COMPSCI 314 S1 C

Physical Layer
Part 2

Telephones and digitised audio

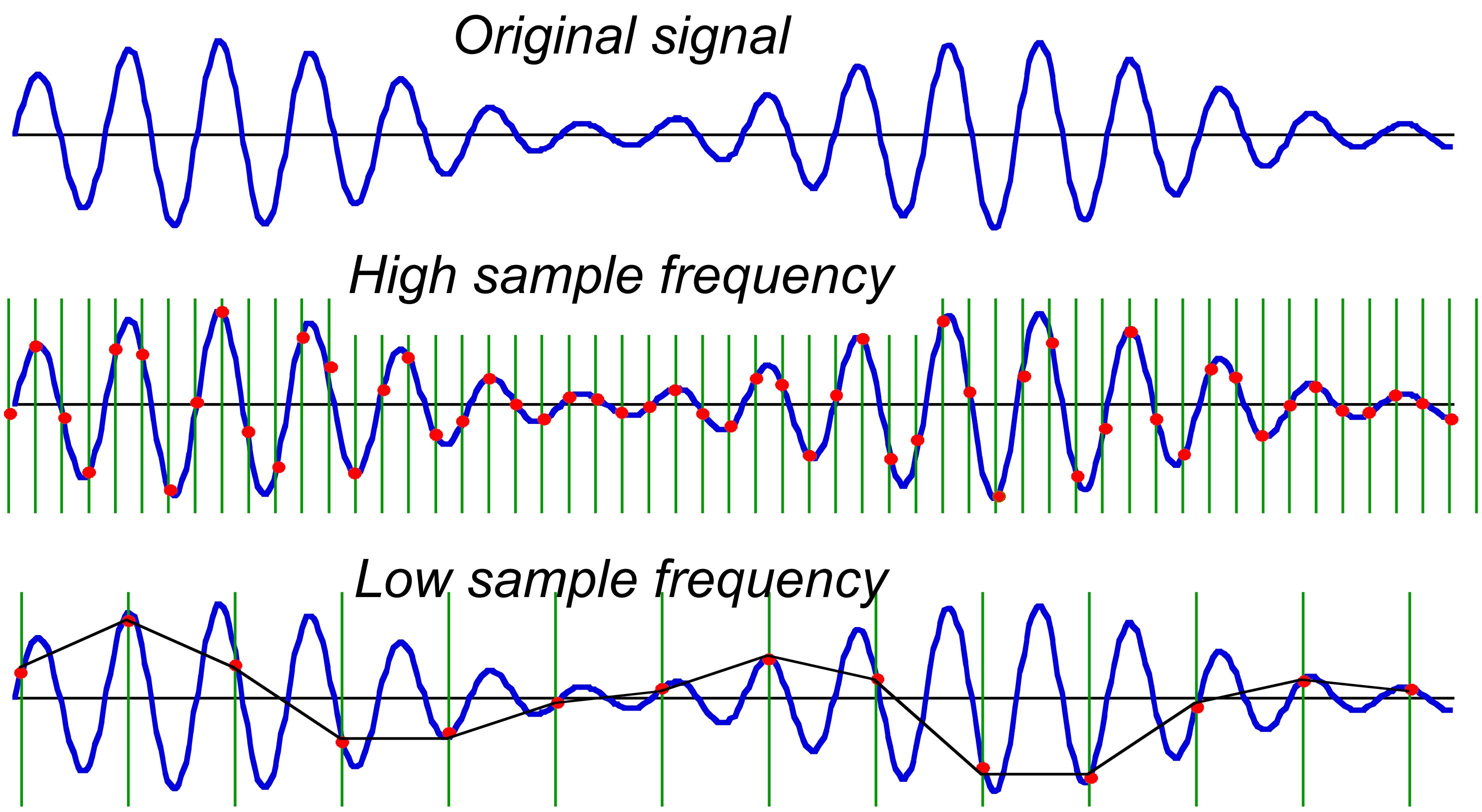
- Telephone signals are typically ‘band limited’ to 3100 Hz:

  $$300 < f < 3{,}400 \text{ Hz}$$

- In traditional telephony, many 3,100 Hz channels were multiplexed onto a single long-distance circuit.
  - Frequency shifting, amplitude modulation, and filtering were used to define channels at a 4 kHz separation.
  - There was a hierarchy of groups, super groups, jumbo super groups, etc.
- In modern telephony, the voice channel is still limited to $300 < f < 3{,}400$ Hz.
  - The analogue-digital conversion runs at 8,000 samples/second with 8-bit resolution, to produce a 64,000 bps digital data stream.
- The analogue signal is “companded” to give better digital resolution (“more bits”) at low signal amplitudes.
  - We use µ-law codecs in North America and A-law codecs in Europe.
- But why 8,000 samples per second?

Nyquist sampling theorem

- A periodic signal, if it is limited to a bandwidth of *W* Hz, is *totally* defined by 2*W* samples per second.



