Measurement Notes

Note 36

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Monitor for Integrity of Doors in a Shield Enclosure

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Abstract

This note extends the SCUTUM concept for monitoring the integrity of a shield enclosure. Arrays of loops are placed around (outside) the perimeter of a door which must open and close. Coaxial cables are used to reroute the transmission-line conductors (passing along the shield surface) around the door opening.

I. Introduction

This note is a sequel to a previous one concerning the detection of slot-like faults in the walls of a shield enclosure [6]. In that paper a technique was presented in which a wire was run parallel to a shield surface (say outside) in a way as to cross seams at right angles to the seams. Using this wire as a transmission line (terminated in its characteristic impedance) a fast-rising pulse can be propagated around the shield in a way to efficiently cover the shield. A similar transmission line can be used on the other side of the shield wall (say inside) to efficiently couple to the magnetic fields penetrating through faulty seams. Three such pairs of transmission lines (one outside and one inside) can be run at right angles to each other to cover a rectangular parallelepiped shield enclosure with seams in two orthogonal directions on all six faces. Note that these transmission lines use the shield itself as one conductor of the two-conductor transmission line. The other conductor may be a wire or other conductor such as a strip (say for lower characteristic impedance) spaced at some constant distance from the shield wall by various assemblies of insulators.

The basic concept in [6] considers a simple box-like structure with seam faults. A real shield enclosure presents additional difficulties for a monitoring scheme. In particular suppose that there is a large penetration (larger than the spacing between monitor transmission-line conductors). If as in the case of a door this is to open and close to allow access then something will have to be done to the transmission-line conductors. One might remove and replace these conductors, or (as discussed later) they can be routed around the penetration.

The presence of a large closeable penetration such as a door is another challenge to an effective monitor scheme. When the door is closed one would like to verify that the door is closed in an electromagnetic sense. In particular similar to [6] there should be some excitation and measurement scheme in which the transfer of electromagnetic fields through the shield surface is presented in a form which is directly relatable to the performance of the equipment inside the shield enclosure [4]. This gives the use of scattering matrix elements which are measured for each kind of penetration as in [5].

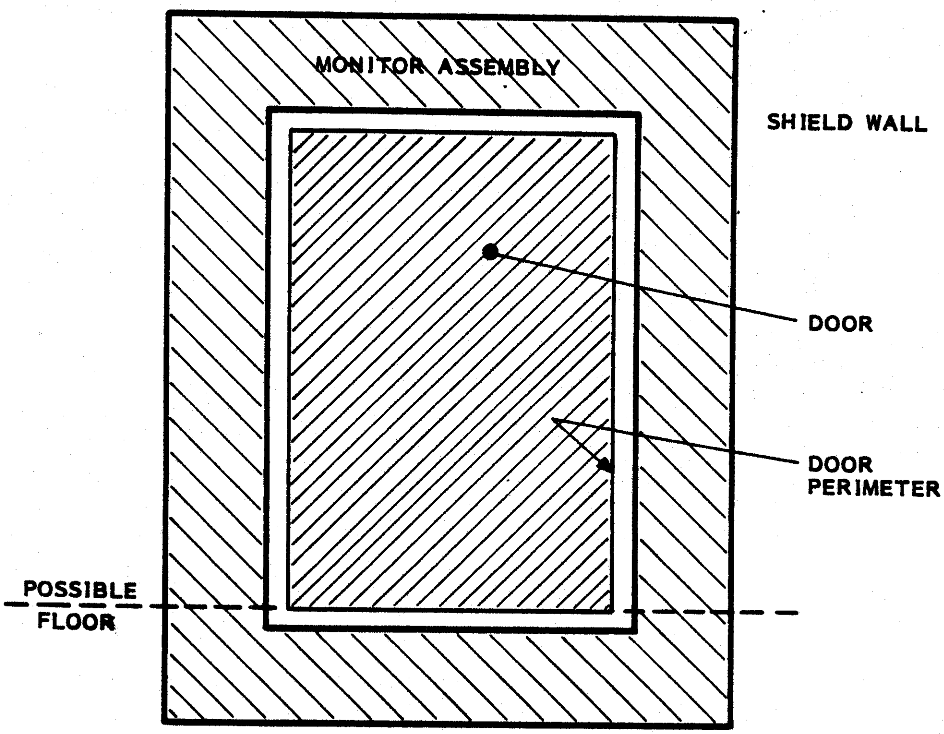
II. Monitor Assembly for Slots Around Door

As in Figure 2.1A let us consider a door in a shield wall as some highly conducting metal sheet which makes imperfect electrical contact with the shield wall around the door perimeter. This imperfect contact may include hinges, metal pressed against metal, gaskets, latches, etc. Let us then think of the door-closure problem as one of monitoring the passage of electromagnetic fields through some collection of slots positioned around the door perimeter. Considerations in [6] then apply.

