Interaction Notes

Note 559

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How to Think About Electromagnetic Interaction: A Statistical Approach

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Abstract

Statistical electromagnetics is used to develop an approach independent of deterministic calculations to evaluate the coupling of external electromagnetic fields to conductors within a cavity. It is shown that it is most useful when systems or threats are either complex or are not well defined. Its applicability to real systems is demonstrated in evaluating both hardening and susceptibility.

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I. Introduction

Back in the 1970s, when EMP (electromagnetic pulse) was the major electromagnetic threat to military systems, Carl Baum wrote a brief, seminal paper on the interaction of systems with EMP ("How to Think About EMP Interaction," Carl E. Baum, Air Force Weapons Laboratory, April 1974). A copy is included as Appendix A. The ideas expressed in that paper (the impracticality of solving the interaction problem with computers, the system definition problem, the value of mathematical and topological decomposition) still apply over twenty-five years later to the variety of electromagnetic interaction problems we face (HPM, EMI, EMC, EMP, etc.). An implicit assumption in the work done at that time in solving the EMP interaction problem was that the desired solutions were deterministic, as opposed to statistical. Figure 1 illustrates the general electromagnetic interaction problem as outlined by Baum. This is a simplified version of Baum's Figure 2, and we have broadened his EMP Interaction to Electromagnetic Interaction.

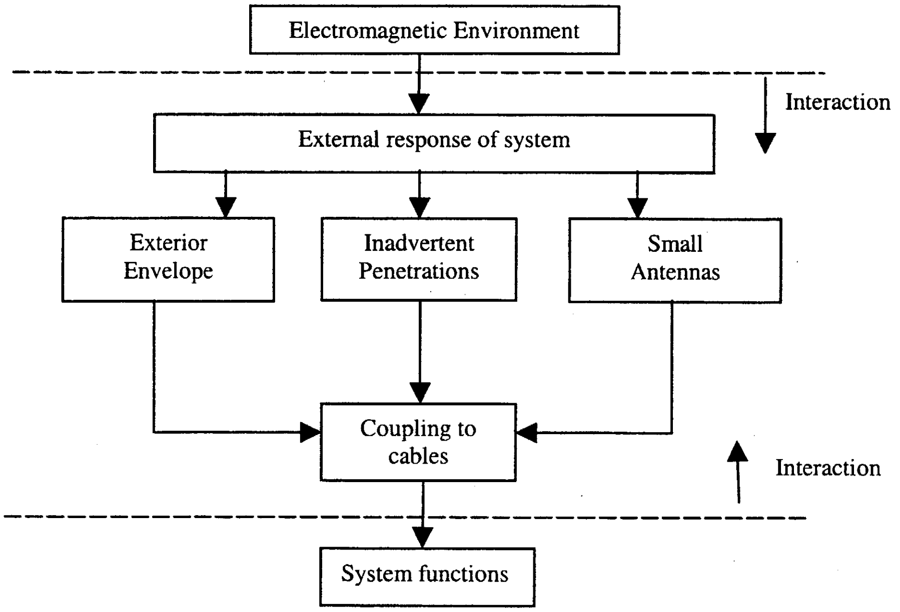

Figure 1. The Electromagnetic Interaction Problem

Significant changes in computer power have taken place since Baum discussed the "impracticality of solving the interaction problem with computers". This has resulted in an improvement of the deterministic models for electromagnetic coupling. One of the best examples of these models is CRIPTE. As good as CRIPTE is, it cannot model systems that are poorly characterized.

In the present paper, we address the "impracticality of solving the interaction problem with computers" noted by Baum. First, we describe a statistical approach to this problem. Second, we demonstrate its applicability to real systems. Third, we describe the hardening of systems using this approach. Statistical Electromagnetics (STEM) is an independent alternative that is applicable to all the topological parts of Figure 1. It can be used alone or in conjunction with other models or deterministic approaches that are applicable to other parts of the problem. Details of this approach are described in the recently published *Statistical Electromagnetics*, Taylor and Francis, 1999, by two of the authors of this paper, Richard Holland and Richard St. John.

II. A Statistical Approach to the Electromagnetic Interaction Problem

Most models built to understand system electromagnetic responses have been deterministic, and it is very useful to decompose systems, as Baum outlined in his paper, using these deterministic models. However, the "electromagnetic mess" that Baum recognized in his paper can be dealt with more successfully, we believe, using a statistical approach. In particular, in systems that are too complex or are unavailable for a hands-on examination, the statistical approach (although not as good as an exact answer) is probably the only solution that can be obtained. In this paper we outline the STEM approach and provide a worked example of its application.

Statistics is used in STEM in two ways. The first characterizes the plethora of nearly random electromagnetic fields in enclosures. The study of this random behavior is the origin of STEM. The second way characterizes the statistical variations in deterministic parameters such as incident power, illumination angle, spectrum, cable lengths, cable bundling configurations, etc. or in inherently variable quantities such as transfer functions of apertures, penetrations, and coupling ratios. These two ways may be combined to find overall survivability/vulnerability probabilities in electromagnetic interaction problems. In this discussion, we will concentrate on the statistical behavior of fields in cavities, but it should be kept in mind that the statistical approach can be applied to numerous other aspects of the problem.

STEM can be used to estimate the probability of effect of incident electromagnetic fields on electronics within any enclosure with a sufficiently high Q. The process requires obtaining data about a variety of enclosures: buildings, satellites, aircraft, mobile units, missiles, etc. STEM combines the variations of the primary physical factors in these enclosures with the electromagnetic environment variations to find the probability of effect.

This approach includes four basic steps in determining the probability that a given electromagnetic environment has an effect on a system (enclosure and internal electronics):

First, the Q and total effective area of the enclosure of interest (a bunker, mobile shelter, fixed command center, aircraft, satellite, etc.) are found through a combination of experiment and analysis.

> The **power** admitted to the enclosure interior is a function of the external field and the paths for energy transfer into the building.

> The paths into the enclosure are apertures, diffusion, and external conductors (see Figure 1). Large apertures, together with diffusion, conducting penetrations, and small aperture penetrations, add to form an effective aperture with units of m^2. This effective aperture in m^2 times the incident power density in W/m^2 yields the power transferred into the volume in W.
>
> Testing gives the "effective aperture" as a quantity with units of m^2, describing the ratio of the incident power density to the power transferred into the enclosure, rather than a physical area.

In the absence of intentional RF absorbers, Q is a function primarily of the construction of the enclosure walls. As with the effective aperture, Q is determined through testing--illuminating the exterior of an enclosure and measuring the interior fields, one finds the product QA_{eff}. Q alone can be found by radiating a known power within an enclosure.

A database with classes of objects is needed to determine the expected range of Q and A_{eff}. The program of acquiring this database can begin with existing experimental and code-derived data. The database is built from a combination of experimental data and the analytical effects of known construction techniques. Ranges in the expected Q and A_{eff} of the enclosure then assist in estimating their distributions. Details of this approach are discussed below.

