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MODELS FOR ELEMENTAL MODELING

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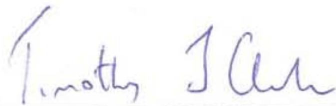

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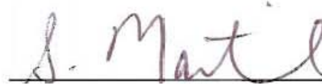

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14. ABSTRACT
We present the results of research into constructing analytical and/or computational models for predicting the probability-of-effect (Pe) associated with high power RF (HPRF) radiation impinging upon digital electronic equipment. Our initial efforts are focused upon those pieces of equipment which serve as nodes in computer networks, such as computers, routers, and switches. We take the problem of predicting HPRF effects for such a system, and present an approach based on partitioning the complete model into a set of sub-models. For each sub-model, we present an analysis of existing computational and theoretical approaches, and how these might be applied and/or extended for the current problem. Finally, we investigate the problem of building predictive models for a microcontroller, as a simplified digital system (a computer on a chip), and present an initial model.

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1.0 Introduction

In this report, we present the results of our thinking—more systematically than has heretofore been the case in the literature, as far as we know—about the task of constructing analytical and/or computational models for predicting the probability-of-effect, P_e, (mainly "upset" presently) associated with high power RF (HPRF) radiation impinging upon digital electronic equipment, with initial efforts focused upon those pieces of equipment which serve as nodes in computer networks (e.g., computers, routers, switches, …). The ultimate outputs of the models will take the form, for each piece of such equipment, of P_e curves or surfaces, these curves/surfaces being functions of various "predictor variables" characterizing the radiation environment at the equipment exterior shell; the resulting P_e models will be used to provide P_e inputs, which quantify HPM-irradiated node behavior, to the RF-PROTEC HPM engagement modeling and simulation code. To achieve these ultimate P_e curves/ surface models, however, several intermediate "sub-models" are required in general. Sub-models are required: (1) for the electromagnetic (EM) field coupling from the exterior to the interior of the equipment enclosure and the consequently established EM fields in that interior; (2) for the resulting induced voltages and currents in wires/cables and at ports to which the former are connected and the consequent induced currents and voltages on circuit board elements (transistors, gates, memory, etc.) and in entire circuits, as well as for the voltages and currents induced directly (i.e., without the intermediary of cables) by these interior fields; (3) for the subsequent disruptive effects of these induced currents and voltages upon the "hardware" functionality of these circuits and circuit boards containing them; and (4) for the implication of these hardware malfunctions for software application execution. Only after each of these phenomena are understood and individually (sub-)modeled can the final overall models (curves/surfaces) be hoped for, at least in the reductionist paradigm.

The remainder of this report is divided into four sections. In Section II, we present some general background concerning the Elemental Modeling problem. Section III focuses firstly upon the first two of the areas enumerated above, namely, the electromagnetic (EM) field coupling from the exterior to the interior of the equipment enclosure and as

well as upon the resulting induced voltages and currents in circuit elements and circuits. Of the four areas listed above, the first is by far the most mature with the second being somewhat less so since the problems it entails are far more complex than those of the first. Section III then continues with a focus upon the last two of the areas enumerated above, namely, the hardware and software disruptions resulting from the induced current and voltages on circuit board elements addressed in Section I. These areas are quite immature—in fact in their infancy--since the response of the relevant circuit entities to HPRF is beyond the usual regime of interest to computer hardware designers. Consequently, the systems under study in this area are, rather than a full computer, instead a much simpler microcontroller. In Section IV, then, we present some modeling results for such a microcontroller. In Section V, some experiments to test the models presented in the earlier sections are suggested and suggestions for future efforts are made. Appendix A contains a paper we have prepared on our microcontroller modeling work to date.

2.0 Background

2.1 Basics

In general, a (theoretical) model is intended to explain some observed situation in nature and—if it is to be a useful model—provide sufficient insight to be able to successfully predict the outcome of future observations of the same or "closely related" phenomena. So we start by discussing the observed situation that we are attempting to model, discussing in turn the basic experiment, the basic observation about this experiment, and the basic question these suggest.

To begin, consider the following **Basic Experiment**. An HPRF source, characterized by several parameters (e.g., single-pulse or multiple-pulse waveform [hence frequency content], intensity, and polarization), emits directed RF energy to some target over some propagation path (again characterized by some set of parameters, although a broad enough set for full characterization may be extremely large)—in our case the target generally being a piece of digital electronics (although it may have also some analog aspects) which is executing software/network tasks—whereupon the RF energy interacts with the target and causes some (perhaps no) target response. Possible

target responses have been classified into a small number of categories, the most common of which are “no effect”, “interference”, “upset”, and “damage”. We are concerned in this report mainly with “no effect” and “upset”.

The **Basic Observation** we wish to model concerning this basic experiment is as follows. When the above experiment is repeated numerous times (“trials”) with a “fixed” set of source parameters (nominally fixed, since sufficiently absolute reproducibility of these parameters from trial to trial appears to be experimentally unattainable within the realm of current experimental equipment), with a fixed propagation path (sufficiently absolutely reproducible from trial to trial), and with a fixed target executing a fixed application software task (a software application being sufficiently reproducible but an operating system housekeeping task-of-the-moment not being generally so), then the effect exhibited by the target, when “no effect” or “interference” or “upset” or “damage” are declared to be the only possible (mutually exclusive) outcomes, appears to be random. That is, “no effect” occurs sometimes, “interference” occurs sometimes, “damage” occurs sometimes, and “upset” occurs the rest of the times, with the latter fraction being termed “probability-of-effect (upset)”, denoted “P_e (upset)”.

The Basic Question to be answered concerning the above experiment is then the following: How does one explain the basic observation in detail (i.e., in a quantitative, predictive manner) from “first” or “second” (or even “third”) principles (the appropriate level being determined as part of the answer). That is, given the source and propagation path parameters and a sufficiently adequate collection of hardware and software parameters characterizing the target (sufficiency also being determined as part of the answer) then how does one construct a model to accurately *predict* the P_e(upset) that will be observed in many trials of the basic experiment using that very (one-and-the-same) target? Of course in a practical sense, the result for one-and-the-same target is not the central question, that central question being rather what the P_e(upset) is for an ensemble of identical targets whose members differ only by manufacturer’s serial number; but from a fundamental understanding point of view, our one-and-the-same-target question is the proper one.

The basic experiment involves three separate pieces: the source, the propagation path, and the target. Our interest in this report focuses solely the target in the following sense. The basic experiment is replaced by another, the **Reduced Experiment**, in which the target is assumed to be immersed in some arbitrary (within the realm of all possibilities allowed for our HPRF context), given, fixed, fully characterized electromagnetic environment impingent upon its outer shell, without explicitly indicating that this environment is in fact the result of the source waveform propagating along some path to the target (the former two are absent). So the problem reduces, from our point of view, to explaining the basic observation for a target immersed in a given EM environment. We assume initially that even if the environment were perfectly reproducible in repeated trials of the reduced experiment that the target response would nevertheless be probabilistic (unless we discover otherwise as a result of our efforts). The activity of answering the basic question for the reduced experiment is called **Elemental Modeling**; for our answer will be given by constructing a model for the probability-of-effect (upset) based upon individual cooperating *target components (“elements”)*, as opposed to regarding the target *in toto* as a single aggregated entity (“black box”).

2.2 The Elemental Modeling Pathway

In the first paragraph of the Introduction we enumerated four areas into which our modeling efforts are divided. These areas then are the major components of our elemental modeling paradigm. These areas may in fact be further subdivided into yet finer pieces, each of which is associated with its own submodel. We illustrate this finer subdivision, which we term the “Elemental Modeling Pathway”, in Fig. 1. The first area above comprises only part of submodel 1 while the second area comprises the remainder of submodel 1 plus submodel 2. The third area above comprises solely submodels 3 – 5 while the fourth area comprises submodel 6. Submodel 7 represents the coalescence of submodels 1 – 6 into the P_e prediction curve/surface itself.

As indicated earlier, our overall elemental model (in Fig. 1) must produce as output P_e (upset) which is probabilistic; hence, some or all of the submodels must also capture this random behavior. A central question then is this: Which of the phenomena

described in those submodels are probabilistic and which are deterministic? An answer to this question may be offered on two levels, namely, an “inherent” level and a “practical” level. That is, a phenomenon may be inherently (i.e., “really” in nature) probabilistic or inherently deterministic; the latter, however, may, for a variety of reasons, be of necessity (i.e., “practically”) treated as probabilistic in any model. Whether a phenomenon is inherently probabilistic or is inherently deterministic is nice to know academically but for application model building it is the practical attribute of the phenomenon that is relevant. In Fig. 1, we have indicated our current assessment of the both the inherent and practical character—probabilistic or deterministic—for each of the submodels and its pieces. The reasons behind these choices will be discussed in more detail as we proceed through this report. The reader should note, however, that it currently appears that *every* submodel is most appropriately probabilistic from a practical point of view.

3.0 The Submodels

In this section we present some details concerning the seven submodels of the Elemental Modeling paradigm depicted in Fig. 1.

3.1 Submodel 1 (First Part) – Cavity Fields

The EM fields at all points interior to an irregular enclosure (”cavity”) which result from the penetration of external fields into it (conducted *via* power and signal cables and radiated through apertures or field penetration thru non-metallic or imperfect conductors comprising the cavity shell) are inherently deterministic. The analytical specification of these fields for irregular cavities is, however, in general presently intractable. On the other hand, computational (“full-wave”) Maxwell equation solvers employing, for example, finite-difference time-domain (FDTD) or time-domain integral-equation (TDIE) techniques, can yield the required field values with high accuracy for the cavity sizes and wavelengths of interest to HPRF *elemental modeling*. Despite the fact that such accurate deterministic solutions are in principle available, a single such

INPUT
(GIVEN SINGLE TARGET AND SOURCE)

- ENCLOSURE INTERFACE DESCRIPTION: GEOMETRY, APERTURES, CABLE PENETRATIONS (D/P)
- INCIDENT SOURCE EM FIELD DISTRIBUTION AT ENCLOSURE INTERFACE $E_{ext}(x, t)$, INCLUDING *EXTERIOR CABLE RUNS* (D/P)
- ENCLOSURE INTERIOR DESCRIPTION
  - GEOMETRY AND STRUCTURAL EM-FIELD "INFLUENCERS" (D/P)
  - WIRE/ WIRE BUNDLE DESCRIPTIONS (D/P)
  - CIRCUIT DESCRIPTIONS FOR ALL ENCLOSURE CIRCUIT BOARDS (D)
  - ENCLOSURE CIRCUIT BOARD CONNECTIVITY (EM TOPOLOGY) (D)

SUBMODEL 1

OUTPUT:

FOR *ENCLOSURE INTERIOR*:
- EM FIELDS
  $E_{int}(x, t)$ $H_{int}(x, t)$ (D/P)
- CURRENTS (I) AND VOLTAGES (V):
  - IN ALL INTERIOR (NON-CIRCUIT-BOARD) WIRES/ WIRE BUNDLES (D/P)
  - AT INPUT PORTS OF ALL CIRCUIT BOARDS (D/P)

