Bulk Current Injection Testing of Cable Noise Reduction Techniques, 50 kHz to 400 MHz

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***Abstract*— This paper presents empirical results of cable noise reduction techniques as demonstrated using bulk current injection (BCI) techniques with radiated fields from 50 kHz - 400 MHz. It is a follow up to the two-part paper series presented at the Asia Pacific EMC Conference that focused on TEM cell signal injection. This paper discusses the effects of cable types, shield connections, and chassis connections on cable noise. For each topic, well established theories are compared with data from a real-world physical system.**

Keywords-bulk current injection; cable noise reduction

I. INTRODUCTION

Cable noise reduction techniques were investigated across a relatively broad frequency range (50 kHz – 400 MHz). The effectiveness of various noise reduction techniques were examined including the use of dedicated return wires, twisted wiring, cable shielding, shield connections, and implementing single-reference grounding. The experimental setup emulates a real-world electrical system, while still allowing us to independently vary a set of operating parameters.

The data presented in this paper using bulk current injection (BCI) is complimentary to the data taken from similar testing using a transverse electromagnetic (TEM) cell [1], [2]. Data from both methods are briefly compared for similarities and differences. Other researchers have shown that both methods are valid cable testing methods for low to moderate frequencies [6]. For completeness, theory for the measurements is repeated in this paper.

II. EXPERIMENT SETUP

The electronic system shown in Fig. 1 consisted of two Hammond shielded electrical enclosures, one containing the source resistance, and the other containing the load resistance. The boxes were mounted on a large aluminium plate acting as the system chassis. Cables connecting the two boxes measured 50 cm in length and were attached to the boxes using BNC or D38999 military-style connectors.

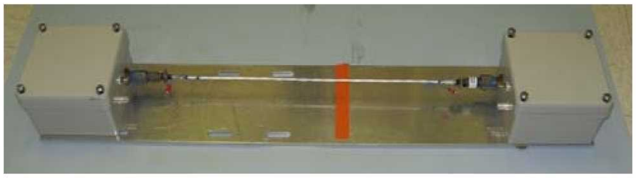

Fig. 1 Electronic system

The full test setup is shown in Fig. 2. Electromagnetic fields were created using an HP8657B signal generator, AR 50WD1000 broadband amplifier, and ETS95236-1/95242-1 BCI probes. Measurements were taken using an Agilent E4401B spectrum analyzer and HP41800 probe.

III. CABLE TYPES

Common-mode and differential-mode currents can cause cables to act as unintentional radiators/receptors in electrical systems. Each is dependent on different properties of the cable and interference signal. Common-mode radiation has been shown to be proportional to cable length and signal frequency, whereas differential-mode radiation is proportional to the area enclosed by the differential mode current and the square of the signal frequency [3].

Reduction of common-mode radiation generally requires minimizing the common-mode current or common-mode signal frequency. As far as cabling, the only significant adjustments that can be made to reduce radiation and reception are to shield the cable, shorten the cable, or to isolate the offending cable with distance.

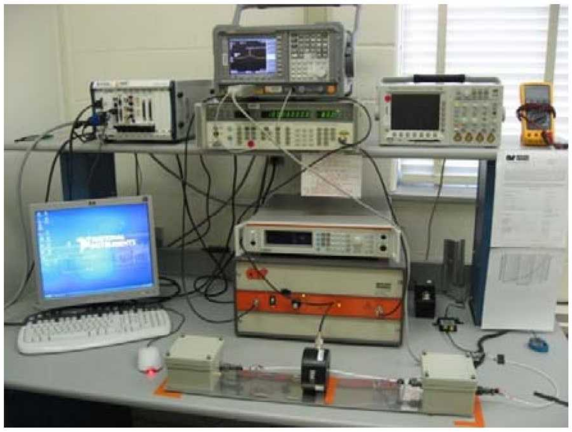

Fig. 2 Experiment test setup

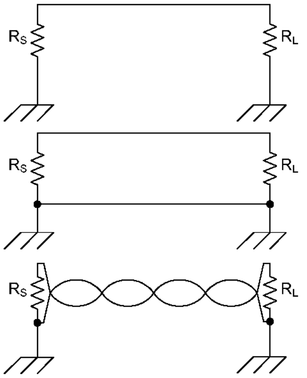

Fig. 3 Single wire, dedicated return, and twisted pair

It should be remembered that common mode currents can cause significant radiation because their fields add resulting in a constant of radiation that is several orders of magnitude larger than that of differential mode currents [3]-[5].