Second, The internal electric or magnetic field is calculated from the **power** admitted into the system enclosure and the Q of the enclosure, using the formula,

$$E^2 = Z_0 \frac{QP_{inc}A_{eff}\lambda}{\pi V}$$

where E is the enclosure mean electric field, Z_0 the impedance of free space, P_{inc} the power density incident on the enclosure exterior, V the enclosure volume, and λ the wavelength. A discussion which leads to the above equation is provided at the end Chapter 10 in *Statistical Electromagnetics*.

Third, the currents on the cables within the enclosure are determined as a function of the physical parameters of the cables and the mean of the square of the internal electric or magnetic field using STEM and a distributed transmission line model.

Fourth, the probability of effect of the incident fields is determined with a knowledge of system susceptibility at the component level. This step uses the relationship between the internal field and the cable current.

The schematic diagram illustrated in Figure 2 below summarizes this four-step process.

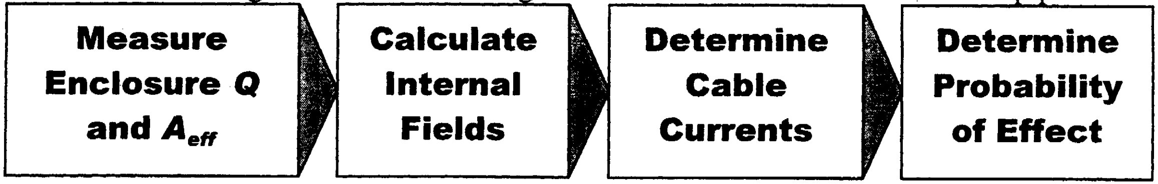

Figure 2. The four-step process to determine probability of effect

III. Application to Real Systems

As an example of the application of this STEM approach to real systems, we consider the creation and use of an enclosure database for aircraft, bunkers, and other buildings. As discussed above, the primary parameters of the database are Q and A_{eff} for each enclosure.

Q and A_{eff} for an enclosure are obtained through two separate measurements: the first is a transfer function yielding a value for the product QA_{eff}; the second is an evaluation of Q using either measurements of the internal field produced by a known power input or by a three-dimensional code calculation. The contents and use of the database are both referenced to 1) a type of enclosure and 2) physical variations in that enclosure.

Creation of the Database

The general principles behind the creation of the database will be shown for two examples: aircraft and bunkers. The same concepts are applicable to satellites, surface vehicles, and all types of buildings.

The database is formed from measurements and analysis over a select group of enclosures. Based on an understanding of the dominant physical processes in Q and A_{eff}, the database can then effectively encompass the entire parameter space of all enclosures. The select group is chosen to represent a range in the major physical parameters expected to affect Q and A_{eff}.

What Should be Measured

A *transfer function* is found from the ratio of the internal electric field to the external electric field (the latter taken in the absence of the structure). The statistics of this transfer function are obtained by varying the frequency of the source, the spatial orientation of the enclosure or the reference probe within the enclosure. The transfer function yields the quantity QA_{eff}. The transfer function can also be found through three-dimensional code calculations if the geometry is sufficiently simple. This latter approach would be applicable to large, relatively empty buildings.

Q is measured by inserting both the reference sensor and a radiating antenna within the enclosure and finding Q from its original definition,

$$Q = 2\pi \frac{\text{total energy in the volume}}{\text{energy lost per cycle}}$$

where the energy lost per cycle is the known power input to the enclosure. For buildings, or other enclosures with simple geometries, the three-dimensional code calculations can also find Q from the losses seen in the walls or from the buildup of the internal field with a known power input.

Building a Database for Aircraft

Aircraft are generally composed of similar materials. The primary difference in aircraft is construction techniques. Let us say that evaluations of the transfer functions of a US aircraft (USAC) and a foreign aircraft (FAC1) show the standard deviation and the average to be larger in FAC1 than in USAC. Let us also assume that the measurement of Q for the two aircraft shows the two have a similar value of Q.

- A_{eff} and Q are both entered as distributions in the database.

An examination of the construction techniques will show if the dominant physical process leading to the difference in QA_{eff} (and thus A_{eff}) is a different quality control in the tolerance of the construction of the electronics bays, a different use of hardening techniques (such as shielded cables or circumferential shield terminations), or a third, unanticipated, difference in materials or construction.

For each equipment bay, transfer functions yield the product QA_{eff} through a measurement of the ratio of the incident and internal electric fields. These measurements can range over location or frequency. Typically, a single measurement of the external field is made in the absence of the aircraft using an EG&G ACD-4 or ACD-7 D-dot probe sensitive to the derivative of the electric field. The internal field is then found using a similar probe inside the aircraft equipment bay operating over the location or frequency range. Measurements in several different aircraft bays characterize the range of the mean value of the electric field expected for the aircraft electronics. The range of the electric field mean values then estimates the variation in the associated probability distribution functions expected for this type of aircraft bay.

- The dominant physical parameters on which Q and A_{eff} depend are noted.

If the database is composed only of these two cases (USAC and FAC1), the statistical variation of Q and A_{eff} can be based on the observed variation in the physical parameters that lead to the measured behavior. How this is used will be discussed shortly.

Building a Database for Bunkers and Buildings

The database for bunkers or buildings would be created in a similar fashion. As with aircraft, various buildings are also composed of similar materials; however, their differences are greater than that expected with aircraft. Construction techniques employ anything from sheet rock to reinforced concrete to sheet steel. Buildings of several types will have to be tested for Q and A_{eff}. Extensive measurements have been made on shield rooms and little additional information is expected from examining these further. Buildings with minimal shielding may not even be appropriately analyzed by STEM, but at present, it is not known what level of shielding can be considered minimal. Buildings with an intermediate amount of shielding (such as those with steel-reinforced-concrete construction or metal, prefabricated construction--Butler buildings) are probably amenable to analysis with STEM and should be investigated. Testing can employ actual measurements or, in the case of steel-reinforced concrete buildings, a three-dimensional code analysis may suffice. For each class of building, say sheet-rock, steel-reinforced concrete, prefabricated metal, etc., as a first step,

- A_{eff} and Q are entered as distributions in the database.

Each type of construction will have physical variations that affect the distributions. Examples would be the presence of windows, spacing of the rebar, wall thickness, use of metal studs, etc. This variation leads to a set of physical parameters that are important in defining Q and A_{eff} for each building type.

- The dominant physical parameters on which Q and A_{eff} depend are noted.

The statistical variation of Q and A_{eff} can be related to the observed variation in the physical parameters that lead to the measured behavior. As in the aircraft example, how this is used will be discussed next.

Use of the Database

The database is used to derive appropriate distributions of Q and A_{eff} for enclosures, which have not been measured. These parameters give the internal electric field as a function of the external field. The internal field is then used to derive the expected current on cables and the probability of effect of an electromagnetic source on the enclosure. The following discussion will focus only on the derivation of distributions for Q and A_{eff}.

