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HardSys/HardDraw: A Smart Topology Based Electromagnetic Interaction Modelling Tool

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Abstract

An intelligent tool for the modelling and analysis of electromagnetic interactions in a complex electrical system is described. The purpose is to determine any unwanted electromagnetic effects which could jeopardize the safety and operation of the system. Modelling the interactions in a system requires the examination of the compounded and propagated effects of the electromagnetic fields. The approach taken here subdivides the modelling task into two parts: a) the definition of the related electromagnetic topology, and b) the propagation of the electromagnetic constraints. *HardSys*, a prototype object-based system implemented in Prolog, is used to propagate the electromagnetic constraints. User interaction is through *HardDraw*, a topology-drawing tool and an attribute interface.

1.0 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 which 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*.

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*. The application of this theory over the years has given insight into *mechanisms* of electromagnetic interaction. These 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. *Non-algorithmic* 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 heuristics used to reason about these components.These heuristics are derived from well known engineering principles and can be viewed as *constraints* on the electromagnetic interaction problem.

The knowledge required in modelling electromagnetic systems includes the *electromagnetic topology* of the system and the *electromagnetic attributes* of each node in the topology. A prototype tool made up of an advisor and a drawing tool has been implemented in Quintus Prolog™ on a Sun™ workstation [1, 2, 3]. The advisor, *HardSys*, helps to analyze the electromagnetic attributes of an electromagnetic system. The user-interface for HardSys is a unique topology-drawing tool called *HardDraw* and is implemented with a Postscript-based user-interface toolkit called GoodNeWS/HyperNeWS (see Fig. 26 for a summary of the architecture).

2.0 Electromagnetic Topology of Systems

In order to model an electromagnetic system, it is first necessary to understand and represent the r*elevant physical* attributes of the system [4, 5, 6, 7]. In this procedure, an electromagnetic system is decomposed into an *electromagnetic shielding topology* and its dual graph or i*nteraction 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 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. A simple example is used to explain how the topological decomposition of systems is performed. The topology of Fig. 1 shows an extension to the theory of [7] in that circuit elements are also represented as volumes.

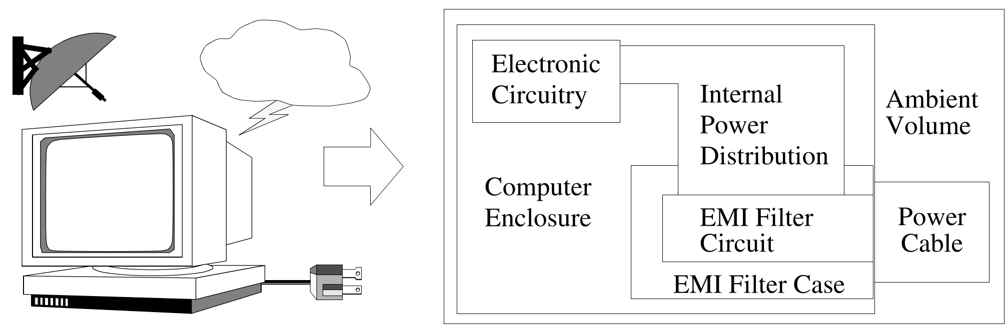


Fig. 1. Example Electromagnetic Topology Decomposition of a System

The interaction sequence diagram is 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***.

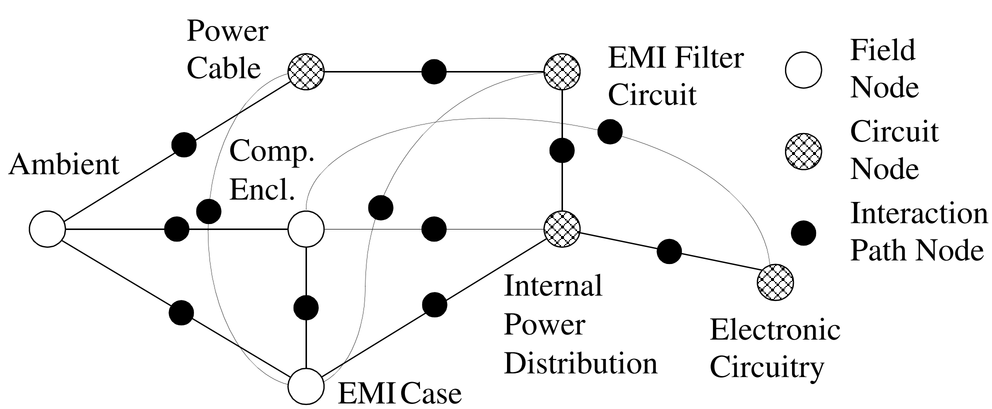


Fig. 2. Equivalent Interaction Sequence Diagram

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.

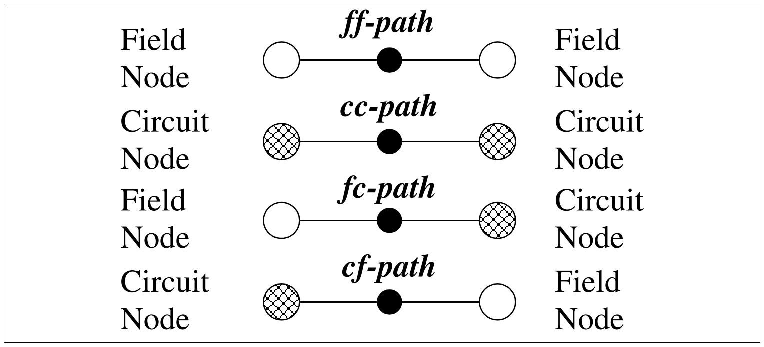


Fig. 3. Interaction path types

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 priori unless previous experience with similar electromagnetic components and topologies is available.

