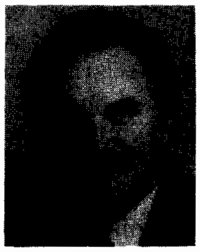
# Simulation model for evaluating interference threat to radiocommunication systems*



by R. G. STRUZAK

*ABSTRACT*

*This article describes an interactive microcomputer simulation model which is intended to serve as an engineering tool for the analysis of man-made interference threat to a radiocommunication system. Simulation technique is used to imitate experiments with the system, environment and their interaction. Various modifications can be simulated and their effects on the system performance analysed. Input data are supplied by the user, and the computer produces pictures, maps and statistics, describing the interference threat. The model allows for experiments with directive antennas, multiple man-made interference sources randomly located in three-dimensional space and with various propagation mechanisms. The areas occupied by the interference sources and victim receivers can be separate or coincide, totally or partially. Assumptions, limitations, algorithms, performance criteria and application examples are presented.*

## 1. Introduction

THIS article describes an interactive microcomputer simulation model developed to analyse electromagnetic compatibility (EMC) problems. EMC is the ability of a system to function satisfactorily in its electromagnetic environment without introducing intolerable disturbance to that environment. In this article, we discuss the interference threat to radiocommunication systems due to man-made interference environment. Limiting of man-made interference is vital to many applications and services, and has been included in the programmes of several national, regional and world-wide organizations. These organizations include, among others, the International Telecommunication Union [ITU, 1989], the International Electrotechnical Commission (IEC), the International Radio Consultative Committee [CCIR, 1986], the International Special Committee on Radio Interference [CISPR, 1987] and the European Economic Community [EEC, 1989]. Interference-free operation of communication systems is becoming more and more difficult to ensure, due to

* The opinions expressed in this article are the author's personal views, and do not necessarily reflect those of the CCIR or the ITU. The model described above is still evolving, as the experience drawn from its use increases. The current version works with personal computers type *IBM PC AT* or compatible. Copies of the simulation software are available through the ITU Telecom Information Exchange Service (TIES) under the directory "RS3".

the growing number of users of the radio-frequency spectrum and growing competition between them [Rotkiewicz, 1982]. The problem of undesired RF radiation from industrial, scientific and medical (ISM) equipment is an example [Struzak, 1985]. In spite of the intentions of 160 or so Member countries of the ITU [ITU, WARC-79], and in spite of many years of efforts [CISPR, 1987], widely acceptable recommendations on ISM radiation limits have not been reached [CCIR, 1986].

Recommendations relating to EMC are usually a compromise between two parties representing opposite interests. Evaluating the interference threat is one of the key problems in finding a compromise. When one party claims to overestimate, and another one to underestimate the interference threat, the only reasonable way is to refer to experimental evidence. As the experimental data available is incomplete, special measuring campaigns would be needed for that purpose. Such campaigns would be too expensive and would require too much time. In seeking a more practical solution, a simulation approach was proposed [Struzak, 1984]. Numerical simulation has become a powerful tool in various applications supplementing traditional mathematical analyses and "real-world" experiments (see, for example [Shannon, 1975]). A simulated experiment is less expensive and avoids all risks of the "real world". It is easier to prepare, to perform, to control and to repeat. It can modify the time scale, if the "real" experiment runs too quickly or too slowly. Processes which normally require months or years to develop can be accelerated to run in minutes. Another important characteristic of numerical simulation is its ability to examine systems which are intractable to experimental manipulation and too complex for exact mathematical treatment. Examining new systems which exist only in conceptual forms, testing hypotheses, or examining postulated modifications to existing systems, are examples of such applications. The first simulations were limited to large computers. Now, microcomputers have as much computing capability as mainframes of only a few years ago, and the technique is becoming more popular. In spite of this trend, the literature on simulation of EMC problems is scarce. The bibliography by Dudewicz [Dudewicz and Karian, 1985] contains about 500 papers on simulation and lists more than 80 application areas, but disregards the EMC issues. Simulation of certain EMC problems is addressed by Lee [Lee and Smith, 1983], Koester [Koester *et al.*, 1986] and Cook [Cook, 1987]. All of them use large computers. Microcomputer models are proposed by Struzak [Struzak, 1984] and Weinberg [Weinberg and Wilson, 1986] to study ISM interference. These models, however, are limited to two-dimensional space, omnidirectional antennas and simplistic propagation mechanisms. The objective of this work was to examine the feasibility of microcomputer simulation of EMC problems involving three-dimensional space, directive antennas, more elaborate propagation mechanisms and random influences.

The rest of the article is organized as follows. The input data and general algorithm are presented in section 2. Major assumptions, limitations and device models are discussed in section 3. Section 4 deals with the output of the simulation. Computational aspects are treated in section 5, and application examples in section 6. Comments on future work are given in section 7, and concluding remarks in section 8.

## 2. General algorithm

The aim of the simulation is to imitate modifications to various parameters of the radiocommunication system, its environment, or both, and to predict the effects of these modifications on system performance. The simulation process involves input data, simulation software, simulation hardware and output data. The input data is transformed into the output data in accordance with the algorithms included in the software. The general algorithm of simulation consists of three major steps illustrated by figure 1. The first step is to determine that which is to be simulated. The input data is applied to define the fixed parameters of the model and the boundaries for its pseudo-random variables, and to determine the EMC criteria and simulation scope. The input data is listed in figure 2 [CISPR, 1987]. They are read from default files or supplied by the user, and have to be selected from populations that might occur in an actual situation. The second step is the simulation of system-environment interaction, and evaluating the performance of individual transmitter-receiver links of the system. Figure 3 illustrates the algorithm applied. Here, concepts of simulation scenes and test points are used. A simulation scene represents a specific configuration of the transmitter, receivers and interference sources (figure 4 shows an example). The test points are the points at which the receivers might be installed. Simulation scenes are generated and the performance of transmitter-receiver links analysed. For that purpose, the relevant input data is applied to the computer programs which contain models of the devices and processes involved. The models are discussed in section 3. Each transmitter-receiver link is examined separately, and the expected values of the signal level and noise margin are computed. These raw simulation results are compared with the EMC criteria. The third and last simulation step is the determination of the system performance and evaluation of the interference threat. On the basis of the examination of the individual communication links, various global measures of the system performance are computed, as discussed in section 4. All phases of the simulation process are displayed on a control panel on the screen. The panel contains several windows, each of them representing a set of data (figure 5).

### Deterministic or probabilistic simulation

The model can be used for deterministic and probabilistic simulation. In the deterministic simulation, the values of all variables can be predicted with precision and in the probabilistic simulation, some of the variables are random and only the boundaries within which they are confined can be determined. Flipping a coin is a good example. Although laws of physics to predict its position (given the initial velocity, spin, etc.) are well known, it is practically impossible to determine in advance whether the coin lands on heads or tails. The probabilistic simulation (known also as the Monte Carlo simulation) amounts to a repetition of simulated trials and a collection of statistics representing global results. In the deterministic simulation, a simulation scene is generated and analysed once for all. There is no reason to repeat deterministic experiments because each of them gives, in principle, the same results. When random input components are present, however, the system performance is subject to statistical dispersion, and each trial may give a different result. In order to obtain results which are statistically significant, the simulation experiment has to be repeated. Simulation scenes are sequentially generated, each time with a new set of random components, and the system performance is determined and treated as a "sample" of statistical data. Section 5 gives more details on repeated trials.

