# Cabling Against Inductive Coupling

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# Facts about cables



- We need cables to connect separated components of a system, to get something useful in and out of a box.
- Together with ground and other conductors cables in an installation usually form loopy networks.
- Cables may run through areas where one has no control of EMI.
- Cable lengths may be comparable to signal wavelengths which makes them efficient rx/tx antennas. They couple nicely to ambient electromagnetic fields.
- The behavior of shielded cables in the presence of magnetic fields has important practical consequences.

This talk was built around pictures taken from the book *“Electromagnetic Compatibility Engineering”* by H.W.Ott.

European XFEL

# Inductive coupling



- Throughout this talk it will be assumed that cables are much shorter than the wavelengths of interest: l < λ/10. Then the distributed mutual inductance

$$M_{12} = M_{21} = M = \frac{\Phi_{12}}{I_1}$$

of two conductors may be assumed to be localized in a transformer.

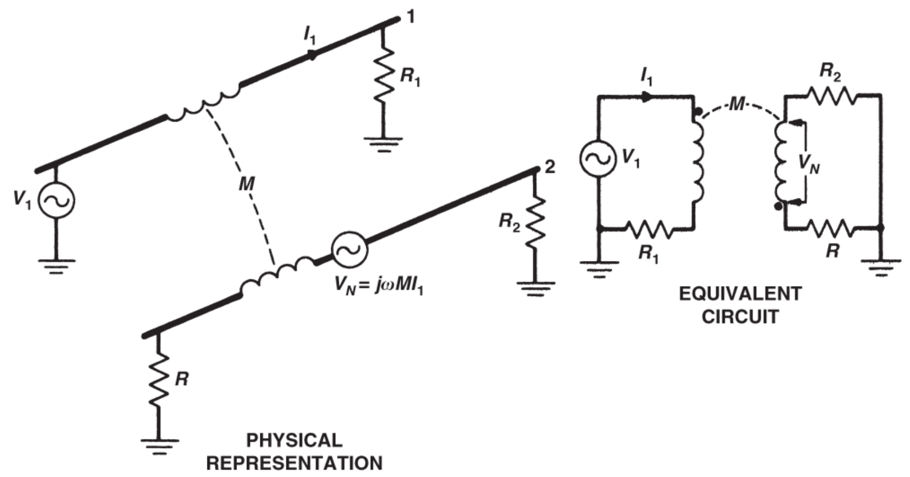
- According to the Faraday-Henry law of induction

$$\oint_L \vec{E} \cdot d\vec{l} = -\frac{d}{dt}\iint_S \vec{B} \cdot d\vec{S}$$

a noise voltage is created in the receiver circuit:

