Signals and Noise

Contents

1 Introduction

One of the coding of information is in form of pulse signals. In this type of coding information is contained in the polarity, amplitude or shape of the signal. These pulses can be either in voltage or in current. There are other modes of coding information as for example amplitud or frequency modulation.

Pulses can be analog or digital. Analog signals code continuously information by varying one or more of its characteristics (i.e. amplitude, shape, etc..). An example of analog signal is a microphone that changes its amplitude accordingly with the sound intensity. Digital signals, on the other hand only take a discrete number of states, most likely 2 represented by 0 an 1. It is posible to define digital signals with ten states (0 to 9), but technically is much more difficult. The great advantage of digital signals wrt analog signals is that they are much less affected by noise and distorsions.

There are devices able to convert analog signals into digital ones (ADC) and digital signals into analog signals (DAC). We will study them later.

Pulses are then the basics entities that carry information, any indesirable tension or current that superimpose to a signal, it is know as noise. We will see the different types of noise and how to protect from them

2 Frequency domain. Bandwidth

A complete understanding of pulse electronics and pulse distorsions requires viewing the pulse in terms of its frequency component. In order to have such a picture we have to use Fourier analysis.

Fourier theorem states that any periodic function may be represented by summing sine waves of different frequencies and amplitudes. Then having a periodic function $f(t)$ of period T defined in the interval $[0, T]$, its Fourier series is:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos(n\omega t) + b_n \sin(n\omega t)]$$

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

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

where $\omega = \frac{2\pi}{T}$ and n is a postive integer number. It is important to point out that the integrals in the previous equation can be evaluated over any complete period (i.e. $[-T/2, T/2]$).

All frequencies play a role in the shaping of the functions. Thus in order to faithfully treat the information the device must be capable to respond uniformly to a infinity rage of frequencies. The problem is that in any device ther are resistive and reactive components which filters the frequencies, so the response is limited to a finite range. The range of frequencies limited by the points at which the response falls by 3 dB is defined as bandwidth.

There is an excellent website where Fourier series:

`http://www.jhu.edu/ signals/fourier2/index.html`

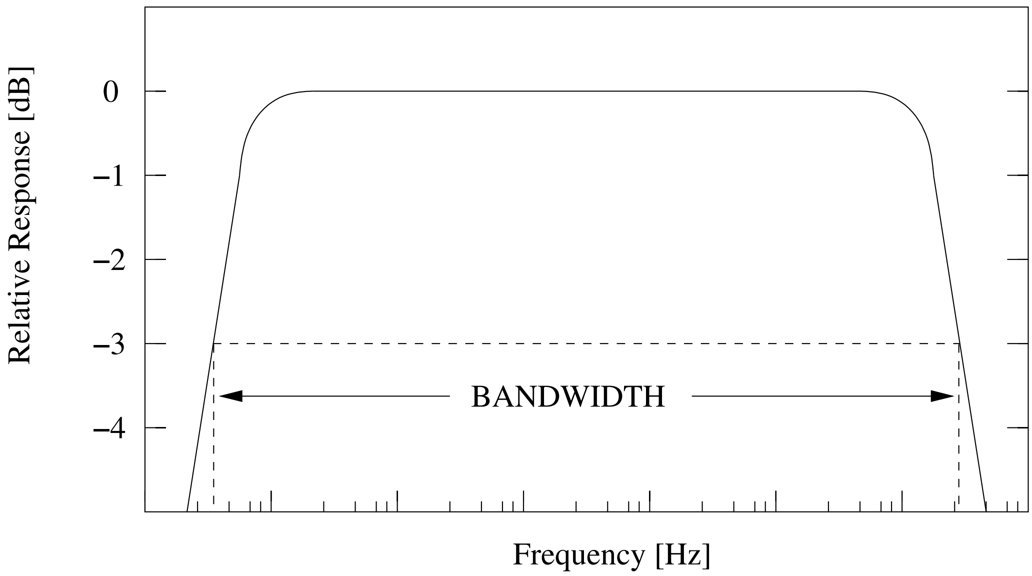

Figure 1: Definition of bandwidth

Some useful definitions are:

pulse: A short surge of electrical, magnetic, or electromagnetic energy. Synonym surge.

signal: 1. Detectable transmitted energy that can be used to carry information. 2. A time-dependent variation of a characteristic of a physical phenomenon, used to convey information. 3. As applied to electronics, any transmitted electrical pulse.

waveform: The representation of a signal as a plot of amplitude versus time.