Using the Database for Aircraft

Let us assume that the database contains only Q and A_{eff} from measurements on a US aircraft (USAC) and a foreign aircraft (FAC1). It includes the primary physical parameters affecting Q and A_{eff}. We will assume we are interested in three other foreign aircraft, FAC2, FAC3 and FAC4.

FAC2 (Made by same country as FAC1)

Let us say FAC2 is made by the same country as FAC1, but FAC2 is a bomber and FAC1 aircraft is a fighter. Since they are made by the same country, we will assume that FAC2 has the same Q and A_{eff} as FAC1. In the absence of any other information, these distributions will be used. Any other assumption requires knowing how the major physical parameters affecting Q and A_{eff} differ between the two aircraft. If we know that cables are shielded differently or that the electronics boxes are made differently, the estimated variation in these parameters will be used to modify the distributions for Q and A_{eff}.

FAC3 (Made by a co-producing country as the manufacturer of FAC1)

We assume that FAC3 is made by a country that is the ally of the producer of FAC1, and that they have obtained FAC1 production facilities. This results in the same assumption as above: FAC3 will have the same Q and A_{eff} as FAC1. Again, in the absence of any other information, these distributions will be used. Again, any other assumption requires knowing how the major physical parameters affecting Q and A_{eff} differ between the two aircraft. If we know that cables are shielded differently or that the electronics boxes are made differently, the estimated variation in these parameters will be used to modify the distributions for Q and A_{eff}.

FAC4 (European aircraft)

European aircraft are made similarly to US aircraft. The first estimate to be used for the Q and A_{eff} of FAC4 would be those entered in the database for USAC. As in the other cases, with more information on the construction techniques on which Q and A_{eff} depend, the variations of the appropriate physical parameters can be combined with the distributions of Q and A_{eff} to get the appropriate distributions needed to derive the internal field strengths.

Using the Database for a Bunker

As in the case of aircraft, the more details that are known about the bunker the better one can estimate the effect that an electromagnetic source may have on the interior electronics. Assume that one can at least see the enclosure and estimate its size. An examination will also show if it has windows and what type of doors it may have. If it has windows, they are the dominant physical characteristic allowing the entrance of energy into the enclosure. The first use of the database will be to derive an A_{eff} from the size of the windows and a Q from a generic enclosure. Further assumptions require more information: if this type or a similar type of bunker has been physically destroyed elsewhere, the distribution in the geometry of the rebar structure can be approximated. This variation affects both Q and A_{eff} and can now be combined with previous estimates for more appropriate distributions for Q and A_{eff}.

IV. Enclosure Hardening

We use aircraft to describe the concept of enclosure hardening, although this approach is applicable to any enclosure. Aircraft fleet hardening requirements for a known external threat are found through the distribution of the internal field mean and the distributions determined from Q and A_{eff}. The enclosure cable current probability distributions are then calculated knowing the physical parameters of the cables and the internal field. From these cable current distributions, the probability of effect is then calculated for the enclosure, and a required hardening is determined.

Consider a typical current prediction using a constant internal field strength and a field strength with a variation is shown in Figure 3. If a component effect threshold is 0.5 mA (vertical dashed line), it can be seen that the probability of the current exceeding that value is zero when one assumes the mean internal energy density from aircraft to aircraft is a constant (solid curve). If the aircraft-to-aircraft mean internal energy density has a Gaussian distribution with a standard deviation 50% of its mean (dashed curve), the probability that the current will exceed 0.5 mA is about 2% (horizontal line marking the intersection of the distribution with the 0.5-mA threshold; this line lies above 98% of the cable-current values).

So, if a few percent probability of effect (2% of the aircraft affected for the case in Figure 3) is acceptable, the aircraft is sufficiently hardened. If this percentage of aircraft affected is not acceptable, further hardening is required. Then either the mean of the internal electric field in each aircraft or its variation from aircraft to aircraft (in this case the 50% standard deviation) must be reduced to lower the probability that the current exceeds the 0.5-mA component threshold.

Both the aircraft mean internal electric field and its fleet variation are reduced through changes in the transfer function. The transfer function itself is related to Q and A_{eff} with their properties related to physical construction. Now, the effect of changes to the construction can be linked to changes in the transfer function (Q and A_{eff}) which can be linked to changes in the mean and variation of the internal electric field. To evaluate the effects of the changes in the construction, a recalculation of the cable current with the newly estimated mean and variation of the internal electric field gives a new Figure 3 and new probability of the current exceeding the 0.5-mA threshold.

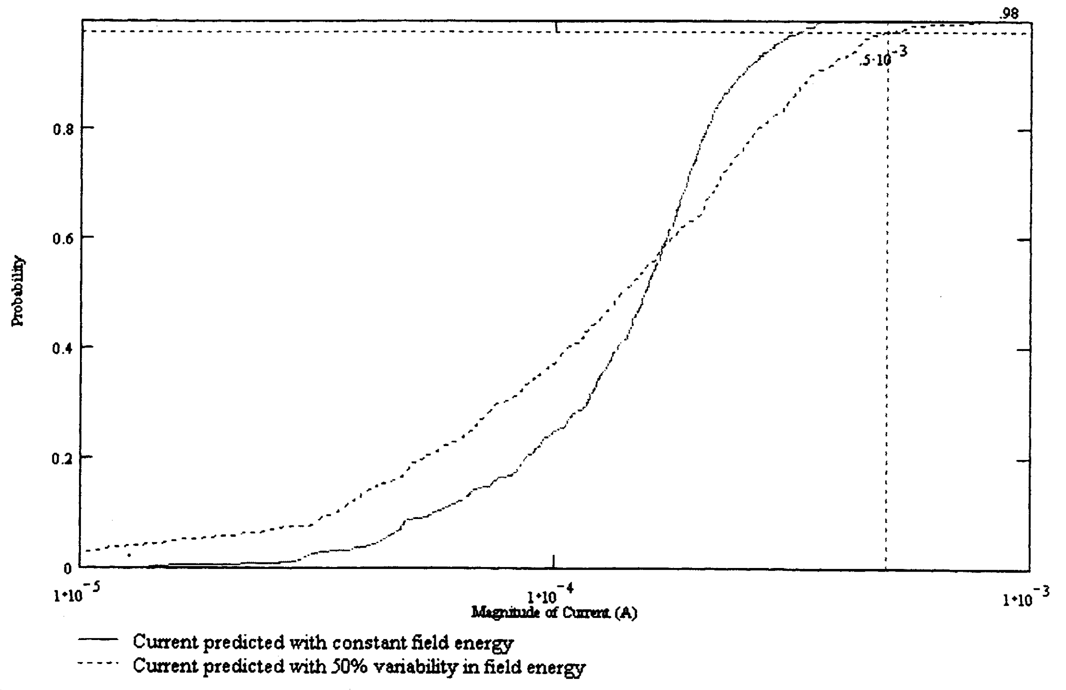

Figure 3. Cumulative distribution function for cable current with constant and variable average field magnitude.