$$V_N = \frac{d\Phi}{dt} = M\frac{dI_1}{dt}$$

- For harmonic AC: $V_N = j\omega M I_1$

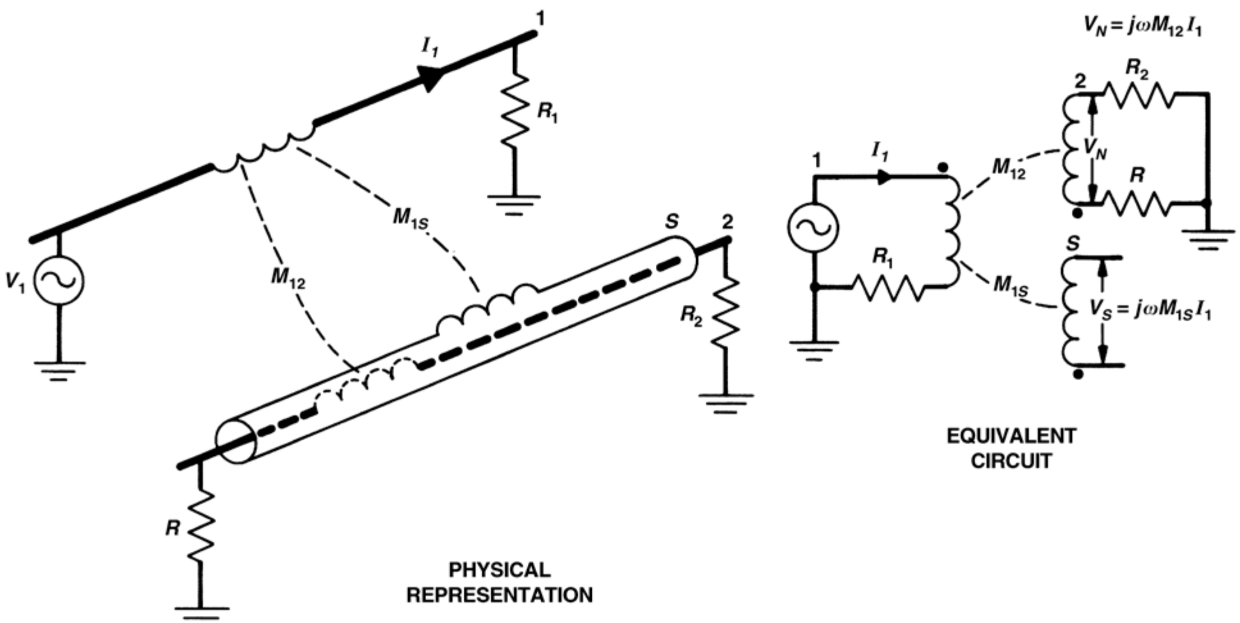



- From $V_N = j\omega BS\cos\theta$ one can see the following handles to reduce inductive coupling:
  - Reduce magnetic field B at the source or by distance.
  - Reduce receiver area S by cable twisting or routing.
  - Optimize orientation of source and receiver.
  - Reduce signal slopes $dI_1/dt$ (ω that is).

# Inductive coupling with shield



- A non-magnetic shield of the receiver represents another secondary coil of the transformer with mutual inductance $M_{1S}$ and induced voltage $V_S = j\omega M_{1S} I_1$.
- The isolated shield does not change the geometric and magnetic properties of the space between source and receiver, i.e. it does not influence $M_{12}$ and there is no change of the noise voltage $V_N$ induced in the receiver.
- The picture does not change if one end of the shield is grounded!




*A non-magnetic shield grounded at only one end does not change the magnetically induced voltage in the shielded conductor.*

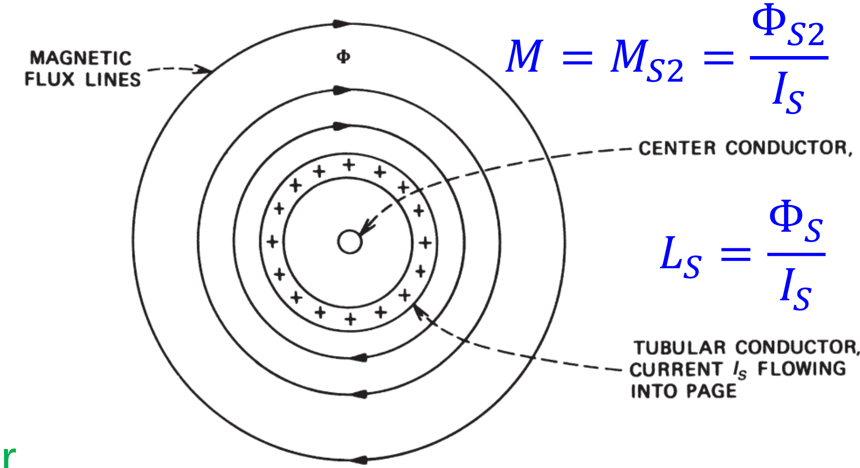
# Inductive coupling with shield grounding at both ends

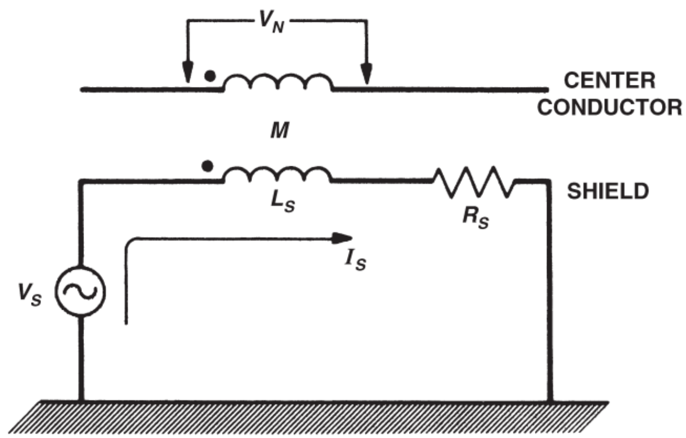
- If both ends of the shield are grounded, the induced voltage $V_S$ will drive a current through the shield which induces another voltage in the receiver.
- For a coaxial cable the mutual inductance of shield and center conductor is just the self-inductance of the shield: $M = L_S$. This is so because the shield current produces no magnetic flux inside the shield which means $\Phi_{S2} = \Phi_S$.
- Now we can evaluate the shield current and the noise voltage coupled to the center conductor: $I_S = \frac{V_S}{j\omega L_S + R_S} = \frac{V_S}{L_S}\left(\frac{1}{j\omega + R_S/L_S}\right)$

