

Minimizing Distortion and Noise in a Pulse-Width Modulated Transmission

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Contents

ABSTRACT	3
BACKGROUND	3
DISTORTION.....	3
COMMON NOISE SOURCES	4
Thermal Noise	4
Shot Noise	4
Flicker Noise	4
Burst Noise (Popcorn Noise)	5
COUPLING MECHANISMS.....	5
Common Mode Noise.....	5
Ground Loops	6
Parasitic Capacitive Coupling	6
Magnetic Coupling.....	7
Radiative Coupling.....	7
GUIDELINES TO NOISE AND DISTORTION REDUCTION	7
REDUCING DISTORTION	7
TOOLS FOR CIRCUIT DESIGN	8
SHIELDING	9
PROPER FIELD WIRING	9
CONCLUSION	10
Bibliography.....	11

ABSTRACT

This application note is a technical guideline intended to reduce the amount of noise added to field measurement from a transducer via a transmitter to a receiver that is acquiring the transmission. This instruction is meant for applications where the transmitter has encoded the field measurement using pulse-width modulation and is driving a transmission line with a signal to be measured by a receiver at a remote location. The discussion herein was modeled for instances where transmission is necessary through an industrial setting where interference from very high voltages is not uncommon. The transmission line implemented herein is a standard shielded twisted pair line.

BACKGROUND

For telecommunication purposes, the utility of pulse width modulation (PWM) lies within the duty cycle of the encoded signal. Like frequency modulation, PWM has inherent noise-immunity that permits an analog signal to be sent on a relatively lengthy wire-line communication channel with minimal interference. The amplitude assumes one of two relatively discrete values similar to digital communication; thereby the noise has to be significant enough to change the switching of the states. However, as the length of the transmission channel increases, the probability of outside interference affecting the signal integrity also increases. Noise and distortion can compromise the function of PWM by skewing the duty cycle and altering the wave shape of the pulse.

DISTORTION

Distortion for a PWM waveform is a direct function of the transmission channel. For a given step function, the rise time of the pulse edge will increase as the cable length increases. Since a pulse is composed of several harmonics of sine functions, the high frequency components of the pulse will have the highest susceptibility to attenuation and delay. If the frequency of the transmission exceeds the bandwidth of the channel, significant distortion will occur.

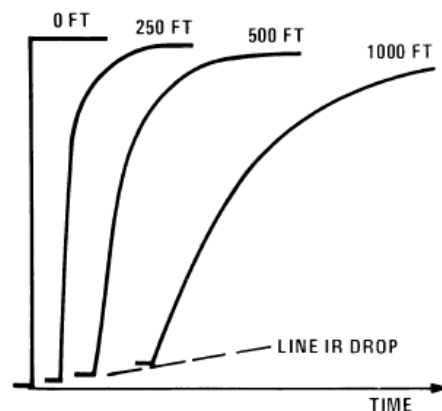


Figure 1 – Example of Distortion of a Pulse Edge with Increased Cable Length ^[2]

COMMON NOISE SOURCES

There are many different mechanisms for generating noise within a circuit. The basic principle involves a noise source that interacts with a circuit via a coupling method. ^[1] It is virtually impossible to have a noise-free circuit; however by understanding the phenomena of noise and distortion, measures can be taken to minimize their impact on critical parameters of the overall design.

Thermal Noise

It is the most prevalent source of noise within a circuit and is due to the thermal agitation of electrons within a conductor and is a primary contributor of “white noise” within a circuit. It is often associated the noise generated by resistors within a circuit. Therefore the non-ideal resistor can be modeled as a noise voltage source in series with an ideal resistor. It can be characterized by the following relationship:

$$\overline{V}_n = \sqrt{kTB R} \quad [V_{rms}]$$

k= 1.38×10^{-23} J/K (Boltzman’s Constant)

T= Temperature in degrees Kelvin

B= Noise bandwidth

R= Resistance ^[3,6]