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Appendix A

How to Think About EMP Interaction

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How to Think About EMP Interaction
(Abstracted from the Proceedings of
the 1974 Spring FULMEN Meeting held
at the Air Force Weapons Laboratory
16 and 17 April 1974)

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I. EMP Interaction

Ever since the general phenomenon of the nuclear electromagnetic pulse (EMP) has been known, its potential significance to system vulnerability has been a matter of interest. However, determining a system's vulnerability to an EMP environment by other than complete threat level tests (as complete as the state of the art would allow in EMP simulation) has been and continues to be a difficult problem.

In attempting to quantitatively analyze how EMP causes transient upset or permanent damage in some object such as a military system one is faced with a formidable problem, EMP interaction.

Definition:

> EMP interaction: the process of the generation of EMP signals in and the propagation of EMP signals into and through a system or a portion thereof.

EMP interaction starts after the EMP environment is given and ends before the system functional analysis. It considers the signals produced at various portions of the system and their relation to each other and to the EMP environment.

II. Difficulty of the Problem

EMP interaction is a formidable problem in two ways. First a system such as a ballistic missile, a communications terminal, an aircraft, a satellite, a ship, etc., is generally an electromagnetic mess. The electromagnetic existence and uniqueness theorems, properly utilized, guarantee that there is a unique solution to a given complicated distribution of conductors, dielectrics, and magnetic materials in space (including even nonlinear and active devices within restrictions) excited by a distribution of sources consistent with Maxwell's equations. However, existence and uniqueness do not in general tell one how to calculate a voltage here or a current there in some complicated problem.

A general approach to solving complicated geometries is to formulate an integral equation (say involving both electric and magnetic current densities) and having the "computer" solve the problem in some way. This is an appealing idea but somewhat naive. It is practical to solve pieces of the EMP interaction problem this way (such as for simplified external shapes of the system of concern) but gridding up an entire system, including pieces of the external skin, zones on apertures, every wire and cable shield, etc., is a formidable problem indeed for the largest computers existing or seriously contemplated.

Even if one could do a moment method gridding of the entire system it is not clear that it would be the best thing to do. Questions of accuracy become extremely difficult. The variation of the response to various parameters of the problem becomes much more complicated because of the very large number of parameters involved. A more clever approach is called for so that at least approximately the rational processes of human minds can comprehend what the important features are, how they depend on the important variables, and what can be done to correct the situation if required. Computer techniques are an invaluable aid in understanding EMP interaction and such techniques will need to be refined and extended. However, by themselves such techniques are not adequate. I suppose that at some point there may be some blurring between analytical and computer techniques (some of which may be already beginning) but this is likely a healthy thing which can lead to yet further progress.

A second problem concerns what a system is in fact as distinguished from what someone represents it to be (as in drawings, etc.). As discussed above the brute force analysis of a complicated system is possible in principle but not necessarily very useful. However, there is a fundamental flaw in the procedure in that the system being analyzed may be (and often is in important respects) the figment of someone's imagination. So before one gets carried away with analyzing a specific system in glorious detail he should stop at some point and question whether or not his various physical assumptions about the system configuration are in fact valid. I would call this the system definition problem.

The system definition problem is primarily an experimental problem. Such experiments are of various types. One can go out and look for oneself to see what the geometry really is. However, this is not completely adequate. Parts of the system are so inaccessible that one cannot see the internal geometry without a major system teardown. Furthermore some details of the relevant impedances (seams, etc.) are not obvious just by looking at them. While the problem is still an experimental one, some aspects of it are non trivial. Note that theoretical studies can help the experimental system definition by establishing in part what aspects of the system geometry, impedances, etc., are more important than others.

III. Decomposing EMP Interaction

As is usual in scientific investigations one tries to split up the problem into a set of problems. Each smaller problem presumably depends on fewer variables. Provided one knows how to combine the solutions of the smaller problems then one knows how to solve the larger problem in some factored manner.

One of the major functions of EMP interaction theory is then the decomposition of the interaction problem into smaller pieces. The smaller problems can then be analyzed. The results of the analysis of such smaller problems lead to various useful results besides the capability of calculating the appropriate impedances and transfer functions associated with the smaller problem. If one understands how a particular part of a system is quantitatively characterized in some efficient form then various benefits follow. First the form of the results of the analysis indicates some of the relevant parameters which can be used to specify types of experiments to be used to measure the more relevant parameters. Second the parameters in the results can be used as forms for specifications of the system performance at this smaller level (i.e., pieces of the system can have specifications imposed). Third the form of the solution can be used to organize engineering data in the form of simple formulas with tabulated or graphed parameters for such formulas for handbook type information.

In decomposing the EMP interaction problem there are at least two approaches to follow. The first is a physical or geometrical or topological decomposition. This is an obvious decomposition in the sense of considering pieces of the system such as antennas, apertures, shields, cables, etc. The problem here is to obtain the response of each piece in a form which allows an approximately consistent combination of the results for various pieces.

A second approach is a mathematical decomposition of the system response and the response of various pieces of the system into regions where various simplifying approximations are possible. By considering the response in separate frequency and/or time regimes the more general solutions can be expressed in more simple, but more approximate, forms. Such simpler forms typically show much more directly the characteristics of the response as a function of the relevant geometrical and impedance parameters.

IV. Physical Decomposition of EMP Interaction According to System Topology

One way to split up the system interaction with EMP is to consider the response of various pieces of the system. This is a decomposition on a physical or geometrical basis since various parts of the system can usually be localized to certain volumes of space.

In a more general sense this type of decomposition of the system is a topological decomposition. Consider that the system has zero, one, two, etc., layers of shielding which we might call topological shields. In an approximate sense each layer surrounds the successive layers as indicated in figure 1. One then thinks of EMP signals propagating from the outside in through successive shield layers (or inside out for cases in which reciprocity can be used).

At each shield layer there are a few kinds of problems to be considered. First, there is the coupling to the outside of the layer giving a distribution of external current and charge densities. Second, there are distributed penetrations through the layer in the usual shielding sense for fields or in terms of distributed equivalent sources (such as with cables). Third, there are discrete penetrations such as antennas, apertures, etc. Note that penetrations can be of a form that penetrate more than one shield layer. An example of this is an antenna feeding through the external envelope directly into the cable interior.

Associated with the various layer exteriors and penetrations there are transfer functions or matrices or more generalized transfer operators. Associated with various physical (topological) features of the system then there can be found transfer functions which when put together form an interaction transfer function into the system. The idea is then to physically decompose the system, associate an appropriate transfer function, equivalent circuit, etc., with each part, and then combine these back together for a system transfer function.

