PROTECTION ENGINEERS GROUP

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Things You May Not Have Heard About Shielding

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Things you may not have heard about…

Shielding

Al Martin
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The issue

Why shielding?

Well the subject has come up in past PEG meetings, so I thought I could add to the discussion some things you might not have heard before.

In particular, what influences the decision on whether to ground one or both ends of the shield…

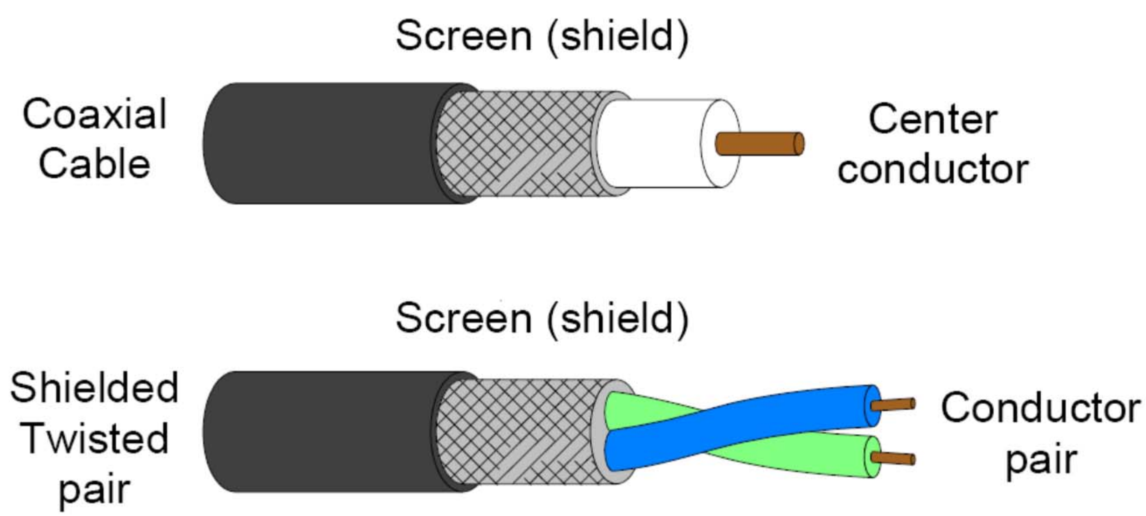
The issue

In discussing the issue of how to ground a shield, it is useful to know something about the theory of shielding, since shielding theory takes into account how the shield is grounded. Once we know from theory what to expect, we can look at the practical issues of shield grounding, and make some conclusions.

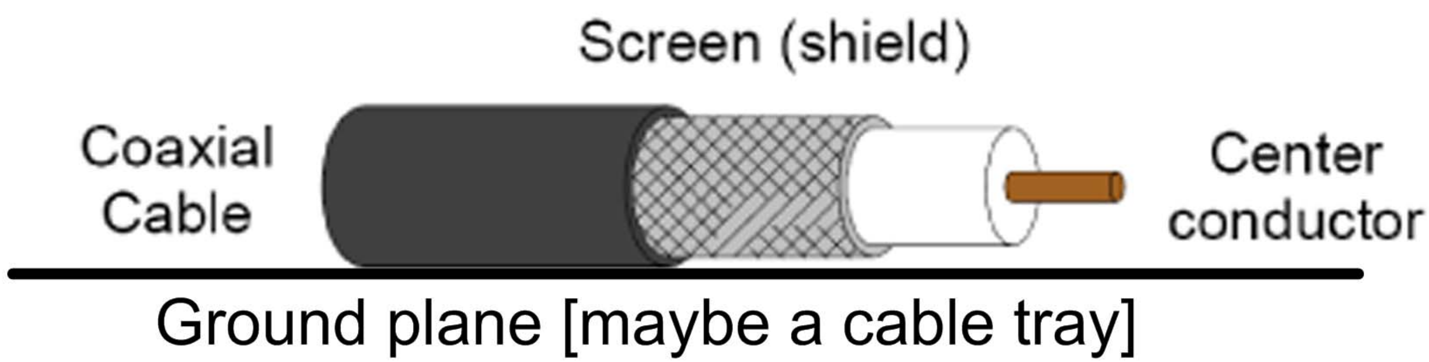
The theory of shielding depends significantly on the physical and electrical environment of the shield, so we need to look at that first...

Physical environment

Starting with the physical environment, we can generally assume that most cable is jacketed, so that a shield is not in contact with a ground plane anywhere except possibly at the ends.

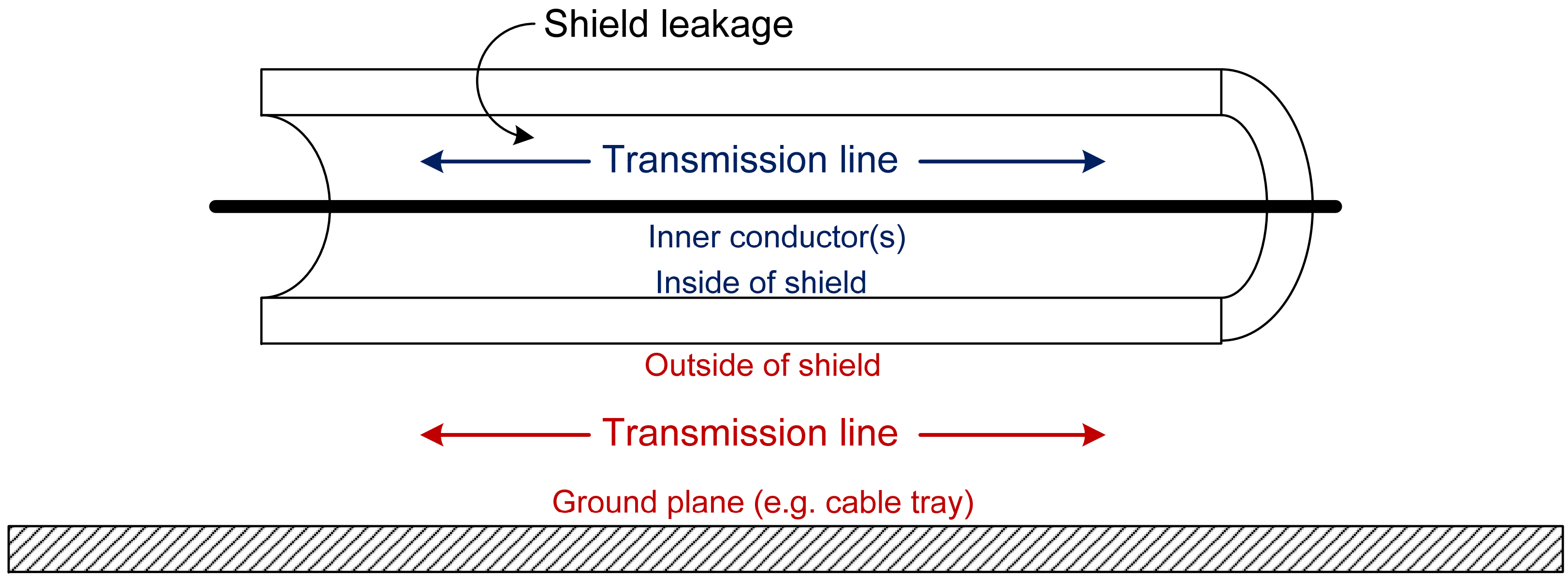


So something like this:



Physical environment

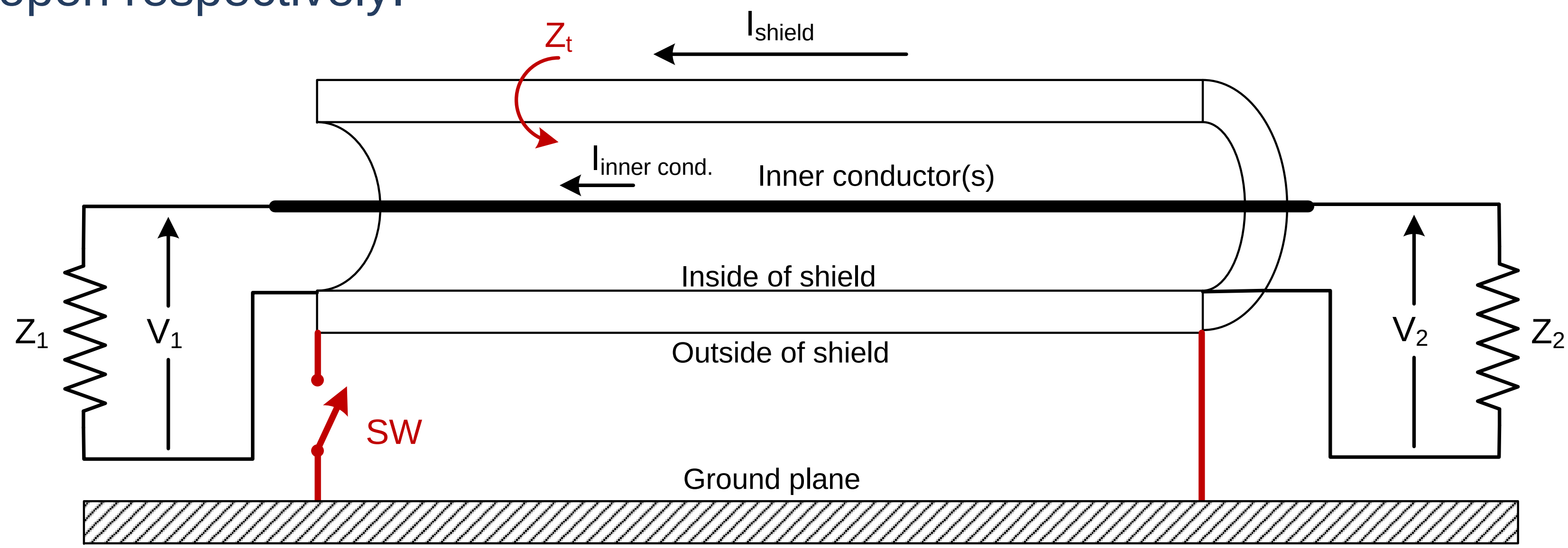
That being the case, a transmission line is formed by whatever ground plane exists and the outside of the shield. Likewise the inside of the shield and the conductors enclosed also form a transmission line. Thus what we have is two transmission lines coupled by the leakage through the shield. So schematically we have something like this:



Physical environment

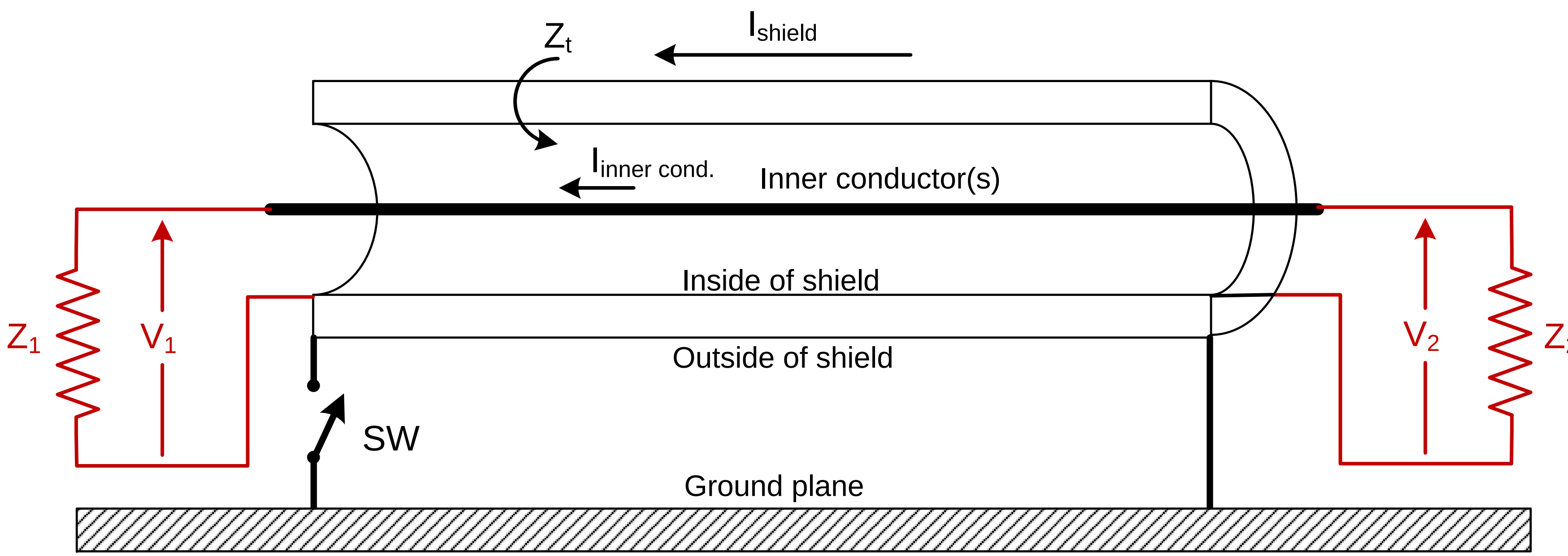
The coupling of the inner and outer transmission lines is characterized by a mechanism called surface transfer impedance, Z_t which will be explained in detail later.

The outer transmission line can be shorted to ground either at both ends or one end, shown schematically by the switch SW being closed or open respectively.



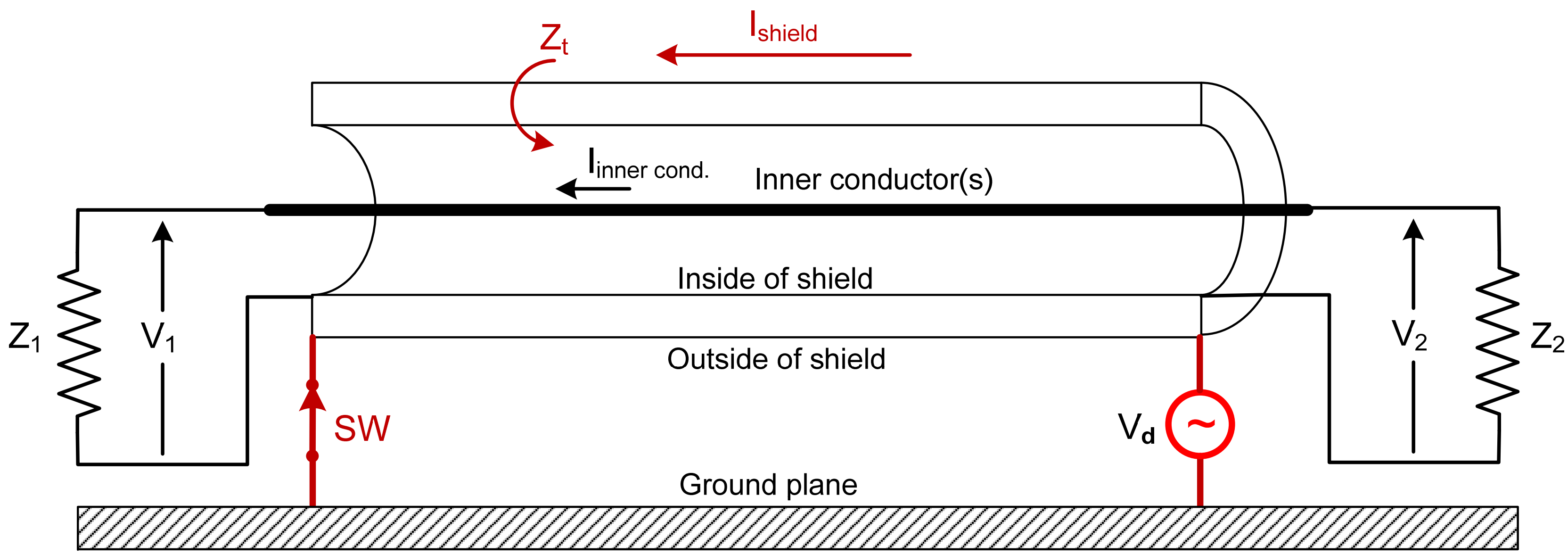
Physical environment

The inner conductors are terminated at each end in an impedance, which is generally an open, short or matched load when measurements are done.



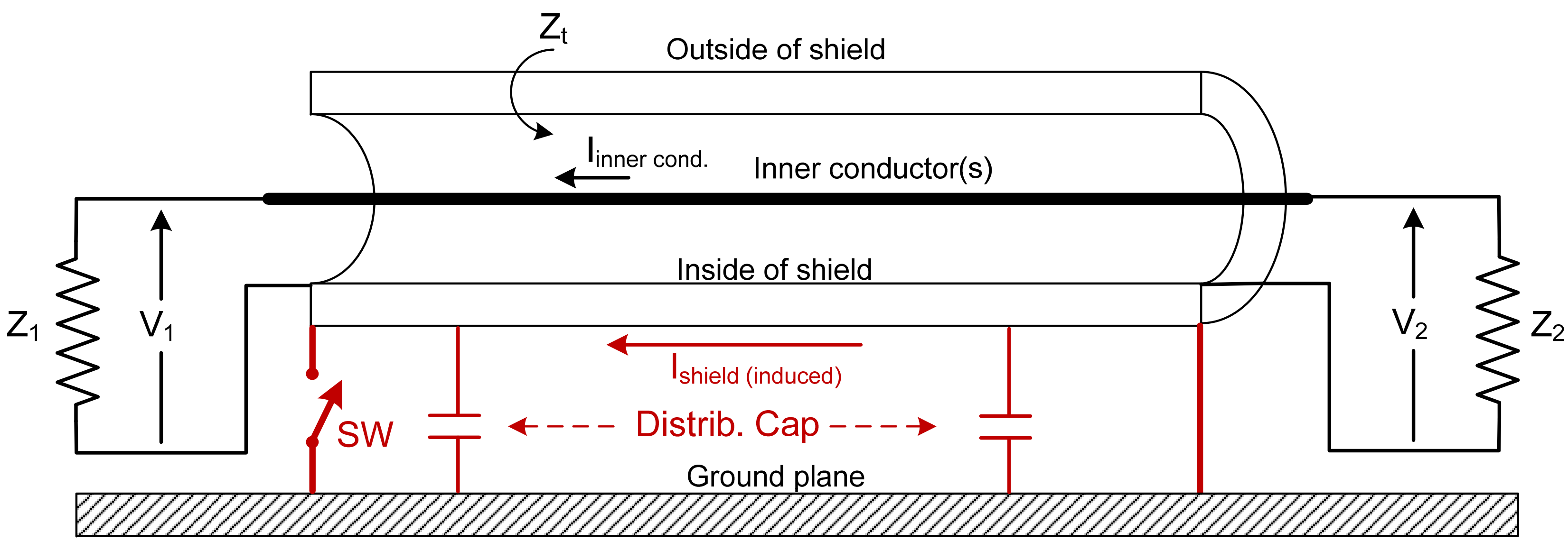
Electrical environment

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.