Shot Noise

A source of noise with minimal impact on a circuit, it is due to the random fluctuations in a DC current due to the discrete nature of charge carriers within a conductor. It is often a phenomena associated with transistors. It can be represented by the following equation:

$$\overline{I}_s = \sqrt{2g I_{DC} B} \quad [A_{rms}]$$

g= 1.6×10^{-19} Coulombs (electron charge)

I_{DC} = DC current

B= Noise bandwidth ^[3,6]

Flicker Noise

Surface defects, contamination and other imperfections often can create traps for charge carriers to accumulate. Flicker noise is the characterization of the random emission of electrons associated with these imperfections. However unlike “white noise” that has a flat power spectral density over all frequencies, flicker noise has frequency dependence. This occurs in active devices or carbon resistors, and can be characterized by the following equation:

$$\overline{I}_f = \sqrt{k_f \frac{I_{DC}^a}{f} B} \quad [A_{rms}]$$

k_f = Flicker coefficient

f= Frequency

a= Flicker exponent (default=1)

B=Noise bandwidth ^[3,6]

Burst Noise (Popcorn Noise)

This source of noise is quite similar to flicker noise in that it is due to contamination and other imperfections that lead to carrier traps, with the exception of the magnitude and mode of emission of the charge carriers. Often heavy ion implantation can lead to these defects. The step-like transitions create a popping often associated with audio speaker noise. The relationship can be exhibited by the following equation:

$$\bar{I}_b = \sqrt{k_b \frac{I_{DC}^c}{1 + (\frac{f}{f_c})^2} B} \quad [A_{rms}]$$

k_b = Burst coefficient

c = Burst exponent (default=1)

f = frequency

f_c = constant for a given noise process

B = Noise bandwidth ^[3,6]

COUPLING MECHANISMS

In many instances, noise is not due to an imperfection as discussed previously, but is due to a functional parameter such as a voltage from a components output or distribution network that is interacting with a device or another portion of the circuit through an unforeseen medium. This is often referred to as interference or *coupling*.

Common Mode Noise

This occurrence can happen when a noise generating impedance is common to several other circuits within an application. For example, certain uses of excessive solder in fabrication can sometimes create a capacitance or accumulation of charge. If such capacitor were to represent a node tied to “ground” of two interfacing devices that device could be graphically represented in the following figure.

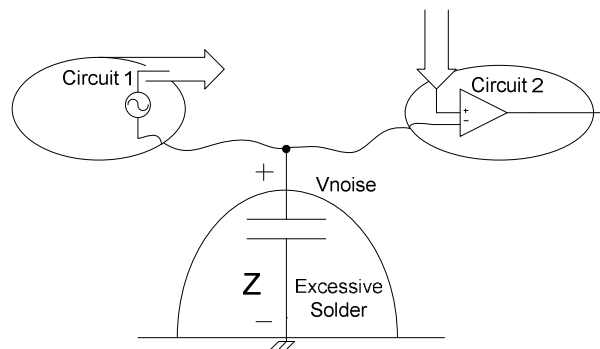


Figure 2 – Example of Common Impedance Noise

Noise of this type often will exhibit a linear response proportional to the current drawn if it is resistive. Otherwise, if it has reactive characteristics, this type is often seen in PWM signals in the form of ringing with a periodic repetition. The natural frequency will be of the standard relationship, $f = 1/2\pi\sqrt{LC}$, with a dampening time constant, $\tau = L/R$.

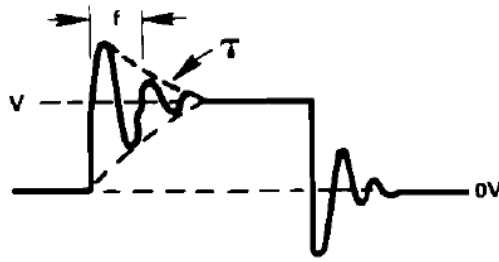


Figure 3 – Pulse with Ringing ^[1]

Ground Loops

From transmission applications, the transmitter and receiver ideally will have the same ground potential. However, the reality is often they do not. If the grounds were to be interconnected, the potential exists for current to conduct and add noise interference into either the transmitter or receiver. The figure below represents how this might occur.

