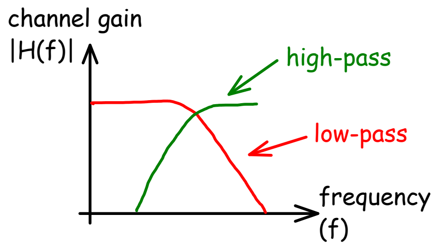
Channel Characteristics and Impairments

This lecture describes some of the most common channel characteristics and impairments.
After this lecture you should be able to: classify channels as high-, low-, or band-pass; use -dB and percentage power definitions of bandwidth; convert between delay and phase shift; compute group delay from phase response; identify some causes of multipath propagation and their effects on the channel frequency response; distinguish between linear- and non-linear distortion; compute the frequencies of IMD products for two-tone inputs; solve problems using equations for SNR, noise and signal powers, noise figure, noise temperature and bandwidth; compute the probability that a Gaussian source will exceed a certain value; identify sources of near-end, far-end and alien crosstalk; distinguish between noise and interference.

Frequency Response

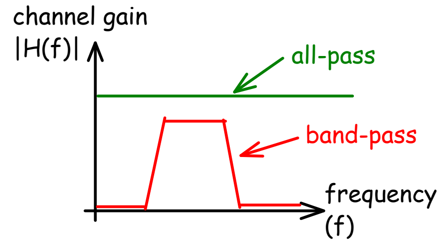
The frequency response of the channel is also called the frequency-domain transfer function, $H(f)$. It is the ratio of the voltage at the output of the channel to the voltage at the input of the channel. It is a complex quantity (includes both amplitude and phase) and is a function of frequency. The ratio of the voltages is called the amplitude response and the ratio of the phases is called the phase response.

If the channel only passes low frequencies it is called a low-pass channel. A typical example is a telephone line. High-pass channels typically result from capacitive or inductive coupling which blocks DC or low-frequency signals.

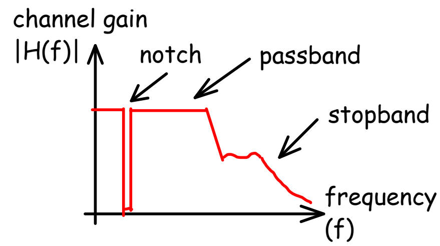


An all-pass channel has a flat amplitude response which would appear to have no effect on the signal but the phase reponse may be non-linear (see below).

A band-pass channel is very common. Some band-pass channels result from attenuation by the channel and other are band-pass due to filtering by the transmitter and/or receiver.



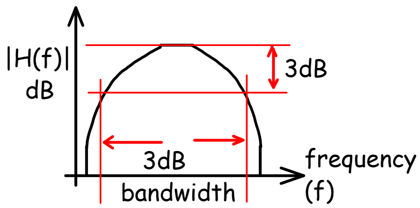
Channels often include several of the above characteristics. For example, a twisted pair loop may include a notch filter to remove 50Hz or 60Hz power line noise, it may have peaks and valleys in the frequency response due to reflections from taps or poor terminations and it will drop off with frequency due to higher losses at higher frequencies.



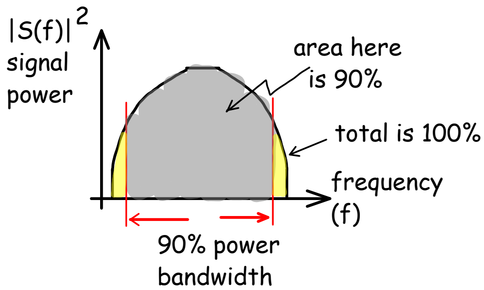
Bandwidth

There are several definitions of bandwidth.

A common definition is the *3dB bandwidth*. This refers to the frequency range where the amplitude response is less than 3dB down from the maximum. Thus a signal component transmitted at the edge of the passband would have half of the power it would have if transmitted at the frequency with the lowest loss. Other bandwidth definitions can use values other than 3dB.



A definition of bandwidth that is often applied to signals rather than channels is the *90% power bandwidth*. This is the frequency range that contains 90% of the signal power. Other values than 90% can be used.



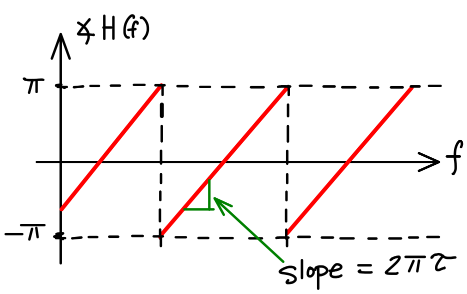
Other definitions of bandwidth are used for specialized purposes.