$$V_N = j\omega M I_S = \frac{j\omega M V_S}{L_S}\left(\frac{1}{j\omega + R_S/L_S}\right) = \left(\frac{j\omega}{j\omega + R_S/L_S}\right) V_S$$

$$M = M_{S2} = \frac{\Phi_{S2}}{I_S}$$

$$L_S = \frac{\Phi_S}{I_S}$$



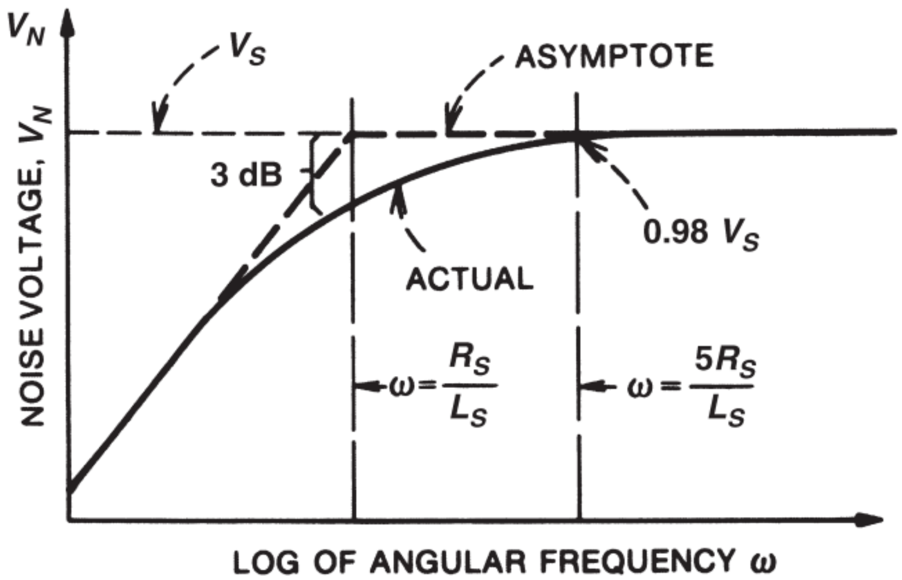
# Cutoff frequency



- The higher the frequency the better the coupling of the shield to the center conductor.
- At the cutoff frequency