As an example, consider the two topological decompositions of a conducting penetration shown in Fig. 4. A conducting penetration can reduce the shielding effectiveness of an enclosure to zero in certain frequency ranges. 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.

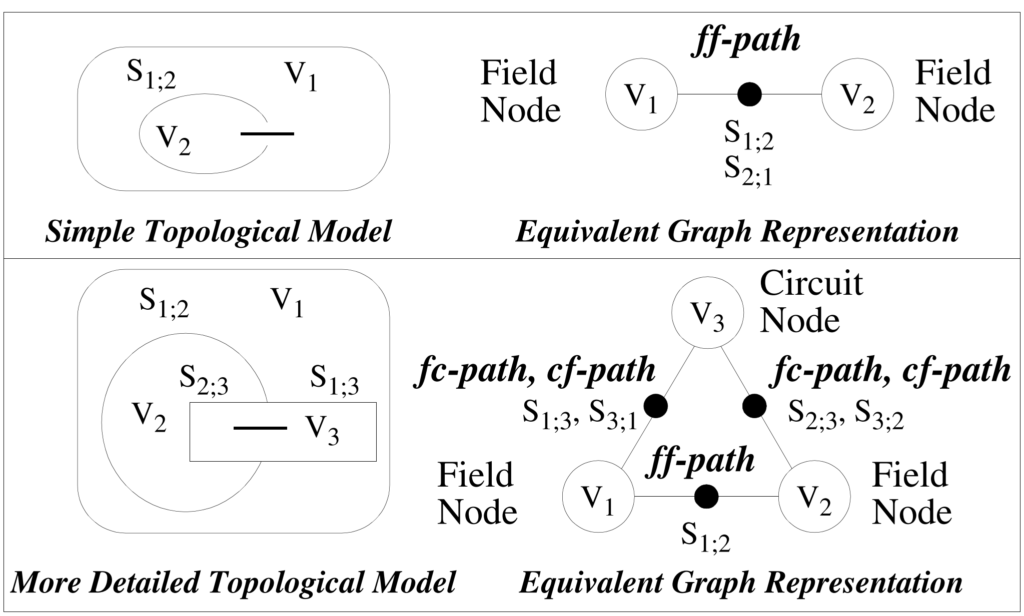


Fig. 4. Two topological representations of the same shielding imperfection

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 a simpler representation with new composite attributes. The imposition of specific attributes on the topology components is discussed in the next section.

3.0 Electromagnetic Component and Path Attributes

The next step in modelling the electromagnetic system is to approximate the propagation of electromagnetic energy from one volume node to another as shown in Fig. 5. 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 and represent the electromagnetic knowledge which is known about a system.

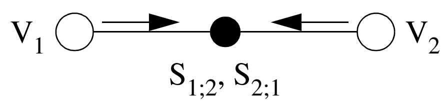


Fig. 5. Single electromagnetic interaction path

A good electromagnetic knowledge representation will have the following characteristics. It should

1) be easily derivable from available experimental/numerical data,

2) be in an easily manipulated qualitative form,

3) yield useful quantitative/qualitative results and recommendations,

4) have the capability to handle exceptions, and

5) have variable levels of approximation (coarse to fine).

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 [8]. Emissions from equipment are often measured using receivers with specific bandwidths of reception over large ranges of frequency [9]. Furthermore, susceptibilities of electronic components such as microelectronic circuitry are also calculated in the frequency domain [10, 11]. Thus all electromagnetic attributes are specified over quantized frequency ranges.

3.1 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 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. These ranges are chosen heuristically based on experience of electromagnetic disturbance levels and on the requirement for a useful number of ranges. Once these values are chosen, the creation of a useful database of disturbances requires that they remain constant.

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

Specification of a *unique* time domain waveform requires not only amplitude information but phase information as well. The phase information can mean the difference between a *coherent wideband* emission and an *incoherent wideband* emission [11, 12]. Thus the representation of a disturbance will also contain a *slot*, or location, for the specification of pertinent phase information.

As an example, the fields produced by a lightning strike can be simulated by the fields produced by a current pulse with pulse width of 50 μs and a 10 to 90 percent rise time of 500 ns [11]. At a distance of 100 m the field disturbance may be approximated and stored in the database as shown in Fig. 7.

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

Each node may contain many disturbance representations derived for all the sources present in that volume. The individual attributes are *frequency range normalized* to a user specified global frequency range list and *added in parallel* to determine the *total disturbance* for the node as shown in Fig. 8. For simplicity, the disturbance for the node (either P or PD) is denoted *ambient field* (AF).

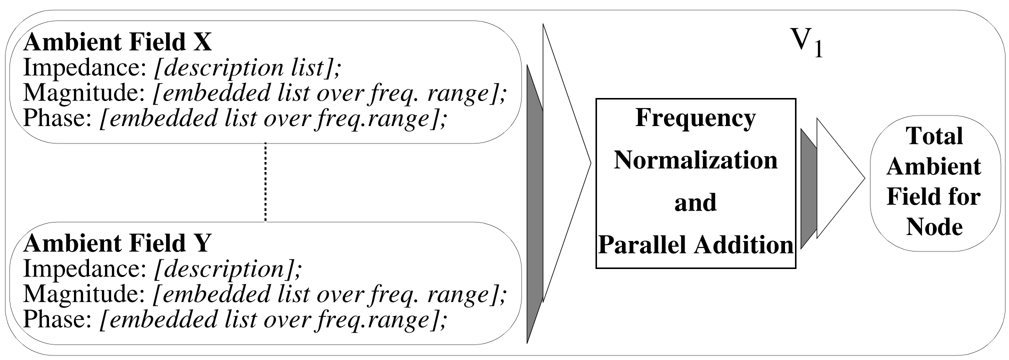


Fig. 8. Ambient field attributes for a typical volume node.

