EVALUATION OF HardSys: A SIMPLE EMI EXPERT SYSTEM

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Abstract

The concepts used in designing *HardSys*, a simple expert system capable of reasoning about EMI problems, are described. These are then evaluated by running the expert system on a test case previously analyzed by an EMI consultant. The test case was a subset of the NEMP hardening of a typical military helicopter. The knowledge representation used in HardSys is of a *fuzzy* nature and it is this *fuzziness* which we have evaluated. The conclusions are that the present knowledge representation is a very powerful tool for EMI engineers.

Introduction

The use of *non-algorithmic* techniques to solve *electromagnetic interaction* problems is investigated. These techniques and procedures are used daily by engineers to solve electromagnetic interference problems of electrical systems.The purpose here is to validate the symbolic knowledge representation of the problem which has been implemented on a computer (see LoVetri et. al. [1]). This knowledge is manipulated using *constraints* derived from the well known EMI engineering principles.

Knowledge Representation

In order to model the EM interaction of a system, it is first necessary that the *relevant physical* attributes of the system be understood. A procedure for accomplishing this has been explained, for example, by Tesche [2], Baum [3] and Messier [4]. In this procedure relevant attributes are divided into an *electromagnetic shielding topology* and the dual graph or *interaction sequence diagram.* The electromagnetic topology consists of a description of the electromagnetically distinct volumes and their associated surfaces. The interaction sequence diagram keeps track of the *interaction paths* throughout the system. The two procedures are not independent of each other, in fact, the interaction sequence diagram can usually be derived from a given electromagnetic shielding topology and the associated electromagnetic attributes of each item in the topology.

To make the topology representation more useful, approximations for the propagation of electromagnetic energy from one volume node to another (see figure 1 below) are made. Thus the electromagnetic attributes of a single electromagnetic component are symbolically represented and implemented as a set of *constraints.* The complete physical model is eventually constructed incrementally and the constraints propagated throughout the graph (topology).

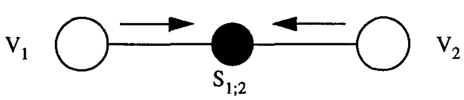

Figure 1: Single node-node interaction in a topology.

In the following sections the representation of the relevant electromagnetic attributes at the individual nodes will be discussed. It must be realized that many representations of this knowledge are possible but that the acceptable scheme is the one which achieves an acceptable trade off between *approximation* and *usefulness*. The characteristics given in table 1 below are desirable in an electromagnetic representation.

Table 1
Desirable Qualities of Electromagnetic Approximation Schemes

1. Easily derivable from available experimental/numerical data.
2. Amenable qualitative form (symbolic manipulation).
3. Derivable useful quantitative results and recommendations.
4. Capability to handle exceptions.
5. Variable levels of approximation (coarse to fine).

Frequency Domain Representation

Most electromagnetic interaction phenomena is calculated, measured and reported as quantified data in the frequency domain. The reason for this is that a lot of useful engineering information about fields, susceptibilities and paths of interaction can be characterized *only* in the frequency domain. The advantages of frequency domain representations are obvious for linear systems; almost any waveform can be transformed into the frequency domain via the Fourier series or transform.

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 [5]). Emissions from equipment are often measured using receivers with specific bandwidths of reception over large ranges of frequency (see Mil-Std-462 and Mil-Std-461C [6], [7]). Susceptibilities of electronic components such as microelectronic circuitry are also calculated in the frequency domain [8]. Thus the frequency domain is discretized into a *set* of, say N, frequency ranges denoted as:

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

Ambient Field Representation

It is possible for each component node in an electromagnetic topology to have an ambient field associated with it. This ambient field quantity represents either the actual measured electromagnetic disturbance emitted by the component node or an approximation of it based on numerical and/or experimental data of similar components. The *decibel* scale is usually used for such representations due to the large range of emission levels possible from the wide range of emitters of electromagnetic radiation.

The first question which arises is as to what types of electromagnetic disturbances are possible. An appropriate classification is:

1) electric field $\boldsymbol{E}$ with units of [V/m or dBV/m];
2) magnetic field $\boldsymbol{H}$ with units of [A/m or dBA/m];
3) and power density $\boldsymbol{P_d}$ with units of [W/m^2 or dBW/m^2];

for ***field nodes***, and:

1) voltage V with units of [V or dBV];
2) current I with units of [A or dBA];
3) and power P with units of [W or dBW];

for ***circuit nodes***.