Bandwidth is a single number and cannot describe all aspects of the transfer function. Other specifications such as the steepness of the filter roll-off or gain ripple in the passband are often important.

Phase Response

The phase response of the channel is the ratio of the phase at the output to the phase at the input. Since the phase "wraps" every 2π, the phase response may have discontinuities.

Phase shifts are often a result of delays through the channel. A time delay of τ introduces a phase shift of $2\pi f \tau$ (radians). The phase shift is a linear function of the delay with the delay defining the slope of the phase versus frequency curve.



Exercise 1: A 100m transmission line has a velocity factor of 0.66. Plot the phase response of the cable over the frequency range 0 to 6 MHz.

Group Delay

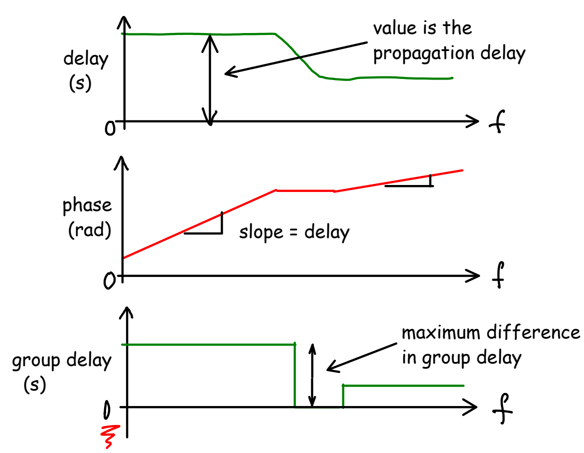
If the delay is constant across frequency then:

- the phase response is linear
- all frequency components will be delayed by the same amount and waveforms will not be distorted

However if some frequencies have longer delays than others or, equivalently, if the phase is not a linear function of frequency then the waveform will be distorted.

Group delay is a measure of how the phase response of the channel deviates from the ideal linear response. It is defined as the derivative (or slope) of the phase response. Thus a channel with a linear phase response has a constant (flat) group delay.

If the slope of the phase response curve has units of radians and the frequency axis has units of radians/second then the slope (the group delay) will have units of seconds. Variations in group delay correspond to differences in delay that the different frequency components of a signal will experience. This is not the same as the delay of any of the frequency components. To avoid distortion the peak group delay of the channel should be limited to a small fraction of the symbol duration.

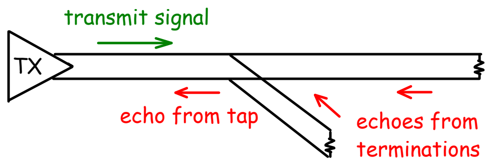


Exercise 2: A telephone line is being used to transmit symbols at a rate of 300 symbols/second. If the group delay must

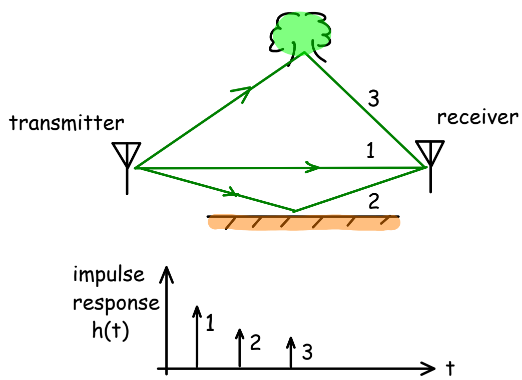
be less than 10% of the symbol period, what is the maximum allowable group delay?

Echo and Multipath

Another source of linear distortion is echoes and multipath propagation. Echoes can be due to transmission lines that are tapped or not properly terminated.



Multipath propagation typically happens on wireless links with non-line of sight (NLOS) paths. Objects will reflect, diffract or scatter the radio signals.



Since the each path length can be different, the delays for each path can be different. The different paths can add up constructively or destructively depending on the frequency and the delay. The frequency response can thus have peaks and nulls.

Non-Linear Distortion

Distortions caused by the amplitude and phase response of the channel are called linear distortions because they can be produced by linear operations on the signal. Linear distortions can be corrected, in principle, by applying a linear filter whose response, at each frequency, is the (complex) multiplicative inverse of the frequency response of the channel. Linear distortion does not affect the frequencies present in the signal.

There are some common distortions that are not linear. A typical example is clipping (the peaks of the signal are cut off) due to the limited dynamic range of an amplifier. Most amplifiers have some degree of non-linearity which causes non-linear distortion.