The total nodal ambient field AF_T is required over the specific *global* frequency range set F_g given by the N-element frequency range list

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

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

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

$$AF_x = ((af_{x1}), (af_{x2}), \ldots (af_{xj}), \ldots (af_{xM-1}), (af_{xM})), \tag{3}$$

where the af_{xj}'s represent a quantized amplitude level previously described.

Each AF_x must be normalized to the global frequency range F_g:

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

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

Frequency Normalization Algorithm

Loop 1: over the F_g ranges (f_{gj-1}, f_{gj}), j=1, ... N;
    set af_{xnj} to ***unknown***;
    Loop 2: over the F_x ranges (f_{xi-1}, f_{xi}), i=1, ... M;
        If $f_{xi} \le f_{gj-1}$ then end loop 2;
        If $f_{xi-1} \ge f_{gj}$ then end loop 2;
        set af_{xnj} to ***worseAF***(af_{xnj}, af_{xi});
    continue *Loop 2*;
continue *Loop 1*;

Fig. 9. Frequency normalization algorithm

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***. 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.

The ***Parallel Addition*** procedure is given in Fig. 10. Given k normalized ambient field representations for a node, say AF_{1n}, AF_{2n}, ... AF_{jn}, ... AF_{k-1n}, AF_{kn}, each consisting of a set of N ambient field values. The total ambient field AF_T is determined as the worst case ambient field value in each frequency range.

Parallel Addition Algorithm:

Loop 1: over the AF_j ambient field sets, j = 1, ... k;
    set AF_{jn} to ***frequency normalize*** AF_j;
continue *Loop 1*;
Loop 2: over the F_g ranges (f_{gi-1}, f_{gi}), i = 1, ... N;
    set af_{Ti} to ***unknown***;
    Loop 3:over the AF_{jn} ambient field sets, j = 1, ... k;
    if af_{jni} = ***unknown*** then set ***unknown flag***;
    set af_{Ti} to ***worseAF***(af_{Ti}, af_{jni});
    continue *Loop 3*;
continue *Loop 2*.

Fig. 10. Parallel addition algorithm

3.2 Component Susceptibility Representation

Each volume node in an electromagnetic topology may also have a *system susceptibility* (SS) associated with it. The system susceptibility is inversely related to the level of disturbance which will cause either ***upset***; or ***permanent damage*** to the susceptible component. That is, the lower the disturbance level which will cause upset or damage to a component the higher the defined susceptibility of that component.

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 [10]. In the case of analogue circuits, definition of a precise disturbance level where upset occurs is not as simple as for logic type circuits. For these types of circuit, damage level may be easier to define. Damage and upset levels of many integrated circuit technologies have been tabulated in [10].

As with the ambient field representation, system susceptibility is represented in the frequency domain as *quantized*, 40 dB levels given in Fig. 11.

very low	if SS is > 84 dBm/m^2/Hz ***or*** dBm/Hz
low	if SS is 44 - 84 dBm/m^2/Hz ***or*** dBm/Hz
medium	if SS is 4 - 44 dBm/m^2/Hz ***or*** dBm/Hz
high	if SS is -36 - 4 dBm/m^2/Hz ***or*** dBm/Hz
extreme	if SS is < -36 dBm/m^2/Hz ***or*** dBm/Hz
nil	--> not susceptible
unknown	propagate as unknown throughout

Fig. 11. System susceptibility definitions

Along with this *level representation*, the type of sensitivity and the effect of failure (i.e. upset or damage) may be given for each frequency range. An example of the SS for CMOS integrated circuits is shown in Fig. 12.

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

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, frequency normalization and parallel addition routines, similar to those used for ambient field with ***worseAF***(af_1, af_2) replaced by***worseSS***(ss_1, ss_2), are used.

3.3 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 and the units for this quantity depends on the two component nodes which the path connects. The SE is defined with discrete *qualitative* levels shown in Fig. 13.

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

Each interaction path may be made up of a number of different parallel paths between volume nodes (see Fig 14). Each of these parallel paths is given an SE characterization and a total SE is obtained via the frequency normalization and parallel addition algorithms.

