An Electromagnetic Interaction Modeling Advisor

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Abstract—**A knowledge-based approach for the modeling of electromagnetic interactions in a system is described. The purpose is to determine any unwanted EM effects that could jeopardize the safety and operation of the system. Modeling the interactions in a system requires the examination of the compounded and propagated effects of the electromagnetic fields. A useful EM modeling approach is one that is incremental and constraint based. The approach taken here subdivides the modeling task into two parts: a) the definition of the related electromagnetic topology and b) the propagation of the electromagnetic constraints. A prototype of some of the EM constraints has been implemented in Quintus Prolog under NeWS on a Sun workstation. User interaction is through a topology drawing tool and a stack-based attribute interface similar to the HyperCard™ interface of the Apple Macintosh computer.**

I. Introduction

THE EFFECTS of electromagnetic interactions in electrical systems are of concern because of the increased pollution of the environment with electromagnetic emissions and because of the increasing susceptibility of system components. The term electrical system is used herein in the general sense to include more than just networks consisting of electronic components. Systems containing biological and/or mechanical components of varying complexity are also included when reference to the term electrical systems is made. The problem is to model the electromagnetic interactions that take place between components in a complex system. The process of rendering these systems acceptably immune to the interactions is called electromagnetic hardening and, once achieved, the system is said to be electromagnetically hardened.

Traditionally, the formal approach to the control of electromagnetic effects has been through the use of official standards [1]–[3]. Inherent in this approach is the politics of meeting standards, that is, when the producer's effort goes into meeting the standard only *after* the equipment has been designed, the real purpose of the standard, that of producing safe and compatible systems, may be lost. Often, little forethought to possible EM problems is put into the design of the equipment. When EM problems are found, it is not uncommon for an equipment manufacturer to spend more time writing waivers than trying to solve the problems.

This is not the *best* approach to rendering systems electromagnetically safe and compatible. From an enforcement point of view, standards are necessary; whether these standards are the only criteria a producer should use to verify a system is questionable. The purpose here is not to derive a foolproof method of enforcing certain standards but to give equipment producers (and other interested parties) a useful tool in the form of a constraint based advisor to be used at the planning stages in the design of a system in order to help make the system electromagnetically reliable.

Theoretically, understanding the phenomena of electromagnetic interactions in electrical systems requires no more complicated theory than that explicated by Maxwell in his *Treatise on Electricity and Magnetism.* Of course the elaboration of this theory over the years has given insight into mechanisms of electromagnetic interaction. Mechanisms of interaction, associated with an electrical system, manifest a complex called the electromagnetic system.

From a practical point of view, it is not at all obvious how the electromagnetic integrity of systems can be assured even for relatively small interaction problems (or what at first may seem to be a small problem). Nonalgorithmic techniques are used daily by engineers to solve electromagnetic problems in electrical systems. The purpose here is to establish an appropriate symbolic description or knowledge representation of the fundamental components in an electromagnetic interaction problem as well as the strategies or heuristics used to reason about these components. These strategies are derived from well-known engineering principles and can be viewed as constraints on the electromagnetic interaction problem.

To model it as such, it is essential to subdivided the modeling task into several processes that operate in a distributed manner. The knowledge required in modeling electromagnetic systems include the electromagnetic topology of the system and the electromagnetic attributes of each node in the topology.

A prototype of some of the constraints used to model electromagnetic interactions has been implemented in Quintus Prolog™ on a Sun™ workstation [4]–[6]. The advisor, HardSys, determines the emitter, susceptor, shielding effectiveness and the likelihood of failure of an electromagnetically affected system. HardSys is interfaced to a unique topology input drawing tool, HardDraw, which runs under an NRC interface implemented in the NeWS™ windowing environment. The implementation of HardSys and HardDraw is also described.

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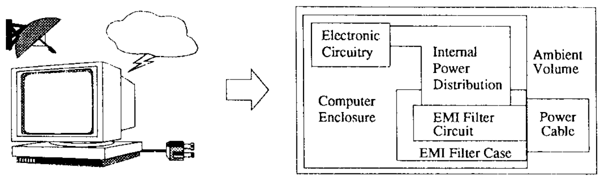


Fig. 1. Example electromagnetic topology decomposition of a system.

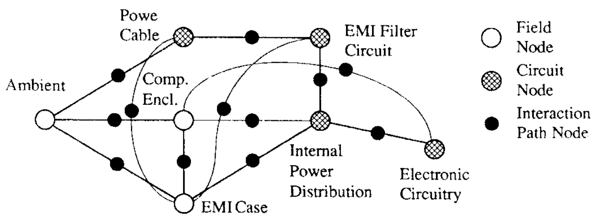


Fig. 2. Equivalent interaction sequence diagram.

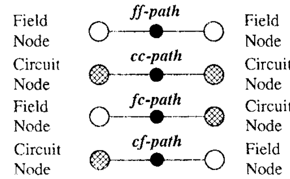


Fig. 3. Interaction path types.

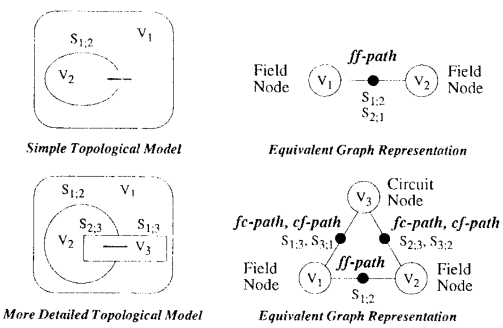


Fig. 4. Two topological representations of the same shielding imperfection.

II. Electromagnetic Topology of Systems

In order to model the electromagnetic system, it is first necessary to understand and represent the relevant physical attributes of the system. An example of a procedure for accomplishing this has been described by Baum [7], [8], Messier [9], [10] and Tesche [11]. In this procedure, an electromagnetic system is decomposed into an electromagnetic shielding topology and its dual graph or interaction sequence diagram.

The electromagnetic topology consists of a description of the electromagnetically distinct volumes and their associated surfaces. The volumes define the electromagnetic components involved in the interaction. The interaction sequence diagram (technically a graph) keeps track of the interaction paths throughout the system. The two procedures are not independent of each other since the interaction sequence diagram can be derived from a given electromagnetic topology. Variations on the labeling of these graphs and topology have been investigated by Noss [12]. Many labeling schemes are possible, each having its own advantages and disadvantages. Labeling will turn out to be unimportant as considered herein since each volume and surface node will be labeled with a physically meaningful name in the software implementation. The details of this theory will not be given here (see Baum [7]), but a simple example, which will be used to explain how the topological decompositions of systems will be used, is given in Fig. 1.