Non-linear distortion results in additional frequency components being generated. The exact frequencies and strengths of these components depend on the type of distortion and the frequency components of the original signal. Typically there will be harmonics of the frequency components at the input as well as frequencies that are combinations of these harmonics. The frequency components that appear at frequencies that are sums of the harmonics are called inter-modulation distortion, IMD). The frequencies of the intermodulation products will be:

$$f_{IM} = \pm n f_1 \pm m f_2$$

where n and m are positive non-zero integers. The *order* of the IMD product is defined as $n + m$.

Exercise 3: The input to a non-ideal amplifier is the sum of two sine waves at frequencies of 1 and 1.2 MHz. What are the frequencies of the even harmonics of these frequencies? Of the odd harmonics? What are the frequencies of the third-order IMD products?

Noise

Noise is a random (unpredictable) signal that is added to the desired signal. Noise can be added by the channel or by the receiver.

Sources of noise include the thermal noise present in any conductor at temperatures above 0 K, "shot" noise generated by semiconductor devices, noise from lightning and from the sun.

Noise is the phenomenon that ultimately limits the performance of any communication system. Noise may cause errors in digital communication system or degrade the quality of an analog signal.

One important metric is the signal-to-noise ratio (SNR) which is the ratio of signal power to noise power.

Exercise 4: A sinusoidal signal is being transmitted over a noisy telephone channel. The voltage of the signal is measured with an oscilloscope and is found to have a peak voltage of 1V. Nearby machinery in inducing a noise voltage onto the line. The voltage of this noise signal is measured with an RMS voltmeter as 100mVrms. The characteristic impedance of the line is 600Ω and it is terminated with that impedance. Why was an RMS voltmeter used? What is the signal power? What is the noise power? What is the SNR?

Thermal Noise Power

A resistor at a temperature above absolute zero has a noise voltage across it's terminals due to the thermal motion of electrons. The voltage of this noise has a Gaussian probability distribution and a flat (constant) frequency spectrum.

The power of this noise in a bandwith B is given by the equation:

$$N = kTB$$

where k is a constant known as Boltzman's constant, T is the resistor's temperature in Kelvin and B is the bandwidth in Hertz.

This is often used as a reference power level when measuring noise, even when the noise itself is not thermal noise.

Noise Figure

Amplifiers and other active devices produce more noise than would be predicted from just considering their input impedance and the gain. The ratio of the output noise power to the noise power that would be generated by an ideal amplifier is its "noise figure" (F). It is usually quoted in dB. This noise figure in dB must be added to the reference thermal noise power when computing the absolute noise power at the output of an active device. This output power, not including the gain, is:

$$N = kTBF$$

If the computation is done in dB units, the value of k is -174 dBm/Hz at 290K (≈ room temperature). To compute the thermal noise power in dBm we must add the bandwidth in dB-Hz ($10 \log B$). In this case the equation is:

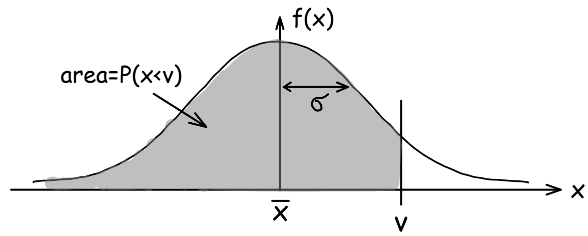
$$N_{dBm} = -174 + 10\log(B) + 10\log(F)$$

Exercise 5: A line amplifier for a cable TV system amplifies the range of frequencies from 54-1002 MHz. The amplifier has a gain of 30 dB and a noise figure of 3 dB. If we connect a 75Ω resistor (the input impedance of the amplifier) to the input how much power will we measure at the output of the amplifier?

Gaussian Probability Distribution

Signals that result from the sum of many small independent events have a probability distribution known as a Gaussian distribution. In communication systems this usually happens due to the sum of of voltages produced by the actions of very many individual photons, electrons or molecules.

The Gaussian distribution is the familiar "bell curve" or "normal" distribution. The probability is a maximum at the average value and drops off to smaller probabilities at larger or smaller voltages.

