Interaction Notes

Note 248

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INTERNAL INTERACTION ANALYSIS: TOPOLOGICAL CONCEPTS AND NEEDED MODEL IMPROVEMENTS

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Abstract

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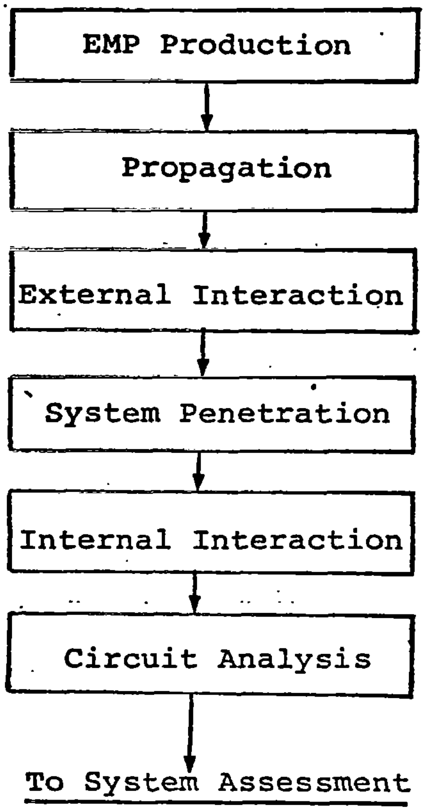
I. Introduction

The prediction of how a complicated system would react in a nuclear environment has been under consideration for a number of years. Both experimental and theoretical studies have yielded information about system survivability and vulnerability, but the problem is by no means completely solved.

As in many complicated problems, attempts are made to simplify the problem by considering small sub-problems which can be treated independently. The total solution to the main problem is then looked upon as a combination of such solutions. In the EMP area, one can divide the analysis of a particular system into the following sub-areas:

1. Study of the production of EMP (EMP Phenomenology)
2. Propagation of EMP
3. Interaction of EMP with the exterior of the system (External Interaction)
4. Coupling, Propagation and Penetration of Energy within the System (Internal Interaction)
5. Transient analysis of driven circuits within the System
6. Overall System assessment.

In many instances, the analysis of each sub-problem is unrelated to the others, except of course, for the excitation of model by another. In a flow diagram, the analysis is seen to occur in a sequence of operations as:



In some cases, there may be interaction between one sub-problem area and another, in a manner which is more complicated than shown above. For example, for a system within the EMP source region, the internal interaction problem cannot be separated from the EMP production process: The presence of the system actually influences the sources of the EMP. Similarly, if an aperture becomes too large, the interaction between the interior and exterior boundary value problems becomes such that they must be examined together. For the present discussion, however, it will be assumed that the above decoupled method of analysis is acceptable.

Much effort has been expended in trying to understand EMP phenomenology and propagation. A similar statement can be made about the external interaction and circuit areas. Although some effort has also been spent in developing the sophistication of the analytical tools in the internal interaction area, it is generally agreed that the highest degree of uncertainty exists in this area.

The area of internal interaction begins at the skin of the system (aircraft, for example) and treats the radiation and propagation within the confines of the system. Thus, it is presumed that the exterior interaction problem has already been solved as well as the penetration problem through the aircraft skin. Quantities of interest to be calculated are typically voltage and current levels at specified input ports to electronic components within the system.

Often the terms "interaction" and "coupling" are used synonymously. There is, however, a substantial difference between internal coupling and internal interaction, both of which will be discussed below. Note that this distinction holds for both internal as well as external problems.

Consider a simplified internal interaction problem of a cable located inside a perfectly conducting shield having an aperture in it as shown in Figure 1. It is assumed that the external problem has been solved and sufficient information is available to determine the