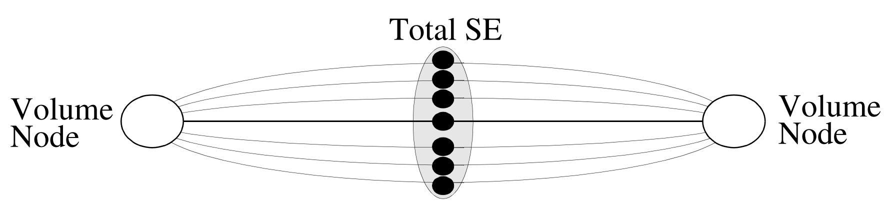


Fig. 14. Interaction Path Composed of Many Parallel Paths

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

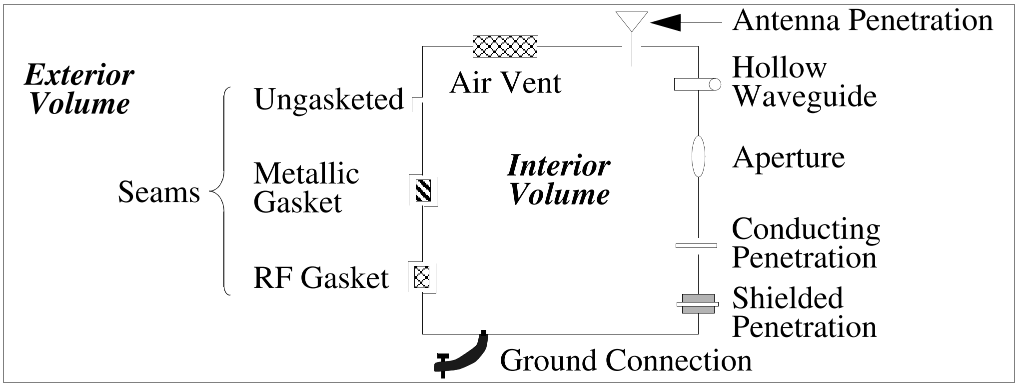


Fig. 15. Typical shield imperfections

As an example, the shielding effectiveness of an aperture [12, 13] is stored as shown in Fig. 16. This attribute would characterize one of the multiple parallel paths making up the total interaction path between the two field nodes.

Shielding Effectiveness: aperture: L = .1; W = .01;

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. 16. Example shielding effectiveness representation

Circuit-circuit path nodes are used to model any interaction between circuit nodes. For example, any electrical circuit connection can be modelled by a cc-node. The level of modelling 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 field 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. This has been found to be a good approximation for frequencies ranging from 100 MHz to 10 GHz [10]. 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 [12]. More accurate models are obtainable for emissions from circuit boards [14].

4.0 Using Constraints to Characterize EMI

The language of *Constraints* was described by Sussman and Steele [15] as a method of deriving useful consequences by propagating conditions through a constraint network (see also Montanari [16]). Presently, constraints are used to define an electromagnetic interaction problem.

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 [17], the statements

```
node( external vol).          node( computer).        node( cpu).
node( power distribution).    node( power cord).      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 supply, power cord).
surface( power distribution, power supply).
```

would declare the existence of six nodes and nine surfaces in the current topology. 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.

Specific electromagnetic attributes can be imposed over the defined 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. These disturbances exist in the data base in the previously described form. Entering these constraints would trigger the *frequency normalization* and *parallel addition* algorithms producing a total disturbance for this node. Nodes which are not instantiated with specific attributes are taken to be *unknown* over all global frequency ranges. The statements

```
susceptibility( node( cpu),
                [[digital, TTL], [digital, CMOS], [analogue, line_driver]]).

susceptibility( node( power supply),
                [[analogue, volt_regulator], [digital, comparator]]).
```

constrain the total susceptibilities of the specified nodes, 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, 30cmX30cm]]).

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 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 them. A search for the worst case shielding path from each susceptible node to all other emitting nodes is performed using *Dijkstra's algorithm* [18, 19, 20] using the *distances* shown in Fig. 17 for each heuristic shielding level.

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. 17. Definition of SE variable distances

The worst case shielding path to the two emitting nodes is highlighted in Fig. 18 with the total shielding represented as

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

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, the value of 2.5 is maintained for the total SE variable.

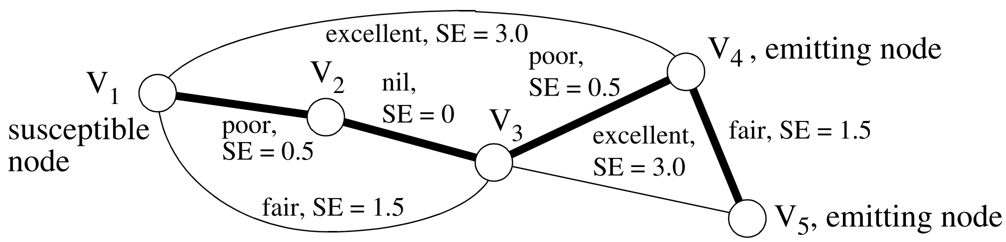


Fig. 18. Example worst case shielding path for a specific frequency

During the search, the individual surfaces on the path are sorted from poorest to best total shielding and kept as a trace. The determination of total shielding between two non-neighbor nodes is the same as imposing a surface between them and is similar to the *slices* concept in [15].

The *likelihood of failure* is determined at the susceptible nodes, by a comparison of the *propagated* electromagnetic disturbance through the worst case shielding path from an emitting node to 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. 19.

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. 19. Ambient field and system susceptibility discrete levels

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

$$PAF = TAF - TSE \tag{5}$$

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

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 MHz - 10 MHz) a level of *high* is specified then this approximates the disturbance with equal probability over a 40 dB ambient field range as shown in Fig. 20. 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 shown in Fig. 20 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 fields 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.