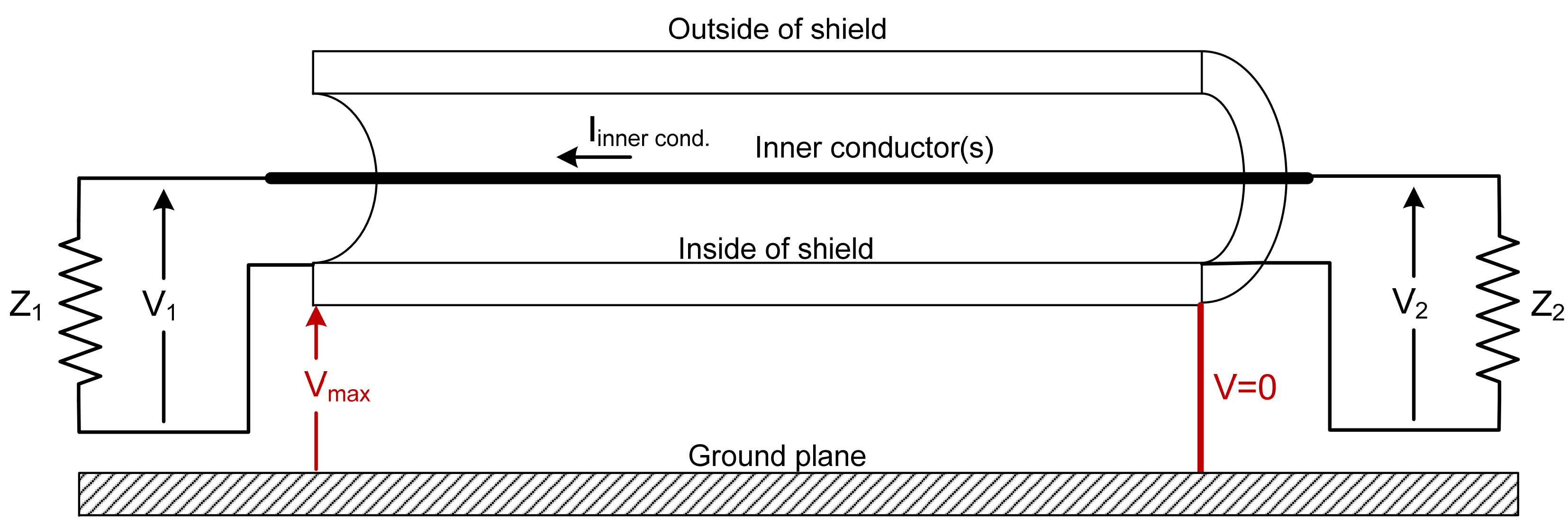
Electrical environment

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



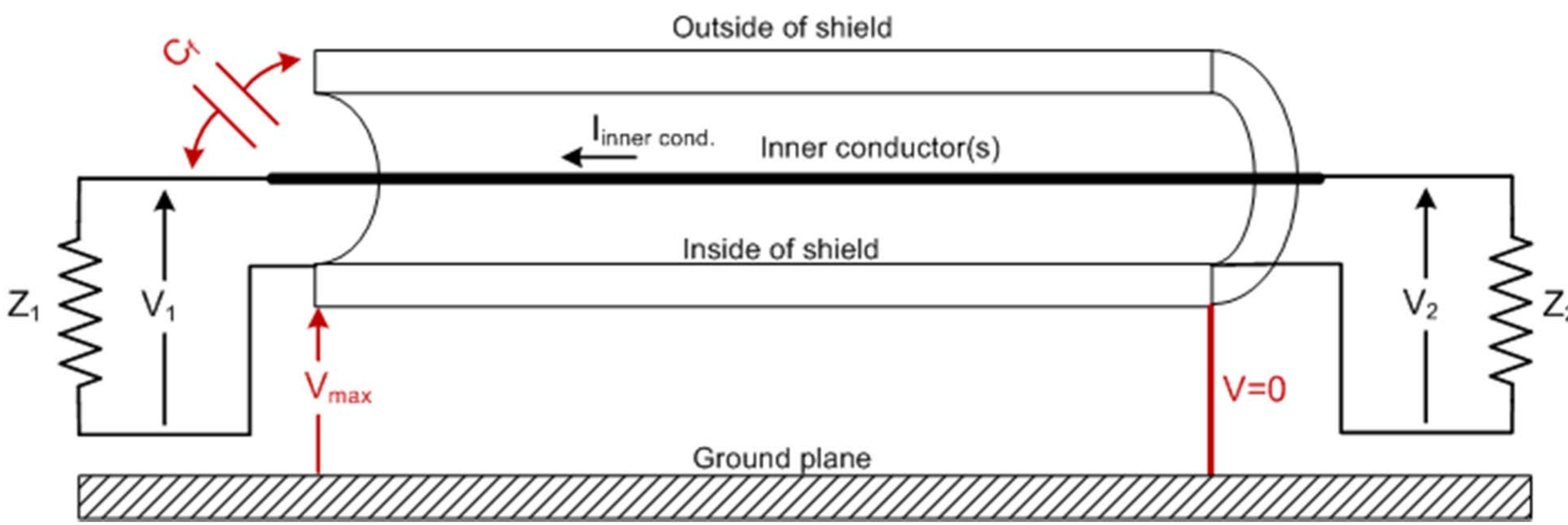
Electrical environment

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.



Electrical environment

At the open end, there is capacitive coupling between the shield and the conductors of the cable due to the fringing capacitance C_f. 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.



The theory of shielding

So that's the physical and electrical environment of a shield, and how those influence the way in which a shield works.

Now we need to consider the characteristics of a shield’s construction, and how that impacts shield performance.

The theory of shielding

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.

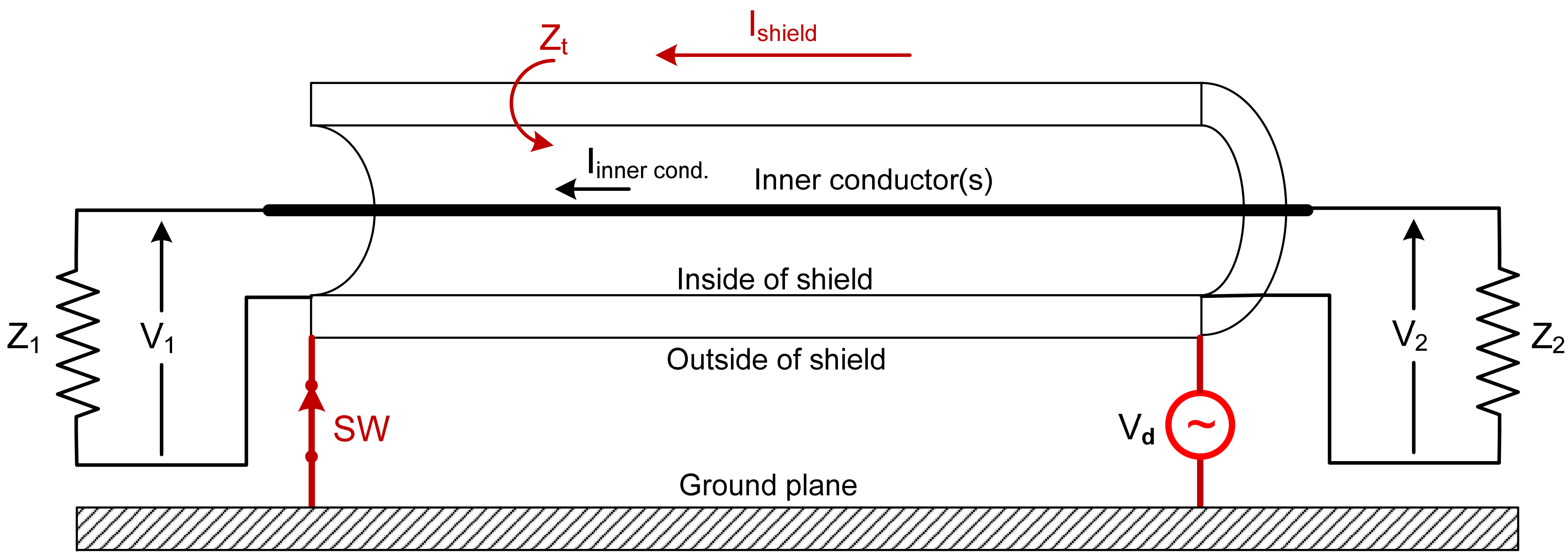
The theory of shielding

The theory of shielding

As a note, the concept of surface transfer impedance is not new. The seminal paper on this subject was written by S.A. Schelkunoff, and appeared in the *Bell system Technical Journal* in 1934.

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. So in figure below, 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.



Surface transfer impedance

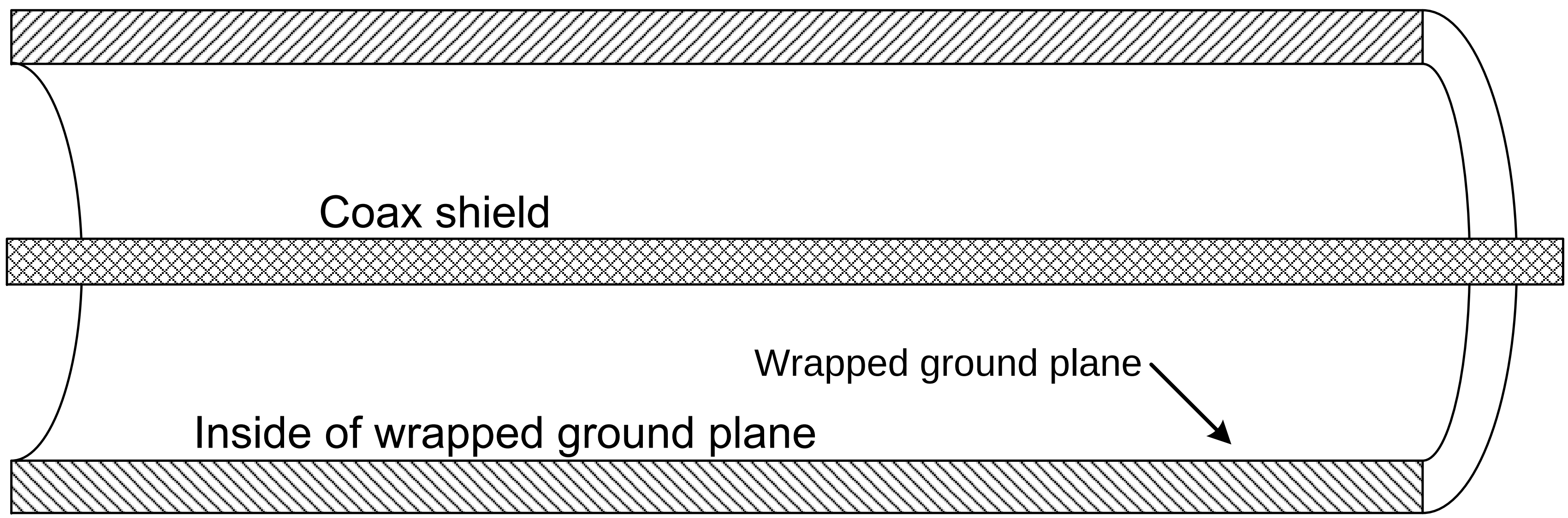
So how do we determine what Z_t is?

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 into how a shield actually works.

Surface transfer impedance

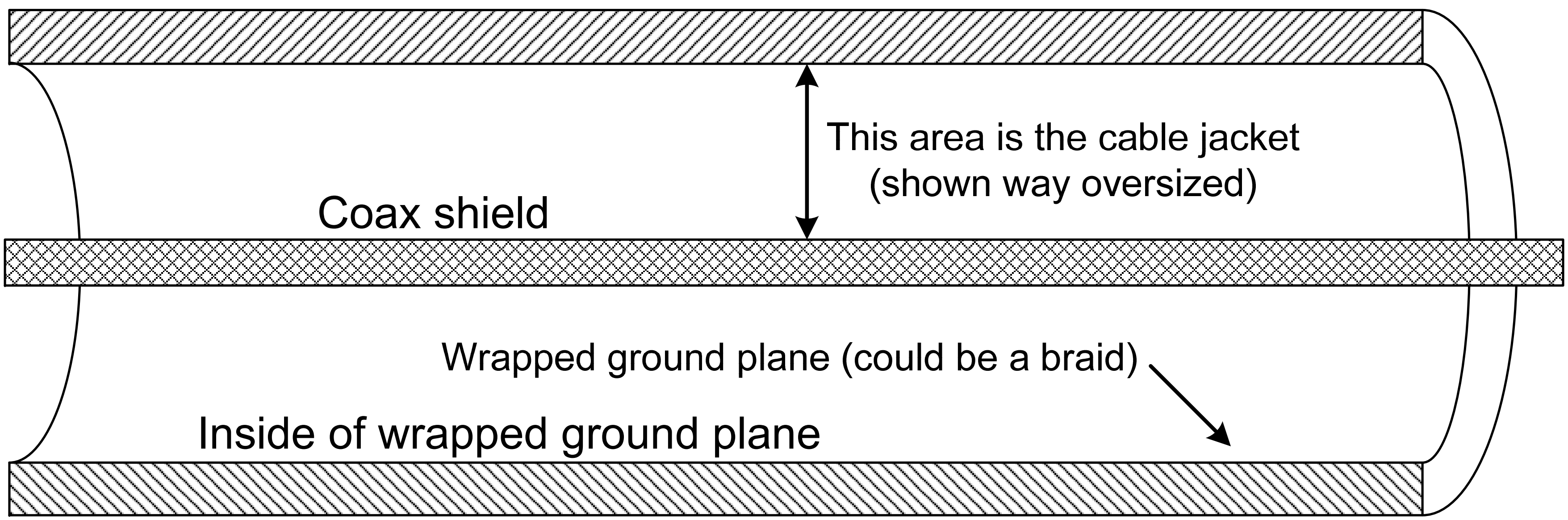
We said earlier that the cable shield and the ground plane form a transmission line. We can't say much about the general case of this, so for simplicity we'll consider a coax with a ground plane wrapped around it, as shown below. In this case the shield and the ground plane form a coax (so we have a coax within a coax, often called a triax).