Reduction of differential-mode radiation is accomplished by lowering the signal frequency (typically dominated by the edge rates), or minimizing the differential-mode current. Cabling considerations can also help reduce radiation and reception, including shielding the cable, reducing the current loop area by using dedicated return wires, shortening the cable, or isolating the offending cable with distance.

In our first investigation, we measured how much load noise reduction was achieved using dedicated return wires as opposed to a single wire and chassis return. We also evaluated any additional improvement that was gained from twisting the two wires (see Fig. 3). For these measurements, unshielded cables were used since cable shielding effects were studied separately.

A. *Theory*

From basic field theory, we would expect that adding a dedicated return wire would reduce the primary current loop area and thus reduce the total magnetic flux coupled into the receptor circuit. This is offset however by the ground loop formed by the chassis connections at each end.

It is also well understood that twisted pair wiring reduces magnetic field coupling because of the alternating polarity of each loop. Induced voltages from one loop cancel with adjacent loops. Twisted pair wiring can also reduce capacitive coupling if the wires are terminated in a balanced way at both ends – often not the case.

A simple model for twisted-pair wiring is shown in Fig. 4. The current and voltage sources model the capacitive and inductive coupling respectively. For the unbalanced case with one wire grounded, half of the current sources will go to zero. This implies that the voltage sources will cancel completely for an even number of twists. For the case of an odd number of twists, a single V_1, V_2 source pair will remain. This is to suggest that unbalanced twisted pair wiring will look like full-length untwisted wiring for capacitive coupling and a very short (single half twist length) untwisted wire for inductive coupling.

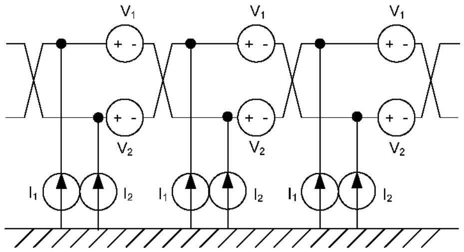

Fig. 4 Model for coupling on twisted pair wiring [3]

B. *Experimental Data*

Load noise was measured for the three configurations: single wire with chassis return, two wires with dedicated return, and twisted pair wiring. A summary of the data is given in Table I. As expected, the inclusion of a dedicated return wire significantly decreased the noise level by 15-25 dB (for frequencies with wavelength much greater than the cable length). Additional improvement from twisting the wiring was shown to be minimal due to very small loop areas in both cases. *The reduction is more pronounced than the TEM cell case, because nearly all of the coupling is due to inductive effects – something highly dependent on current loop area.*

TABLE I
LOAD NOISE FOR VARIOUS WIRE CONFIGURATIONS

Frequency (MHz)	**Single Wire (dB)**	**Two Wire (dB)**	**Twisted Pair (dB)**
0.05	0	-27.6	-27.8
0.10	0	-27.0	-27.0
0.20	0	-23.6	-24.0
0.50	0	-22.1	-22.4
1	0	-14.7	-15.0
5	0	-12.9	-13.1
10	0	-6.2	-16.8
20	0	-0.6	-11.4
50	0	6.8	-3.8
100	0	4.0	-4.5
200	0	8.3	-5.5
400	0	5.2	-10.4

As with many cable noise reduction techniques, the results become unpredictable at higher frequencies. This is because as the signal wavelength approaches (or exceeds) the cable length, standing wave and secondary coupling mechanisms patterns begin to dominate load noise.

