Abstract—We examine the effects of using an unshielded cable as a reference standard for the evaluation of the high-frequency shielding effectiveness of cables. We placed an unshielded cable (wire) in five different configurations in our reverberation chamber. In each configuration, we measured the coupling between the cable and a source antenna. We observed large variations (up to 20 dB) in the results which we traced to impedance mismatches associated with the various configurations. We used post-processing to correct for these mismatches, and the results were much more consistent from configuration to configuration, and were also consistent with a well-matched horn antenna. However, two configurations still showed anomalies, illustrating some of the problems associated with using bare wires as reference standards.

Keywords—shielding effectiveness; cable shielding; shielding measurements; reverberation chamber

I. INTRODUCTION

When measuring the high-frequency shielding effectiveness of a cable (which we interpret as either the radiation from a cable to its environment or the coupling to a cable from its environment), it is relatively easy to determine the relative shielding of two cables in a given setup: simply measure the coupling associated with each cable. Assuming both cables are impedance-matched with the measurement system and placed in identical configurations (resulting in similar pattern characteristics), any difference in the coupling can be attributed to differences in shielding. However, if we are interested in the absolute shielding of a cable, some sort of reference standard with known shielding must be used. One logical candidate for a reference standard is an unshielded cable, that is, a cable that has had its shield removed. We will refer to this as a "naked" cable. This approach has been used and documented in technical papers and standards [1][2][3]. In this paper, we investigate the effects of using a naked cable as a reference standard, and compare the results to a well-matched and efficient antenna, which is an alternative reference standard used in reverberation chamber measurements [4].

An alternate method of measuring the shielding effectiveness is by using surface transfer impedance measurements. We are intentionally avoiding those measurements because such measurements become difficult at higher frequencies [5].

To evaluate the potential problems associated with using a naked cable as a reference standard, we placed an unshielded cable in five different configurations to simulate different terminations and orientations of a cable. We then evaluated the average coupling between the naked cable and an antenna using our reverberation chamber. Although our measurements were performed in a reverberation chamber, the results should be roughly applicable to measurements in other facilities.

We found that simply using a naked cable as a reference standard can result in errors of up to 20 dB in estimates of absolute shielding effectiveness simply due to errors in the reference. However, by carefully accounting for the mismatches introduced by removing the shield, we can significantly reduce the uncertainty associated with the reference to less than 2 dB, and less than 1 dB if we perform additional data processing.

In this paper, we begin by addressing some of the ideal characteristics of a “good” shielding measurement, such as reciprocity and a low sensitivity to changes in cable configuration. We then describe some of the potential problems associated with measuring the shielding effectiveness of cables in general, and with measuring naked cables in particular. These include pattern characteristics of the cables and mismatch characteristics introduced by removing the shield of a cable. Finally, we will propose possible corrections to these problems using post-processing of our measurement data.

II. THE IDEAL MEASUREMENT

Before describing a measurement system or results, we first examine the characteristics we would like to have in a shielding measurement. These ideals may not be attainable, but it is still helpful to describe the ideal situation.

Ideally, our measurement system should be a 2-port system, with one port (Port 1) connected to the source or receiving element (an antenna where appropriate for a particular facility, or to the input/output of a TEM or GTEM cell) and the other port (Port 2) connected to the cable under test (CUT). The
source or receiving element should be well matched and efficient (low ohmic losses). Both ports should have the same characteristic impedance so that they can be connected to a network analyzer or other standard equipment.

Given the above configuration, it would be convenient if the measured shielding were identical regardless of whether the cable is the source or receiver, that is, reciprocity is a goal. This will be guaranteed if the above assumptions are valid and the final shielding estimates are based on the transmission coefficients \( S_{12} \) and \( S_{21} \), since these should be equal [6].

Finally, the estimated shielding should be independent of the cable orientation (different bends and loops). This should be true whether the other end of the CUT is connected back to a ground plane or left hanging in the test environment as long as any bends do not cause a significant change in the mechanical/physical properties of the shield.