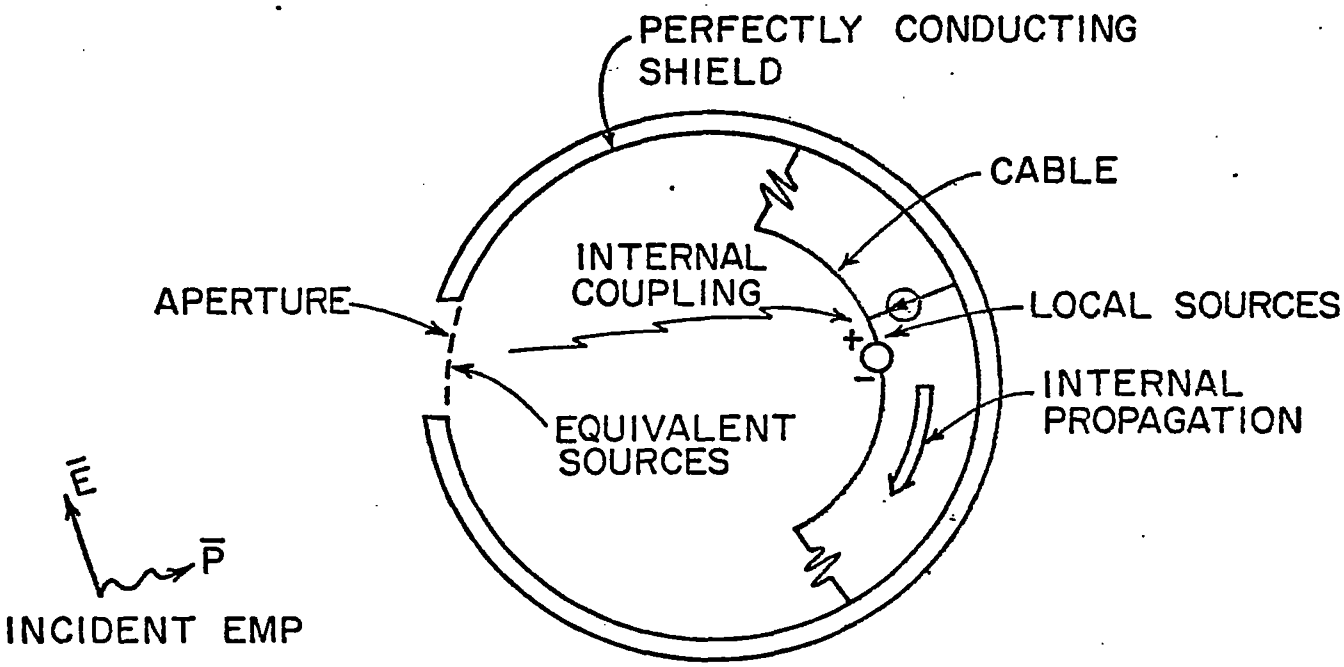


Figure 1. Simplified Internal Interaction Problem

aperture field distributions. The steps in carrying out the internal interaction analysis are then given by the following:

1. With the solution of the exterior problem, and knowledge of the equivalent sources in the aperture which radiate into the interior region of the shield, compute the fields exciting the cable. This procedure is referred to as determining the "coupling" of the EMP energy to the cable and results in local sources exciting the cable.

2. Knowing these local cable sources, determine how they affect the cable. This calculation which gives the distribution of charges and currents on the cable as it's most important result, is called the "internal propagation" calculation, and usually involves the use of the transfer function concept, which will be discussed later.

3. With a knowledge of the currents and charges on the cable, determine how this energy penetrates through the cable shield, thereby exciting additional wires within the cable sheath. Such a "penetration" problem thus serves as a starting point for another internal interaction calculation performed in a smaller, better shielded region inside the cable.

This entire process is referred to as "internal interaciton" within the volume enclosed by the perfectly conducting shield. The internal coupling problem is a subset of the interaction problem and involves only the determination of local exciting sources, not the solution of the propagation problem.

Following the notion of non-interaction between sub-problems, the usual approach for treating the internal interaction problem is to define transfer functions which relate the frequency domain voltages or currents at the inputs to the various circuits to the excitations of the interior regions of the system. These excitations, found as outputs from the external interaction problem, are usually the equivalent aperture electric and magnetic dipole moments caused by the fields passing through apertures or similar breaks in the skin of the system. Considering a system with n ports of entry, it is possible to define two excitation vectors, each of dimension n as

$$\overline{P}(\omega) = \begin{bmatrix} \overline{P}_1(\omega) \\ \overline{P}_2(\omega) \\ \vdots \\ \overline{P}_n(\omega) \end{bmatrix}$$

$$\text{and } \overline{M}(\omega) = \begin{bmatrix} \overline{M}_1(\omega) \\ \overline{M}_2(\omega) \\ \vdots \\ \overline{M}_n(\omega) \end{bmatrix} \tag{1}$$

where each $\overline{P}_i$ or $\overline{M}_i$ refers to the equivalent dipole moment of the i^{th} port of entry. In the most general type of port of entry, both terms will exist, but there may be special cases where either one or the other type of dipole moment is zero or very small. Note that these individual dipole moments are themselves vector quantities.

The response of the internal coupling network is assumed to be described in the form of either short circuit current or open circuit voltage at the wire terminals which are deemed important for the system functioning. Assuming m such wires, the voltage response is represented by a vector $\overline{V}_{oc}(\omega)$ where

$$\overline{V}_{oc}(\omega) = \begin{bmatrix} V_{oc_1}(\omega) \\ \vdots \\ V_{oc_m}(\omega) \end{bmatrix} \qquad (2)$$

The relationship between the response and the excitations is assumed to be through the matrix equation

$$\overline{V}_{oc}(\omega) = \overline{\overline{T}}_E(\omega)\cdot\overline{P}(\omega) + \overline{\overline{T}}_M(\omega)\cdot\overline{M}(\omega) \qquad (3)$$

where $\overline{\overline{T}}_E$ and $\overline{\overline{T}}_M$ are m×n matrices of transfer functions for both electric and magnetic dipole moment excitation. These transfer functions contain results of both the internal coupling and internal propagation analyses. The basic problem in the internal interaction area, therefore, is to accurately define the elements of the transfer function matrices in Equation (3).

Presently, there exists a number of difficulties in defining the elements of the matrices in Eq. (1). These stem from not having sufficient theoretical or numerical analytical methods to obtain parameters for the various coupling propagation and penetration models, as well as the possible inapplicability of some of the models, which may oversimplify the problem.

Because the area of internal interaction appears to be one of the weaker links in the overall system analysis, an improvement of the models and methods of analysis is clearly desirable. This note begins a sequence of reports which will deal primarily with the internal interaction mechanisms. The purpose of this note, therefore, is to define exactly what comprises the internal interaction area, and to present a preliminary view of needed improvements in the area. It is anticipated that future notes will describe in more detail many of the "typical" geometries encountered in internal interaction, including their dimensions, as well as indicate which are the areas of greatest uncertainty in the analysis.