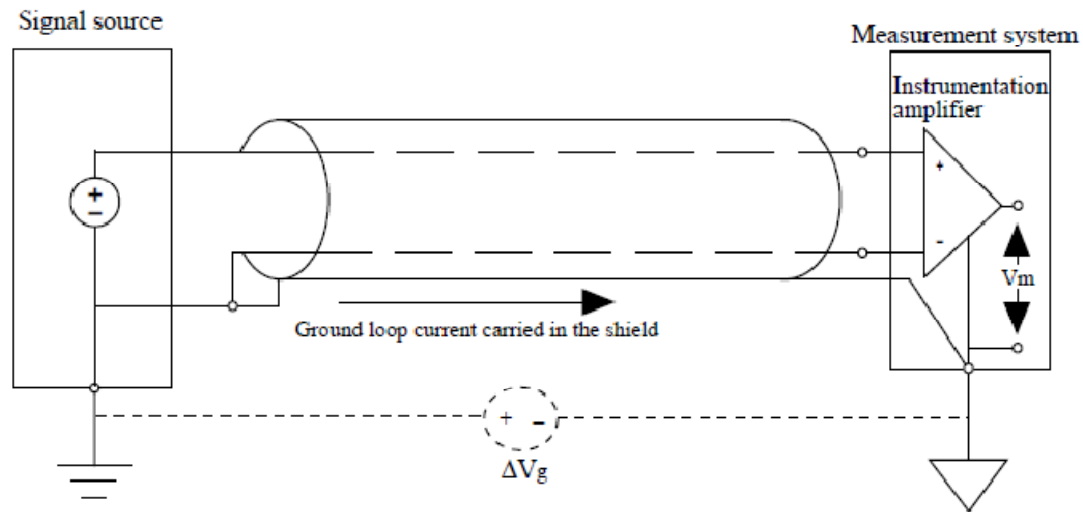


Figure 4 – Improper Shield Termination Causing a Ground Loop ^[5]

Parasitic Capacitive Coupling

For PWM applications, the fast rise and fall times of the pulse edges often create sources of noise with any stray capacitance that exists within the design through capacitive coupling. “Crosstalk” between adjacent traces or potentials is also a source of noise that exists through capacitive coupling where often the dielectric is air.

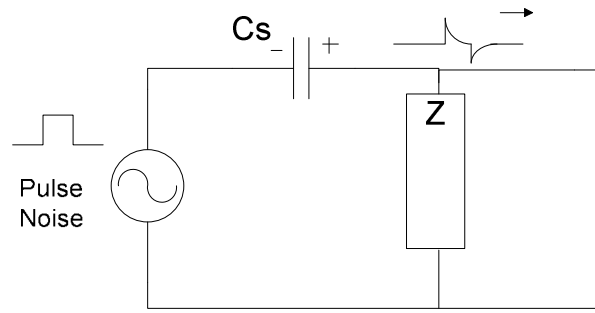


Figure 5 – Pulses Interacting with Stray Capacitance to Generate Noise

Magnetic Coupling

If the field transmitter is being used in an industrial setting, it is in relatively close proximity to very high voltage power lines. High current conducting AC power lines can generate strong magnetic fields that could potentially cause magnetic coupling with adjacent devices and circuitry. In addition to cabling effects, any motors, solenoids, or relays that maybe nearby have frequently collapsing magnetic fields that can create coupling within the circuit.

Radiative Coupling

Radiative coupling can encompass several noise sources, including cosmic rays. Radio and television broadcasts already take up a significant amount of airway bandwidth. The remaining spectrum is being rapidly allocated for automation, medical and communication purposes. Normally, a low frequency operating circuit would not be affected by such high frequencies. Some integrated circuits can generate noise from their non-linear junctions via these stray frequencies through a process called audio rectification.^[5] Though the power spectral density of these waves may be small, when rectified the current can cause troublesome noise for low non-filtered inputs.