SUBMODEL 2

OUTPUT:

FOR EVERY *CIRCUIT BOARD*:
- INDUCED I's AND V's
  - IN EACH CIRCUIT BOARD ELEMENT (OR ELEMENT CLUSTER) (D/P)
  - IN EACH CIRCUIT BOARD CONDUCTOR (D/P)

AS A RESULT OF CAVITY EHIV

SUBMODEL 3

OUTPUT:

FOR INDIVIDUAL *CIRCUIT BOARD ELEMENTS* (OR ELEMENT CLUSTERS):
- EFFECT OF INDUCED ELEMENT I's AND V's ON *ELEMENT FUNCTIONALITIES*
  - DIGITAL SIGNALS (P)
  - PHYSICAL DAMAGE (P)

SUBMODEL 4

OUTPUT:

FOR INDIVIDUAL *CIRCUIT BOARDS* (OR CIRCUIT BOARD CLUSTERS):
- EFFECT OF MODIFIED ELEMENT FUNCTION-ALITIES ON *BOARD FUNCTIONALITY*
  - DIGITAL SIGNALS (P)
  - PHYSICAL DAMAGE (P)

SUBMODEL 5

OUTPUT:

FOR *ENTIRE SYSTEM*, COLLECTIVE EFFECT OF SIMULTANEOUS COUPLING TO ALL ENCLOSURE CIRCUIT BOARDS AND ALL WIRES/ WIRE BUNDLES:
- EFFECT OF INDUCED I's AND V's ON *COLLECTIVE SYSTEM FUNCTIONALITY*
  - SYSTEM DIGITAL SIGNALS (P)
  - SYSTEM PHYSICAL DAMAGE (P)

SUBMODEL 6

OUTPUT:

EFFECTS ON SOFTWARE TASKS EXECUTION (OS & APPS) (P)

SUBMODEL 7

OUTPUT:

DECLARATION OF *PROBABILITY* OF EFFECT LEVEL
- I, U (P)
- D/WSE, D/WOSE (P)
- .....

D = INHERENTLY AND PRACTICALLY DETERMINISTIC
P = INHERENTLY PROBABILISTIC
D/P = INHERENTLY DETERMINISTIC BUT PRACTICALLY PROBABILISTIC

Figure 1. The Elemental Modeling Pathway

solution for a given cavity with all cavity field-influencing parameters specified and fixed is, from a practical point of view, inadequate. The reason for this inadequacy is twofold. Firstly, it turns out that the field values at any given point inside a cavity in which numerous electromagnetic modes are supported (such cavities are of relevance to our problem) are extremely sensitive to the minute details of many of the geometrical features of the cavity and its contents (wires, circuit boards, etc.). Secondly, the variability found in cavity field-influencing features among real-world realizations of ostensibly identical copies of a particular cavity is large enough to exceed the insensitivity limits associated with the first point above. These two factors taken together imply that any particular representation of cavity (enclosure) details for the purpose of computation will likely not give the correct field values corresponding to any particular real-world realization of the modeled enclosure, of which realizations there are in general as many as there are real-world copies (with two realizations "differing" if the difference in values between the two of a given feature exceeds the insensitivity limit for that feature). To accommodate this reality, it is desirable to seek not a single deterministic specification of the cavity fields but rather a probabilistic specification of those fields, with the associated randomness forced upon us because of our inability to specify the cavity field-influencing features precisely enough: *the associated randomness captures this imprecision in the cavity field-influencing features*. In other words, for repeated shots at a single particular target (the Basic Experiment) one would expect the internal cavity fields to be precisely reproduced since the fields are in fact deterministic (there are other aspects of the target response [digital signal processing] which may in fact lead to variations in the shot to shot cavity field values *via* circuit conductor re-radiation). But our inability to specify the cavity features sufficiently precisely does not allow us to predict precisely what those reproducible field value are, so we are forced to a probabilistic model of the inherently deterministic behavior.

In order to obtain this probabilistic specification of the fields (and, subsequently, voltages and currents induced in particular wires/wire bundles [cables] as well as at particular circuit ports and throughout the circuits themselves [*when the required circuit parameters can be adequately specified*]), there are two ways to proceed. In the first

("brute force") method, one may use a computational Maxwell equation solver to find, for given specified values of the cavity field-influencing features, a single value for each of the vector field (**E** and **H**) components at every discrete spatial location of interest inside the cavity for each discrete time step in the time range of problem execution. The imprecision in the cavity field-influencing features may then be captured by ascribing *statistical distributions* to them and by then performing an extensive series of computations, each member of the series using particular values for each of the features sampled from the aforementioned feature distributions. The result is then a statistical distribution of possible field values at each spatial point of interest at every instant of time; one of course may choose various coarser measures of the time behavior, e.g., time-averaged fields or peak-over-time fields. In this way, results which are inherently deterministic but practically probabilistic (appropriately so) are achieved; it is also clear that the randomness incorporated in this way manifestly captures the imprecision in the cavity field-influencing features. There are, however, two difficulties associated with this approach: one must obtain and prescribe the distributions for the relevant features; and the computational intensity required for this approach is burdensome because there are in general numerous parameters that should be treated in this statistical way so that one must perform hundreds (or perhaps even thousands) of individual computer "trials" to develop adequate-confidence statistics. There are, however, techniques which exist or are in development— these methods falling in the emerging field of *uncertainty quantification*—that may significantly reduce the computational intensity required to implement the above program. Be that as it may, this approach is nevertheless applicable in principle.

The second method to obtain the probabilistic specification of the fields is based upon the ideas of "statistical electromagnetics" (STEM). In this approach, one attempts to obtain an analytical representation of the statistical behavior of the interior cavity fields and thus avoid the intense computation required in the previous method. Thus, the goal of STEM is to eliminate the need to prescribe many (but not all) of these feature distributions in favor of prescribing a lesser number of cavity field statistical distributions at cavity interior points (or voltage and current distributions at cavity internal circuit

ports) in their stead; these field distributions presumably result as a consequence of some sort of collective behavior of the cavity features but the former have the advantage that they are in fact relatively *insensitive* to the exact forms of the latter (i.e., the field distributions are “universal”) and depend only upon a *small number of parameters* characterizing the collective behavior of the features. For example, it is proposed that all cavities having one and the same volume, V, and, additionally, one and the same quality factor, Q, possess one and the same cavity field distribution function despite the fact that the set of such cavities in fact have differing shapes and differing cavity absorber details and would in general require numerous non-STEM distributions to capture all possible variations in their relevant features. While such a statistical representation is indeed attractive and obtainable, it is not at all obvious that the randomness captured in the two currently fashionable versions of this methodology (see below) is randomness associated with the imprecision in the cavity field-influencing features as opposed to the randomness in something else. (As an example of “something else”, we offer the probabilistic nature of the eigenvalue distribution which results from a probabilistic solution approach to the EM boundary value problem for the irregularly shaped cavity, which eigenvalue distribution is incorporated into the field statistical distribution in the wave chaotic STEM methodology). In our opinion, a precise characterization of the nature of this randomness is still an open problem.

The above discussions attribute the probabilistic nature of the cavity fields to real-world variations in the cavity enclosure and our inability to quantitatively capture these variations precisely enough in any particular target. Nevertheless, any particular target is a single, invariant target (assuming the target has no memory from shot to shot) so exactly the same internal fields should be present from shot to shot (assuming strict source invariance from shot to shot) even if those fields cannot be precisely predicted in advance. Yet the Basic Observation of Section II refers to a single particular (“one-and-the-same’) target for which the behavior is observed to be probabilistic; hence the considerations of the previous paragraphs, while necessary in the practical sense for any of our models, nevertheless play no part in explaining the Basic Observation. There are several possibilities to consider with respect to a single, particular target. Firstly, it

may be the case that there is in fact no probabilistic field behavior as far as a single particular target is concerned—after all, such fields are inherently deterministic—and the probabilistic behavior of the Basic Observation arises from the subsequent digital circuit anomalous behavior induced by the cavity HPRF. Secondly, at the frequencies relevant to HPRF, re-radiation from cavity wires/cables/circuits may be significant and therefore will contribute to the cavity fields. Since this re-radiation depends upon the detailed current patterns in the wires and digital circuits, and these current patterns in turn are to some extent probabilistic, especially when perturbed by HPRF, then the re-radiation is to some extent probabilistic as well; hence the total cavity field may be too. Finally, despite the assumption in Section II that the HPRF source is nominally reproducible from shot to shot, the real-world non-exact reproducibility of the HPRF source may (almost certainly!) make the single particular target cavity fields random.

We now present some details of the tools available which implement the brute-force methodology and which implement the STEM methodologies. The most promising candidate for performing the deterministic field computations, as well as for computing the coupling of the fields to wires/cables and induced circuit port and circuit voltages and currents, is the code EMTOPOL [1] which uses the TDIE approach to compute the cavity interior fields resulting from cavity external irradiation, uses the TD-BLT (time-domain/Baum-Liu-Tesche) approach [2] to compute the resulting induced voltages and currents in cables ("multiconductor transmission lines" [MTL's]), and uses TD-Spice [3] with nonlinear device capability to compute coupling to circuit ports as well as to compute circuit internal voltages and currents. For computation of only the fields, the TMax FDTD code [4] has been—and will continue to be—used.

Concerning STEM methodologies, there are presently two major, distinct lines of argument that result in them; we will term the first "traditional" STEM and term the second "wave chaotic" STEM to reflect the nature of the technique it employs. Both of these presently require as constraints that the *cavity be highly over-moded and that the cavity Q not be "too small"*; we designate such a cavity as HOM/AQ. A summary of the current state of the art, including a fairly complete bibliography, is given in [5] although that paper concentrates mainly on the traditional approach. A conclusion of [5] is that

traditional STEM is weakly founded and that "consensus and rigor are lacking, and as a consequence, STEM cannot be compared to well-established theories like statistical mechanics…". Nevertheless, since traditional STEM may have some role to play in an overall elemental model (since alternatives are few), we briefly summarize here its main lines of reasoning, gleaned from [6].