The calculation route for Z_t: The basics

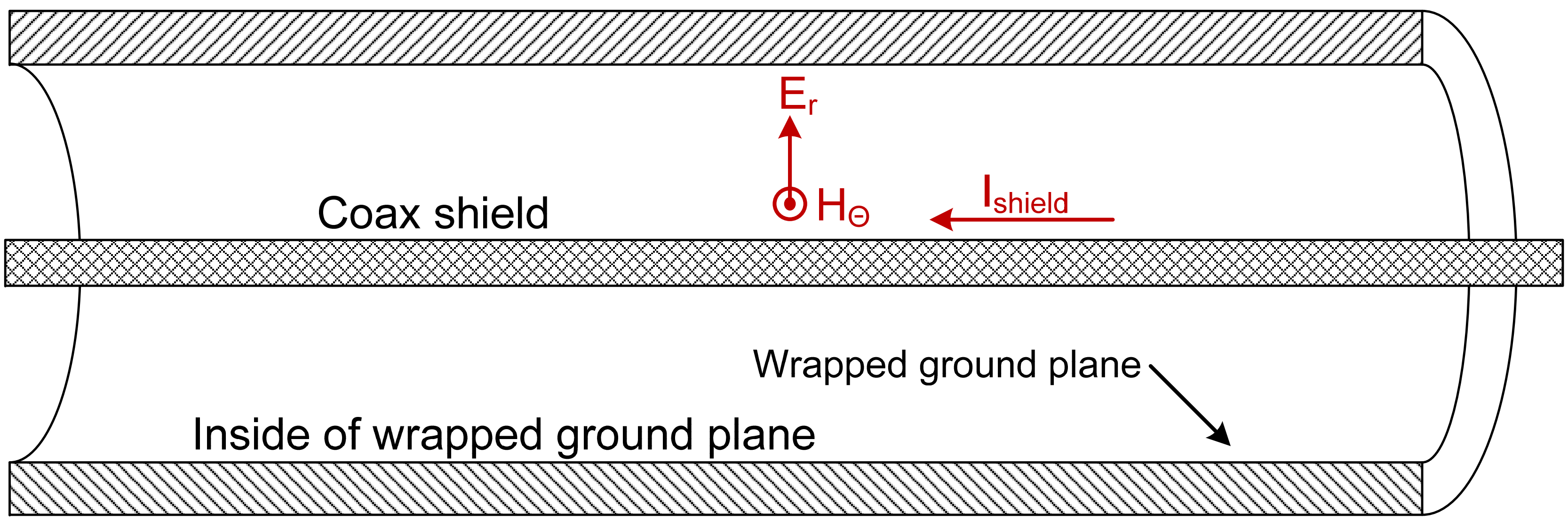
So is this realistic?

Actually yes, when measurements of Z_t are done on a jacketed shielded cable. To do a well-defined measurement you need a controlled environment. The way you do that is to form a triax by pulling a braid over the jacket as explained in [4].



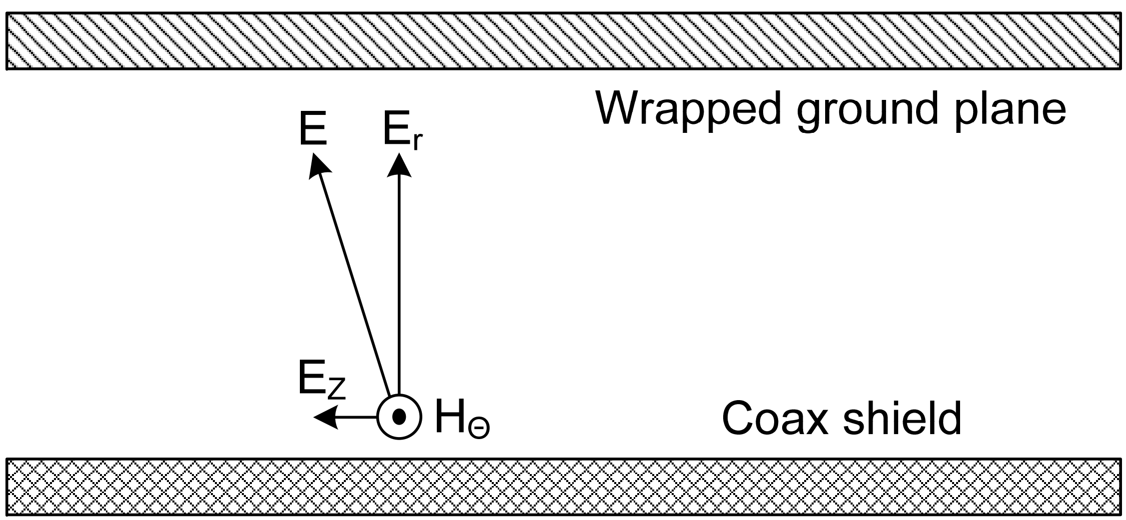
The calculation route for Z_t: The basics

Now let's suppose a current I_{shield} 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 below for the case of perfect conductors where the electric field is only radial (E_r) and the magnetic field is only circumferential (H_Θ).



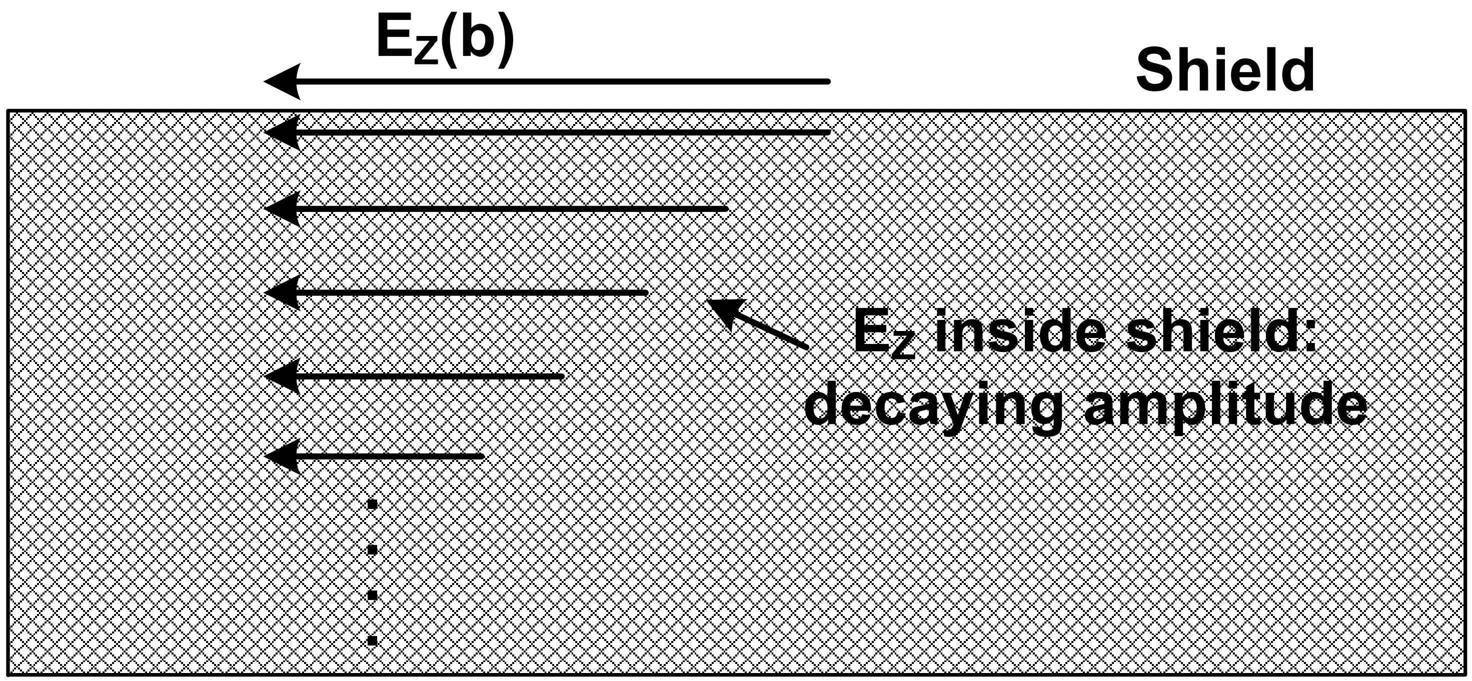
The calculation route for Z_t: The basics

The case where the E-field (E_r) is radial, and the H-field (H_Θ) is circumferential is 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 below.



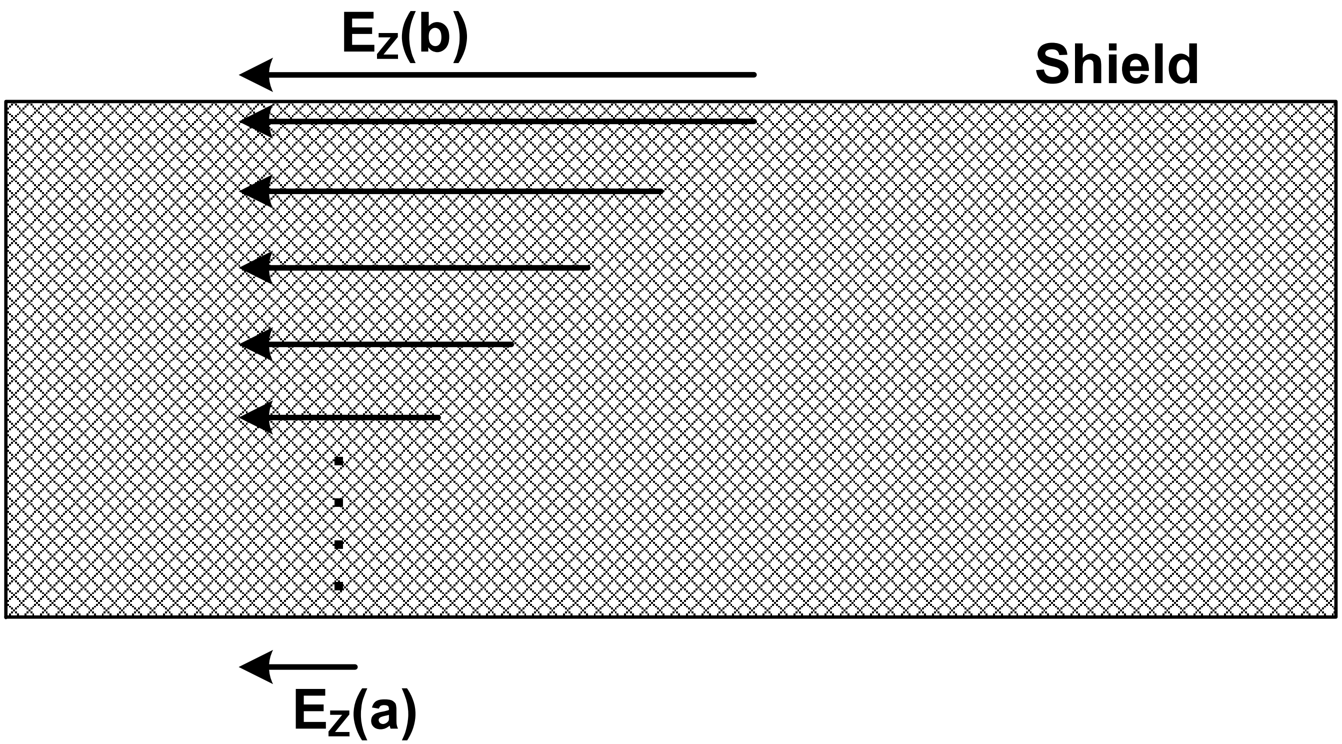
The calculation route for Z_t: The basics

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"). Let E_Z(b) be the field on the outside of the shield.