Results point to the need to include a dedicated return wire for every signal and power connection (preferrably twisted pairs). Additionally in our case, the chassis offered a very uniform impedance (a single sheet of heavy gauge aluminum between boxes), but in many cases, the chassis structure is much more complicated – which could lead to significant frequency dependent characteristics if used for signal return. One final drawback from using the chassis for signal or power return, is that it can introduce ground bounce in a system due to impedance sharing.

IV. SHIELD CONNECTIONS

One of the most pervasive questions that integrators wrestle with is how to effectively connect the cable shield. Many options exist, including tying the shield to:

- the chassis at the source and/or load using a conventional connector and pigtail connection,
- the chassis at the source and/or load using an EMI backshell with 360 degree coverage,
- a "quiet ground" in the system by routing it through a pin on the connector.

It is well understood that a shield can be an effective tool to reduce capacitive and inductive coupling. Numerous sources have shown that grounding the shield at one end will eliminate much of the capacitive coupling, but grounding it at both ends is required to reduce inductive coupling [1]-[5].

Unlike data taken with a TEM cell [1], [2], the BCI method of signal injection is dominated by inductive coupling. Therefore, little if any reduction of induced noise is expected from tying the shield to the chassis at one end when using BCI injection. It should be made clear that this is not an indication that single-ended shielding is not useful, but rather is only a characteristic of BCI testing. For that reason, capacitive coupling is not discussed in this paper, rather the reader is referred to [1] for additional information.

A. Inductive Coupling

The noise voltage at the source and load ends due to inductive coupling can be approximated by

$$V_S^{IND} = \frac{R_S}{R_S + R_L} j\omega M_{NR} I_N \frac{R_{SH}}{R_{SH} + j\omega L_{SH}} \tag{1}$$

$$V_L^{IND} = -\frac{R_L}{R_L + R_S} j\omega M_{NR} I_N \frac{R_{SH}}{R_{SH} + j\omega L_{SH}} \tag{2}$$

where R_S, R_L, and R_{SH} are the source, load, and shield resistances, and M_{NR} is the mutual inductance from the circuit with noise current I_N [3].

The effect of a shield is seen only in the last term of each equation. If the shield is not connected at both ends, the shield inductance will go to zero, driving the last term in the equations to unity – the shield thus offering no inductive noise reduction.

However, if the shield is grounded at both ends, the magnetic flux generated in the shield-to-ground plane circuit will generate a corresponding voltage in the shield that produces a current that counteracts the induced noise current.

B. Pigtails and 360-degree EMI Connectors

The term "pigtail" is used to denote the break in the shield required to tie it to ground – often at the backshell of the connector. The effect of the exposed signal wire and pigtail extension of the shield is to allow noise coupling to both the signal and shield. It is generally understood that the longer the pigtail, the worse the effect. *Experiments in a TEM cell showed that minimizing the pigtail length/area can improve the load noise by up to 5 dB [1].*

Some connectors avoid the pigtail problem with backshells specifically designed to offer full coverage of the signal wires, (i.e. 360-degree shield connection). The performance of "EMI" connectors of this sort were compared to standard backshells that used pigtail connections. Fig. 5 shows the two connector types.

Fig. 5 EMI and standard pigtail connectors

C. Experimental Data

In our experiment, we measured the induced noise voltage at the load while varying the shield connection. Table II presents a summary of the test results. The headings OO, SO, OS, SS, and SS-EMI denote the particular shield connection, where O stands for open and S stands for short. So for example, OS indicates that the shield was left disconnected at the source side and connected at the load side. For all cases, the same shielded twisted pair wire was used. The SS-EMI case denotes a 360-degree connector versus the other standard connector with pigtail. The SS-PIN case denotes routing the shield through a connector pin to a quiet ground inside the box.

