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Characterization of the Cumulative Effects of Ultrawideband Device Emissions

Prepared for Industry Canada, Spectrum Engineering Branch, Spectrum Research Project E-05

Qingsheng Zeng **Arto Chubukjian**

Communications Research Centre
CRC Report No. CRC-RP-2003-004
Ottawa, Ontario, Canada, March 2003

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ABSTRACT

This research report presents work carried out at the Communications Research Centre (CRC) on ultrawideband (UWB) device emissions. The main thrust of the work is to evaluate the cumulative effects of these devices upon the electromagnetic environment, specifically their possible contributions to the raising of the electromagnetic environment ambient levels. The work was carried out through a Spectrum Research Project for the Spectrum Engineering Branch (DGSE) of Industry Canada, in support of their spectrum management goals, International Telecommunication Union (ITU) activities, and near-term plans.

The goal was to characterize this effect quantitatively, and, to develop an electromagnetic compatibility (EMC) assessment tool, for the determination of the possible interference potential of UWB devices, with respect to conventional radiocommunications systems. This goal was accomplished by the incorporation of the latest regulatory specifications, and by the application of appropriate scientific techniques.

EXECUTIVE SUMMARY

The advent of the ultrawideband (UWB) technology upon the commercial (non-military) world is one of the promising developments in the wireless communications field, yet it has raised concerns with respect to its effects upon the electromagnetic (EM) spectrum, and its potential for causing interference to services operating therein.

The research work was carried out during the 2002-03 fiscal year (FY), through a Spectrum Research Project, for the Spectrum Engineering Branch (DGSE) of Industry Canada, to address some of the concerns by characterizing their effects, and also in support of their spectrum management goals, International Telecommunication Union (ITU) activities, and near-term plans.

A key electromagnetic compatibility (EMC) consideration in the sharing of the spectrum, whenever a multitude of low-power devices is concerned, is their cumulative spectral power contributions to the EM environment. While one or a few devices may not cause interference, a large number operating within an area could raise the ambient level of the EM environment sufficiently to affect the operations of other radiocommunications systems that are located within the same environment.

Several studies have been conducted previously, in North America and elsewhere, on the cumulative effects issue of UWB devices, but these pre-dated the Federal Communications Commission's (FCC) First Report and Order [1]. For the first time, a set of regulatory limits has been imposed on the technology and its applications. This action established a common datum for all subsequent studies related to this technology, and removed the uncertainties involved with differing assumptions.

Consequently, our approach endeavoured to apply the new regulatory conditions in our study, to formulate a more realistic evaluation technique, and to achieve a useable output. It was decided that the placement of UWB devices within an evaluation zone should be in a random manner, and therefore non-uniformly-spaced, thus reflecting the uncertainties involving the locations of UWB devices in an uncontrolled environment.

In the course of the study, various complementary analysis techniques were devised and applied to accomplish the goal of characterizating the cumulative effects of a large number of UWB devices on the EM environment. Starting with a datum, the cumulative effects of the UWB emitters upon the EM environment were quantified in terms of device density, frequency, and power output. An EMC assessment tool was devised as a methodology to assess any potential interference to other radiocommunications systems operating within the same environment. Finally, the EMC methodology, while devised for UWB devices, is equally applicable to all other low power portable devices.

1.0 INTRODUCTION

1.1 BACKGROUND

The advent of the ultrawideband (UWB) technology upon the commercial (non-military) world is one of the promising developments in the wireless communications field, yet it has raised concerns with respect to its effects upon the electromagnetic (EM) spectrum, and its potential for causing interference to services operating therein.

An event that underscored the importance of this technology was the regulatory action taken in February 2002 by the U.S. Federal Communications Commission (FCC), in the adoption of a First Report and Order [1]. This action permitted the marketing and operation of certain types of new products incorporating UWB technology, in accordance with specified device types, power levels, and frequency bands (Baseline: CFR Part 15, Sub-Part 209, a specified maximum permissible spectral power density (SPD) of -41.3 dBm/MHz). The identified categories of UWB devices and applications are the following:

1. Imaging Systems

    a) Ground Penetrating Radar (GPR) Systems
    b) Wall Imaging Systems
    c) Through-Wall Imaging Systems
    d) Medical Systems
    e) Surveillance Systems

2. Vehicular Radar Systems

3. Communications and Measurement Systems

However, for electromagnetic compatibility (EMC) and spectrum management purposes, the FCC also regrouped the above breakdown in conjunction with five prescribed emission masks, namely,

Mask 1: GPRs, Wall Imaging, and Medical Imaging Systems;
Mask 2: Through-Wall Imaging and Surveillance Systems;
Mask 3: Indoor Systems;
Mask 4: Outdoor Hand-held Systems;
Mask 5: Vehicular Radar Systems.

Table 1 shows the requisite suppression required at some discrete frequencies, in accordance with these emission masks.

FCC UWB EMISSION MASK VALUES (at Discrete Frequencies) in dB					
Frequency GHz	GPRs, Wall and Medical Imaging	Through Wall Imaging, Surveillance	Indoor Systems	Outdoor Hand-held Systems	Vehicular Radar Systems
1	-24	-12	-34	-34	-34
2	-12	-10	-12	-22	-20
3	-10	0	-10	-20	-20
4	0	0	0	0	-20
5	0	0	0	0	-20

Table 1 : Suppression in dB Relative to Baseline SPD of -41.3 dBm/MHz

Further information on the UWB field can be found in CRC summary background material [2], which provides an understanding of the characteristics and critical attributes of the UWB technology. It brings together many of the technical issues and the wide-ranging arguments involved in this field. Moreover, it presents important EMC aspects and highlights the challenges that must be overcome in order to accommodate the UWB technology within the radio spectrum, with minimal disruption to other services and users. Another source of information on UWB technology is available on the Æther Wire & Location, Inc. web page [3], with an extensive bibliography and links to other sources.

1.2 PURPOSE OF THE RESEARCH

The research work was carried out during the 2002-03 fiscal year (FY), through Spectrum Research Project E-05, for the Spectrum Engineering Branch (DGSE) of Industry Canada, in support of their spectrum management goals, International Telecommunication Union (ITU) activities, and near-term plans. Specific research goals were:

- The development of an appropriate method or technique to quantify the aggregate effects of emissions from UWB devices on the EM environment, specifically their contributions to the raising of the EM environment ambient levels;

- To evaluate the harmful interference potential involving existing and planned radiocommunication equipment and systems in several radiocommunication services, when immersed in such an environment;

- To develop an EMC analysis tool, to be applied in the determination of the interference potential of UWB devices with respect to conventional radiocommunications systems.

1.3 SCOPE OF THE WORK

A key EMC consideration in the sharing of the spectrum, whenever a multitude of low-power devices are concerned, is their cumulative spectral power contribution to the EM environment. Although UWB devices may be considered as non-conventional communications systems, in the context of FCC's First Report and Order [1], they fall into the low-power device category in the frequency domain.

While one or a few devices may not cause interference, a large number operating within an area could raise the ambient level of the EM environment sufficiently, to affect the operations of other radiocommunications systems that are located within the same environment.