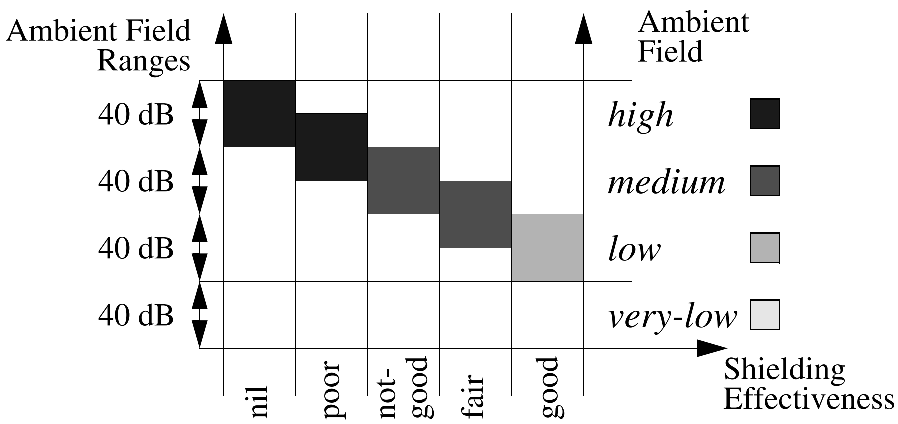


Fig. 20. High ambient field approximation propagated through good SE

The likelihood of failure is reported as being one of the discrete values shown in Fig. 21 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

$$FI_{\text{for node}} = PAF_{\text{all emitting nodes}} - SS_{\text{total for node}}. \tag{6}$$

If the likelihood of failure of any susceptor is too great, then parameters in one or all of the three constraining factors must be modified at one or more locations in the topology. Many ways will exist to reduce the likelihood of failure at a specific node, each with advantages and disadvantages. This is where the traces which were developed throughout the analysis will help.

extreme	if FI Š 1.5
high	if 0.5 ≤ FI < 1.5
marginal	if -0.5 ≤ FI < 0.5
low	if -1.5 ≤ FI < -0.5
very low	if -2.5 ≤ FI < -1.5
nil	FI < -2.5 or associated with a non-susceptible nodes
unknown	if either susceptibility or disturbance are *unknown*

Fig. 21. Likelihood of failure discrete levels

Visually it is convenient to refer to Fig. 22 to understand how the likelihood of failure is determined. Notice how the calculated FI is not uniquely determined by the *reported* PAF and system susceptibility (highlighted block).

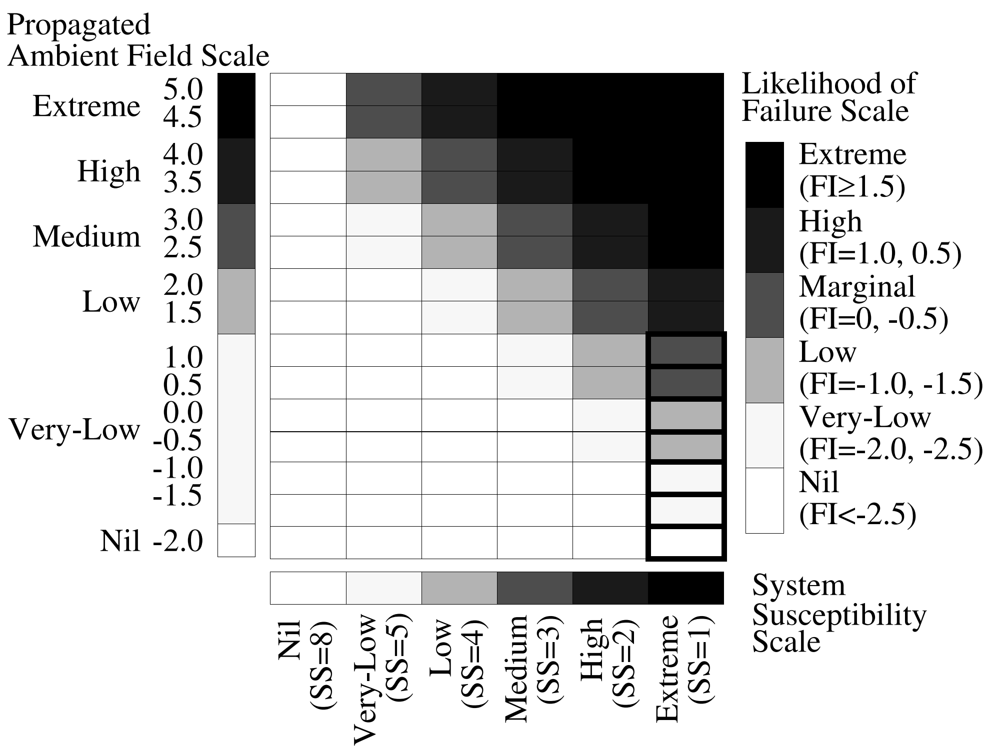


Fig. 22. Likelihood of Failure Chart

This procedure for determining the likelihood of failure is justified heuristically by an understanding of what each FI level represents. The ambient field ranges can be plotted on a graph of the susceptibility levels, as shown below in Fig. 24, where the likelihood of failure results for a system susceptibility of *medium* are shown across the top of the figure.