In the topological decomposition of Fig. 1, an extension to the standard theory of [7] has been made in that circuit elements are also represented as a volume. The interaction sequence diagram can be obtained as a graph with nodes or vertices representing volumes and edges representing surfaces. The graph representing the topology of Fig. 1 is shown in Fig. 2. Note the different node representation for field nodes, circuit nodes, and interaction path nodes. Field nodes and circuit nodes contain attributes specific to field and circuit type quantities, respectively. This leaves a possibility of four interaction path node types, which are summarized in Fig. 3.

Paths between field nodes, which will be denoted *ff* paths, take field quantities and attenuate them producing field quantities on the other side. Paths between circuit nodes (*cc* paths) attenuate circuit disturbances. The other two possible combinations are *fc* paths and *cf* paths with corresponding meanings.

Of course, this is not the only possible topological decomposition of this physical system. Many other decompositions are possible, and some may in fact be more appropriate, depending on which component and via which interaction paths the greatest risk of failure manifests itself. These considerations cannot be known a *a priori* unless previous experience with similar electromagnetic components and topologies is available.

As an example, consider the two topological decomposition of a conducting penetration shown in Fig. 4. A conducting penetration can render to nil the shielding effectiveness of an enclosure in certain bandwidths. This is because field energy can couple onto the conductor penetrating the shield and then be radiated again on the other side. This is more clear in the second topological decomposition.

Thus, a more detailed topological model may help to understand an interaction path phenomenon. Later, it will be shown how a complex graph can be collapsed into the simpler representation with new composite attributes. The imposition of specific attributes on the topology components is discussed in the next section.

III. Electromagnetic Component and Path Attributes

The next step in modeling the electromagnetic system is to approximate the propagation of electromagnetic energy from one volume node to another. Electromagnetic attributes are introduced for each electromagnetic component in the topology as well as for the interaction paths between the components. These attributes constrain the propagation of the electromagnetic disturbances throughout the topology. These at-

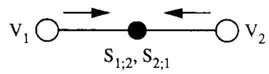


Fig. 5. Single electromagnetic interaction path.

tributes are implemented as a constraint network representing the complete electromagnetic system. To describe this procedure, it is sufficient to consider just one electromagnetic interaction path, as is shown in Fig. 5.

The attributes are used to represent the electromagnetic knowledge known about a system. It must be realized that many representations of this knowledge are possible but that the acceptable scheme is the one that achieves an acceptable tradeoff between approximation and usefulness. A good electromagnetic representation will have the following characteristics; it should

1) be easily derivable from available experimental/numerical data
2) be in an amenable qualitative form (symbolic manipulation)
3) yield useful quantitative/qualitative results and recommendations
4) have the capability to handle exceptions
5) have variable levels of approximation (coarse to fine).

These characteristics are used to derive an appropriate approximation for the electromagnetic attributes. The form of these attributes is now described.

A. Frequency or Time Domain

Most electromagnetic interaction phenomena are calculated, measured, and reported as quantified data in the frequency domain. The reason for this is that most useful engineering information about fields, susceptibilities, and paths of interaction can be characterized best in the frequency domain.

For example, the concept of frequency domain filtering can be used to characterize almost all linear paths of interaction. It is well known that an aperture in a shield acts as a high-pass filter in the path of the electromagnetic fields (see Schulz *et al.* [13]. Emissions from equipment are often measured using receivers with specific bandwidths of reception over large ranges of frequency (see [3] and [14]). Furthermore, susceptibilities of electronic components such as microelectronic circuitry are also calculated in the frequency domain [15]. Thus, all electromagnetic attributes associated with nodes and edges are specified over quantized frequency ranges. Each attribute does not need to be specified over the same frequency ranges. A normalization procedure is used to combine attributes specified over different frequency ranges to a common global frequency range for the problem.

B. Electromagnetic Disturbance Representation

Each component node in an electromagnetic topology may have an electromagnetic disturbance associated with it. Field quantities and circuit quantities will describe the electromagnetic disturbance for field nodes and circuit nodes, respectively. Thus, an appropriate classification is to define power density PD with units of [W/m^2 or dBW/m^2] for field nodes and power P with units of [W or dB] for circuit nodes. The magnitude of a disturbance in a specific frequency range can be specified as being one of several discrete values. The specific ranges are shown in Fig. 6, where the bracketed values represent the equivalent electric field for free-space far fields and the voltage equivalent in a 50-Ω circuit.

extreme	if PD is > 84 dBm/m^2/Hz (>10 kV/m/Hz) if P is > 84 dBm/Hz (> 3.5 kV/Hz)
high	if PD is 44 - 84 dBm/m^2/Hz (.1 - 10 kV/m/Hz) if P is 44-84 dBm/Hz (35 V/Hz - 3.5 kV/Hz)
medium	if PD is 4 - 44 dBm/m^2/Hz (1 - 100 V/m/Hz) if P is 4-44 dBm/Hz (350 mV/Hz - 35 V/Hz)
low	if PD is -36 - 4 dBm/m^2/Hz (10 mV/m - 1 V/m/Hz) if P is -36-4 dBm/Hz (3.5 mV/Hz - 350 mV/Hz)
very low	if PD is < -36 dBm/m^2/Hz (< 10 mV/m/Hz) if P is < -36 dBm/Hz (< 3.5 mV/Hz)
nil	--> no disturbance
unknown	(propagate as unknown throughout)

Fig. 6. Field-type power density and circuit-type power disturbance definitions.

The specific range values shown in Fig. 6 are chosen heuristically based on experience of electromagnetic disturbance levels and on the requirement for a useful number of ranges. The values assigned to each quantized range are quite arbitrary, but once these values are chosen, the creation of a useful database of disturbances requires that these values remain constant.

Now, it is clear from the theory of the Fourier transform (see Körner [16]) that the frequency representation of a unique time domain waveform requires not only the amplitude information but the phase information as well. The phase information can mean the difference between a coherent wideband emission and an incoherent wideband emission (see Mil-Std-462 [14] and Duff [17]). A coherent broadband emission will produce a disturbance at the receiver that is proportional to the receiver bandwidth whereas an incoherent broadband emission will produce a disturbance at the receiver that is proportional to the square root of the receiver bandwidth. Thus, the importance of classifying an emission as coherent or incoherent relates to how the emission interacts with its path and, ultimately, with the susceptor. For example, if a receiver or susceptor is sensitive to peak voltage disturbances, then an emission that is coherent in the bandwidth of the susceptor will produce twice the peak voltage as that of an incoherent emission in the same bandwidth. Thus, the representation of a disturbance will also contain a slot, or location, for the specification of pertinent phase information. This information may also vary over specific frequency ranges.