The calculation route for Z_t: The basics

The E_z field will reach some (greatly attenuated value) $E_z(a)$ on the inside of the shield:



The calculation route for Z_t: The basics

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

$$E_Z(a) = Z_{aa}I_a + Z_tI_b$$
$$E_Z(b) = Z_tI_a + Z_{bb}I_b$$

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].

The calculation route for Z_t: The basics

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:

$$E_Z(a) = \frac{Z_{aa}}{Z_t} E_Z(b) + \left[\frac{Z_t^2 - Z_{aa} Z_{bb}}{Z_t} \right] I_b$$

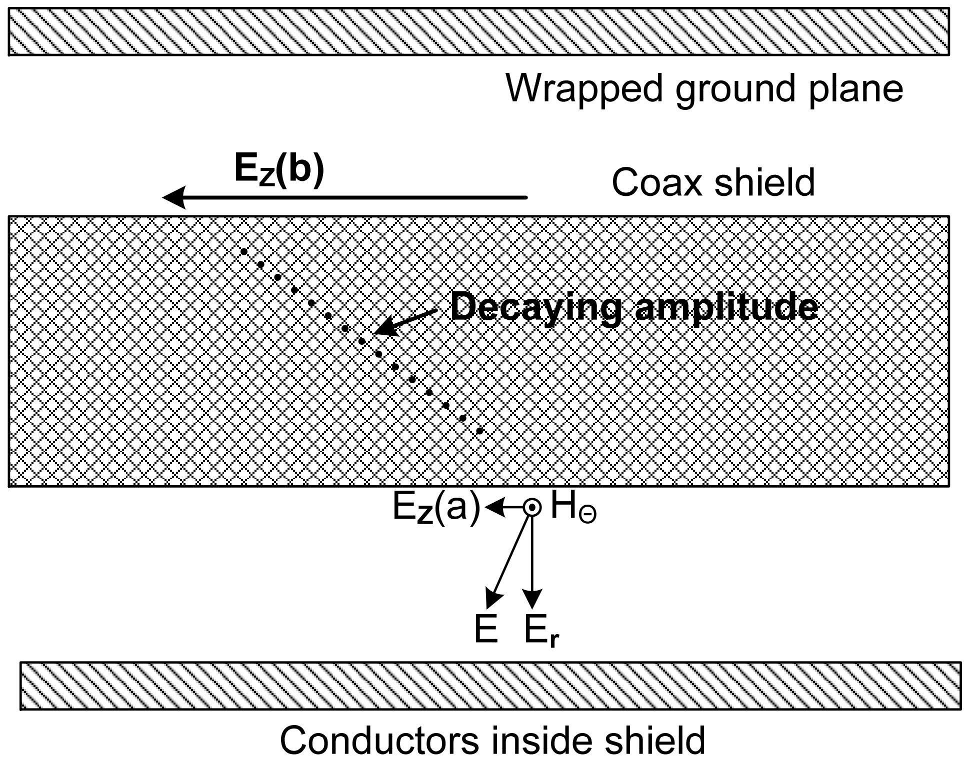
Ignoring the terms that are small

$E_Z(a) = Z_t I_b$

TE connectivity

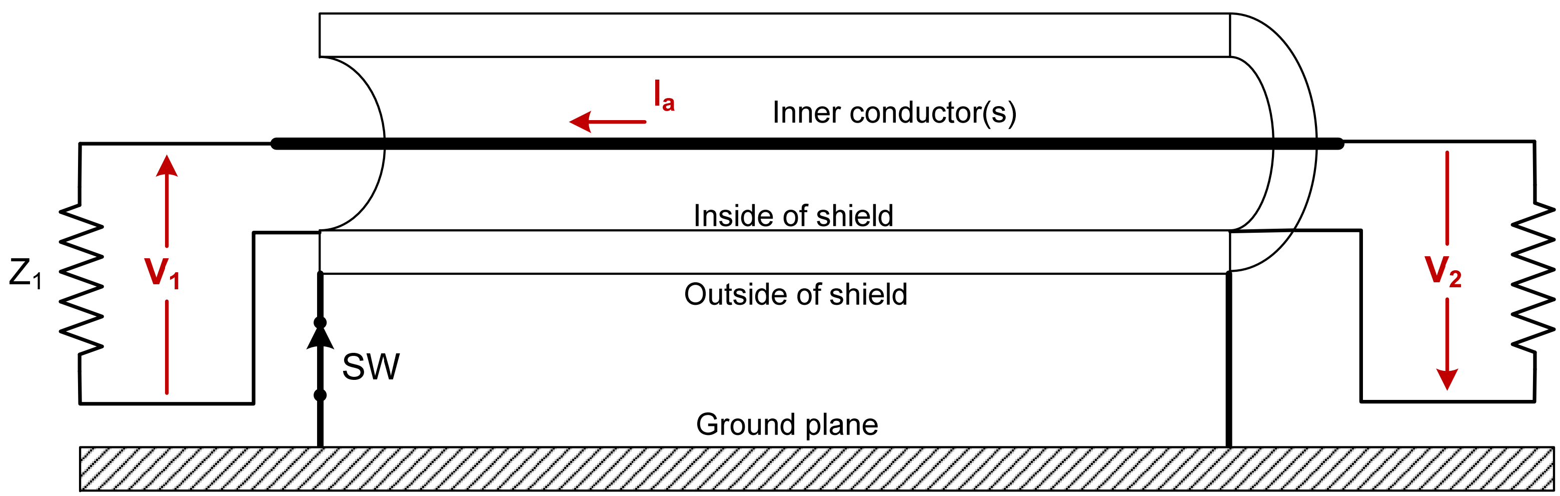
The calculation route for Z_t: The basics

Inside the shield, $E_z(a)$ drives a basically TEM wave (if the conductor resistance is small) that propagates along the conductors of the cable as illustrated below



The calculation route for Z_t: Solid shields

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, as shown in the figure below. The amplitude of the current [and hence V_1 and V_2] depends on $E_Z(a)$, which in turn depends on Z_t and I_b.



The calculation route for Z_t: Solid shields

A formula for calculating Z_t for solid shields was given by Shelkunoff as

$$Z_t = \frac{UR_{DC}}{\sqrt{\cosh U - \cos U}} \qquad (1)$$

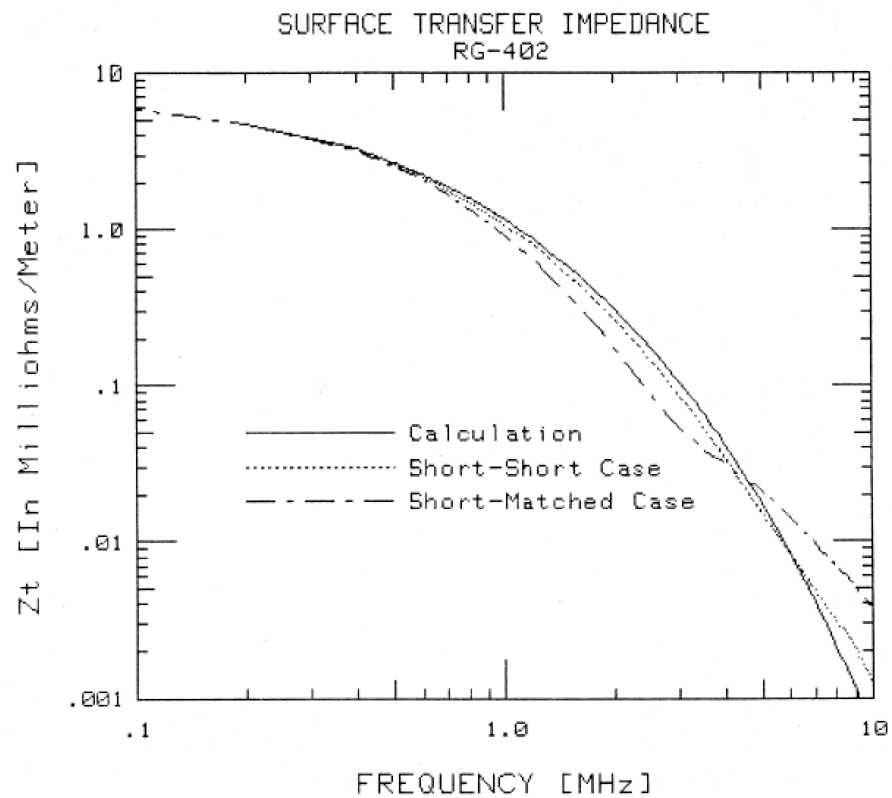
$$U = 303t\sqrt{\mu_r \sigma_r f} \qquad (2)$$

where $\boldsymbol{R_{DC}}$ is the dc resistance of the shield, ***t*** is the thickness of the shield in centimeters, μ_r is the permeability of the shield relative to air, σ_r is the conductivity of the shield relative to copper, and ***f*** is the frequency in megahertz. Notice what Z_t depends on – in particular, frequency.

TE connectivity

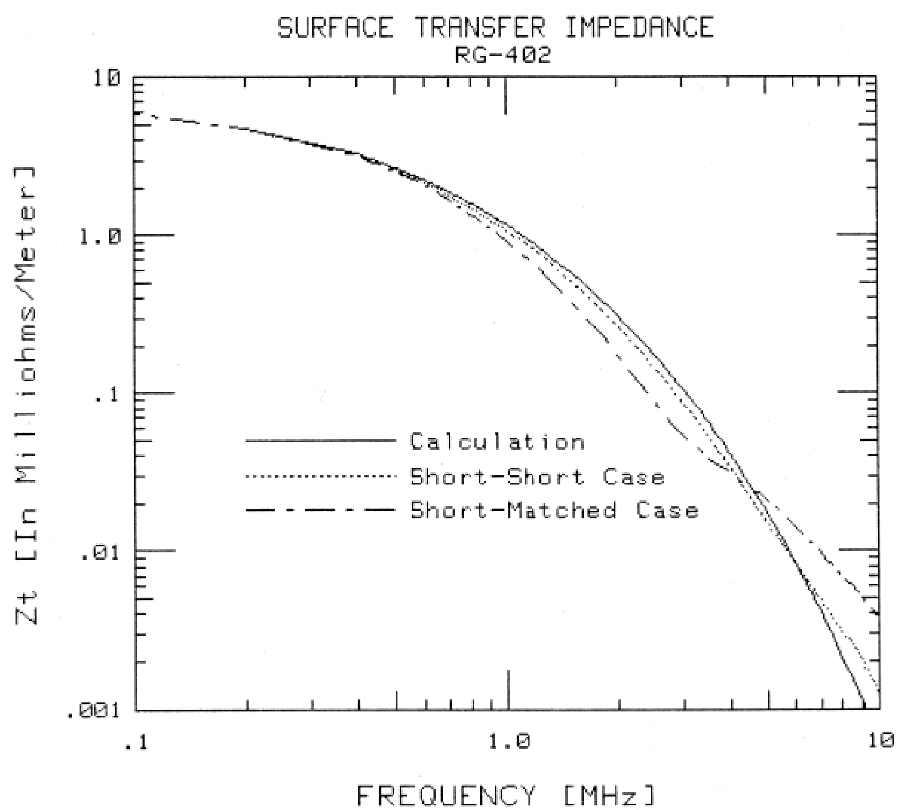
The calculation route for Z_t: Solid shields

To see whether Shelkunoff's formula for Z_t actually works, we made a measurement on RG402, a solid-shield coax [3]. The results are shown below, where the terms short-short and short-matched refer to two different methods of measuring Z_t .



