TEM Cell Testing of Cable Noise Reduction Techniques from 2 MHz to 200 MHz – Part 2

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Abstract— **This paper presents empirical results of cable noise reduction techniques as demonstrated in a TEM cell operating with radiated fields from 2 - 200 MHz. It is the second part of a two-paper series. The first paper discussed cable types and shield connections. In this second paper, the effects of load and source resistances and chassis connections are examined. For each topic, well established theories are compared to data from a real-world physical system. Finally, recommendations for minimizing cable susceptibility (and thus cable emissions) are presented.**

I. Introduction

There are numerous papers and textbooks that present theoretical analyses of cable noise reduction techniques. However, empirical data is often targeted to low frequencies (e.g. <50 KHz) or high frequencies (>100 MHz). Additionally, a comprehensive study showing the relative effects of various noise reduction techniques is needed. These include the use of dedicated return wires, twisted wiring, cable shielding, shield connections, changing load or source impedances, and implementing load- or source-to-chassis isolation.

We have created an experimental setup that emulates a real-world electrical system, while still allowing us to independently vary a host of parameters. The goal of the experiment was to determine the relative effectiveness of various noise reduction techniques when the cable is in the presence of radiated emissions from 2 MHz to 200 MHz.

II. Experiment Setup

The reader is referred to the experimental setup as described in the first part of this paper series, *TEM Cell Testing of Cable Noise Reduction Techniques from 2 MHz to 200 MHz – Part 1* (1).

III. Load / Source Resistances

For electrically short lines, it has been shown that the simplified inductive-capacitive model shown in Fig. 1 can be used to predict crosstalk-coupled noise (2,4).

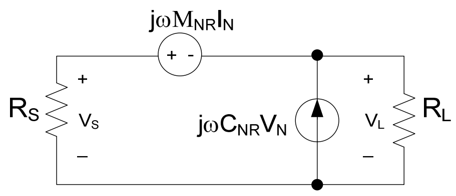

Fig. 1 Simplified inductive-capacitive coupling crosstalk model

From the model it can be seen that the induced load and source noise can be approximated by (2,4)

$$V_S = \frac{R_S}{R_S + R_L} j\omega M_{NR} I_N + \frac{R_S R_L}{R_S + R_L} j\omega C_{NR} V_N$$

$$V_L = -\frac{R_L}{R_S + R_L} j\omega M_{NR} I_N + \frac{R_S R_L}{R_S + R_L} j\omega C_{NR} V_N$$

where R_S, R_L are the source and load resistances, M_{NR}, C_{NR} are the inductance and capacitance between the noise generation and receiving circuits, and I_N, V_N are the current and voltage in the noise generation circuit.

It can also be shown that inductive coupling will dominate the load voltage if

$$\frac{M_{NR}}{C_{NR}} > R_S R_{GL}$$

where R_{GL} is the load resistance of the noise generator circuit. Similarly, capacitive coupling will dominate if the inequality is reversed. From this, we can infer that for small/large source resistances the circuit will tend to be dominated by inductive/capacitive coupling respectively.

An interesting result comes from evaluating the load voltage expression for combinations of very large (*Max*) or very small (*Min*) load/source values, where for simplicity we've kept all *Min* values equal, and all *Max* values equal. Simplifying gives the following expressions.

$$V_{L(Min,Min)} \cong -\frac{1}{2} j\omega M_{NR} I_N$$

$$V_{L(Min,Max)} \cong -1 j\omega M_{NR} I_N$$

$$V_{L(Max,Min)} \cong R_{Min} j\omega C_{NR} V_N$$

$$V_{L(Max,Max)} \cong \frac{R_{Max}}{2} j\omega C_{NR} V_N$$

From these expressions, we can reasonably predict that the worst induced noise would likely occur in the case of inductive noise coupling when the source resistance was minimum and the load resistance was maximum (*Min,Max*), and in the case of capacitive noise coupling when the source and load resistances were both maximum (*Max,Max*).

Data from our experiment is given as Table I. Measurements were made in dBm and converted to V_{RMS}. As predicted, the worst case noise voltage levels were seen for the *Min,Max* and *Max,Max* configurations. The smallest noise was measured for the *Max,Min* case – also in agreement with the original equations. Results suggest that with all things being equal, load circuits that have higher input resistance would correspondingly suffer higher induced EMI noise voltage.