This work characterizes the cumulative effects of a large number of UWB devices on the EM environment, and the resulting EMC methodology of assessing potential interference to others. The EMC methodology, while devised for UWB devices, is equally applicable to all other low power portable devices. A few examples are provided on the use of the methodology.

2.0 RESEARCH APPROACH

2.1 EVALUATION TECHNIQUE

One of the most common techniques used in evaluating the cumulative effects of UWB devices is to place evenly spaced set of transmitters within a rectangular area, and to sum up the total contribution at a given victim location within this area. There are other variants to this technique, such as placing evenly spaced UWB devices along concentric rings within a circular area under consideration.

The evenly spaced transmitters technique does have merit, as far as the cumulative effects on a victim are concerned. However, where the goal is to quantify the general EM environmental profile due to cumulative emissions, the technique of evenly placing the UWB devices is not suitable, because the resulting environmental profile would exhibit evenly spaced peak values, at the locations of the transmitters. To demonstrate this unsuitability, and to provide a comparison with the technique used in the course of this research, a simulation with evenly-spaced set of transmitters was carried out.

Several studies using the above technique have been conducted previously, notably in North America and the U.K. [4],[5], on the cumulative effects of UWB devices, but these pre-dated the Federal Communications Commission's (FCC) First Report and Order [1]. For the first time, a set of regulatory limits has been imposed on the technology and its applications. This action established a common datum for all subsequent studies related to this technology, and removed the uncertainties involved with differing assumptions.

Consequently, we endeavoured to apply the new regulatory conditions in our study, to formulate a more realistic evaluation technique and to develop a useable methodology.

In our view, the evaluation of the cumulative effects of UWB devices on the EM environment should utilize a technique that reflects the real world situation as much as possible. Accordingly, we have shaped our approach on three basic concepts:

The placement of UWB devices within the evaluation zone should be in a random manner, and therefore, unevenly spaced. Most UWB device users will exhibit mobile behaviour (especially where outdoor hand-held devices are concerned), therefore, the whereabouts of the UWB devices will be unknown and unpredictable. Thus, random placement of UWB devices appears the most appropriate representation.

The evaluation of the cumulative power (or spectral power density) should be carried out throughout the area of assessment rather than at a single point (victim location), to ensure that *anywhere within the area, the obtained value will be consistent. The best tool for this approach is to overlay a fine mesh grid on the area of assessment.* The large number of evaluation points (namely, at each mesh grid point) would provide much more detail and granularity within the assessment zone.

It is necessary to repeat the evaluations a large number of times due to the statistical nature of the approach, in order to attain confidence.

The main steps of this approach are:

a) Assume that each UWB device radiates the maximum permissible spectral power density specified in [1], namely -41.3 dBm/MHz; and is in operation concurrently, for a worst-case situation; (N.B.: FCC defines this limit as an EIRP of -41.3 dBm measured with a resolution bandwidth of 1 MHz [1]).

b) Apply propagation path loss models of Free-Space and Log-Distance (n = 2 and n = 3 respectively), at a frequency of 1 GHz.

c) Place 100 randomly distributed – as opposed to evenly-spaced – UWB devices within three evaluation zones of 100 m by 100 m, 300 m by 300 m, and 1000 m by 1000 m, while assuming that these zones are located in dense urban areas. Further, apply no minimum separation criterion to the UWB device placement (N.B. : the MATLAB random number generator used has a uniform probability density function).

d) Overlay a 100 by 100 mesh grid over the evaluation zone (101 x 101 grid points).

e) Compute at each grid point the total spectral power density received from all of the 100 UWB devices (assume that all UWB signals arrive at each grid point concurrently, and are added up).

f) Repeat steps c) through e) with 100 random distribution sets, to build up the necessary statistical data.

g) From step f) obtain the mean value of the spectral power density at each grid point.

h) Finally, determine the environmental spectral power density within the zones.

It should be mentioned that there is no particular reason why the number of UWB devices within an evaluation zone was chosen to be 100. Any other large number would equally suffice. Similarly, the number of random distribution sets, i.e., 100, is also arbitrary. Again, any large number such as 70, 80, 110, etc, would be suitable.

2.2 MATHEMATICAL FORMULATION

The set of 100 UWB transmitters placed randomly within an evaluation zone is represented by:

$$\mathbf{U} = \{U_1, U_2, U_3, ...,U_k, ...,U_{100}\} \qquad (2\text{-}1)$$

The x and y coordinates of the kth UWB device, (U_k), are $x_u(k)$ and $y_u(k)$ respectively, both in metres.

Each mesh point of the 100 x 100 mesh grid overlaid on the evaluation zone is represented by $c_{m,n}$, the $(m,n)^{th}$ mesh point, whose x and y coordinates are $x_g(m)$ and $y_g(n)$ respectively, both in metres (g denotes mesh).

These coordinates can be represented as a matrix,

$$\begin{pmatrix} c_{0,0} & c_{1,0} & c_{2,0} & \cdots & c_{100,0} \\ c_{0,1} & c_{1,1} & c_{2,1} & \cdots & c_{100,1} \\ c_{0,2} & c_{1,2} & c_{2,2} & \cdots & c_{100,2} \\ \vdots & \vdots & \vdots & & \vdots \\ c_{0,100} & c_{1,100} & c_{2,100} & \cdots & c_{100,100} \end{pmatrix}$$

The distance between a mesh point $c_{m,n}$ and a UWB device U_k is given by $d_k(m,n)$, in metres, where,

$$d_k(m,n) = \{ (x_u(k) - x_g(m))^2 + (y_u(k) - y_g(n))^2 \}^{0.5} \qquad \text{metres} \qquad (2\text{-}2)$$

The propagation path loss L_k between a mesh point $c_{m,n}$ and a UWB device U_k is a function of frequency F and distance $d_k(m,n)$. Thus,

$$L_k = f(F,d_k(m,n)) \qquad \text{dB} \qquad (2\text{-}3)$$

Let Q represent the spectral power density of UWB device U_k. Assume each UWB device is operating at the maximum FCC limit of -41.3 dBm/MHz.

