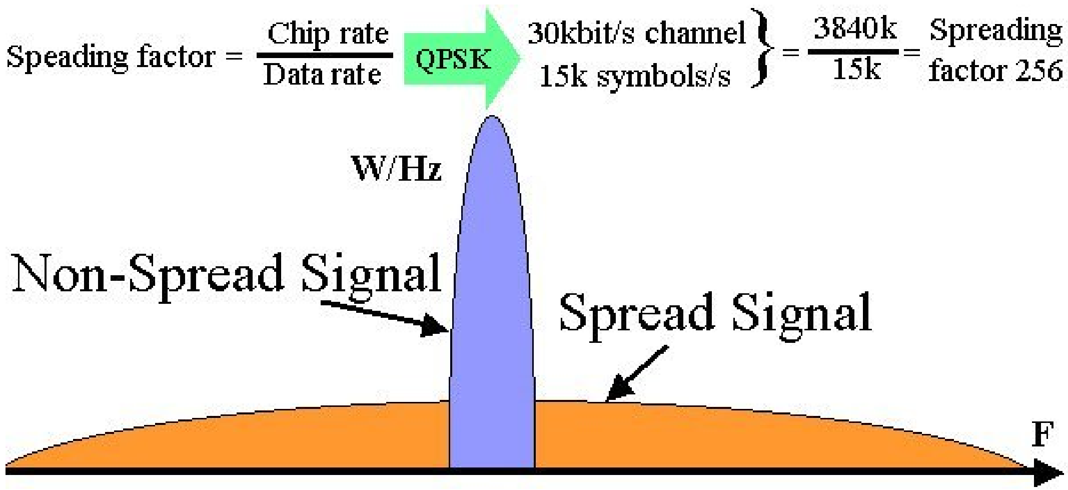


    - » and transmitting the result
  - – original data recovered by multiplying transmitted signal by code sequence