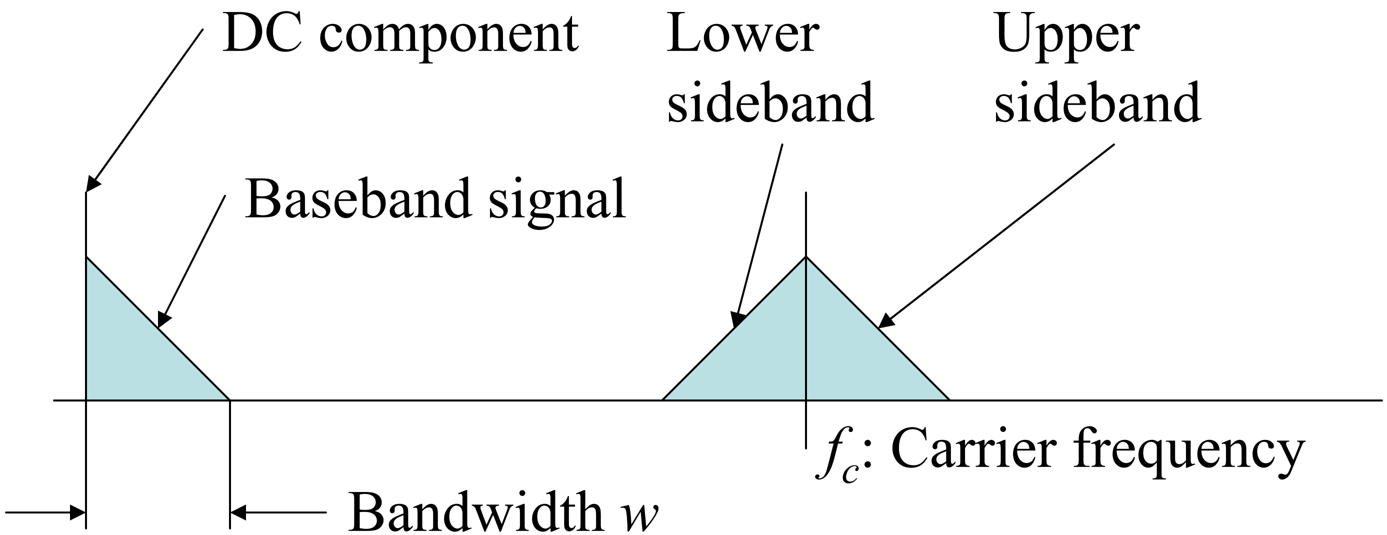
- We cannot reconstruct a signal if we have less than 2W samples/sec.

Sampling of audio and TV signals

- If the sample rate is R, then a frequency $f = R/2 + \mathrm{d}$ is “folded” or “aliased” into $f' = R/2 - \mathrm{d}$.
  - After sampling, the aliased f can not be distinguished from f'.
  - The reconstructed analogue signal will have power at f'.
- Telephones:
  - Bandwidth $W = 3{,}100$ Hz, sample rate $R = 8{,}000$ Hz, 8 bits/sample: 64 kbps.
- Audio CDs:
  - Bandwidth $W = 22{,}100$ Hz, sample rate $R = 44{,}200$ Hz, 16 bits/sample, two stereo channels: 1.4 Mbps of data.
  - CDs have an error-correction protocol, so use a raw data rate > 2 Mbps.
- Older CDs sometimes had trouble from aliasing.
  - Cymbals and other instruments with complex high-frequency harmonics, could sound very hollow and empty.
  - Later CD recordings sample much faster than 44 kHz, and then use digital filtering to minimise aliasing effects.
- “Oversampling” takes the digital data from the CD and uses a complex interpolation to predict sampling at a faster rate.
  - This predicted sample is used to regenerate the audio.
- A television signal, $W = 6$ MHz, needs a sample rate $R > 12$ MHz.

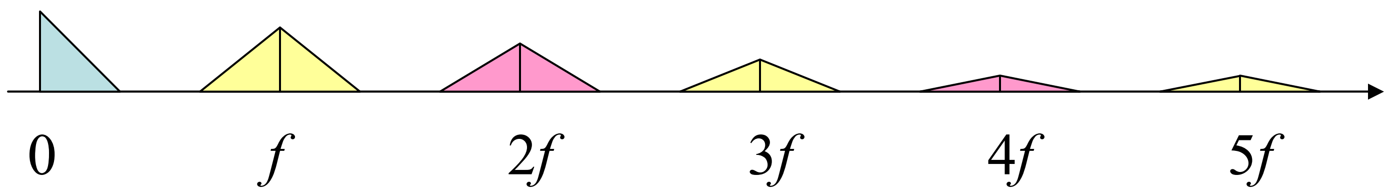
Alternate look at sampling

- A conventional way of representing a modulated signal and its sidebands shows how the baseband signal is displaced by the carrier frequency, with the upper sideband resembling the baseband signal and the lower sideband being inverted in frequency.



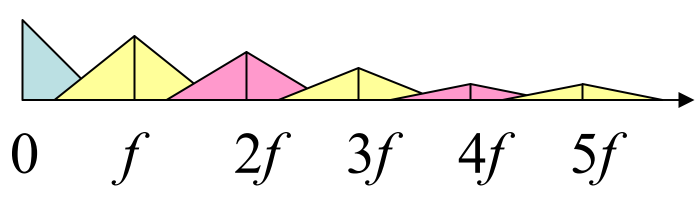
- Sampling can be looked at as a form of modulation where the carrier is a regular train of very narrow pulses at the sampling frequency.
- Such a pulse train at frequency f has a “comb” spectrum at frequencies f, $2f$, $3f$, $4f$, … up to some very high frequency.
- Each “tooth” of the comb is surrounded by a copy of the sidebands.

- With a high sampling rate (short interval $1/f$ between samples) the "teeth" are widely spaced.
  - The sets of sidebands do not interfere when $f > 2w$.
  - The samples accurately reflect the baseband signal.

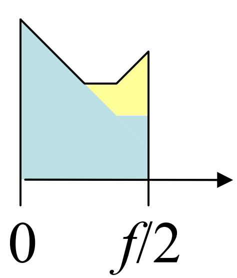


- With a low sampling rate, the teeth are closely spaced.
  - The sidebands interfere when $f < 2w$.
  - The samples are ambiguous, with a mixture of components from the correct signal and the adjacent sidebands.
  - The data cannot be recovered.

