A review of shielding performance
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INTRODUCTION
What determines how effective a cable shield is going to be? And how does the decision to ground or not ground a shield impact its effectiveness? Fortunately there is a well-developed theory of shielding, which will be discussed as a way to get a general understanding of what can be expected of shield performance. But there’s more to it. The manner in which the shield is terminated can significantly affect its effectiveness, as we shall see.

THE THEORY OF SHIELDING
A model of the physical environment
The theory of shielding starts with a model of the physical environment of the shield. The model assumes that the cable is jacketed, so that a shield is not in contact with a ground plane anywhere except possibly at the ends. That being the case, a transmission line is formed by whatever ground plane exists and the outside of the shield. Likewise the inside of the shield and the conductors enclosed also form a transmission line. Thus what we have is two transmission lines coupled by the leakage through the shield (see Figure 1).

Figure 1: The basic model of the physical environment.

The coupling of the inner and outer transmission lines is characterized by a mechanism called surface transfer impedance, $Z_t$. In most installations the shield, and hence the outer transmission line, is shorted to ground either at both ends or one end, shown schematically in Figure 2, by the switch SW being closed or open respectively.
The inner conductors are terminated at each end in some impedance, which when measurements are done, is generally an open, short or matched load.

A model of the electrical environment.
If the shield is terminated at both ends, current can flow along the outside of the shield. This current can be due either to ground loops caused by the grounds at the ends of the cable being at different potentials ($V_d$), or it can be due to induction from external fields, or both. In either case the external shield current is coupled into the inner circuits via the surface transfer impedance, $Z_t$.

If the shield is terminated at only one end, the ground loop is broken. Current is limited to that which is induced to flow through the distributed capacitance between the outside of the shield and the ground plane (see Figure 3).

The induced current may be small, in which case the important quantity is the voltage distribution along the cable. The voltage is zero where the cable is terminated, but can be high at the open end for frequencies where the cable exceeds one-tenth of a wavelength, because at that point it becomes a very efficient antenna.
At the open end, there is capacitive coupling between the shield and the conductors of the cable due to the fringing capacitance $C_f$ (see Figure 4). As the voltage across this capacitance can be high, a significant current can be coupled into the conductors of the cable through the fringing capacitance.

![Diagram](image)

**Figure 4:** The basic schematic for coupling when one end of the shield is open-circuited.

So far we have considered a model of the physical and electrical environment of a shield. Now we need to consider the characteristics of a shield’s construction, and how that impacts shield performance.

**Surface transfer impedance**

To begin with, let’s consider a cable grounded at both ends. To see how a cable grounded in that way works, we need to discuss surface transfer impedance. Simply stated, surface transfer impedance relates the voltage developed across circuits inside a shielded cable to currents flowing on the outside of the cable. Thus in Figure 2 with the switch closed, the current $I_{shield}$ on the outside of the shield gives rise to $V_1$ and $V_2$ on the conductors inside the shield, via $Z_t$.

So how do we determine what $Z_t$ is? Well we can measure it, or we can calculate it. The measurement route has been described in [3], and an example will be shown later. The calculation route is worth discussing because it provides an insight to the physics involved.

We said earlier that the cable shield and the ground plane form a transmission line. We can’t say much about the general case of this, so for simplicity we’ll consider a coax with a ground plane wrapped around it, as shown in Figure 5.
In this case the shield and the ground plane form a coax (so we have a coax within a coax, often called a triax). This configuration can be achieved in practice for a jacketed shielded cable by pulling a braid over the jacket; which is often done for measuring $Z_t$, as explained in [4].