TABLE II
LOAD NOISE WITH VARIOUS SHIELD CONNECTIONS

Frequency (MHz)	**OO (dB)**	**SO (dB)**	**OS (dB)**	**SS (dB)**	**SS-PIN (dB)**	**SS-EMI (dB)**
0.05	0	-0.2	0.2	-3.3	-1.0	-12.4
0.10	0	-0.3	0.0	-4.9	-1.6	-14.4
0.20	0	-0.5	0.1	-6.7	-2.8	-17.9
0.50	0	-0.3	0.1	-10.2	-5.0	-23.4
1	0	-0.3	0.0	-12.2	-5.9	-27.6
5	0	0.7	0.8	-11.0	-5.0	-36.7
10	0	0.3	-0.1	-14.9	-6.5	-38.3
20	0	3.4	-0.1	-13.4	-6.1	-22.1
50	0	1.0	4.8	-6.7	0.1	-15.9
100	0	-5.2	0.4	-13.7	-3.6	-25.8
200	0	1.5	-6.2	-15.5	-3.0	-31.7
400	0	-7.1	6.4	7.0	-7.7	-20.9

As expected, there was little noise reduction seen from tying the shield to one side (either source or load). This is different than TEM cell testing, because the dominant coupling in BCI is magnetic and will not be reduced by single-ended shield connections.

For shields tied to both ends, the reduction ranges from 3-7 dB for very low frequencies – believed due to a tradeoff between shielding benefits and the ground loop and shield cutoff characteristics. As frequency increases (but still below λ/20), effectiveness improves to 10-15 dB. The shielding is shown to be less effective by about 5-8 dB if routed through a pin to an internal ground. Finally, the EMI backshell showed an improvement of 11-32 dB over other shielding configurations.

As frequencies increased and the cable began to exceed the short-cable approximation of λ/20, the results became dominated by standing wave patterns and secondary coupling paths. Any potential benefit of shielding became unpredictable. Fig. 6 shows the actual measured load noise with the various shield connections.

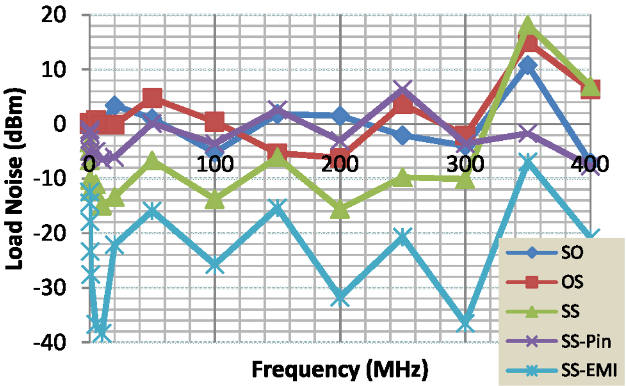

Fig. 6 Load noise with different shield connections

V. CHASSIS CONNECTIONS

It has been demonstrated by numerous researchers that significant noise reduction can be achieved through single-reference ground strategies [3], [10]. 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 higher-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. In our experiment we are able to measure the benefits of single-reference versus multi-reference grounding up to 400 MHz for a very simple two-box system connected by a low-impedance chassis.

To examine the effects of single-reference grounding for higher frequencies, we compared the load noise for two configurations as shown in Fig. 7. The load noise measured across frequency is given in Fig. 8 and Fig. 9, with the second plot focusing in on the low frequencies. Once again, the sinusoidal pattern in the first figure is due to the standing wave patterns for the cable.

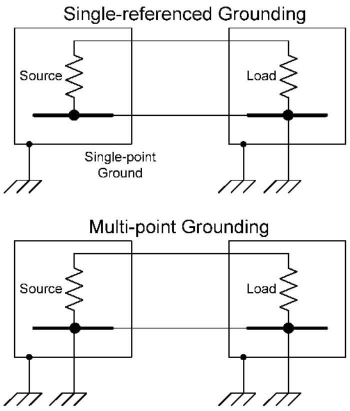

Fig. 7 Single- and multi-point grounding connections (R_S=100 Ω, R_L=1 MΩ)