GUIDELINES TO NOISE AND DISTORTION REDUCTION

REDUCING DISTORTION

In order to reduce distortion, it is important to understand the bandwidth of the channel relative to the maximum switching speed of the PWM output from the transmitter. Use of the Nyquist rate is a model for digital transmission, though it can be a tool for use with PWM even those it is analog. For example, Level 1 Twisted Pair cable used for telephony has a bandwidth of 0.4 MHz. In order to not have significant distortion, using the Nyquist principle, the maximum frequency of transmission must not exceed half of 0.4 MHz or 200 kHz.

It was discussed previously that as the length of the transmission line increases, the more attenuation (I^2R losses) or delay will lengthen the rise and fall time of the pulses. Where applicable, if the length of the transmission line cannot be shortened, the use of repeaters may help to keep the signal integrity. Reconstruction of the PWM output is not perfect and potentially lengthens the duty cycle based on the triggering threshold of the repeater. As the number of repeaters increases within the transmission, the

quality will decline. Several applications can be used as a repeater, such as a comparator circuit or a microcontroller.

Circuit design is also a worthy consideration in order to minimize distortion. For example, in order to maximize the gain from the pre-amplifier stage to the amplifier stage within the instrumentation that may represent the modulating input, staging should be established such that the input of the amplifier stage is seen as a high impedance relative to the output of the pre-amplifier. For transistor amplifier designs emitter follower (or common collector) amplifiers are used to perform this function. For integrated circuit designs, unity-gain buffers (or voltage followers) can be utilized to also provide the necessary input impedance to prevent loading or reduction in gain.

TOOLS FOR CIRCUIT DESIGN

Unfortunately, many of the effects discussed in the *Common Noise Sources* section, cannot be corrected. Though, through identifying the likely sources of noise, many can be compensated for. The following are some tools that might be helpful to reduce the number of noise sources within a circuit design:

- Reduce the number of resistors with values greater than 1 M Ω . Resistors greater than 1 M Ω have a greater likelihood to generate thermal noise.
- Use input filters at either the transmitter or receivers for notably noisy environments. Flicker and Burst noise have frequency dependence; therefore use of low-pass or band-pass filters to reduce the noise bandwidth.
- Assume there to be a magnetic field within the immediate vicinity of an inductor. Limit the use of inductors in filter design.
- For power supplies or ICs with high switching speeds, ensure proper methods for heat sinking are implemented.
- When fabricating PCB traces, ensure that the use of wide traces (> 0.5 cm) are minimized.
- Limit the number of 90 degree turns in designing traces.
- Avoid the use of long loops of wire or cabling, especially over sensitive ICs.
- If digital ICs, such as a microcontroller, are used, provide sufficient separation between the digital and analog on the PCB. Digital ICs require clocks with rapid switching speeds that can couple with analog components.
- Use high quality tantalum capacitors to filter power supplies or voltage regulators.
- Limit the bandwidth of frequency used in design to as low as reasonably achievable. The lower the frequency, the distributed capacitance or inductance of a circuit will manifest. Also, the lower the frequency, the larger the wavelength ($\lambda = c/f$) becomes to exceed the dimension of the transmitter or receiver.
- If high frequency oscillators are used, avoid running traces over or underneath them. Conductors surrounding high frequency oscillators have the potential to act as antennas. For example antennas are typically designed for $\lambda/8$, so for a 1 GHz oscillator: $\lambda/8 = [3e8(m/s)/1(GHz)]/8 = 3.75$ cm. A trace of 3.75cm could act as a noise antenna.

- Avoid using too much solder or generating “dirty” solder joints where contamination could potentially be trapped.

SHIELDING

Perhaps the simplest, though the most effective, method of noise protection is the use of shielding. There are many ways to employ shielding, and its use has many associations. For a noisy industrial environment, where there is notable EMI, shielding can be used by installing the transmitter or receiver inside a metallic enclosure. Often it is not the high frequency noise that is troublesome, but noise at low frequencies, such as 60 Hz, that shielding cannot always prevent. As seen in the figure below, steel is perhaps the best and reasonably affordable source of shielding; much more than copper or aluminum.