In considering the decomposition of the system according to physical features (topology) so as to establish generalized transfer functions for each piece an interaction sequence diagram as in figures 2 through 5 is useful. As one can see such a diagram is somewhat like a logic flow diagram (say for a computer program). Note, however, that an interaction sequence diagram allows flow in both directions simultaneously as required. This allows the transfer function in a given direction ("into" the system) to be influenced by conditions such as impedances at the next level to which a signal is coupling. Coupling from one level to the next can then be thought of in some kind of generalized chain matrix form where required.

Topological shielding levels can be identified with various physical features of systems. One typical type of system would have two layers of shielding as indicated in figure 2. The first layer is the metal envelope (skin) such as commonly used in missiles and aircraft; the second layer is the cable shields (braided or otherwise) together with black box shields which are electrically connected to the cable shields. Given the two shielding layers then one can consider penetrations through each. For convenience I have divided such penetrations into two kinds: distributed and discrete. Distributed interaction includes the usual kind of shielding (diffusion and inductive) as well as arrays of apertures over most of the shield. Discrete interaction includes deliberate antenna penetration, apertures (one or a few holes, including impedance loading), and other more complicated localized penetrations associated with conductors attaching to and/or passing through the shield.

Intermediate shielding layers are possible for systems. They might involve multiple outer walls, conduits for signal cables (including multiaxial conduits), and/or multiply shielded cables. By such techniques shielding orders of three and higher can be achieved. By shielding order I mean the number of shielding layers that are considered to be independent in some approximation.

Figures 2 through 5 show a few possible types of interaction sequence diagrams. Figure 2 is a case with a shielding order of 2, the shielding layers being external skin and cable shielding. Figure 3 is for a shielding order of 1 with the external skin as the shielding layer. Figure 4 is for a shielding order of 1 with the cable shields as the shielding layer. Figure 5 is for a shielding order of 0.

V. Mathematical Decomposition of EMP Interaction for Various Frequency and Time Regimes

Another way to split up the system interaction with EMP is to consider different time and frequency regimes in comparison to times (or frequencies) characteristic of the size of the system (or portion thereof) of concern. By so doing certain simplifications in the approximate mathematical form of the EMP interaction result. These simpler approximate mathematical forms have certain factorizations explicit in them which allow the factors to be separately studied and make the parametric study of interaction problems less tedious and conceptually simpler.

As illustrated in figure 6 one starts with two items: characteristic times associated with some object (system exterior, aperture, etc.) and a frequency or time regime of concern. Comparing these two items gives three cases of interest which one can call three electrical sizes.

First there is the electrically small object for which quasi static techniques apply; in this case the response factors according to orthogonal incident field components. This can be extended to a Rayleigh series in powers of the frequency. For objects which are electrically small in one or two dimensions (the cross section) but electrically large in another dimension (the length) other types of low frequency (related to cross section) asymptotic expansions apply.

Second there is the resonant size object with wavelengths on the order of the object size. Needless to say expansion in terms of the complex resonant frequencies and modes is quite appropriate here. This is an important part of the singularity expansion method (SEM) which can include some other terms for completeness. Eigenmodes of various types can also be used in the resonance region but are not as efficient as SEM. However, eigenmodes can be combined with SEM to increase the efficiency of SEM.

Third there is the electrically large object for which high frequency asymptotic expansions apply. A common type of such an asymptotic expansion is an extension of geometrical optics known as the geometrical theory of diffraction (GTD). In this asymptotic approximation the response is represented in terms of inverse powers of frequency as well as other terms such as exponentials. A time domain form for such GTD expansions is also directly obtainable.

As may typically be the case one is interested in a broadband response of an object extending from electrically small to electrically large. One can try to use straightforward numerical procedures to obtain the response for "all" frequencies or times, but with some loss of understanding of the results, particularly in a parametric sense. Better one can construct the frequency and/or time response from the forms appropriate to various frequency and/or time regimes. Note that numerical procedures may typically be needed in the various regimes but with some gain in efficiency. An increasingly powerful way to represent the frequency and time domain solutions together is in the SEM expansion in the complex frequency plane. This works well for electrically small and resonant size objects and thus low and intermediate frequency regimes. For the electrically large regime asymptotic forms seem to be better suited and ways are being considered to tie these into SEM.

Note that in decomposing a system some portions may be electrically large while others are electrically small for some frequency band of interest. Thus in analyzing a system one may construct transfer functions for the different pieces based on different approximations. The total system transfer function (to some position inside) may then for a particular frequency band be a hybrid using more than one type of approximation.