These quantities are not independent of each other and can be related to each other via the wave impedance $\bar{Z}$ (since $\boldsymbol{E}$ and $\boldsymbol{H}$ are generally vectors, $\bar{Z}$ is a tensor of rank two) as:

$$\boldsymbol{P_d} = (\boldsymbol{E} \times \boldsymbol{H}); \tag{2}$$

$$\boldsymbol{E} = \bar{Z}\boldsymbol{H}. \tag{3}$$

for field nodes, and similarly via a circuit impedance for circuit nodes.

If the maximum dimension of a radiating component (i.e. current carrying component or aperture) is given as D then a boundary distance between the *far field* and *near field* region can be defined as

$$r = \frac{\lambda}{2\pi}, \text{ for } D \ll \lambda \tag{4}$$

$$r = \frac{D^2}{2\lambda}, \text{ for } D \geq \frac{\lambda}{2} \tag{5}$$

where λ is the wavelength of the emission (see Duff [9] pp 2.10-2.21).

In the far field or *radiation field* the electric and magnetic field vectors can be shown to propagate perpendicular to each other with an impedance of ≈ 377 Ω and both fall off or attenuate as 1/r. In the near field or *induction field* the impedance between the perpendicular components of the electric and magnetic field vectors is > 377 Ω for *electric* or *high-impedance fields* and < 377 Ω for *magnetic* or *low-impedance fields*. One other difference in the near field region is that all the directional components of both vectors may exist.

Ambient Field Simplifications

The first simplification which is made for field nodes is to ignore the directional properties of the magnetic and electric fields (i.e. they are treated as scalars). Thus $\boldsymbol{E}$ becomes E, $\boldsymbol{H}$ becomes H, and $\boldsymbol{P_d}$ becomes P_d. In a sense this takes the worst case field orientation properties and will not allow accounting for poor coupling of fields from emitter to susceptor due to physical orientation in space. Similar simplifications are made in [8]. Thus equations (1) and (2) become

$$P_d = EH = \frac{E^2}{Z} = H^2 Z \quad [\mathrm{W/m^2}]; \tag{6}$$

$$E = ZH \quad [\mathrm{V/m}]. \tag{7}$$

These now are the equivalent relations as for circuit nodes with V, I, and P in the circuit node representation being replaced by E, H, and P_d in the field representation.

Next the impedance of the node is quantized as being either:

1) electric (Z >> 377 Ω) or high (Z >> 100 Ω);
2) magnetic (Z << 377 Ω) or low (Z << 100 Ω); or
3) plane wave (Z ≈ 377 Ω) or medium (Z ≈ 100 Ω).

This attribute is used to determine the way in which the field propagates through an interaction path.

The final approximation is the quantization of the (AF) strength into seven *qualitative* levels. These are defined in terms of *power density* P_d or *power* P to be (bracketed term corresponds to equivalent plane wave electric field; also for circuit node read as dBm):

1) ***extreme*** if AF is > 84 dBm/m^2/Hz (>10 kV/m/Hz);
2) ***high*** if AF is 44 - 84 dBm/m^2/Hz (.1 - 10 kV/m/Hz);
3) ***medium*** if AF is 4 - 44 dBm/m^2/Hz (1 - 100 V/m/Hz);
4) ***low*** if AF is -36 - 4 dBm/m^2/Hz (10 mV/m - 1 V/m/Hz);
5) ***very low*** if AF is < -36 dBm/m^2/Hz (< 10 mV/m/Hz);
6) ***nil*** --> no ambient field;
7) ***unknown***: (propagate as unknown throughout).

The possibly numerous individual ambient field attributes for all the sources associated with a volume node (say V_1, as in above figure) can be *frequency range normalized* and *added in parallel* in order determine the *total ambient field* emitted from a node. This is described in the following section where field nodes are specifically dealt with (circuit nodes are dealt with in a similar fashion).

Parallel Addition and Frequency Normalization

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 frequency range set F_g (*global* frequency range set) given by the N frequency ranges

$$F_g = ((f_{g0}, f_{g1}), (f_{g1}, f_{g2}), \ldots, (f_{gj-1}, f_{gj}), \ldots, (f_{gN-1}, f_{gN})). \tag{8}$$

Then, if a specific ambient field AF_x is stored in the database over a specific frequency range set F_x given by the M frequency ranges

$$F_x = ((f_{x0}, f_{x1}), (f_{x1}, f_{x2}), \ldots, (f_{xj-1}, f_{xj}), \ldots, (f_{xM-1}, f_{xM})), \tag{9}$$

then AF_x can be represented by the set of M ambient field amplitudes

$$AF_x = ((af_{x1}), (af_{x2}), \ldots, (af_{xj}), \ldots, (af_{xM-1}), (af_{xM})), \tag{10}$$

for a certain impedance attribute AFZ_x. 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} where

$$AF_{xn} = ((af_{xn1}), (af_{xn2}), \ldots, (af_{xnj}), \ldots, (af_{xnN-1}), (af_{xnN})), \tag{11}$$

This proceeds by the following algorithm:

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*;

where 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***;
- and ***worseAF(high, low)*** returns ***high***.