II. Topological Concepts of Shielding

In order to facilite the analysis and understanding of internal interaction problems, Baum(1) has recently introduced the concept of topological shielding. Using this approach, one defines a number of surfaces through which EMP energy must pass in order to eventually excite a critical component of a curcuit. The most obvious of such surfaces is the exterior skin of the aircraft or missile. Upon penetrating this outer skin, one encounters additional surfaces which serve to enhance the shielding of the system. Smaller, metallic enclosed areas in the 747 aircraft and the conduit system in the B-1 are examples. Similarly, inside these surfaces, another surface may be evident in the form of the braid shielding on cables.

For each of these surfaces, it is possible to define a number of fundamental problems which must be understood to permit the determination of the energy penetration into shielded regions. These include field penetration through apertures (both large and small), diffusion through the surface and direct energy injection due to conducting paths.

Similarly, a number of problems can be defined to determine how energy propagates within a particular region (say on a coaxial waveguide), and then to determine distributions of charge and currents on the shielding walls. Examples of such problems will be given later.

To permit a precise description of the system topology, it is convenient to label each of the shielding surfaces by a unique identifier. For convenience, the exterior surface of the system will be denoted by $s=1$, with the value of s increasing in steps of unity moving into the system. Each s surface separates two volumes which are denoted by the symbol v, with the volume external to the entire system being denoted by $v=0$. Upon penetrating the $s=1$ surface, the inside volume is labeled by $v=1$, etc. The total number of surfaces penetrated in going from the external region to ports of the critical circuits is said to be the shielding level of the system. Figure 2 shows a simplified schematic of this concept.

With this notation, the $s=1$ shielding layer of an aircraft usually will refer to the aircraft skin. However, some exceptions can always be found, and such definitions must be used with caution. Consider, for example, the open Wright biplane shown in Figure 3, which was completely unprotected from electromagnetic radiation. If it had a radio which was enclosed in a metallic enclosure, the $s=1$ layer would be that shield, and the aircraft would be an example of a system with a shielding level of 1. If, however, there were no radio or metallic enclosure, the aircraft would have a shielding level of 0. In a conventional, metallic skin aircraft, the s_2 shielding layer is often simply the braided shield of co-axial cables and the metallic shields surrounding electronic