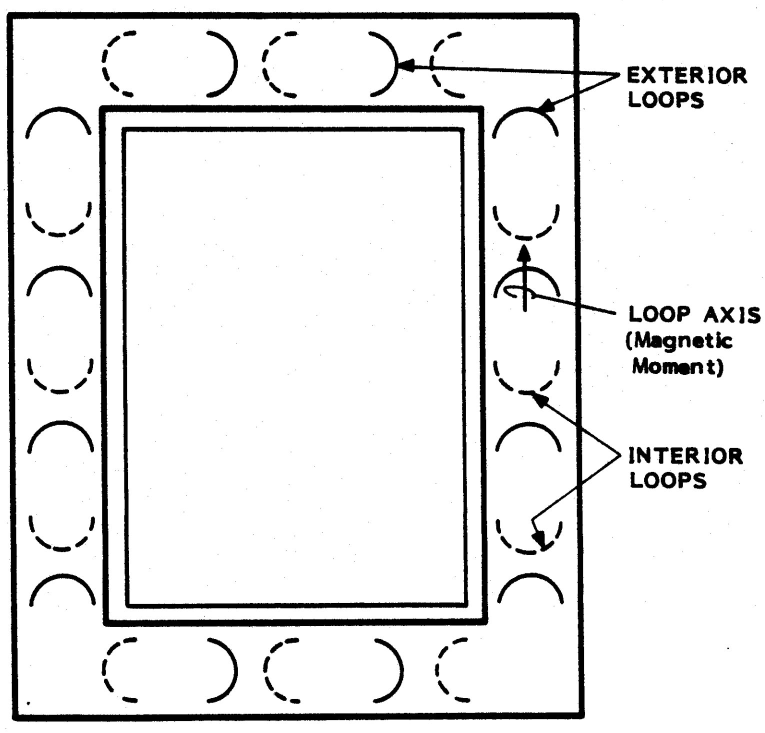
On the shield wall outside but near the door perimeter there is attached a monitor assembly as in Figure 2.1A. This monitor assembly is present on both exterior and interior shield-wall surfaces. One part (say the exterior part) might be termed an excitation assembly while the other part (say the interior part) might be termed the measurement assembly. These two parts could also be termed transmitter and receiver, and due to reciprocity (except perhaps for noise problems) their roles can be interchanged.

Note that in this configuration the monitor assembly is not disconnected or moved but remains electrically attached (all around the door) to the shield wall while the door is opened and closed and various things pass through the door opening. Note there may be a floor at the level of the bottom of the door perimeter. Part of the monitor assembly is then below the floor and this region of the floor should be dielectric so as to not interfere with the operation of the monitor assembly.

Now as in [6] if the door perimeter is modeled as an array of slot apertures (perhaps impedance loaded), then we wish to have the excitation assembly place a magnetic field on the slot parallel to the slot, or equivalently place a surface current density on the slot in a direction perpendicular to (so as to cross) the slot. This is accomplished as indicated in Figure 2.1B by a set of loops which have their axes parallel to the nearby door perimeter. Each loop then produces an equivalent magnetic dipole moment parallel to the local door perimeter. The ensemble of loops forming the excitation array (say on the outside of the shield), if driven together with the same phase and amplitude in frequency domain (or pulse in time domain), then produces what can be locally approximated as an equivalent line magnetic dipole. This configuration can also be considered as producing a magnetic frill around the door.