Unfiltered output of sampler

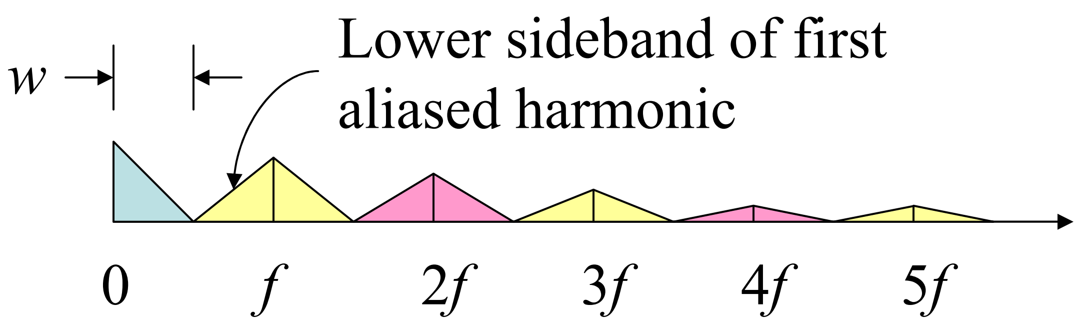


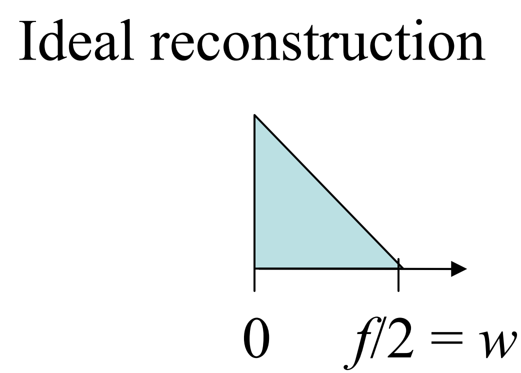
Best possible reconstruction from samples



Nyquist rate

- If the sampling frequency f is exactly twice the signal bandwidth w, there is no interference.
- The sampling is unambiguous and the original signal can be reconstructed.
  - Accurate reconstruction would require an ideal anti-aliasing filter: lowpass of precisely w, with no distortion.
- The minimum sampling rate $f = 2w$ is called the *Nyquist rate*, after the engineer who first investigated it.
  - In practice, even with high-quality digital anti-aliasing filters, we must sample at $f > 3w$ if we want an accurate reconstruction.





Digital communications

- Digital communication standards are based on telephone standards.
  - One 64 kbps channel is 8 bits per sample, at 8,000 samples per second.
- There are two groups of standards, one at around 1–2 Mbps and the other above 50 Mbps.
  - The low data rates are for ISDN (Integrated Services Digital Network).
  - The high rates are for B-ISDN (Broadband ISDN).
- The North American T1 or DS-1 standard handles 24 telephone channels, each 64 kbps.
  - Each frame has an 8-bit sample for each of the 24 channels, with 1 framing bit ending the frame.
  - (193 bits/frame)(8000 frames/second) = 1.544 Mbps
  - The framing bit “flips” on alternate frames.
  - Two channels have their LSB reserved for signalling.

Frame has 193 bits

Channel 1	Channel 2	Channel 3	…	Channel 24	0/1

Each channel has 8 bits

(Channels 6 & 12 have 7 data + 1 signalling bit)

Framing bit

ITU-T E-1 standard

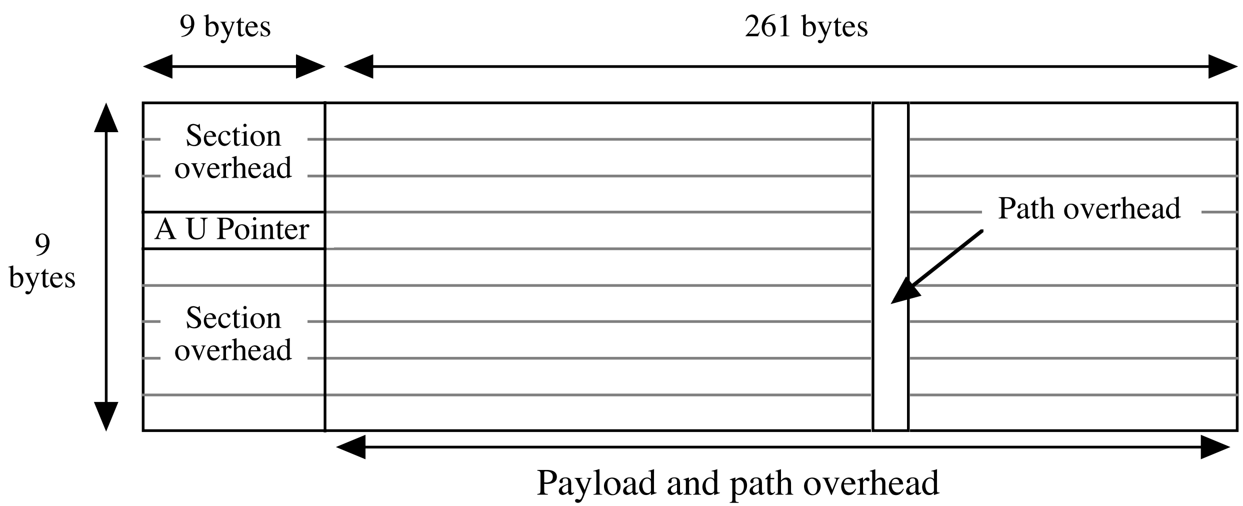
- The European ITU-T E-1 standard uses a frame with 32 8-bit “slots”.
  - With 8,000 frames per second, at 32×64 kbps = 2.048 Mbps.
  - Slot 0 is used for frame alignment
  - Slot 16 is used for signalling
  - The remaining slots are used for data.

- Multiplexing, or grouping, of channels

North America				ITU-T		
Circuit	Bit rate (Mbps)	Channels		Circuit	Bit rate (Mbps)	Channels
DS1	1.544	24		E1	2.048	30
DS1C	3.152	48		E2	8.448	120
DS2	6.312	96		E3	34.368	480
DS3	44.736	672		E4	139.264	1,920
DS4E	139.264	1,920		E5	565.148	7,680
DS4	274.176	4,032				

Synchronous Digital Hierarchy: SDH, or SONET

- The ITU-T (formerly CCITT) specifies a Synchronous Digital Hierarchy, or SDH, based on a 125µs frame (8,000 frames/second).
  - SONET is similar; it was developed earlier by Bellcore.
- The basic STS-1 frame has 9 rows of 90 columns of bytes (octets).
  - The bytes are transferred in “raster scan” order: left to right, top to bottom.
  - The STM-1 frame holds 3 interleaved STS-1 frames.
  - Higher speed STM-*n* frames hold *n* of the basic STM-1 frames.
  - For an STM–*n* frame, send the first bytes of the first row, one for each channel in order, then the second bytes, and so on.
- Three levels of link protocols: sections, lines, paths (end-to-end).