As an example, the fields emitted by a lightning strike can be simulated by the fields produced by a current pulse with a pulse width of 50 μs and a 10-to-90 percent rise time of 500 ns [17]. The average strike has a current amplitude of 30 kA. At a distance of 100 m, the field disturbance may be approxi-

Disturbance Type:	Lightning Emission (100 m distance)
Impedance:	[Plane Wave]
Magnitude:	f < 10 kHz ---> *medium*
	100 < f < 400 kHz ---> *low*
	400 kHz < f < 1 GHz --->*very-low*
	1 GHz < f ---> *nil*
Phase:	[Coherent]

Fig. 7. Example ambient field representation stored in the database.

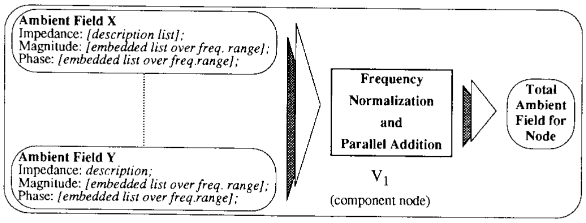


Fig. 8. Ambient field attributes for a typical volume node.

mated by a 50-kV/m double exponential waveform, which, in the frequency domain, is stored in the database as shown in Fig. 7.

Each volume node in a topology may contain many disturbance representations derived for all the sources present in that volume. The individual disturbance attributes for all the sources associated with a volume node are frequency range normalized and added in parallel to determine the total disturbance for the node, as in Fig. 8. Since these procedures are independent of the type of node (circuit or field), the disturbance for the node (either P or PD) will be denoted as ambient field (AF) to simplify discussion.

The total ambient field produced at a node (say V_1) due to the individual ambient fields imposed in that node volume needs to be determined in an appropriate manner so that one consistent representation can be propagated throughout a system topology. It is assumed for the moment that the total nodal ambient field AF_T is required over a specific global frequency range set F_g given by the N frequency ranges

$$F_g = ((f_{g0}, f_{g1}), (f_{g1}, f_{g2}), \cdots (f_{gj-1}, f_{gj}), \cdots (f_{gN-1}, f_{gN})). \quad (1)$$

If a specific ambient field AF_x is stored over a specific frequency range set F_x of say M frequency ranges, then

$$F_x = ((f_{x0}, f_{x1}), (f_{x1}, f_{x2}), \cdots (f_{xj-1}, f_{xj}), \cdots (f_{xM-1}, f_{xM})), \quad (2)$$

$$AF_x = ((af_{x1}), (af_{x2}), \cdots (af_{xj}), \cdots (af_{xM-1}), (af_{xM})). \quad (3)$$

Each of the af_{xj}'s is one of the quantized amplitude levels described previously. Now, before AF_x can be summed into the total ambient field AF_T, it must be normalized to the global frequency range F_g and can be written as AF_{xn}

```
Frequency Normalization Algorithm

Loop 1: over the Fg ranges ( fgj-1, fgj), j=1, ... N;
    set afxnj to unknown;
    Loop 2: over the Fx ranges ( fxi-1, fxi), i=1, ... M;
        If fxi ≤ fgj-1 then end loop 2;
        If fxi-1 ≥ fgj then end loop 2;
        set afxnj to worseAF( afxnj, afxi);
    continue Loop 2;
continue Loop 1;
```

Fig. 9. Frequency normalization algorithm.

```
Parallel Addition Algorithm:

Loop 1: over the AFj ambient field sets, j = 1, ... k;
    set AFjn to frequency normalize AFj;
continue Loop 1;
Loop 2: over the Fg ranges ( fgi-1, fgi), i = 1, ... N;
    set afTi to unknown;
    Loop 3: over the AFjn ambient field sets, j = 1, ... k;
        if afjni = unknown then set unknown flag;
        set afTi to worseAF( afTi, afjni);
    continue Loop 3;
continue Loop 2.
```

Fig. 10. Parallel addition algorithm.

where

$$AF_{xn} = ((af_{xn1}), (af_{xn2}), \cdots (af_{xnj}), \cdots (af_{xnN-1}), (af_{xnN})). \quad (4)$$

This frequency normalization is performed by the algorithm given in Fig. 9.

The function worseAF(af_1, af_2) returns the higher value ambient field but returns unknown if and only if both af_1 and af_2 are unknown. For example

- worseAF(unknown, very low) returns very low
- worseAF(unknown, unknown) returns unknown
- worseAF(high, low) returns high.

Thus, the effect of frequency normalization is to take, for each normalized ambient field value in a global frequency range, the worst ambient field value from the set of specific ambient field values whose frequency ranges overlap the global frequency range. Obviously, the choice of global frequency ranges will have an effect on the ambient field value, which is ultimately propagated throughout the system topology.

When multiple specific ambient fields are specified for a volume node, a procedure called parallel addition, which is given in Fig. 10, is performed. Given k normalized ambient field representations for a node, say AF_{1n}, AF_{2n}, $\cdots$ AF_{jn}, $\cdots$ AF_{k-1n}, AF_{kn}, each consists of a set of N ambient field values. The total ambient field AF_T can now be determined as the worst-case ambient field value in each global frequency range.

C. Component Susceptibility Representation and Approximation

Each volume node in an electromagnetic topology may also have a system susceptibility (SS) associated with it. The

very low	if SS is > 84 dBm/m²/Hz *or* dBm/Hz
low	if SS is 44 - 84 dBm/m²/Hz *or* dBm/Hz
medium	if SS is 4 - 44 dBm/m²/Hz *or* dBm/Hz
high	if SS is -36 - 4 dBm/m²/Hz *or* dBm/Hz
extreme	if SS is < -36 dBm/m²/Hz *or* dBm/Hz
nil	--> not susceptible
unknown	propagate as unknown throughout

Fig. 11. System susceptibility definitions.

System Susceptibility: CMOS Integrated Circuit	
Level:	f < 200MHz ---> *high*
	200 MHz < f < 10 GHz ---> *medium*
	10 GHz < f ---> *nil*
Type:	[peak sensitive]
Effect:	[upset]

Fig. 12. Example system susceptibility representation.

system susceptibility is inversely related to the level of disturbance that will cause either upset or permanent damage to the susceptible component, that is, if the disturbance level that will cause upset or damage to a component is low, the defined susceptibility of that component will be high.

There are many ways to define the susceptibility of an electromagnetic component. For instance, many logic circuits will be upset by peak voltage disturbances at their input terminals [18]. These disturbances must fall within the bandwidth of the logic device in order for an effect to be seen. In the case of analog circuits, definition of a precise disturbance level where upset occurs is not as simple as for logic-type circuits. For these types of circuits, damage level may be easier to define. Damage and upset levels of many integrated circuit technologies (both logic and analog) have been tabulated in [15].