The interference spectral power density at mesh point $c_{m,n}$ due to UWB device U_k is:

$$I_k(m,n) = Q - L_k \qquad \text{dBm/MHz} \tag{2-4}$$

The total interference spectral power density at mesh point $c_{m,n}$ due to **U**, i.e., <u>all</u> 100 UWB devices, is:

$$i(m,n) = \sum_{k=1}^{100} i_k(m,n) \qquad \text{mW/MHz} \tag{2-5}$$

$$I(m,n) = 10\log_{10}(i(m,n)) \qquad \text{dBm/MHz} \tag{2-6}$$

The total interference spectral power density values are obtained for all 101 x 101 mesh grid points. I(state) represents the set of these values at each mesh grid point, for a particular random distribution case (state).

$$I(\text{state}) = \begin{pmatrix} I_{0,0} & I_{1,0} & I_{2,0} & \cdots & I_{100,0} \\ I_{0,1} & I_{1,1} & I_{2,1} & \cdots & I_{100,1} \\ I_{0,2} & I_{1,2} & I_{2,2} & \cdots & I_{100,2} \\ \vdots & \vdots & \vdots & & \vdots \\ I_{0,100} & I_{1,100} & I_{2,100} & \cdots & I_{100,100} \end{pmatrix} \tag{2-7}$$

The above procedure was repeated for 100 separate random distributions, resulting in a set of 100 distinct I(state) matrices. Then, the mean interference spectral power density matrix is computed:

$$\bar{i} = \frac{1}{100} \sum_{\text{state}=q}^{(q+99)} I(\text{state}) \qquad \text{mW/MHz} \tag{2-8}$$

$$\overline{I} = 10\log_{10}(\overline{i}) \quad \text{dBm/MHz} \tag{2-9}$$

where q is the state number of the random number generator in Matlab.

Finally, all the values so obtained can be plotted to determine the cumulative spectral power density value within the evaluation zone. The entire procedure is repeated for all three evaluation zones, and for the two propagation path models.

2.3 PROPAGATION PATH LOSS MODELS

The two propagation path loss models used in this study were simple ones on account of the close distances between the UWB transmitters and the evaluation points, i.e. up to 1000 metres. As mentioned above, these were the Free-Space and Log-Distance models, where the path loss varies inversely with distance at second and third powers respectively. The expressions, derived in Appendix E, are given (in logarithmic terms) by:

$$L_{FS} = -27.56 + 20 \log_{10} f_{MHz} + 20 \log_{10} d_m \quad \text{dB} \tag{2-10}$$

$$L_{LD} = -27.56 + 20 \log_{10} f_{MHz} + 30 \log_{10} d_m \quad \text{dB} \tag{2-11}$$

In generalized form, both expressions can be represented by [6]:

$$L = L_{FS}(d_0) + 10\, n \log_{10} (d / d_0) \quad \text{dB} \tag{2-12}$$

where: $d_0 = 1$ m

$n = 2.0$	Free-Space
$n = 2.7 - 3.5$	Urban Area Cellular
$n = 3.0 - 5.0$	Shadowed Urban Cellular

Given that the locale was assumed to be dense urban, $n = 3$ was chosen for the Log-Distance model in this study.

3.0 DETERMINATION OF ENVIRONMENTAL SPECTRAL POWER DENSITY WITHIN AN EVALUATION ZONE

The environmental spectral power density must now be determined within an evaluation zone. This section presents the analysis for the 100 m by 100 m evaluation zone. The analyses for the 300 m by 300 m and 1000 m by 1000 m evaluation zones are presented in the Appendices.

As mentioned before, a 100 by 100 mesh grid was overlaid on each zone of evaluation, the grid having a total of 10,201 grid points. The separation between grid points is 1, 3, and 10 metres for zones 100 m by 100 m, 300 m by 300 m, and 1000 m by 1000 m, respectively. At each grid point, I(m,n), the total interference spectral power density from all 100 UWB devices was calculated from Equations (2-5) and (2-6). This is illustrated in Figure 1, where the summation paths of interference from five UWB transmitters into three grid points are shown. In all cases, a far-field condition is assumed, because the UWB devices have electrically small antennas, whose far-field limit is given by the inverse of the propagation constant or wavenumber, i.e., wavelength/2π. At a frequency of 1 GHz, the far-field limit is under 5 cm. This was verified by reviewing the distance data between each UWB transmitter location and each grid point for sample distribution sets.

Figure 2 shows an example of a randomly distributed population of UWB transmitters within the 100 m by 100 m evaluation zone. Similar examples for 300 m by 300 m and 1000 m by 1000 m evaluation zones are shown in Appendix A, Figures A-1 and A-2 respectively. The UWB transmitter coordinates were generated by a MATLAB random number function.

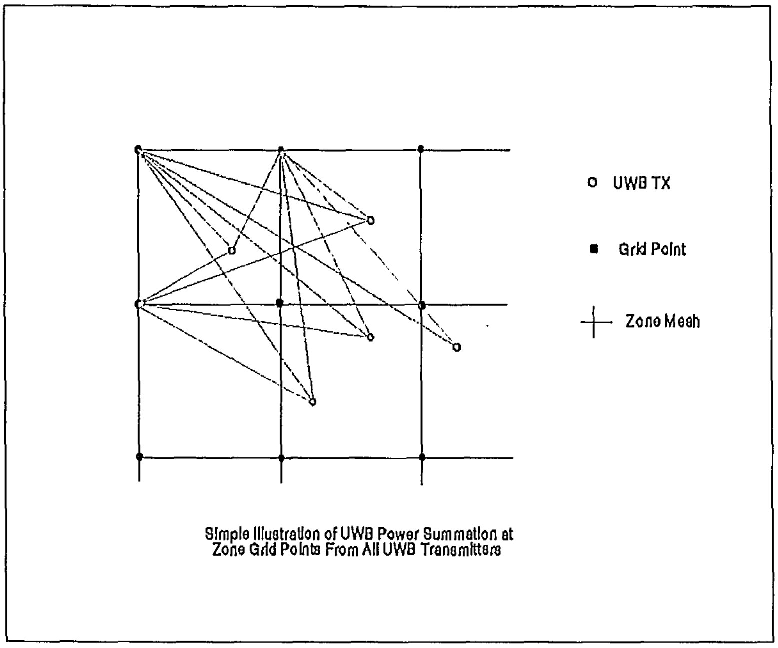

Figure 1 : Illustration of Spectral Power Density Summation Paths at Each Grid Point

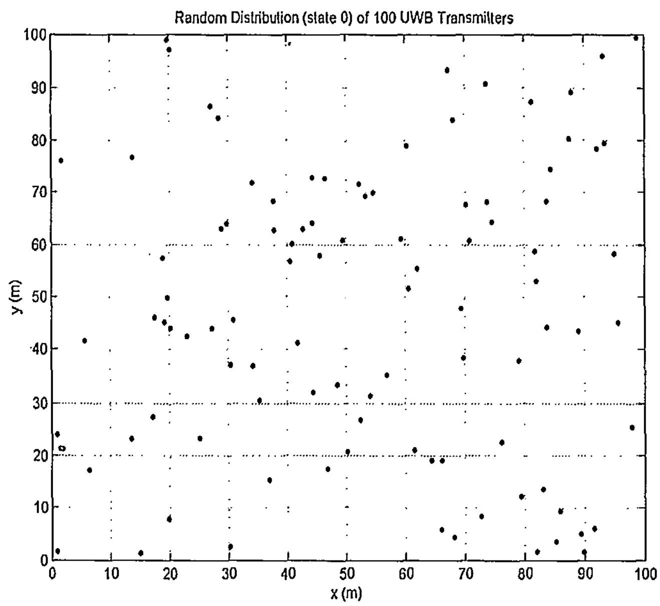

Figure 2 : Illustration of 100 Randomly Distributed UWB Transmitters within the 100 m by 100 m Evaluation Zone

3.1 SPECTRAL POWER DENSITY CONTOUR PLOTS

One interesting way to present the results of the summation is by means of contour line diagrams, generated from the interference spectral power densities obtained at the grid points using Equations (2-5) and (2-6). The contours are generated by joining the grid points that have quasi-equal values (within a small ± variation). The interval between each contour line is 2 dB. For easy comparison between the propagation path loss models, the range of contour line values was kept the same within each evaluation zone, although these values differ by 10 dB from zone to zone.