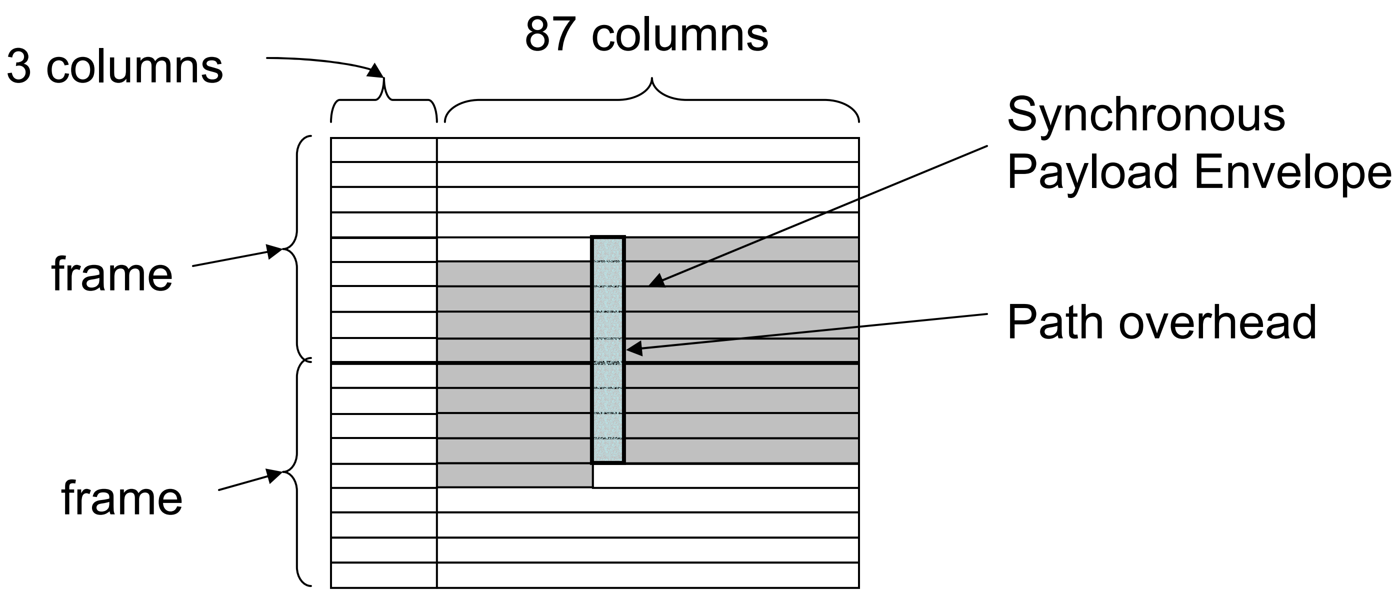
S T M - 1 frame

STM-1 Frame: overhead layouts

Section Overhead	Framing A1	Framing A2	STS-ID C1	Trace J1
	BIP-8 B1	Orderwire E1	User F1	BIP-8 B3
	Data Com D1	Data Com D2	Data Com D3	Signal Label C2
Line Overhead	Pointer H1	Pointer H2	Pointer Action H3	Path Status G1
	BIP-8 B2	APS K1	APS K2	User F2
	Data Com D4	Data Com D5	Data Com D6	Multiframe H4
	Data Com D7	Data Com D8	Data Com D9	Growth Z3
	Data Com D10	Data Com D11	Data Com D12	Growth Z4
	Growth Z1	Growth Z2	Orderwire E2	Growth Z5
				Path Overhead

Floating STS-1 Frames

- The actual data frame “floats” within, and across, transmission frames.
  - This accommodates clock variations between the sender and the frame.
- The AU Pointer of the section header gives the byte offset within the physical frame of the start of the data frame.
  - The data frame starts at the first byte of the Path Overhead.



SONET and ITU transmission speeds

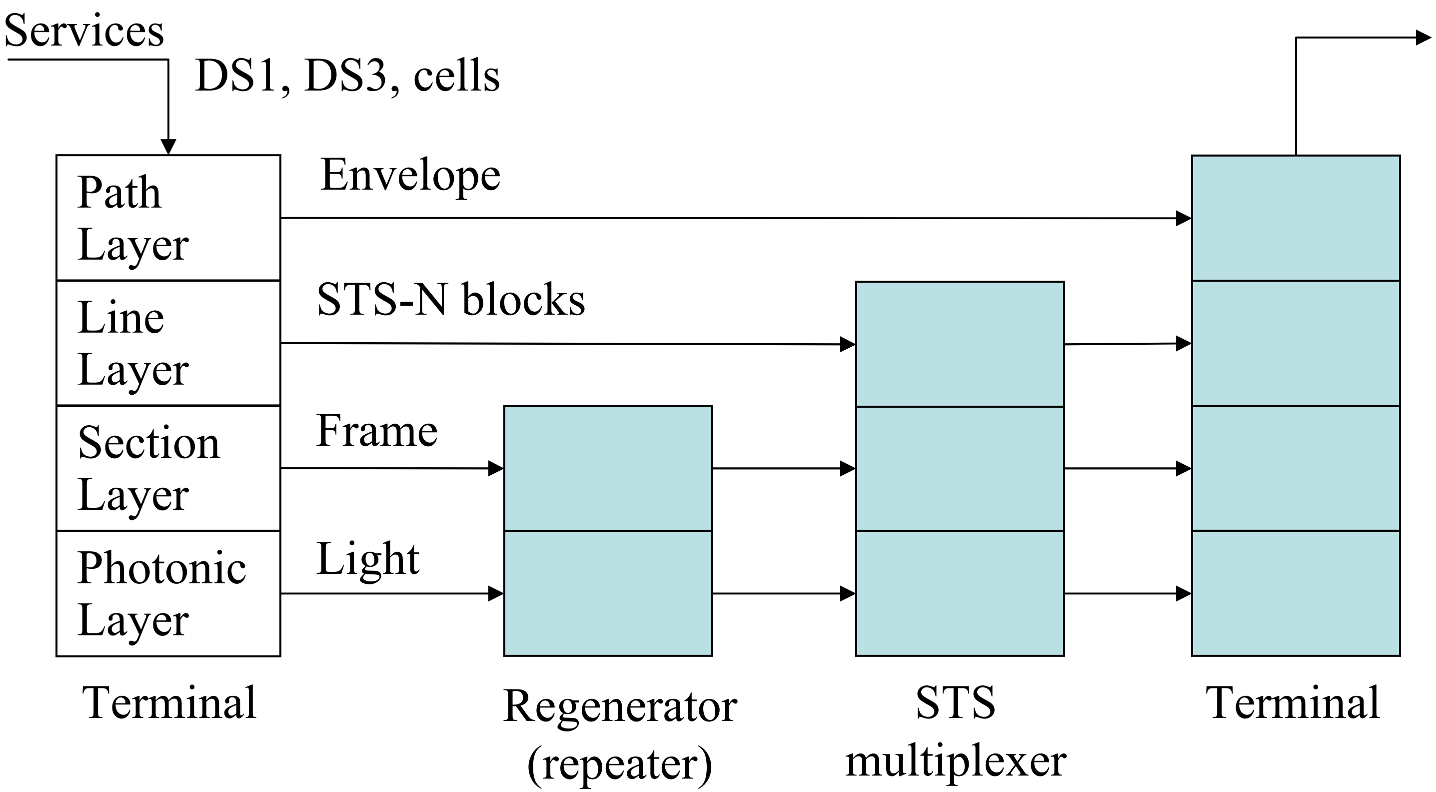
- The defined transmission speeds for the North American (SONET) standards and the ITU (CCITT) standards are shown below.