The calculation route for Z_t: Solid shields

The plot on the last slide 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.



OK, but I don't have a solid shield – mine's braided or wrapped. So what about those…?

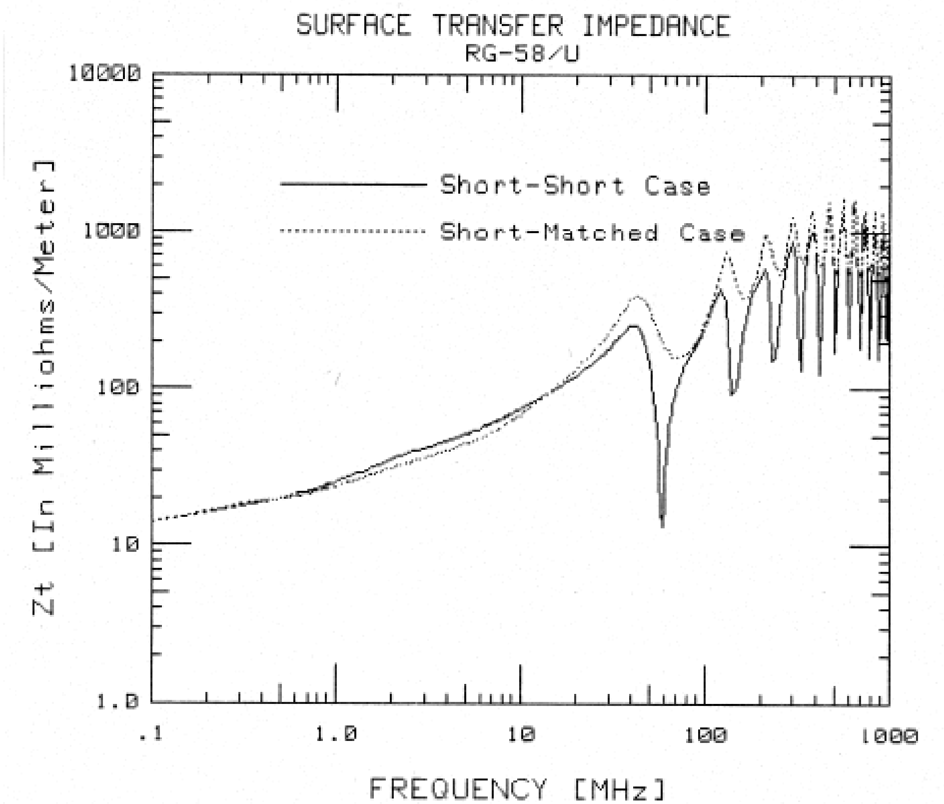
The Measurement route for Z_t: Braided/wrapped shields

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 slots because of the insulating oxide between the layers of the [typically aluminum] wrap. 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.

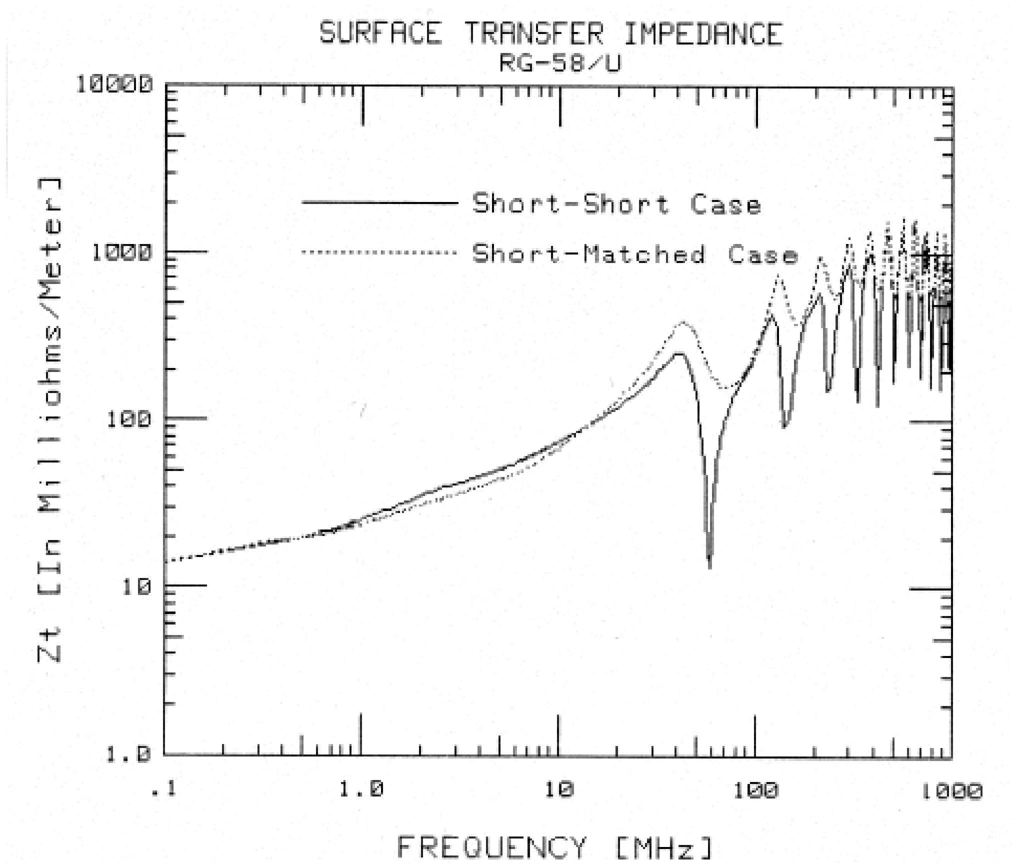
The Measurement route for Z_t: Braided/wrapped shields

Generally what is done is to produce a sample of the braided cable, and then measure its Z_t as a function of frequency. 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 below



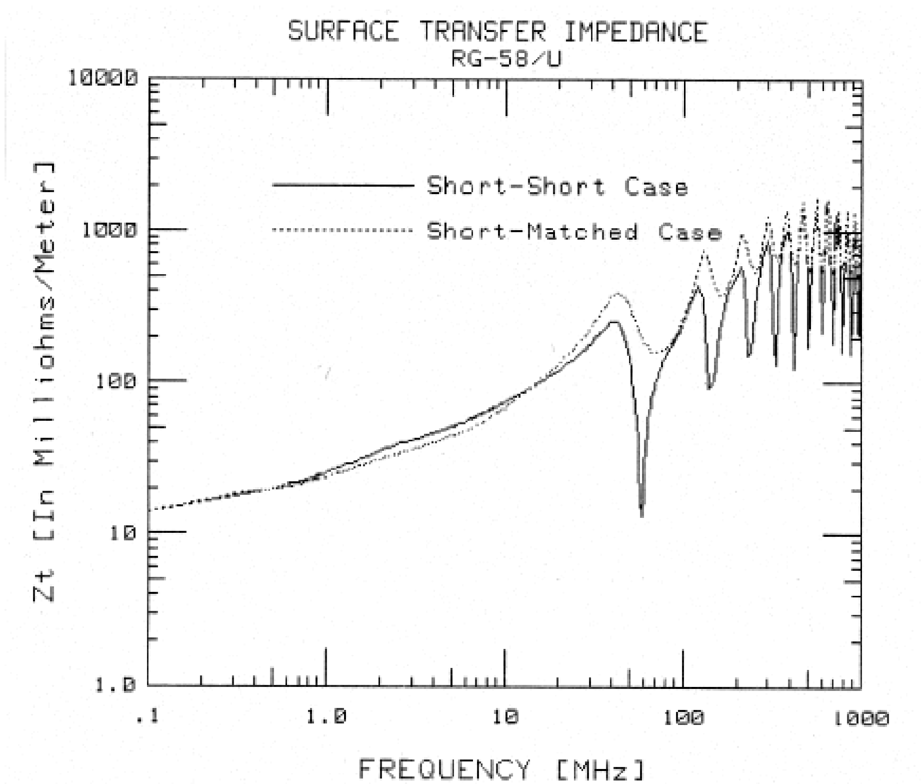
The Measurement route for Z_t: Braided/wrapped shields

Notice that in contrast to solid shields, Z_t for a braided shield increases with frequency, and eventually becomes oscillatory due to transmission-line effects. Wrapped shields in general show the same behavior as braided ones.



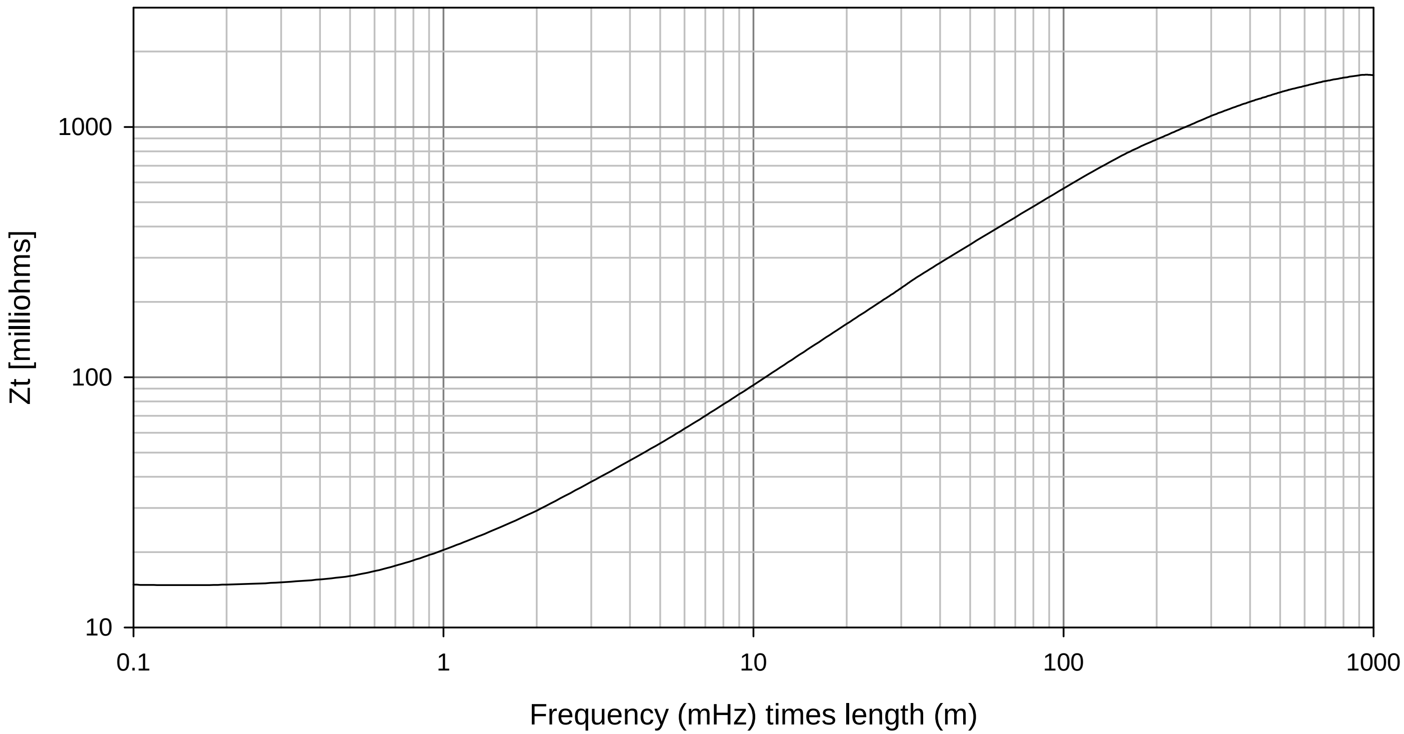
The Measurement route for Z_t: Braided/wrapped shields

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.