The fundamental claimed experimental observation that leads to the hope that STEM may indeed adequately describe nature, at least as concerns HOM/AQ cavities, is as follows. If one experimentally drives a HOM/AQ cavity by a source residing *inside* the cavity and if, further, one considers an associated set of experimental parameters—any one such parameter being denoted here generically by x—such as cavity internal spatial position, cavity field frequency, cavity orientation relative to the exciting source transmitting antenna, cavity field-measuring sensor orientation, or any of several other parameters that may be relevant (e.g., stirrer paddle orientation inside a mechanically varied mode-stirred chamber) then, as any one of these parameters is varied while the others remain fixed and the *power flux density* inside the cavity is measured at randomly sampled values of this variable parameter (the power flux density being measured in any arbitrary but globally fixed direction except when the flux density sensor orientation is the parameter varied), it turns out that for *each such parameter x*, the graph of the resulting power flux density frequency-of-occurrence *vs*. power flux density, say ϕ, replicates a so-called two-degrees-of-freedom χ^2 density function (PDF) which occurs in probability theory, namely, $f^{(x)}(\phi) \equiv (1/\mu_x)e^{-\phi/\mu_x}$ for $\phi \geq 0$ and $f^{(x)}(\phi) = 0$ otherwise, where μ_x is the mean of the distribution. Furthermore, it is claimed in [6] that there is strong evidence to suggest that *μ_x is in fact independent of the particular parameter, x*, so that one may write rather $f(\phi) \equiv (1/\mu)e^{-\phi/\mu}$ with one and the same μ for all x. Thus it is hoped that a unifying probabilistic theory based upon this observed "statistical regularity" may be successful.

The above discussion was phrased in terms of cavity *internal* sources and field *power flux density*; but cavity *external* sources in the case of leaky cavities having a large number of small apertures (rather than a small number of large apertures)—the former

arrangement being of particular interest for HPRF modeling—and field *components* themselves (as opposed to field power density)—of particular interest for wire/cable and port coupling—are also addressed by traditional STEM. In brief summary, Lehman [7] proposed the so-called Lehman distribution PDF for the overall power flux density inside such an externally illuminated leaky cavity: $f^{\Lambda}(\phi) = \Lambda^2 \phi K_2(2(\Lambda\phi)^{1/2})$ if $\phi \geq 0$ and $f^{\Lambda}(\phi) = 0$ otherwise, where K_2 is the second order modified Bessel function of the second kind and Λ is a parameter whose value depends upon the specifics of the physical situation being modeled and for which $\Lambda = 3/\mu_{\Lambda}$ (μ_{Λ} being the f^{Λ} distribution mean); this distribution purports to capture the "universal" behavior of the cavity radiation fields. The quantity Λ is specified for given a leaky cavity by specifying instead μ_{Λ} which in turn is approximated as $\mu_{\Lambda} \approx (c/3)(Q/\omega V)P_{in}$, where c is the vacuum speed of light, ω is the frequency of the electromagnetic radiation externally impingent upon the apertures of the leaky cavity, Q and V are the cavity quality factor (at frequency ω) and volume respectively, and P_{in} is the cavity inward power leakage which takes into account the externally impingent field power as well as the configuration of the cavity external apertures. So the problem of finding Λ for the cavity is converted to that of finding Q and P_{in}. Finding Q accurately is generally difficult and the most accurate non-experimental determination involves using a computational Maxwell equation solver; however, if the cavity Q is a less sensitive function of geometrical details than are pointwise field values, then only a relatively few of these computations may be required to adequately specify Q. Alternatively, it may be possible to analytically estimate Q sufficiently well for a given application. Finding P_{in} involves determining the power flow through the cavity apertures, a relatively routine exercise for many standard aperture shapes. We thus observe that while the Lehman distribution on the one hand attempts to capture the "universal" behavior of the cavity radiation fields, the individual character of differing cavities is captured on the other hand *via* μ_{Λ} through Q, V and P_{in}.

We next discuss wave chaotic STEM which appears at this point to rest on a somewhat firmer footing than its traditional counterpart [8, and references therein]. The reason for

this greater firmness is that the wave chaotic approach rests directly upon consideration of the electromagnetic eigenmodes and eigenvalues which lie at the foundation of the solution to the Maxwell equations for the cavity fields. Despite this firmer foundation, however, the practical application of its results requires essentially the same input information as does traditional STEM, namely, ω, cavity Q and V, cavity surface aperture (external "port") specification, and cavity internal wire/cable specifications (including termination impedance); and it produces as output a probabilistic distribution of field-induced voltages at each of several arbitrarily chosen internal ports inside the cavity. The computation of the port voltages is performed in two stages. The first stage requires as input $\omega = 2\pi c/\lambda$, Q, and V, from which the single quantity $\alpha \equiv 4\pi(V/\lambda^3)(1/Q)$ is formed and used to form a single parameter (α) probability distribution for the port driving field to be used in turn to compute, in the second stage, probabilities for the induced voltages at the aforementioned specified ports. This α-parametrized distribution is claimed to be universal in the sense that all HOM/AQ cavities which have the same values of Q (ω fixed) as well as the same values of V will give rise to the same voltage distribution at a given port (as specified by the same given impedance). The probabilistic nature of the driving field arises from the probabilistic distribution of cavity eigenvalues invoked by a random-matrix-theory-based solution—a method used at the foundation of the model—of the time-independent boundary value problem for the cavity, this probabilistic solution being used in lieu of the exact (deterministic) solution for such eigenvalues which is generally unobtainable analytically for an irregularly shaped cavity. The price paid for abandoning pursuit of an ostensibly unattainable exact solution (whose value from a practical point of view is, in addition, questionable) is acceptance of a less precise statistical solution, a perfectly acceptable compromise under this circumstance of intractability yielding no solution at all. The second stage is not universal but depends upon the geometric and electrical details of the cavity walls and the cavity external ports, these details being captured in a quantity termed cavity "radiation impedance", Z_{rad}. The combination of the α-parametrized distribution and Z_{rad}, along with the specification of the field in-leakage through the cavity external

surface ports and the impedances of the field-absorbing cavity internal ports then produces probability distributions for the voltages induced at the internal ports.

It is clear from the above discussions on both traditional and wave chaotic STEM that—aside from the foundational issues—traditional STEM and wave chaotic STEM are using the same input information but are merely partitioning the solution steps in slightly differing ways: In traditional STEM, the operative parameter μ_Λ contains both the universal Q and V and the particular P_{in} (which requires the cavity external excitation power and the configuration of the external apertures) while in wave chaotic STEM the operative parameter α contains only the universal Q and V while the cavity particulars are captured by Z_{rad} and the cavity driving excitation must in addition be specified. Finally, in either STEM case, if the values taken on by the set of three quantities Q, V and P_{in} , or Q, V and Z_{rad}, are not precisely known, then they may themselves be represented by feature distributions which may be sampled *via* numerous computer runs to build composite, weighted STEM-like distributions for their outputs; but once again only three such feature distributions are involved here rather than the very many more that would be required if a STEM approach were not taken.

There are several issues associated with the STEM approach in both its incarnations, both practical and fundamental, some of which have already been pointed out previously. Here are the practical issues.

(1) The cavity Q must somehow be available. For a precise value of Q, minimally a single full-wave computation needs to be performed (at each ω of interest) to determine the cavity Q; but if Q is very sensitive to small changes in cavity internal structure (Q may be insensitive to absorptive processes but not necessarily so to reflective processes) then a cavity Q averaged over many configurations (i.e., over many computer runs) may be required. Of course, one may attempt to infer Q with accuracy that is “good enough” through other, computationally less intensive means.

(2) The internal wires/cables and internal ports are terminated in impedances representative of the real-world impedances extant when actual circuits are connected to them. These must somehow be determined.

(3) Variations in aperture details or radiation impedances arising from real-world realizations of target features must be incorporated if P_{in} and Z_{rad} are very sensitive to these variations. This may require devising distributions for these as well as necessitate numerous computations to sample from these distributions.

And here are the fundamental issues.

(4) The efficacy of the models under the condition that the smallest dimension of the cavity is smaller than or not much greater than the monochromatic field wavelength, and hence the cavity may not be HOM, must be assessed for the HPRF application.

(5) The wave chaotic model in its original formulation does not incorporate "scars" [8], i.e., high field intensity regions of the cavity interior ("hot spots") which result from periodic (non-chaotic) ray paths in the wave chaotic framework. These regions are precisely those which may be of primary interest for HPRF effects. Can the importance of these scars for HPRF target geometries be quantified (or at least assessed) and, if determined to be important, can currently formulated wave chaotic STEM be augmented to incorporate these scars and, if so, how? There has been some recent work [8] to attempt to overcome this deficiency—by incorporating "finite-length" (short) ray paths into the formalism. The efficacy of this enhancement vis-*à-vis* our basic question still needs to be assessed.

There are two additional techniques/tools which should be mentioned that exist to analytically *approximate* the values of coupled interior fields, voltages, and currents inside a cavity (for, as we have pointed out earlier, these quantities cannot be analytically computed exactly in general): "Trends and Bounds" (TAB) [9] and the JEM-RF code [10]. The goal of the TAB technique is to obtain the transfer functions (in the frequency domain) that describe how the external electromagnetic environment in which the target is immersed is coupled to components inside the target cavity. A transfer function itself is in turn described in terms of a coupling cross section, such a cross section being roughly the ratio of the magnitude of the induced effect (voltage or current or absorbed power) in a load (e.g., wire or cable connected to a circuit) to the magnitude of the causative stimulus (incident field or power density); there are in fact three types of cross sections used in this approach (equivalent height, equivalent

length, and effective aperture). A cross section contains only a few parameters, one of which is incident field frequency and the others of which are based upon the physical dimensions of the load, thus making it readily calculable analytically. In the TAB technique, the functional dependence of the cross section upon frequency is represented by a piecewise linear continuous graph plotted on a log-log scale (a power law behavior thus being assumed), these segments being referred to as “trends”. The intersections where neighboring graph lines meet depend only upon the various physical lengths of the elements that play major roles in coupling to the load (such as the dimensions of a coupling aperture or wires/cables that lead to critical electronics). The ordinate values of these graph intersections, being local extrema, are termed “bounds” and are determined from physical principles The major utility of this approach from the Elemental Modeling perspective is to possibly provide some guidance on the *relative* effectiveness of disturbances of differing frequencies; the use of this approach directly to build a *detailed* predictive model in any absolute sense seems implausible at this point.