It is clear that the susceptibility of an electromagnetic component can only have meaning when defined in the context of the disturbing source. Therefore, in order to achieve compatibility and allow direct comparison with the ambient field representation, the system susceptibility is represented in the frequency domain as quantized (40 dB levels), which is similar to that of the ambient field. The quantization levels are shown in Fig. 11, where the types of units are dictated by the type of node being characterized.

Along with this level representation, information about the type of sensitivity and the effect of failure (i.e., upset or damage) can be given for each frequency range. As an example, the SS of CMOS integrated circuits may be specified as shown in Fig. 12.

Volume nodes may contain many system susceptibility characterizations. For example, the volume node representing a circuit board may be characterized by specifying susceptibilities for CMOS, TTL, and line driver integrated circuits. These specific SS values are stored in a database and can be retrieved by the user to characterize each node in a topology. Once the specific system susceptibilities of a volume node have been defined, the frequency normalization and parallel addition routines, which are similar to those used

excellent	if SE > 100 dB
good	if 80 < SE < 100 dB
fair	if 60 < SE < 80 dB
not good	if 40 < SE < 60 dB
poor	if SE < 40 dB
nil	--> no shielding
unknown	propagate as unknown throughout

Fig. 13. Shielding effectiveness definitions.

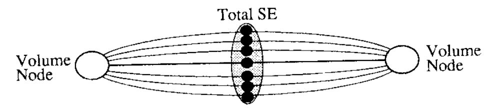


Fig. 14. Interaction path composed of many parallel paths.

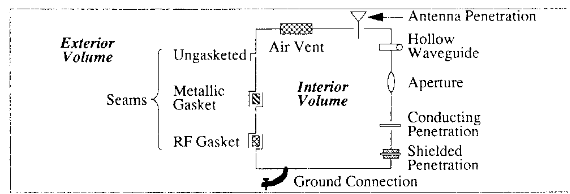


Fig. 15. Typical shield imperfections.

in the ambient field case, can be used. The difference will be that the function worseAF(af_1, af_2) will be replaced by the function worseSS(SS_1, SS_2).

D. Interaction Path Shielding Effectiveness Representation

The shielding effectiveness (SE) is a representation of the path characteristics between two component nodes and is used to determine the amount of attenuation the ambient field will encounter when crossing an interaction path. The SE is also given over discrete frequency ranges in order that its representation be compatible with that of the ambient field and the system susceptibility. The question of units for this quantity depends on the two component nodes, which it connects. For example, the SE between a circuit node and a field node will require units appropriate to the task of converting the ambient field from one node to the units of the other. As in the ambient field and system susceptibility representations, the SE is defined with discrete qualitative levels shown in Fig. 13.

Each interaction path may be made up of a number of different parallel paths between volume nodes. Each of these parallel paths is given an SE characterization, and these characterizations are again frequency normalized and added in parallel via algorithms similar to the ambient field and system susceptibility algorithms. The topological and graphical representations of these interaction paths can be summarized as shown in Fig. 14.

As an example of multiple parallel paths between two field nodes in a topology, consider the exterior and interior volumes of the shielded enclosure shown in Fig. 15. Each shield imperfection may be characterized as one parallel path in the total interaction path.

For example, the shielding effectiveness for apertures in thin conducting shields having lengths of 0.5 and 0.1 m and

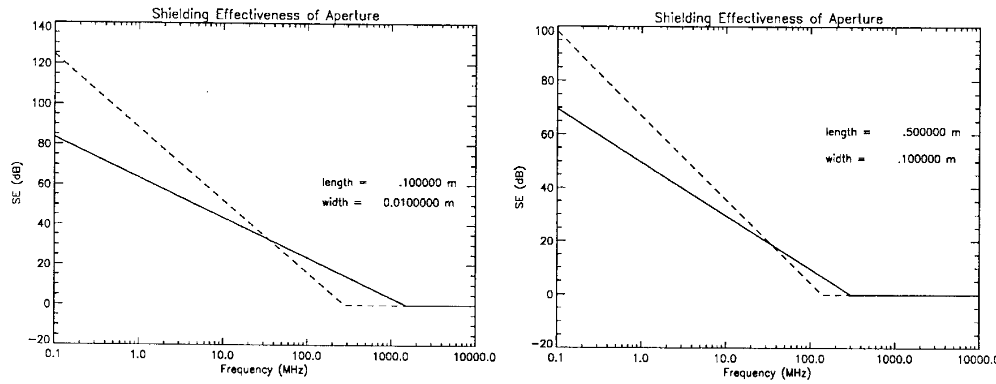


Fig. 16. Shielding effectiveness of apertures.

Shielding Effectiveness: aperture: L = .1; W = .01; (Vitek)

Level: f < 500 kHz ---> *excellent*
500 kHz < f < 2 MHz ---> *good*
2 MHz < f < 6 MHz ---> *fair*
6 MHz < f < 12 MHz ---> *not-good*
12 MHz < f < 300 MHz ---> *poor*
300 MHz < f ---> *nil*

Fig. 17. Example system susceptibility representation.

widths of 0.1 and 0.01 m, respectively, are shown in Fig. 16. The solid line is calculated from the mathematical model given by Ott [18], whereas the broken line is calculated from a measurements model given by Vitek [19]. It is apparent from the figures and from the coarseness of the required approximations that either of these models can be used to derive SE values to characterize the interaction path. Thus, the simpler model should be used as a first approximation. If the aperture happens to be on a critical path (to be described later), a more accurate model should be used.

The shielding effectiveness of the second aperture is stored in the database, as is shown in Fig. 17. This attribute would characterize one of the multiple parallel paths making up the total interaction path between the two field nodes.

Similarly, simple models for each type of possible imperfection for a conducting shield are available in the literature and in manufacturer's specifications. It is not the intent here to accumulate the required models that would exist in the database of the advisor but to show the types of models that are appropriate and available.

Circuit-circuit path nodes are used to model any interaction between circuit nodes. For example, most power-line entries into an equipment enclosure that are electrically filtered, ribbon cable connectors on a circuit board, and data transmission cables between circuits may also be modeled in this way. In effect, any electrical circuit connection can be modeled by a *cc* node. The level of modeling detail required for the system will dictate the definition and introduction of *cc* nodes into the topology.

Field-circuit nodes are used to define the coupling of fields to circuit nodes. For example, the coupling of far fields to printed wiring boards (PWB's) may be approximated by the maximum effective aperture A_{em} for a half-wave dipole where the received power P is calculated from the incident power density P_d as

$$P = A_{em} P_d \,[\mathrm{W}], \qquad A_{em} = 0.13\lambda^2 \,[\mathrm{m}^2] \qquad (5)$$

where λ is the wavelength (in meters) of the incident radiation. This has been found to be a good approximation for frequencies ranging from 100 MHz to 10 GHz [15]. For lower frequencies, an $A_{em} = 1$ is an appropriate worst-case approximation.

