ELEX 3525 : Data Communications
2015 Winter Session

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; compute THD; 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

We can model a channel as a filter. The frequency response of this filter is called the frequency-domain transfer function, typically denoted as $H(f)$. It is the ratio of the voltage at the output of the channel to the voltage at its input:

$$H(f) = \frac{V_{\text{out}}}{V_{\text{in}}}$$

This frequency response is a complex quantity that 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:

$$|H(f)| = \frac{|V_{\text{out}}|}{|V_{\text{in}}|}$$

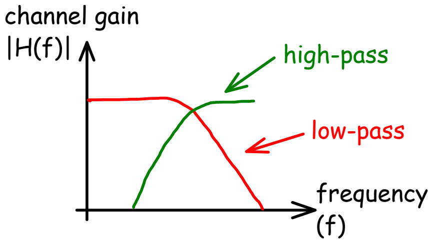
and

$$\angle H(f) = \angle V_{\text{out}} - \angle V_{\text{in}}$$

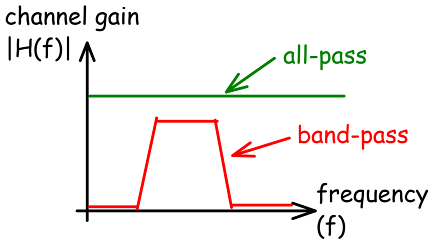
Exercise 1: A 10 dBm signal is applied to one end of a 50 ohm co-ax cable at frequencies of 1, 10 and 100 MHz. At the other end you measure voltages of 7, 4 and 0 dBm respectively. Plot the amplitude of the transfer function of the channel formed by this cable. Show dB on the vertical axis and log of frequency on the horizontal axis.

If the channel primarily passes signals below a certain frequency it is called a low-pass channel. A typical example is a twisted-pair cable because the distributed inductance and capacitance form a low-pass filter.

High-pass channels often result from capacitive or inductive (e.g. transformer) coupling which blocks DC or low-frequency signals.

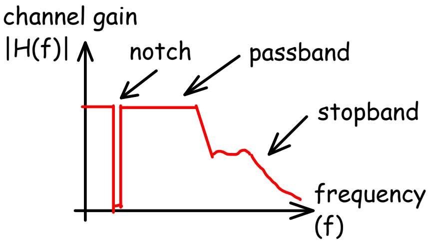


A band-pass channel is very common. A common-example would be a transformer-coupled telephone line. Some band-pass channels result from attenuation by the channel but in other cases the band-pass nature of the channel intentional and is designed into the system to separate signals at different frequencies.



An all-pass channel has a flat amplitude response which would appear to have no effect on the signal. However filters with all-pass characteristics are sometimes used because of their effect on the channel's phase response.

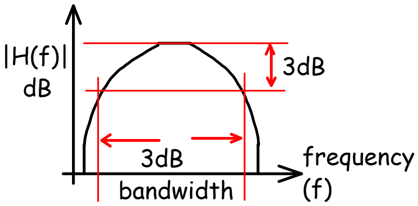
Channels often include several of the above characteristics. For example, a twisted pair loop may include a notch filter to remove 50Hz or 60Hz power line noise, it may have peaks and valleys in the frequency response due to reflections from taps or poor terminations and it will drop off with frequency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



Bandwidth

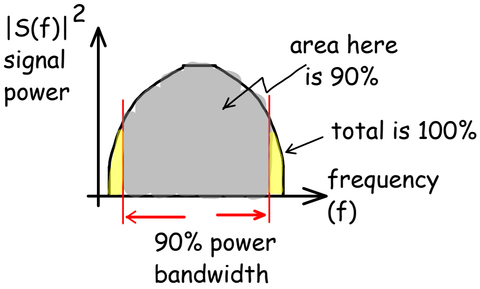
There are several definitions of bandwidth.

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. Other bandwidth definitions can use values other than 3dB.



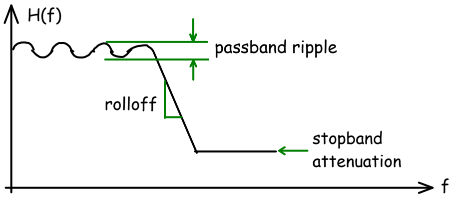
Exercise 2: How much *power* would a signal transmitted at the edge of the 3 dB bandwidth passband have compared to the the power it would have if transmitted at the frequency with the lowest loss? What would be the ratio of the *voltages*? What if the bandwidth was defined as the 6 dB bandwidth?

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.