The JEM-RF computer code implements a model comprising four elements to compute narrowband RF coupling to, and response of, a target; each such element embodies an exact or approximate analytical expression for the aspect of the problem that it addresses. The first element addresses the determination of a total coupling cross section from the target exterior to the target interior and includes cross section contributions from aperture in-leakage (circular and rectangular apertures only) and cavity absorption (aperture out-leakage, wall losses, circuit card absorption losses, and other cavity absorber losses). This total coupling cross section then leads to a computation of the RF fields induced in the target interior. The second element addresses the coupling of the induced internal fields determined in the first element to circuits residing in the target interior; this coupling is expressed in terms of coupled voltage rather than in terms of (the more traditional) coupled power and is computed for a circuit board as the product of the area of the board times the induced RF $d\mathbf{B}/dt$ at the location of the board. This is a coarse model and provides an upper bound to the induced voltage (more on this upper bound aspect shortly). The third and fourth

elements address the effect of the induced RF voltages upon the circuits in which they are induced. The presumption here is that the RF voltages are rectified by circuit nonlinear semiconductors and it is the averaged rectified voltage value—the so-called "rectification equivalent voltage"—that is the significant attribute for inferring deleterious circuit effects. In the third element, then, the rectification equivalent voltage is computed analytically as a function of RF frequency. In the fourth and final element, the effect of the induced rectification equivalent voltages upon circuits is inferred by comparing the magnitudes of these voltages with the magnitudes of the normal circuit operating voltages (in the absence of RF interference): if the former is a "significant" fraction of the latter then the positive occurrence of an effect is declared. Versions 1-4 of JEM-RF are geared to defensive applications and use "defense-conservative" bounding models (e.g., aperture coupling assumes normal incidence). Nevertheless, some of the analytical expressions for cross sections and voltages *may* be of use in future elemental models. Recently [11], Version 5 of JEM-RF, which attempts to relax some of the assumptions employed for the defense-conservative approach, was released. The philosophy of the approach is to assign probability distributions to parameters that may take on values over a range (e.g., angle of incidence for aperture coupling) and thus compute a consequent probability of effect. However, the criterion for declaring whether or not an effect has occurred is the same as it is in earlier versions, namely, whether or not the induced rectification equivalent voltages—for any particular set of possible system parameters sampled from the parameter distributions—are a significant fraction of the normal circuit operating voltages. This notion of randomness, attributable to randomness in system parameter values, is not the same as that associated with the HPM community's notion of P_e in which the occurrence of an effect is random even when set of possible system parameters remains (ostensibly) unchanged. So it appears that the latest version of JEM-RF, despite its enhancements, offers no fundamental augmentation of Elemental Modeling methodology beyond that mentioned above as already existing in the earlier versions.

3.2 <u>Submodel 1 (Second Part) – Currents & Voltages in Cables & at Ports</u>

At present, the only tool available designed specifically to compute currents and voltages induced in cavity cables and at ports connected to cavity circuits is the

EMTOPOL computer code mentioned earlier. To reiterate, EMTOPOL uses the TDIE approach to compute cavity interior fields resulting from cavity external irradiation (by solving the full Maxwell equations), uses the TD-BLT (time-domain/Baum-Liu-Tesche) approach [2] to compute the resulting induced voltages and currents in cavity cables ("multiconductor transmission lines" [MTL's]), and uses TD-Spice [3] with nonlinear device capability to compute coupling to circuit ports. Also, as indicated earlier, EMTOPOL further computes circuit internal voltages and currents (Submodel 2) via the TD-Spice model; there is, however, presently no computation of the voltages and currents induced directly (i.e., without the intermediary of cables) into circuits by these interior fields. In addition to EMTOPOL, some FDTD codes have the general ability to couple fields to wires and circuits [12] but we are aware of no such codes which currently tailor these generic capabilities to the solution of the specific cavity problem presented at the beginning of this paragraph.

3.3 Submodel 2 – Currents & Voltages in Circuit Elements and Circuits

Once currents and voltages at the input ports of all circuit boards are available, as provided by Submodel 1, these currents and voltages may then be incorporated as drivers in circuit models of the boards. To be sure, these circuit models are both very complex and, more seriously, perhaps unavailable because of their company-proprietary nature, although one may be able to construct models of reasonable facsimiles of these circuits. Further, there are additional circuit drivers which, in principle, should be accounted for, namely, direct field coupling— without the intermediary of cables—into circuit elements. There are two approaches that may be followed to produce the outputs required from this submodel. In the first, all cavity circuit boards participate in a single calculation so that the full mutual board coupling is automatically accounted for. Because of the complexity of such a calculation, a second alternative procedure may be employed in which only one selected board (or a small cluster of selected boards) is modeled in full detail in any single calculation, with the remaining, non-selected boards taken into account in the circuit representing the selected board(s) *via* the specification of the formers' impedances and other relevant circuit-influencing electrical properties (e.g., mutual inductances between the selected board and each of the non-selected boards) with the couplings among the non-selected

boards themselves perhaps neglected. In any case, the leading contender to be employed in performing the circuit computations appears to be the TD-SPICE code mentioned earlier in Section III.B in connection with the EMTOPOL code capability in this arena.

3.4 Submodels 3 – 7

At the present time, there appears to be little to no modeling capability in place to address these areas in the context of RF pulse irradiation. The systems of interest are extremely complex and much work will need to be done to develop these models. There has been, however, experimental work done over the past twenty five years or so on the interaction of RF with very basic elements (e.g., a single CMOS inverter or small chain of such inverters, either with or without concomitant electrostatic protection diodes) [13, and references therein] but no *fundamental* models have yet been formulated based upon these fragmentary results. Attempts to produce submodels for simple yet more complex systems—individual and grouped logic gates as well as an eight-bit microcontroller—are underway. The microcontroller is attractive in that it is intermediate in complexity—between individual transistors on the one hand and a complete computer on the other—yet is capable of executing software. In the next section, we report on our own progress to date in our initial attempt at constructing a simple model to predict P_e (upset) for a (generic) microcontroller exposed to an EM pulse.

4.0 Microcontroller Modeling

As a first effort in modeling the functional upset of a microcontroller induced by RF irradiation, we have provided a model to mathematically formalize the long-standing conjecture that P_e(upset) of a computer as a function of RF pulse length should be nondecreasing (assuming that the RF frequency and intensity are effective in producing any effect whatsoever). Even in the relatively simple case of a microcontroller, there are many simplifications that need to be made at the early stages of a model development sequence, with some simplifications being excised at later stages as knowledge about microcontroller response to such RF irradiation is gained through experiment and theoretical insights. The simplifications made in our initial model are documented in detail in a paper we have prepared on our microcontroller modeling

effort and have included as an Appendix ; consequently, we say no more about those in the present section. In summary of our results, however, we offer the following abstract:

> We construct simple probabilistic models for predicting the frequency of occurrence of experimentally observed upsets (i.e., perturbations of normal execution) induced in microcontroller computers that are exposed to high power electromagnetic (RF) pulses. In particular, we consider the interaction between—on the one hand—a single, periodic signal pulse train consisting of perfectly square wave pulses and—on the other hand—a perfectly square single RF pulse. *Results for upset probability are given in terms of the period and amplitude of the signal pulse train, the width and amplitude of the RF pulse, and parameters describing the relative timing between the two.*

As noted, predictions are made for P_e(upset) for the microcontroller as a function of the parameters indicated in the italicized sentence of the previous paragraph.

5.0 Conclusions

The state-of-the-art in the cavity EM field description portion (Submodel 1--first part) of any potential elemental model is by far the most mature of the pieces of the Elemental Modeling Pathway, notwithstanding the circumstance that the STEM description of such fields still poses important, relevant unanswered questions; the state-of-the-art in the determination of cable induced currents and voltages (Submodel 1--second part) is also fairly mature. Beyond Submodel 1, the state-of-the-art in the *sufficiently accurate* determination of currents and voltages thereby induced in circuit elements and circuits (Submodel 2) is far less mature than the methodologies of Submodel 1 while the state-of-the-art in the remaining the Elemental Modeling Pathway areas are essentially in their infancy.

There is much work remaining to be done before an initial, *credible* elemental model is available. In the next section, we suggest some possibilities to be pursued in this direction.

6.0 Recommendations for Future Work

This section is divided into two parts, the first concerning the Elemental Modeling Pathway and the second concerning microcontroller modeling.

6.1 Elemental Modeling Pathway

(1) EMTOPOL computations should be performed to determine its efficacy (by performing simple experiments to measure induced currents and voltages at circuit board ports inside cavities).

(2) The field-to-circuit coupling methodology in EMTOPOL appears simplistic at best and erroneous at worst. This methodology should be further assessed and improved if required.

(3) The importance of direct field coupling in influencing induced circuit currents and voltages should be assessed and incorporated into EMTOPOL if important.

(4) The use of uncertainty quantification ideas to reduce computational intensity required in EM code predictions to adequately represent statistical variations, attributable to uncertainties in cavity field-influencing features, should be investigated.

(5) The adequacy of wave-chaotic STEM for predicting voltages and currents inside cavities of interest for the HPRF problem should be assessed (by performing simple experiments as well as relevant EMTOPOL computations).

6.2 Microcontroller Modeling

(1) Experimental results need to be obtained to support or refute the current simple model. Since the model makes predictions of P_e(upset) as a function of RF pulse width and intensity, experiments designed to acquire data consistent with such a determination should be performed. (If the model is incorrect, that should become apparent after a small number of experiments.)

(2) The current simple microcontroller model does not explicitly incorporate the narrowband frequency associated with the RF pulse. There have been some very recent experimental results which exhibit some possibly “quasi-regular” frequency behavior. An extension of the current model to include this frequency behavior currently appears to be a plausible next step.

(3) Experiments need to be performed as an aid in suggesting alternative models to the current (simplistic) one. Precisely what these experiments are to be may be guided by testing proposed hypotheses, the hypotheses themselves being suggested by what is gleaned from other ongoing experiments. In any case, software executing on the microcontroller should be an integral piece of most (if not all) of these experiments.

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Appendix

A Simple Probabilistic Model for Microcontroller Upset Resulting from Exposure to an RF Pulse

David Dietz

A.0 *Abstract*

We construct simple probabilistic models for predicting the frequency of occurrence of experimentally observed upsets (i.e., perturbations of normal execution) induced in microcontroller computers that are exposed to high power electromagnetic (RF) pulses. In particular, we consider the interaction between—on the one hand—a single, periodic signal pulse train consisting of perfectly square wave pulses and—on the other hand—a perfectly square single RF pulse. Results for upset probability are given in terms of the period and amplitude of the signal pulse train, the width and amplitude of the RF pulse, and parameters describing the relative timing between the two.

A.1 *Introduction*

In this paper, we present simple probabilistic models for predicting the frequency of occurrence of upsets (i.e., perturbations of normal execution) induced in microcontroller computers that are exposed to high power electromagnetic (RF) pulses. This induced upset phenomenon has been observed experimentally to be stochastic: A given microcontroller in the process of successfully executing a given software task is exposed to an RF pulse and it is observed whether an upset occurs or not; in repeated trials of this experiment with the given microcontroller, for which trials the RF pulse and exposure procedure are ostensibly identical for each repetition thereof, the microcontroller is in general upset in some of these trials but not in others. We take at face value the sufficient experimental reproducibility from trial to trial of all the requisite RF exposure parameters and are thus led to speculate that the above stochasticity of the upset phenomenon is a consequence of the probabilistic nature of the timing relationships between the occurrence in time of the RF pulse time envelope on the one hand and, on the other hand, the occurrences in time of the rise and fall transitions of clock and data signal streams during the RF pulse time interval. That is, if we were able to determine which particular low-level software instructions (i.e., assembly instructions or their component microinstructions) were executing during the RF pulse interval—each such low-level instruction of course resulting in well-defined (essentially

deterministic) signal stream patterns on the many microcontroller signal lines—and, further, if we understood the (perhaps deterministic) effects of the RF pulse upon these deterministic signal streams, then *perhaps* the overall effect on the microcontroller could be understood deterministically. But the timing of the RF pulse envelope relative to that of the instruction streams is in general random since on this (nanosecond) time scale the RF pulse onset instant (and hence also the RF pulse envelope time interval) is random with respect to the particular instruction that happens to be executing at that onset instant. In an attempt to ultimately model the general situation addressing an arbitrary software task executing on the microcontroller, we start by considering the simpler situation in which a functionally minimal assembly language program having only a few instructions is executing in a repetitive loop.

