Keywords: twisted pair, differential instrumentation amplifier, precision resistors, cancelling interference, RFI, EMI, radio frequency, electromagnetic, lowpass filter, clean signals, FPGA

APPLICATION NOTE 4644

Use a Twist and Other Popular Wires to Reduce EMI/RFI

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Abstract: Alexander Graham Bell patented twisted pair wires in 1881. We still use them today because they work so well. In addition we have the advantage of incredible computer power within our world. Circuit simulators and filter design programs are available for little or no cost. We combine the twisted pair and lowpass filters to produce spectacular rejection of radio frequency interference (RFI) and electromagnetic interference (EMI). We also illustrate use of a precision resistor array to produce a customizable differential amplifier. The precision resistors set the gain and common mode rejection ratios, while we choose the frequency response.

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Introduction

A twist. "The Twist.[1]" A twisted pair. Alexander Graham Bell patented twisted-pair wires in 1881. Remarkably, we still use them because they work so well. In addition, today by harnessing incredible computer power in field-programmable gate arrays (FPGAs), circuit simulators, and filter design programs we can make a twisted-pair wire even more useful in data communication.

FPGAs place considerable power and flexibility in the design engineer's control. Relatively low-volume projects that would never be feasible in custom application-specific integrated circuits (ASIC) become practical. Many high-volume projects use the FPGAs to prototype and try new functions before committing to custom silicon. The strength of an FPGA is in complex digital processing, and as a result some analog signal processing is limited by the digital noise. External analog gain, offset, filtering, and processing can help the FPGA better serve the application.

This article shows how to combine a twisted-pair wire and lowpass filters to produce spectacular rejection of radio frequency interference (RFI) and electromagnetic interference (EMI). We also illustrate use of a precision resistor array to produce a customizable differential amplifier which helps pull the signal out of the interfering noise and improves FPGA performance. The precision resistors set the gain and common-mode rejection ratios while we choose the frequency response.

The Importance of a Twist

Amazingly a "twist" has become important in data communications. The seemingly simple twist of a pair, or pairs, of wires can reduce crosstalk, RFI and EMI.

With the explosive growth of the Internet and computers, we might think that twisted-wire pairs are a recent invention. We would be wrong. **Figure 1** is a copy of Alexander Graham Bell's 1881 patent. He describes the interaction between many twisted pairs.
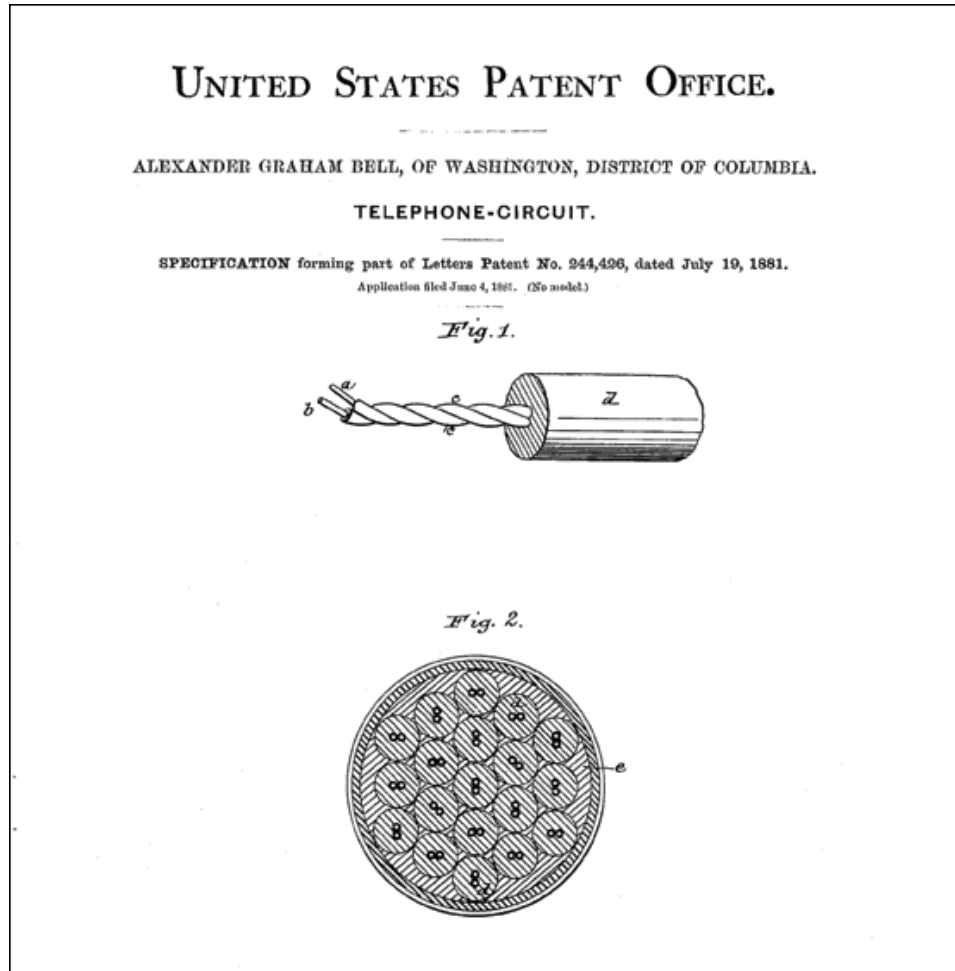