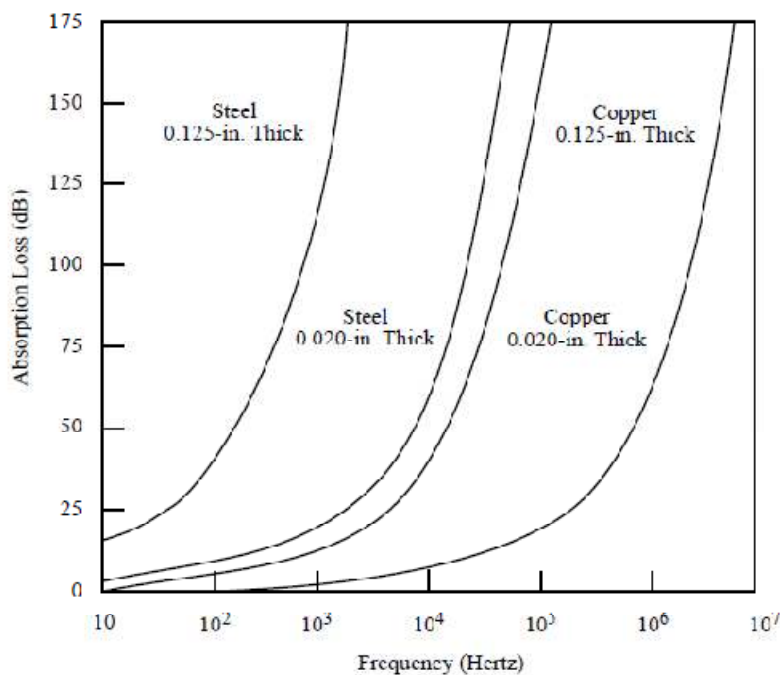


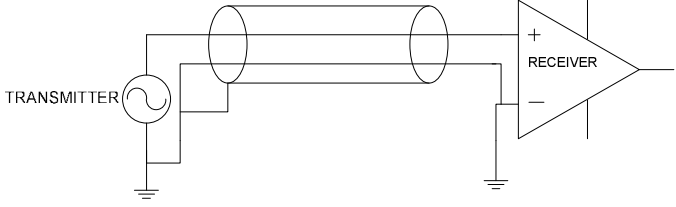
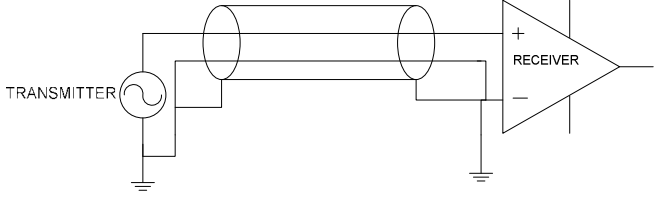
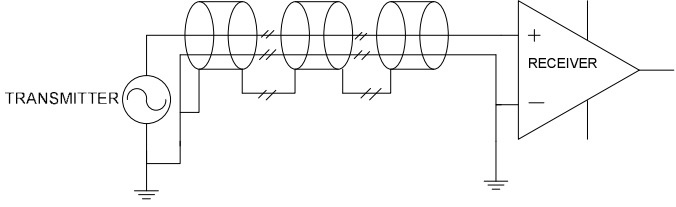
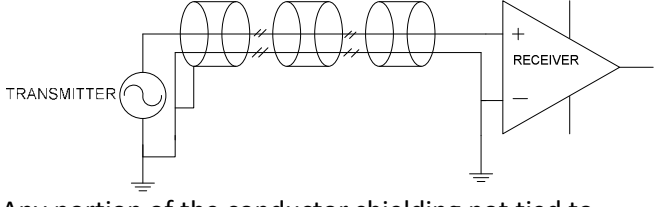
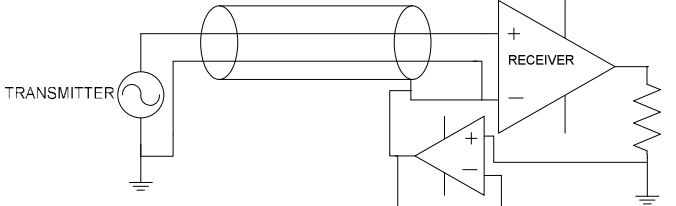
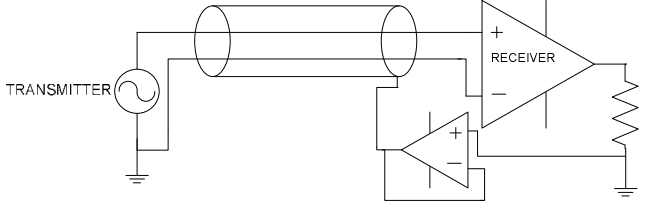
Figure 6 – Absorption Loss of Steel and Copper Relative to Frequency ^[5]