A. General Scheme



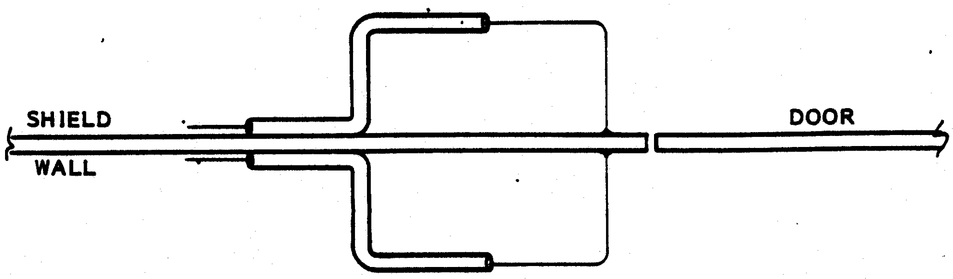
B. Loops Around Door

Figure 2.1. Door Monitor

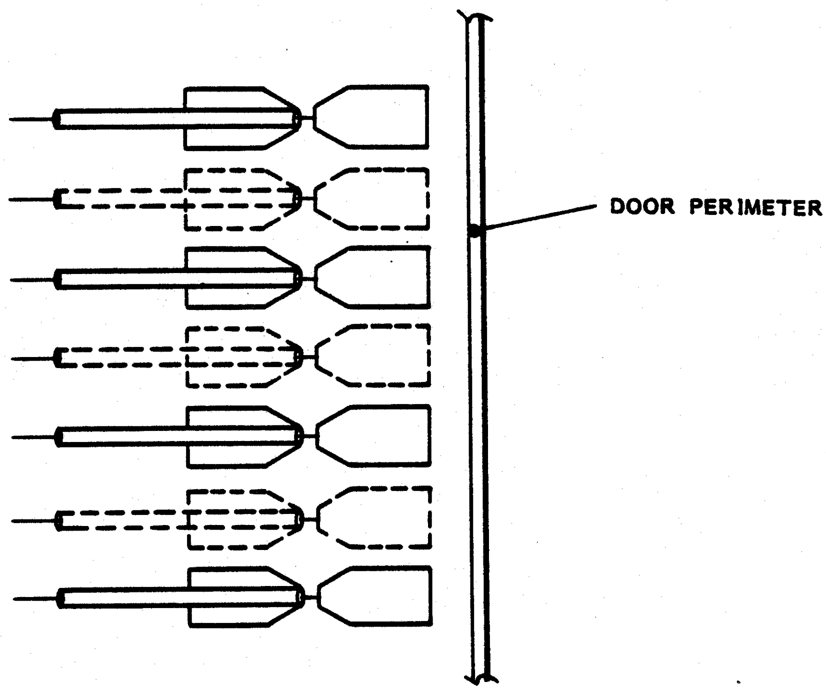
Next let the measurement assembly (say on the inside of the shield) consist of a similar set of loops, also oriented (by reciprocity considerations) with axes parallel to the local door perimeter. The exciting loops can be driven with the same signal, or driven separately, or in some combination to give various current patterns on the exterior in the vicinity of the door. Monitoring the loops of the measurement assembly one can determine if there is significant penetration around the door perimeter. By considering the signals received by the separate loops one can locate the fault. Carrying the procedure further if one wishes, one can use pairs of individual excitation and measurement loops to better localize faults that have been discovered.

Note in Figure 2.1B that the two sets of loops are set in alternating positions on opposite sides of the shield wall. This allows for a greater uniformity of sensitivity of fault detection with respect to position along the door perimeter.

Figure 2.2 shows some of the design considerations for the loop details. There are the questions of shape and spacing. A larger loop gives a greater excitation, but if made too large will have limitations at high frequencies. This can be ameliorated as indicated in Figure 2.2B by lowering the loop inductance by widening the conductors in the direction of the loop axis as discussed in [1]. If the signals for the excitation loops are to come from a common location, then cables (transmission lines) are needed to transmit the signals. One would like a low cable impedance to maximize the current in the loops. One end (at least) of each cable should be terminated in its characteristic impedance to avoid resonances. Similar requirements apply to the receiving loops.



A. View Parallel to Shield



B. View Normal to Shield

Figure 2.2 Loop Design

III. Excitation of Door Perimeter by Individual Loops

In Section 2 the door perimeter was considered as an ensemble of slot apertures. On a local basis the currents generated by the exciting loops flow across such a slot and the magnetic field (parallel to the slot) penetrates through. However, the situation is more complicated than that for the transmission lines running around the shield.

Considering each individual exciting loop as an equivalent magnetic dipole with a moment parallel to the slot one can readily compute the magnetic field, and hence surface current density crossing the slot (assumed short circuited, i.e. closed) [3]. In the near field (distances small compared to a radian wavelength from the magnetic dipole) the surface current density is solenoidal (i.e. approximately divergenceless). As such the current crossing the door perimeter in one direction is matched by an equal current in the opposite direction. Of course these currents cross at different places.