III. POTENTIAL PROBLEMS

When conducting any shielding measurement, there is the possibility that problems and uncontrolled variables in the technique may arise. In order to produce a meaningful measurement, those problems should be addressed and minimized. Two of the problems that we anticipated when we began this investigation were pattern effects and mismatch effects.

The radiation pattern of an electrically long cable can be quite complicated, and will be sensitive to the configuration and length of the cable. To avoid this problem, we performed all measurements in a reverberation chamber since pattern characteristics are generally unimportant in such a facility.

A second potential problem is the possible mismatch errors and reflections due to the impedance characteristics of the transmission line not being maintained. These mismatch errors and reflections will reduce the coupling to the naked cable, resulting in errors in determining the shielding effectiveness of any other cables. However, we will show that many of these effects can be reduced or eliminated using post-processing techniques. Examples of this mismatch will be presented below.

IV. MEASUREMENT SETUP

All measurements were conducted in a reverberation chamber with 2 paddles turning continuously. Both paddles were mounted on a vertical shaft. One paddle had a diameter of 2.5 m (nearly wall to wall), and the bottom of the paddle was approximately 0.7 m below the ceiling of the chamber. The other paddle was mounted on a vertical shaft with a diameter of 0.85 m and a height of 1.8 m above the floor.

In our testing, the naked cable was mounted on the wall of the reverberation chamber in five different configurations as described below. Admittedly, this wall-mounted configuration is not consistent with IEC 61000-4-21, which requires that the CUT be connected to a well-shielded cable so that it is 1 meter away from the walls and within the working volume of the chamber. However, complying with this requirement was not practical for our application for several reasons. For one, following the standard would have forced us to ignore the loop configurations. Second, the standard assumes that the CUT is well matched. If the shield is removed, this will not be the case, and the connecting cable can become a significant, even dominant source of radiation. To avoid these potential complications, we have chosen to connect the CUT to the wall of the reverberation chamber in five different configurations as described below. The fields near a wall have been analyzed in detail by Hill [7], and the simplification of placing the cables on the wall should not have a negative impact on our results. This is confirmed in our results, presented below.

A dual-ridged horn antenna was used as a source or receiving element in all of the experiments. All four S-parameters were measured using a VNA (vector network analyzer). Port 1 of the analyzer was connected to the horn, and port 2 was connected to the CUT. The data were averaged over 100 sweeps.

Each wire configuration consisted of 35 cm of wire bent in some unique orientation. Although one standard [3] states that a cable length of 1 m is to be used, using shorter cables allowed us to work with a smaller number of resonant frequencies.

In all of our measurement configurations, one end of the cable was connected to a bulkhead feed-through in the wall of the chamber. For the other end, we attempted to simulate conditions found in various papers or standards, as described below.

In IEC 61000-4-21, the other end of the cable is terminated using an impedance-matched load and left in the test environment. Since a load will have no effect if the shielding of the cable is removed (no current flow through the load), the naked-cable version of this setup is equivalent to a monopole. We evaluated the effect of using a straight monopole (Figure 1), a monopole bent 90 degrees at the midpoint (Figure 2), and a monopole bent 180 degrees at the midpoint (Figure 3).

In SCTE 48-3 2004 and in a paper by Jesch [2], the other end of a test cable is connected to another bulkhead connector, forming a half-loop. This half-loop is generally terminated to match the impedance of the shielded cable. For our measurements, we terminated the half-loop with a 50 ohm resistor (Figure 4), and we also shorted the end directly to the chamber wall (Figure 5), similar to what was done by Wang and Koh [1].