– *G* is the *spreading factor*

  » chosen so that transmitted signal occupies the entire frequency band



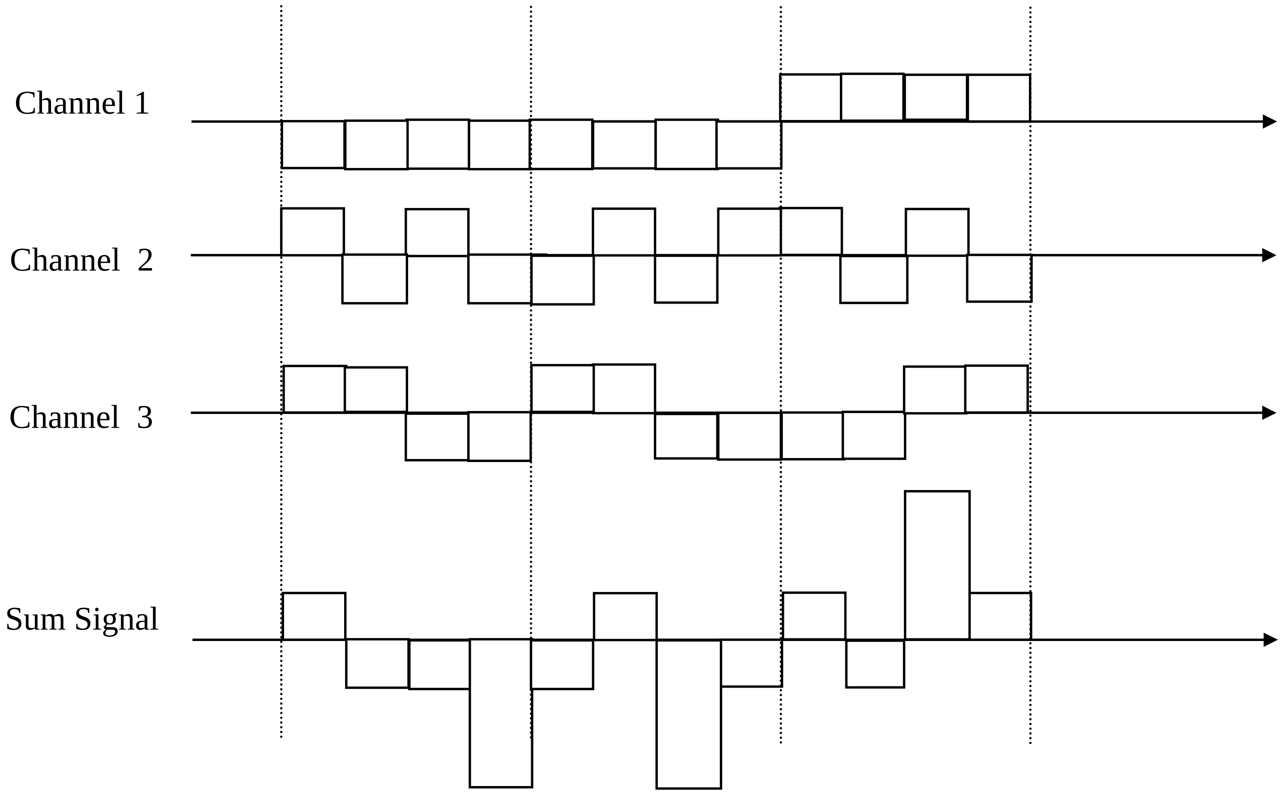


– example of 3 channels transmitting simultaneously:

» channel 1 code : (-1, -1, -1, -1) : transmitting (1, 1, 0) ≡ (+1, +1, -1)

» channel 2 code : (-1, +1, -1, +1) : transmitting (0, 1, 0) ≡ (-1, +1, -1)

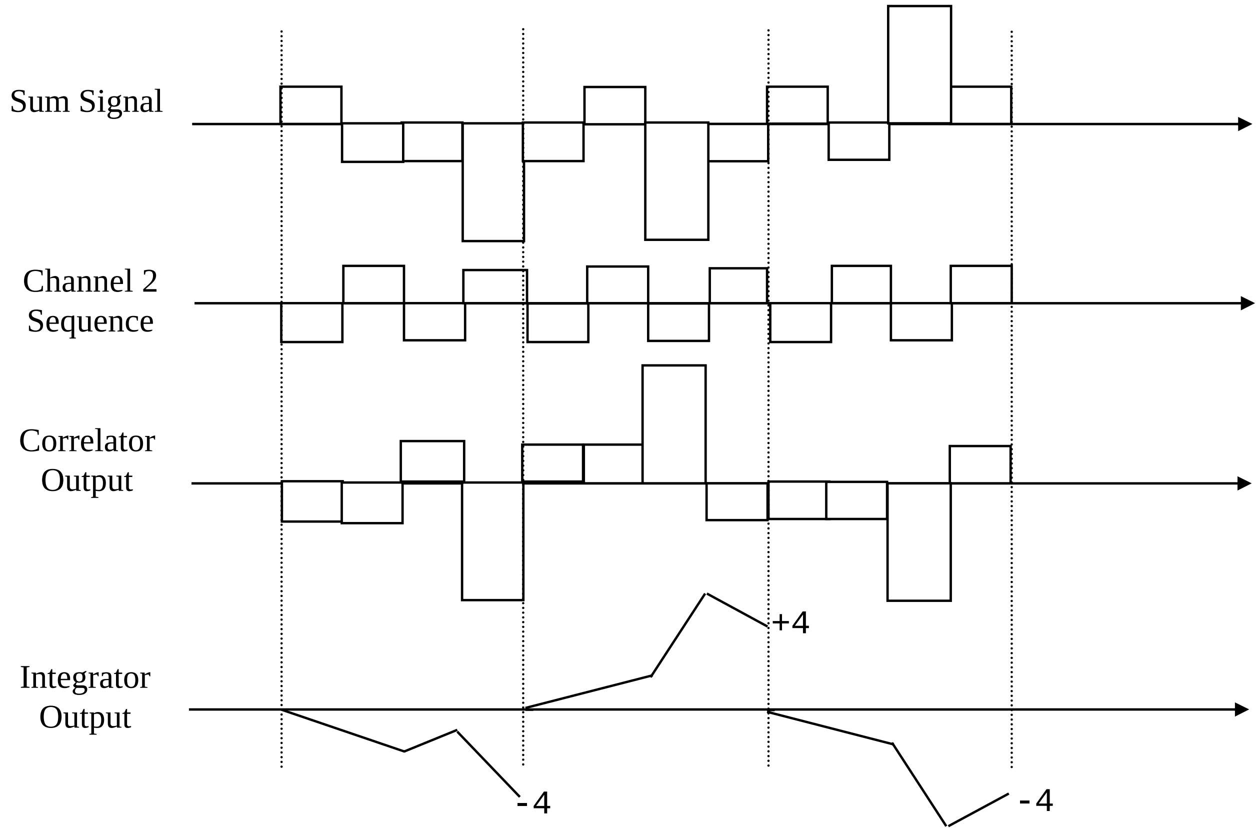
» channel 3 code : (-1, -1, +1, +1) : transmitting (0, 0, 1) ≡ (-1, -1, +1)