A brief, focused description of the problem we initially address is then as follows. A microcontroller executing one and the same minimal set of assembly language instructions in a repetitive loop, and thereby having streams of clock and data signals on its various signal lines, is exposed to a "short" RF pulse and is subsequently upset or is not upset. We then want to construct models to predict the *upset probability* as a function of RF pulse parameters and those of the assembly-instruction-induced microcontroller signal streams.

In Section II we present some ideas which bear on our development, in Section III, of models which *begin* to address the above problem. In Section IV we conclude.

A.2 *Modeling Preliminaries*

A.2.1. Signal Pulse Trains and RF Pulses

To describe the models that we have constructed in pursuit of the above-stated objective, we first address four relevant areas which impact the details of those models.

The first area pertains to the mode of exposure—in laboratory experiments to be performed to help assess the validity of our models and which experiments must therefore be encompassed by our models—of the microcontroller to the incident RF pulse: RF radiation field immersion or direct RF voltage injection into selected ports. While the former is ultimately the mode of interest, it suffers—from the scientific

investigation point of view—from the non-specificity of its effect; that is, radiation field immersion in general may couple simultaneously to numerous conducting paths of the microcontroller and thus simultaneously influence numerous signal lines (clock and data). Incorporating this complexity into an initial model is not desirable; it is better, we believe, to initially *confine the RF excitation to a single signal line* in order to attempt to understand and model this simpler situation—and that is what we do. This confinement of excitation is achieved experimentally by the direct injection technique.

It is to be noted, however, that confinement of the excitation to a single signal line, with possible resultant perturbation of the signal on that line, does not imply confinement of the perturbation of the microcontroller entirely to that line: signal lines other than the excited one may in general also be perturbed. These additional perturbations in other microcontroller signal lines may be captured in a non-specific-signal-line manner by noting whether the injected RF pulse has or has not caused an upset in the microcontroller as a whole, as evidenced by an upset in program execution. As a related issue, it is also feasible that a perturbation of the excited single signal line does not cause upset of microcontroller program execution. The *detailed* connection between the excitation and subsequent perturbation of the single signal line, on the one hand, and subsequent microcontroller execution upset on the other, is currently an open question, the answer to which we hope to obtain as part of our current research. It may indeed turn out that, given a precise timing relationship between the incident RF pulse and the signal on the single excited signal line, we find the effect on all other microcontroller lines—hence upon the microcontroller itself—is in fact deterministic. In the meantime, in the absence of that knowledge, we will restrict ourselves in this paper to providing models of microcontroller-as-a-whole execution upset probability rather than providing models of (perhaps deterministic) signal line perturbation probabilities for the numerous, individual microcontroller signal lines.

The second area pertains to the type of signal stream being carried by the RF-injected signal line—clock or data. The former is more attractive from a modeling point of view in that it is, when unperturbed, completely periodic in time and thus easy to capture. Data signal streams on any particular line are, on the other hand, aperiodic in general;

nevertheless, they may be coarsely (but *perhaps* adequately) approximated by assuming that they are, on average, logic high for half of any ("long enough") time interval of interest and logic low for the other half of that interval so that in some coarse sense they are equivalent to a periodic clock–type signal stream. In any case, in our models we consider a *periodic signal pulse train composed of individual square pulses with each individual square pulse having one and the same amplitude*; further, the individual pulses are taken to be perfectly square, with vertical rises and falls, and the pulse train is thus completely characterized by its period $\tau_{signal} > 0$ and amplitude $V_{signal} > 0$. More precisely, the basic individual square pulse, $w: [0, \tau_{signal}) \rightarrow \{0, V_{signal}\}$, is given by

$$w(t) \equiv \begin{cases} V_{signal} & \text{if} \quad 0 \leq t < \tau_{signal}/2 \\ 0 & \text{if} \quad \tau_{signal}/2 \leq t < \tau_{signal} \end{cases} \tag{1}$$

and the entire pulse, $P_{signal}: [0, \infty) \rightarrow \{0, V_{signal}\}$, is given by

$$P_{signal}(t) \equiv w(t - [t/\tau_{signal}]\, \tau_{signal}), \quad t \geq 0, \tag{2}$$

where $[\cdot]$ denotes the usual greatest integer function.

The third area pertains to the characterization of the injected RF pulse. This pulse is in reality a Gaussian modulated sine wave with the modulation envelope extending between voltage extremes that we denote as $\pm V_{RF}$. However, in our models we *represent the RF pulse as a (single) perfectly square, positive-only-going pulse of width* $\tau_{RF} \geq 0$ *and amplitude* $V_{RF} \geq 0$. This approximation captures both the Gaussian envelope amplitude and its temporal width but captures neither the sinusoidal frequency nor the temporal excursions between $\pm V_{RF}$ of the actual Gaussian modulated pulse. Indeed, in the interest of initial simplicity, *we have chosen not to represent these latter two attributes of the RF pulse in our current model.*

The fourth and final area pertains to the interaction between the signal pulse train and the injected RF pulse. This interaction is completely characterized in our models (once τ_{signal}, V_{signal}, τ_{RF} and V_{RF} are specified) by the relative timing between the signal pulse train and the onset of the RF pulse. There are two timing possibilities: synchronous and

asynchronous. In the synchronous case, we are interested in the situation in which the leading edge (rise) of the RF pulse occurs at some *fixed*, specified instant $t_0 + \theta \geq 0$, with $0 \leq \theta < \tau_{signal}/2$, following some instant $t_0 \in \{ j \cdot \tau_{signal}/2 \mid j \in \mathbb{N}_0 \}$ ($\mathbb{N}_0$ denotes the non-negative integers) at which the signal pulse train rises (j even) or falls (j odd). In the asynchronous case, we are interested in the situation in which the offset θ from such a $t_0 = j \cdot \tau_{signal}/2$ is not fixed but rather is *uniformly distributed* in the interval $0 \leq \theta < \tau_{signal}/2$; further, j may be either fixed or may be *uniformly distributed* in $\mathbb{N}_0$. The synchronous case is of interest both for addressing controlled laboratory experiments as well as for serving as a basis upon which the asynchronous case model is constructed, while the asynchronous case is of interest for "real-world" RF excitation. In our models, we treat both the synchronous and asynchronous cases.

The parameters introduced above to describe the physical attributes represented in our models are these: τ_{signal} and V_{signal} for the signal pulse train, τ_{RF} and V_{RF} for the RF pulse, and j and θ for the interaction between the two. We will find it convenient to scale time in units of $\tau_{signal}/2$ and we thus define

$$\Theta \equiv \theta/(\tau_{signal}/2) \in [0, 1) \qquad \text{and} \qquad \Delta \equiv \tau_{RF}/(\tau_{signal}/2) > 0; \tag{3}$$

further, we will also find it convenient to scale voltage in units of V_{signal} and thus define

$$Y \equiv V_{RF} \,/\, V_{signal}. \tag{4}$$

Our basic scaled parameter set then becomes $\{\Delta, Y, j, \Theta\}$ and our models will be based upon this full set or upon some subset of these in reduced versions of the most general case.

There is yet one more assumption that we make in all of the models we present here: we assume a threshold behavior for the efficacy of the RF pulse in causing an effect; i.e., that there is some (sharp) threshold $V^*_{RF} \geq 0$ such that a disruptive effect occurs iff $V_{RF} \geq V^*_{RF}$. In reality, there is no sharp threshold but rather an interval, I_V, of voltage values such that if $V_{RF} \in I_V$ then there is some probability, say $P_e(V_{RF})$—neither zero nor one—with which an effect will occur; furthermore, in I_V, this $P_e(V_{RF})$ monotonically

increases smoothly but rapidly with V_{RF} from values near zero to values near one. In general, V^*_{RF} is chosen from among the voltage values in I_V according to some appropriate criterion such as being the (unique) value of V_{RF} for which $P_e(V_{RF}) = ½$. We allow the possibility that V^*_{RF} depends upon Δ, j and Θ, in which cases we may sometimes write $V^{*\,\Delta,j,\Theta}_{RF}$, and we denote

$$Y^*_{RF} \equiv V^*_{RF} \,/\, V_{signal}. \tag{5}$$

Also, V^*_{RF} *is frequency dependent but we do not incorporate this frequency dependence explicitly into our current model.*

In summary then, we consider the synchronous or asynchronous interaction between—on the one hand—a single, periodic signal pulse train consisting of perfectly square wave pulses having common amplitude and—on the other hand—a perfectly square single RF pulse, with the models addressing either the full parameter set $\{\Delta, Y, j, \Theta\}$ or some subset of the latter; further, the disruption interaction displays a threshold behavior.

A.2.2. Probability

As indicated in the *Introduction*, we are interested in predicting upset *probability*. Hence the proper setting for our models is a probabilistic one. This entails specification of a probability space, $(\Omega, \mathcal{A}, \mathcal{P})$, for each such model, with the choices of these three entities being model-dependent. In every choice, however, the event, $\mathcal{E}$, that "an upset occurs" must be a member of $\mathcal{A}$ and $\mathcal{P}(\mathcal{E})$ must give the probability of upset.

It is important to point out that stochasticity arises in our models on two differing levels. Firstly, even when all the basic parameters are fixed (synchronous case), we allow the possibility that the occurrence of microcontroller upset is not deterministic. (If, on the contrary, upset turns out to be deterministic in the synchronous case then this situation can be accommodated by declaring that upset probabilities be either zero or one.) Secondly, probability plays a natural role when one or both of the two basic parameters j and Θ are randomly distributed (asynchronous case); the technique used in this case is to take a weighted superposition of synchronous upset probabilities, with the weights

dictated by the specified distribution(s) of those basic parameters which are random. (In the current paper, we take these random distributions to be uniform based on "real-world" considerations but our method can easily accommodate arbitrary distributions if necessary.)

In the synchronous setting, in which Δ, Y, j and Θ are fixed, the outcome set, Ω, need not encompass any of these four parameters; but the probability measure, $\mathcal{P}$, will in general depend upon all four. In some models, $\mathcal{P}$ may not depend upon some of these four: in the sequel we will explicitly present the full range of possibilities for $\mathcal{P}$ in the synchronous setting. In the asynchronous setting, in which at least Δ and Y are fixed and Θ is not fixed (being distributed uniformly in [0, 1)) and j may or may not be fixed (being distributed uniformly in $\mathbb{N}_0$ in the latter case), Ω need not encompass the fixed parameters but must include Θ and must also include j if it is not fixed. $\mathcal{P}$ in general cannot depend upon Θ, nor upon j if it is not fixed, but may depend upon all fixed parameters (including j in case it is fixed). Again, in some models, $\mathcal{P}$ may not depend upon some of these fixed parameters; and again, in the sequel we will explicitly present the full range of possibilities for $\mathcal{P}$ in the asynchronous setting. In any case, for each of our models we will explicitly display the parameters upon which $\mathcal{P}$ depends; in the most general case this results in $\mathcal{P}^{\Delta, Y, j, \Theta}$ while other cases require that fewer parameters be attached to $\mathcal{P}$.