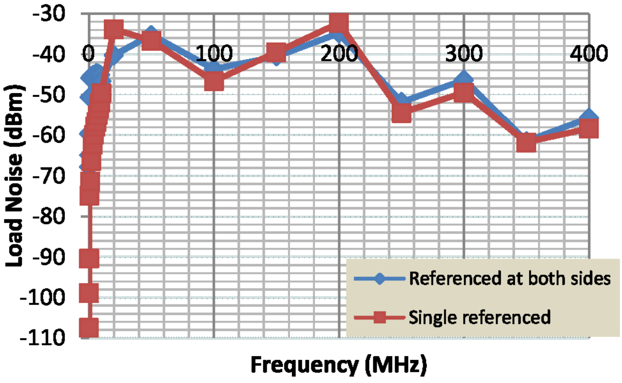

Fig. 8 Load noise for source, load, or grounds referenced to both sides

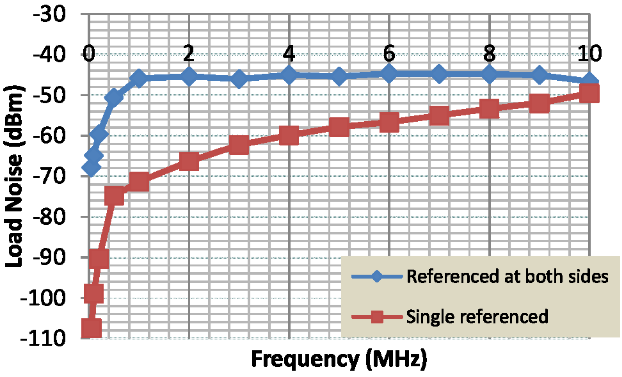

Fig. 9 Load noise for source, load, or grounds referenced to both sides

Table III presents the data with noise levels 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). For signals with wavelengths much longer than the cable length, the single-referenced connection demonstrated significantly reduced load noise (25-40 dB).

TABLE III
NOISE FOR SPG AND MPG CONNECTIONS

Frequency (MHz)	Tied at both ends (dB)	Tied at one end (dB)
0.05	0	-39.61
0.10	0	-34.02
0.20	0	-30.76
0.50	0	-24.19
1	0	-25.48
5	0	-12.48
10	0	-2.98
20	0	6.43
50	0	-1.41
100	0	-3.02
200	0	2.49
400	0	-2.64

The data is similar to that taken for TEM cell testing, both sets demonstrating a significant benefit from using single-reference grounding at low frequencies.

D. BNC Connections

When given the choice of tying the cable shield to the chassis (likely through a pigtail) or routing it through a pin to an internal ground, we found that lower noise is achieved with a chassis connection. However when using a coax cable with BNC connection, a specific trade must be considered.

Two general options exist as shown in Fig. 10: use a standard 1-pin BNC connector, tying the shield through a 360° connector to the chassis, or use an isolated 2-pin BNC connector, routing the shield into the system enclosure and tying it to a quiet ground. In the first case, the cable acts as an extension of the Faraday cage but introduces a ground loop. In the second case, a single-referenced ground can be established at the expense of penetrating the box with the shield conductor.

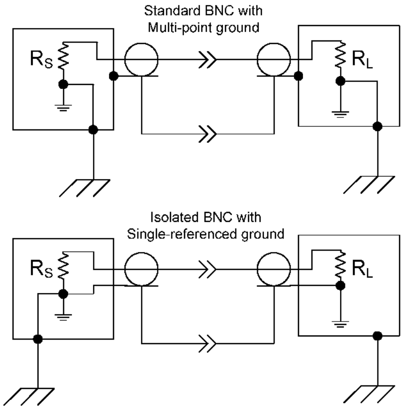

Fig. 10 Coaxial connections with standard or isolated BNC connections

Both unmatched ($R_S=100\Omega$, $R_L=1M\Omega$) and matched ($R_S=50\Omega$, $R_L=50\Omega$) impedances were considered, and the data is given in Table IV. In each case, the data is normalized for the standard BNC connection. Experiments demonstrated that the isolated connections exhibited lower noise for frequencies below a few hundred kilohertz. As frequency increased however, the standard connections offered lower noise. This is believed due to the tradeoff between the benefits of the Faraday cage shielding versus the single-reference grounding. *As far as we are aware, this is the first publication of this comparison for both matched and unmatched terminations across a wide frequency range.*