$$\omega_c = \frac{R_S}{L_S}$$

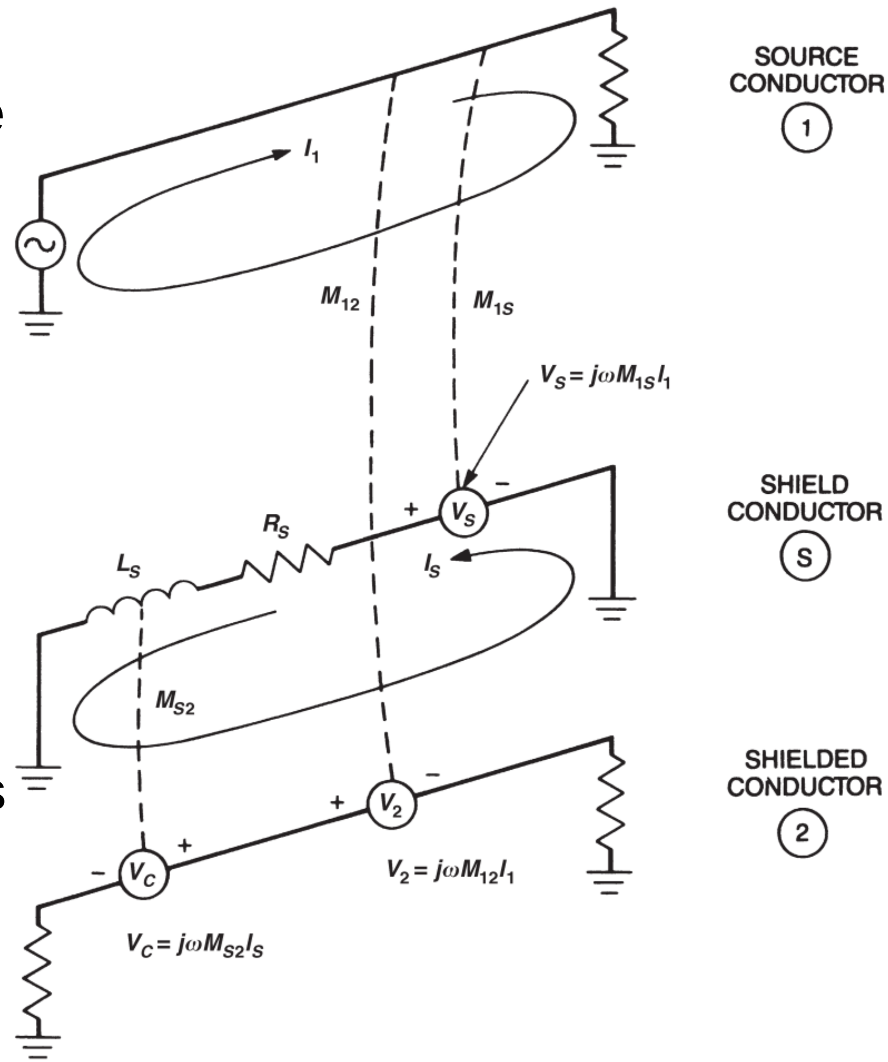
  the coupling is 70%, at $5\omega_c$ it is already 98%.
- Low quality (high $R_S$) shields have high cutoff frequencies.
- Example: For RG58C/U coaxial cable $f_c$ = 2 kHz.




Now we have all ingredients to calculate the coupling of a current-carrying bare conductor 1 to a conductor 2 with a shield grounded at both ends.

# Inductive coupling into a shielded cable

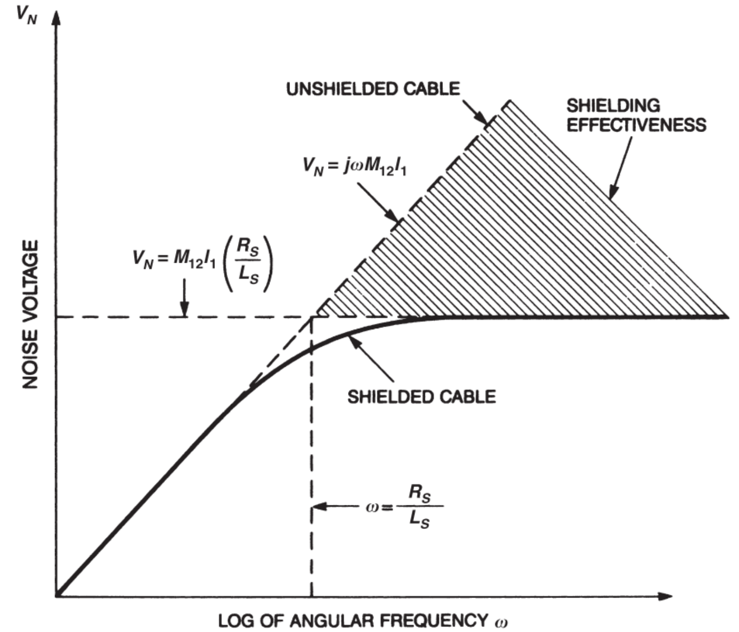
- $V_2 = j\omega M_{12} I_1,\ V_S = j\omega M_{1S} I_1$
  Since shield and center conductor are concentric, $M_{1S} = M_{12}$ and $V_S = V_2$.
- Shield current as calculated above, $I_S = \frac{V_S}{L_S}\left(\frac{1}{j\omega+\omega_c}\right)$, induces a voltage $V_c = j\omega M_{S2} I_S$ in the center conductor. Using $M_{S2} = L_S$ this yields
  $V_c = V_S\left(\frac{j\omega}{j\omega+\omega_c}\right)$.
- Because of the additional induction step the signs of $V_c$ and $V_2$ are different, and the total noise voltage is
  $V_N = V_2 - V_c = j\omega M_{12} I_1\left(1 - \frac{j\omega}{j\omega+\omega_c}\right) =$
  $j\omega M_{12} I_1\left(\frac{\omega_c}{j\omega+\omega_c}\right)$