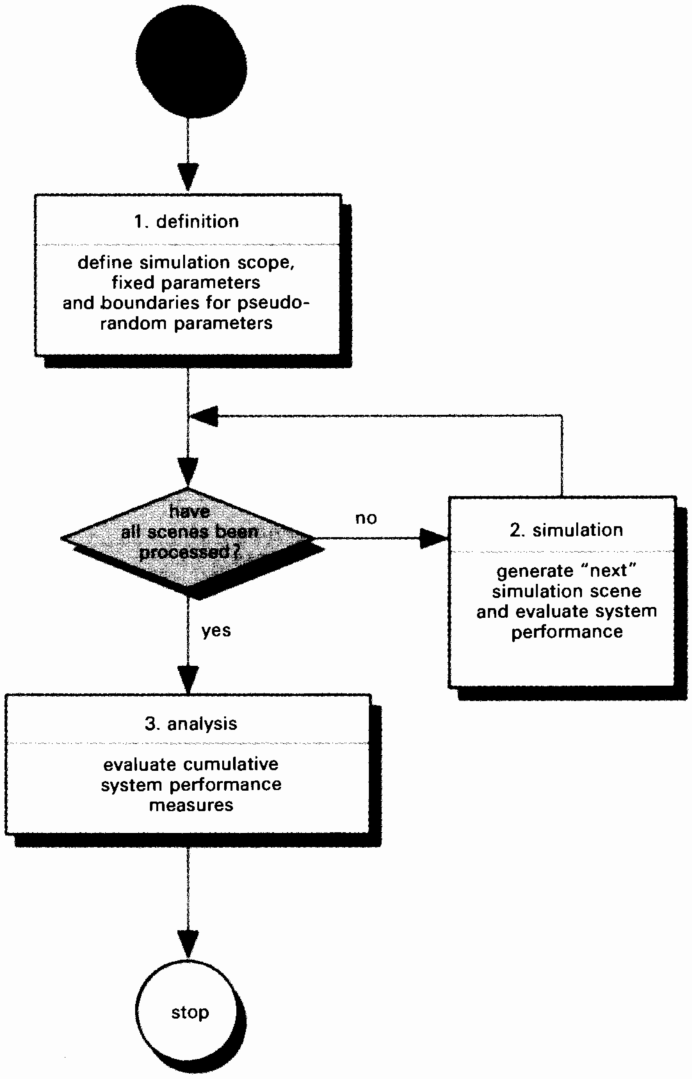



*Figure 1—General algorithm of simulation experiments (simplified)*

## 3. Assumptions, limitations, device models

In computer modelling, all assumptions, variables, and relationships must be described by numbers, with an accuracy commensurate with the accuracy required of the results. Even external influences, left out in real-world experiments, have to be defined precisely. The assumptions, on which our model is based, are discussed below, together with the model limitations.

### Radio communication system

Simulated in the computer, it consists of one transmitting and one or more receiving stations. If two or more wanted transmitters are involved, as for example in hyperbolic navigational systems, each of them has to be treated separately. If there is more than one receiving station, all are of the same type. A narrow-frequency band is taken into account. It means that a separate model has to be created to simulate each spurious or non-linear response of the receivers. The distribution of the wanted signal is defined by the transmitting antenna and propagation model. Reflected signals are disregarded.

### Antennas

The transmitting and receiving antennas can be isotropic or directional; adaptive antennas are not included. Receiving antennas are situated at test points and, if they are directional, they are pointed towards the transmitter. An antenna model represents the directive radiation pattern of the original antenna in consistency with the objectives of the simulation.

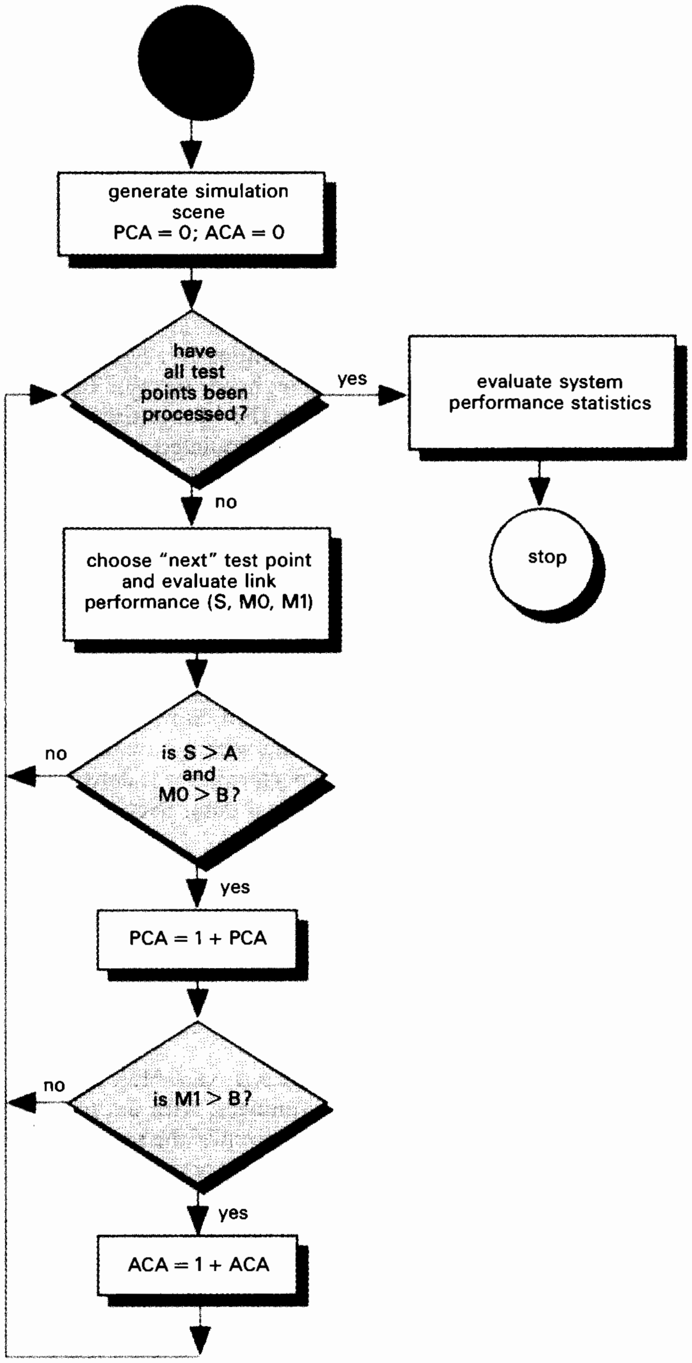
| input data |
| --- |
| parameters defining communication system<br><br>reference level of wanted signal<br>transmitting antenna pattern*<br>receiving antenna pattern*<br>receiver noise level* |
| parameters defining interference environment<br><br>number of RFI sources<br>deployment of RFI sources in 3D space*<br>RFI source radiation level*<br>RFI source screening/attenuation*<br>external background noise level* |
| parameters defining propagation process<br><br>propagation loss of wanted signal*<br>propagation loss of unwanted signals* |
| parameters defining EMC criteria<br><br>minimum acceptable level of wanted signal<br>minimum acceptable signal-noise margin |
| parameters defining test domain<br><br>position of test area in 3D space<br>dimensions of test area<br>number of test points |
| parameters marked by * involve pseudo-random components imitating natural variability, random spread and measuring uncertainty |

*Figure 2–Input parameters of the simulation model*

In our case, two models are provided: one for the transmitting antenna and another for the receiving antenna. The models are in the form:

antenna gain = (antenna gain in the azimuth plane + antenna gain in the elevation plane + random component) [dB] *(1)*

The gains are relative to the maximum gain. The gain in the azimuth plane and in the elevation plane are mutually independent. Examples are shown in figure 5.




A = minimum acceptable signal level
ACA = actual coverage area size
B = minimum acceptable noise margin
M0 = background-noise margin
M1 = resultant-noise margin
PCA = potential coverage area size
S = signal level

*Figure 3–System performance evaluation algorithm (simplified)*

**Interference environment**

This environment, simulated in the computer, consists of two components. The first is the background environmental noise and it is assumed to be independent of direction and distance. The second component is the noise from unwanted man-made radio-frequency interference (RFI) sources and it depends on the distance from, and direction to, the sources. Only radiation phenomena are taken into account. The sources are randomly distributed in space and have random radiation patterns. The area occupied by them is in the form of a three-dimensional rectangular box (figure 4). It can be separate or coinciding, totally or partially, with the area occupied by the communication system. The RFI sources are of the point-type; distributed sources (e.g. power lines) are not included in the model. Radiation limits are usually defined as the level of unwanted signal at a reference distance from the source, and the simulation model accepts this definition. Local attenuation of radiation by buildings, or by additional screening structures, is taken into account. The distribution of interfering signals is determined by the propagation model. The interference sources are co-frequency with the transmitter. Off-channel interference can be simulated by introducing equivalent co-channel interference source(s). Frequency-hopping and intermittent sources are excluded. A narrow frequency band is taken into account. It means that a separate model has to be created to simulate each harmonic or spurious radiation.