Our basic physical premise for the models presented in this paper is that the probability of occurrence of an upset ("effect") in a microcontroller signal pulse train—and occurrence of a subsequent upset in the microcontroller itself—by injection into the signal line, at scaled time instant $j + \Theta$, of an RF pulse having scaled width Δ and scaled amplitude Y, depends upon—in addition to Y and j—only the number $n \in \mathbb{N}_0$ of rise plus fall transitions of the signal pulse train encompassed by the RF pulse. In terms of our basic parameters, n depends solely upon Δ and Θ according to

$$n = \mathcal{N}(\Delta, \Theta) \equiv \begin{cases} [\Delta + \Theta] & \text{if } \Theta > 0 \\ [\Delta + \Theta] + 1 & \text{if } \Theta = 0; \end{cases} \tag{6}$$

in particular, n *is independent of* Y *and j*. As one consequence of this premise, the parameters upon which $\mathcal{P}$ depends are (at most) n, Y, and *j*; we thus write, in lieu of $\mathcal{P}^{\Delta, Y, j, \Theta}$ (the most general case, for example), rather $\mathcal{P}^{\mathcal{N}(\Delta, \Theta), Y, j}$, i.e., $\mathcal{P}^{n, Y, j}$. Also, consistent with the above premise, we stipulate that the dependence of the upset threshold voltage $V^{*\,\Delta, j, \Theta}_{\mathrm{RF}}$ upon Δ, *j* and Θ is only *via j* and n, i.e., $V^{*\,\Delta, j, \Theta}_{\mathrm{RF}}$ becomes $V^{*\,n, j}_{\mathrm{RF}}$ in the most general case; further, the dependence upon *j* or n may in some cases be absent so that $V^{*\,\Delta, j, \Theta}_{\mathrm{RF}}$ becomes $V^{*\,n}_{\mathrm{RF}}$ or $V^{*\,j}_{\mathrm{RF}}$ or even simply V^{*}_{RF} (no dependence upon basic parameters). In case the threshold depends upon n, we require that it be nonincreasing in n (at every fixed *j* in the case of $V^{*\,n, j}_{\mathrm{RF}}$).

In the models presented in this paper, it is assumed that the number, n, of signal pulse train transitions encompassed by the RF pulse is reckoned as that number which would occur if the signal pulse train were not perturbed by the RF pulse (despite the allowed possibility that the amplitudes of the signal pulse train might indeed be modified); in particular, if the perturbed signal pulse train effectively ceases to exist before the otherwise encompassed n transitions have actually occurred, then n is to be interpreted as the number of transitions encompassed had the signal pulse not ceased to exist.

Finally, we will not explore the most general possible *j*-dependence of $\mathcal{P}^{n, Y, j}$; rather we will illustrate such behavior using simply a dependence upon the parity of *j*—even or odd—which parity correlates with the first encompassed signal pulse train transition being a rise or a fall respectively.

In what follows, we construct probability spaces to capture the behavior outlined above in this Section.

A.3 ***Models***

To construct our probabilistic models, we first consider the following trial defining a random experiment. A periodic pulse train, as described in Eqs. (1) and (2), defined for all $t \geq 0$ and having period τ_{signal} and amplitude V_{signal} and a rising edge at $t = 0$, is streaming on a microcontroller signal line whereupon the latter is subjected at time instant $t^{\#} = j \cdot \tau_{signal}/2 + \theta \geq 0$, where $j \in \mathbb{N}_0$ and $\theta \in [0, \tau_{signal}/2)$ (hence $t^{\#} = [j + \Theta] \cdot (\tau_{signal}/2)$), to an RF pulse having rising edge occurring also at time instant $t^{\#}$ and having fixed (from trial to trial) width τ_{RF} and fixed amplitude V_{RF}. The synchronous version of this experiment has j and Θ being the same from trial to trial (and likewise, therefore, also n) while the asynchronous version of this experiment comes in two varieties: both have Θ being sampled uniformly from [0, 1) but the first variation has j fixed from trial to trial while the second variation has j being sampled uniformly from $\mathbb{N}_0$. The outcome observed in the synchronous case is merely whether microcontroller upset has occurred or not. The outcome observed in the first variation of the asynchronous case is the value of Θ and whether microcontroller upset has occurred or not while the outcome observed in the second variation of the asynchronous case is the values of j and Θ and whether microcontroller upset has occurred or not. The observed value of Θ implies, *via* Eq. (6), a corresponding value of n.

A.3.1 Synchronous Models

For the above random experiment, in which n, Y, and j are fixed, the associated probability space, denoted by $(\Omega_S, \mathcal{A}_S, \mathcal{P}_S^{n,Y,j})$, is specified as follows. For the outcome set we take

$$\Omega_S \equiv \{\varepsilon, \ \bar{\varepsilon}\} \equiv \mathcal{O}, \tag{7}$$

where ε (resp. $\bar{\varepsilon}$) denotes "effect occurs" (resp. "no effect occurs"); note that Ω_S itself is independent of Δ, Y, j and Θ. For σ-algebra $\mathcal{A}_S$ we take

$$\mathcal{A}_S = \{ \varnothing, \{\varepsilon\}, \{\bar{\varepsilon}\}, \mathcal{O} \} = \mathbb{P}(\mathcal{O}) \tag{8}$$

(the power set of $\mathcal{O}$). The events of interest are

$$\mathcal{E}_S = \{\varepsilon\} \qquad \text{(an effect occurs)} \tag{9}$$

and

$$\bar{\mathcal{E}}_S = \Omega_S \setminus \mathcal{E}_S = \{\bar{\varepsilon}\} \qquad \text{(no effect occurs).} \tag{10}$$

We must now specify the probability measure $\mathcal{P}_S^{n,Y,j}$. We do not know at this point what that ought to be; indeed, it is an open question, the answer to which may be suggested—at least initially—by experiment. Nevertheless, we may provide some structure as a guide in seeking answers and in using those answers once they become available; so that is what we do. In some sense, then, what we provide in this paper is a partial model supplemented by a modeling framework which we may use to discover and incorporate the currently missing pieces when available.

Be that as it may, we propose that in the most general case

$$\mathcal{P}_S^{n,Y,j}(\mathcal{E}_S) = Q_S^{n,Y,j}(\mathcal{E}_S) \equiv \begin{cases} 0 & \text{if } Y < Y^{*\,n,j}_{RF} \\ q(n,Y,j) & \text{if } Y \geq Y^{*\,n,j}_{RF}. \end{cases} \tag{11}$$

The function $q\colon \bigcup_{\langle n,j\rangle \in (\mathbb{N}_0)^2} (\{n\} \times [Y^{*\,n,j}_{RF}, \infty) \times \{j\}) \to [0,1]$ (where $\langle\cdot,\cdot\rangle$ denotes an ordered pair) is somewhat arbitrary, subject only to the constraints to be discussed shortly. When—as discussed earlier—the *j*-dependence is based only upon parity, we also have

$$q(n,Y,j) = \begin{cases} q_{\text{even}}(n,Y) & \text{if } j \text{ even} \\ q_{\text{odd}}(n,Y) & \text{if j odd} \end{cases} \tag{12}$$

where $Y^{*\,n,j}_{RF} \equiv Y^{*\,n,\text{even}}_{RF}$ if j is even and $Y^{*\,n,j}_{RF} \equiv Y^{*\,n,\text{odd}}_{RF}$ if j is odd. Explicitly, in this case we have

$$\mathcal{P}_S^{n,Y,j}(\mathcal{E}_S) = Q_S^{\pm\,n,Y,j}(\mathcal{E}_S) \equiv \begin{cases} Q_S^{+\,n,Y}(\mathcal{E}_S) & \text{if } j \text{ is even} \\ Q_S^{-\,n,Y}(\mathcal{E}_S) & \text{if } j \text{ is odd} \end{cases} \tag{13}$$

where, for j even and odd respectively, we define

$$\overset{+}{Q}_{\mathrm{S}}^{\,n,Y}(\mathcal{E}_{\mathrm{S}}) \equiv \begin{cases} 0 & \text{if } Y < Y^{*\,n,\,\mathrm{even}}_{\mathrm{RF}} \\ q_{\mathrm{even}}(n,Y) & \text{if } Y \geq Y^{*\,n,\,\mathrm{even}}_{\mathrm{RF}} \end{cases} \tag{14}$$

and

$$\overset{-}{Q}_{\mathrm{S}}^{\,n,Y}(\mathcal{E}_{\mathrm{S}}) \equiv \begin{cases} 0 & \text{if } Y < Y^{*\,n,\,\mathrm{odd}}_{\mathrm{RF}} \\ q_{\mathrm{odd}}(n,Y) & \text{if } Y \geq Y^{*\,n,\,\mathrm{odd}}_{\mathrm{RF}}. \end{cases} \tag{15}$$

The function q is somewhat arbitrary, subject only to the following constraints. Consider first the simpler case in which $\mathcal{P}_{\mathrm{S}}^{n,Y,j}(\mathcal{E}_{\mathrm{S}})$ and $Y^{*\,n,j}_{\mathrm{RF}}$ are in fact independent of j. Then we have either

$$\mathcal{P}_{\mathrm{S}}^{n,Y,j}(\mathcal{E}_{\mathrm{S}}) = Q_{\mathrm{S}}^{n,Y}(\mathcal{E}_{\mathrm{S}}) \equiv \begin{cases} 0 & \text{if } Y < Y^{*\,n}_{\mathrm{RF}} \\ q''(n,Y) & \text{if } Y \geq Y^{*\,n}_{\mathrm{RF}}, \end{cases} \tag{16}$$

with $q'' \colon \bigcup_{n \in \mathbb{N}_0} (\{n\} \times [\,Y^{*\,n}_{\mathrm{RF}}, \infty)) \to [0, 1]$, or

$$\mathcal{P}_{\mathrm{S}}^{n,Y,j}(\mathcal{E}_{\mathrm{S}}) = \hat{Q}_{\mathrm{S}}^{n,Y}(\mathcal{E}_{\mathrm{S}}) \equiv \begin{cases} 0 & \text{if } Y < Y^{*\,n}_{\mathrm{RF}} \\ q'(n) & \text{if } Y \geq Y^{*\,n}_{\mathrm{RF}}, \end{cases} \tag{17}$$

with $q' \colon \mathbb{N}_0 \to [0, 1]$; and we have, further, two additional possibilities, given again by Eqs. (16) and (17) except that the thresholds $Y^{*\,n}_{\mathrm{RF}}$ are in fact n-independent (being then written simply as Y^{*}_{RF}). In the case of Eq. (17) (and its n-independent analogue) we demand only that q' be nondecreasing and, in addition, $q'(0) = 0$ and $\lim_{n \to \infty} q'(n) =$

$q'_{max} \le 1$. In the case of Eq. (16) (and its n-independent analogue) we demand that both the maps $q''(n, \bullet)$ and $q''(\bullet, Y)$ be nondecreasing with $q''(0, Y) = 0$,

$\lim_{n \to \infty} q''(n, Y) = q''^{Y}_{max} \le 1$ and $\lim_{Y \to \infty} q''(n, Y) = q''^{n}_{max} \le 1$. The constraints to be imposed on q in the most general case of Eq. (11) are then a straightforward extension of those imposed in the more restricted situations.