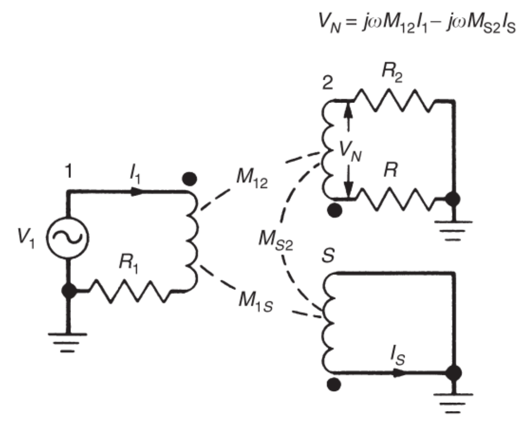
# Inductive coupling into shielded cable vs. f



- Below the cutoff frequency $\omega_c$ shielded and unshielded cable behave similarly, i.e. the shield is hardly effective. This is due to its weak coupling to the center conductor.
- Above $\omega_c$ the noise voltage approaches a constant value $V_N = \omega_c M_{12} I_1$. Compared to the linearly rising unshielded case this means a shielding effectiveness that rises with frequency.

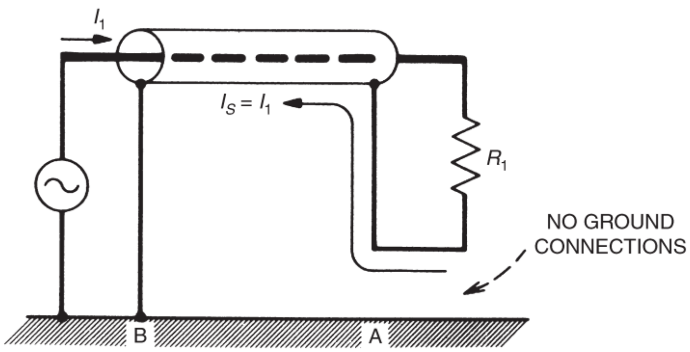



- $R_S$ includes all elements in the shield circuit: shield material, ground impedance, connections,… All of these must be kept small for good shielding.
- In the transformer model a shield grounded at both ends is represented by a certain number of shorted windings on the secondary side.

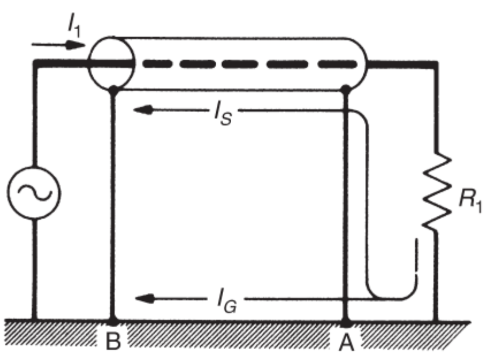


# Shielding for suppression of emission

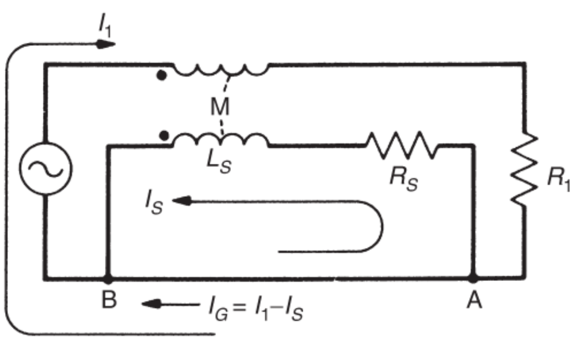
- If a load is not grounded, all the inner conductor current is sent back through the shield, the outside magnetic fields cancel, and there will be no emission from the setup, independent of f. *Large scale setups of this kind are mostly forbidden for safety reasons.*




- What is the return current path for a shield grounded at both ends? The shield mesh equation $I_S(j\omega L_S + R_S) - I_1(j\omega M) = 0$ and $M = L_S$ yield $I_S = I_1\left(\frac{j\omega L_S}{j\omega L_S + R_S}\right) = I_1\left(\frac{j\omega}{j\omega + \omega_c}\right)$, i.e. $I_S \to I_1$ for $\omega \gg \omega_c$.
- The current return path is frequency dependent: Lower $R_S$ return through ground at low f, lower $L_S$ return through shield at high f.