The circuit-field nodes are used to represent the emission of fields from circuit nodes. For example, currents existing on a PWB will radiate electromagnetic energy. Some estimations for the level of these emissions are derived from approximating the sources as loop and dipole radiators [18]. More accurate models are obtainable for emissions from circuit boards (see for instance Raut [20]), but a coarse worst-case model may be sufficient as a first approximation. In addition, actual measurement data may be used for specific PWB's. A complete database of emission data for specific PWB's, which would be fine tuned as better models or experimental data become available, may be kept.

V. Using Constraints to Characterize EMI

The language of constraints was described by Sussman and Steele [21] as a method of deriving useful consequences by propagating conditions through a constraint network. A formal overview of constraint networks as applied to picture processing has been presented by Montanari [22]. Presently, constraints are used to define an electromagnetic interaction problem. The likelihood of a component node failing is also defined via the propagation of imposed conditions in the topology through appropriate constraints.

Definition of the electromagnetic topology for a problem is accomplished by defining the discrete electromagnetic components (i.e., each node) with a suitable name. For example, in a Prolog type syntax [23], the statements

```
node(external_vol).                           node(computer).    node(cpu).
node(power distribution).                     node(power code).  node(power supply).
surface(external_vol, computer).              surface(external_vol, power cord).
surface(external_vol, power supply).          surface(computer, cpu).
surface (computer, power distribution).       surface(computer, power supply).
surface(cpu, power distribution).             surface(power distribution, power supply).
surface(power supply, power cord).
```

would declare the existence of six nodes and nine surfaces in the current topology. These 15 statements define a small electromagnetic topology (or graph). A surface declaration is said to constrain two components into sharing a surface. Similarly, the statement

global_frequency(frequency_range_x).

will constrain the global frequency variable to the frequency ranges defined in frequency_range_x, which is stored in the database as a list of discrete frequency ranges. It should be noted that the number of discrete frequency ranges defined will affect the speed of computation for the 1) frequency normalization, 2) parallel addition, 3) worst-case shielding path determination, and 4) risk of failure operations. Thus, a coarse global frequency range set is preferred during preliminary investigations.

Once the electromagnetic topology has been defined, the specific electromagnetic attributes can be distributed over the topology. For example, the statement

disturbance(node(external_vol), [[standard, NEMP], [standard, LEMP], [cw, HF]]).

will constrain the external_vol node to have disturbances associated with the list of disturbances contained in the list. All three of these disturbances exist in the database in the form described previously. Entering these constraints would trigger the frequency normalization and parallel addition algorithms, producing a total disturbance for this node. Nodes not instantiated with specific attributes are taken to be unknown over all global frequency ranges. The statements

Susceptibility(node(cpu), [[digital, TTL], [digital, CMOS], [analog, line_driver]]).
susceptibility(node(power supply), [[analog, volt_regulator], [digital, comparator]).

constrain the two specified nodes to have total susceptibilities derived from the susceptibilities of the listed components, while the statements

```
shielding(surface(external_vol, computer), [[shield, wire-mesh-gasket],
                                            [shield, honey-comb-cooling-vent]]).
shielding(surface(external_vol, power cord), [[coupling, short-cable]]).
shielding(surface(external_vol, power supply), [[shield, wire-mesh-gasket]]).
shielding(surface(computer, cpu), [[coupling, pcb, 30 cm × 30 cm]]).
shielding(surface(computer, power distribution), [[coupling, short-ribbon-cable]]).
shielding(surface(computer, power supply), [[shield, aluminum]]).
shielding(surface(cpu, power distribution), [[filter, nil]]).
shielding(surface(power distribution, power supply), [[filter, feed-thru caps]]).
shielding(surface(power supply, power cord), [[filter, EMI-461]]).
```

constrain the shielding effectiveness of particular interaction paths in the topology.

Information regarding the interaction between any two nodes in the topology is explicitly derived by determining the worst-case shielding path between all susceptible nodes to all emitting nodes. A search for the worst-case shielding path from each susceptible node to all other emitting nodes is performed using Dijkstra's algorithm [24]–[26] and using the distances shown in Fig. 18 for each heuritic shielding level.

For example, the worst-case shielding path to the two emitting nodes is highlighted in Fig. 19. The total shielding for the two interaction paths is represented as

total_shielding(path(v1, v4), [. . . [not-good] . . .]).
total_shielding(path(v1, v5), [. . . [good] . . .]).

where the second argument of total_shield is an imbedded list of the shielding effectiveness for each frequency range. Notice that although the total SE variable for path($v1$, $v5$) adds up to 2.5 (corresponding to slightly above the good level), the value of good is displayed for the total shielding. Internally, though, the value of 2.5 is maintained for the total SE variable.

During the search, the individual surfaces on the path are sorted from poorest total shielding to the best total shielding. In this way, the surface, which is the determining factor in the total shielding of the path, is ascertained. In effect, the determination of a total shielding between two nonneighbor nodes is the same as imposing a surface between these two nodes, which is similar to the slices concept in [21].

The likelihood of failure can be determined at the susceptible nodes by a heuristic method of propagating the electromagnetic disturbance from an emitting node to a susceptible node through the worst-case shielding path and then comparing the propagated ambient field with the susceptibility of the node. The specific disturbance and susceptibility levels at a node are assigned discrete AF and SS numerical values, as in Fig. 20.

excellent	SE = 3.0
good	SE = 2.0
fair	SE = 1.5
not good	SE = 1.0
poor	SE = 0.5
nil	SE = 0.0 --> no shielding, and
unknown	propagate as unknown throughout

Fig. 18. Definition of SE variable.

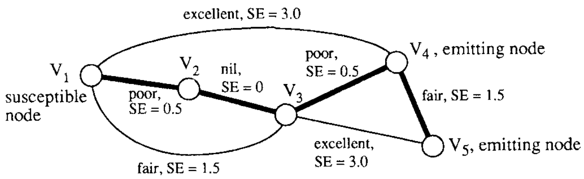


Fig. 19. Example worst-case shielding path for a specific frequency.

extreme	AF = 5; SS = 1
high	AF = 4; SS = 2
medium	AF = 3; SS = 3
low	AF = 2; SS = 4
very low	AF = 1; SS = 5
nil	AF = -2 --> no disturbance SS = 8 --> not susceptible
unknown	(propagate as unknown throughout)

Fig. 20. Ambient field and system susceptibility discrete levels.

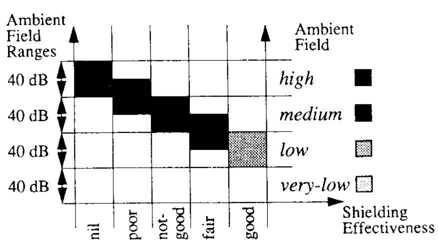


Fig. 21. High ambient field approximation propagated through good SE.