Figures 3 and 4 show the spectral power density contours obtained with Free-Space and Log-Distance propagation path loss models, respectively, within the 100 m by 100 m evaluation zone, for one particular set of randomly distributed UWB transmitters. Similar diagrams for 300 m by 300 m and 1000 m by 1000 m evaluation zones are shown in Appendix B, Figures B-1 through B-4.

As mentioned above, the technique of evenly placing the UWB devices results in evenly spaced peak values of spectral power density at the locations of the transmitters, and the contours exhibit symmetry. This is evident from the contour diagram shown in Figure 5, obtained with the Free-Space path loss model within the 100 m by 100 m evaluation zone. In the next Section, the unsuitability of this technique in determining the environmental spectral power density will be shown.

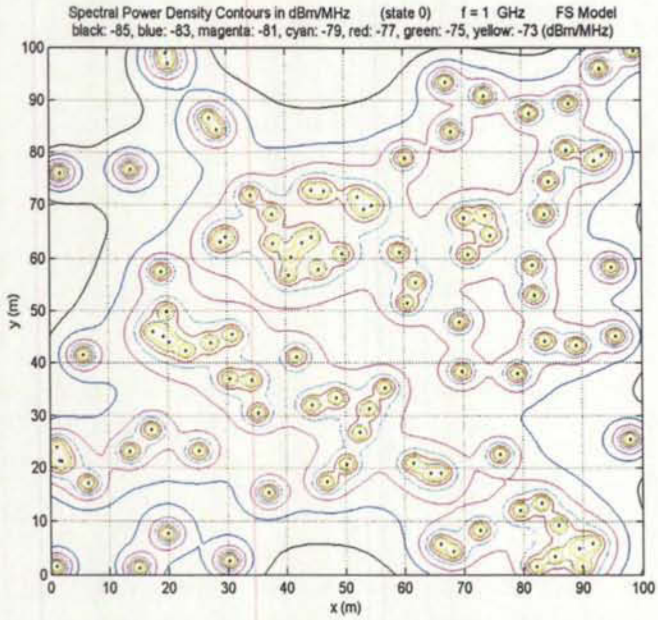

Figure 3 : Spectral Power Density Contours (Free-Space) within the 100 m by 100 m Evaluation Zone

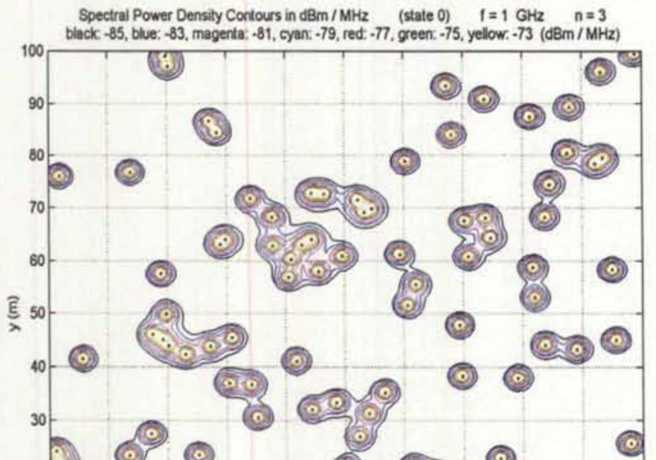

Figure 4 : Spectral Power Density Contours (Log-Distance) within the 100 m by 100 m Evaluation Zone

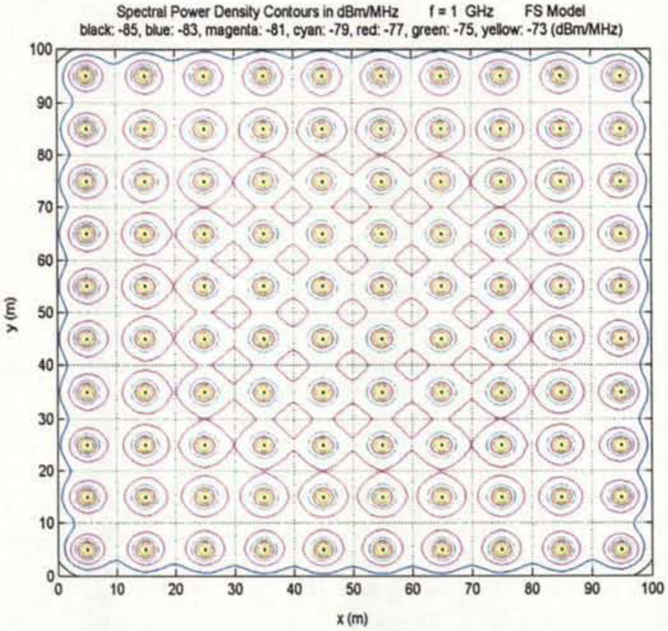

Figure 5 : Spectral Power Density Contours (Free-Space) within the 100 m by 100 m Evaluation Zone for Evenly Spaced UWB Transmitters

3.2 SCATTER DIAGRAMS AND HISTOGRAMS

The determination of the environmental spectral power density within an evaluation zone was accomplished by analysing the values obtained at each of the mesh grid points.

First, the mean interference spectral power density at each grid point was calculated, by means of Equations (2-8) and (2-9), for each evaluation zone. The resulting three-dimensional matrix of 10,201 values can be plotted in a three-dimensional graph (x and y coordinates of the grid point, and its value). However, such a three-dimensional scatter diagram would make it difficult to see significant attributes such as the concentration of the mean interference spectral power density values forming a band. Therefore, it appeared preferable to view the scatter diagrams along x- or y- axes.

Figures 6 and 7 show the scatter diagrams for the case of Free-Space and Log-Distance propagation path loss models, respectively, within the 100 m by 100 m evaluation zone, viewed along the y-axis. Similar diagrams for 300 m by 300 m and 1000 m by 1000 m evaluation zones are shown in Appendix C, Figures C-3 through C-6. As the views along the x-axis are similar to the views along the y-axis, only two such plots are presented in Appendix C (Figures C1 and C2), for illustration purposes.

Next, a probability density plot was produced from the mean interference spectral power density matrix elements. The environmental spectral power density value is determined from the mode of the histogram data.

Figures 8 and 9 show the histograms for the case of Free-Space and Log-Distance propagation path loss models, respectively, within the 100 m by 100 m evaluation zone. Appendix D, Figures D-1 and D-2 show the histograms for 300 m by 300 m and 1000 m by 1000 m evaluation zones for the case of the Log-Distance propagation path loss model.