PHYSICAL REPRESENTATION

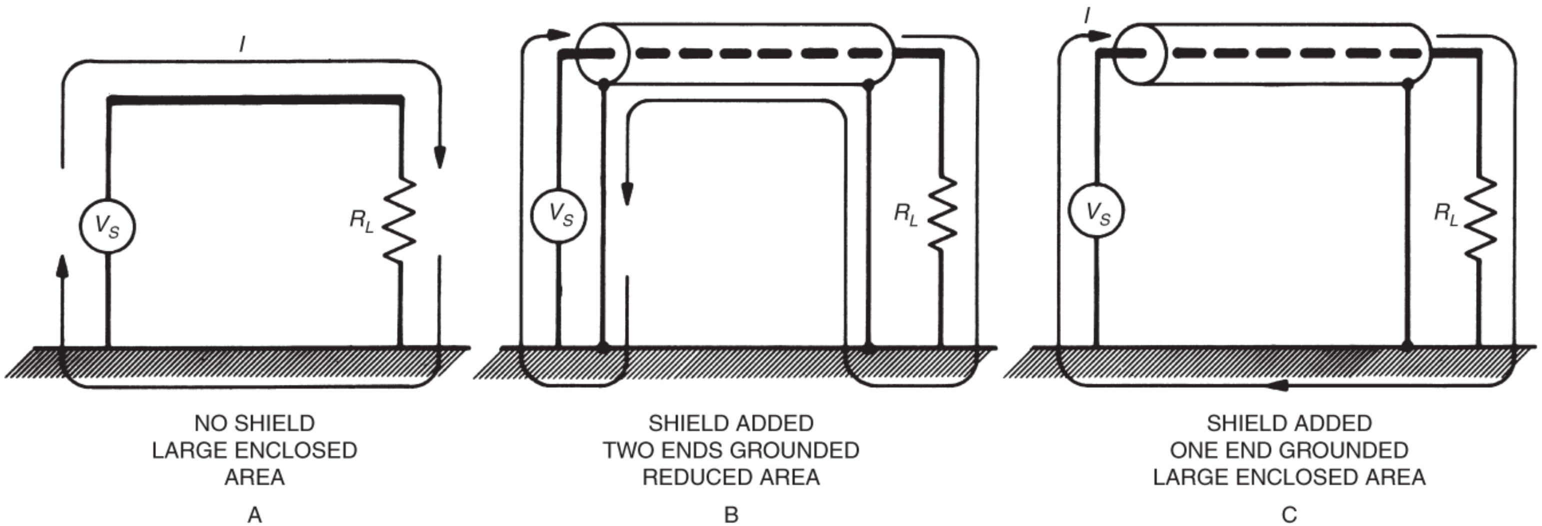


EQUIVALENT CIRCUIT

# Receiver protection against magnetic fields



- The best way to protect against ambient magnetic fields at a receiver is to reduce the area of the circuit.

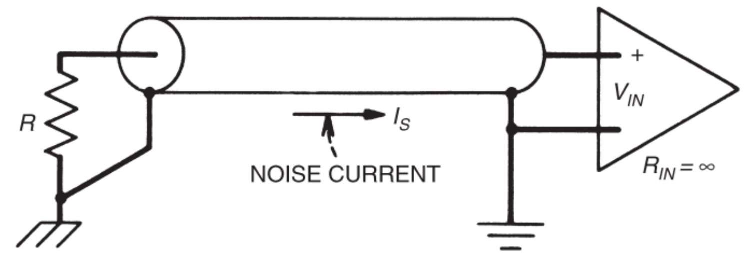



- To know the circuit means to know where the current is flowing, especially the return current. The current path may not be the planned one and may not be the same under all circumstances (e.g. f dependence).
- In complex systems it might be cumbersome to find out. Measurements usually help ☺

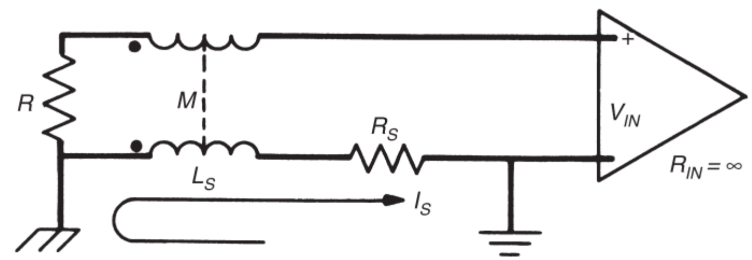
# Disadvantage of grounding both shield ends