Given some equivalent dipole moment $\vec{m}_{eq}$ let it be parallel to the y axis as in Figure 3.1 with

$$\vec{m}_{eq} = m_{eq} \vec{1}_y \tag{3.1}$$

Here the shield wall and door are idealized as the x,y plane. The resultant magnetic field (quasi-static or near-field) is [3]

$$\vec{H} = \frac{1}{4\pi r^3} \left\{ 3 \vec{1}_r \left[\vec{1}_r \cdot \vec{m}_{eq} \right] - \vec{m}_{eq} \right\} \tag{3.2}$$

In the x,y plane we have

$$z = 0$$

$$r = \left[x^2 + y^2 \right]^{\frac{1}{2}}$$

$$\vec{1}_r = 1_x \cos(\phi) + \vec{1}_y \sin(\phi) \tag{3.3}$$

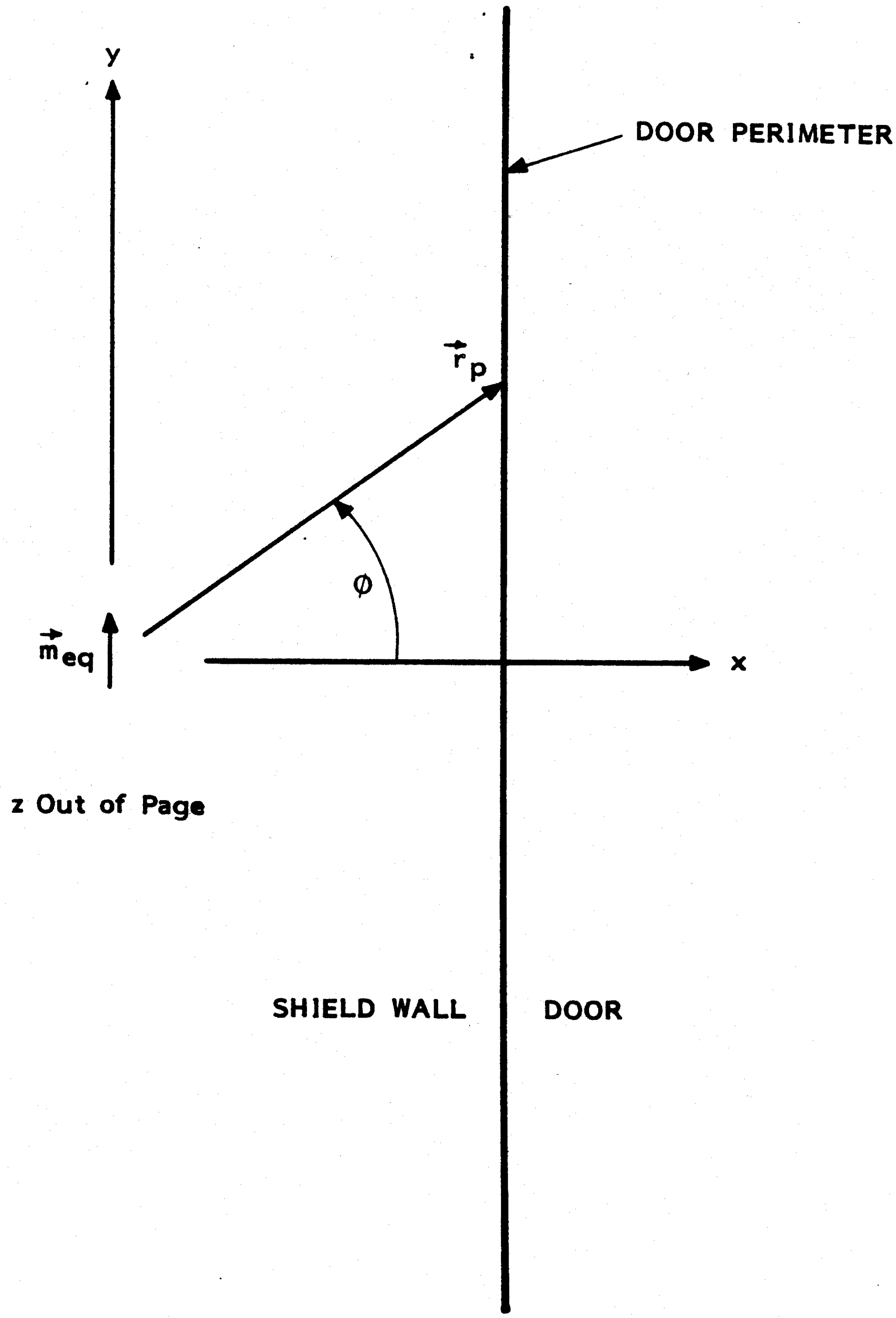


Figure 3.1. Location of Equivalent Magnetic Dipole with Respect to Door Perimeter