TABLE I
LOAD NOISE VOLTAGE FOR VARIOUS SOURCE/LOAD RESISTANCE

Frequency (MHz)	**Min,Min (VRMS)**	**Min,Max (VRMS)**	**Max,Min (VRMS)**	**Max,Max (VRMS)**
2 MHz	1.4E-5	3.1E-5	6.0E-6	2.5E-5
5 MHz	1.4E-4	2.6E-4	7.6E-5	1.3E-4
10 MHz	5.2E-4	7.4E-4	4.3E-4	5.0E-4
20 MHz	3.5E-3	4.0E-3	3.2E-3	3.2E-3
50 MHz	1.4E-1	1.6E-1	1.9E-1	2.0E-1
100 MHz	1.0E-2	1.3E-2	1.3E-2	1.7E-2
150 MHz	1.1E-2	1.1E-2	1.2E-2	1.2E-2
200 MHz	1.5E-2	1.6E-2	1.5E-2	1.6E-2

IV. CHASSIS CONNECTIONS

It has been demonstrated previously that significant noise reduction can be achieved through single-reference ground strategies (3-8). Reductions are a result of eliminating “ground loops” – noise introduced by ground differences, and by establishing smaller current loop areas – thus reducing electromagnetic susceptibility. However, there remains some question as to the effectiveness of such strategies when applied to high-frequency systems. Parasitic capacitance and inductance allow for high-frequency signals to return on uncontrolled paths. Furthermore, as wire lengths begin to approach the interference signal wavelength, standing wave patterns can degrade any potential improvement.

To examine the effects of single-point grounding for higher frequencies, we compared the load noise for three configurations as shown in Fig. 2.

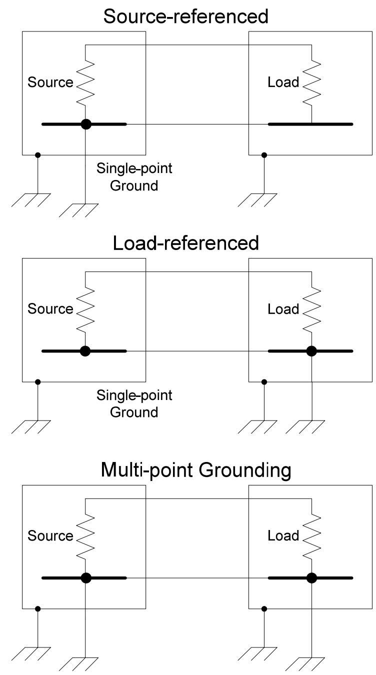

Fig. 2 Single- and multi-point grounding connections (R_S=100 Ω, R_L=1 MΩ)

The load noise measured across frequency is given in Fig. 3. The sinusoidal pattern is due to the standing wave patterns for the cable.

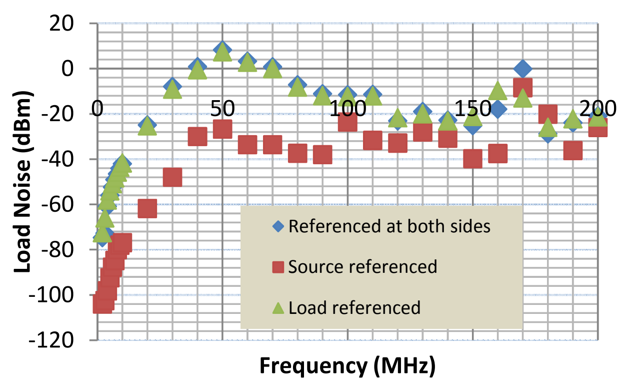

Fig. 3 Load noise for source, load, or grounds referenced to both sides

Table II presents the single-reference and multi-reference data for this simple system. The noise levels are normalized to the multi-point ground (MPG) case. This is done to demonstrate the effect of establishing a single-point ground (SPG) connection without allowing other frequency-dependent factors to obfuscate the findings (e.g. parasitic coupling, wavelength). The source-referenced (a.k.a. balanced load) connection offers significantly reduced load noise (30-35dB). At much lower frequencies (50 kHz), the benefits have been shown to be up to 60 dB (3,4). It is worth noting that the load-referenced case offered little if any improvement over the multi-point ground case. This result is thought to be due to our measuring the load noise referenced to the noisy chassis.