SONET designation	"Optical" designation	ITU designation	raw bitrate Mbps	payload rate Mbps
STS-1	OC-1		51.84	48.384 *
STS-3	**OC-3**	**STM-1**	**155.52**	**149.76**
STS-9	OC-9	STM-3	466.56	449.28
STS-12	**OC-12**	**STM-4**	**622.08**	**599.04**
STS-18	OC-18	STM-6	933.12	898.56
STS-24	OC-24	STM-8	1,244.16	1,198.08
STS-36	OC-36	STM-12	1,866.24	1,797.12
STS-48	**OC-48**	**STM-16**	**2,488.32**	**2,396.16**
...				
STS-192	**OC-192**	**STM-64**	**9,953.28**	**9,598.64**

* http://www.tek.com/Measurement/App_Notes/SONET/structure.pdf

SONET Layers

- Section repeaters interpret 9 bytes of each frame.
- Line multiplexers interpret 18 bytes per frame.
- End-to-end path logic interprets 9 bytes per frame.



Digital coding

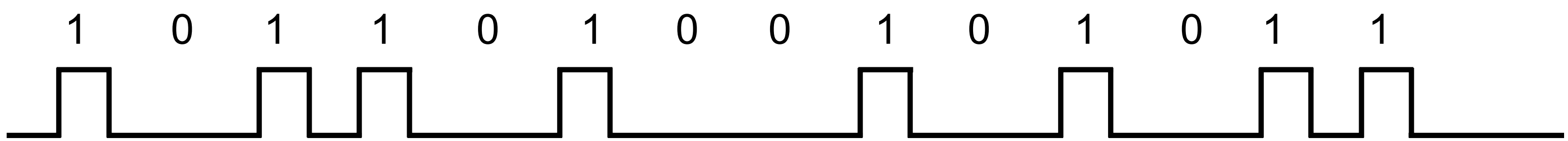
- Here are some of the main digital codes which you may meet
- These are ways of encoding a digital signal onto a transmission medium, usually wire or fibre
- All but the simplest (NRZ, NRZI and NRZ1) allow clocks to be recovered from the transmitted (or recorded) bit stream
  - The more complex codes minimise the number of data transitions (baud rate) for given data (bit rate)
  - As the *transmission medium* can handle a limited baud rate, this minimizing transitions maximises the *data rate*

Digital coding (2)

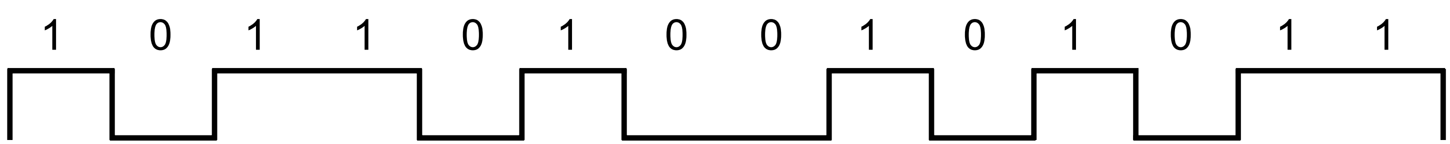
- The names are not standardised
  - What is here is as accurate as I can get, but you will certainly find variations, and many textbooks differ
- Most encode 0s and 1s into sequences of 0s and 1s, but some encode into sequences of +1, 0, –1
- Some codes rely on DC signaling. For long links it's better to use 'differential' codes that don't (i.e. their average signal level is zero).
- You should know NRZ, NRZI, NRZ1 and Manchester codes; the others are for information only.

Digital coding (3)

Return to Zero (RZ), or NRZ-L A pulse for 1, no pulse for a 0. Some versions use +ve and -ve pulses, for 1 and 0 respectively

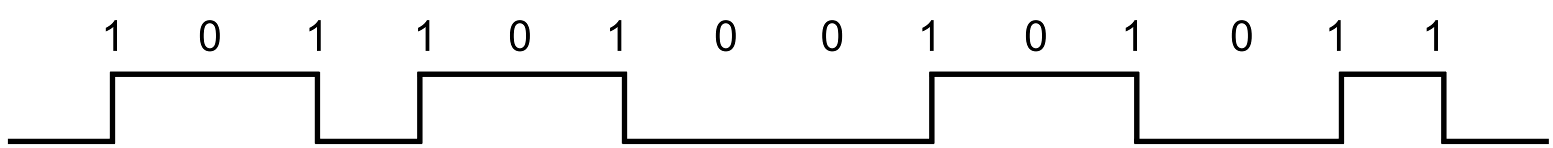


Non-Return to Zero (NRZ) A 0 or 1 level as required



Non-Return to Zero 1 (NRZ1, or NRZ-M)