The scatter is caused by the fact that as a rule, grid points closer to the UWB transmitters will have higher values of spectral power density, because the closest UWB transmitters will make the highest contribution. Given the random distribution of the UWB transmitters within an evaluation zone, in some distribution sets it will happen that an UWB transmitter will be at the same location (or be very close to) as in other distribution sets. This will then cause the grid points in the vicinity to have higher mean values.

In addition, the scatter is larger in the case of the results obtained using the Log-Distance propagation path loss model, due to the higher path loss for the same distance. As can be seen from the contour plot in Figure 4, the contours are bunched up more near the UWB transmitters, compared to Figure 3. The net effect will be a more pronounced scatter.

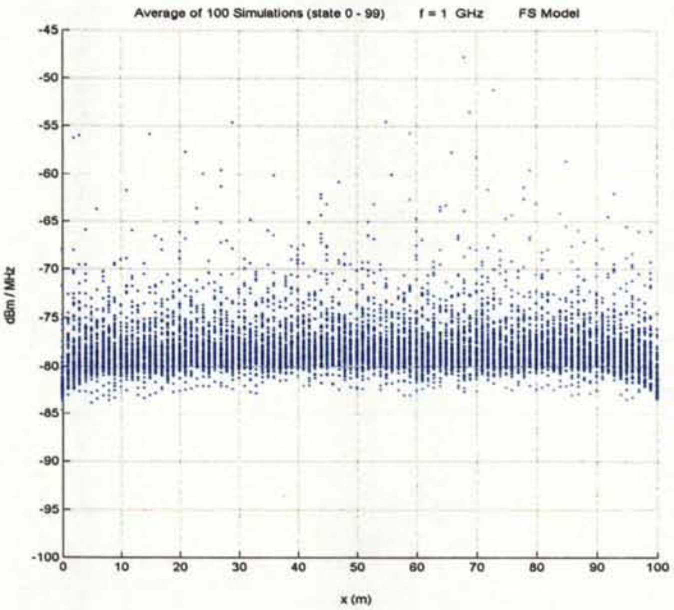

Figure 6 : Scatter Diagram (Free-Space) within the 100 m by 100 m Evaluation Zone (viewed along y-axis)

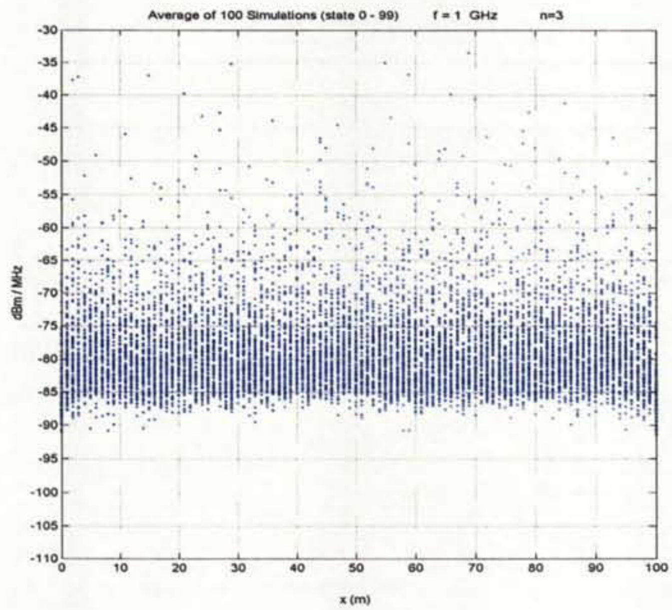

Figure 7 : Scatter Diagram (Log-Distance) within the 100 m by 100 m Evaluation Zone (viewed along y-axis)

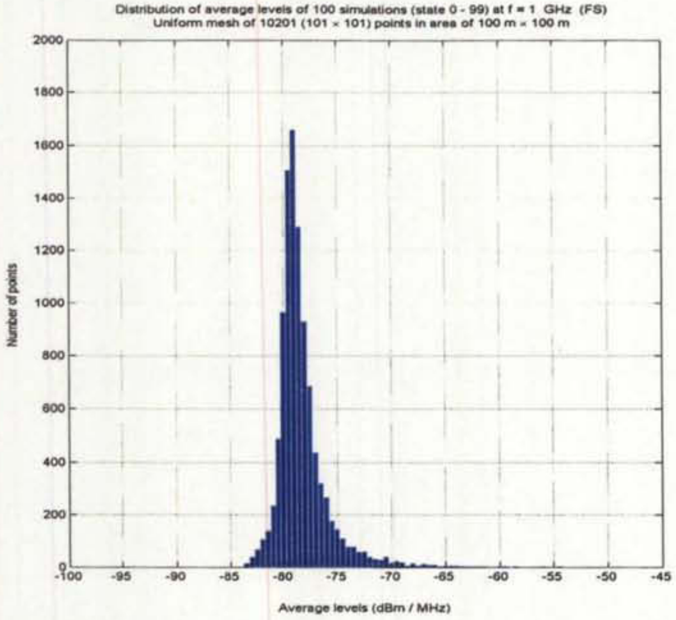

Figure 8 : Histogram (Free-Space) within the 100 m by 100 m Evaluation Zone

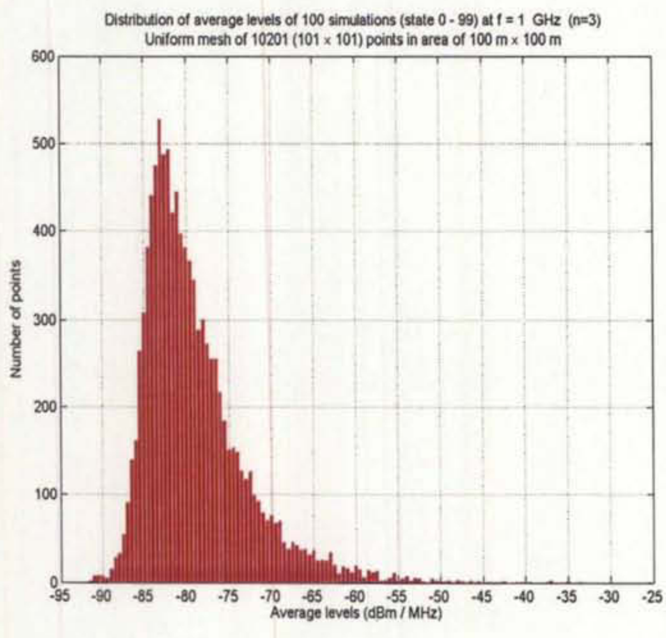

Figure 9 : Histogram (Log-Distance) within the 100 m by 100 m Evaluation Zone

3.3 SIMULATION NUMBER AND CONVERGENCE TREND RELATIONSHIP

To keep the computational task manageable, all the simulations were carried out with only 100 separate random sets. The intuitive expectation was that simulations involving a larger number of random sets would result in a constriction of the bands in the scatter diagrams, and at the same time, increase the population of points within that band. That is, simulations involving larger number of random sets would make the band along which most of the values are concentrated, narrower and denser. From a statistical perspective, a larger number of simulations would decrease the standard deviation value of the histograms. This would make the determination of the environmental spectral power density more accurate.