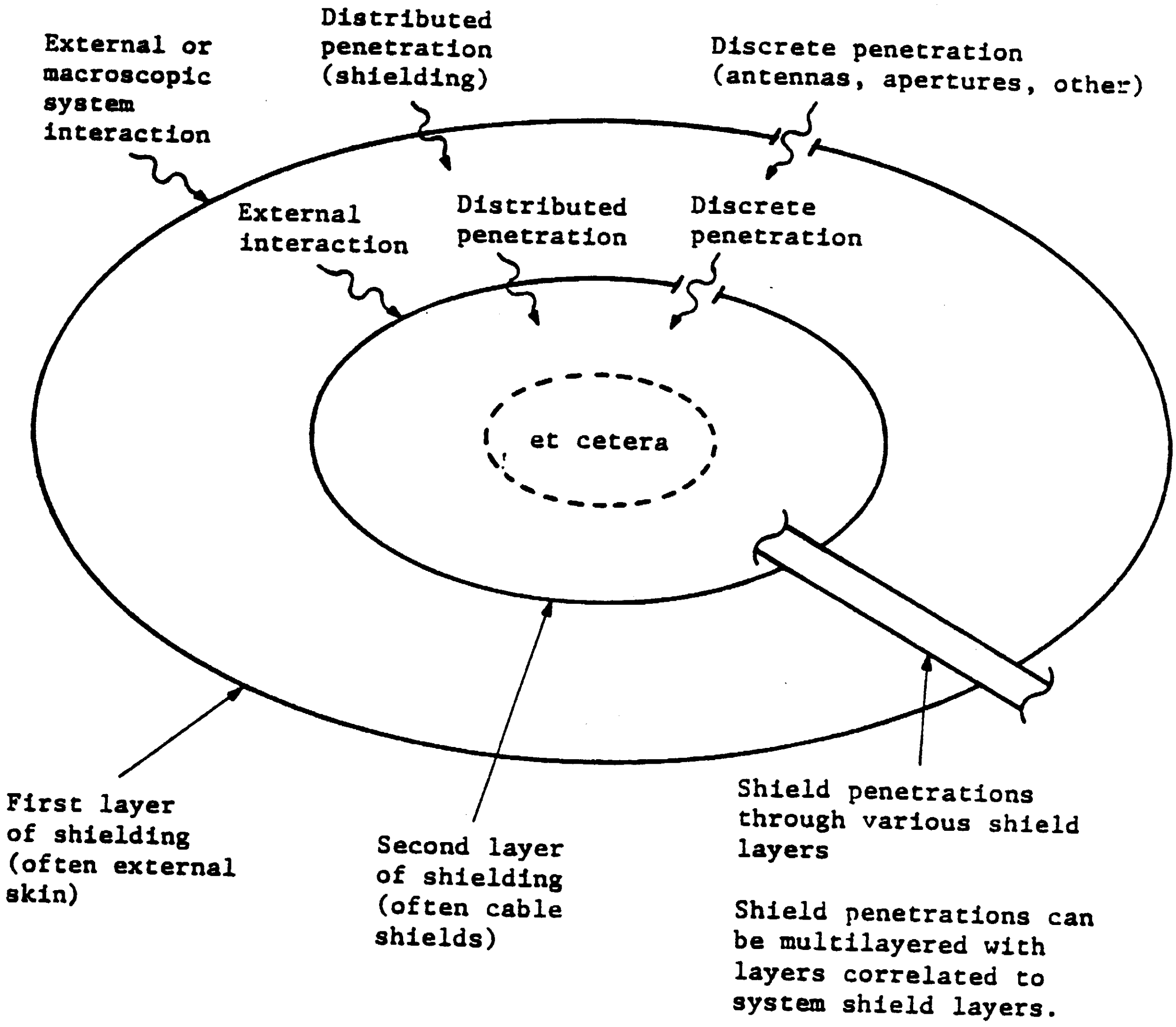

Figure 1. Topological Shielding

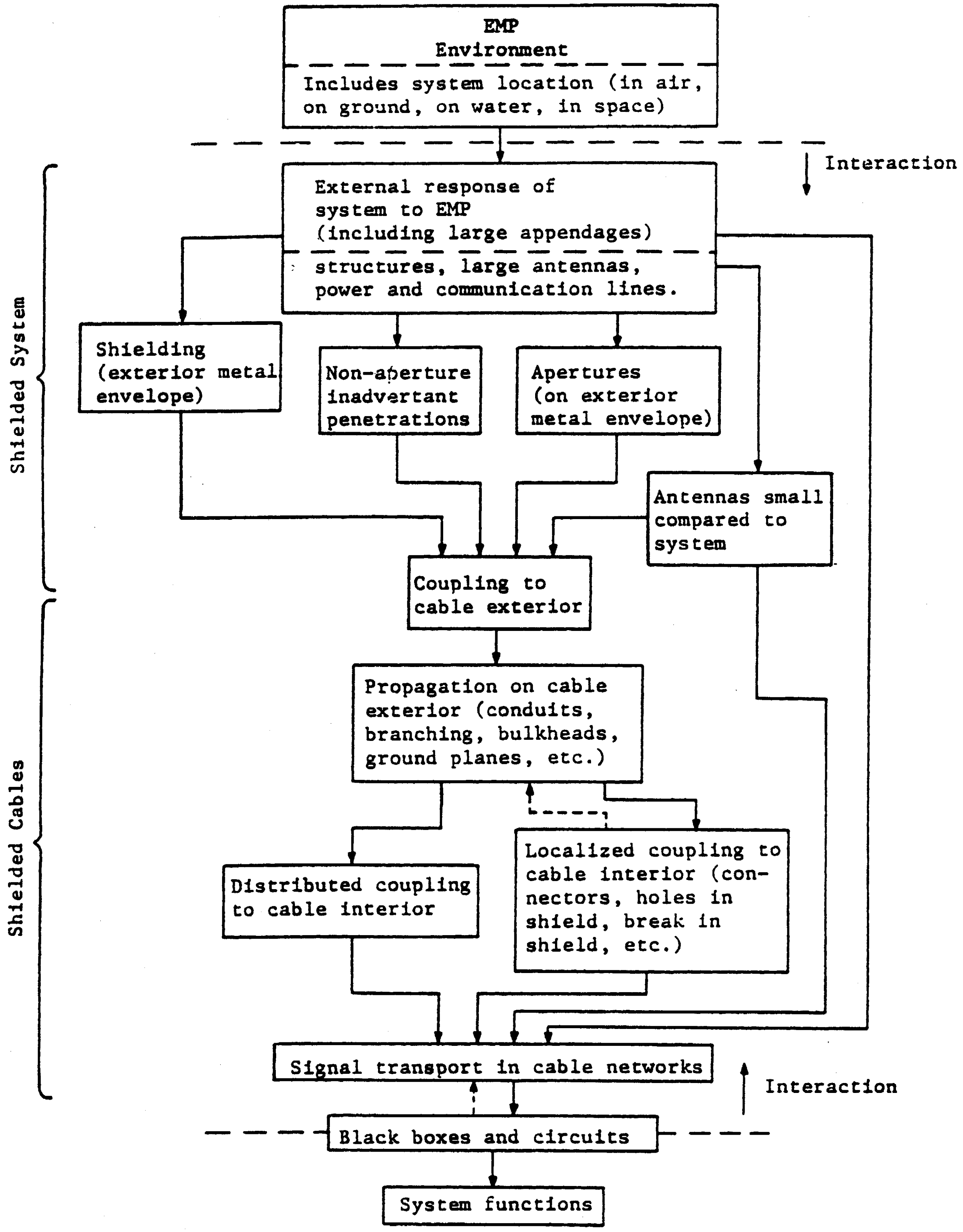

Figure 2. EMP Interaction Sequence for Shielded System with Shielded Cables: Shielding Order = 2