Some simple examples of candidate functions of the type q' are: (i) $q'_1(n) = 1 - (n + 1)^{-\gamma}$, $\gamma > 0$, (ii) $q'_2(n) = 1 - (n + 1)^{-\gamma}$ if $n \le N^* \in \mathbb{N}$ & $q'_2(n) = 1$ if $n > N^*$, and (iii) $q'_3(n) = 1 - e^{-n}$; and there are many others. Some candidates of the type q'' can be obtained from the three examples above of q' by multiplying each of those by Y/Y_{sat} if $Y^*_{RF} \le Y \le Y_{sat}$ for some "saturation" $Y_{sat} > Y^*_{RF}$, where $Y_{sat} = V_{sat}/V_{signal}$ for some saturation V_{sat}, or by multiplying them instead by 1 if $Y > Y_{sat}$; to wit (for m =1, 2, 3),

$$q''_m(n, Y) \equiv q'_m(n) \bullet \begin{cases} Y/Y_{sat} \text{ if } Y^*_{RF} \le Y < Y_{sat} \\ 1 \quad \text{if } Y_{sat} \le Y < \infty. \end{cases} \tag{18}$$

And product functions (in variables n and Y) by no means exhaust all the possibilities for q''. Once again, which of these many possibilities to choose may be suggested by experiment.

The expressions in Eqs. (11), (13), (16), and (17) then give the probability of microcontroller upset in the cases in which they are applicable as indicated.

A.3.2 Asynchronous Models

A.3.2.1. <u>Case of *j* fixed</u>

For the above random experiment, in which Δ, Y and j are fixed but Θ is not, the associated probability space, denoted by $(\Omega^{(2)}_A, \mathcal{A}^{(2)}_A, \mathcal{P}^{Y,j}_A)$, is specified as follows. For the outcome set we take

$$\Omega^{(2)}_A \equiv \{\langle \Theta, \omega \rangle \mid \Theta \in [0, 1) \ \& \ \omega \in \mathcal{O}\} = [0, 1) \times \mathcal{O}; \tag{19}$$

note that $\Omega_A^{(2)}$ itself is independent of Δ, Y, and j.

To specify $\mathcal{A}_A^{(2)}$ we reason as follows. First of all, the following must be events:

$$\mathcal{E}_A^{(2)} \equiv \{\langle \Theta, \omega \rangle \in \Omega_A^{(2)} \mid \omega = \varepsilon\} \qquad \text{(an effect occurs)} \tag{20}$$

$$\bar{\mathcal{E}}_A^{(2)} = \Omega_A^{(2)} \setminus \mathcal{E}_A^{(2)} \qquad \text{(no effect occurs).} \tag{21}$$

Second of all, by our premise discussed in Section II, our upset probability assignment will only depend upon—in addition to Y and j—the number, n, of rise plus fall transitions of the signal pulse train encompassed by the RF pulse; and by Eq. (6), $n = \mathcal{N}(\Delta, \Theta)$, independently of Y and j. Since Y and j are fixed in the present case then the only other fundamental events of interest are these:

$$\mathcal{T}_{A,2}^{n}(\Delta) \equiv \{\langle \Theta, \omega \rangle \in \Omega_A^{(2)} \mid \mathcal{N}(\Delta, \Theta) = n\} \qquad (n \in \mathbb{N}_0)$$

(exactly n signal pulse transitions encompassed by RF pulse); (22)

note that $\mathcal{T}_{A,2}^{n}(\Delta) = \mathcal{J}_A^{n}(\Delta) \times \mathcal{O}$ where

$$\mathcal{J}_A^{n}(\Delta) \equiv \{\Theta \in [0, 1) \mid \mathcal{N}(\Delta, \Theta) = n\} \tag{23}$$

and that $\{\mathcal{T}_{A,2}^{n}(\Delta)\}_{n \in \mathbb{N}_0}$ is a partition of $\Omega_A^{(2)}$. Now by Eq. (6), if $\Theta = 0$ then $\mathcal{N}(\Delta, \Theta) = [\Delta + \Theta] + 1$ so $\Theta \in \mathcal{J}_A^{[\Delta+\Theta]+1}(\Delta) = \mathcal{J}_A^{[\Delta]+1}(\Delta)$. Suppose next that $\Theta \in (0, 1)$; then, again by Eq. (6), $\mathcal{N}(\Delta, \Theta) = [\Delta + \Theta]$ so $\Theta \in \mathcal{J}_A^{[\Delta+\Theta]}(\Delta)$ iff $[\Delta + \Theta] = n$. Now in general we have (when $\Theta \in (0, 1)$) that $\Delta < \Delta + \Theta < \Delta + 1$; if $\Delta < \Delta + \Theta < [\Delta] + 1$, which holds iff $0 < \Theta < 1 - (\Delta - [\Delta])$, then $[\Delta + \Theta] = [\Delta]$, while if $[\Delta] + 1 \le \Delta + \Theta < \Delta + 1$, which holds iff $1 - (\Delta - [\Delta]) \le \Theta < 1$, then $[\Delta + \Theta] = [\Delta] + 1$. Thus $\mathcal{J}_A^{[\Delta]}(\Delta) = (0, 1 - (\Delta - [\Delta]))$ and $\mathcal{J}_A^{[\Delta]+1}(\Delta) = [1 - (\Delta - [\Delta]), 1) \cup \{0\}$ and $\mathcal{J}_A^{n}(\Delta) = \varnothing$ if $n \neq [\Delta], [\Delta] + 1$. Hence the only nontrivial subsets of Ω_A of the type in Eq. (22) are $\mathcal{T}_{A,2}^{[\Delta]}(\Delta)$ and $\mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)$. Since $\mathcal{J}_A^{[\Delta]}(\Delta) \cup \mathcal{J}_A^{[\Delta]+1}(\Delta) = [0, 1)$ and $\mathcal{J}_A^{[\Delta]}(\Delta) \cap \mathcal{J}_A^{[\Delta]+1}(\Delta) = \varnothing$ then

$$\mathcal{K}_A \equiv \{\varnothing, \mathcal{J}_A^{[\Delta]}(\Delta), \mathcal{J}_A^{[\Delta]+1}(\Delta), [0, 1)\} \tag{24}$$

is a σ-algebra in [0, 1) and we take $\mathcal{A}_A^{(2)}$ to be the σ-algebra in $\Omega_A^{(2)}$ generated by $\mathcal{K}_A \times \mathbb{P}(\mathcal{O})$. Clearly $\mathcal{T}_{A,2}^{[\Delta]}(\Delta)$, $\mathcal{T}_{A,2}^{[\Delta]+1}(\Delta) \in \mathcal{A}_A^{(2)}$; further,

$$\mathcal{E}_A^{(2)} = (\mathcal{E}_A^{(2)} \cap \mathcal{T}_{A,2}^{[\Delta]}(\Delta)) \cup (\mathcal{E}_A^{(2)} \cap \mathcal{T}_{A,2}^{[\Delta]+1}(\Delta))$$

$$= (\mathcal{J}_A^{[\Delta]}(\Delta) \times \{\varepsilon\}) \cup (\mathcal{J}_A^{[\Delta]+1}(\Delta) \times \{\varepsilon\}) \in \mathcal{A}_A^{(2)} \tag{25}$$

and

$$\bar{\mathcal{E}}_A^{(2)} = \big((\mathcal{J}_A^{[\Delta]}(\Delta) \times \{\bar{\varepsilon}\}) \cup (\mathcal{J}_A^{[\Delta]+1}(\Delta) \times \mathcal{O})\big) \cap \big((\mathcal{J}_A^{[\Delta]+1}(\Delta) \times \{\bar{\varepsilon}\}) \cup (\mathcal{J}_A^{[\Delta]}(\Delta) \times \mathcal{O})\big) \in \mathcal{A}_A^{(2)}. \tag{26}$$

Finally, we must specify the probability measure $\mathcal{P}_A^{Y,j}$. We will restrict ourselves here to merely specifying $\mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)})$ (rather than in defining $\mathcal{P}_A^{Y,j}$ on all of $\mathcal{A}_A^{(2)}$ as is formally required—the full specification of $\mathcal{P}_A^{Y,j}$ on all of $\mathcal{A}_A^{(2)}$ such that $\mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)})$ is as to-be-specified is standard so we will not further occupy ourselves with this technicality here). To this end, using the first equality Eq. (25) we have

$$\mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)}) = \mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)} \cap \mathcal{T}_{A,2}^{[\Delta]}(\Delta)) + \mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)} \cap \mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)) \tag{27}$$

and whenever $\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]}(\Delta)) > 0$ and $\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)) > 0$ we also have

$$\mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)}) = \mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)} \mid \mathcal{T}_{A,2}^{[\Delta]}(\Delta))\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]}(\Delta)) + \mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)} \mid \mathcal{T}_{A,2}^{[\Delta]+1}(\Delta))\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)). \tag{28}$$

Hence, to specify $\mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)})$ it is sufficient to specify $\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{n}(\Delta))$ and $\mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)} \mid \mathcal{T}_{A,2}^{n}(\Delta))$ for $n = \mathbf{[\Delta]}, \mathbf{[\Delta]} + 1$. We now address these in turn. First, guided by the discussion following Eq. (23), we take, *since* Θ *is uniformly distributed on* [0, 1),

$$\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]}(\Delta)) = 1 - (\Delta - \mathbf{[\Delta]}) \quad \text{and} \quad \mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)) = (1 - (\Delta - \mathbf{[\Delta]})) - 1 = \Delta - \mathbf{[\Delta]}. \tag{29}$$