![Figure 1. 35 cm straight monopole used in the measurements.](image_url)
V. Initial Results

We measured all four S-parameters for all of the test configurations. Our first approach was to evaluate the squared magnitude of $S_{21}$ ($|S_{21}|^2$). We then averaged that result over 100 paddle positions to give $<|S_{21}|^2>$, where $<$ > indicates ensemble averaging over paddle position. This is equivalent to measuring the average power received on the cable normalized to an incident power on the antenna of 1 watt. Second, we evaluated $<|S_{22}|^2>$ (notice here we take the phasor average of $S_{22}$ before determining the magnitude, as opposed to the computation of $<|S_{21}|^2>$ given above). This is equivalent to measuring the free space reflection coefficient of our CUT when used as a radiating antenna [8]. Figure 6 shows the reflection and transmission coefficients plotted out as a function of frequency for our 35 cm half loop antenna configuration (the 35 cm refers to the circumference of the half loop). The peaks in the reflection coefficient correspond to the valleys in the transmission coefficient. But what do the valleys represent? Do they represent a characteristic of the naked cable itself or simply a cable mismatch? Figures 7 and 8 show our individual results for each of the wire configurations that we tested. Figure 7 shows the results for two of our monopole configurations: the 35 cm monopole with a 90 degree bend at the halfway point and the 35 cm straight monopole. Figure 8 displays two more configurations; the 35 cm monopole bent in half (180 degree bend) and the 35 cm half loop terminated with a 50 ohm resistor.

The results shown in Figures 7 and 8 indicate that the results will vary based on the configuration of the CUT. However, as we will show later, this variation can be accounted for and removed for most types of configurations.
As discussed before, there is a possibility that the valleys in the transmission coefficient graph could represent some unknown characteristic of that naked cable or its configuration. This possibility assumes that $S_{21}$ would represent the shielding of our naked cable. This can be done, though it isn’t practical.

Due to the wide variations in results due to different configurations, the choice of any single particular configuration must be accompanied by a large uncertainty estimate (approximately ± 10 dB at low frequencies). This high uncertainty makes this measurement method undesirable.

As an alternative, we will treat the transmission valleys as though they are representative of a mismatch. If they are treated as a mismatch, it may be possible to remove the errors (with a few exceptions as we will show later). Correcting this mismatch will yield significantly more accurate shielding measurement results.

Initially, we will assume 1 watt of incident power into the antenna. If the antenna is efficient and perfectly matched, this should be equivalent to assuming 1 watt of power transmitted into the chamber. If the antenna is efficient but not perfectly matched, then $|S_{11}|^2$ represents the power reflected back to the source, and is the power transmitted into the chamber. Some of that power couples to the cable, where it is either received and measured as $|S_{21}|^2$, dissipated as heat through ohmic losses in the cable or the terminating load on the other end of the cable, or reradiated back into the chamber. Unfortunately it is not possible to measure directly the power that is reradiated or dissipated by the cable. However, we can estimate the power that would have been measured if the cable had been well matched by treating it as an efficient but poorly matched antenna [8]. Assuming that the ohmic losses are low, we have the corrected power received on the cable ($P_{R,C}$):

$$P_{R,C} = \frac{|S_{21}|^2}{1 - |S_{22}|^2}$$

(1)

If we normalize equation (1) to a net transmitted power of 1 watt we get a received power of:

$$P_{R,NC} = \frac{|S_{21}|^2}{(1 - |S_{11}|^2)(1 - |S_{22}|^2)}$$

(2)
This equation has the benefit of being reciprocal again, since if we transmit on the cable and receive on the antenna we get the same result but with $S_{12}$ in the numerator instead of $S_{21}$. That is, the normalized corrected power received on the antenna ($P_{R,NA}$) when the cable is the source is:

$$P_{R,NA} = \frac{\langle |S_{12}|^2 \rangle}{(1-|S_{11}|^2)(1-|S_{22}|^2)}$$  \hspace{1cm} (3)

The principal disadvantage to the corrections given in (1)-(3) is that the denominators can be quite small when the reflection coefficients are large (near unity) When this is the case, a small error in $S_{22}$ can result in a significant error in the corrected received power. Below, we will take a look at how this actually affects the measurement results.

VII. Measurement Results

We processed our results for all five configurations using equation (3), and the results are given in Figure 9. The data show that when the correction is applied, all of the antenna configurations (monopole, half loop, etc) end up yielding similar results, especially above 500 MHz, although the results from the terminated half-loop are consistently below those of the others. Below 500 MHz, the monopole with the 180 degree bend and the shorted half-loop also show some significant differences. We suggest two possible causes for these exceptions.