Figure 1. U.S. Patent 244,426, granted in 1881 to Alexander Graham Bell.[2]

In Mr. Bell's words,

The several circuits are composed each of two wires—a direct and a return wire—forming a metallic circuit. Inductive disturbance in the telephone and in other electrical instruments connected with a metallic circuit when the later is placed in the neighborhood of other electrical circuits arises from the unequal inductive effect of the later upon the two wires, for it is obvious that if the direct and return wire were affected equally the current generated in one would neutralize and destroy that created in the other. The disturbance can be avoided by placing the two wires in the same inductive relation to the disturbing currents, or, other conditions being the same, by placing them at equal distance from said circuits.[3]

In these sage words more than 125 years old, we have the modern principle of differential signaling.[4] **Figure 2** shows how a magnetic field generated by current flowing in wire A causes an unwanted current to flow in wire B.
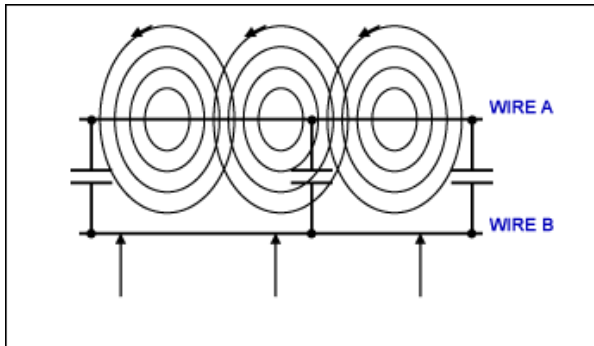

Figure 2. Crosstalk between wires: a magnetic field generated by current flowing in wire A causes an unwanted current to flow in wire B.

Capacitors are drawn between the wires to indicate stray distributed capacitance. As we increase the frequency of the interfering crosstalk, the capacitive coupling becomes more dominate. In **Figure 3** we see the canceling effect described by Mr. Bell. When an interfering signal is applied equally to both sides of the twisted pair, the interfering signal is neutralized and destroyed. At radio frequencies the stray capacitance will couple energy between the wires. Again, because the interference is equal and opposite in the twisted pair, the RFI tends to cancel out. Receiving the twisted-pair signal with a differential enhances the cancelation effect.
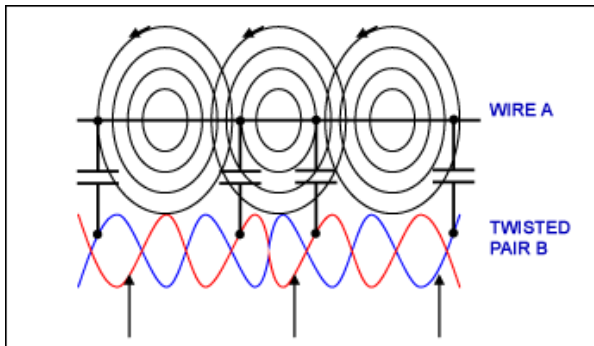

Figure 3 Crosstalk between wires is cancelled when an interfering signal is applied equally to both sides of a twisted-pair wire.