Now let’s suppose a current is flowing along the outside of the shield. From Maxwell’s equations, this current will generate a travelling wave which has electric and magnetic fields, as illustrated in Figure 6. If the conductors have no resistance, the E-field ($E_r$) is radial, and the H-field ($H_\Theta$) is circumferential (the TEM mode that some of you may be familiar with). However since the shield has some resistance, the product of the current flowing on the shield and the shield resistance will generate an E-field $E_z$ in the Z direction, so that the resultant E-field is no longer radial but “tipped” as shown in Figure 7.
Because the shield has a finite resistance, the $E_z$ field doesn’t vanish in the shield, but has a strongly decaying value as a function of the penetration depth (related to the concept of “skin depth”), shown schematically in Figure 8. The $E_z$ wave reaches some (greatly attenuated value) $E_z(a)$ on the inside of the shield:

From circuit theory, $E_z(a)$ is related to $E_z(b)$ by the relations:

$$E_z(a) = Z_{aa} I_a + Z_{tb} I_b$$

$$E_z(b) = Z_{tb} I_a + Z_{bb} I_b$$

Where $I_a$ is the current on the inside of the shield, $I_b$ is the current on the outside of the shield, $Z_{aa}$ is the surface impedance of the shield inside, and $Z_{bb}$ is the surface impedance of the shield outside. $Z_{aa}$, $Z_{bb}$ and $Z_t$ can be calculated from the physical properties of the case, e.g. Schelkunoff [1].

Rearranging the equations on the previous slide, the $E_z(a)$ field at the inside of the shield can be expressed in terms of the current $I_b$ and voltage $E_z(b)$ at the outside of the shield as:
\[ E_Z(a) = \frac{Z_{aa}}{Z_t} E_Z(b) + \left[ \frac{Z_t^2 - Z_{aa} Z_{bb}}{Z_t} \right] I_b \]

Ignoring the terms that are small

\[ E_z(a) = Zt I_b \]

The calculation route for \( Z_t \): Solid shields

A formula for calculating \( Z_t \) was given by Shelkunoff as

\[ Z_t = \frac{UR_{DC}}{\sqrt{\cosh U - \cos U}} \]

\[ U = 303 \sqrt{\mu_r \sigma_r f} \]

where \( R_{DC} \) is the dc resistance of the shield, \( t \) is the thickness of the shield in centimeters, \( \mu_r \) is the permeability of the shield relative to air, \( \sigma_r \) is the conductivity of the shield relative to copper, and \( f \) is the frequency in megahertz. Notice that \( Z_t \) depends on frequency.

Inside the shield, \( E_z(a) \) drives a basically TEM wave (if the conductor resistance is small) that propagates along the conductors. The current \( I_a \) caused by the wave that travels inside the shield gives rise to voltages \( V_1 \) and \( V_2 \) across the terminations of the cable (see Figure 2). The amplitude of the current [and hence \( V1 \) and \( V2 \)] depends on \( E_z(a) \) and \( Z_t \).

To see whether Shelkunoff’s formula actually works, we made a measurement on RG402, a solid-shield coax [3]. The results are shown in Figure 9, where the terms short-short and short-matched refer to two different methods of measuring surface transfer impedance. Figure 9 shows that Shelkunoff’s formula is a good predictor of surface transfer impedance [and hence shielding effectiveness]. It also shows that for a solid shield, shielding effectiveness keeps getting better as frequency increases.
Figure 9. Example of $Z_t$ for a solid shield

The measurement route for $Z_t$: Cables with braided (wrapped) shields
Braided shields behave differently from solid ones, due to the holes in the shield created during the braiding process. The situation is similar for wrapped shields, which look like slot antennas. The holes or slot couple the fields outside the shield to the fields inside the shield by mutual inductance and capacitance. Surface transfer impedance can be calculated for this case, e.g. see [2]. But it’s messy, in particular because it is hard to determine what the mutual capacitance and inductance are.

Generally what is done is to produce a sample of the braided or wrapped cable, and then measure its $Z_t$ as a function of frequency (as a measure of shielding effectiveness). As an example, using a method developed to do this [3], we measured the $Z_t$ of RG-58U, a widely used coaxial cable. The result is shown in Figure 10. Notice that in contrast to solid shields, $Z_t$ for a braided shield increases with frequency, and eventually becomes oscillatory. Wrapped shields in general show the same behavior as braided ones.
Figure 10. Example of $Z_t$ for a braided shield

An important point, as explained in [5], is that $Z_t$ increases to a first peak value as frequency is increased; and this peak is never exceeded as frequency is further increased. The frequency at which the first peak occurs depends on the length of the cable, and moves to lower frequencies as cable length increases. Indeed $Z_t$ can be plotted against the product of frequency and cable length. For example, a plot like the one in Figure 11 can be generated by fitting a curve to the peak values of the data plotted in Figure 10.
Figure 11. $Z_t$ from Fig. 10 plotted as the product of frequency and cable length.