**Propagation**

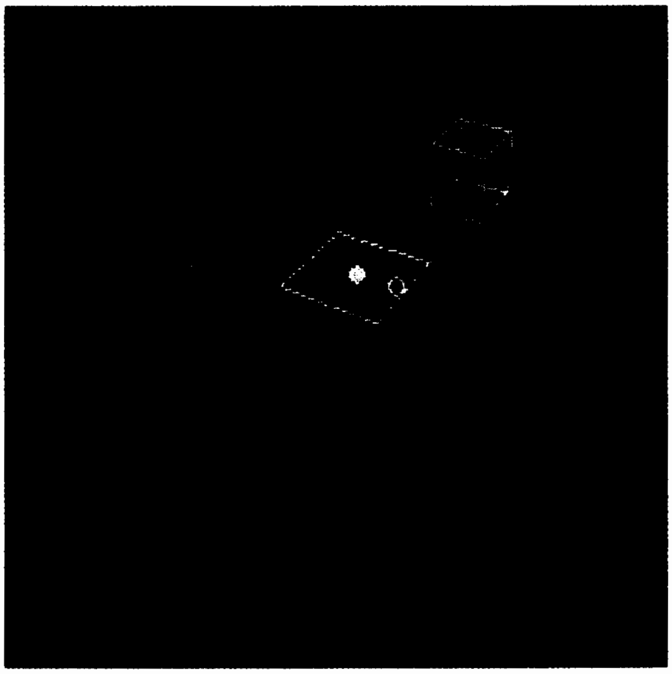
A propagation model determines the level of wanted (or unwanted) signal which is exceeded (or not exceeded, respectively) at the receiving antenna during a given proportion of time. For instance, the level of the wanted signal may be required to be not less than A dB during 99.9% of time, and the level of undesired signal—not greater than B dB during 0.1% of time. Zero-gain antennas are assumed at both the transmitting and receiving stations. The software offers a class of models simulating different propagation mechanisms, from which the user selects a model which is the most appropriate for his application (see, for example [CCIR, 1986]). Propagation loss is assumed to be dependent on distance, but independent of the bearing to the radiation source. It means that actual terrain shadowing, reflections, and multipath propagation are disregarded. Two separate propagation models are provided, one for the wanted signal and another for the interfering signals. The models are in the form:

$$\text{signal level} = (\text{reference signal level} + \text{propagation loss} + \text{random component})\ [\text{dB}] \qquad (2)$$

All variables are relative to a given reference level. An example is shown in figure 5.

**EMC criteria and link performance**

It is assumed that the degradation of communication links is attributable to two elements: the first is the internal (receiver) noise and the second is the external noise and unwanted signals. The signal level and the noise level serve as the measure of performance of each individual transmitter-receiver link. They are computed using formulas listed in figure 6. The computations involve models of antennas and propagation processes, and require determination of distances and direction angles between the receivers and radiation sources (figure 7). "Signal" is the wanted signal, and the *resultant noise* includes



red point = transmitter position
blue point = reference point
green lines = co-ordinate axes
yellow lines = test area borders
red lines = interference source area borders

*Figure 4—Simulation scene as shown on the computer display. Red point: transmitter position; blue point: reference point. The system performance is determined at a number of test points distributed over the test area. The size and position of the test area is defined by the user*

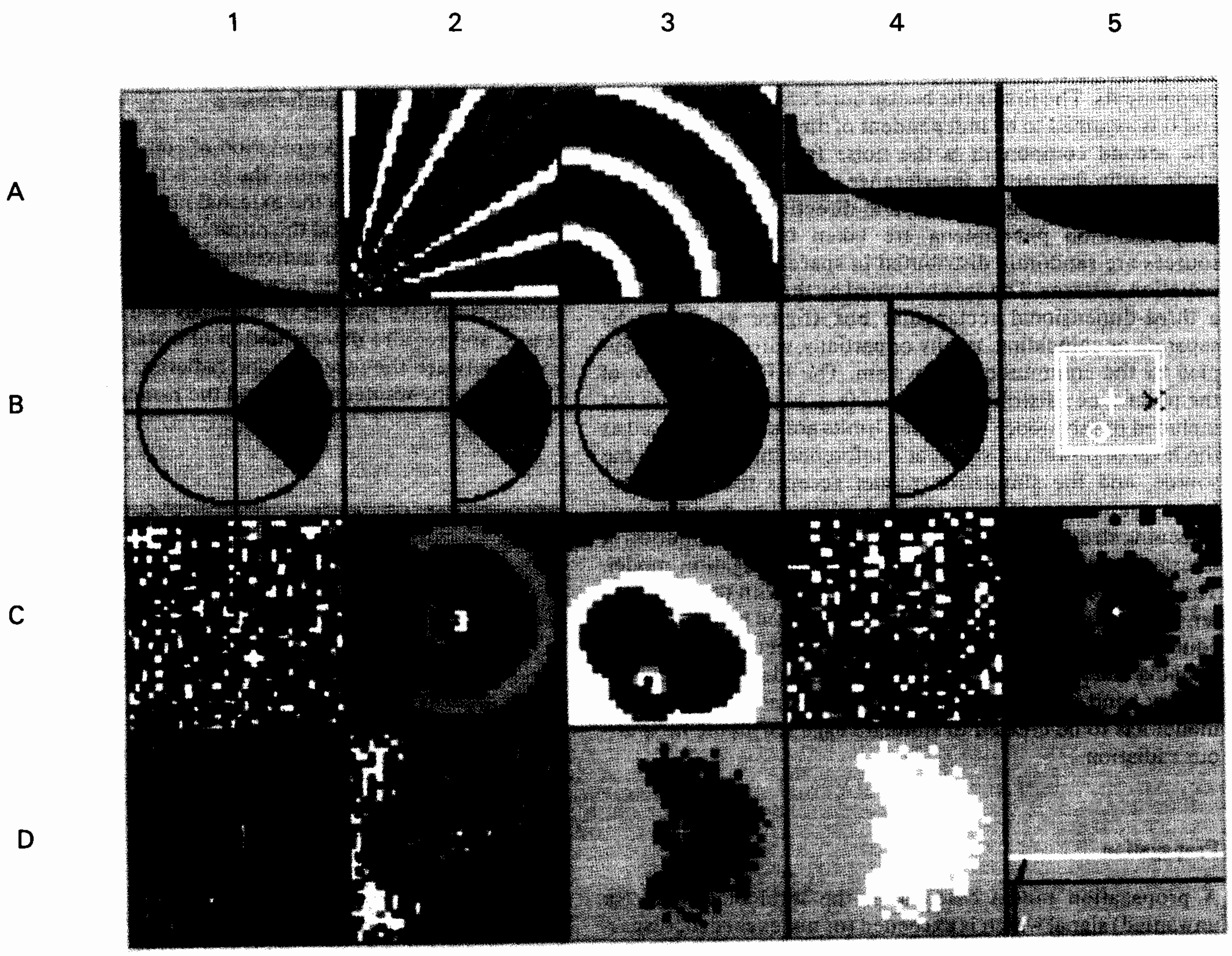



*Figure 5–Control panel displaying various phases of simulation experiment on the computer screen. The windows represent the following data (letters indicate the rows and numbers indicate columns):*

*A1: signal correction factor; A2: direction angles; A3: distances; A4: wanted signal propagation; A5: unwanted signals propagation*

*B1: receiving antenna pattern (azimuth); B2: receiving antenna pattern (elevation); B3: transmitting antenna pattern (azimuth); B4: transmitting antenna pattern (elevation); B5: test area and view of interfering source area*

*C1: noise map; C2: wanted signal map; C3: interfering signal map (current); C4: interfering signal map (cumulative); C5: noise margin map (background)*

*D1: noise margin map (resultant); D2: wanted-unwanted signal margin map; D3: coverage map (potential); D4: coverage map (actual); D5: coverage loss index (current, cumulative, maximum and minimum values)* the internal and external noise *(background noise)* and all *undesired signals.* The effect of multiple interference signals and noise is calculated by means of the power sum method. This seems to be a reasonable approach to continuous disturbances; discontinuous ones may require another approximation. The noise causes a degradation of the link performance and, in some cases, can lead to a disruption of the normal operation of the link. "Normal", in this context, refers to "satisfying given technical and operational requirements". The criterion of the "normal" operation built in the model requires that both the wanted signal level and the noise margin are greater than their respective minimum acceptable values. The *noise margin* is the difference between the levels of the wanted signal level and resultant noise. It is also called "protection margin", "signal/noise ratio", etc. (in some systems, the *noise temperature* concept is used; such systems can be simulated, if the temperature is "translated" into an equivalent noise margin). Numerical values of the minimum signal and minimum noise margin are set up by the user, depending on the application, signal processing method, error correction, etc. [CCIR, 1986].

**Noise and random components**

Random components, like the receiver noise and environmental noise, are modelled using a standard random number generator. It produces pseudo-random numbers, uniformly distributed.