As in Figure 3.1 let the door perimeter be specified by

$$\vec{r}_p = (d,y,0)$$

$$-\infty \le y \le \infty \quad \text{(an idealization)} \tag{3.4}$$

On this line we have

$$r_p = \left[d^2 + y^2\right]^{\frac{1}{2}} = \frac{d}{\cos(\phi)} \tag{3.5}$$

Also the magnetic field on and parallel to the door perimeter is

$$H_y = \vec{H}\cdot\vec{1}_y = \frac{\cos^3(\phi)}{4\pi d^3}\, m_{eq} \left\{3 \sin^2(\phi) - 1\right\} \tag{3.6}$$

This gives the variation of the magnetic field exciting the possible slot apertures on the door perimeter.

Observe from (3.6) that the magnetic field along the door perimeter reverses sign at two places given by

$$\phi = \pm\,\phi_o \; , \; y = \pm\, y_o$$

$$\sin(\phi_o) = \sqrt{\frac{1}{3}} \; , \; \phi_o \simeq 35.3°$$

$$y_o = \frac{d}{\sqrt{2}} \simeq .707d \tag{3.7}$$

One can consider $-\phi_o < \phi < \phi_o$ as the principal lobe of the near-field antenna pattern. For effective illumination of the door perimeter the principal lobes of adjacent loops should overlap, so loops should be spaced no more than about d apart.

While our discussion here has been in terms of the loops of the excitation assembly, reciprocity gives the same requirements to the loops in the measurement assembly on the other side of the shield wall.

From (3.6) we have some estimate of the field strength for a given magnetic dipole moment. Note the factor d^{-3} so we may wish to have the loop close to the door perimeter. However, a loop spacing of about d then implies many loops for small d. Since the magnetic moment takes the form

$$m_{eq} = I \, A_{eq}$$

$$I \equiv \text{current}$$

$$A_{eq} \equiv \text{equivalent area (including image)} \qquad (3.8)$$

then for a given current one can increase A_{eq} by making the loops larger. As one moves back from the door perimeter one can make the loops larger (say as some constant times d^2). So a factor of d^2 reduces the factor d^{-3} in (3.6) to d^{-1} which is not so severe.

IV. Some Considerations Concerning Electromagnetic Penetration Along the Door Perimeter

The previous discussion has been in terms of individual loops. If the excitation loops are driven together with identical signals, then a magnetic frill is produced around the door. This effectively drives the entire door with respect to the shield wall. In effect the source is electric, not magnetic, albeit inductively coupled.

A similar effect is achieved (more efficiently) by connecting a wire to the door to drive it with respect to the shield. Current is deposited on the door and must flow to the shield wall (noting to include displacement currents). However, this electrical connection must be disturbed every time the door is opened or closed. One might think of an array of such electrical connections crossing the door perimeter. This would produce larger currents crossing the loop perimeter with all currents crossing with the same polarity, i.e. all from door to shield (or conversely). Again, the disadvantage is mechanical in making and breaking connections.

Another possible excitation and monitor scheme involves equivalent electric dipoles with electric dipole moment perpendicular to the shield walls (both outside and inside). This gives a capacitive coupling to the door which is inefficient at low frequencies. This is similar to the excitation by direct connection to the door except that the wires are interrupted by small capacitors (large impedances).

If the connection of door to shield is broken all around the perimeter then this excitation all around the perimeter (whether inductively or by direct contact) gives really a dominantly electric coupling and the door behaves as a hatch aperture [10]. This is, however, an extreme case which is not representative of more typical cases of partial electrical connection between door and shield.