The first cause is the sensitivity of the denominator in the earlier equation (3) when $S_{22}$ is close to 1. A small error in $S_{22}$ can result in a significant error in the corrected received power. As can be seen in Figure 6, the magnitude of the reflection from the terminated half-loop is very large below 400 MHz. It is difficult to compensate for such a large mismatch. We observed a similar effect in measurements of the 35 cm monopole with 180 degree bend. This configuration showed a very large mismatch near 400 MHz, resulting in a notch in the transmission characteristics at this frequency, as shown in Figure 8. In the case of the 35 cm monopole with a 180 degree bend, the results of this large mismatch can still be seen in the corrected data (Figure 9).

The second cause may be due to possible ohmic losses in the cable. In the case of the terminated loop, the resistance of the termination introduces losses into the test configuration, and the estimation of the power received by the cable was low because it did not account for the power coupled to the termination. This is also illustrated in Figure 9. Here, the 35 cm half loop terminated to a ground plane with a 50 ohm resistor shows significantly lower normalized receive power than that of the other cable configurations. Again, this is due to the fact that the 50 ohm resistor is a source of loss and violates our assumption that the antenna is an efficient radiator.

In Figure 9, we also present the case where the unshielded cable is replaced by an efficient and well matched horn antenna. The results are quite similar to all of the other configurations that we tested. This is expected, since Hill has shown [9] that all well matched and efficient antennas are equivalent in a reverberation chamber. However, any imperfections in the horn should be small, resulting in smaller corrections than those associated with the naked cables. This result implies that an antenna should be used in place of a naked cable, if possible. This should avoid many of the mismatch problems such as those illustrated in Figure 8. The only caveat to this is that the measurements must now be done in a reverberation chamber so that the pattern effects of an antenna are no longer a factor.

If an antenna is not used as a reference, then all possible mismatch corrections should be applied to obtain results as close as possible to those obtained with an antenna. In our measurements, the agreement between antenna coupling and CUT coupling is good. Above 500 MHz, and neglecting the case of the terminated half-loop, the difference between the horn-to-horn coupling and the corrected CUT-to-horn coupling is typically less than 2 dB, with a standard deviation of 0.62 dB. This could be substantially reduced using frequency smoothing techniques [8]. Below 500 MHz, the errors are somewhat larger, but the errors have known sources as discussed earlier. Neglecting the problems near 400 MHz on the 35 cm monopole with 180 degree bend and near 200 MHz
for the shorted half-loop, the differences are still typically less than 2 dB, but with a standard deviation of 0.8 dB.

To see the overall impact of the corrections, Figure 10 shows the difference in dB introduced by using the correction in equation (3). Our corrections significantly affect the lower frequencies where the difference in measurements can be higher than 20 dB.

![Figure 10: An example of the difference in results (dB) between the two different measurement methods for the 35 cm shorted half loop.](image)

Figure 10 shows that the mismatch decreases with frequency and the corresponding difference shown in Figure 9 also decreases with frequency. This shows that errors introduced by using a naked cable will be most pronounced at the lower frequencies, regardless of the measurement method. The main cause of the large difference at lower frequencies is that the impedance mismatch is significantly more pronounced in the lower frequencies.

Though our demonstration was done using measurements from a reverberation chamber environment, the mismatch effects will be present in any measurement environment with any setup. The corrections that we give in equation (3) should apply to any measurement facility and setup; although this has not yet been demonstrated.

VIII. CONCLUSIONS

We have demonstrated some of the possible effects of using a naked cable as a reference in a shielding measurement. We have also suggested some techniques that will help mitigate the negative effects of using a naked cable as a reference standard. Included with our potential solution is a mathematical correction that is to be applied to the measurement data to correct for any possible impedance mismatches. However, this correction should be used with care. There are instances in which the impedance mismatch can be so large that the correction can’t completely compensate for its effects.

We demonstrate the need and effectiveness of our corrections by demonstrating their use on five different antenna configurations.

REFERENCES