**Test domain**

The performance of the radiocommunication system depends on the performance of its transmitter-receiver links. With mobile systems, as for instance in aeronautical communications, all expected locations of transmitting and receiving stations must be taken into account. In the simulation model, these locations coincide with the test points. Such an approach may require a great number of computations. A quick order of magnitude analysis illustrates this point. The test domain should be large enough to embrace a significant part of the system and its behaviour in time. On the other hand, the resolution of the model has to be fine enough to capture the smallest scales that are relevant. The number of test points, with a regular time-space grid, yields

$$N_{4D} = \left(\frac{D_{máx}}{D_{mín}}\right)^4 \qquad (3)$$

where $N_{4D}$ is the number of nodes of the grid. $D_{max}$ and $D_{min}$ denote the length scales associated with the largest and smallest distances in space or in time, respectively. If $D_{max}$ is 100 times greater than $D_{min}$, then there are $10^8$ test points. At each of them, all relevant signals have to be evaluated. With $10^2$ RFI sources, there are $10^8 \times 10^2 = 10^{10}$ signals to evaluate. Even with 0.1 ms per signal, this would require $10^6$ s, or about 300 h, of computing time. To keep the simulation time within practical limits, we exclude the time variable and restrict the test domain to a plane. The plane can, however, be fixed at different positions, which is equivalent to a series of cuts through the volume of interest. Thus, a possibility exists to explore the system performance in three dimensions (figure 4). The number of test points, $N_{2D}$, amounts now to:

$$N_{2D} = \left(\frac{D_{máx}}{D_{mín}}\right)^2 \qquad (4)$$

**output data:**
**link performance measures**

data on signal received

$$S = 10^{\left(\frac{S_o \times PA \times TA \times RA}{20}\right)}$$

data on noise margin

$$M0 = 20 \log \left[\frac{S}{\sqrt{NR^2 + NB^2}}\right]$$

$$M1 = 20 \log \left[\frac{S}{\sqrt{NR^2 + NB^2 + \sum_{i=1}^{NIS} I_i^2}}\right]$$

$$I_i = 10^{\left(\frac{I_{io} \times LA \times PA \times RA}{20}\right)}$$

i = 1, 2, 3, ..., NIS
$I_i$ = unwanted signal from i-th RFI source [V]
$I_{io}$ = signal $I_i$ at the reference distance [V]
LA = local screening/attenuation factor
M0 = background-noise margin [dB]
M1 = resultant-noise margin [dB]
NB = background-noise [V]
NR = receiver noise [V]
NIS = number of RFI sources
PA = propagation attenuation factor
RA = receiver antenna discrimination factor
S = wanted signal [V]
$S_o$ = signal S at the reference point [V]
TA = transmitter antenna discrimination factor

*Figure 6–Output simulation data (raw): definition of performance measures of individual radiocommunication link*

The data of the previous example would give $10^4$ test points and 100 s of computing time. With the time variable not involved explicitly, the simulation model is valid for a short instant of time. During that time, neither the system, nor the environment, nor their interaction, can change significantly. The test points are now distributed over a test plane, which may be inadequate for those systems for which the curvature of the Earth is relevant (e.g. satellite systems).

## 4. System performance measures

During the simulation process, the system performance is examined at each test point. With a large number of test points, this produces huge collections of numerical data. The analysis of such collections surpasses the possibility of human perception and, as an aid, we use maps. Colour maps of the test area provide a visual display of the variable values and status of communication links at all test points. There are several kinds of maps produced: signal maps, noise maps, noise-margin maps, and coverage maps, which give information about the operation conditions of communication links. Examples are shown in figure 5 (see also figures 11 to 13). Such a pictorial representation of abstract concepts helps to identify interference structures which may be too complex to conceptualize otherwise. Moreover, some statistical indices are provided which characterize the overall situation by a few numbers only (figure 8). Basic statistics and interference statistics are provided to quantify the degree of interference threat; we will discuss them below. In addition to the maps and statistics, histograms of distributions of variables are provided (figure 9).

### Coverage area and coverage loss

At any given time, each communication link may be in one of two possible states: "normal operation" or "unacceptable operation". The *coverage area* is defined as the set of test points under "normal operation". In reality, we refer to the *actual* coverage area which is defined with the actual interference environment. However, we also introduce here the concept of the *ideal*, or *potential* coverage area which is determined with an *ideal environment*. The ideal environment consist of the background noise only: all RFI sources are inactive or removed. Note that it is unrealistic to expect that all existing RFI sources can be really switched-off or removed, but the concept is useful for reference purposes. The actual coverage area is usually less than the potential coverage area, and the difference, or *coverage loss*, indicates the degree of interference threat. In order to quantify this threat, the potential and actual coverage areas are compared one with another

| **distance and direction from point $P_2$ to point $P_1$** |
|---|
| $$\text{distance} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$ |
| $$\text{azimuth angle} = \arctan\left[\frac{y_1 - y_2}{x_1 - x_2}\right]$$ |
| $$\text{elevation angle} = \arctan\left[\frac{z_1 - z_2}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}\right]$$ |
| $x_1, y_1, z_1, x_2, y_2, z_2$ are co-ordinates of the points |

*Figure 7–Distance and direction (vector) from point* $P_2$ *to point* $P_1$

point-by-point, and each test point is marked "0" or "1". The "0" means "no harmful interference", the "1" means "unacceptable interference". The characteristics "1" and "0" are qualitative in nature and follow the binomial distribution. The requirement of exact representation of the coverage areas calls for a large sample, i.e. a large number of test points. With too small a sample, the results are statistically insignificant. With too large a sample, the simulation time is too long. Some aspects of the sample size are discussed in section 5.

### Coverage loss index

It represents the expected likelihood that a receiver, operating normally without RFI sources, will suffer unacceptable interference after the RFI sources are activated. Its definition is given in figure 8. It involves the relative difference between the actual and potential coverage areas of the system [Anderson, 1976]. This index has a straightforward interpretation. In addition to the *loss in the geographical coverage area*, it represents the relative *loss in the population served*, if the population is distributed uniformly over the area of interest. In economic terms, it may be interpreted as the *loss of capital* due to radio interference. A simple reasoning leads to that conclusion. The total cost of the radiocommunication system is distributed among these radio links which work normally in the absence of RFI sources. When the RFI sources are active, the coverage loss index gives the proportion of the links which cannot continue to work normally. It is exactly the proportion of the total cost which cannot be used as intended. In the literature, rather than the coverage loss index, the interference complaint index and the probability of interference have been applied. They are discussed below.

**Interference complaint index**

The CISPR uses a concept which we will call "interference complaint index" [CISPR, 1975]. It is the likelihood of unacceptable interference suffered by a receiver. It is defined as the number of interference complaints divided by the total number of receiver licences (figure 8). Under some conditions, it can be derived from the coverage loss index. If the number of receiver locations is the same as the number of licences, NRP = NRL, and if the number of receivers suffering interference coincides with the number of complaints, NRI = NIC, then both indices are equal (the equality is valid as well if these numbers remain in the same proportion). The coverage loss index involves uniform criteria and characteristics of the system, whereas the interference complaint index relates to a population of different receivers and subjective, case-by-case, EMC criteria. As a result, the two indices can only be approximatively equal.

**Probability of interference**

The probability of interference is used by Weinberg [Weinberg and Wilson, 1986]. He takes into account all receivers, all RFI sources, and all possible interactions between them. Under certain conditions, this probability can be derived from the coverage loss index. As is seen from figure 8, the probability of interference involves the number of receivers *and* the number of RFI sources, whereas the coverage loss index involves *only* receivers. Thus, if the same interference criteria are applied, the coverage loss index is NIS times greater than the probability of interference, where NIS is the number of interference sources.