The propagated ambient field (PAF) is determined by subtracting the total shielding effectiveness of the path traversed (i.e., the SE value) from the AF value, that is

$$\text{PAF} = \text{TAF} - \text{TSE}$$

where TAF is the total ambient field emitted by a node, and TSE is the total shield effectiveness of a path. Now, since non-integer values of SE exist (for example, a shielding effectiveness of fair $\leftrightarrow$ SE = 1.5), it is not always the case that the ambient field drops a level after passing through a shielded path.

Setting an ambient field attribute to a certain level implies that there is an equal probability for the amplitude being any value in the range of amplitudes in the level. For example, if in the frequency range 1–10 MHz a level of high is specified, then this approximates the disturbance with equal probability over a 40-dB ambient field range, as is shown in Fig. 21. If this level is propagated across a poor shield, the resulting AF probability distribution would lie somewhere between the high level and the medium AF level, as is shown in Fig. 21,

extreme	if FI 1.5
high	if $0.5 \le \text{FI} < 1.5$
marginal	if $-0.5 \le \text{FI} < 0.5$
low	if $-1.5 \le \text{FI} < -0.5$
very low	if $-2.5 \le \text{FI} < -1.5$
nil	FI < -2.5 or associated with a non-susceptible nodes
unknown	if either susceptibility or disturbance are *unknown*

Fig. 22. Likelihood of failure discrete levels.

which, as a worst case, would be reported as high. Thus, a good shielding effectiveness would reduce the high AF by at least 80 dB, producing a low propagated AF.

Once the propagated ambient field from all other emitting nodes in the topology has been determined for a susceptible node, they are added in parallel using the parallel addition algorithm. In doing this, a trace of the highest PAF to lowest PAF is kept for each frequency range in the global frequency range.

The likelihood of failure is reported as being one of the discrete values shown in Fig. 22 for each global frequency range. The discrete level assigned to a frequency range is dependent on a failure index variable denoted FI. This is calculated for a susceptible node by subtracting the total system susceptibility of the node from the total propagated ambient field from all other emitting nodes in the electronic topology

$$\text{FI} = \text{PAF} - \text{SS}. \tag{7}$$

If the likelihood of failure of any susceptor is too great, parameters in one or all the three constraining factors must then be modified at one or more locations in the topology in order to reduce the likelihood of failure, that is, the electromagnetic disturbance located at a node may be reduced (if one has control of the emitter), the susceptibility of the receptor may need to be decreased, and/or the shielding effectiveness of specific surfaces may be increased. There will usually exist more than one way to reduce the likelihood of failure at a specific susceptor, where each has its own advantages and disadvantages. This is where the traces that were developed for the worst PAF will help. In addition, for the worst PAF, the critical path is stored with a trace of lowest to highest SE, thus giving the most probable surface to enhance in the topology.

Visually, it is convenient to refer to Fig. 23 to understand how the likelihood of failure is determined. Notice how the calculated FI is not uniquely determined by the reported PAF system susceptibility. For example, a PAF reported as very low may be stored numerically as from -1.5 to 1.0 and produce from nil to marginal likelihood of failure for an extreme susceptibility. This example is highlighted in Fig. 23.

This procedure for determining the likelihood of failure is justified heuristically by an understanding of what each FI level represents. Recall that the disturbance levels (here referred to as ambient field levels) as well as the susceptibility levels are defined to correspond to the same power levels. Thus, the ambient field ranges can be plotted on a graph of

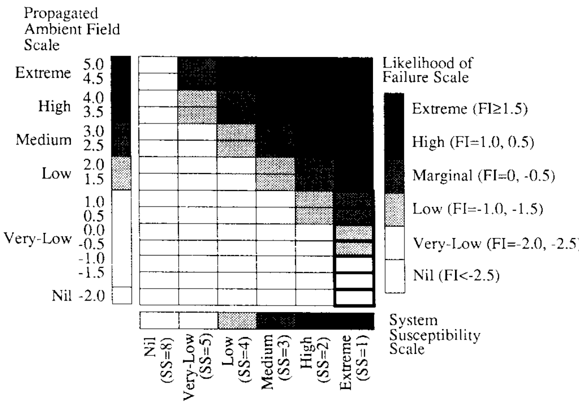


Fig. 23. Likelihood of failure chart.

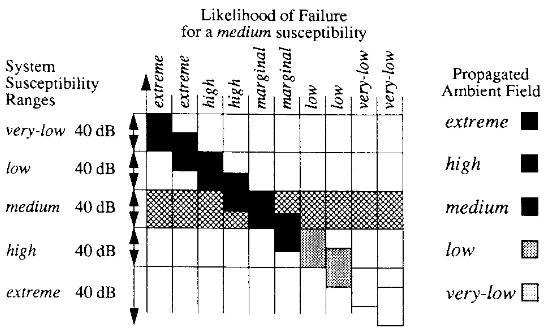


Fig. 24. Overlap of PAF ranges with SS ranges to determine FI.

the susceptibility levels, as is shown in Fig. 24, where the likelihood of failure results for a system susceptibility of medium are shown across the top of the figure.

Note that on the plot, there are two ambient field ranges for each level shown in the propagated ambient field key at the right of the figure. This is again due to the 20-dB discretization of the shielding effectiveness data. For the case where there is an overlap between the PAF distribution and the SS distribution, the likelihood of failure is said to be high or marginal (high if the PAF distribution overlaps above the SS distribution). When the PAF distribution lies totally above the SS distribution, the likelihood of failure is then said to be high or extreme, depending on how much higher the distribution lies. Alternatively, the likelihood of failure is determined as low, very low, or nil, depending on how much lower the PAF distribution is than the SS distribution.

VI. Grouping of Electromagnetic Component Nodes

Given a graph G for which the edge set E can be partitioned into two nonempty subsets, say E_1 and E_2, such that the subgraphs generated from these subsets, that is $G[E_1]$ and $G[E_2]$, have just a node ν in common, then ν is called a cut node [26]. As an example, nodes ν_1, ν_3, and ν_5 in Fig. 25 are cut nodes.

A set of nodes forms a valid grouping if it is equal to a node set of one of the subgraph partitions generated by a cut node. The valid grouping includes the cut node, and the

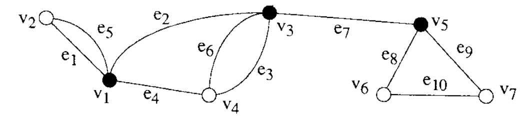


Fig. 25. Cut node and cut edge examples.