Note that $\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]}(\Delta)) > 0$ for any $\Delta > 0$ but $\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)) > 0$ iff $\Delta \notin \mathbb{N}$. Next, we take

$$\mathcal{P}_A^{Y,j}(\mathcal{E}_A^{(2)} \mid \mathcal{T}_{A,2}^{[\Delta]}(\Delta)) = Q_S^{[\Delta],Y,j}(\mathcal{E}_S) \tag{30}$$

and, in case $\mathcal{P}_A^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)) > 0$,

$$\mathcal{P}_{A}^{Y,j}(\mathcal{E}_{A}^{(2)} \mid \mathcal{T}_{A,2}^{[\Delta]+1}(\Delta)) = Q_{S}^{[\Delta]+1,Y,j}(\mathcal{E}_{S}) \tag{31}$$

so that when $\Delta \notin \mathbb{N}$ then Eq. (28) yields

$$\mathcal{P}_{A}^{Y,j}(\mathcal{E}_{A}^{(2)}) = (1 - (\Delta - [\Delta]))Q_{S}^{[\Delta],Y,j}(\mathcal{E}_{S}) + (\Delta - [\Delta])Q_{S}^{[\Delta]+1,Y,j}(\mathcal{E}_{S}) \qquad (\Delta \notin \mathbb{N}), \tag{32}$$

which is simply a *weighted average of the two synchronous results that apply when* n = $[\Delta]$, $[\Delta] + 1$, while when $\Delta \in \mathbb{N}$ then Eq. (27), along with Eqs. (29) and (30), yields,

$$\mathcal{P}_{A}^{Y,j}(\mathcal{E}_{A}^{(2)}) = \mathcal{P}_{A}^{Y,j}(\mathcal{E}_{A}^{(2)} \mid \mathcal{T}_{A,2}^{[\Delta]}(\Delta))\mathcal{P}_{A}^{Y,j}(\mathcal{T}_{A,2}^{[\Delta]}(\Delta)) = Q_{S}^{[\Delta],Y,j}(\mathcal{E}_{S}) \qquad (\Delta \in \mathbb{N}). \tag{33}$$

Note that the result in Eq. (33) also follows from Eq. (32) even when $\Delta \in \mathbb{N}$ so the latter equation (i.e., (32)) suffices in fact for all $\Delta > 0$.

The expression in Eq. (32) then gives the probability of microcontroller upset in the present case.

A.3.2.2. *Case of j not fixed*

In this case, Δ and Y are fixed but j and Θ are not, with j distributed uniformly on $\mathbb{N}_0$. For the above random experiment, the associated probability space, denoted by $(\Omega_{A}^{(3)}, \mathcal{A}_{A}^{(3)}, \mathcal{P}_{A}^{Y})$, is specified as follows. For the outcome set we take

$$\Omega_{A}^{(3)} \equiv \{\langle j, \Theta, \omega\rangle \mid j \in \mathbb{N}_0 \;\&\; \Theta \in [0, 1) \;\&\; \omega \in \mathcal{O}\} = \mathbb{N}_0 \times [0, 1) \times \mathcal{O}; \tag{34}$$

note that $\Omega_{A}^{(3)}$ itself is independent of Δ and Y. To specify $\mathcal{A}_{A}^{(3)}$ we observe that the following must be events:

$$\mathcal{E}_{A}^{(3)} \equiv \{\langle j, \Theta, \omega\rangle \in \Omega_{A}^{(3)} \mid \omega = \varepsilon\} \qquad \text{(an effect occurs)}, \tag{35}$$

$$\bar{\mathcal{E}}_{A}^{(3)} = \Omega_{A}^{(3)} \setminus \mathcal{E}_{A}^{(3)} \qquad \text{(no effect occurs)}, \tag{36}$$

$$\mathcal{T}_{A,3}^{n}(\Delta) \equiv \{\langle j, \Theta, \omega\rangle \in \Omega_{A}^{(3)} \mid \mathcal{N}(\Delta, \Theta) = n\} = \mathbb{N}_0 \times \mathcal{J}_{A}^{n}(\Delta) \times \mathcal{O} \qquad (n \in \mathbb{N}_0)$$

(exactly n signal pulse transitions encompassed by RF pulse), (37)

$$\mathcal{J}_{\text{even}} \equiv \{\langle j, \Theta, \omega\rangle \in \Omega_{A}^{(3)} \mid j \in \mathbb{N}_0^{\text{even}}\}, \tag{38}$$

and

$$\mathcal{J}_{\text{odd}} \equiv \{\langle j, \Theta, \omega\rangle \in \Omega_{\text{A}}^{(3)} \mid j \in \mathbb{N}_0^{\text{odd}}\}. \tag{39}$$

Noting that

$$\mathcal{N}_{\text{A}} \equiv \{\varnothing, \mathbb{N}_0^{\text{even}}, \mathbb{N}_0^{\text{odd}}, \mathbb{N}_0\} \tag{40}$$

is a σ-algebra in $\mathbb{N}_0$, we then take $\mathcal{A}_{\text{A}}^{(3)}$ to be the σ-algebra in $\Omega_{\text{A}}^{(3)}$ generated by $\mathcal{N}_{\text{A}}$ x $\mathcal{K}_{\text{A}}$ x $\mathbb{P}(\mathcal{O})$ ($\mathcal{K}_{\text{A}}$ as defined in Eq. (24)) and it is easy to see that the five subsets of $\Omega_{\text{A}}^{(3)}$ given by Eqs. (35) - (39) are events in $\mathcal{A}_{\text{A}}^{(3)}$. To specify $\mathcal{P}_{\text{A}}^{Y}$ we observe that, again, $\mathcal{T}_{\text{A},3}^{n}(\Delta) = \varnothing$ if $n \neq \mathbf{[}\Delta\mathbf{]}, \mathbf{[}\Delta\mathbf{]} + 1$ so that $\{\mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{even}}, \mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{odd}}, \mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{even}}, \mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{odd}}\}$ is a partition of $\Omega_{\text{A}}^{(3)}$; hence, if $\Delta \notin \mathbb{N}$, so that $\mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{even}}), \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{odd}}) > 0$, then

$$\begin{aligned}
\mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)}) = {} & \mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)} \mid \mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{even}})\, \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{even}}) \\
& + \mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)} \mid \mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{odd}})\, \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{odd}}) \\
& + \mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)} \mid \mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{even}})\, \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{even}}) \\
& + \mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)} \mid \mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{odd}})\, \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{odd}})
\end{aligned} \qquad (\Delta \notin \mathbb{N}) \tag{41}$$

while if $\Delta \in \mathbb{N}$, so that $\mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{even}}), \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{odd}}) = 0$, then

$$\begin{aligned}
\mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)}) = {} & \mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)} \mid \mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{even}})\, \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{even}}) \\
& + \mathcal{P}_{\text{A}}^{Y}(\mathcal{E}_{\text{A}}^{(3)} \mid \mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{odd}})\, \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{odd}}).
\end{aligned} \qquad (\Delta \in \mathbb{N}) \tag{42}$$

Now since *j is uniformly distributed on* $\mathbb{N}_0$ we then take (see Eq. (29))

$$\begin{aligned}
\mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{even}}) &= (1/2)(1 - (\Delta - \mathbf{[}\Delta\mathbf{]}) = \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\text{odd}}) \\
\mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{even}}) &= (1/2)(\Delta - \mathbf{[}\Delta\mathbf{]}) = \mathcal{P}_{\text{A}}^{Y}(\mathcal{T}_{\text{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\text{odd}});
\end{aligned} \tag{43}$$

also we take

$$\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{E}_{\mathrm{A}}^{(3)} \mid \mathcal{T}_{\mathrm{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\mathrm{even}}) = Q_{\mathrm{S}}^{+[\Delta],Y}(\mathcal{E}_{\mathrm{S}}),$$
$$\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{E}_{\mathrm{A}}^{(3)} \mid \mathcal{T}_{\mathrm{A},3}^{[\Delta]}(\Delta) \cap \mathcal{J}_{\mathrm{odd}}) = Q_{\mathrm{S}}^{-[\Delta],Y}(\mathcal{E}_{\mathrm{S}}) \tag{44}$$

and, in case $\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{T}_{\mathrm{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\mathrm{even}})$, $\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{T}_{\mathrm{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\mathrm{odd}}) > 0$, then also

$$\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{E}_{\mathrm{A}}^{(3)} \mid \mathcal{T}_{\mathrm{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\mathrm{even}}) = Q_{\mathrm{S}}^{+[\Delta]+1,Y}(\mathcal{E}_{\mathrm{S}}),$$
$$\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{E}_{\mathrm{A}}^{(3)} \mid \mathcal{T}_{\mathrm{A},3}^{[\Delta]+1}(\Delta) \cap \mathcal{J}_{\mathrm{odd}}) = Q_{\mathrm{S}}^{-[\Delta]+1,Y}\mathcal{E}_{\mathrm{S}}). \tag{45}$$

Thus finally we have, for all $\Delta > 0$,

$$\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{E}_{\mathrm{A}}^{(3)}) = (1/2)(1 - (\Delta - [\Delta]))\big(Q_{\mathrm{S}}^{+[\Delta],Y}(\mathcal{E}_{\mathrm{S}}) + Q_{\mathrm{S}}^{-[\Delta],Y}(\mathcal{E}_{\mathrm{S}})\big)$$
$$+ (1/2)(\Delta - [\Delta])\big(Q_{\mathrm{S}}^{+[\Delta]+1,Y}(\mathcal{E}_{\mathrm{S}}) + Q_{\mathrm{S}}^{-[\Delta]+1,Y}(\mathcal{E}_{\mathrm{S}})\big) \tag{46}$$

or, analogously to Eq. (32) (and, as expected),

$$\mathcal{P}_{\mathrm{A}}^{Y}(\mathcal{E}_{\mathrm{A}}^{(3)}) = (1/2)\big((1 - (\Delta - [\Delta]))Q_{\mathrm{S}}^{+[\Delta],Y}(\mathcal{E}_{\mathrm{S}}) + (\Delta - [\Delta])Q_{\mathrm{S}}^{+[\Delta]+1,Y}(\mathcal{E}_{\mathrm{S}})\big)$$
$$+ (1/2)\big((1 - (\Delta - [\Delta]))Q_{\mathrm{S}}^{-[\Delta],Y}(\mathcal{E}_{\mathrm{S}}) + (\Delta - [\Delta])Q_{\mathrm{S}}^{-[\Delta]+1,Y}(\mathcal{E}_{\mathrm{S}})\big) \tag{47}$$

The expression in Eq. (46) or (47) then gives the probability of microcontroller upset in the present case.

A.4 *Conclusion*

We have presented simple models which provide expressions for the probability of upset of a microcontroller executing a sequence of software instructions (program). These models are based upon the interaction of the microcontroller clock signal pulse train with an RF pulse injected into the clock signal line. There are several approximations and assumptions made in the models, as delineated in detail in Section II. The most fundamental of these is that the probability of occurrence of an upset in a microcontroller signal pulse train—and occurrence of a subsequent upset in the microcontroller itself—by injection into the signal line of an RF pulse depends upon only the number of rise plus fall transitions of the signal pulse train encompassed by the RF

pulse. In addition, since some of the intermediate probability distributions required to specify the overall microcontroller upset probability are at present—as far as we are aware—unknown, what we have provided in this paper is, in some sense, a partial model supplemented by a modeling framework which may be used to discover and incorporate these currently missing pieces when available.

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