Twisted-pair wiring can also be wrapped with a shielding conductor sheath which acts as an electrostatic shield. As radio frequency (RF) signals are further attenuated, the shield increases the stray capacitance and acts like a lowpass filter. The wires' resistance and inductance are a series component; the stray capacitance to ground forms the lowpass filter. This is a good thing when the communications link is only using low frequencies such as telephone audio or other narrowband signals.

Using a Lowpass Filter to Reduce RFI

For example, the speed of a temperature measurement may be limited by the physical mass of the object measured. A home heating unit may only need to measure temperatures every minute or two. Because the mass of the air, walls, floor, and ceiling is large, the temperature changes slowly. Consequently, measuring millions of times a second will not improve either the heater's temperature measurement or temperature control.

We move outside. RFI can be generated on outside wires into a dwelling. The example is a home, my home, about a mile from a 50,000W AM radio station. Unfortunately, the phone wires picked up the station at 1.37MHz.The signal was rectified in the phones, reproducing the station's audio on the phone line. This was quite annoying to hear and made it impossible to use telephone modems. The station's studio is next to the transmitter and antenna, so the fix was simple. By definition, the engineers are experts at removing 1.37MHz from their audio and telephone systems. So we called them on the "noisy" phone and asked what lowpass filter they used.
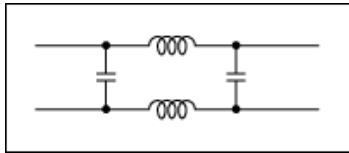

Figure 4. A lowpass filter schematic.

Why does such a simple filter as **Figure 4** work so well? The secret is in the physics: what do we want to keep and what do we want to reject in the lines? In this case our wanted telephone audio was 300Hz to 3kHz and the unwanted signal was 1.37MHz. The difference between the frequencies is a ratio of more than 450.

Using FilterFree by Nuhertz®[5] we made a Butterworth response filter and graphed its response (**Figure 5**). The filter is essentially flat to 3kHz and > 135dB down at 1.37MHz. The 135dB is an attenuation of 5.6 million times. When the radio station plugged in the filter, they solved the issue and are not interfering with the phone line any more.
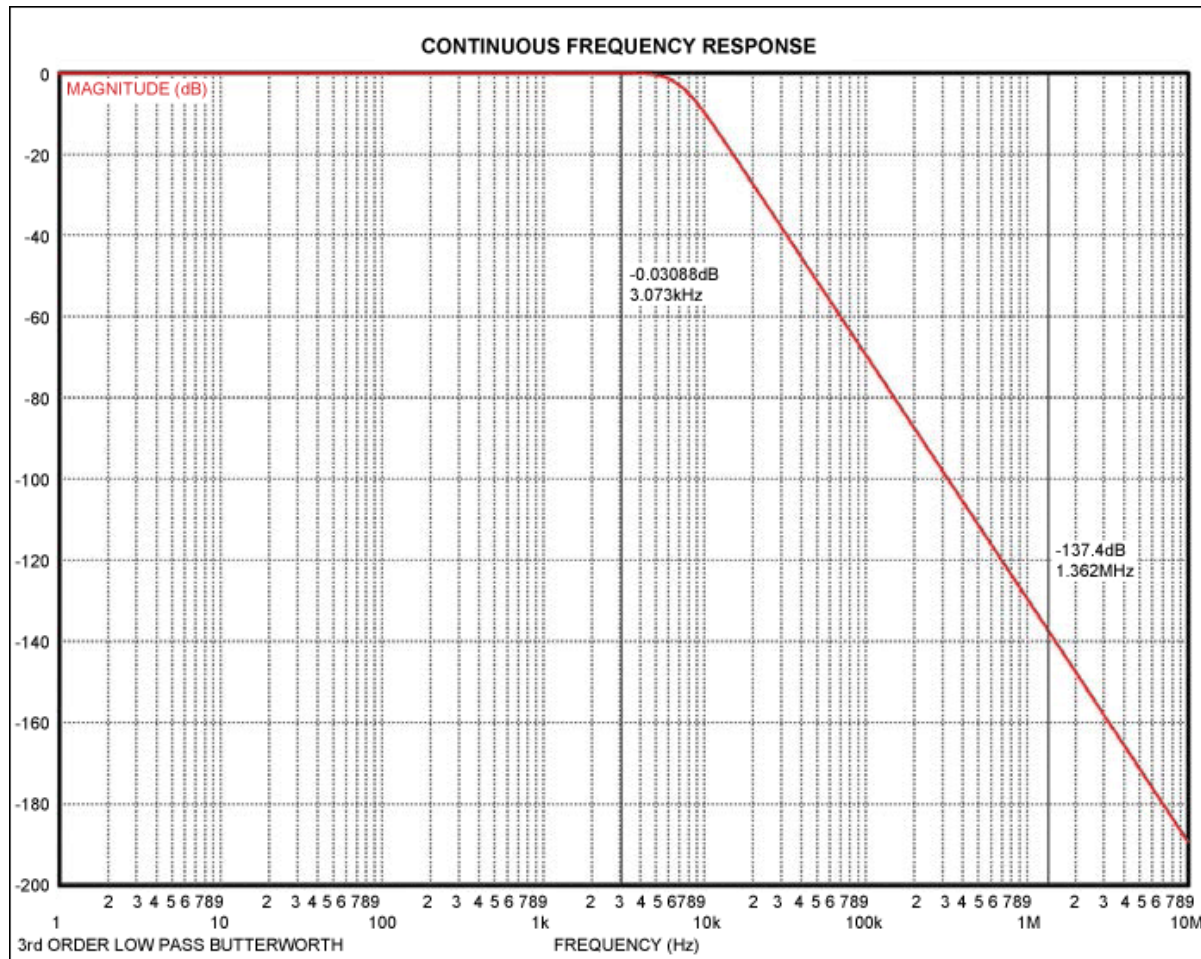
CONTINUOUS FREQUENCY RESPONSE

