A Rocky Mountain Chapter White Paper: “Impedance Mismatches and Reflections”

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The following is adapted from an article I wrote about just why (and how) impedance mismatches cause reflections. That article originally appeared in the December 2005 issue of *Communications Technology*.

It has long been a fundamental of transmission line theory that an open circuit, short circuit or pure reactance terminating a transmission line are incapable of absorbing power from a forward, or incident wave. Thus, all incident current and voltage are reflected back toward the source. It’s sometimes difficult to understand why this happens. Intuition suggests that a short at the end of the line will short-circuit the RF to ground, and an open circuit will radiate the RF into the air. But the RF really is reflected back towards the source in both cases. Grab a cup of coffee and read on to see why. For reference, much of the following explanation is paraphrased or excerpted from information in the books *Reflections* by M. Walter Maxwell, published by the American Radio Relay League; and *Handbook of Coaxial Microwave Measurements*, originally published by GenRad, Inc. and reprinted by Gilbert Engineering (now Corning-Gilbert).

Transmission line theory tells us that the characteristic impedance Z_c of a transmission line is defined as the ratio of voltage V to current I in a traveling wave: Z_c (ohms) = V/I. For this discussion, assume the transmission line is lossless; things get really messy when attenuation is factored in the discussion. I’ll use “+” and “-” to designate incident (forward) and reflected (rearward) traveling waves.

Imagine an incident wave leaving a signal source – say, the output of an amplifier, tap, or perhaps the upstream output of a cable modem. As the incident wave leaves the source, it “sees” the characteristic impedance Z_c of the line as a resistive load. The incident wave is an electromagnetic signal, so half of its energy is in the electric field (because of voltage) and half is in the magnetic field (because of current).

The incident voltage V^+ and current I^+, which are constant along the transmission line, are in phase because Z_c is resistive. As the incident wave travels along the transmission line, the ratio V^+/I^+ in the line equals the line’s characteristic impedance Z_c. So far, so good.

Shift your thoughts for a moment to the load or termination at the end of the transmission line. The ratio of total voltage to total current *at the load* equals the terminating impedance: $V_t/I_t = Z_t$. If the incident wave is the only wave on the transmission line, then $V_t = V^+$ and $I_t = I^+$. Under these conditions, the load impedance Z_t and transmission line impedance Z_c are equal, and all incident power is absorbed by the load.

What happens if the end of the transmission line is an open circuit ($Z_t = \infty$)? We know that there is no current in an open circuit, so the magnetic field at the open circuit collapses. The collapsing magnetic field creates an electric field with the same energy as the original magnetic field. The new electric field adds in phase with the original electric field, making the voltage at the open circuit twice the voltage of the incident wave. This represents the development of a standing wave – current is minimum, and voltage maximum (remember, the incident current and voltage were constant along the line until now).

The higher voltage at the open circuit and its electric field causes a reflected voltage wave V^- to start traveling back towards the source. The new reflected wave is the same magnitude as the original incident wave (no energy was absorbed by the open circuit), so reflection coefficient $\Gamma = V^-/V^+ = 1$. The motion of the new reflected electric field results in a new magnetic field whose phase is opposite that of the original magnetic field. The new magnetic field's motion causes current to increase to the same magnitude as the original, so we have a reflected current wave I^- with the opposite polarity and traveling in the opposite direction of the incident current I^+. If we look at just the reflected wave, $V^-/I^- = -Z_c$. The minus sign in front of Z_c simply indicates that we're dealing with a reflected wave traveling back toward the source.

The total voltage or current at the load at any given point in time is the sum of voltages or currents of the incident and reflected waves: $V = V^+ + V^-$ and $I = I^+ + I^-$. We know the reflected voltage is in phase with the incident voltage because the sum of the two at the open circuit load is double the original incident voltage – they add because they are in phase. The reflected current is out of phase with the incident current because the sum of the two is zero at the open circuit – they cancel because they are out of phase.

OK, so what happens if the end of the transmission line is a short circuit ($Z_t = 0$)? The general mechanism for the creation of a reflection is the same as for an open circuit, but the electric and magnetic field actions and reflection polarities are reversed. The sum of incident and reflected voltage waves is zero at the short circuit load – they cancel because they are out of phase. The sum of incident and reflected current at the short circuit load is double the original incident value – they add because they're in phase. In other words, with a short circuit load the reflected voltage V^- is out of phase with the incident voltage V^+, and the reflected current I^- is in phase with the incident current I^+.

When $Z_c \neq Z_t$ – that is, when an impedance mismatch exists between the line and load – a reflection occurs. The reflected and incident waves interact to produce a standing wave. The standing wave's distribution of voltage and current is a result of the superposition of the two traveling waves moving in opposite directions. Unlike the constant relationship V^+/I^+ in the incident traveling wave, the ratio of total voltage to total current in a standing wave is not a constant but varies from point to point along the transmission line. This shows up as the familiar "standing wave" (aka amplitude ripple) on a sweep display.