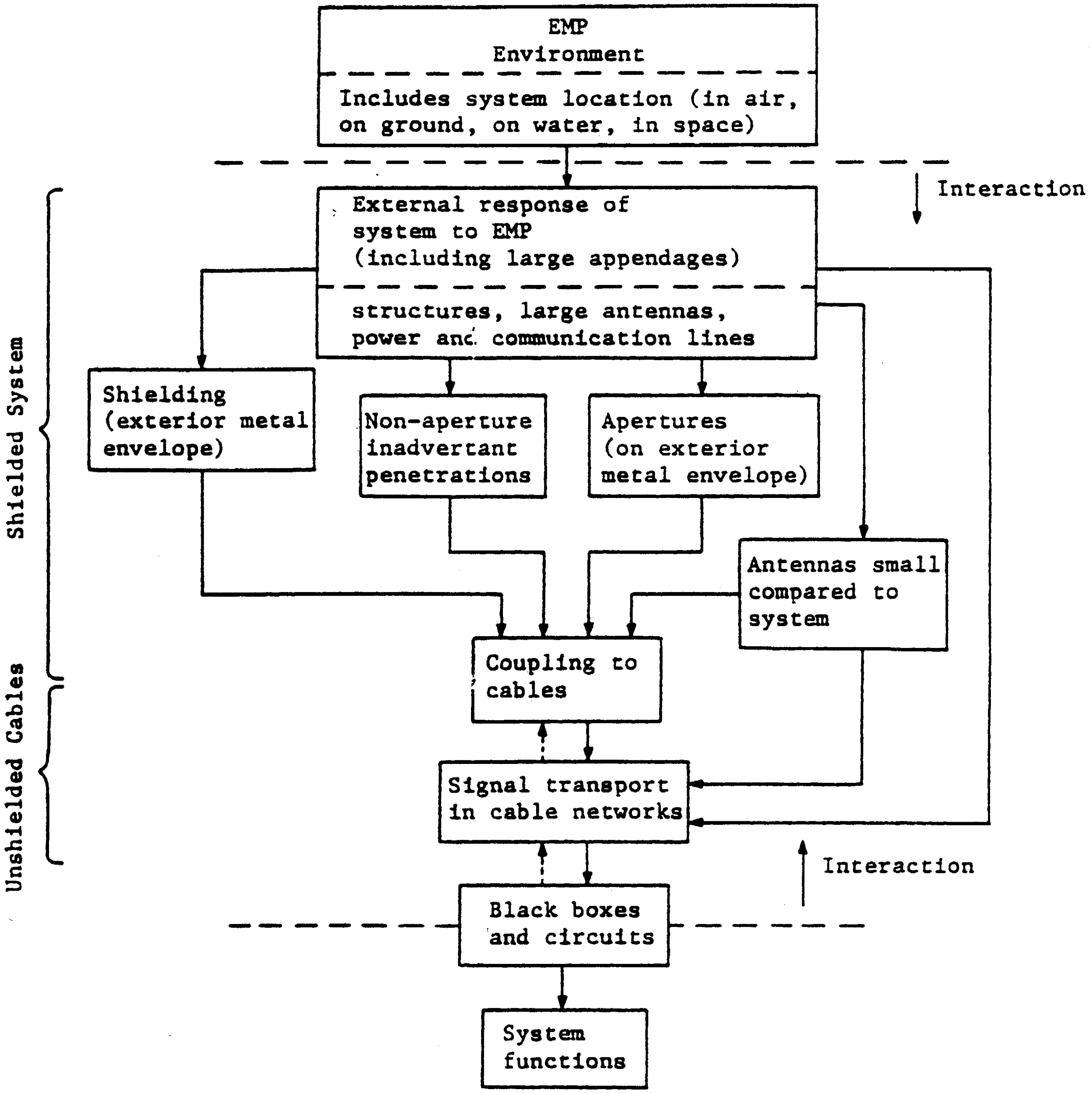

Figure 3. EMP Interaction Sequence for Shielded System with Unshielded Cables: Shielding Order = 1

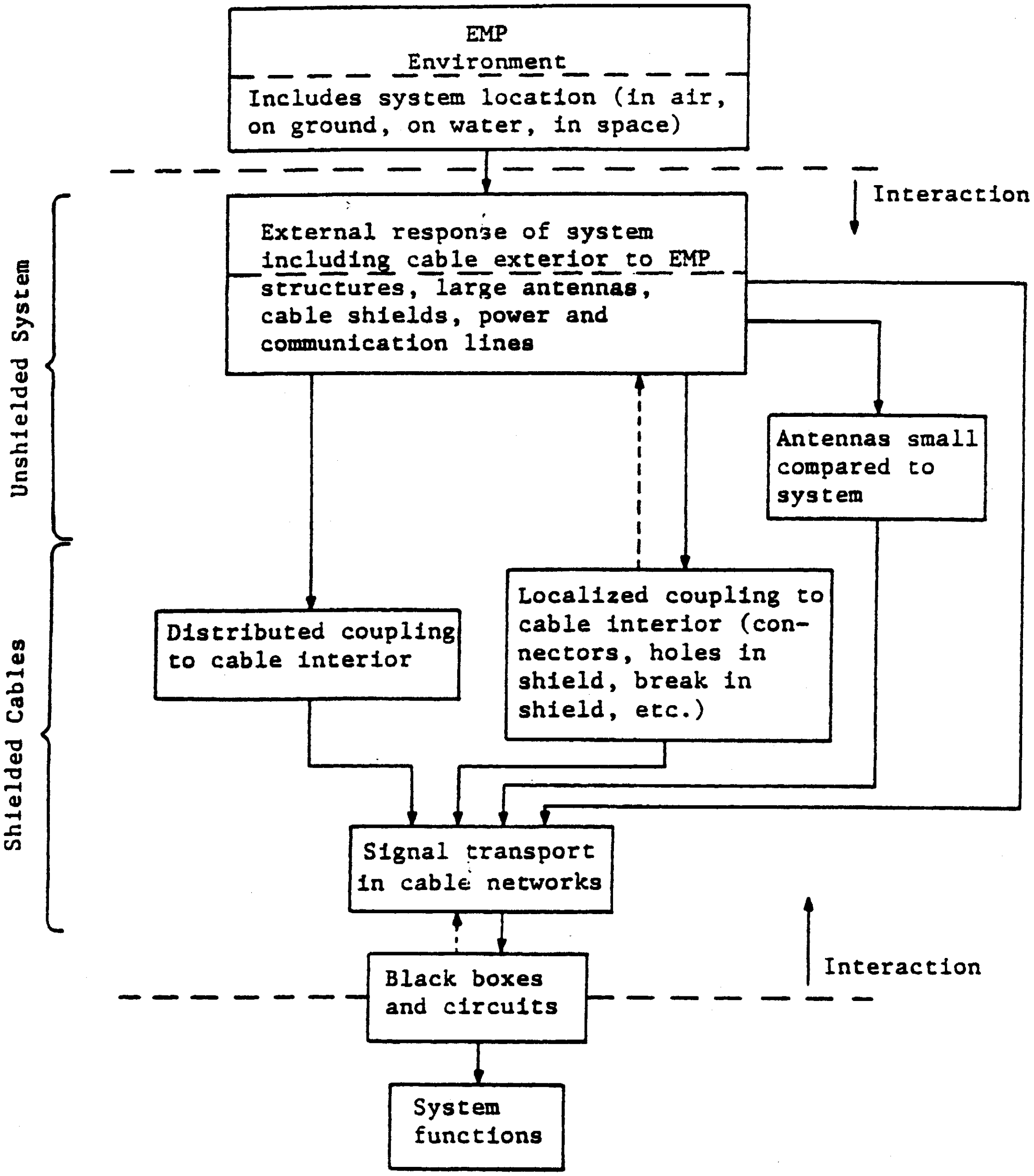

Figure 4. EMP Interaction Sequence for Unshielded System with Shielded Cables: Shielding Order = 1