## 5. Computational aspects

**Test sample**

The sample size, i.e. the number of test points, determines the uncertainty with which statistical performance measures of the system are estimated. Let the "population mean" of a variable relate to an unlimited set of all possible test points, and let the "sample mean" relate to a limited set of test points involved in the experiment (sample). Because of a limited

| output data: system performance measures | |
|---|---|
| **basic statistics** | **interference statistics** |
| $\text{mean} = \frac{\sum_{i=1}^{n}(x_i)}{n}$ | $\text{coverage loss index} = \frac{NRI}{NRP}$ |
| $\text{variance} = \frac{\sum_{i=1}^{n}(\text{mean} - x_i)^2}{n}$ | $\text{interference complaint index} = \frac{NIC}{NRL}$ |
| $\text{standard deviation} = \sqrt{\text{variance}}$ | $\text{probability of interference} = \frac{NRI}{NRP \times NIS}$ |
| i = 1, 2, 3, ..., n<br>n = sample size<br>$x_i$ = signal level, noise level, or noise margin at i-th test point | NIC = number of interference complaints<br>NRI = number of receiver locations excluded from the potential coverage area due to RFI<br>NRL = number of receiving stations licences<br>NRP = size of the potential coverage area<br>NIS = total number of RFI sources |

*Figure 8—Output simulation data: definition of system performance statistics*

sample, the population mean and the sample mean of the same variable may differ. The probability that they differ by no more than a quantity ERR (error) is subject to the following Tchebysheff's inequality [Burington and May, 1953]:

$$P\{(\text{mean} - \text{mean*}) < \text{ERR}\} > 1 - \frac{\left(\frac{\text{variance}}{\text{ERR}}\right)^2}{n} \qquad (5)$$

$P\{x\}$ is the probability of event $x$, mean is the population mean, mean* is the sample mean, variance is the population variance, and $n$ is the sample size. By selecting a sufficiently large sample ($n$), the probability that the sample mean will fall within a small interval about the population mean can be made as near to unity as desired. If, for example, the maximum acceptable error equals 10% of the variance with a probability of 0.95 or greater, then the sample size should not be less than 2000 test points.

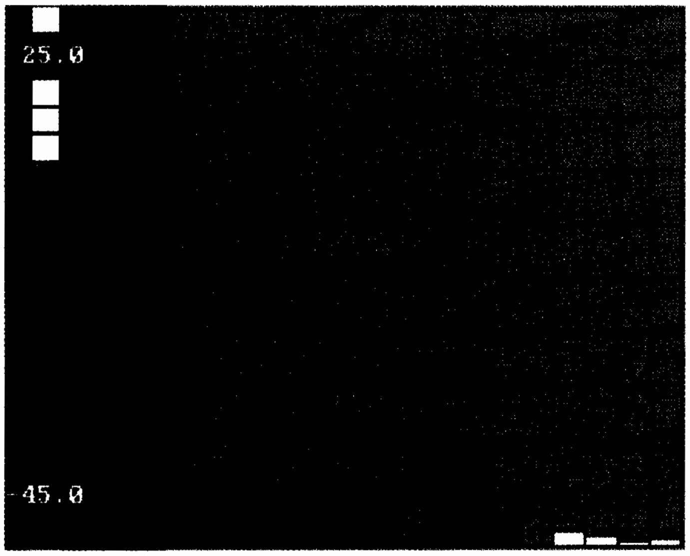



*Figure 9—Histogram of noise margin over the test area as shown on the computer display. The colour scale on the left indicates the 5-dB value intervals, between -45 and 25 dB. The vertical bars indicate the percentage of test points at which the noise margin falls into the specific interval. The cumulative curve represents the percentage of test points having a noise margin less or equal to a specific value*

**Coverage area**

The coverage area size imposes a limit on the coverage loss index. Let the total number of test points diminish, other conditions being constant. Then, the number of test points without interference, and the number of test points suffering interference, will change. As long as there are many test points, their ratio remains constant. With too small coverage area size, the model resolution imposes a limit. A simple example illustrates this point. Let the potential coverage area consist of 100 test points, and let one of these points suffer unacceptable interference. The coverage loss index is 1/100. If the number of test points is diminished by one, then there are two cases possible: either the test point suffering interference is a member of the new potential coverage area, or it is not. In the first case, the coverage loss index is 1/99 and in the second it equals zero. The limit imposed on the coverage loss index is:

$$\text{coverage loss index} \geq \frac{1}{n} \qquad (6)$$

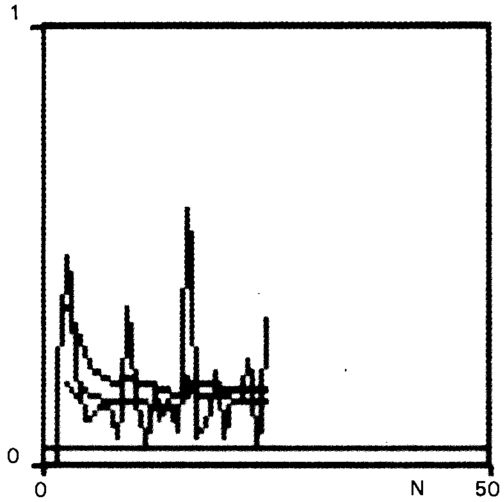
For example, if a low coverage loss index is of interest, say $10^{-3}$, then the potential coverage area should contain 1000 test points or more.

**Repeating tests**

In the Monte Carlo simulations, the required number of runs can be determined at the beginning of the simulation experiment. However, the simulation model also accepts another approach: instead of taking a decision before the simulation experiment begins, a sequential analysis of cumulated data indicates when sufficient number of observations have been made. For that purpose, the cumulative mean and standard deviation of the coverage loss index is calculated after each run. After a sufficient number of runs, the mean differs from its asymptotic or "true" value by no more than a given quantity (formula *(5)*). This shows that further repetitions are superfluous. The cumulative mean is the final result of the repeated simulation experiment. The variance shows how the individual scenes are spread out from the mean. Figure 10 shows an example.

**Acceleration of computation**

To keep simulation time short, two provisions are made: firstly, simulation variables are represented as integers, as much as possible and secondly, the number of repeated computations is kept to a minimum. The antenna and propagation models are stored in the computer memory and to use them, vectors joining the test points and radiation sources have to be determined (figure 7). With 100 sources and 1000 test points,




red horizontal line = maximum value observed (about 60%)
blue horizontal line = mimimum value observed (about 3%)
green line = values observed for individual simulation scenes
black line = cumulative mean value
light-blue line = cumulative standard deviation

*Figure 10–Coverage loss index versus the number of repetitions in a repeated experiment as shown on the computer display. Problistic simulation, a single interference source, 1600 test points, 25 repetitions*

there are $10^5$ vectors. Instead of computing each vector from original formulas, we use precomputed tables. In order to determine the resultant level of the unwanted signal at the test points, we process the signals in pairs. The greater signal of the pair is selected and the difference between the signal levels is calculated. If the difference is greater than 30 dB, then the lower signal is disregarded, otherwise a correction factor is applied to the greater signal. The correction factor is computed only once.

## 6. Applications

The simulation model is "user friendly". It is "menu driven" and does not require any knowledge of programming languages. Its input data can easily be adapted to the user's needs and it is not restricted to any specific EMC problem, communication system, or radio interference source, except for limitations indicated in section 3. A typical application example is shown in figure 11. This figure presents results of experiments which imitate actual measurements of signal level at the output of the receiving antennas. It takes only a few minutes to collect the results from thousands of test points distributed over a large area and to analyse them statistically. Based on such data, one can evaluate the interference threat without the necessity of a costly "real-world" measuring campaign (such a campaign, however, may be required to validate the model, or to verify the conclusions). An important feature of the simulation model is its flexibility in creating a variety of interference scenarios. This facilitates sensitivity analyses and helps to examine the effects of variation of the technical design decisions. It also allows for the generation of "if-then" data for such decisions. The results, even complex ones, are presented in graphical form, easy to understand. This makes the model a useful tool for didactic application and also for examining relative effectiveness of the various measures undertaken to reach EMC. The simulation model does not contain any optimization algorithm to generate explicitly a "best" solution with respect to predetermined criteria. Instead, such a solution can be approached experimentally, utilizing a step-by-

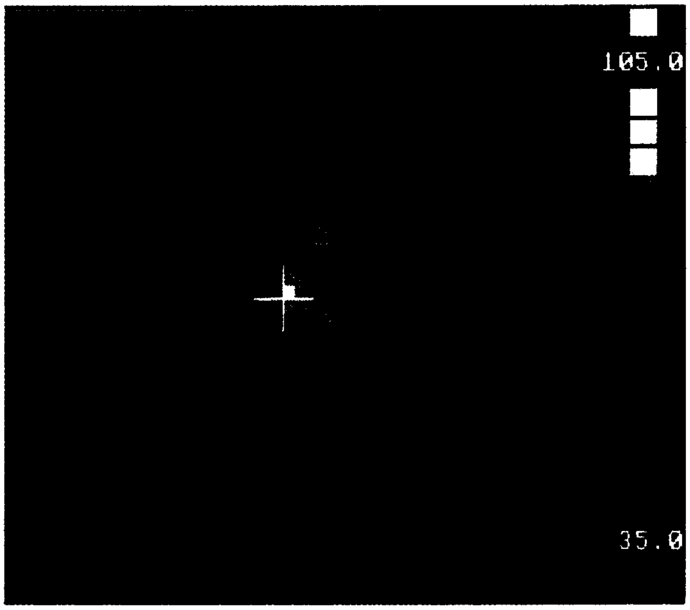



*Figure 11–Map of the wanted signal level over the test area as shown on the computer display. The colour scale at the right side indicates the signal level in 5-dB steps. Areas where the signal level is below 35 dB are in black; areas with the level above 105 dB are in white. The transmitter position coincides with the white cross. Probabilistic simulation, a single interference source, 1600 test points, simulation time about 1 min*