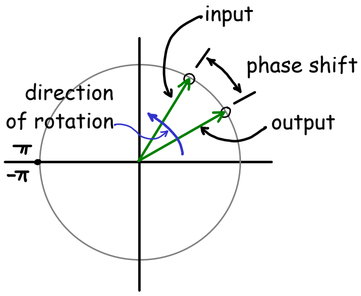
Other definitions of bandwidth are used for specialized purposes.

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



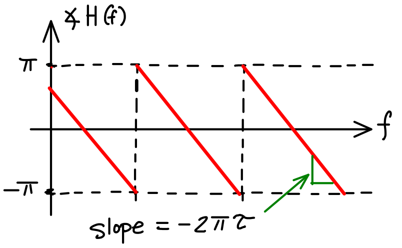
Phase Response

The phase response of the channel is the difference in phase between the output and the input[1]. Phase shifts are often a result of delays through the channel. As you can see from the diagram below, delaying a sinusoid is equivalent to changing its phase. A time delay of τ introduces a phase shift of $-2\pi f\tau$ (radians).



This phase shift is therefore a linear function of the delay with the delay defining the slope of the phase versus frequency curve.

Unlike magnitude, it's not possible to measure phase shifts outside the range of $-\pi$ to π (or equivalently, 0 to 2π). This causes the phase to "wrap" every 2π and the phase response appears to have discontinuities.



Exercise 3: 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.

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[1] To divide two complex values we divide the magnitudes and subtract the phases.

Group Delay

If the delay is constant across frequency then:

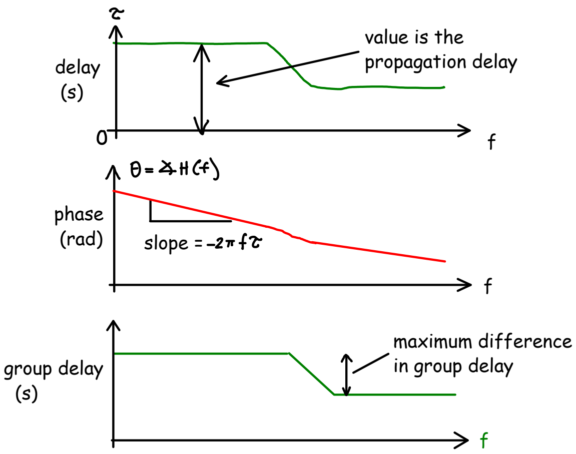
- the phase response is linear
- all frequency components will be delayed by the same delay
- any waveform will be undistorted (assuming a flat amplitude response)

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 because some frequency components will arrive at the receiver ahead of others.

We measure variation from linear phase using a quantity called group delay. It is defined as the derivative (or slope) of the phase response. A channel with a linear phase response has a constant (flat) group delay. Variations in group delay measure how much the phase response deviates from the ideal linear response.

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 thus correspond to *differences* in delay that the different frequency components of a signal will experience. This is not the same as the *end-to-end* delay of these frequency components.

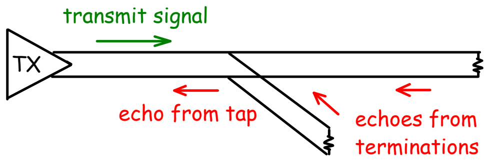
To avoid distortion the peak group delay of the channel should be limited to a small fraction of the symbol duration.



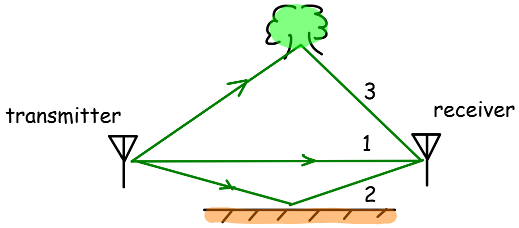
Exercise 4: A telephone line is being used to transmit symbols at a rate of 300 symbols/second. If the group delay must be less than 10% of the symbol period, what is the maximum allowable group delay?

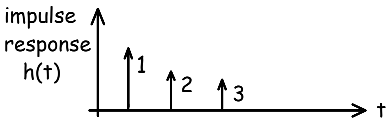
Echo and Multipath

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 filter whose response, at each frequency, is the (complex) multiplicative inverse of the frequency response of the channel. Linear distortion does not change the frequencies that are present in the signal.

In practice there are limitations to how much linear distortion we can correct because the gain required to compensate for the attenuation will also amplify any received noise. Thus, in practice, large attenuations cannot be reversed.

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.

Unlike linear distortion, non-linear distortion creates new frequency components. The exact frequencies and levels 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.