To test this proposal, additional simulations were carried out within the 100 m by 100 m evaluation zone using 200 and 1000 random sets.

Figures 10 and 11 show the scatter diagrams obtained with the Free-Space propagation path loss model for 200 and 1000 simulations, respectively, and comparisons made with Figure 6 (100 simulations). It can be seen that the band formed by the concentration of points does get narrower with increased number of simulations. A similar trend is also noticeable, though not as plainly, in the scatter diagrams obtained with the Log-Distance propagation path loss model, Figures 12 and 13, when these are compared with Figure 7. Figures 14 through 17 show the related histograms.

Further examination of this trend analysis with respect to the population of points is presented in Figures 18 and 19. Figure 18 shows the percentage of the mean interference spectral power density matrix elements, obtained with the Free-Space propagation path loss model, and having values between -75 dBm/MHz and -80 dBm/MHz in the 100 m by 100 m evaluation zone. Figure 19 shows similar information obtained with the Log-Distance propagation path loss model, for two separate ranges of mean interference spectral power density values. The effect of an increased number of simulations is readily discernible in both Figures.

From the data for the 100 m by 100 m evaluation zone, a statistical comparison of the simulations, including the case for evenly spaced UWB transmitters, is given in Table 2.

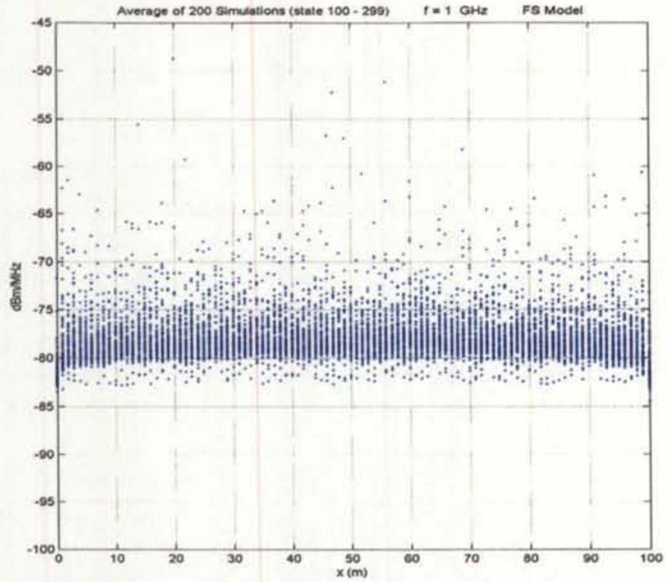

Figure 10 : Scatter Diagram (Free-Space) within the 100 m by 100 m Evaluation Zone (viewed along y-axis) of 200 Simulations

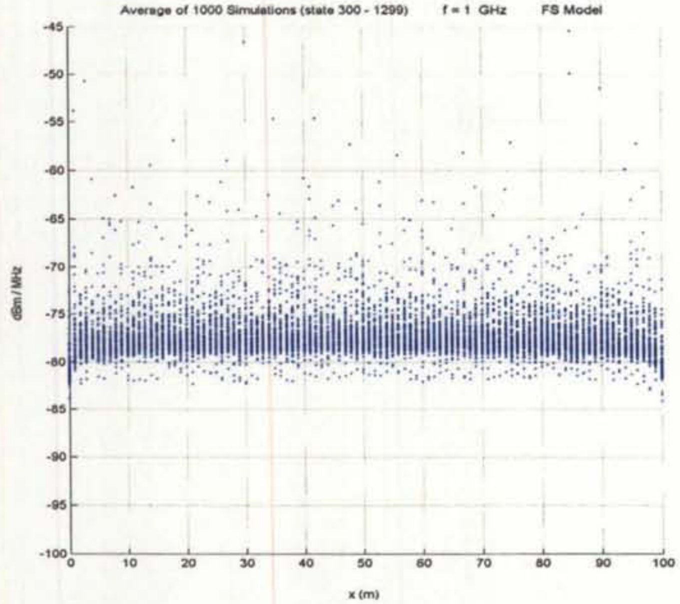

Figure 11 : Scatter Diagram (Free-Space) within the 100 m by 100 m Evaluation Zone (viewed along y-axis) of 1000 Simulations

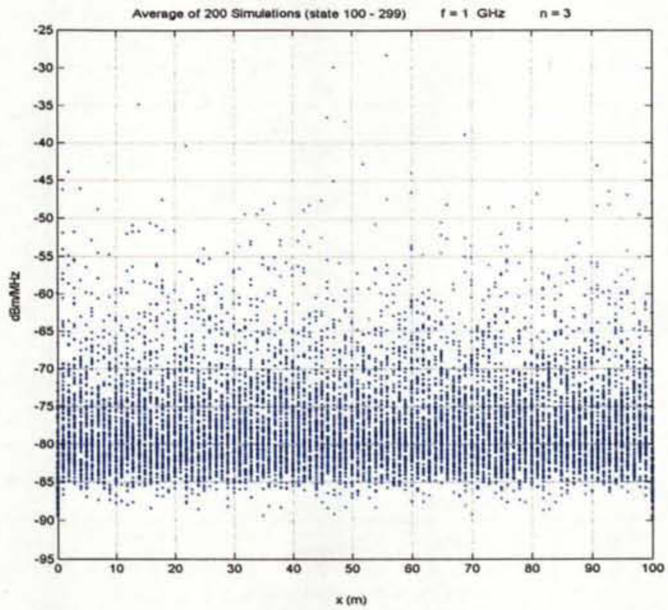

Figure 12 : Scatter Diagram (Log-Distance) within the 100 m by 100 m Evaluation Zone (viewed along y-axis) of 200 Simulations

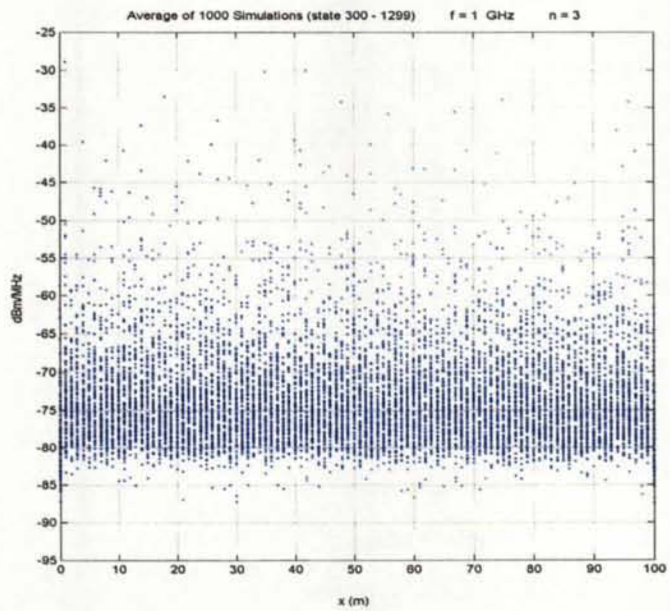

Figure 13 : Scatter Diagram (Log-Distance) within the 100 m by 100 m Evaluation Zone (viewed along y-axis) of 200 Simulations