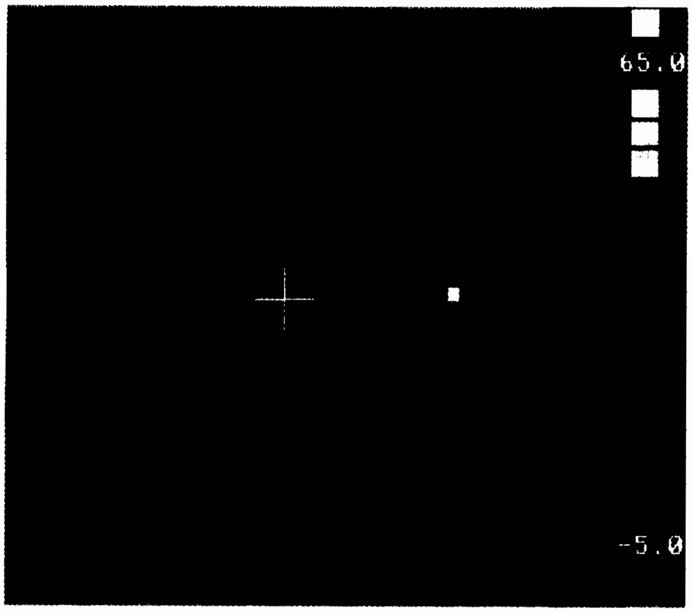
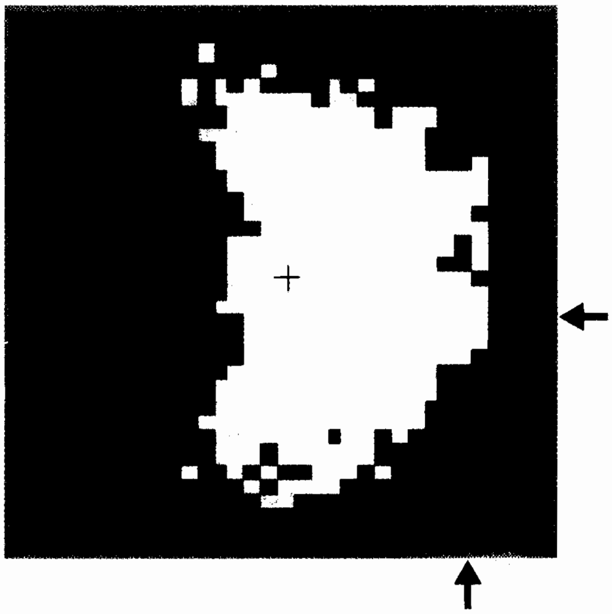



*Figure 12—Map of the interfering signal level over the test area as shown on the computer screen. The colour scale at the right side indicates the signal level in 5-dB steps. Areas where the signal level is below −5 dB are in black; areas with the level above 65 dB are in white. The transmitter position is marked by "+"; the interference source position coincides with the white square. Note the interference-free region in the form of "8" between the transmitter and interference source. Probabilistic simulation, a single interference source, 1600 test points*

step simulation and evaluation process. Iterative application of simulation and evaluation leads to a learning process regarding the impact of alternative solutions. When a compromise solution is sought to satisfy conflicting interests, the alternatives may be proposed by the various interest groups involved. This may be helpful in overcoming those difficulties in deriving the EMC recommendations which result from the lack of experimental data. Another characteristic of the model is that it introduces a number of variables permitting the examination of complex interference situations in more detail than previously possible. It is to be remembered, however, that the model cannot correct errors in the input data as some errors may even cumulate. In practical applications, simulation results have to be critically reviewed, with allowance for an uncertainty margin.

## 7. Future work

Future work is planned to remove certain limitations of the model and to answer some new questions related to its applications. Two examples illustrate this point: in figure 12 an interference-free area is visible in the form of the figure "8". What conditions must be met to generate such interference-free areas? How to maximize them? Figure 13 shows interference regions on a coverage map. With a single source, a single interference region might be expected; the map, however, shows a few such regions, some of them far away from the source. In which circumstances do such "far" RFI regions appear? How to minimize them? A general answer is that these are the effects of the spatial distribution of the equipment, propagation processes, antenna radiation patterns, etc. A detailed analysis is beyond the scope of this article; however, such an analysis might offer new elements in discussions of EMC issues.



yellow = actual coverage area
red = area lost due to unacceptable interference
red + yellow = potential coverage area

*Figure 13—Map of the coverage area as shown on the computer screen. The interference source position is indicated by the arrows. Probabilistic simulation, a single interference source, 1136 test points. The coverage loss index is about 20%*

## 8. Concluding remarks

A new microcomputer model, imitating interactions between radiocommunication systems and the environment, has been described. The histograms, maps, and statistical indices produced by the model may help to evaluate interference effects on the system performance. The coverage loss index has been introduced to quantify the interference threat. The model is a new simulation tool, creating new opportunities. The essential characteristic of simulation is the use of models for experimentation. Having a simulation model of a real system or process, it is quite easy to alter the various parameters of the model and observe how it operates with these changes. If the model and input data are correct, conclusions drawn from these observations are applicable to the original system or process. This characteristic makes simulation techniques promising as regards engineering and management applications. Both, good engineering and effective management, require an understanding of the system of concern and a means of studying the impact of the various alternatives possible. The simulation model fulfills these requirements.

## Acknoledgements

The first prototype of the simulation model described in this article was created when the author was with the Institute of Telecommunications, Wroclaw [Struzak, 1984]. At that time, he also served as the Chairman of CCIR Interim Working Party 1/4 on ISM radiation limits, and various versions of the simulation software were submitted for tests by the Members of the Working Party. Their co-operation is gratefully acknowledged, as is the encouragement of CCIR Director Mr R. C. Kirby. Comments of Messrs T. Dvorak, R. Showers and K. A. Hughes are greatly appreciated.