TABLE II
NOISE FOR SINGLE- AND MULTI-POINT CONNECTIONS

Frequency (MHz)	**Tied at both ends (dB)**	**Source referenced (dB)**	**Load referenced (dB)**
2 MHz	0	-29.3	+2.2
5 MHz	0	-36.4	+2.0
10 MHz	0	-34.9	+0.3
20 MHz	0	-36.9	-0.4
50 MHz	0	-35.0	-0.9
100 MHz	0	-12.1	-0.9
150 MHz	0	-14.6	+4.1
200 MHz	0	-5.0	-0.3

TABLE III
LOAD NOISE FOR LOAD BLEED RESISTOR CONNECTIONS

Frequency (MHz)	**Tied at both ends (dB)**	**Bleed R=1KΩ (dB)**	**Bleed R=10KΩ (dB)**	**Bleed R=100KΩ (dB)**
2 MHz	0	-0.4	-19.6	-22.9
5 MHz	0	-0.9	-26.1	-38.1
10 MHz	0	-1.4	-30.6	-36.5
20 MHz	0	-4.4	-34	-36.3
50 MHz	0	-13.1	-33.8	-34.8
100 MHz	0	-5.2	-11.5	-11.6
150 MHz	0	-2.2	-14.6	-13.8
200 MHz	0	-3.8	-5.1	-4.6

A. Bleed Resistors

In many cases, subsystems are tied to chassis at a remote location through bleed resistors – resistors that are large enough that they have little electrical effect on the circuit, but permit stray charge to discharge to ground (see Fig. 4).

We sought to examine the effects of bleed resistors on noise susceptibility. Logically, one might conclude that a bleed resistor of any appreciable value would act in a way that is similar to floating the ground from the chassis (single-point referencing). Likewise when using a very small bleed resistor, the noise level is expected to approach that of referencing the system to ground at both ends. In fact, this is exactly what we found.

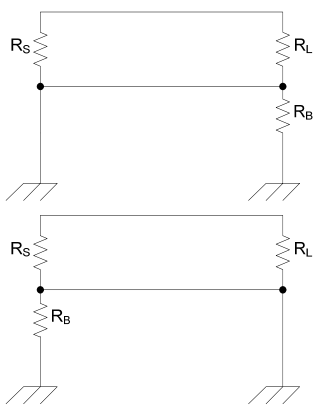

Fig. 4 Bleed resistors at load or source end

Table III presents the effects of using varying load bleed resistors, with the source end tied directly to chassis. Similar results can be shown for bleed resistors at the source. Once again, the results are normalized to the case where both sides are referenced directly to chassis. Notice how the values compare to those of the source-referenced case in Table II. For very large bleed resistors, the noise approaches that of single-point referencing, and as the bleed resistor decreases in value, the load noise approaches that of the multi-point ground.

It should be noted that bleed resistors can interfere with very small common-mode currents sometimes required for analog circuits. Also, the use of isolation resistors on both ends is sometimes done for fault protection – keeping the power system from being destroyed by a wire-to-chassis short. However, this can cause circuit-to-chassis voltage differences that can leave the circuits susceptible to noise. Also, for high-frequencies (>1 MHz), isolation from chassis is nearly impossible to truly achieve due to parasitics – leaving the system parasitically connected to chassis, something that is generally detrimental to system noise performance (5).

V. CONCLUSIONS

Part 2 of our investigation into cable noise reduction techniques yielded four important conclusions. Once again, we confirmed that reduction techniques only work reliably for electrically short cables (less than $\lambda/20$). In our case that related to a maximum frequency of about 10 MHz. This reinforces the need to keep cable lengths short with respect to the signal wavelength.

Theory and measurements agreed that the worst induced noise voltage occurs in the case of inductive noise coupling when the source resistance is minimum and the load resistance is maximum (*Min*,*Max*), and in the case of capacitive noise coupling when the source and load resistances are both maximum (*Max*,*Max*). This suggests that circuits that offer lower load resistance will exhibit lower levels of coupled input voltage noise.

Results demonstrated the advantage of single-referencing the electronic system to chassis. A noise reduction of up to 36dB was shown for the case where the chassis was connected to the source side. Measurements demonstrate that significant noise reduction can be achieved through single-reference grounding (balanced loads), but the benefit is not as significant as reported for low-frequency systems.

Finally, we sought to examine the effects of bleed resistors on noise susceptibility. We found that a bleed resistor of any appreciable value acts in a way that is similar to floating the ground from the chassis (single-point referencing). Likewise with a very small bleed resistor, the noise level approaches that of referencing the system to ground at both ends.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

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