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

Now when more than one specific ambient field is specified for a volume node ***Parallel Addition*** will be performed. Given k ambient field representations in a node, say $AF_1, AF_2,..., AF_j,... AF_{k-1}, AF_k$, the first step is to frequency normalize these as $AF_{1n}, AF_{2n},..., AF_{jn},... AF_{k-1n}, AF_{kn}$. At this point each of the k ambient fields 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 for each global frequency range. Specifically the following algorithm can be applied:

Parallel Addition Algorithm

Loop 1: over the AF_j ambient field sets, j=1,..., k;

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_j ambient field sets, j=1,..., k;

if af_{ji} = ***unknown*** then set ***unknown flag***;

set af_{Ti} to ***worseAF***(af_{Ti}, af_{ji});

continue *Loop 3*;

continue *Loop 2*.

Examples of Ambient Field Attributes

The fields emitted by a lightning strike can be simulated by that produced by a current pulse with pulse width $\tau \approx 50$ μs and a 10 to 90 percent rise time $\tau_r \approx 500$ ns (see Duff [9]). The average stroke has a current amplitude of 30 kA. A typical value for peak radiated field strength is 50 kV/m at 1 km distance. If this is modelled as a double exponential pulse then the time domain waveform and the associated frequency domain representation are as in figure 3.

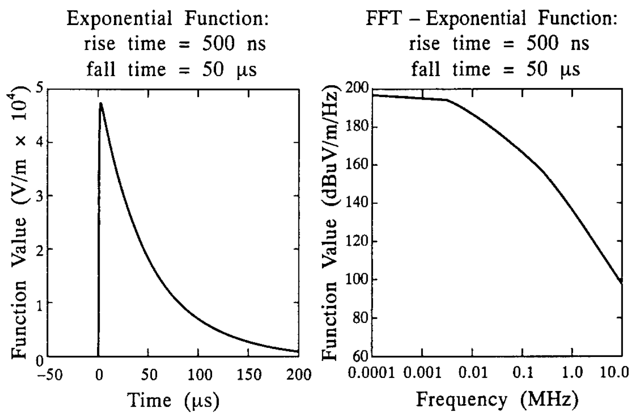

Figure 2: Lightning Emission (Time & Freq. Domain)

This would be stored as a frequency-ambient field strength table for a lightning emission:

- ***frequency range ---> ambient field strength***
  1) f < 2 kHz ---> extreme
  2) 2 kHz < f < 100 kHz---> high
  3) 100 kHz < f < 7 MHz ---> medium
  4) 7 MHz < f < 70 MHz ---> low
  5) 70 MHz < f ---> very low

Component Susceptibility Representation

Each component node in an electromagnetic topology also has a *system susceptibility* associated with it. This system susceptibility quantity represents either the actual measured susceptibility of the component node or an approximation to this value based on numerical predictions based on component models and/or experimental measurements made on similar components. The representation of the component susceptibilities is in a *quantized* form (40 dB steps) defined in terms of either received *power* or *power density* to be:

1) ***extreme*** if SS is > 84 dBm/m²/Hz ***or*** dBm/Hz;
2) ***high*** if SS is 44 - 84 dBm/m²/Hz;
3) ***medium*** if SS is 4 - 44 dBm/m²/Hz;
4) ***low*** if SS is -36 - 4 dBm/m²/Hz;
5) ***very low*** if SS is < -36 dBm/m²/Hz;
6) ***nil*** --> not susceptible;
7) ***unknown***: (propagate as unknown throughout).

The type of units dictate the type of node present or representable.

Path Shielding Effectiveness Representation

The shielding effectiveness (SE) determines the amount of attenuation the ambient field will encounter before the field energy reaches the susceptor. It also takes into account any unit transformations which will allow the direct comparison of received disturbance to susceptibility level. Like the ambient field, this attenuation is also defined with seven *qualitative* levels. These are:

1) ***excellent*** > 100 dB;
2) ***good*** 80 - 100 dB;
3) ***fair*** 60 - 80 dB;
4) ***not good*** 40 - 60 dB;
5) ***poor*** < 40 dB;
6) ***nil*** --> no shielding;
7) ***unknown***: (propagate as unknown throughout);

Since the susceptibility of EM components is usually given in terms of the actual received power [8] a coupling coefficient *may* be represented in this SE in order to convert the ambient field data to the units of *power* or *power density* required. Thus the SE nodes in the bipartite representation deals with the conversion from field node to circuit node and vice versa (note that this implies the importance of directionality in the graph).