*(Original language: English)*

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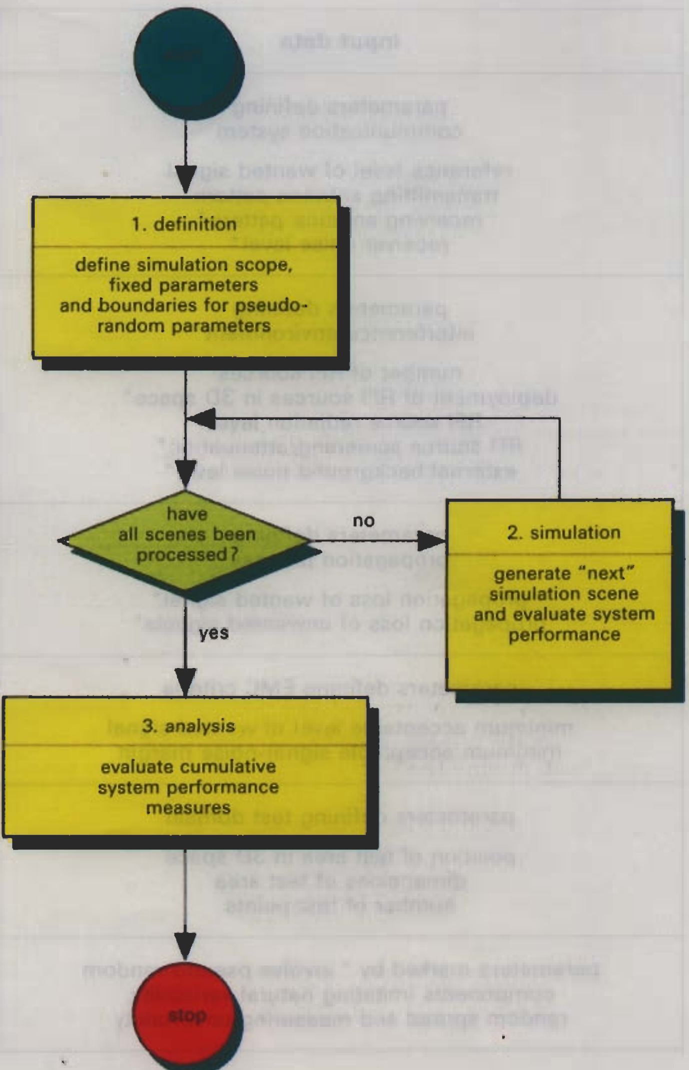
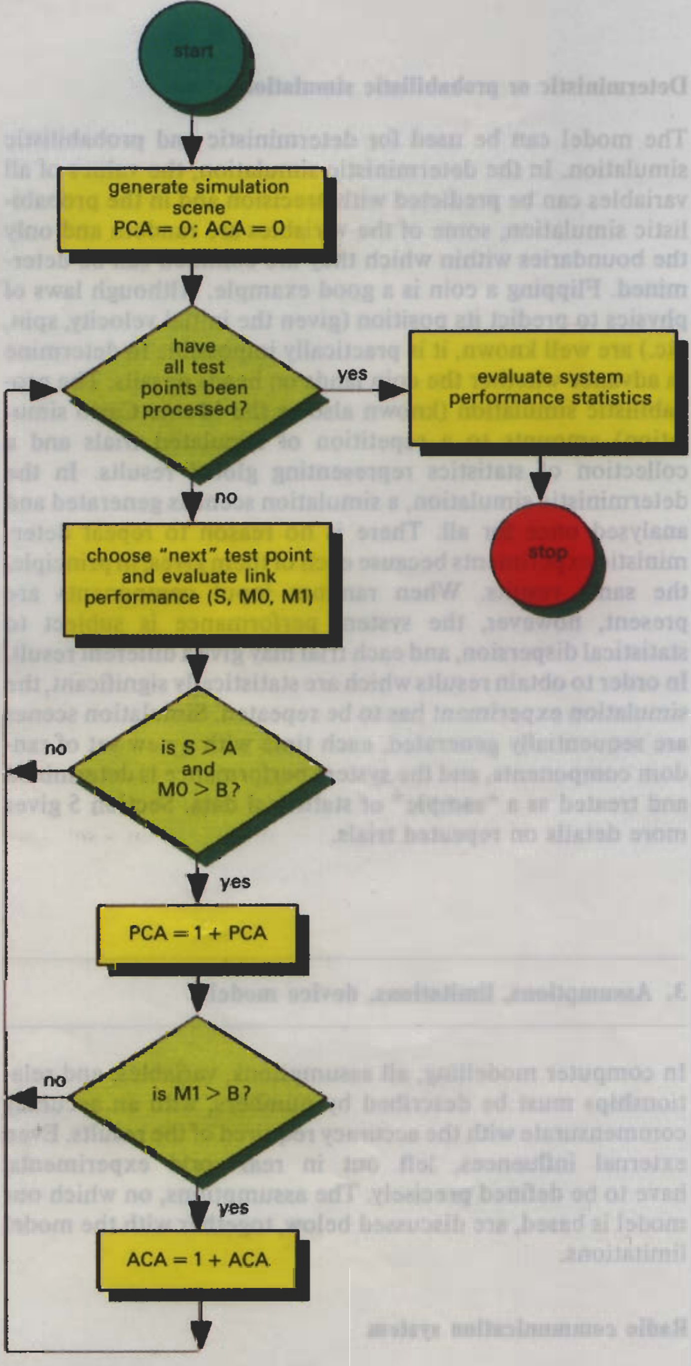
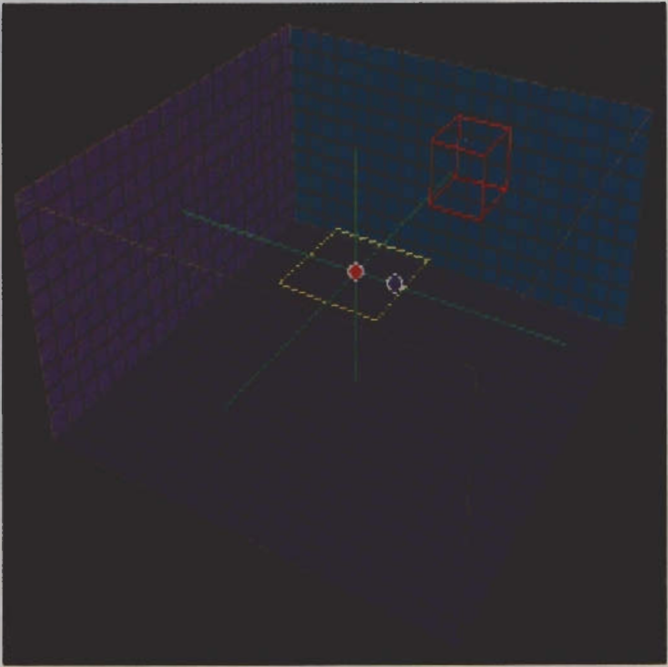



*Figure 1—General algorithm of simulation experiments (simplified)*



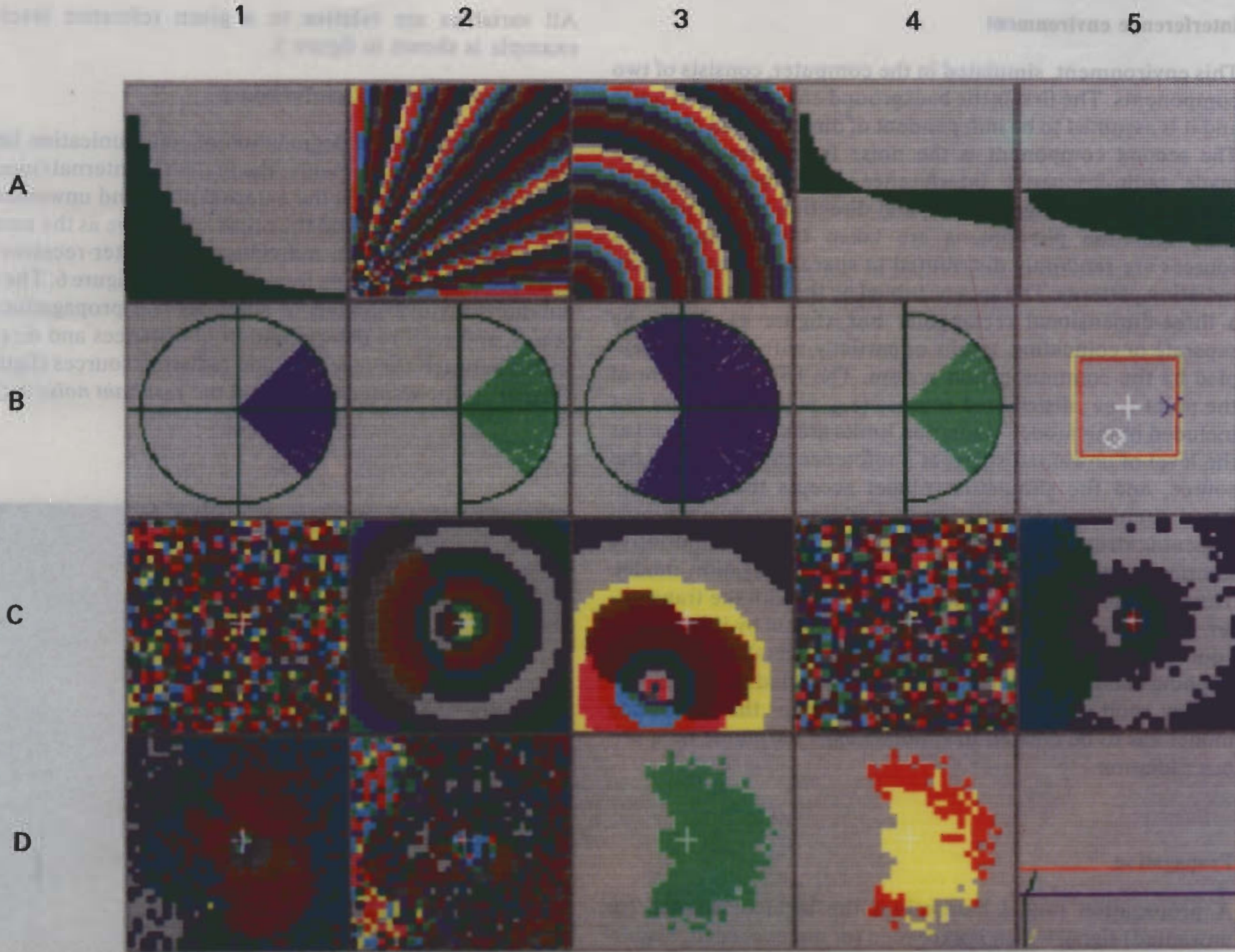

A = minimum acceptable signal level
ACA = actual coverage area size
B = minimum acceptable noise margin
M0 = background-noise margin
M1 = resultant-noise margin
PCA = potential coverage area size
S = signal level