In figure 2 shows an ideal rectangular pulse, where we can define the following features:

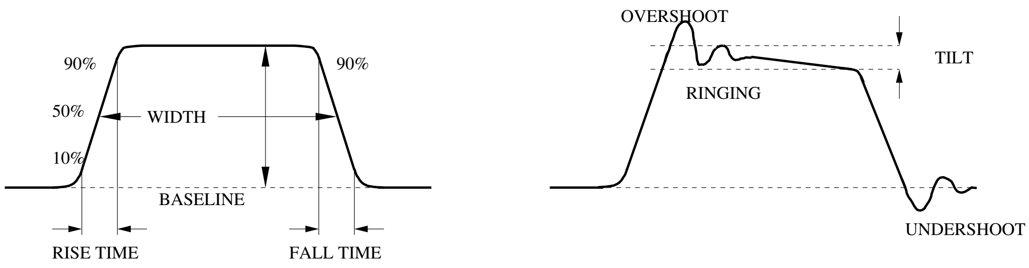

Figure 2: Definition of pulse characteristics and on the right some of the distorsions can affect them

- *Baseline*: Is the voltage or current level to which the pulse decays. While this is usually zero, it is possible for the baseline to be at some other level due to the superimposition of a constant dc voltage or current or to fluctuations in the pulse shape, count rate, etc...
- *Pulse Height* or *Amplitude*: Is the height of the pulse as measured from the instantaneous value of the baseline beow this peak.
- *Signal Width*: Is the full width of the signal taken at the half-maximum of the signal (FWHM)
- *Leading Edge*: Is that flank of the signal that arrives first in time
- *Falling Edge*: Is that flank of the signal that arrives last in time. Also known as tail
- *Rise Time*: This is the time it takes the pulse to rise from 10% to 90% of its full amplitude. The rise time essentially determines the rapidity of the signal and is extremely important for timing applications.
- *Fall Time*: Is the time it takes for the signal to fall from 90% to 10% of its full amplitude.
- *Polarity*: A unipolar pulse is one which has one major lobe entirely (excepting a small possible undreshoot) on one side of the baseline. In contrast, bipolar pulses cross the baseline and form a second major lobe of opposite polarity.
- *Overshoot* and *Undershoot*: In the transition of any parameter from one value to another, the transitory value of the parameter that exceeds the final value. Note: Overshoot occurs when the transition is from a lower value to a higher value. When the transition is from a higher value to a lower value, and the parameter takes a transitory value that is lower than the final value, the phenomenon is called undershoot Origin of the overshoot and ringing is the use of a limited bandwidth. See Gibbs effect. The overshoot is about 9% of the amplitude. Adding frequencies the width of the overshoot will be smaller but not its amplitude. See Gibbs phenomenon.
- *Ringing*: is the tendency of band-limited square waves to oscillate on the peaks.
- *Tilt*: is a measure of low-frequency behaviour. As low as low-frequency are filtered, phase shifts are introduced which cause the leading edge of the square wave to rise and the falling edge to fall. This produces a tilt to the top and bottom of the wave. The tilt is usually expressed as a percentage of the peak amplitude of the square wave.

Signals can be also be fast or slow. Fast signals refers usually to signals with rising edges of the order of few nanoseconds or less. Fast signals are very important for timing applications and high count rates and it is important to preserve the fast rising edge over the whole system, that is we have to deal with the parasitic resistors, capacitances and inductances that effectively filters and distort the signals. A second problem is the distorsions produced in the interconections and transmision of the signals.

3 Noise

The term noise can be applied to anything that obscure a signal, noise can be then another signal (interference), but most often, however, we use the term to describe random noise of a physical origin that most of the time is thermal. The noise can by charactetrized by:

- frequency spectrum,
- amplitude distribution
- the physical mechanism that generates it,

Understand or keep under control noise is essentia lin the design and performance of any device, because it sets limits as minimum signal voltage or maximum speed at which the device can work.

The most important fundamental noise mechanism are:

- shot noise
- Johnson noise
- 1/f noise
- interference with unwanted signals
- grounding

3.1 Shot or Schottky noise

An electric current is the flow of discrete electric charges. If interactions between carriers can be neglected, this is a perfect example of a Poisson distribution. Then for an electrical signal, the average current is,

$$\langle I \rangle = \frac{qN}{T}$$

where N is the number of carriers of charge q that arrives in a time T. If the time between the arrival of electrons is bigger that the time the electron needs to arrive, then we can write

$$I(t) = q \sum_{n=1}^{N} \delta(t - t_n)$$

where t_n is the arrival time for the n-th electron. Taking the Fourier transform we have:

$$I(f) = \lim_{T\to\infty} == \int_{T/2}^{T/2} e^{i2\pi ft} q \sum_{n=1}^{N} \delta(t-t_n) = q \sum_{n=1}^{N} e^{i2\pi f t_n}$$

So computing the power spectrum

$$S_f(f) = \langle I(f)I^*(f)\rangle = \lim_{T\to\infty} \frac{q^2}{T} \int_{T/2}^{T/2} \left(\sum_{n=1}^{N} e^{i2\pi f t_n} \sum_{m=1}^{N} e^{i2\pi f t_m} \right) = \lim_{T\to\infty} \frac{q^2 N}{T} = q\langle I\rangle$$

The cross terms $n \neq m$ vanish in the expectation because their times are independent.