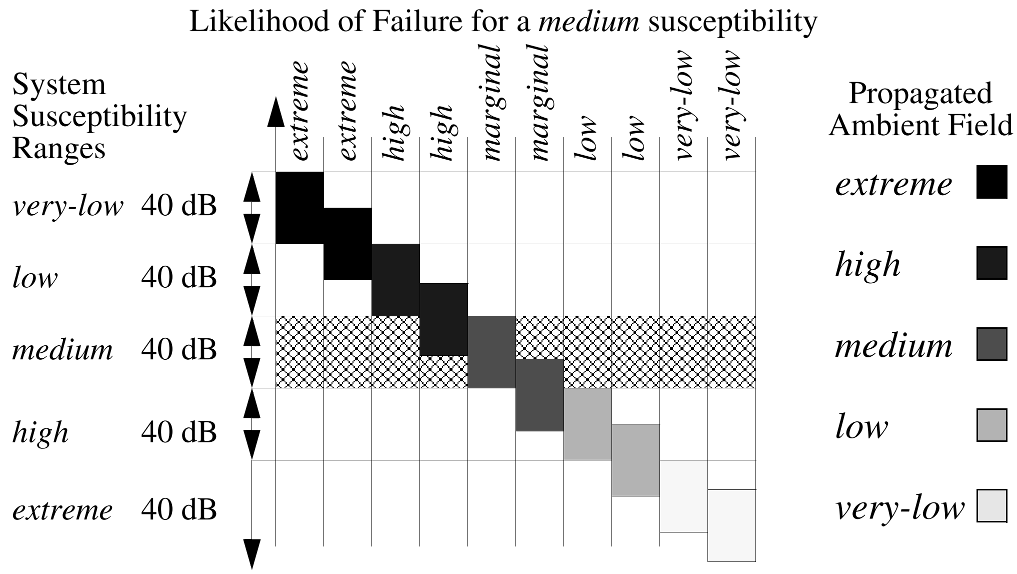


Fig. 23. Overlap of PAF ranges with SS ranges to determine FI

Note that, due to the 20 dB discretization of the shielding effectiveness, there are two ambient field ranges for each level shown in the propagated ambient field key at the right of the figure. 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 then the likelihood of failure is 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.

5.0 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 v in common, then v is called a cut node [20]. As an example, nodes v_1, v_3, and v_5 in Fig. 24 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 group is represented by a *grouped node* in place of the cut node. In the right most graph of Fig. 24, v_5, v_7 and v_6, are grouped into node v_3.

The process of grouping is used to reduce the search space in the worst case shielding path algorithm. The subgraph containing nodes which are not expected to change may be grouped as a valid grouping.

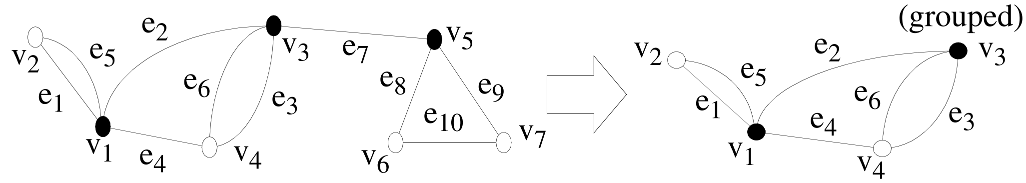
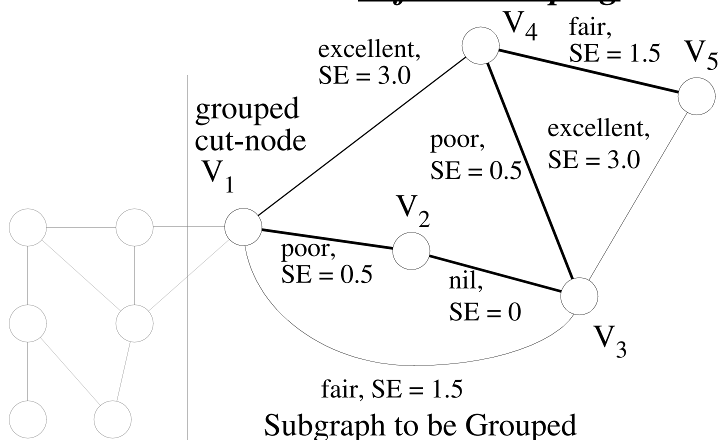


Fig. 24. Cut node and cut edge examples

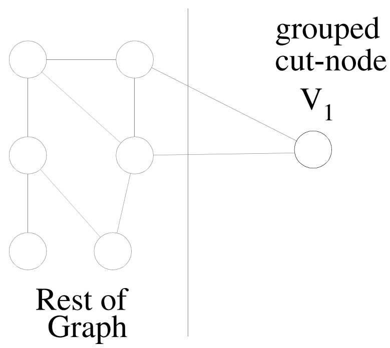
A grouped node must derive its attributes from its subgraph attributes. This is accomplished by determining the *single source minimal spanning tree* for the subgraph, with the cut-node as the root node. The susceptibility as well as the ambient field attributes of each node in the subgraph are then 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 shielding path to the root node from the total SS value of the node being grouped. An example of the grouping process is shown in Fig. 25.

Before Grouping



Node	Self Attributes SS	AF
V_1	low (4)	medium (3)
V_2	nil (8)	nil (-2)
V_3	low (4)	nil (-2)
V_4	high (2)	extreme (5)
V_5	extreme (1)	medium (3)

After Grouping



Node	Self Attributes SS	AF	Worst SE to V_1	Propagated Att. SS+SE	AF-SE
V_1	low (4)	medium (3)	———	low (4)	medium (3)
V_2	nil (8)	nil (-2)	poor (0.5)	nil (8.5)	nil (-2.5)
V_3	low (4)	nil (-2)	poor (0.5)	low (4.5)	nil (-2.5)
V_4	high (2)	extreme (5)	not-good (1.0)	medium (3)	high (4)
V_5	extreme (1)	medium (3)	good (2.5)	medium (3.5)	very-low (0.5)
Parallel Addition of Attributes				medium (3)	high (4)

Fig. 25. Example of grouping a subgraph in a cut-node

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 grouped node susceptibility and ambient field attributes. As an example, for the grouped nodes of Fig. 25 the trace of the grouped SS attribute would be represented as the list [V_4, V_5, V_1, V_3, V_2] while 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 group.