Why this happens is explored further in [5] and [4], where the oscillatory behavior as a function of the length of the cable and frequency is discussed; and also why $Z_t$ reaches a peak value at some frequency, and then decreases as frequency is further increased.

**EFFECT OF A SHIELD ON WAVESHAPE**

Regardless of how the braided or wrapped cable shield is terminated, it basically acts like a high-pass filter. The result is that a surge travelling on the inner conductors of a shielded cable will have a steeper rise-time than the inducing surge on the outside of the shield. As an illustration, the effect of a shield grounded at both ends on the frequency spectrum of a lightning surge is shown in Figure 12. Here the frequency spectrum of a 4.5x77 negative first lightning surge has been multiplied by the $Z_t$ spectrum shown in Figure 11, assuming a 10 m long cable. Figure 12 shows that the low-frequency components of the surge are suppressed. The result is that the surge appearing on the inner conductors of the cable will have a steeper rise time than the surge on the outside of the shield. Note that a similar effect would occur if the shield were grounded at only one end, since the resulting capacitive coupling also suppresses the low-frequency components of the surge.
THE EFFECT OF SHIELD TERMINATION

Having looked at shielding theory, there is the practical matter of how to terminate the shield. This decision depends on the environment in which the cable is installed.

If a shield is terminated at only one end, a relatively high voltage may exist at the open end of the shield. Because a capacitance exists between the end of the shield and the cable conductors, electrical interference can be injected directly into the cable loads. The magnitude of this capacitance depends a lot on the installation, so it can’t really be calculated. The capacitive coupling is greatest at high frequencies, where the capacitive reactance is the lowest.

The argument has been made [6] that bonding a shield at only one end destroys its effectiveness, and there is some truth to it, especially at high frequencies, as shown in Figure 13 based on data in [7]. The implication of that remark is that a shield should never be bonded at one end only. But the remark was made in the context of saying that a properly designed system doesn’t have ground loops – a condition which may not be achievable in practice.

As a note, the difference between the “no shield” and the “360° at one side” plots in Figure 13 is 18 dB at 1 mHz. Extrapolating this plot to 100 Hz [a pretty risky thin to do] leads to an estimated difference between the two curves of 63 dB. So a shield grounded at only one end may have reasonable performance at audio frequencies, but not at broadcast radio frequencies and higher.
Figure 13. The effect of terminating a shield at only one end.

Grounding a shield at both ends eliminates the capacitive coupling problem, and is most effective when the potential difference between the two shield terminations is low. In this case the ground loop currents will be small, and the shield will have its maximum effectiveness, provided it is terminated properly. As pointed out in [6], proper termination is for the shield to be bonded at each end with a 360° termination. For example, as shown in Figure 14.

Figure 14. Two examples of 360° shield termination

If that is not done, much of the benefit of terminating a shield at both ends may be diminished or lost; for example, as shown in Figure 15 from data in [7]. Note the loss of shielding effectiveness when pigtails are used (see also [8]).
CONCLUSIONS
Back to the original questions: What determines how effective a cable shield is going to be? And how does the decision to ground or not ground a shield impact its effectiveness?

The theory of shielding gives a general understanding of what can be expected of shield performance, but the manner in which the shield is terminated also has a significant impact on the effectiveness of the shield.

An important factor to consider is whether or not the grounds at opposite ends of the cable are at close to the same potential. If they are, ground-loop currents will be minimal. In this case grounding both ends of the shield is likely to give the best shielding performance. If the grounds are at substantially different potentials, ground-loop currents could be a problem, and in this case leaving one end of the shield unterminated may give the best overall shielding performance, providing that shielding against high frequencies is not an issue.

The decision to terminate or not terminate depends on the application. Unfortunately there is no rule that applies to all situations, and an experiment is often required to determine the best way to terminate the shield.

References