So the power spectrum is independent of the frequency (white noise) and is proportional to the current. In case the charges does not arrive as δ functions then the width of the impulses roll the spectrum off for high frequencies.

To find fluctuations we can use the Parseval's Theorem to relate the average total energy in the spectrum to the total average variance

$$\langle |x(t)|^2 \rangle = \int_{-\infty}^{\infty} S(f)df$$

In the case of the shot noise , as the power spectrum is independent of the frequency, the integral is just the twice the bandwith of the system. The factor 2 cames because we consider both positive and negative frequencies. Note that for a perfect system (infinte bandwidth), the variance is then infinite. So we have that:

$$\langle I^2_{noise} \rangle = 2q\langle I\rangle \Delta f$$

Let's understand that this value is a rms. In fact the value of the shot noise current is in general unpredictable and follows a gaussian distribution with mean 0 and rms the value quoted in the previous formula.

In case the charriers are not independent the shot noise is much lower. Examples are metallic conductors where there are long-range correlations between charge carriers.

3.2 Johnson or Nyquist noise

Is the noise associated with the relaxation time of thermal fluctuations in a resistor. Small voltage fluctuations are caused by the thermal motion of the electrons, which then relax back through the resistance. The rms noise voltage is given by:

$$\langle V^2_{noise} \rangle = 4kTR\Delta f$$

where R is the value of the resistor, T the temperature in Kelvin and Δf the bandwith of the measuring system. As in the case of shot noise Johnson noise is white and gaussian.

See Fluctuation-Dissipation Theorem (pag. 31 Gershenfeld)

3.3 $1/f$ noise

In a wide range of transport processes, from electrons in resistors to notes in music, the the power spectrum diverges at low frequencies inversely proportional to the frequency:

$$S(f) \propto f^{-1}$$

This noise is scale invariant and there is still no convincing explanation on the source of it.

In case of electronic noise seems to have a reasonable explanation, in a conductor ther are many types of defects (lattice vacants, dopants..) which have different energies, So there is a possibility to thermally excite to a higher energy that later relax to a lower one, which affect the conductivity of the material. In case of just two states the power spectrum is a Lorentzian:

$$S(f) = \frac{2\tau}{1 + (2\pi f\tau)^2}$$

were τ is the relax time between states. If there is a distribution of activation times, then the power spectrum is:

$$S(f) = \int_0^\infty \frac{2\tau}{1 + (2\pi f\tau)^2} p(\tau) d\tau$$

where if the distribution of barrier heights $p(E)$ is flat then:

$$\tau = \tau_0 e^{E/kT} \quad \rightarrow p(\tau) \propto 1/\tau$$

so integrating $S(f) = 1/f$.

4 Electromagnetic Compatibility. Grounding and Shielding

Electromagnetic compatibility is the polite term when we refer to grounding electronic system and shielding signals. Let's begin with an example. In figure 3 is sketched a so called single-ended amplifier that has two serious problems:

- Any fluctuating voltage around the signal wire can capacitatively couple (electrostatic coupling) with it producing an interference. There are also other couplings, not sketched in the figure, as the magnetic coupling to closed loops and electromagnetic coupling where wires act as antennas.
- Source and amplifier are grounded at different locations. Current must flow throw the pathway connecting grounds, so any resistance will produce a change between relative potentials, or even worse, this differnce can depend on the load and on everything else using grounds. This is called a ground loop.

To solve this problem various techniques, advices and even black magic can be found elsewhere. Some environments worth to avoid are:

- Near a radio or TV station (RF interference)