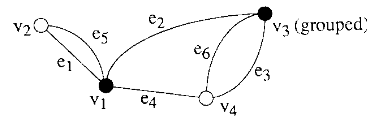
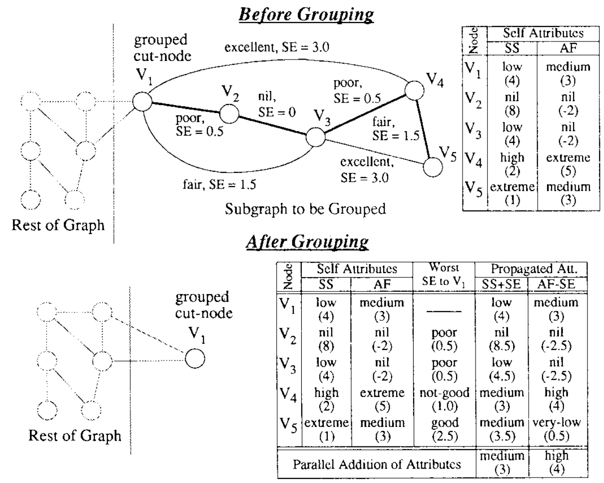


Fig. 26. Grouped vertex example.



Node	Self Attributes SS	AF
V1	low (4)	medium (3)
V2	nil (8)	nil (-2)
V3	low (4)	nil (-2)
V4	high (2)	extreme (5)
V5	extreme (1)	medium (3)

Node	Self Attributes SS	AF	Worst SE to V_1	Propagated Att. SS+SE	AF-SE
V1	low (4)	medium (3)	——	low (4)	medium (3)
V2	nil (8)	nil (-2)	poor (0.5)	nil (8.5)	nil (-2.5)
V3	low (4)	nil (-2)	poor (0.5)	low (4.5)	nil (-2.5)
V4	high (2)	extreme (5)	not-good (1.0)	medium (3)	high (4)
V5	extreme (1)	medium (3)	good (2.5)	medium (3.5)	very-low (0.5)
Parallel Addition of Attributes				medium (3)	high (4)

Fig. 27. Example of grouping a subgraph in a cut node.

group is represented in the graph by a grouped node in place of the cut node. For example, in Fig. 26 nodes ν_5, ν_7, ν_6, and cut node of ν_3 of Fig. 25 form a valid grouping and are represented by grouped node ν_3.

Similarly, nodes ν_1, ν_2, and ν_4, could also have been grouped into node ν_3. Thus, there are usually many options for grouping in a graph. The process of grouping is used to reduce the search space in the worst-case shielding path algorithm. The subgraph containing nodes that are not expected to change may be grouped as a valid grouping. This results in the removal of the grouped nodes from the search space of the minimum path algorithm.

In order that a grouped node accurately represents the subgraph from which it was formed, it must derive its attributes from the subgraph attributes. This is accomplished by determining the single source minimal spanning tree for the subgraph, in terms of shielding effectiveness, with the cut node as the root node. The susceptibility as well as the ambient field attributes of each node in the subgraph are then propagated to the root node and added in parallel along with the self attributes of the cut node to form a new grouped system susceptibility and ambient field for the grouped node. This is accomplished by subtracting the total SE for the worst-case shield path to the root node from the total SS value of the node being grouped. For example, Fig. 27 shows a subgraph to be grouped into the cut node v_1 as well as attributes for the individual nodes for a specific global frequency range (note V_3 has no AF, whereas V_2 has neither SS nor AF). The SE of the individual paths is shown on the subgraph, and the worst-case shielding path is highlighted.

After grouping, node V_1 is left with a grouped system susceptibility of medium and a grouped ambient field of high. Thus, even if attributes of nodes in other parts of the graph change or even if the topology of the rest of the graph changes, the minimal spanning tree search for this particular subgraph does not need to be repeated. Similarly, if attributes or the topology of the grouped nodes change, the minimal spanning tree of the rest of the graph (assuming that the cut node is still a valid cut node) will not change. Note that although the minimal spanning trees of either graph components (i.e., the grouped node component or the rest of the graph component) may not change, the likelihood of failures of the individual nodes therein may change.

In order that information is not lost about which node might be failing when the likelihood of failure of a grouped node is calculated, a trace is kept of the node in the group contributing the most to the group node susceptibility attribute. Thus, if the likelihood of failure is determined to be high in a certain frequency range, the trace of the susceptibility attribute will then list, in order from worst SS to best SS, the nodes contributing to the grouped SS. Similarly, a record of the worst propagated ambient fields is kept in the form of a trace.

As an example, for the grouped nodes of Fig. 27, the trace of the grouped SS attributed would be represented as the list $[V_4, V_5, V_1, V_3, V_2]$, whereas the grouped AF trace would be held as $[V_4, V_1, V_5, V_2, V_3]$. From these traces, one can immediately determine which nodes' SS to increase or which nodes' AF to decrease if an interaction problem exists within the grouped node.

VII. Implementation

The heuristic techniques and procedures described herein have been implemented in the form of an electromagnetic interaction advisor on a Sun Microsystem SPARCstation 1™ [5], [6]. The implementation consists of two main parts; a smart topology drawing tool referred to as HardDraw and an electromagnetic interactions expert system referred to as HardSys.

The purpose of HardDraw is to give the user of the software an easy way to input the electromagnetic topology of systems. The smart topology drawing tool is implemented on top of four existing development tools. These are: NeWS™ [27], [28], GoodNeWS [29], HyperNeWS [30], and Quintus Prolog™ [31]. The multiple stack interface of HardDraw runs under HyperNeWS/GoodNeWS, which runs under the Sun Microsystems Network Windowing System (NeWS™).

Once the electromagnetic topology has been entered and the volume/surface node attributes have been defined, reasoning about the possible interactions therein is performed by HardSys, which is an expert system written in Prolog [31]. An object-oriented knowledge representation approach is taken based on that of Stabler [32]. A predicate was added for modifying an object's methods. The electromagnetic component nodes and surfaces are implemented as objects with methods describing the attributes associated with each. Any name can be used to label an object; the object is then referenced using node(name) as the object name. When a node is created, it is created with many methods for storing the attributes or constraints that will be imposed.

VIII. Conclusions and Future Plans for the EMI Advisor

Work on the electromagnetic interactions advisor is ongoing in order to bring it to the level of a usable commercial software tool. the future plans in this development can be described as falling under the following three categories:

1) Knowledge representation and search technique enhancements
2) user interface enhancements
3) knowledge acquisitions and validation.

The representations of the electromagnetic quantities such as disturbance level and shielding effectiveness are currently being modified to fuzzy representations using trapezoidal membership functions [33]. The search technique used thus far is theoretically the most efficient [25] although implementation techniques to improve efficiency can be applied. For example, automatic grouping of nodes by the advisor is a possibility to be examined. Changes in the knowledge representation may also yield better search times.