6.0 Implementation

The heuristic techniques and procedures described herein have been included in a prototype implementation on a Sun Microsystem SPARCstation-1™. The implementation consists of two main parts; a smart topology-drawing tool referred to as ***HardDraw,*** and an electromagnetic interactions advisor referred to as ***HardSys***. A picture of the overall structure of the system is shown below in Fig. 26.

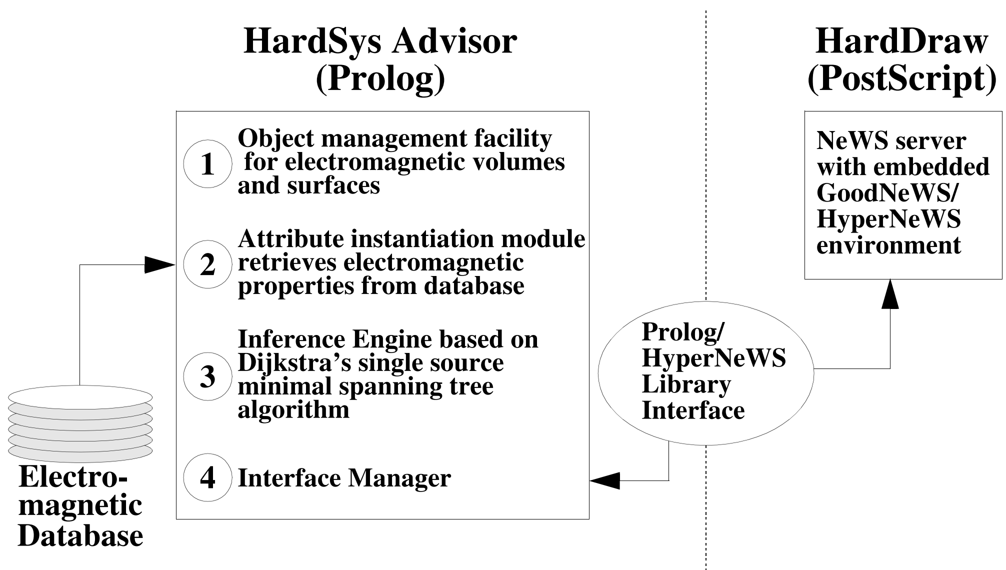


Fig. 26. Overall system architecturs

The purpose of *HardDraw* is to give the user of the software an easy way to input the electromagnetic topology of systems (see Fig. 27 below). This smart topology-drawing tool is implemented with a NeWS™ -based [21] user-interface toolkit called GoodNeWS/HyperNeWS [22, 23]. It communicates with HardSys by means of a Prolog/HyperNeWS library.