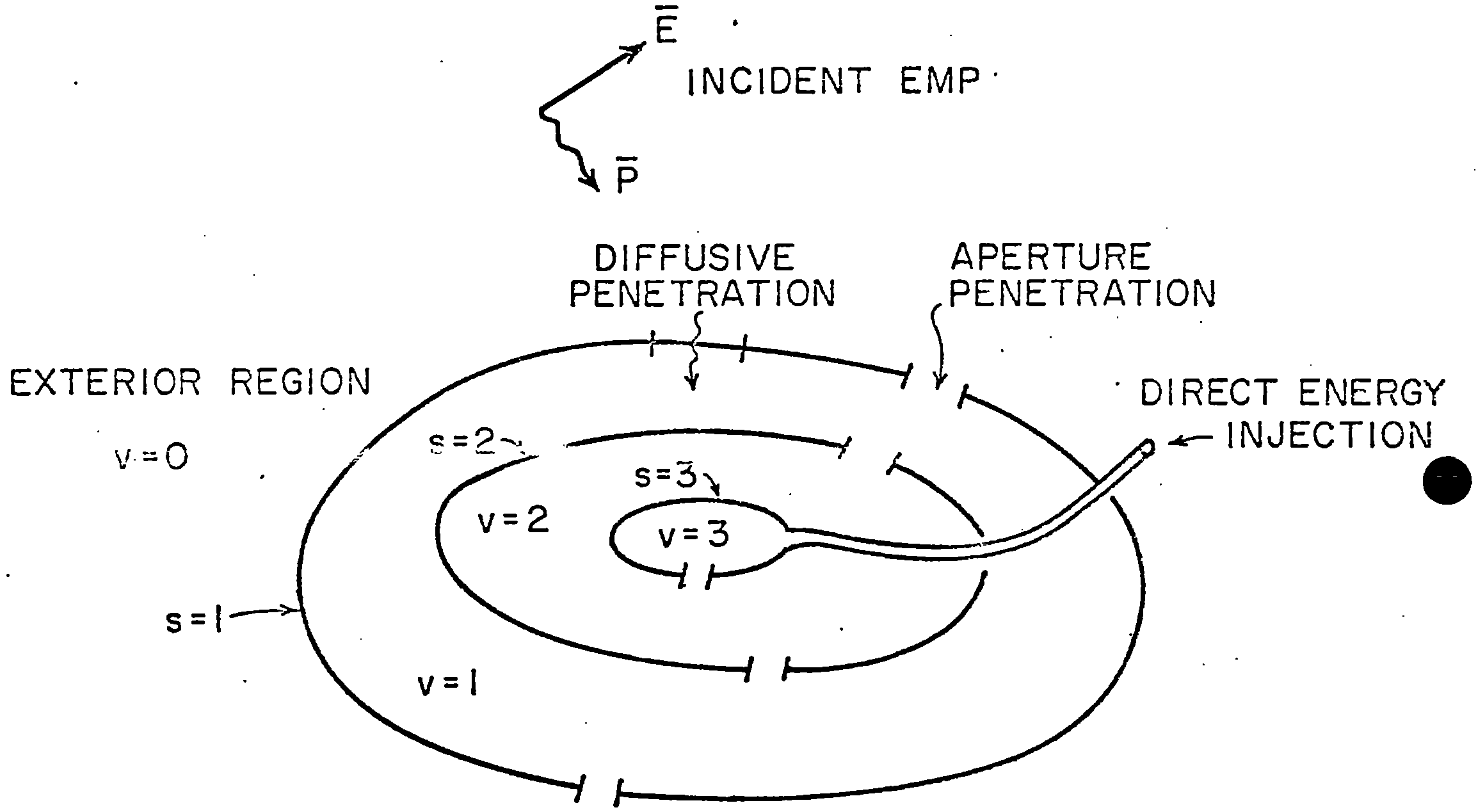


Figure 2. Simplified Shield Topology

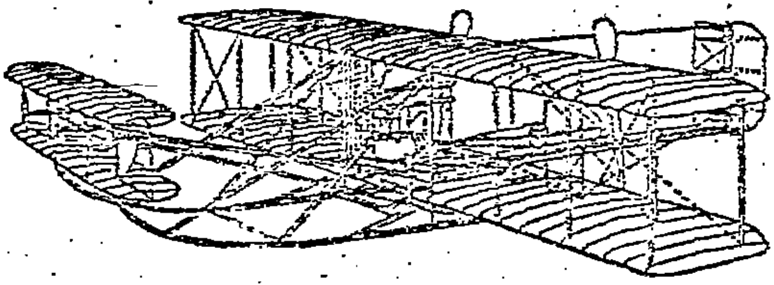


Figure 3. Unshielded Aircraft

components. The B-1 aircraft, as shown in Figure 4, is an example of a system with a possible shielding level of 3, the three surfaces being the aircraft skin, the conduit skin, and the outer conductor of co-axial lines (if any) within the conduit.

It is to be noted that the above definition is not sufficient to completely describe a complex system in a topological sense. An actual aircraft will have many individual compartments located inside the $s=1$ surface, but which do not lie within the $s=2$ layer. These voids, such as the bomb bay, wheel wells, equipment bays, etc., can act much like a shielded enclosure and are seen in the B-1 of Figure 4. Thus, much of the formalism which can be applied to the analysis of the shielding properties of the s surfaces can also be used for treating these enclosures.

Because all of these sub-volumes occupy part of the same v volume, it is necessary to employ another index, t, to be able to distinguish between the various regions. Figure 5 shows an example of a more complete version of a a shielded system. Within the $v=1$ region, it is noted that there are four sub-volumes labeled by $t=1,2,3$ and 4. Thus, a particular volume within a system can be labeled by two parameters, v and t, which will be defined as the longitudinal and transverse shielding numbers, respectively. With the topological description of a system, it is possible to identify a number of generic problems

FEB - Forward Equipment Bay
CEB - Central Equipment Bay
FWB - Forward Weapons Bay
CWB - Central Weapons Bay
WWCEB - Wheel Well Central Equipment Bay
WWLEB - Wheel Well Left Side Equipment Bay
AWB - Aft Weapons Bay
AEB - Aft Equipment Bay