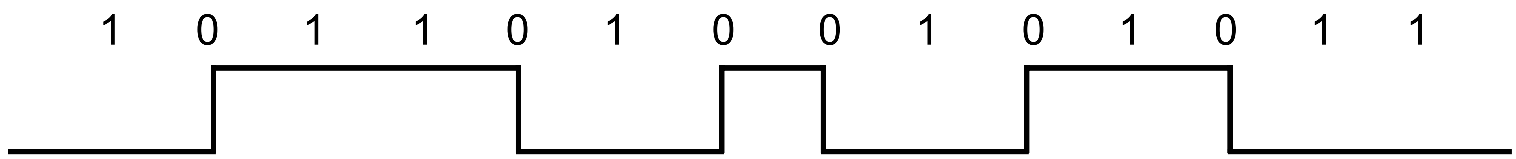
A transition for a 1, no change for a 0



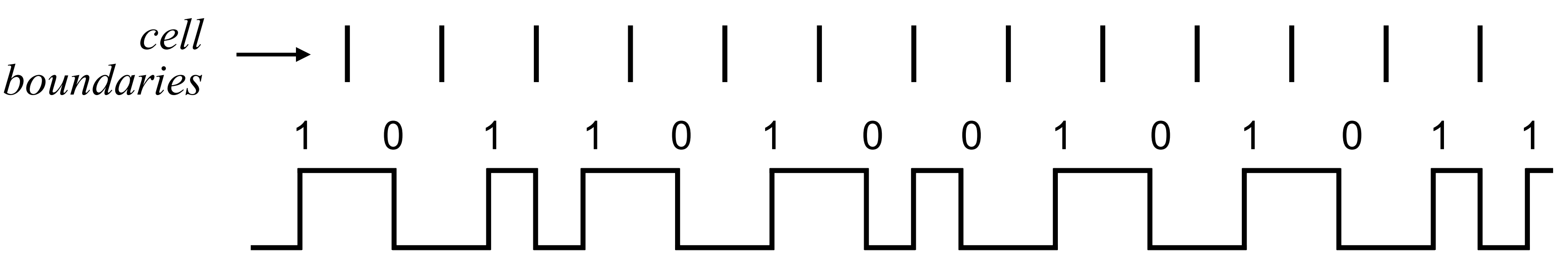
Digital coding (4)

Non-Return to Zero , Inverted (NRZ-I, or NRZ-S)

A transition for a 0, no change for a 1

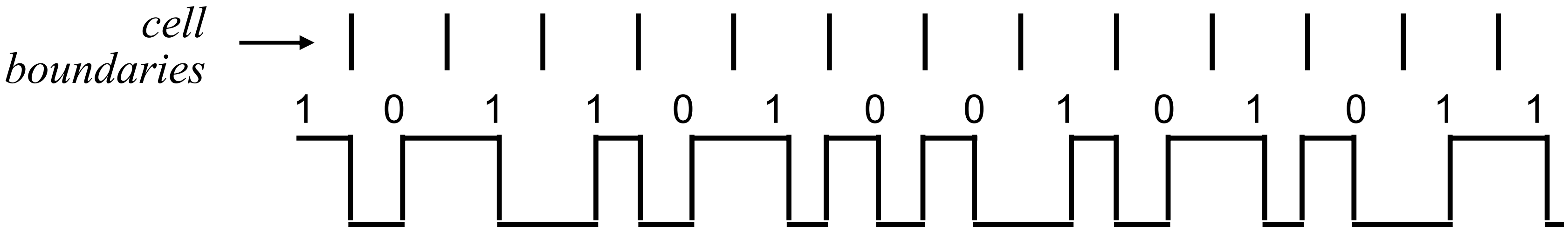


Phase, or Manchester, Encoding (PE) The centre of each bit cell has a transition to the value of that bit; adjacent like bits have a transition on the cell boundary, unlike bits have no transition between cells

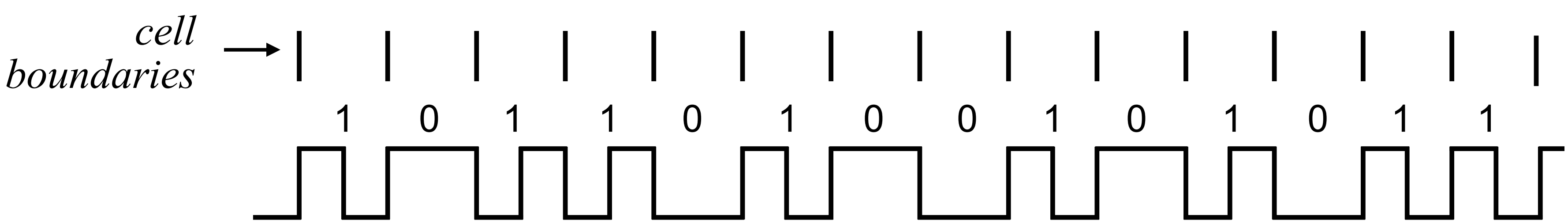


Digital coding (5)

Differential Manchester Encoding The centre of each bit cell has a transition; a 0 bit starts with a transition at the cell boundary, while a 1 bit has no leading transition.