– example: decoding channel 2:

» received signal remultiplied by code sequence (-1, +1, -1, +1)

» result integrated over each time-slot:



» to regenerate original (-1, +1, -1) ≡ (0, 1, 0)

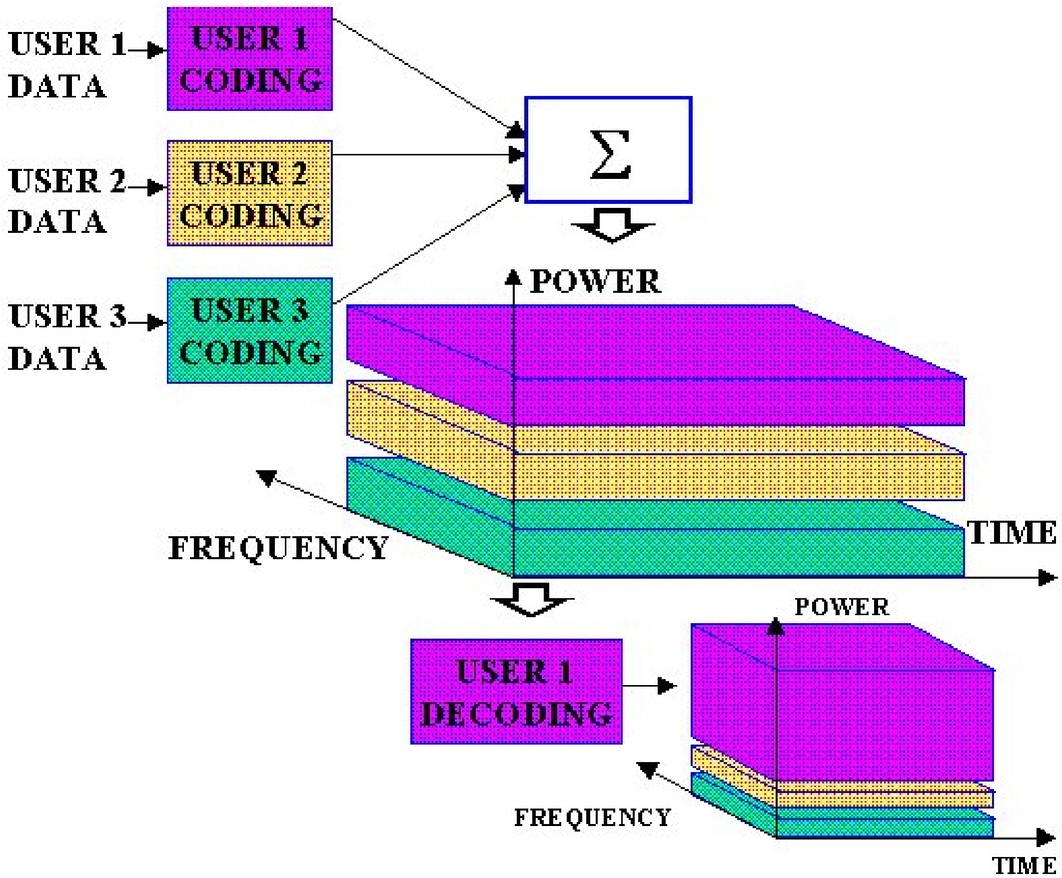
– good rejection of other coded signals when *orthogonal* code sequences used