-0.03088dB
3.073kHz

-137.4dB
1.362MHz

3rd ORDER LOW PASS BUTTERWORTH FREQUENCY (Hz)

Figure 5. Using a lowpass filter, the telephone audio passes through the lines while the radio station's RFI is rejected.

Would a simpler filter work as well? A shareware tool, Solve Elec,[6] is a circuit simulator with "Low pass filter.eln," a single RC filter. Using that RC filter and changing the values to provide an 8kHz -3dB point gives us the response of **Figure 6**.
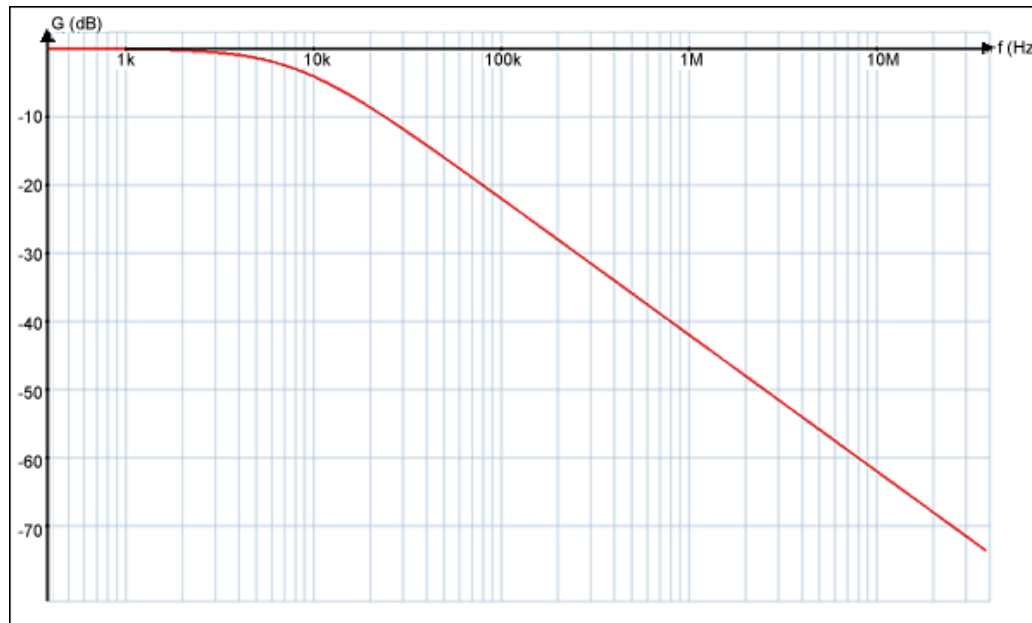
Figure 6. A simple RC filter response for the RFI on the phone lines in the example here.