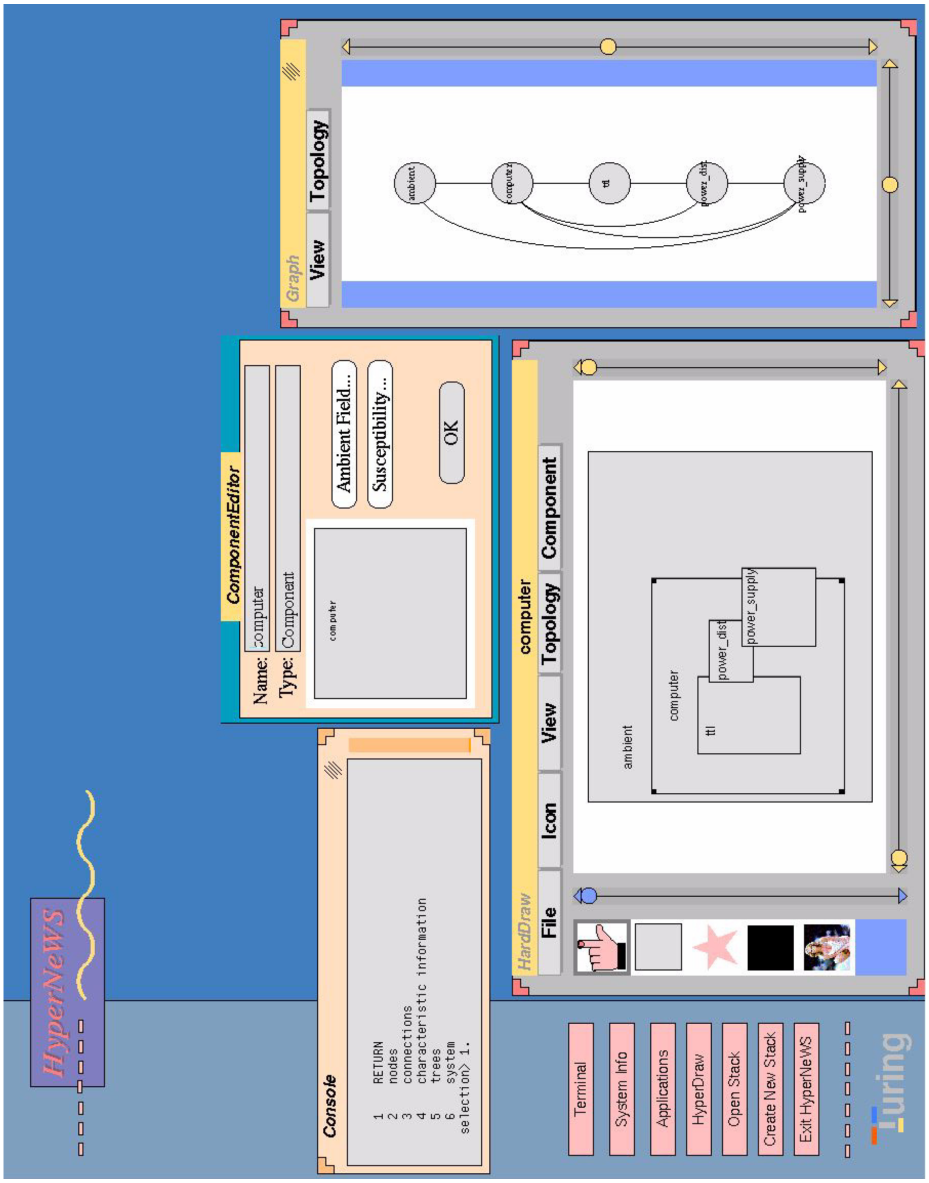


Fig. 27. Example HardDraw session

Once the electromagnetic topology has been entered and the volume/ surface attributes have been defined, reasoning about the possible interactions therein is performed by HardSys, an expert system written in Quintus™ Prolog [24]. An *object-oriented knowledge representation* approach is taken based on that of Stabler [25]. The electromagnetic component nodes and surfaces are implemented as *objects*. The electromagnetic attributes associated with each node or surface are implemented as *methods* of those objects. 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 which will be imposed.

7.0 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 three categories:

1) knowledge representation and search technique enhancements;
2) user interface enhancements; and
3) knowledge acquisition and validation.

The search technique used thus far is the *theoretically* most efficient [19] 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 heuristically guided to 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.

Knowledge acquisition is the problem of how to acquire accurate EMI data from the many sources available 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 on the design of real systems.

References

[1] LoVetri, J., Abu-Hakima, S., Podgorski, A. S., Costache, G. I., “Hard-Sys: Applying Expert System Techniques to Electromagnetic Hardening”, *IEEE 1989 National Symposium on Electromagnetic Compatibility*, pp. 383 - 385, Denver, Co., May 23-25, 1989.

[2] LoVetri, J., and Graham, D. P. W., “Constraint Propagation Through Electromagnetic Interaction Topologies”, *ANTEM’90, Symp. on Antenna Tech. and Appl. Electromagnetics*, Winnipeg, Manitoba, August 15-17, 1990.

[3] LoVetri, J., and Podgorski, A. S., "Evaluation of HardSys: A Simple EMI Expert System", *1990 IEEE Int. Symp. on EMC*, Washington, D.C., August 21-23, 1990.

[4] Baum, C. E., "Electromagnetic Topology, A Formal Approach to the Analysis and Design of Systems", *Interaction Notes*, Note 400, Air Force Weapons Lab, September, 1980.

[5] Baum, C. E., "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.

[6] Messier, M. A., "EMP Hardening Topology Expert System (Hard Top)", *Electromagnetics*, vol. 6, no. 1, pp. 79 - 97, 1986.

[7] Tesche, F. M., "Topological Concepts for Internal EMP Interaction", *IEEE Trans. on Ant. and Prop.*, vol. AP-26, no. 1, pp. 60 - 64, Jan., 1978.

[8] Schulz, R. B., Plantz, V. C. and Brush, D. R., "Shielding Theory and Practice", *IEEE Trans. Electromagn. Compat.*, vol. 30, no. 3, pp. 187 - 201, August, 1988.

[9] U.S. Department of Defense, "Measurement of Electromagnetic Interference Characteristics", *Mil-Std-462*, July 31, 1967.

[10] McDonnel Douglas Astronautics Co. *Integrated Circuit Electromagnetic Susceptibility Handbook*, Report MDG-E1929, Box 516, St. Louis, Missouri, (314) 232-0232, August 1978.

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

[12] Ott, H. W., *Noise Reduction Techniques in Electronic Systems*, John Wiley & Sons, New York, 1988.

[13] Vitek, C., "Predicting the Shielding Effectiveness of Rectangular Apertures", *IEEE 1989 National Symposium on EMC*, Denver, Colorado, pp. 27 - 32, May 23 - 25, 1989.

[14] Raut, R., "On the Computation of Electromagnetic Field Components from a Practical Printed Circuit Board", *1986 IEEE Int. Symp. on EMC*, pp. 161 - 166, San Diego, CA, Sept. 16 - 18, 1986.

[15] Sussman, G. J. and Steele, G. L., "Constraints - A Language for Expressing Almost-Hierarchical Descriptions", *Artificial Intelligence*, vol. 14, pp. 1 - 39, 1980.

[16] Montanari, U., "Networks of Constraints: Fundamental Properties and Application to Picture Processing", *Information Science*, vol. 7, pp. 95 - 132, 1974.

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

[18] Dijkstra, E. W., "A Note on Two Problems in Connexion with Graphs", *Numerische Mathematik*, vol. 1, pp. 269 - 271, 1959.

[19] Ahuja, R. K., Mehlhorn, K., Orlin, J. B., and Tarjan, R. E., "Faster Algorithms for the Shortest Path Problem", *J. of the Ass. for Comp. Mach.*, vol. 37, no. 2, pp. 213-223, April 1990.

[20] Bondy, J. A., and Murty, U. S. R., *Graph Theory with Applications*, American Elsevier Pub. Co., Inc., 1976.

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

[22] The Turing Institute, *GoodNeWS1.3 User Guide*, The Turing Institute, Glasgow, Scotland, September, 1989.

[23] The Turing Institute, *HyperNeWS1.3 User Manual*, The Turing Institute, Glasgow, Scotland, September, 1989.

[24] Quintus Computer Systems Inc., *Quintus Prolog Development System Manual (Release 2.4)*, Quintus Computer Systems Inc., Mountain View, California.

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