» e.g. using Walsh functions

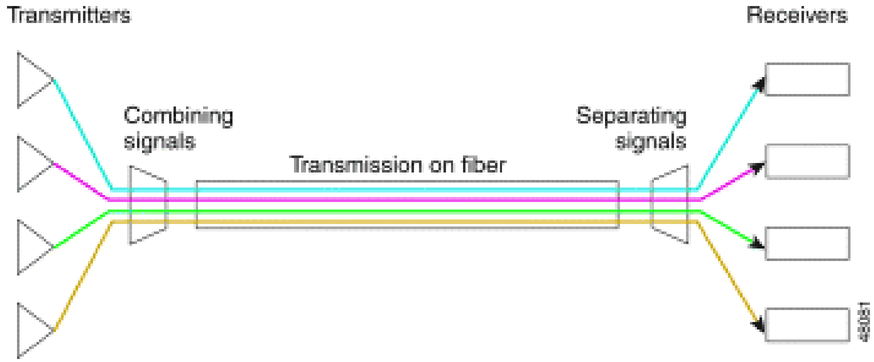
» good immunity to noise and interference

» used in military systems for this reason

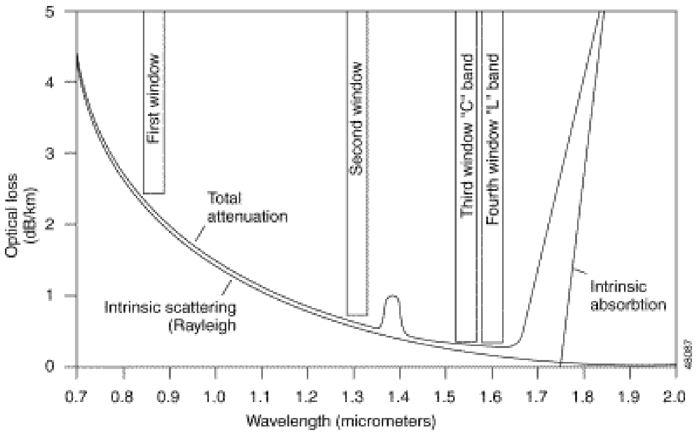
– recovered signal power greater than noise and other coded signal power

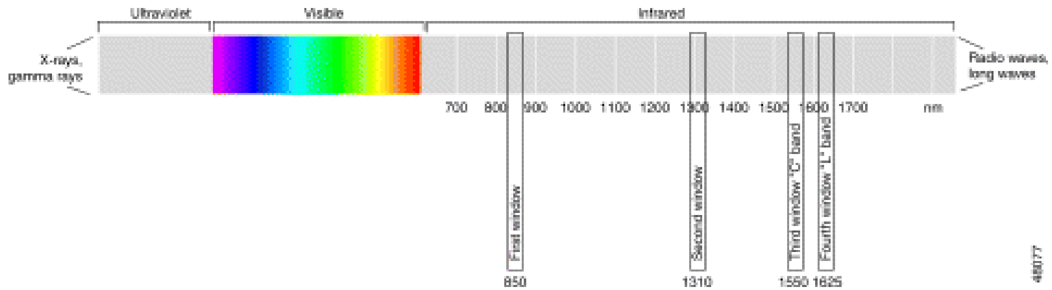


- Wavelength Division Multiplexing (WDM and DWDM):
  - the equivalent of frequency division multiplexing in the optical domain
  - to make use of the enormous bandwidths available there



  - a 100 nm wide band of wavelengths from 1250nm to 1350nm:
    - » frequency at 1250nm = c / 1250nm = $3x10^{8}$ / $1.25x10^{-6}$ = $2.4x10^{14}$
    - » frequency at 1350nm = c / 1350nm = $3x10^{8}$ / $1.35x10^{-6}$ = $2.22x10^{14}$
    - » bandwidth = $2.4x10^{14}$ – $2.22x10^{14}$ = $0.18x10^{14}$ = 18 TeraHz





– Light Emitting Diodes (LEDs)