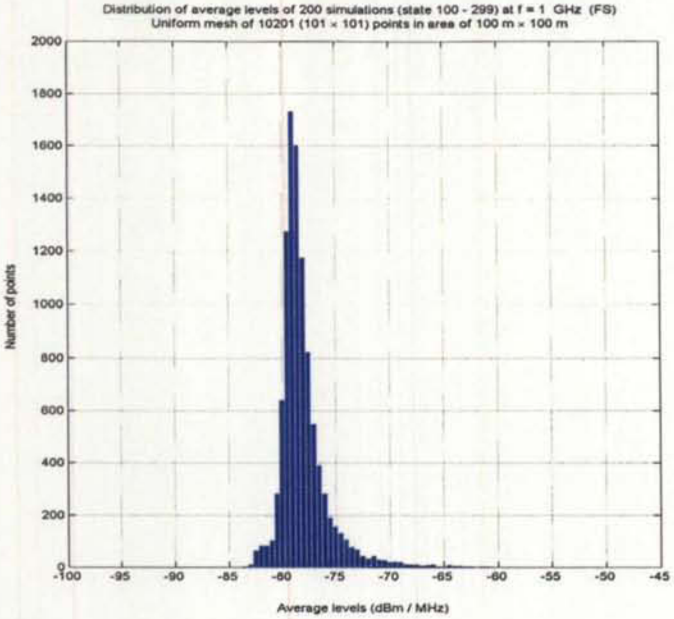

Figure 14 : Histogram (Free-Space) within the 100 m by 100 m Evaluation Zone 200 Simulations

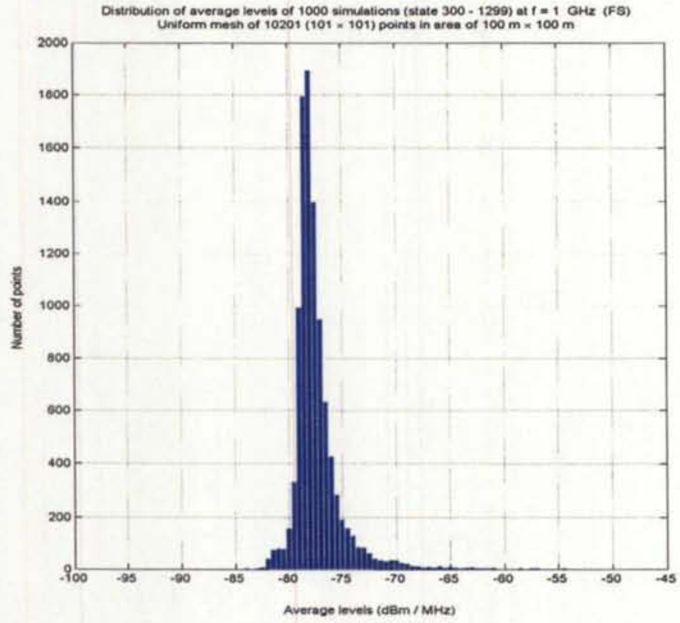

Figure 15 : Histogram (Free-Space) within the 100 m by 100 m Evaluation Zone 1000 Simulations

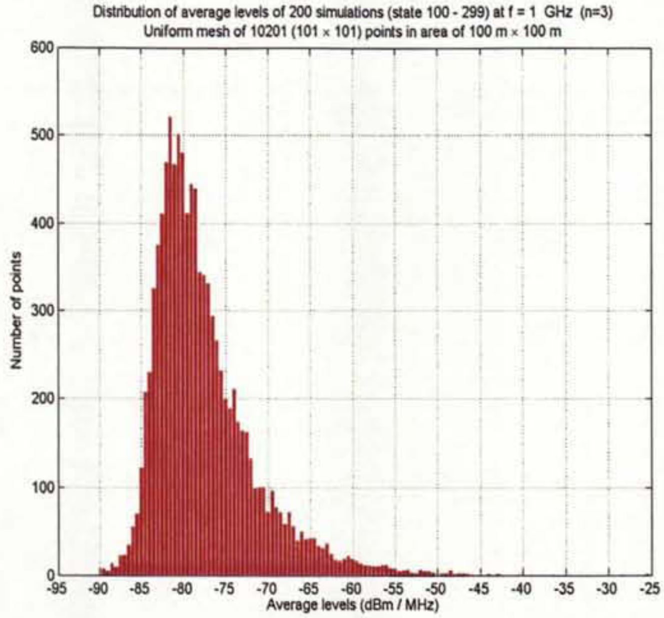

Figure 16 : Histogram (Log-Distance) within the 100 m by 100 m Evaluation Zone 200 Simulations

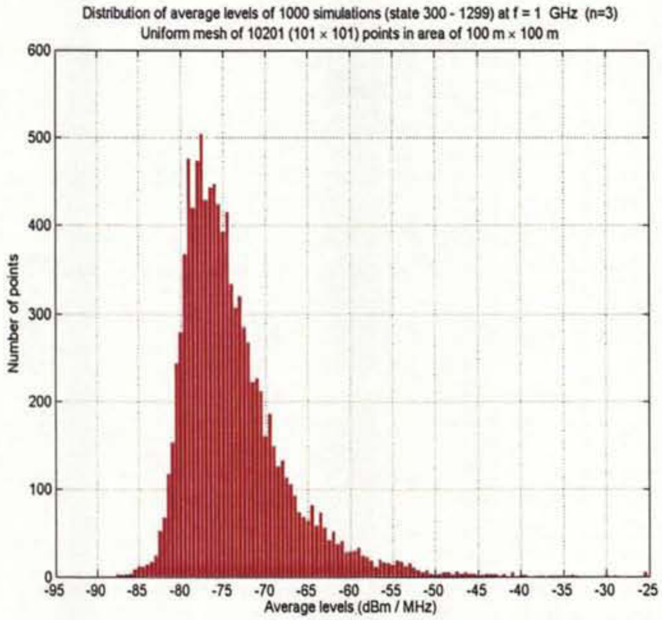

Figure 17 : Histogram (Log-Distance) within the 100 m by 100 m Evaluation Zone 1000 Simulations