The capability to handle *non-linear* paths which depend on the AF across them is not currently implemented but will be provided in the future.

Constraint Propagation and Probability of Failure

The propagation of the ambient field constraint across a shielding node consists of transforming the field (i.e. redefining it) by the amount of shielding effectiveness. This is implemented by taking into account the range of values associated with each discrete AF and SE value. The process is graphically summarized in figure 4 where the final AF is derived from the initial by moving down the chart. Thus an initially *high* AF is redefined as *low* in passing through a *good* SE. Intermediate ranges of AF are internally represented but are worst-case rounded when communicated to the user. For example, an initially *medium* AF is internally represented as being between *medium* and *low* when passing through a *poor* SE but is communicated as medium to the user.

The *probability of failure* (PF) at a susceptible node can be determined from figure 4 with discretized values of PF shown on the right of the figure. Thus the PF can be determined for all nodes from the propagated ambient fields to those nodes and the node system susceptibility (SS). Notice that each discrete propagated AF can produce more than one PF for each SS. This is do to the internally represented intermediate values of AF just discussed.

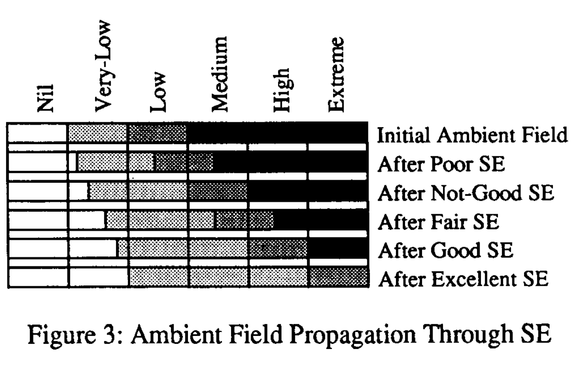

Figure 3: Ambient Field Propagation Through SE

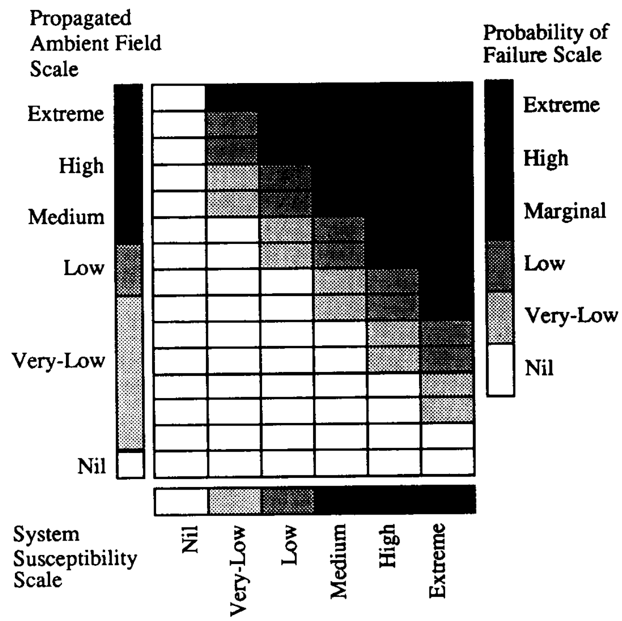

Figure 4: Probability of Failure Chart

NEMP Hardening of Typical Helicopter

The EMI prediction concepts discussed above were applied to data obtained for the *Canadian NSA helicopter*. The use of the topological approach helps also in defining a general view of shielding and filtering requirements at the design stages of a project.

The topology of the NSA helicopter was simplified into the basic surfaces: the aircraft skin; the equipment shield; and the interconnecting cables. The specific topology used is shown below in figure 5 with the associated bipartite graph shown in figure 6. Note that in figure 6 the circuit nodes are shaded while the field nodes are not. The smaller solid nodes represent the surfaces where the shielding effectiveness data is stored.