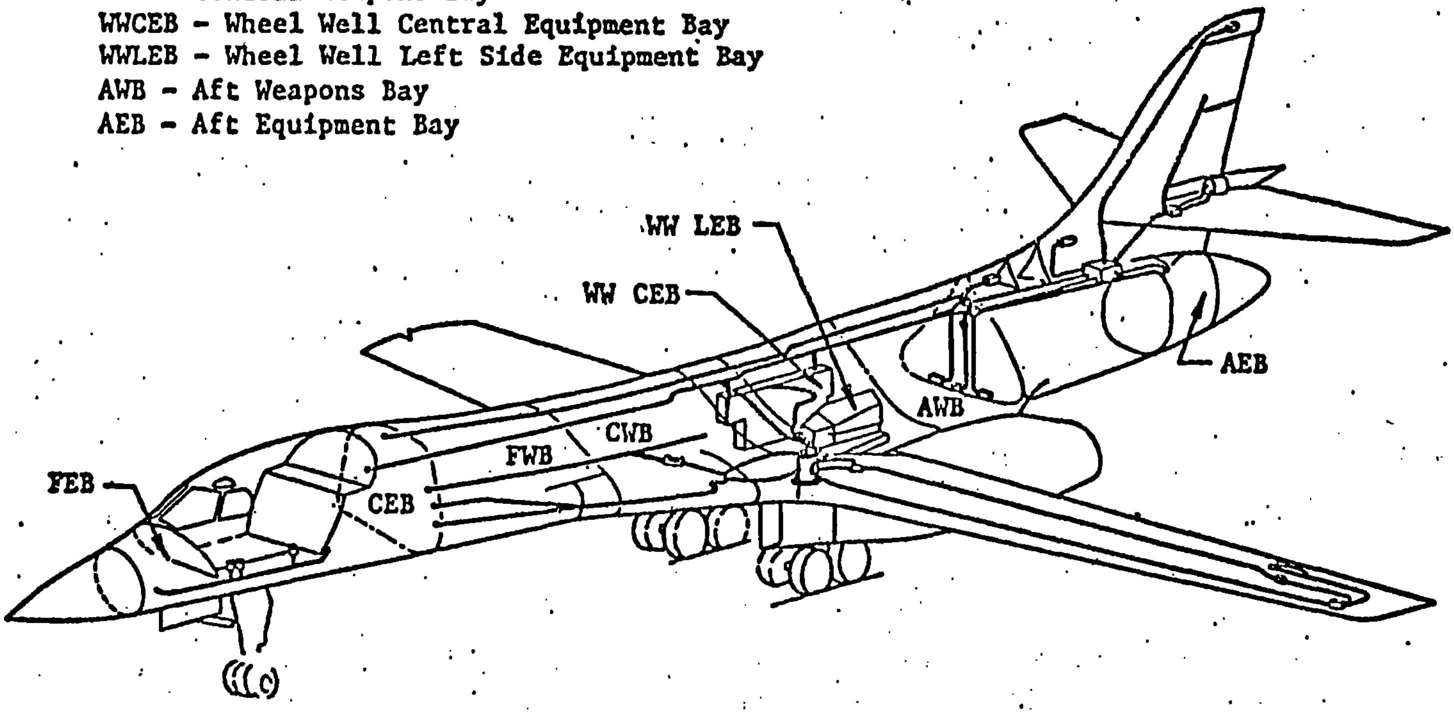


Figure 4. B-1 Aircraft Showing Conduit System and Topological Configuration

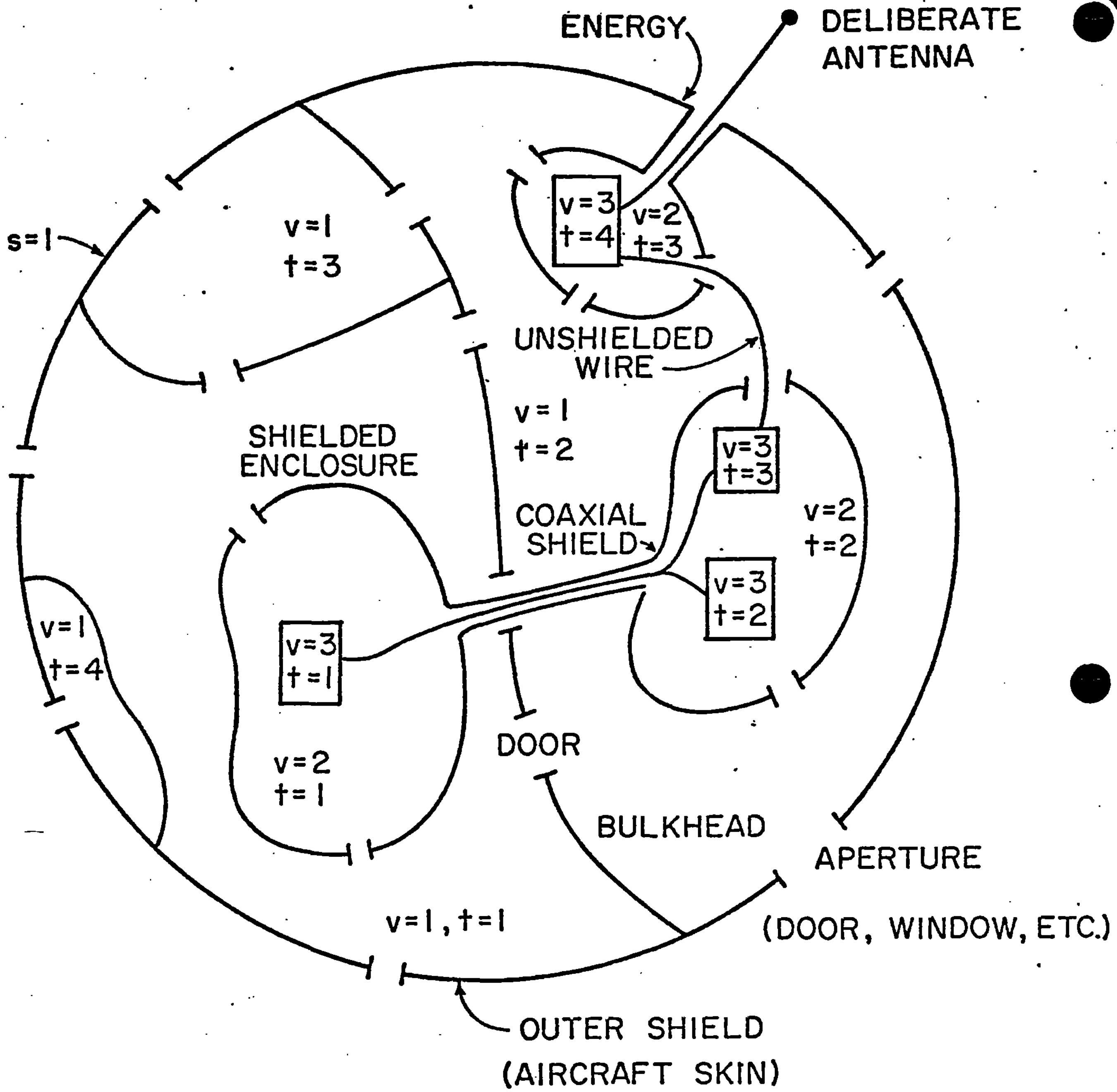


Figure 5. More General Topological Model

which occur in the area of internal interaction, as well as make a more rigorous definition of internal interaction.

According to common usage, the term "external interaction" relates to the determination of the currents and charges induced on surface s=1 of a system, due to external sources in v=0. The response may be either in the time or frequency domain and are often accomplished by solving an appropriate boundary value problem.

Using the results of the external interaction results on s=1, the currents and charges used to determine equivalent sources serve to quantify the exteranl penetration mechanisms and permit an evaluation of the energy which penetrates the first shielding layer.