The telephone audio at 3kHz dropped less than 0.5dB, but the radio station's RFI dropped about 44dB, or a ratio of more than 150 times attenuation. In fact, we could also use the resistance and inductance of the phone line as the series element and just add a small capacitor to ground to reduce the radio station RFI even further.

Consider now a factory temperature-measurement system where the wires are hundreds of feet long and can act as a radio antenna. There is more opportunity for RFI here. If the speed of the needed temperature measurement remains consistent over a defined period of time, then adding a lowpass filter in series with the sense wires will remove RFI. How should we receive the signal on the twisted pair? Differentially, of course, to make sure that the unwanted signals really cancel each other. **Figure 7** shows such a circuit.
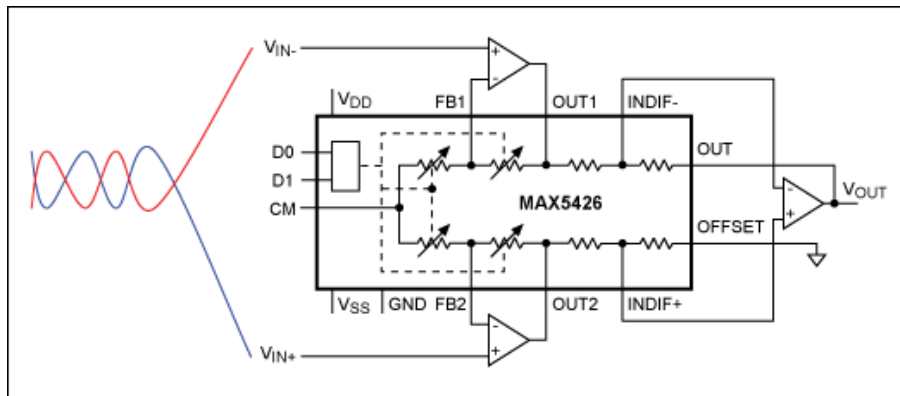
Figure 7. A differential amplifier using the MAX5426 precision resistor network gives the designer choices with amplifier characteristics.

The circuit configuration of Figure 7 is also called an instrumentation amplifier. While many completely integrated circuits are available with the op amps in the package, the MAX5426 precision resistor array gives a designer unique control over the amplifier characteristics. The precision resistors allow digital selection of differential gains of 1, 2, 4, or 8 with a choice of accuracy from 0.5% to 0.025%. Precision resistor matching allows excellent common-mode rejection of more than 79dB. The op amp is selected by the circuit designer and allows the frequency response to be tailored to the application. Thus the front-end filtering can be augmented.

Conclusion

We can still listen to Chubby Checker and "The Twist" through the Internet or over the air waves. And although Alexander Graham Bell long ago understood the principles of twisted pairs, he would marvel at what modern science can do with those twisted-pair wires, circuit design, simulation tools, and FPGAs. With just the right twist of a wire and a lowpass filter, you can reduce EMI and RFI and make data communication more robust.

References
1. Chubby Checker's 1960 pop music hit, "The Twist," has been rerecorded in many forms. According to his website, "The Twist" is the only song to be #1 twice and it is also the #1 song of all time (Billboard Magazine, September, 2008).
2. For the patent information, go to www.google.com/patents?id=DEBJAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false. For general information on the invention, see http://en.wikipedia.org/wiki/Invention_of_the_telephone or http://en.wikipedia.org/wiki/Alexander_Graham_Bell.
3. Alexander Graham Bell at United States Patent and Trademark Office; U.S. Patent 244,426, http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PALL&p=1&u=%2Fnetahtml%2FPTO%2Fsrchnum.htm&r=1&f=G&l=50&s1=0244,426.PN.&OS=PN/0244,426&RS=PN/0244,426.
4. The term "metallic circuit" was used to avoid confusion with earlier telephone circuits. Telephones were originally connected with a single wire and used a ground return path to save copper wire. As electric power and trolley cars wires were placed near the phone wires, interference occurred.
5. For more information, go to www.nuhertz.com.
6. For more information, go to www.physicsbox.com/indexenglish.html.

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