Frequency Modulation (FM) A transition at every cell boundary and at the middle of every "1" cell. Also known as Binary FM, Phase-Encoding Mark or Double- Frequency

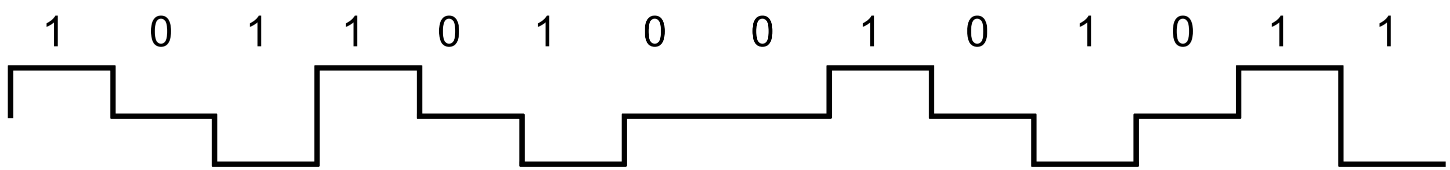


3-level Codes

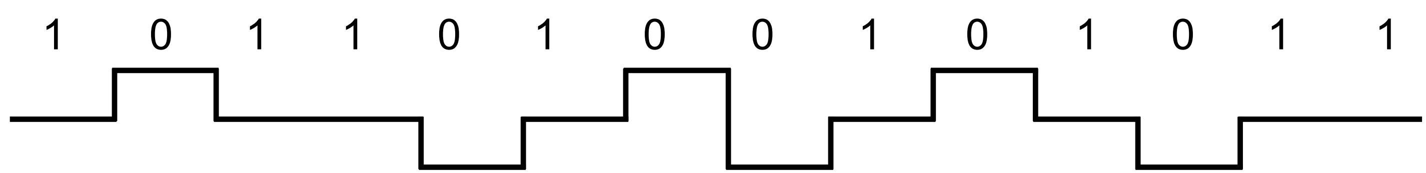
Many codes for very high speed transmission use 3 levels {–1, 0, +1}, with alternating +ve and –ve levels to maintain a DC balance.

These codes are often used in optical communication. Lasers in these cases have varying amplitude, but are *never* turned right off (for a zero etc.)

Bipolar AMI (alternate mark inversion) 0 → no line signal (0), 1 → alternate –1 and +1 (This code is used in North America)



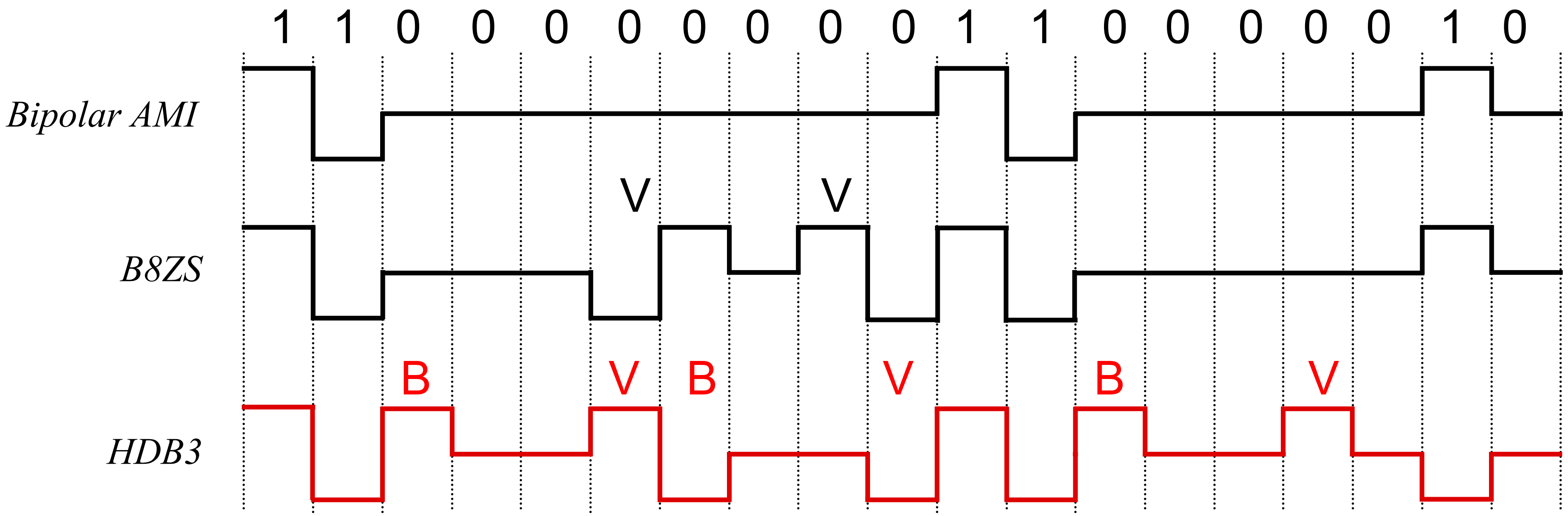
Pseudo Ternary 0 → alternate –1 and +1, 1 → no line signal (0). (Europe and Japan)



3-level Codes (2)

Bipolar, with 8-Zeros Substitution (B8ZS) Same as bipolar AMI, but any string of 8 zeros is replaced by a string with *two* code violations

High Density Bipolar — 3 Zones (HDB3) Same as bipolar AMI, but any string of 4 zeros is replaced by a string with *one* code violation, as 100V, or B00V.



Optical transmission

Most data transmission of more than a few metres is now over ‘optical fibre’ or, simply, ‘fibre.’ Points to note are —

- Most communication uses infrared, so you never see any visible light!
  - *Never look at the end of a fibre unless you are sure about the other end!*
  - *The infrared has a power density like looking directly into the sun.*
- Light sources may be
  - lasers (for high speed, long distance, expensive) or
  - LEDs (Light Emitting Diodes): slower, shorter distances, lower costs.
- Several types of fibre (details later)

– Multimode	short distances, low speed, lower cost
– Graded multimode	medium performance and cost
– Single mode	long distance, high, expensive

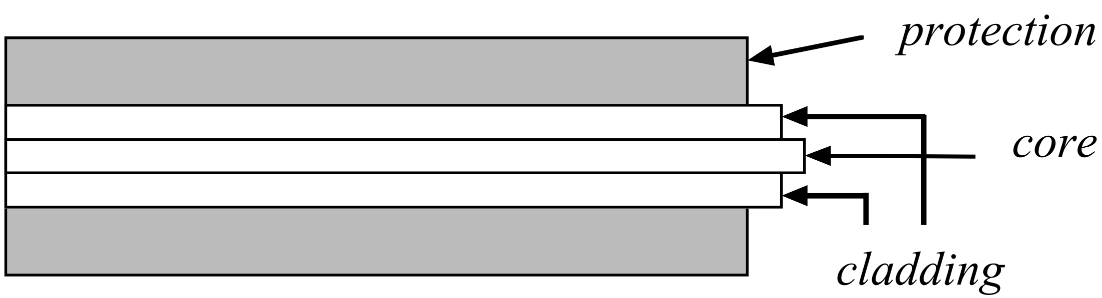
- Core is optically denser (higher refractive index, μ)
- Cladding is optically less dense (lower refractive index, μ)