Energy that penetrates s=1 will then radiate into v=1 and be distributed over s=2. In some cases, the problem will be similar to an unbounded radiation problem with a small excitation source (aperture on s=1) and a small cable shield (s=2) located far away. At other times, the problem may take on characteristics resembling more of a waveguide geometry, with waves being continuously reflected off of s=1 and s=2. Nevertheless, the main concern is to compute the induced charges and currents on the s=2 surface to be able to permit the consideration of fields with the v=2 volume. Internal interaction within a typical volume v=n, therefore, may be formally defined as the following: The excitation and propagation of charge and current on an internal longitudinal layer or surface s=n+1, due to sources on surface s=n or within the volume v=n. The sources on s=n are due to field penetrations through the shielding layer and those in v=n are due to cables or similar conductors which can inject signals into the region. (SGEMP/IEMP would be another mechanism for producing v=n sources.)

Finally, it is desirable to introduce the concept of the order of the internal interaction. This simply denotes the v value of the volume in which the internal interaction and propagation is being considered, or the s layer for considerations of surface penetration. Thus, exterior penetrations (from v=0 to v=1) are described as penetrations of order 1 and internal interaction within v=1 are also said to be of first order. The maximum shielding order possible on a system is equal to the level of shielding, and it is usually true that the larger the shielding level, the harder the system is to EMP penetrations.

Another useful diagram for understanding internal interaction problems is the interaction sequence diagram. This is a diagram of all possible interaction paths from one volume to another in the system topological model. Thus, it may be regarded as a diagram orthogonal to the topological model.

A portion of the interaction sequence diagram for the geometry of Figure 5 is illustrated in Figure 6. The dotted lines represent the topological configuration of

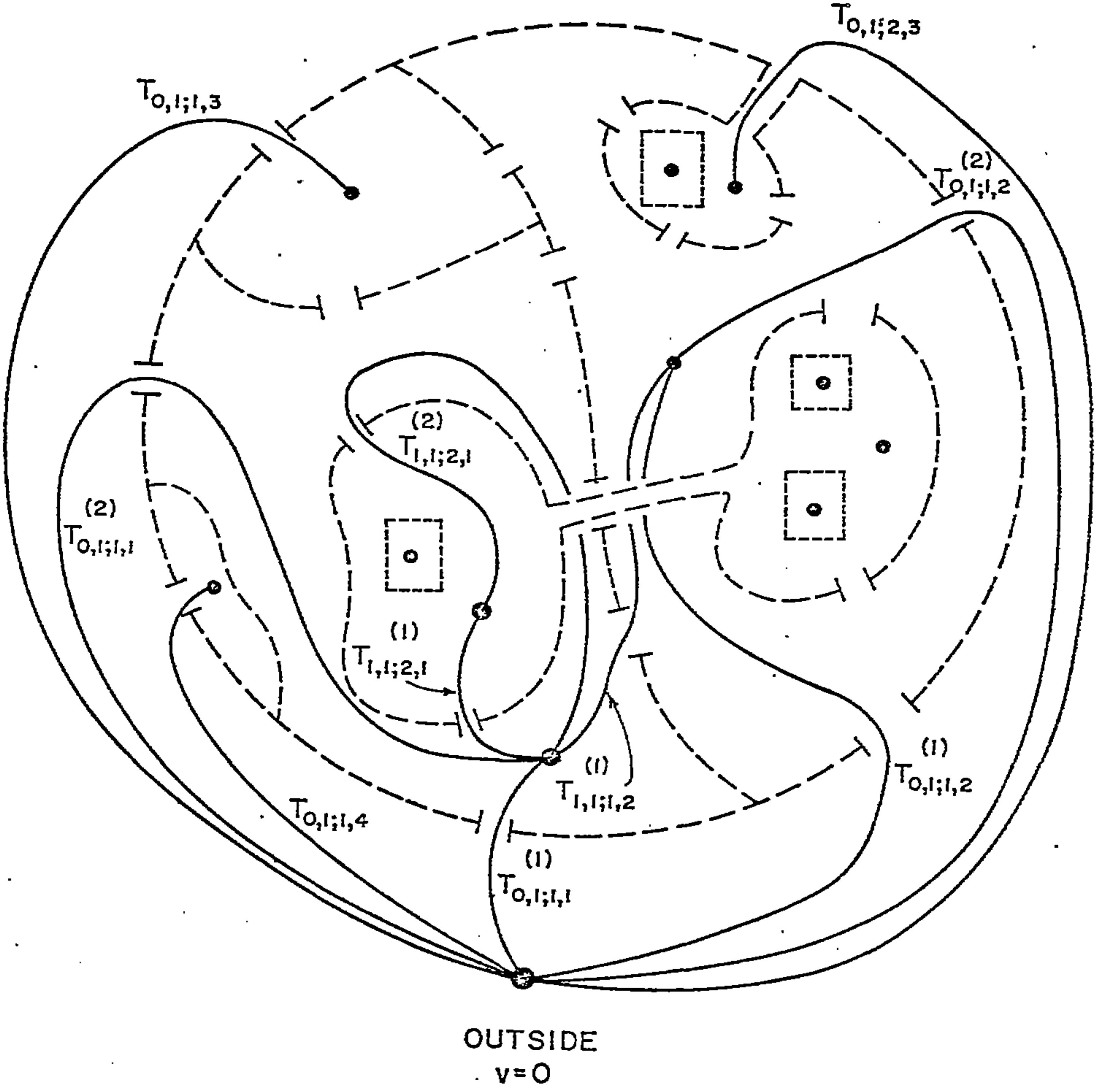


Figure 6. Interaction Sequence Diagram

the system and the solid lines are the interaction paths from the outside (v=0) to various volumes inside. The transfer function for a particular path connecting the v,t region to the v',t' region is denoted by $T_{v,t;v',t'}$. For more than one port of entry, the superscript (1), (2) or (n) will distinguish between the different transfer functions.