The Measurement route for Z_t: Braided/wrapped shields

Indeed Z_t can be plotted against the product of frequency and cable length. For example, a plot like the one below can be generated by fitting a curve to the peak values of the data plotted in the previous slide.



The Measurement route for Z_t: Braided/wrapped shields

Why all this this happens is explored further in [4] and [5], where the oscillatory behavior as a function of the length of the cable and frequency is discussed.

Very briefly, the coupling through the holes at one point on the cable generates a wave that is out of phase with a wave generated by the coupling through the holes at another point. The oscillations are caused by the constructive and destructive combination of these waves.

Summary: Cables grounded at both ends

So that's the story for cables grounded at both ends.

Essentially a shield grounded at both ends acts like a single-turn loop antenna for external fields, which cause a current to flow by induction. Currents may also be conducted from one end of the cable to the other, if the two ends are at different ground potentials.

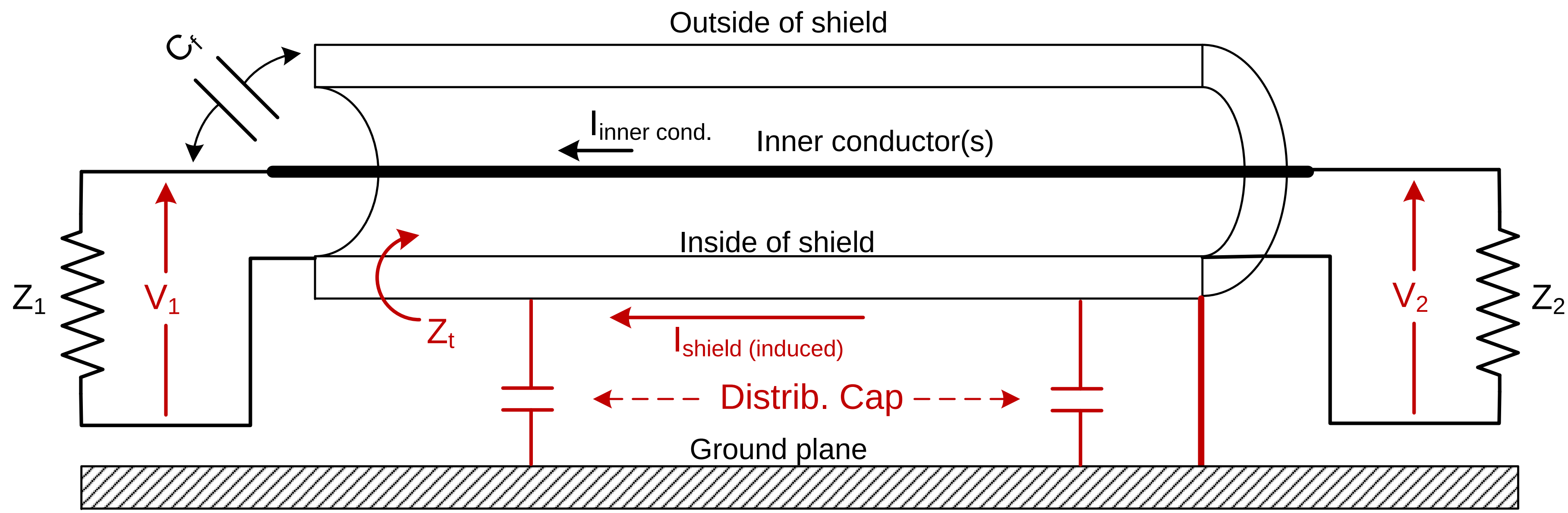
In either case the current on the outside of the cable causes voltages to appear across the loads on the inside of the cable via a coupling factor known as surface transfer impedance, Z_t

Cable grounded at one end only

What about cables grounded at only one end?

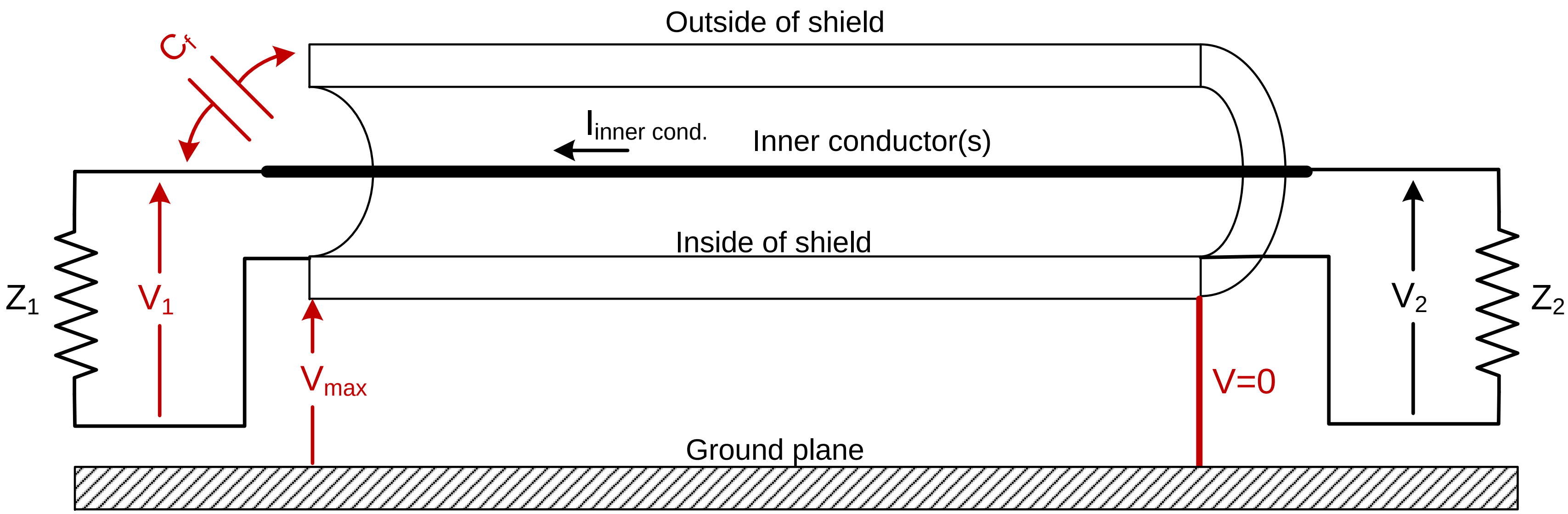
Cable grounded at one end only

In this case the ground-loop currents are eliminated. But external fields (for example from a radio transmitter) may cause current to flow through the distributed capacitance of the cable to ground. So some coupling via Z_t can occur, as was the case for shields grounded at both ends.



Cable grounded at one end only

But more importantly, there is a fringing capacitance between the unterminated end of the cable shield and its conductors. EMI can be coupled directly into the protected circuits via this fringing capacitance.



The magnitude of this capacitance depends a lot on the installation, so it can't really be calculated. As a general rule, the longer the exposed distance between the end of the shield and the point where the cable is terminated, the larger this capacitance will be.

Summary: Cables grounded at one end only

Cables whose shields are grounded at one end only can have voltages induced across the cable loads in 2 ways:

1) The shield can act like a monopole antenna, which could have a relatively high voltage at its unterminated end. This voltage causes current flow through the fringing capacitance of the cable, which in turn develops a voltage across the loads on the cable.

2) Induced currents flowing through the distributed capacitance between the cable shield and ground can develop voltages across the loads on the cable via the Zt coupling mechanism, in the same way as for cables grounded at both ends.

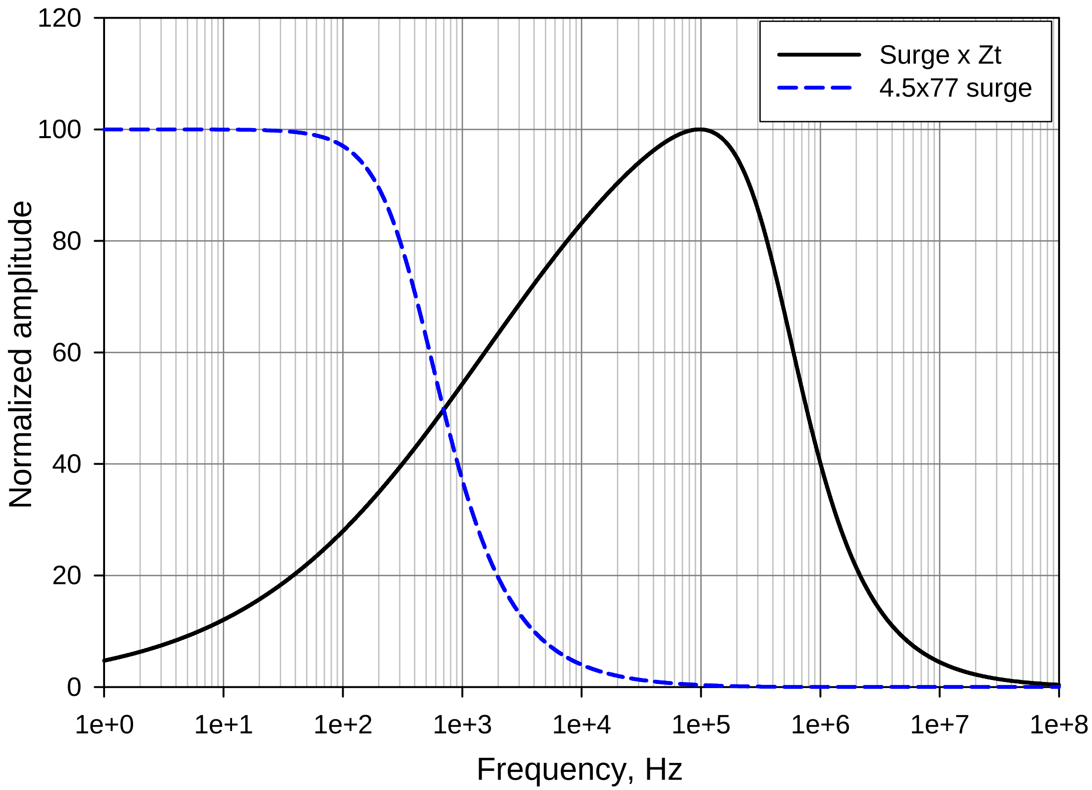
Effect of a shield on waveshape

Regardless of how the 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 the following slide.