***Figure 3 – System performance evaluation algorithm (simplified)***



red point = transmitter position
blue point = reference point
green lines = co-ordinate axes
yellow lines = test area borders
red lines = interference source area borders

*Figure 4—Simulation scene as shown on the computer display. Red point : transmitter position ; blue point : reference point. The system performance is determined at a number of test points distributed over the test area. The size and position of the test area is defined by the user*


1
2
3
4
5
A
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C
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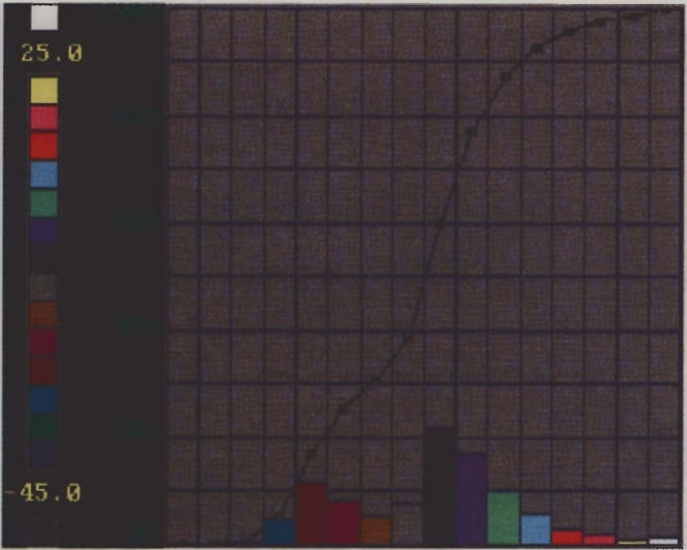
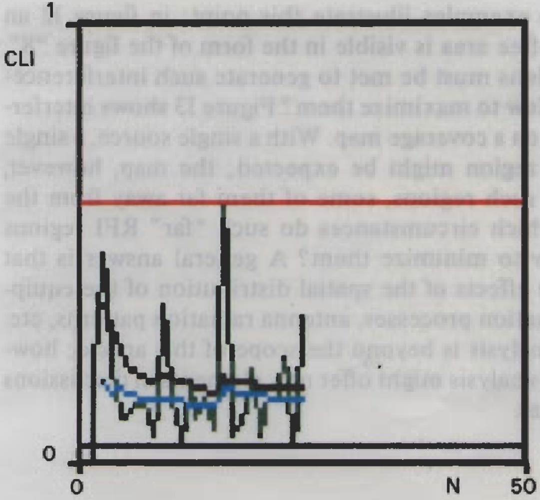



*Figure 9—Histogram of noise margin over the test area as shown on the computer display. The colour scale on the left indicates the 5-dB value intervals, between −45 and 25 dB. The vertical bars indicate the percentage of test points at which the noise margin falls into the specific interval. The cumulative curve represents the percentage of test points having a noise margin less or equal to a specific value*




red horizontal line = maximum value observed (about 60%)
blue horizontal line = mimimum value observed (about 3%)
green line = values observed for individual simulation scenes
black line = cumulative mean value
light-blue line = cumulative standard deviation

*Figure 10—Coverage loss index versus the number of repetitions in a repeated experiment as shown on the computer display. Probablistic simulation, a single interference source, 1600 test points, 25 repetitions*

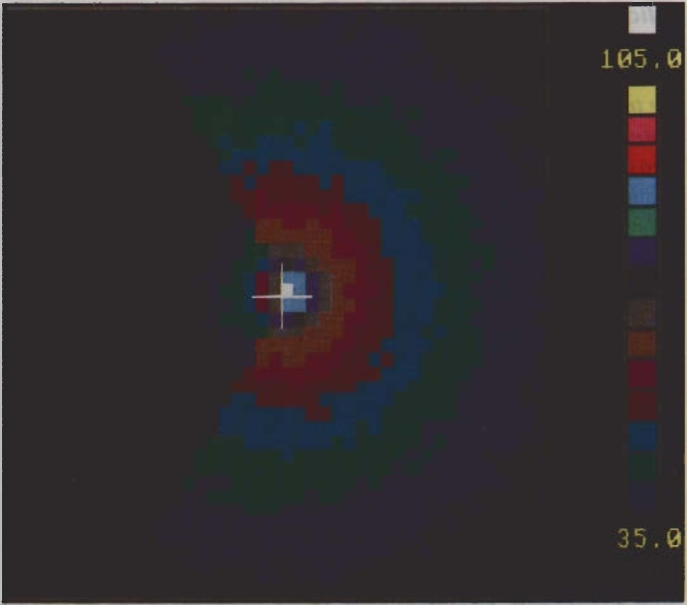
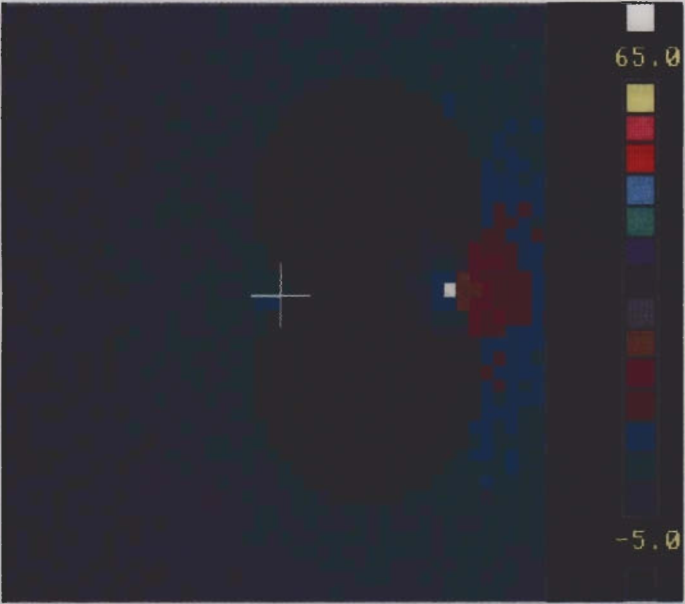



*Figure 11—Map of the wanted signal level over the test area as shown on the computer display. The colour scale at the right side indicates the signal level in 5-dB steps. Areas where the signal level is below 35 dB are in black; areas with the level above 105 dB are in white. The transmitter position coincides with the white cross. Probabilistic simulation, a single interference source, 1600 test points, simulation time about 1 min*

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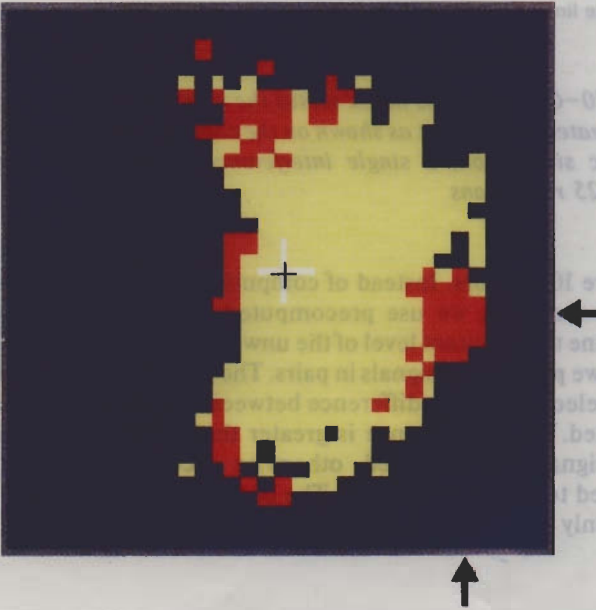

yellow = actual coverage area
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*Figure 13—Map of the coverage area as shown on the computer screen. The interference source position is indicated by the arrows. Probabilistic simulation, a single interference source, 1136 test points. The coverage loss index is about 20%*