TABLE IV
NOISE FOR STANDARD AND ISOLATED BNC CONNECTIONS

Frequency (MHz)	Unmatched		Matched	
	Standard BNC (dB)	Isolated BNC (dB)	Standard BNC (dB)	Isolated BNC (dB)
0.05	0	-25.2	0	-31.3
0.10	0	-15.7	0	-22.1
0.20	0	-7.8	0	-13.8
0.50	0	5.8	0	-0.3
1	0	7.9	0	1.6
5	0	32.7	0	18.9
10	0	18.9	0	2.3
20	0	14.8	0	3.3
50	0	4.9	0	-10.1
100	0	8.7	0	-6.9
200	0	24.4	0	10.1
400	0	7.6	0	-18.9

E. 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. 11).

We examined the effects of bleed resistors on noise susceptibility. Logically, one would conclude that a bleed resistor of any appreciable value would act in a way that is similar to single- referencing. Likewise when using a small bleed resistor, the noise level should approach the multi-ground case. In fact, this is exactly what we found.

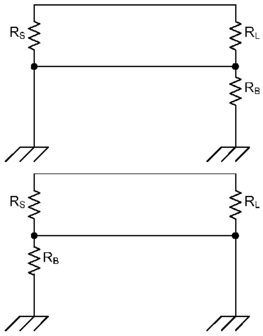

Fig. 11 Bleed resistors at load or source end

Table V presents the effects of using varying source bleed resistors, with the load 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 III.

TABLE V
LOAD NOISE FOR BLEED RESISTOR CONNECTIONS

Frequency (MHz)	**Tied at both ends (dB)**	**Bleed R=20Ω (dB)**	**Bleed R=100Ω (dB)**	**Bleed R=1KΩ (dB)**
0.05	0	-18.3	-29.7	-38.8
0.10	0	-14.5	-24.8	-33.3
0.20	0	-12.6	-21.9	-29.8
0.50	0	-8.6	-16.4	-23.2
1	0	-9.6	-17.8	-24.5
5	0	-1.4	-6.7	-11.8
10	0	0.8	0.8	-2.7
20	0	0.9	2.4	2.2
50	0	0.1	0.2	-2.2
100	0	-3.3	-3.0	6.6
200	0	2.1	2.7	12.3
400	0	5.5	5.6	12.5

For any reasonably large bleed resistors (>1kΩ), 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. *Once again this data is in general agreement with that taken using a TEM cell.*

VI. CONCLUSIONS

This paper focused on the effectiveness of cable noise reduction techniques with the system stimulated using bulk-current injection. The investigation is analogous to, and largely in agreement with, measurements taken using a TEM cell [1], [2]. The fundamental conclusions are the same for both experiments. First and foremost is the reduction techniques only work reliably for electrically short cables. 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 interference signal wavelength.

The use of dedicated return was shown to reduce the magnetic coupling by about 15-27 dB. For additional noise immunity, the return can be twisted with the power or signal line. However twisting of cables does not reduce capacitive coupling for unbalanced applications, and in our measurements was shown to offer only minimal additional improvement in susceptibility.

Given that BCI couples energy into the cable using magnetic fields, this experiment did not allow the benefits of single connection shielding to be measured. It did however confirm that shielding connected at both sides can reduce the inductively coupled noise. Pigtail connections outperformed routing the shield through a pin to an internal ground by about 5-8 dB. EMI backshells were shown to offer an additional 11-32 dB of noise rejection over pigtails.

Results demonstrated the advantage of single-referencing the electronic system to chassis. A noise reduction of up to 40 dB was measured. A specific case with coax cable and BNC connections was examined. Data suggests that at low frequencies, an isolated BNC connection with the shield routed to a ground inside the enclosure offered lower noise than conventional connections. As frequency increased however, the conventional case demonstrated lower noise due to the improved shielding.

VII. REFERENCES

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