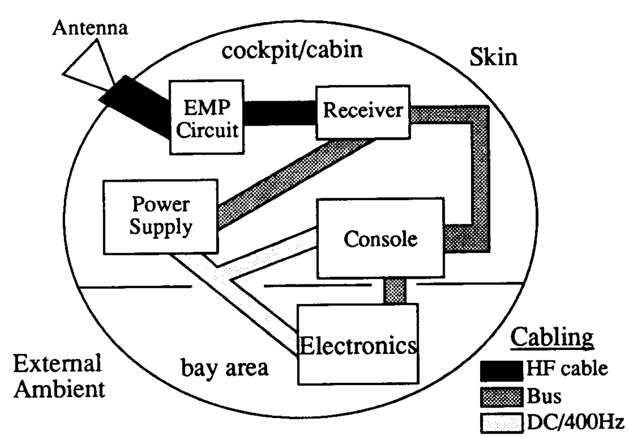

Figure 5: NSA Topology

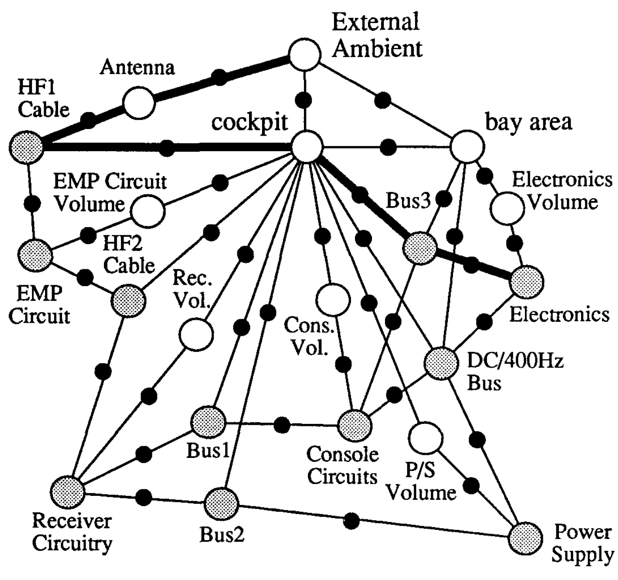

Figure 6: Equivalent Bipartite Graph

The description of the external electromagnetic threat was based on a *composite ambient electric field* (see Podgorski [10]) threat defined by a combination of lightning, NEMP, and microwave threats.The data for the individual threats was entered individually and HardSys constructed the composite threat. For example the NEMP threat was represented as

- ***NEMP Threat***
  1) f < 3 MHz ---> high
  2) 3 MHz < f < 3 GHz---> medium
  3) 3 GHz < f < 30 GHz ---> low
  4) 30 GHz < f ---> very low

In this way the threats could be deleted individually in order to determine a new probability of failure at the susceptible nodes.

The shielding properties of the helicopter shell and equipment cabinets with the associated cabling was also entered in the appropriate form.The shielding effectiveness of the helicopter skin was assumed negligible above 10 GHz and drastically reduced by large windows and doors below 10 MHz. The SE of the *external ambient/antenna* path was assumed *nil* in the HF and UHF bands while set to *excellent* outside these bandwidths.The coupling to the printed circuit boards was based on an average sized printed circuit board of 1x1 ft^2 and short connector runs. Thus, for example, the SE from a field node to a circuit node was approximated by that of a half-wave dipole:

$$P = A_{em} P_d \text{ [W]}; \qquad (12)$$

where A_{em} is the *maximum effective aperture* for a half-wave dipole:

$$A_{em} = 0.13\,\lambda^2 \text{ [m}^2\text{]}; \qquad (13)$$

where λ is the wavelength [m] of the incident radiation. This has been found to be a good approximation for frequencies ranging from 100 MHz to 10 GHz [8]. For lower frequencies an maximum effective aperture of $A_{em} = 1$ is a good worst case approximation.

The *numerical data/tables* obtained for the susceptible systems of the helicopter were converted into a representation which HardSys could handle. Sensitivity analysis of the analogue and digital circuits was based on analysis of MOS and TTL technology respectively (see McDonnell Douglas report [8]). As for the ambient fields the susceptibilities for each node was entered individually and HardSys determined the composite susceptibility at each node.

HardSys provides the worst case path through the topology which causes the worst probability of failure. For example, in the 10 MHz to 100 MHz frequency range the worst case path from the external ambient to the electronic circuits in the bay area is highlighted in figure 6. This path caused a *marginal* PF.

The combination of the composite threat and the susceptibilities of the defined circuits made possible the estimation of the total shielding effectiveness requirements and the threshold field strength levels required for upset. All the relevant information can be displayed by HardSys in graphical form right on the topology or in tabular form.

Conclusions

The classification of the specific EM characteristics in a fuzzy nature and implementing these into the topology of a system proved valuable for the determination of the worst case paths in the system. The approximations on these *weakest links* could then be refined and tested experimentally if so desired. This tool/methodology is useful in helping an EMI/EMC engineer understand the many interactions possible in a system. The crudeness of the approximations was not a problem considering the purpose of the tool.

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