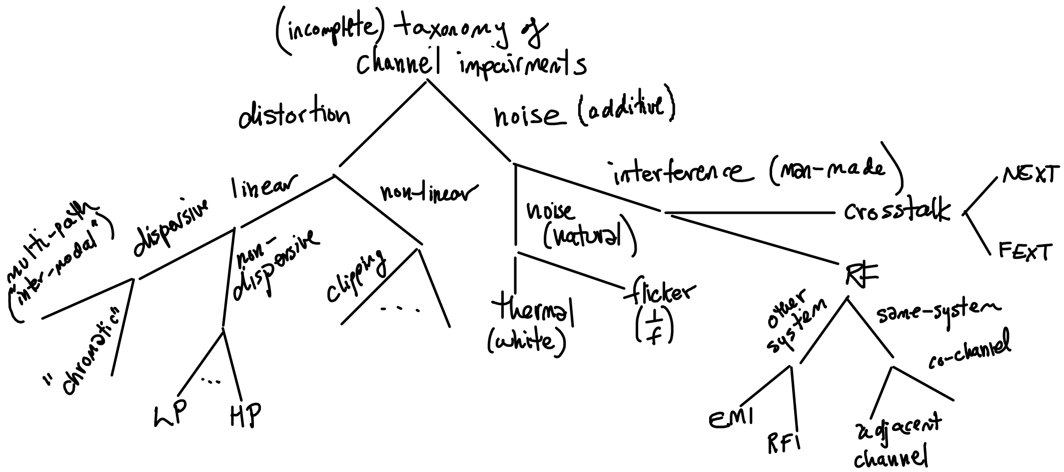


It's often useful to know the probability that the voltage of a Gaussian noise signal will exceed a certain voltage. If the signal x has a DC (mean) value $\overline{x}$ and an RMS AC voltage σ then the probability that the noise voltage is less than v is given by the Gaussian (Normal) cumulative distribution function (CDF). This is the area under the Gaussian distribution curve to the left of (less than) the value v.

The argument to the normalized Gaussian CDF function, t, is calculated by subtracting the mean, $\overline{x}$, and dividing by the standard deviation, σ, of the distribution:

$$t = \frac{v - \overline{x}}{\sigma}$$

Exercise 6: The output of a noise source has a Gaussian (normally) distributed output voltage. The (rms) output power is 20mW and the output impedance is 100Ω. What fraction of the time does the output voltage exceed 300mV? Hint: the variance (σ^2) of a signal is the same as the square of its RMS voltage.



You can also use the Logistic function approximation[1]:

$$F(t) = \frac{1}{1 + e^{-1.7t}}$$

where t is calculated by subtracting the mean and dividing by the standard deviation as above. This approximation has a maximum error of about 0.01.

Interference

Interference is a random man-made signal that has a similar effect as additive noise.

Interference may be caused by communication systems or other electrical devices. An interfering communication system may be unrelated or it may be part of the same system.

Examples of interference include:

- the signal from a cell phone may couple onto a phone line and cauze a "buzzing" noise (known as RFI - Radio Frequency Interference)
- at night the signal from a remote AM broadcast station may reach further than usual and cause interference to a local station.
- two WLAN cards may decide to transmit a packet at the same time resulting in neither one being received correctly (a "collision")
- the commutator on an electric motor may cause interference to a radio receiver
- the clock signals within a PC may cause interference to a TV receiver (known as EMI, Electro-Magnetic Interference)

Wireless systems are particularly vulnerable to interference because of the wide difference in the levels of the transmitted and received signals. Wireless systems classify own-system interference into Co-Channel (same channel) and Adjacent Channel (next channel).

Power ratios similar to SNR that include the effect of interference include:

- SIR - Signal to Interference Ratio
- SINR - Signal to Interference plus Noise Ratio
- SINAD - Signal to Interference plus Noise And Distortion Ratio

Crosstalk

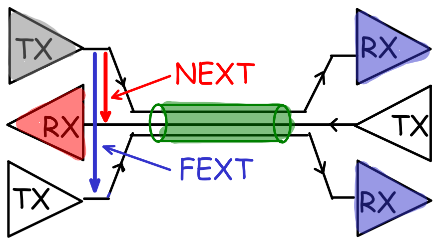
Crosstalk is interference due to coupling between conductors that are run in the same cable. For example, telephone loops are often carried in cables with 25 or more pairs. There will be some coupling between the pairs. Signals on one pair can thus leak into another pair in the same cable. Another example is the coupling between pairs used in LAN UTP cables. Crosstalk will be affected by shielding, twist patterns

[1] S. Bowling *et al*, *A logistic approximation to the cumulative normal distribution*, *JIEM*, vol. 2, no. 1, pp. 114-127,

and other design details. Datasheets will often specify crosstalk at different frequencies.

We can distinguish between:

- Near-end crosstalk (NEXT) is the leakage of the signal being transmitted onto the signal being received at the same location.
- Far-end crosstalk (FEXT) is the leakage of the signal being transmitted onto the signal being received at the other end of the link.



Note that the coupling between pairs in a cable happens throughout the length of the cable. The difference between NEXT and FEXT is in which receiver is affected (the near one or the far one), not where the coupling takes place.

Some DSL systems measure the coupling between pairs and subtract out the crosstalk. "Alien crosstalk" refers to crosstalk from other cables. It is usually not possible to cancel out this crosstalk.

Power sum (PS) crosstalk refers to the sum of the crosstalk from all of the other pairs in the cable.