A typical way to test for non-linear distortion, particularly for bandpass channels, is to pass a signal composed of two frequencies through the channel – a "two-tone intermodulation distortion" (IMD) measurement. 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 $n + m$.

The most important of these are the third-order distortion products because the fall near the original (desired) signal components. On the other hand, harmonics appear at multiples of the original frequencies and are often relatively easy to filter out.

Exercise 5: 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 harmonics of these frequencies? What are the frequencies of the third-order IMD products?

Another measure of non-linear distortion is the Total Harmonic Distortion (THD). This is the ratio of signal power to the total power of all of the harmonics products and is often used for baseband (lowpass) channels. This is typically measured by putting a sine wave through the channel and dividing the total power by the power when the sine wave is removed with a notch filter.

Noise and SNR

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

Some sources of noise include the thermal noise that is present in any resistor at temperatures above 0 K, "shot" noise generated by semiconductor devices, electrical equipment such as motors and some lights, lightning and 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 6: 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 is adding noise 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 constant power at all frequencies[2].

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

$$N = kTB$$

where k is a constant known as Boltzman's constant (1.4×10^{-23} J/K), 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.

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[2] Noise with the same power at all frequencies is called 'white" noise.

Exercise 7: What are the units of N assuming the units above?

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:

$$N = kTBF$$

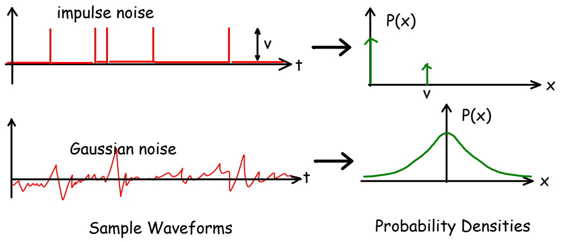
If the computation is done in dB units, the value of k is -174 dBm/Hz at 290K ($\approx$ room temperature). To compute the thermal noise power in dBm we must add the bandwidth in dB-Hz ($10 \log B$). In this case the equation is:

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

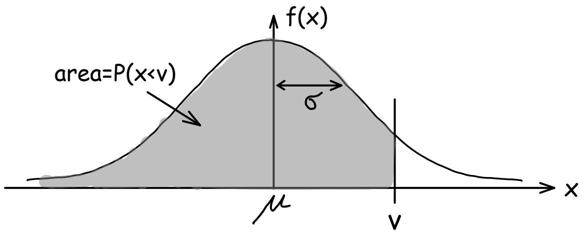
Exercise 8: A line amplifier for a cable TV system amplifies the range of frequencies from 54-1002 MHz. The amplifier has a gain of 30 dB and a noise figure of 3 dB. If we connect a 75Ω resistor (the input impedance of the amplifier) to the input how much power will we measure at the output of the amplifier?

Gaussian Probability Distribution

In addition to the distribution of the noise power in frequency, we also need to know how the voltage is distributed. For example, impulse noise has only two voltage levels (zero and the peak value of the impulse).



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.

The Gaussian distribution is determined by two values: the mean (μ) and the variance (σ^2).

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 μ 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 plot in Figure 1 shows the shape of the Gaussian density function and also gives the cumulative probabilities along a second x-axis.

To find the probability that the voltage is greater than v we can use the fact that the sum of all probabilities is 1. Thus $P(x > v) = 1 - P(x \leq v)$.

To compute $P(v)$ we first compute a normalized value, t by subtracting the mean, μ, and dividing by the standard deviation, σ, of the distribution:

$$t = \frac{v - \mu}{\sigma}$$

Exercise 9: What are the units of t?

Exercise 10: 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.