V. Incorporation of Door Monitor into SCUTUM Concept

One of the problems this door monitor presents concerns the SCUTUM concept discussed in [6]. In this case there are transmission lines running around the conducting shield, both inside and out. There is a sufficient density of these to effectively cover the entire shield surface. Where these encounter a large penetration like a door, they could of course be run right across the door, but when the door is opened these transmission-line conductors may need to be removed (disconnected) in the vicinity of the door to allow access.

One way to get around this difficulty is illustrated in Figure 5.1. Consider, for example, signal 1 arriving from the left. Let the transmission-line conductor connect to the center conductor of a coaxial cable, the shield of which is in continuous electrical contact (ideally) with an extension of the ground plane of the monitor assembly (which is in turn in continuous electrical contact with the shield wall). Routing the coax around the door, then on the opposite side signal 1 exits to the right on the continuation of the transmission-line conductor along the shield wall. Similarly one may have signals which have to cross the door in an orthogonal direction. As illustrated in Figure 5.1 signal 2 enters a coax from the bottom, is routed around the door, and exits from the top.

The coaxial cables have some characteristic impedance Z_c. For signals to propagate in one direction (in pulse or broad-band-CW sense) on the transmission lines around the shield it is necessary that their characteristic impedance also be Z_c. Then there will be no reflections (ideally) at the connections into and out of the coaxes. An appropriate choice for Z_c is constrained by the practical range of coax impedances at the high end and by practical impedances of the conductor-over-ground-plane (shield) transmission lines at the low end. If we take Z_c as about 100Ω then the coax is still practical. In addition the transmission lines around the shield can be constructed of conducting strips parallel to the shield surface. The width of these strips is about the same as the spacing [2] (assuming air dielectric).