Currently, the advisor works in the analysis mode, that is, the physical topology along with the associated node attributes are first entered, and the system then determines if any interaction problems exist. In the design mode, the advisor would be given some global constraints to satisfy, and it would be free to choose or design the system within these constraints. For example, a global constraint may be a weight and cost limit. The system would then choose subcomponents from a database with each having unique cost and weight attributes as well as system susceptibilities and electromagnetic emissions. Shielding components may also be chosen in a similar way. Of course, in such a process, more than one solution would exist; thus, heuristic guided design would be appropriate.

Knowledge acquisition is the problem of how to acquire accurate EMI data from the many sources and how to categorize it so that it can be presented to the user in a logical and efficient manner. Validation of the knowledge base, once created, requires the use of the advisor in the design of real systems.

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References

[1] B. Keiser, *Principles of Electromagnetic Compatibility*. Norwood, MA: Artech House, 1987.
[2] D. R. J. White, *Electromagnetic Interference and Compatibility*

(*EMI Control Methods and Techniques*), Gainesville, VA: Don White Consultants, 1973, vol. 1-6.

[3] U.S. Department of Defense, "Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference," Mil-Std-461C, Aug. 4, 1986.

[4] J. LoVetri, S. Abu-Hakima, A. S. Podgorski, and G. I. Costache, "HardSys: Applying expert system techniques to electromagnetic hardening," in *Proc. IEEE National Symp. Electromagn. Compat.* (Denver, CO), May 23-25, 1989, pp. 383-385.

[5] J. LoVetri and D. P. W. Graham, "Constraint propagation through electromagnetic interaction topologies," in *Proc. Antem'90, Symp. Antenna Tech. Appl. Electromag.* (Winnipeg), Aug. 15-17, 1990, pp. 766-771.

[6] J. LoVetri and A. S. Podgroski, "Evaluation of HardSys: A simple EMI expert system," in *Proc. IEEE Int. Symp. Electromagn. Compat.* (Washington, DC), Aug. 21-23, 1990, pp. 228-232.

[7] C. E. Baum, "Electromagnetic topology, A formal approach to the analysis and design of systems," Interaction Notes, Note 400, Air Force Weapons Lab., Sept. 1980.

[8] —, "On the use of electromagnetic topology for the decomposition of scattering matrices for complex physical structures," Interaction Notes, Note 454, Air Force Weapons Lab., July 1985.

[9] M. A. Messier, "EMP hardening topology expert system (Hard Top)," Interaction Notes, Note 449, Air Ford Weapons Lab., June 1985.

[10] —, "EMP hardening topology expert system (Hard Top)," *Electromagn.*, vol. 6, no. 1, pp. 79-97, 1986.

[11] F. M. Tesche, "Topological concepts for internal EMP interaction," *IEEE Trans. Antennas Propagat.*, vol. AP-26, no. 1, pp. 60-64, Jan. 1978.

[12] R. S. Noss, "Alterntive labeling schemes in electromagnetic topology," *Electromagn.*, vol. 6, no. 1, pp. 21-31, 1986.

[13] R. B. Schulz, V. C. Plantz, and D. R. Brush, "Shielding theory and practice," *IEEE Trans. Electromagn. Compat.*, vol. 30, no. 3, pp. 187—201, Aug. 1988.

[14] U.S. Department of Defense, "Measurement of electromagnetic interference characteristics," Mil-Std-462, July 31, 1967.

[15] McDonnel Douglas Astronautics Co., "Integrated circuit electromagnetic susceptibility Handbook," Rep. MDG-E1929, St. Louis, MO, Aug. 1978.

[16] T. W. Körner, *Fourier Analysis.* Cambridge, UK: Cambridge University Press, 1988.

[17] W. G. Duff, *Fundamentals of Electromagnetic Compatibility, A Handbook Series on Electromagnetic Interference and Compatibility, vol. 1.* Gainesville, VA: Interference Control Technologies, 1988.

[18] H. W. Ott, *Noise Reduction Techniques in Electronic Systems.* New York: Wiley, 1988.

[19] C. Vitek, "Predicting the shielding effectiveness of rectangular apertures," in *Proc. IEEE Nat. Symp. Electromagn. Compat.*, May 23-25, 1989, pp. 27-32.

[20] R. Raut, "On the computation of electromagnetic field components from a practical printed circuit board," in *Proc. IEEE Int. Symp. Electromagn. Compat.*, Sept. 16-18, 1986, pp. 161-166.

[21] G. J. Sussman and G. L. Steele, "Constraints-A language for expressing almost-hierarchical descriptions," *Artif. Intell.*, vol. 14, pp. 1-39, 1980.

[22] U. Montanari, "Networks of constraints: Fundamental properties and application to picture processing," *Inform. Sci.*, vol. 7, pp. 95-132, 1974.

[23] W. F. Clocksin and C. S. Mellish, *Programming in Prolog.*, New York: Springer-Verlag, 1984.

[24] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numerische Mathematik*, vol. 1, pp. 269-271, 1959.

[25] R. K. Ahuja, K. Mehlhorn, J. B. Orlin, and R. E. Tarjan, "Faster algorithms for the shortest path problem," *J. Assn. Comp. Mach.*, vol. 37, no. 2, pp. 213-223, Apr. 1990.

[26] J. A. Bondy and U. S. R. Murty, *Graph Theory with Applications.* New York: Elsevier, 1976.

[27] M. J. Arden, J. Gosling, and D. S. H. Rosenthal, *The NeWS Book*, New York: Springer-Verlag, 1989.

[28] Sun Microsystems, *X11/NeWS Release* 1.0 *Manual.* Mountain View, CA: Sun Microsystems, Aug. 1989.

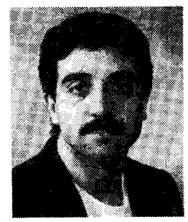
[29] The Turing Institute, *GoodNeWS*1.3 *User Guide*, Glasgow, Scotland: Turing Institute, Sept. 1989.

[30] —, *HyperNeWS*1.3 *User Manual*, Glasgow, Scotland: Turing Institute, Sept. 1989.

[31] Quintus Computer Systems Inc., *Quintus Prolog Development System Manual.* Mountain View, CA: Quintus Computer Systems, Release 2.4.

[32] E. P. Stabler, Jr., "Object-Oriented Programming in Prolog," *AI Expert*, pp. 46-57, Oct. 1986.

[33] A. Kaufmann and M. M. Gupta, *Introduction to Fuzzy Arithmetic.* New York: Van Nostrand Reinhold, 1985, pp. 68-76.



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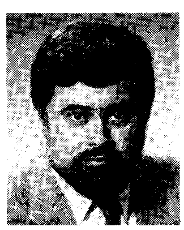

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