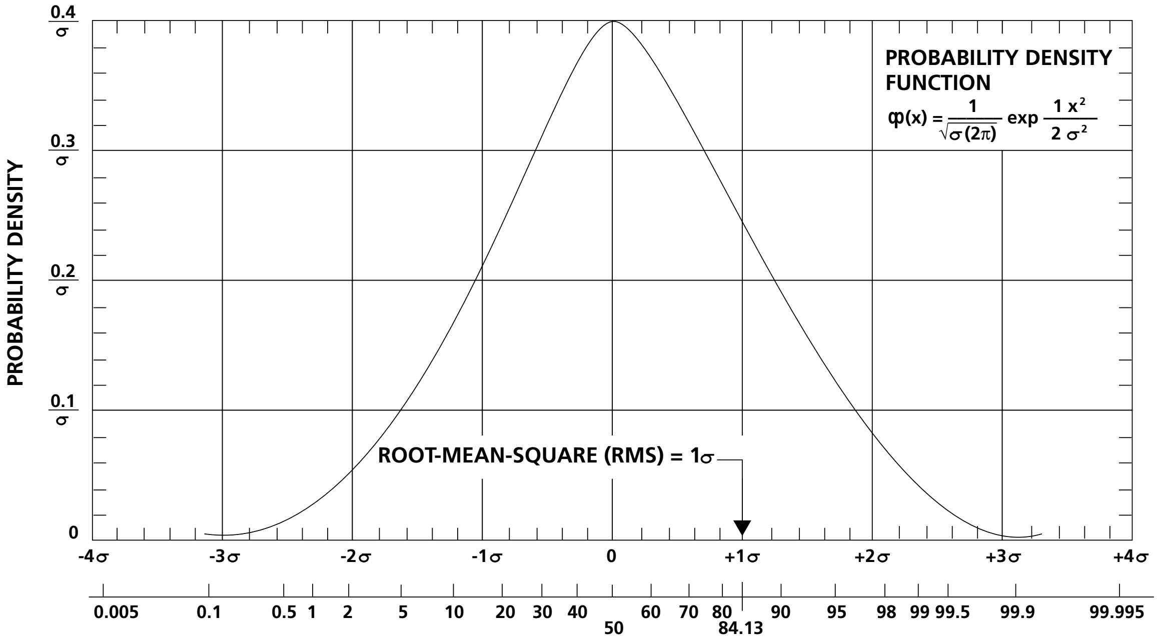


Figure 1. Gaussian Voltage Distribution

Figure 1: Gaussian density function and values of the cumulative distribution.

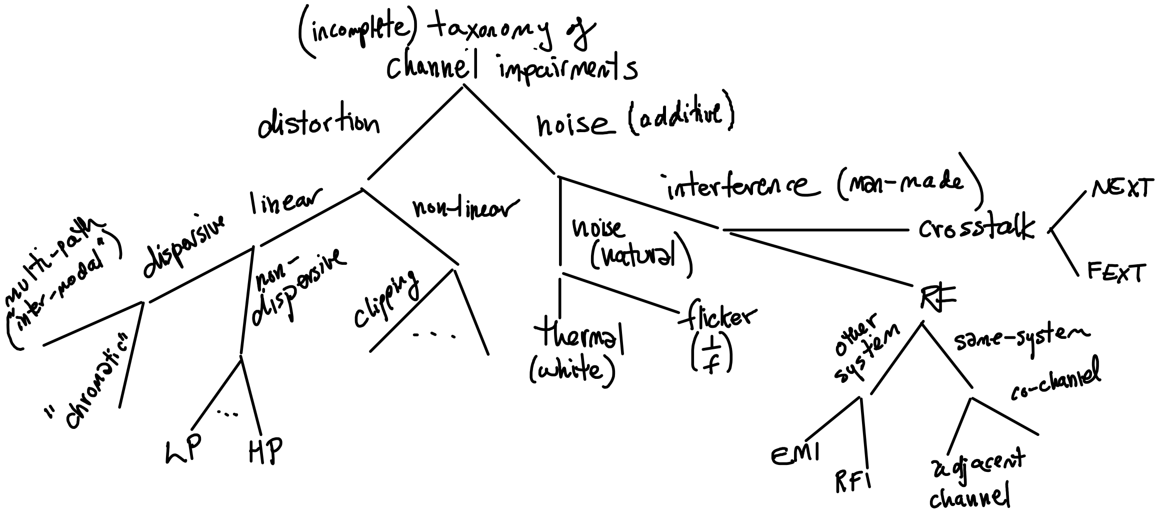


Figure 2: Taxonomy of Channel Impairments.

Some calculators will compute this ($P()$ function) You can also use the Logistic function approximation[3]:

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

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.

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

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 cause 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.

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

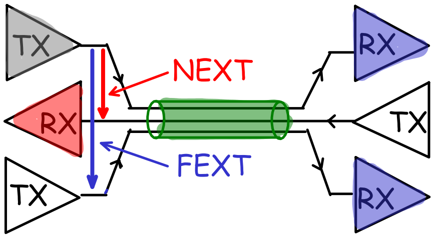
- SIR - **S**ignal to **I**nterference **R**atio
- SINR - **S**ignal to **I**nterference plus **N**oise **R**atio
- SINAD - **S**ignal to **I**nterference plus **N**oise **A**nd **D**istortion **R**atio

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 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.