The wire used for transmission should be a shielded twisted-pair wire. The twisting helps to eliminate the influence of crosstalk within the channel, as well as minimize the impact of EMI. The principle works by having opposing currents twisted together, the net magnetic field created between the two conductors are cancelled out. The shield further limits the amount of interference that occurs on a lengthy channel. The shield provides a surface area for noise sources to deposit their charge, and if properly grounded, the drain wire will provide a path for the charge carriers to travel to ground.

PROPER FIELD WIRING

As mentioned previously, shielded twisted pair wire should be used for PWM transmission to the receiver. Rigid cabling, such as coaxial cabling, has better noise immunity performance, but it is more expensive and does not have the flexibility or adaptability of twisted-pair wire. Also as previously,

discussed if the frequency of transmission is kept sufficiently low, twisted pair will provide an ample signal-to-noise ratio (SNR). To be effective, the shield must be grounded to the same referencing as the transmitting signal. Therefore, if the signal is chassis-grounded, the shield must also be chassis-grounded. In the following table are some “do’s” and “don’ts” of ground-referenced field wiring. Floating reference measurements are possible for PWM transmission, but not recommended as they have a higher susceptibility to noise.

Do	Don't
 Only tie one end of the shield (transmitter-side recommended) to ground.	 Tying the both ends of the shield to their respective grounds has the potential to introduce ground loops.
 For any breaks in the wire or junctions, the shields of each section must be tied together back to a common ground.	 Any portion of the conductor shielding not tied to ground has the ability to accumulate charge and cause interference.
 A voltage follower can sometimes be implemented as a driven “guard” and give feedback to the shield that is tied to the signal common.	 If the feedback is not tied to signal common, additional noise could be added by the guard driving shield to greater potential difference.

CONCLUSION

Noise is an inevitable anomaly of circuit design. By understanding the causes and mechanisms of electronic noise, deliberate compensation or minimization can be designed. For PWM transmission the duty cycle and pulse shape have critical significance. Noise can be minimized within the transmitter and receivers, but it is the twisted pair transmission line where the system is exposed to its potentially greatest vulnerability. Limiting the distortion and the accumulation of noise along the transmission line can best provide the most effective impact in noise reduction over the overall telemetry system.

Bibliography

- [1] Alan Rich, "Understanding Interference-Type Noise," *Analog Dialogue*, vol. 16, no. 3, pp. 120-123, 1982.
- [2] Bill Fowler, "Transmission Line Characteristics," *National Semiconductor - Application Note 108*, pp. 1-7, 1986.
- [3] G. Wierzba, *Noise in Integrated Circuits - ECE 404: Radio Frequency Electronics Circuits*, Michigan State University: Lulu, 2012.
- [4] Alan Rich, "Shielding and Guarding," *Analog Dialogue*, vol. 17, no. 1, pp. 1-6, 1983.
- [5] Syed Jaffar Shah, "Field Wiring and Noise Considerations for Analog Signals," *National Instruments - Application Note 025*, pp. 1-26, April 1992.
- [6] Henry W. Ott - AT&T Bell Labs, "Noise Reduction Techniques in Electronic Systems, 2nd Edition," New York, Wiley, 1976, pp. 56-59, 93-95.