Characteristics of optical fibres

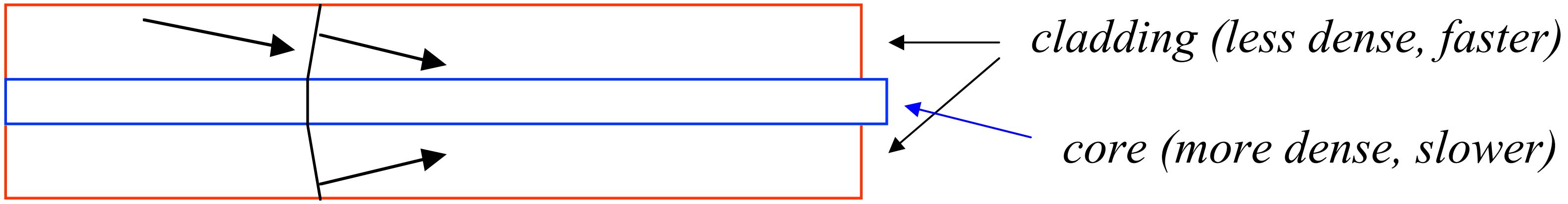
	Multi-Mode	Graded Index	Single Mode
Light Source	LED or laser	LED or laser	Laser
Bandwidth	20 MHz/km	> 1 GHz/km	> 1000 GHz/km
Splicing	Difficult	Difficult	Difficult
Application	Computer data links, LANS	Moderate length telephone	Long distance telecommunications
Cost	Least Expensive	More expensive	Most expensive
Core diameter	> 80 μm	50 – 60 μm	1.5 – 5 μm
Cladding diameter	> 160 μm	100 – 120 μm	15 – 50 μm
Attenuation	.05 – 2.0 dB/km	0.5 – 2.0 dB/km	< 0.15 dB/km

- Many fibres now use multiple wavelengths or 'colours' (Wavelength Division Multiplexing or WDM)

Optical transmission



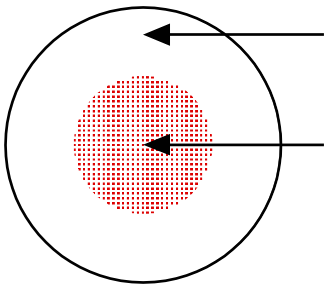
- As light travels perpendicular to the wave front, it focuses around the core.
- Light travels slower in the optically denser core ($\mu_{core} > \mu_{cladding}$); the wave front becomes concave.



- Light keeps away from the surface of the cladding (and from scratches etc.)
- *or* light suffers internal reflection from cladding/core boundary; this is the usual explanation and the effect is the same.

Transmission modes

With smaller cores, the light all travels closer to the core. An end-on view of the power density in the cable (‘*single mode*’) is like

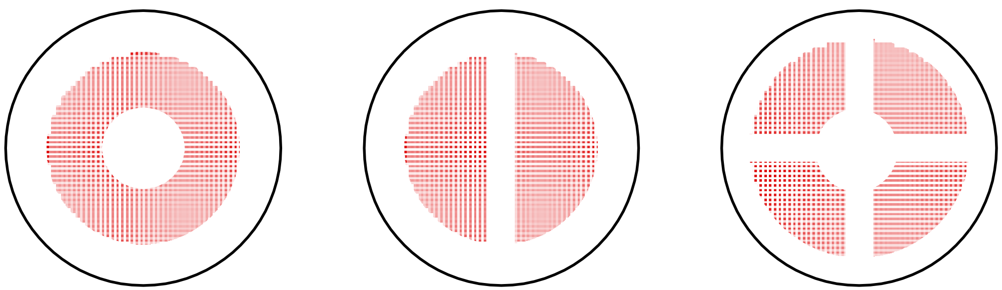


No signal power near edges

Power concentrated near middle

(Depends only on core diameter.)

As the core diameter increases, different power distributions or “modes” become possible, such as



Modes travel at different speeds

Signal swaps between modes, or power ‘leaks’ between modes

Multimode signals “blur” with distance because the modes travel at different speeds and interfere with each other.

Optical Miscellanea (1)

Optical Amplifiers

Optical fibres doped with Erbium and ‘pumped’ with a suitable laser power source can amplify optical signals with no need to for conversion electronics.

Optical amplifiers are simple and reliable, with very high bandwidth.

Cable systems using optical amplifiers can support wavelength mulitplexing. We can allocate ‘colours’ (i.e. wavelength ranges) to carry *n-Gb/s* channels of digital data. Such systems are described as DWDM (dense) or CWDM (coarse).

Southern Cross Cable

`http://www.southerncrosscables.com/`

As an example of a long distance fibre cable, the Southern Cross cable links Australia, New Zealand, and U.S.A., in a redundant ring structure.

10 Gbps per colour or wavelength;

16 wavelengths/fibre pair

3 fibre pairs per cable

480 Gbit/s capacity per cable

Some 2004 costings:

155 Mbps (STM-1) 2 yr lease	$150,000 US per month
155 Mbps (STM-1) capacity	50,220 GByte/month
Cost per GByte (100% load)	$2.99
Cost per GByte (at 50% load)	$5.97
Cost for one telephone circuit	$0.11 per hour

Optical Miscellanea (2)

Solitons

Most materials are dispersive, changing their refractive index with *wavelength* (prisms, rainbows, etc). A few are also dispersive with signal *amplitude*.

If the refractive index changes suitably with both *wavelength* and *amplitude*, the two types of dispersion interact to allow single pulses to maintain their shape for very long distances, perhaps thousands of kilometres in glass.

Solitons may well become important for very long distance transmission.