- A shield grounded at both ends may pick up noise current $I_S$ from two sources:
  - Induced currents in the shield-ground loop.
  - Potential difference between the grounding points.
- The mesh equation for the otherwise dead input circuit is
  $$V_{IN} = -j\omega M I_S + j\omega L_S I_S + R_S I_S$$
  Using $M = L_S$ this yields the noise input voltage $V_{IN} = R_S I_S$.




PHYSICAL REPRESENTATION



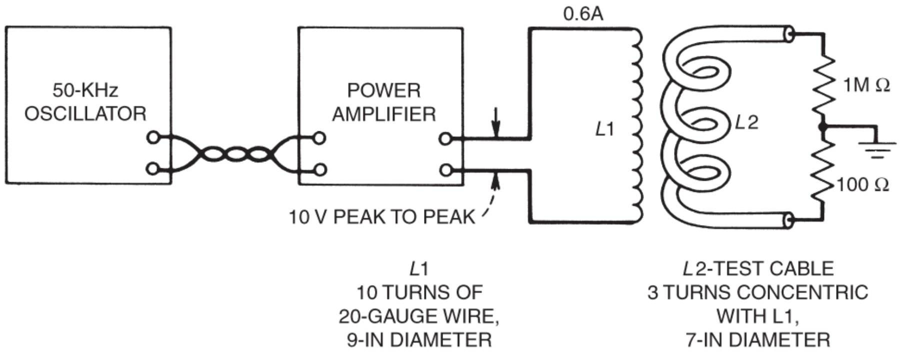

EQUIVALENT CIRCUIT

- This is a case of common impedance coupling, because the shield must serve two purposes: Signal current return and noise current conductor.
- Separating these functions leads to three-conductor solutions like shielded twisted-pair cables. At high frequencies the skin effect makes a normal coaxial cable have three conductors: Signal current on the center conductor, signal return on the inside, noise conduction on the outside shield surface.

# Cable test setup



- Ott has used a simple setup to test the shielding effectiveness of several cable connections. The 50 kHz measurement frequency is far beyond cutoff for all cables.