Effect of a shield on waveshape

In the plot below the frequency spectrum of a 4.5x77 negative first lightning surge has been multiplied by the Z_t spectrum shown previously for an RG58/U coax, assuming a 10 m long cable. This plot [normalized] shows the suppression of the low-frequency components of the surge (so the coupled surge looks more like a spike).



Effect of a shield on waveshape

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.

To terminate or not to terminate

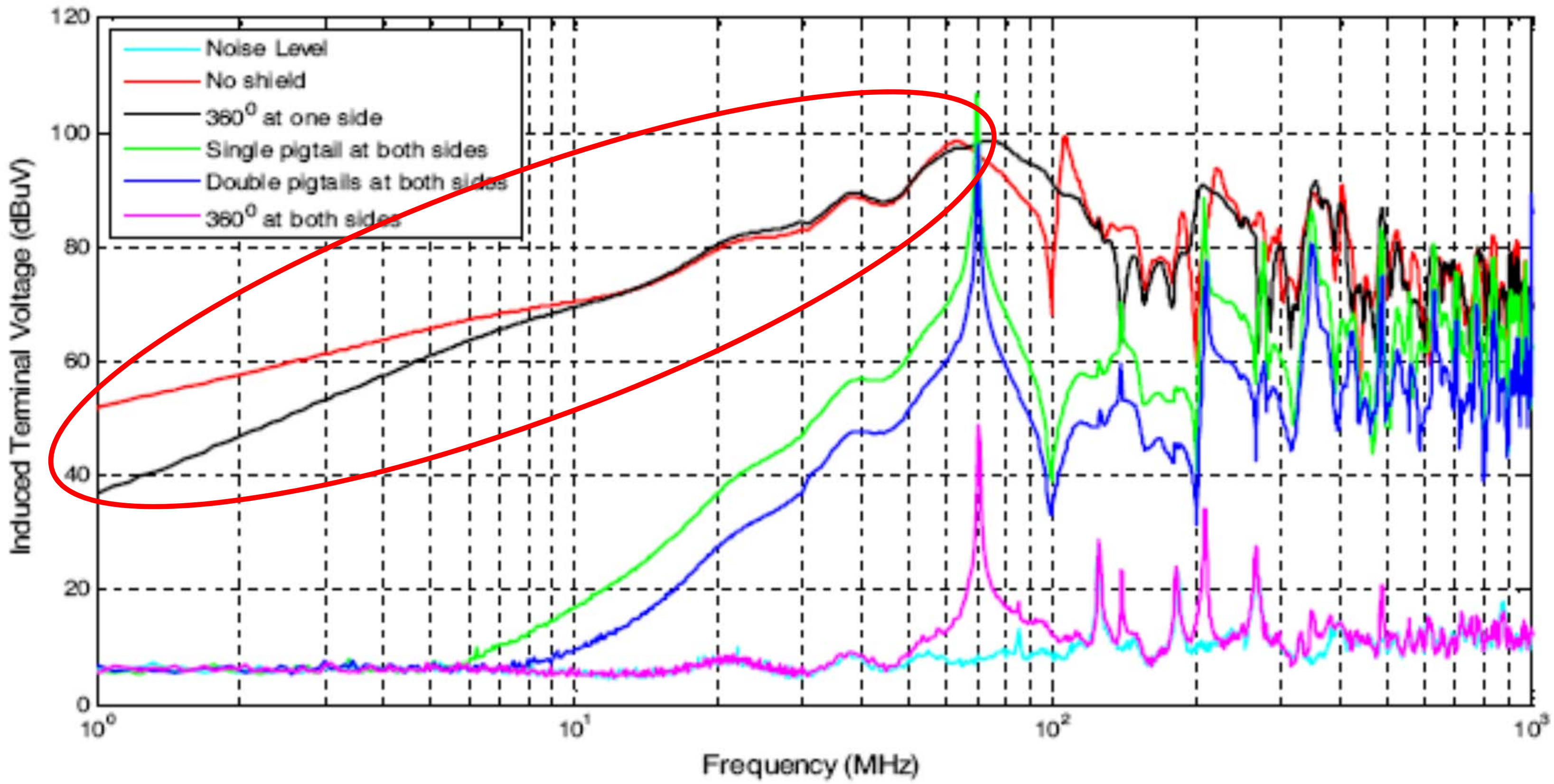
The decision to terminate or not terminate depends on the environment in which the cable is installed.

To terminate or not to terminate

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. This effect is greatest at high frequencies, where the capacitive reactance is the lowest.

To terminate or not to terminate

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 below from data in [7]:



To terminate or not to terminate

As a note, the difference between the “no shield” and the “360º at one side” plots in the previous slide 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. In some installations that may be good enough [especially if 60 Hz hum due to a ground loop is the problem].

To terminate or not to terminate

The implication of the remark that a shield bonded at one end only loses effectiveness, is that a shield should never be terminated this way.

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.

To terminate or not to terminate

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.

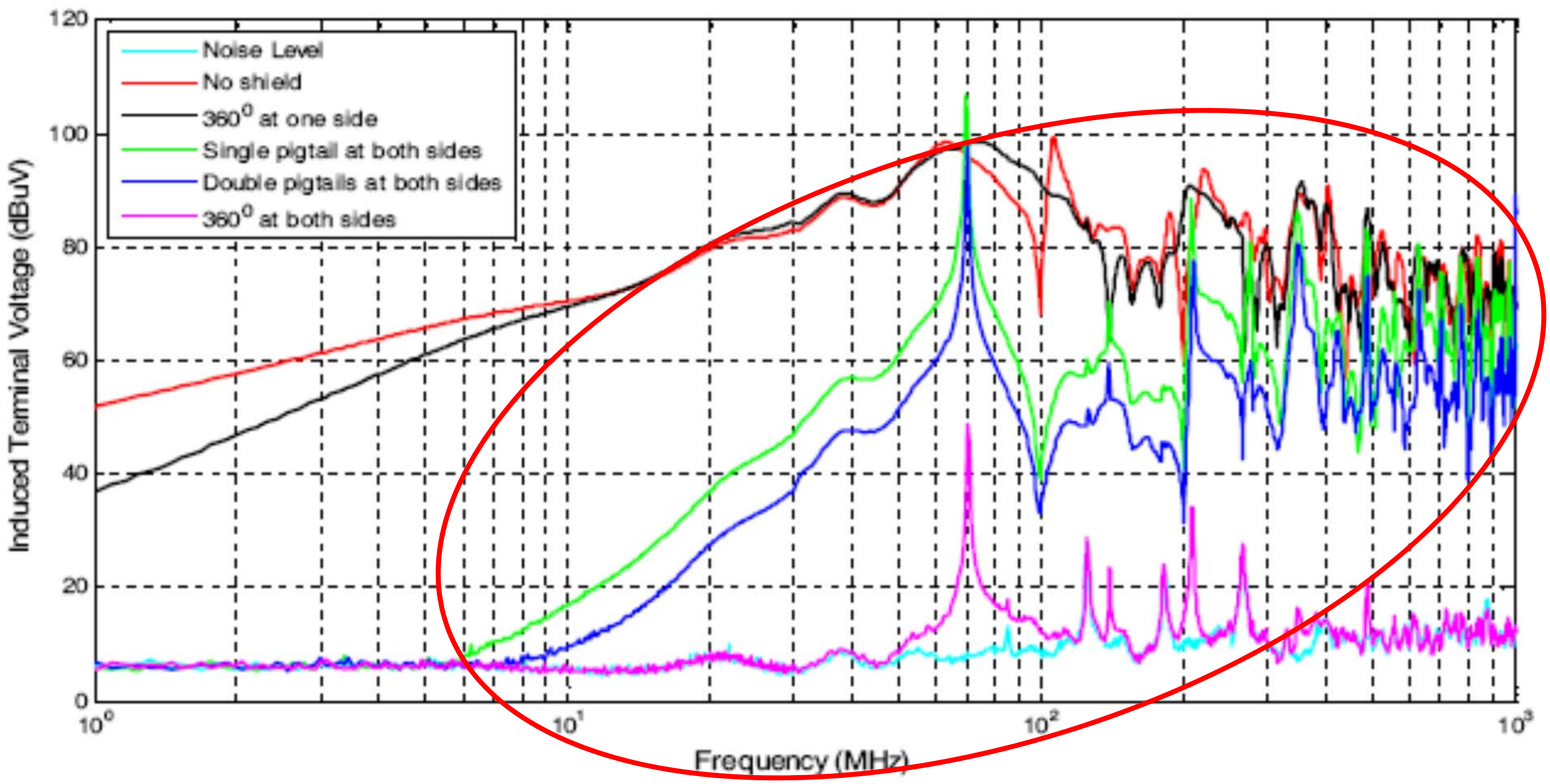
To terminate or not to terminate

As pointed out in [6], proper termination is for the shield to be bonded at each end with a 360º termination. For example, like this:

Cable braid soldered to copper foil, foil soldered to connector shell

To terminate or not to terminate

If that is not done, much of the benefit of terminating a shield at both ends may be diminished or lost; for example, the data below from [7]. Note the loss of shielding effectiveness when pigtails are used.



Conclusions

In the end the decision to terminate or not terminate depends on the application. Unfortunately there is no rule that applies to all situations. 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. When that is the case, grounding both ends of the shield is likely to give the best shielding performance.

Conclusions

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 (poor high frequency performance is the downside of terminating the shield at only one end).

Conclusions

Since it is not always clear what the shielding issues are, an experiment is often required to determine the best way to terminate the shield; as for example Nisar's presentation at the 2013 PEG [8].

References

[1] Shelkunoff, S.A., “The electromagnetic theory of coaxial transmission lines and cylindrical shields”. *Bell Syst. Tech. J.*, vol 13, pp 532-579, Oct. 1934

[2] Merewether, D.E., and T.F. Ezell, “The effect of mutual inductance and mutual capacitance on the transient response of braided-shield coaxial cables”. *IEEE Trans. On EMC.*, vol EMC-18, pp 15-20, Feb 1976

[3] Martin, A.R., and M. D. Mendenhall, “A fast, accurate and sensitive method for measuring surface transfer impedance”. *IEEE Trans. On EMC.*, vol EMC-26, pp 66-70, 1984

[4] Martin, A.R., and S.E. Emert, “Shielding effectiveness of long cables”. In *IEEE Int’l Symp on EMC, San Diego*, pp 13-18, 1979.

[5] Martin, A.R., “The shielding effectiveness of long cables, III: Maximum leakage”. In *5th Symposium and Technical Exhibition on EMC, Zurich, T. Dvorak, Ed.*, pp 379-84, 1983

[6] Waldron, Tony and Keith Armstrong, “Bonding Cable Shields at Both Ends to Reduce Noise” www.compliance-club.com/archive/old_archive/020514.htm

[7] Üstüner, F., N. Tarim, and E. Baran, ” Experimental Investigation of the Shield Termination Effect on the Field-to-Cable Coupling Level”. In *Progress In Electromagnetics Research Symposium Proceedings, KL, MALAYSIA, 2012*, pp19-22

[8] Chaudhry, Nisar, “Ground or not to ground – Ethernet protection (part 2)” *ATIS PEG Conference 2013 Presentations*. Alliance for Telecommunications Industry Solutions (ATIS) www.atis.org

And finally……

Questions?

or

Hakuna matata