Notice that the entire interaction sequence diagram can be quite complicated. In many cases, only the most important coupling paths are considered, thereby reducing the complexity of the analysis. For example, the cross-volume transfer function $T^{(1)}_{1,1;1,2}$ may yield much smaller effects than other transfer functions providing excitations to the v=1,t=1 and v=1 and t=2 regions, and can thus be neglected.

It is clear that the above formalism can be somewhat ambiguous in certain circumstances. For example, if an aperture becomes too large, it is difficult to define two distinct volumes on either side of the aperture. How, therefore, does one decide what the largest aperture is so as to permit such a topological distinction between the two regions? Notwithstanding such difficulties, however, the outlined topological description of complicated systems can aid in providing a unified approach to define important problems in internal interaction and to eventually permit a more rigorous analysis of the complete system.

III. Preliminary View of Needed Improvements of Internal Interaction Models

From the topological description of a system, it is seen that there are two basic categories of problems which are of interest in internal interaction analysis. They involve the penetration of EMP energy through shielded regions and the subsequent propagation of energy within the volume separating two regions. By being able to solve and understand the solutions to a variety of such problems, the much more complex analysis of an actual aircraft can be considered.

In a recent note, Baum, et al.(2) describes and categorizes various types of apertures which serve as ports of entry for EMP. Although numerical results were not given, the basic topological configurations of several classes of apertures were discussed. A few numerical studies of aperture penetration have been completed recently(3,4), but it still appears that much work needs to be considered in the following general problem areas:

1. Apertures on curved surfaces
2. Apertures on bodies of finite extent
3. Multiple aperture and/or other obstacle interaction

For a further description of the needed improvements in the aperture penetration problem, the reader is referred to

Reference 2. The remainder of this report will concentrate on the methods of calculating how energy propagates within shielded regions after it has penetrated a shielding surface.

In the area of energy propagation within the shielded layers, the bulk of the past work and analysis has involved transmission line theory. A large effort has gone into developing the common mode, single wire model(5). However, the common mode approach is useful only when a bundle of cables has a common source and a common load.

A bundle of cables connected to separate loads, even if they are equal, will excite many other modes on the transmission line. The common mode analysis is particularly inadequate when different modes have different propagation constants, such as cables with dielectric claddings. Thus, even in a simple branched system, such as shown in Figure (7), the common mode analysis can not be rigorously applied, even between points A and B.

The application of the single wire analysis to extremely complex cable systems is not justified because cable bundles rarely terminate in a common load. Extensive experimental verification of the single wire model as described in Reference 5 amounts to a reconfirmation of the textbook transmission line theory for simple cables and gives an indication that a more rigorous multimode theory is needed for complex cables.

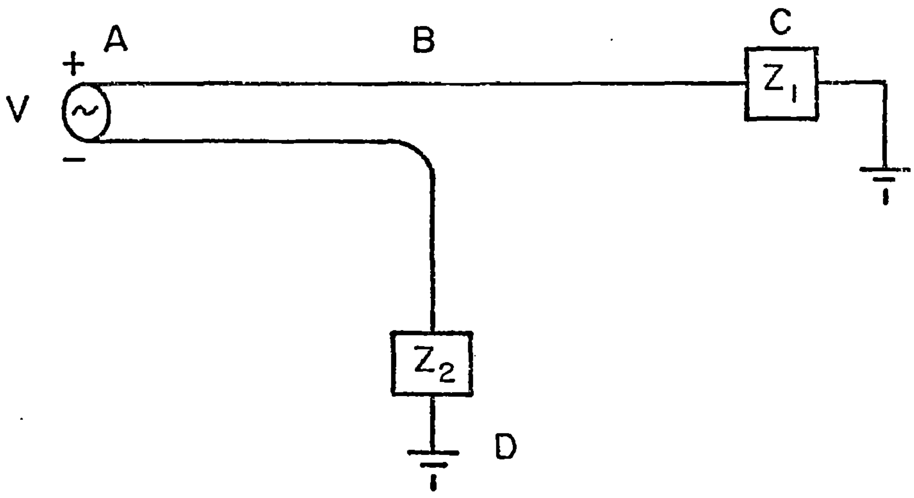


Figure 7. Simple Branched Cable

For example, comparisons of calculated results and experimentally-determined direct drive cable responses were made for transfer functions in the frequency domain, so as to provide accuracy estimates of the single line model. Simple cable configurations showed less than 2 db (25 percent) variation to 30 MHz, reconfirming the basic transmission line theory. However, cables with several branches, many wires and unequal terminations, agreed to only within 6-12 db (100-300 percent) at resonant frequencies and as poorly as 20-30 db (900-3000 percent) at some antiresonances. The difficulty is, of course, that the differential currents, which are prevalent for unequal terminations and sources, are not included in the common mode single wire model.

If one insists that a single line model be used for analysis, there are further sources of errors introduced in attempting to identify the geometry of the single wire system. A principal source of error in the single wire model is in the definition of the simplified cable diagram which provides input parameters to the common mode single wire model. This definition includes cable branch identification, branch and segment lengths, and cable excitations. Errors as large as 6db in the Thevenin responses are cited due to uncertainties about how close two cables are and for what length they parallel each other. Branching uncertainties near where the Thevenin response is calculated lead to errors as large as 20 db. Uncertainties in branch and segment lengths can be estimated to 10 percent, and primarily lead to shifts in resonant frequencies and Thevenin response errors of less than 3 db.