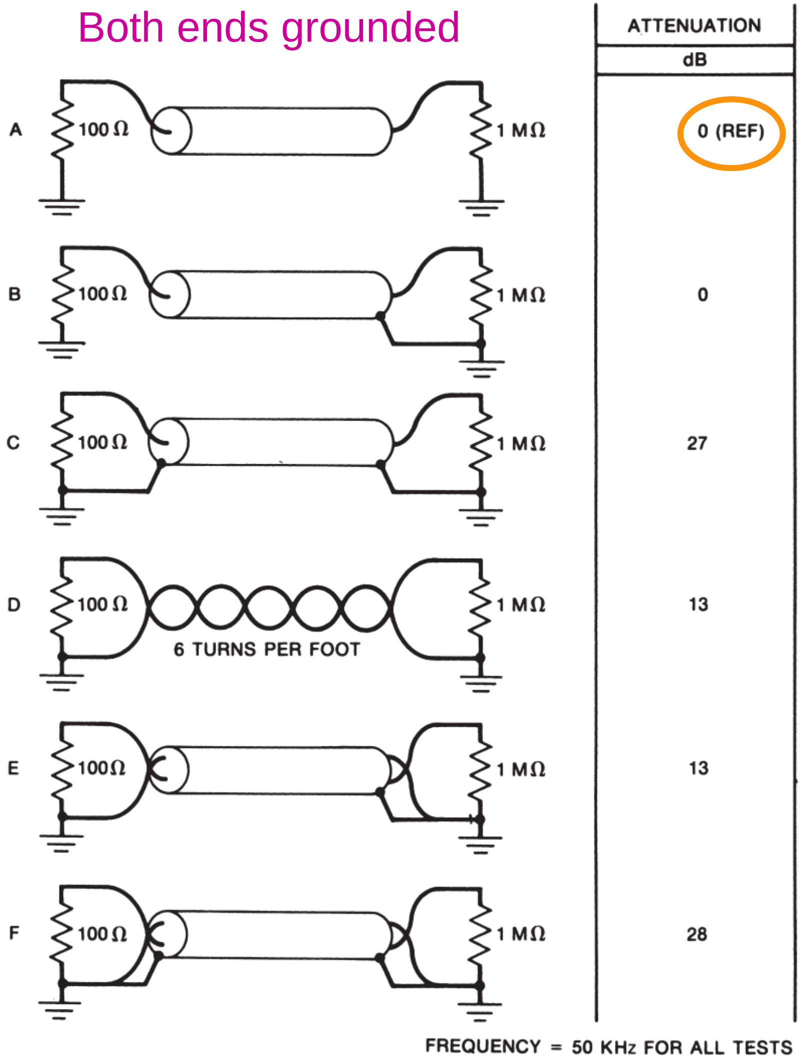



- The results can be summarized as follows:
  - Circuits grounded at both ends (A to F) perform always worse than those with an ungrounded load (G to K). This is due to noise coupled into the ground loop.
  - Shield grounding at one end only (B and E) has no effect.
  - Twisted-pair cables may suffer from ground loop noise which can be shunted away with a shield (D and F).

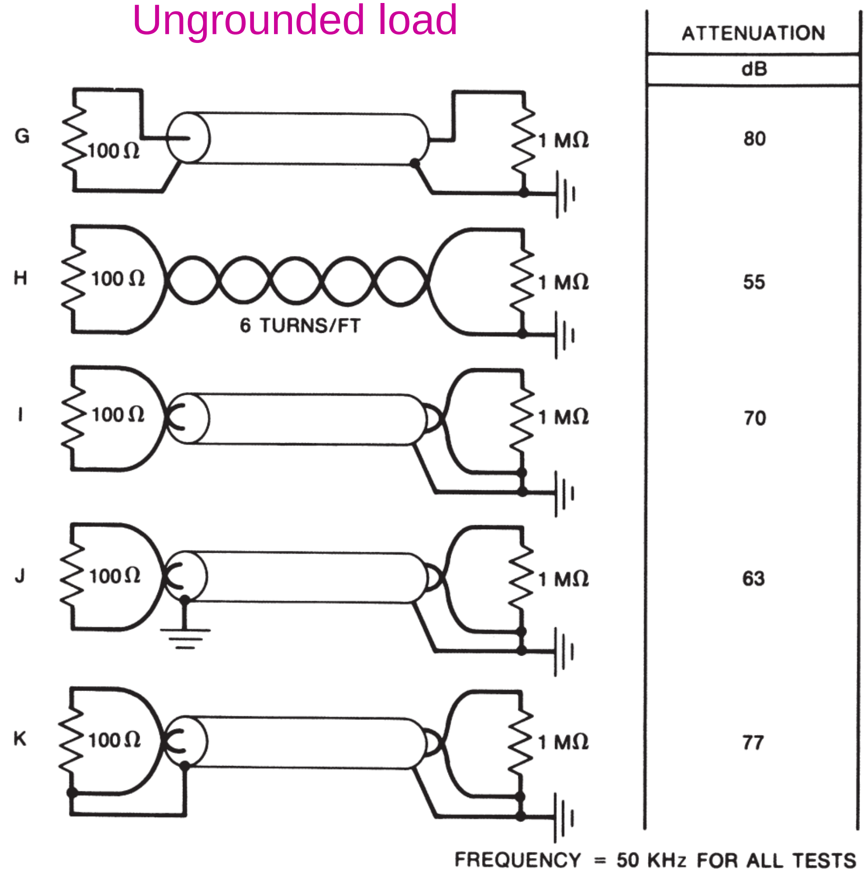
# Cable test results



## Both ends grounded




## Ungrounded load




(from Ott, Chapter 2.9)

# Lessons learnt



- Shielding against magnetic fields needs shield current to flow. In most cases this means grounding the shield at both ends.
- Shielding against magnetic fields works best at high frequencies, well beyond the cutoff frequency $\omega_c = R_S/L_S$.
- At low frequencies the noise pick up in the shield ground loop may be a problem. 3-conductor cables may help here.
- Inductive coupling is fought most efficiently by clever cable placement.
- Minimize the receiver circuit loop area! But what is the receiver circuit?
- Try to understand the current flow in the system! Measuring helps a lot.