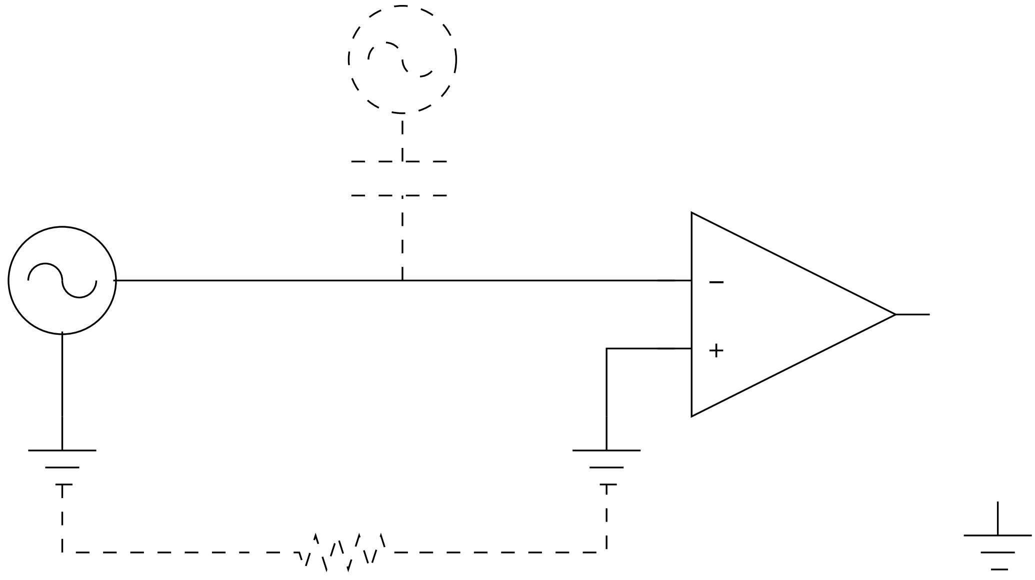

Figure 3:

- Near a subway or railway (impulsive interference and power line garbage)
- Near high-voltage lines (radio interference, frying sound)
- Near motors and elevators (power-line spikes)
- in a building with triac lamp and heater controllers (power-line spikes)
- Near equipment with large transformers (magnetic pickup)
- Near arc welders (unbelivable pick up of ALL sorts)

Let's view some methods to avoid the couplings:

- Capacitive coupling: Reduce capacitance, add shielding, move wire near ground plane.
- Inductive or magnetic coupling: Avoid large enclosed areas (twisted pairs), surround susceptible devices with high-μ shield conductor.
- Radiofrequency coupling: Quite difficult to detect: hidden resonant circuits.

Before treat about grounding, we can define three different grounds:

- Main ground or earth. Real ground on each location. It can vary from one point to another. The main ground in a place can be obtained from the wall plug. How to get a good "absolute" ground: connect with a calefaction pipe of drill a hole (1 meter) fill it with salt and water and introduce a metallic pin (need to be refilled from time to time)
- Signal ground. "0 V" definition for signals and in general for the instrumentation.
- Chassis ground. Potencial of the box. For safety it should be connected to the main ground. to avoid electrocutions (Audio systems risks)

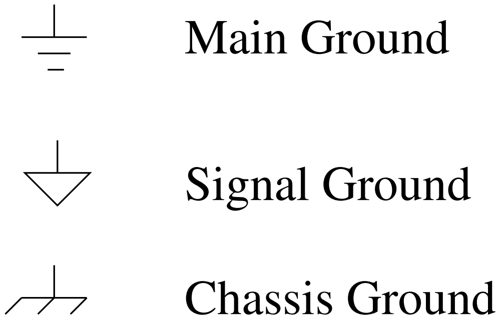

Figure 4: Ground graphical representation

The graphical representation of each ground is shown in figure 4

There are four basic approaches to deal with grounds:

1. Single point grounding. See Fig 5-a. Chassis ground is connected to earth at each individual component. Signal ground is connected to earth at an unique point called *ground mecca*.
2. Multiple point grounding. See Fig 5-b. Chassis ground is connected to signal ground. Not reliable, specially if the setup is changed continuouslly. Can be the configuration in a rack where chassis ground is the same everywhere.
3. Floating ground. See Fig 5-c. Signal ground is completely isolated from earth. Useful when earth carries significant noise. Relies on input filters!!!
4. Telescoping. The best to avoid ground loops on signal lines.

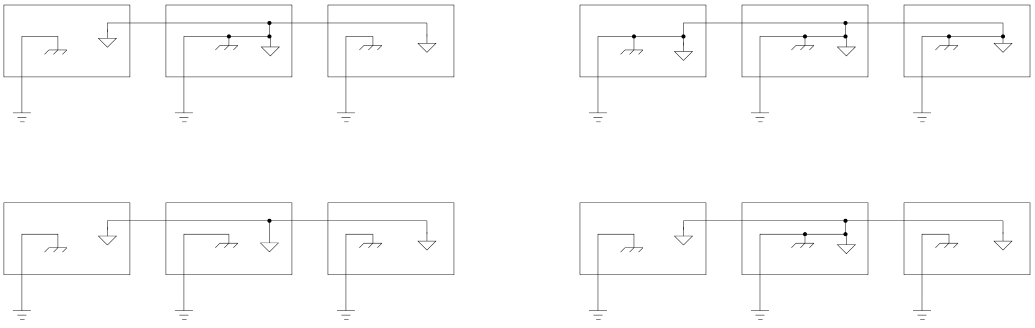

Figure 5: Different techniques to avoid ground loops a) single point grounding b) multiple point grounding c) floating grounding d) telescoping