It is therefore evident that the N-wire multimode is the only correct way to analyze the complicated cables found in the internal coupling areas. In some cases, N may not be the number of cables in a particular bundle, but rather the number of different terminations.

Some limited work in the area of multimode cable analysis has been performed. Usually, however, a number of simplifications are made which severely limit the usefulness of the results. The calculations of the self and mutual inductances between cables within a bundle are often made using a simple formula which is only correct if the distances between the cables are much greater than the diameters of the cables. This condition obviously is not satisfied in many cable bundles. In addition, to find the mutual capacitances, the previous work uses the inversion of the inductance matrix which is valid only in a uniform dielectric medium. That condition is also not satisfied by a cable bundle where each cable has an individual dielectric cladding. In addition, the same previous work uses only an average dielectric constant which is obtained from experimental measurement. This procedure makes comparison of theory and experiment meaningless, because they are no longer independent.

The proper way of handling the multimode problem is to find the inductance and capacitance matrices separately through the solutions of boundary value problems. Frankel(6) gives one a good account of this approach in his book.

Aside from difficulties involved with the understanding of how energy propagates on an N conductor line, there are added problems with the calculation of how these lines are excited by an incident field or through penetrations in the shielding layers. Experience with F-111 port of entry closure tests indicates that the identification of cable excitation magnitudes and locations is often difficult. It is pointed out that while many of the major ports of entry have been identified for the B-1, actual penetrations into the cables are uncertain. The main items of importance are connectors, conduit joints, unshielded wires and terminations, and flexible braid shields.

IV. Possible Applications of Statistical Analysis to Internal Interaction

Throughout this discussion, a tacit assumption has been made regarding the solvability of an actual, electrically-complicated system. It is presumed that by looking at the system closely enough, a number of relatively simple geometrical configurations between cables, apertures, etc., will be evident. The results of analyses applied to each problem can then be combined to predict the behavior of the entire system.

It may well be, however, that such a deterministic approach is not efficient due to the large degree of mutual interaction between the elements of the system. The possibility exists, therefore, that a statistical approach to the internal interaction problem may prove to be useful for analysis.

There are at least two senses in which statistical notions might be applied to analysis of internal coupling problems. The first is essentially descriptive and can be applied to many aspects of the complete problem. For example, the distribution of the values of the terminating impedances on a "typical" multiconductor cable, the number and separation of branches of a wire bundle, the distribution in size and shape of internal cavities in an aircraft, or the distribution of values of transfer impedance at a typical joint in the skin of a shield enclosure, such as an aircraft, could be described statistically. Statistical descriptive data can be expected to be useful in bouding the coupling problem, as well as providing more direct inputs to analytical techniques.

The second application of statistical analysis is predictive and might be regarded as very closely analogous to the use of statistical methods in chemistry and physics, where the very complexity of certain problems causes overall regularities to arise. Some regularities can be accurately described. Such collective characteristics as the distribution of velocity of particles in a gas can be accurately predicted by an appropriate theory. Several possibilities for the development and application of a statistical analysis of interaction phenomena (in this second sense) also suggest themselves.

One might, for example, choose to regard the electrical interior of an aircraft as consisting of an enormous number of weakly-coupled circuits which are excited by inputs from a number of primary penetrations. The distribution of energy amongst individual circuits (or modes of oscillation of the total circuit network) should be predictable from basic descriptive data and a theoretical model analogous to that used in the statistical mechanics of gases.

Another application at a more detailed level could be to the propagation characteristics of cables. "Single-conductor" equivalents of very complex cables have been constructed and applied to analysis of certain internal interaction problems. Statistical assumptions regarding the distribution of total core current amongst propagation modes in the bundle are implicit in the use of such a model. It is evident that refinements of such a model would be useful. A brute-force approach could include "Monte-Carlo" evaluations of average cable parameters by looking at a distribution of deterministic cases. A number of authors (7,8) have looked into some aspects of this problem and one (9) is presently applying statistical concepts to the internal interaction area.

Still another question that could be considered statistically involves the gross propagation characteristics of a cavity. In many places in an aircraft, for example, bulkheads are literally covered with cables, pipes, and other metallic/dielectric structures. The conventional assumption of perfectly-conducting boundaries is probably less appropriate in such a situation than the determination of some statistically-defined effective surface impedance.

It is clear that inputs of data from statistical analysis as it is used in the first sense above would be important for the second kind of analyses. It is also clear that carefully planned experiments would be necessary to demonstrate the validity and usefulness of a predictive statistical model of coupling phenomena.

V. Summary and Conclusions

This note has discussed various topological concepts of shielding as applied to the internal interaction of EMP energy to aircraft and illustrated these concepts with some sample geometries. Using such a topological approach to internal interaction problems provides a logical basis for dividing the overall problem into penetration problems from one shielding level to another and coupling and propagation problems in within the particicular shielded region.

A preliminary examination of needed improvements of internal interaction models leads to the conclusion that the frequently-employed single line transmission line model ("bulk" or "common" mode model) is inaccurate. More effort should be put into developing more sophisticated transmission line models for the internal interaction area.

Finally, a brief discussion of statistical methods and their relation to internal interaction is given. It is anticipated that a statistical approach could have a potentially large impact on analysis for extremely large and complicated systems if it is done properly.

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