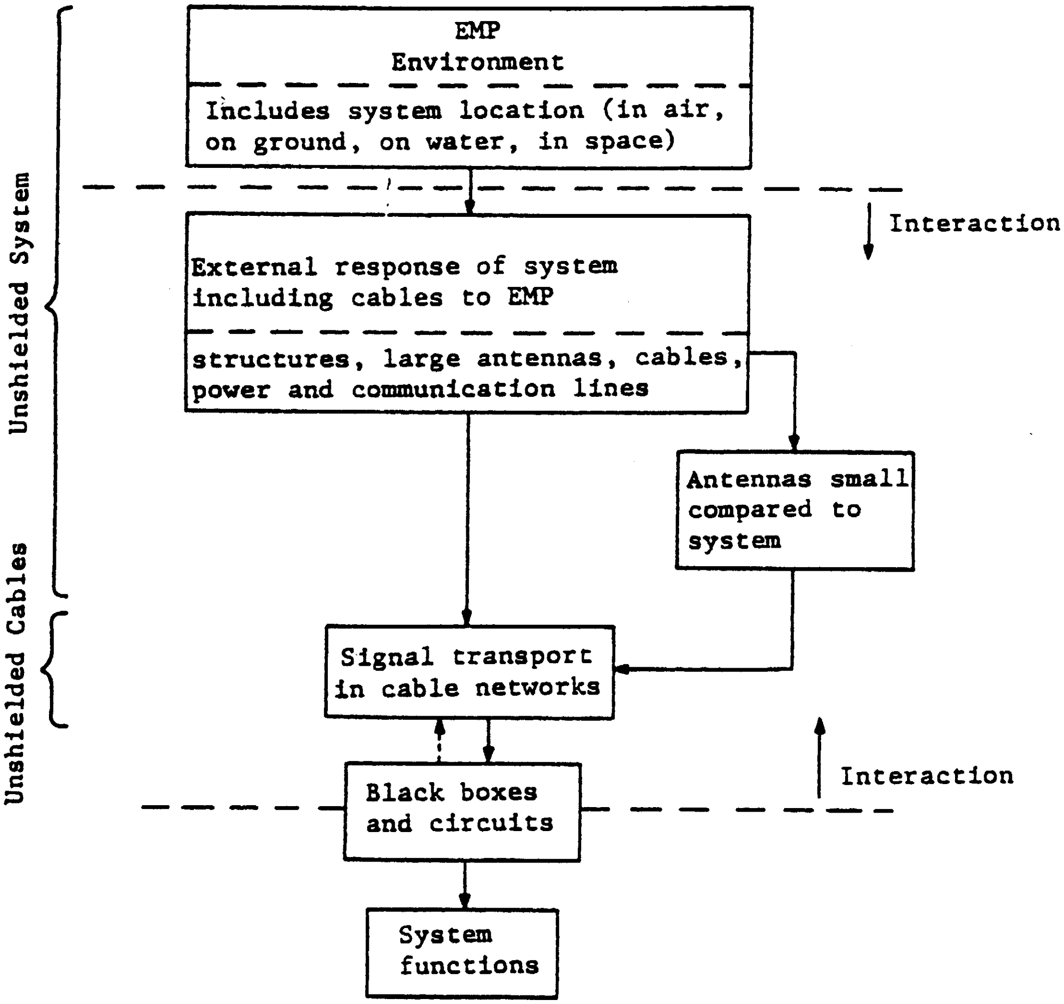

Figure 5. EMP Interaction Sequence for Unshielded System with Unshielded Cables: Shielding Order = 0

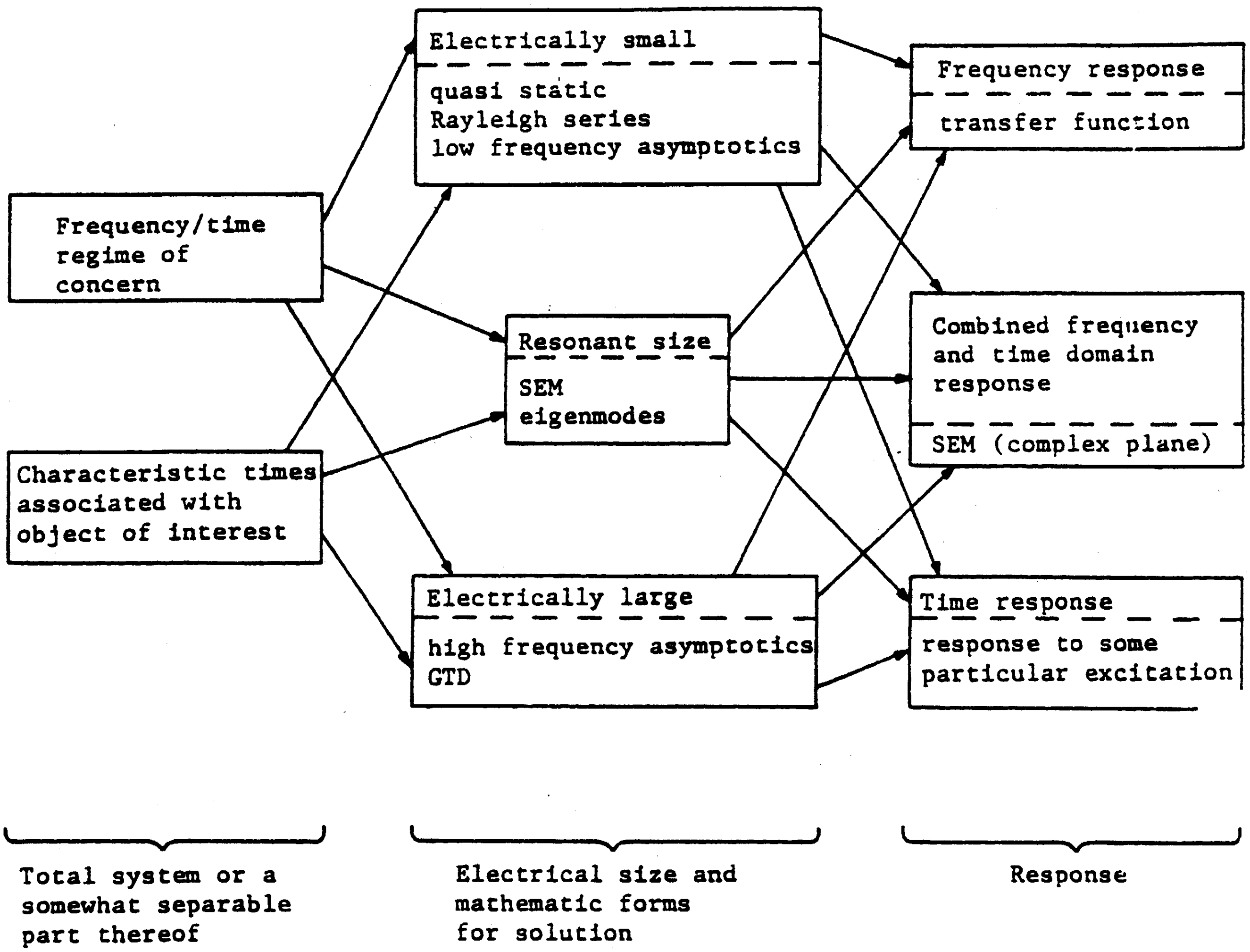

Figure 6. Mathematical Decomposition of EMP Interaction