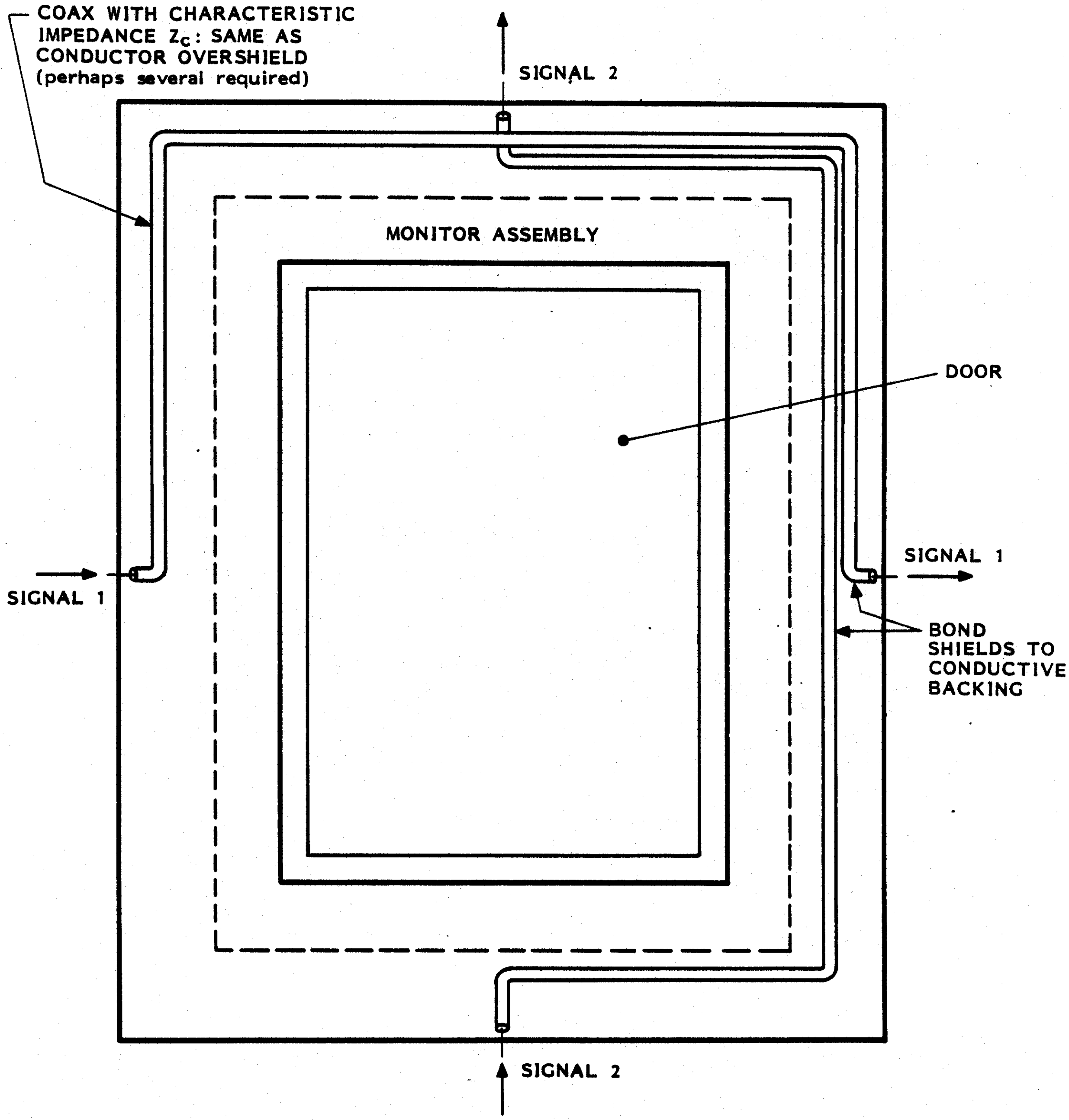


Figure 5.1. Rerouting Transmission Lines Around Door

If one desires higher impedances for the transmission lines around the shield and/or lower impedances for the coaxes, then some matching is needed at the junctions of these to remove reflections. Resistive matching can be used, but at a loss of energy at each such junction. Transformers can be used to avoid this loss. Even amplifiers (with appropriate power sources) can be used.

In order to raise the coax impedance one might think of using a wire above the ground plane in its place. However, with what may be a rat's nest of equipment associated with the monitor assembly and transmission-line bypass, there could be much undesirable crosstalk. Coaxial cables are a simple way to provide isolation (by shielding) of the various signals.

VI. Concluding Remarks

This combined door-monitor assembly and door bypass (for the SCUTUM transmission lines) has some interesting properties. From the point of view of practical operation it has the mechanical property of no moving parts. The door monitor of course needs electrical excitation and electrical indicators which may be permanently attached or brought in and connected as necessary.

The door bypass assembly has some interesting topological properties. Consider the shield as a two-dimensional space. A signal is propagating along one of the transmission lines, say with signal 1 in Figure 5.1. Our "flatland" inhabitants [8,9] see this signal propagate along and then suddenly vanish when the line connects into the coax. In a two-dimensional sense the coax is acting like a black hole. Then the signal suddenly reappears from the other end of the coax which acts like a two-dimensional white hole. Since signals can propagate both into and out of any such coax ends we might call such things gray holes.

Topologically the coax shield bonded to the effective shield surface makes with it a multiply connected surface. This is a two-dimensional analog of what is referred to as a wormhole in a three-dimensional space [7], except that transmission-line waves instead of electric flux lines are being passed through it.

References

1. C.E. Baum, Maximizing Frequency Response of a B-dot Loop, Sensor and Simulation Note 8, December 1964.

2. T.L. Brown and K.D. Granzow, A Parameter Study of Two Parallel Plate Transmission Line Simulators of EMP Sensor and Simulation Note 21, April 1968.

3. C.E. Baum, Some Characteristics of Electric and Magnetic Dipole Antennas for Radiating Transient Pulses, Sensor and Simulation Note 125, January 1971.

4. C.E. Baum, Electromagnetic Topology: A Formal Approach to the Analysis and Design of Complex Electronic Systems, Interaction Note 400, September 1980, and Proc. EMC Symposium, Zurich, March 1981, pp. 209-214.

5. F.C. Yang and C.E. Baum, Use of Matrix Norms of Interaction Supermatrix Blocks for Specifying Electromagnetic Performance of Subshields, April 1983, also as (same authors) Electromagnetic Topology: Measurements and Norms of Scattering Parameters of Subshields, Electromagnetics, 1986, pp. 47-59.

6. C.E. Baum, Monitor for Integrity of Seams in a Shield Enclosure, Measurement Note 32, April 1987.

7. C.W. Misner, K.S. Thorne, and J.A. Wheeler, Gravitation, W.H. Freeman and Co., San Francisco, 1973.

8. D. Burger, Sphereland, Barnes and Noble Books, 1983.

9. E.A. Abbott, Flatland, New American Library, New York, 1984.

10. K.S.H. Lee (ed.) EMP Interaction: Principles, Techniques, and Reference Data, Hemisphere Publishing Corp., New York, 1986.