» cheap with speeds only up to 1Gbps

» wide spectrum best suited to multimode fibre

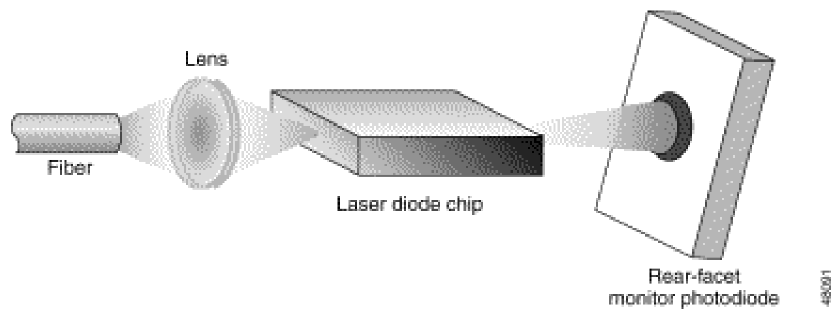
– Semiconductor lasers

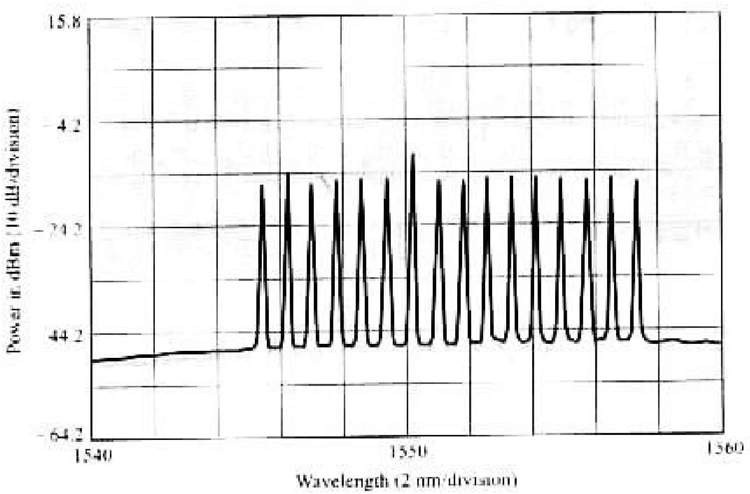
» emit nearly monochromatic light, well suited for WDM

» use multiple semiconductor lasers set at precisely selected wavelengths

- tunable lasers possible but only within a small range – 100-200 GHz

» light launched into the fibre through a lens

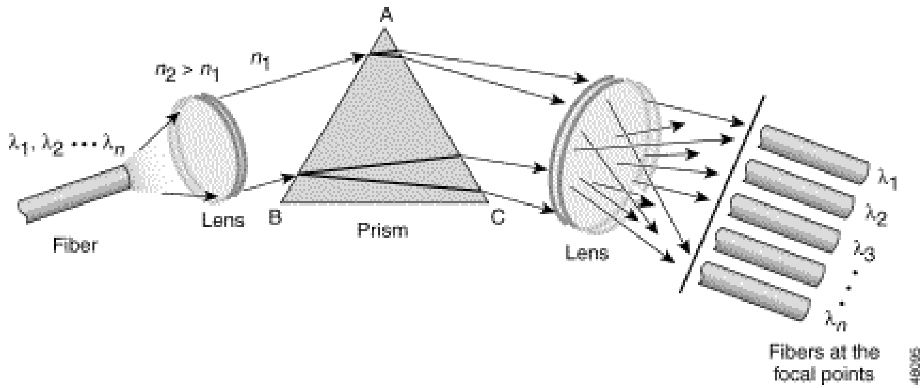




– techniques for multiplexing and demultiplexing

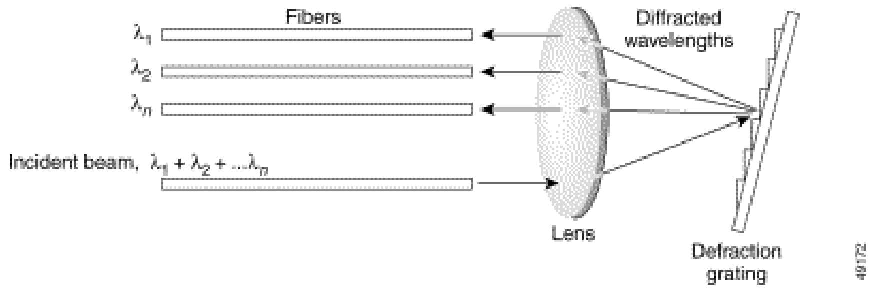
– Prism Refraction:

» each wavelength component *refracted* differently



– Waveguide Grating Diffraction:

» each wavelength *diffracted* a different amount

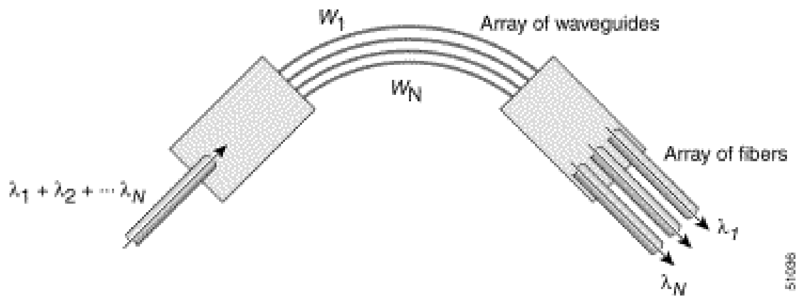


– Arrayed Waveguide Grating:

  » or *optical waveguide router*

  » fixed difference in path length between adjacent channels

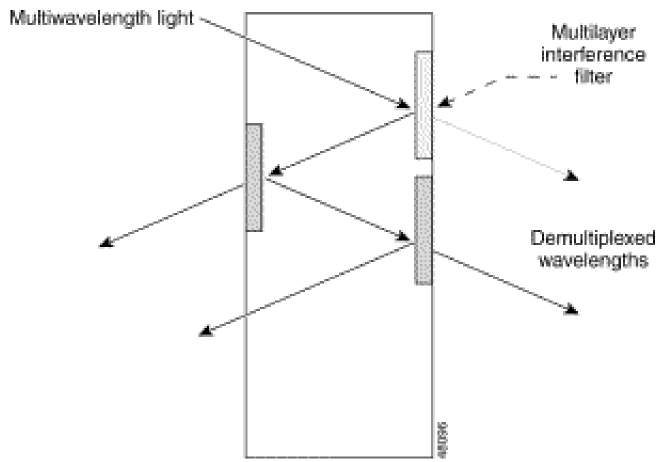
  » good for large channel counts



– Multilayer Interference Filters:

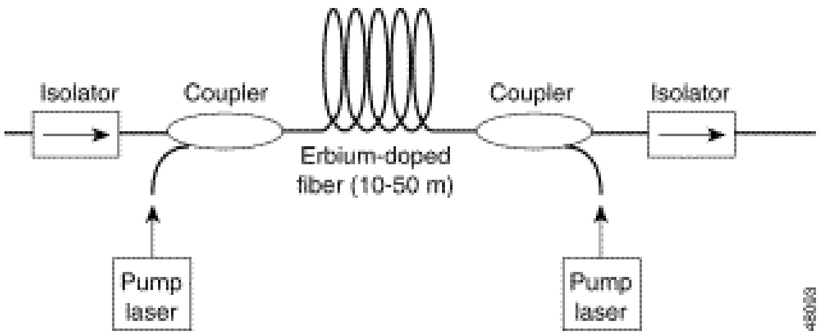
  » a sandwich of thin films

  » each filter transmits just one wavelength



– last two gaining prominence commercially

- Optical amplifiers
  - – attenuation limits length of propagation before amplification and regeneration needed
  - – originally, optical signals had to be converted back to electrical signals and then converted back to optical domain again
  - – Erbium-Doped Fibre Amplifier (EDFA)
    - » invented at Southampton University



    - » injected light stimulates the erbium atoms to release their stored energy
    - » noise also added to the signal
    - » but still capable of gains of 30 db or more
      - - amplification every 120km; regeneration every 1000km
    - » a vital technology for inter-continental and trans-continental links