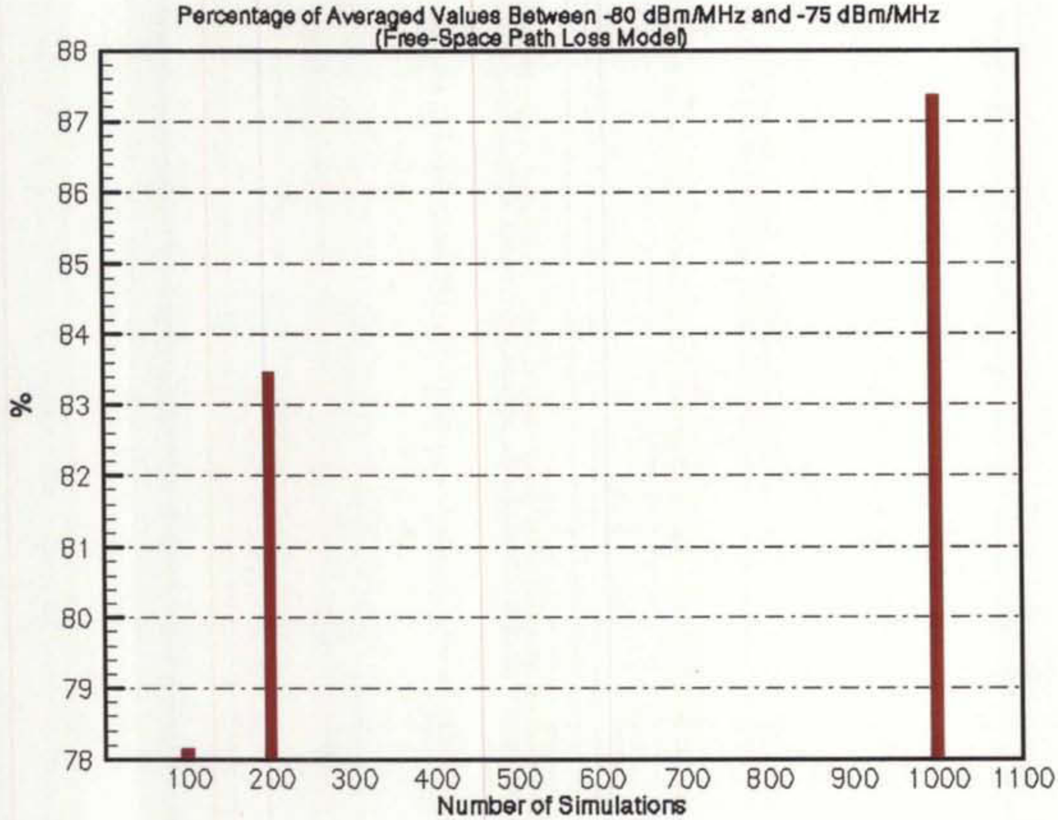

Figure 18 : Population vs Number of Simulations within the -75 to -80 dBm/MHz Interval
100 m by 100 m Evaluation Zone (Free-Space Model)

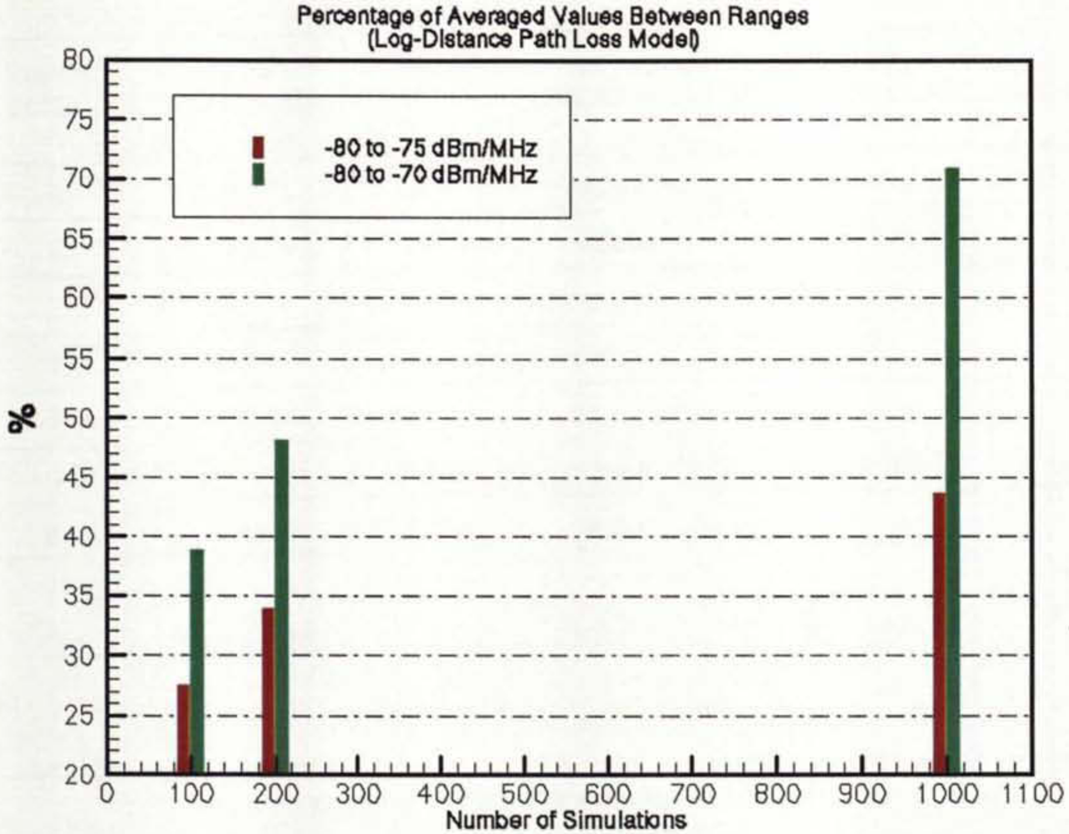

Figure 19 : Population vs Number of Simulations within Indicated Ranges
100 m by 100 m Evaluation Zone (Log-Distance Model)

UWB TX Distribution	Number of Simulations	Propagation Path Loss Model	Mode dBm/MHz	Median dBm/MHz	Standard Deviation dB
Random	100	Free-Space	-79.0	-78.8	2.5
Random	200	Free-Space	-78.9	-78.5	2.4
Random	1000	Free-Space	-78.1	-77.9	2.3
Random	100	Log-Distance	-83.2	-80.4	6.4
Random	200	Log-Distance	-81.5	-78.9	6.3
Random	1000	Log-Distance	-77.5	-75.2	6.4
Evenly Spaced	1	Free-Space	-81.1	-81.0	31.6

Table 2 : Statistical Comparison of Simulations (100 m by 100 m Evaluation Zone)

It is concluded that the intuitive expectation was correct, in that the probability density plots (histograms) get narrower, and the respective standard deviations get smaller, as the number of simulations increases. Further work with much larger number of simulations was not attempted due to computational limitations, and also because the use of histograms simplified the process of determining the required values.

3.4 DISCUSSION ON EVENLY SPACED VS RANDOMLY DISTRIBUTED TRANSMITTERS TECHNIQUES

The matter of UWB transmitter distribution within an area of evaluation was briefly discussed before in this report. In our view, the evenly spaced transmitter distribution does not represent the real world situation, and is also unsuitable for determining the environmental spectral power density with any confidence. With an evenly spaced transmitter population, there is no need to carry out a large number of simulations, unlike that which is required with randomly distributed transmitter populations. Even if the respective locations of the transmitters were shifted, and computations were repeated, the evenly spaced transmitter profile would still yield the same environmental spectral power density.

Figure 20 represents the scatter diagram of 100 evenly-spaced UWB transmitters within the 100 m by 100 m evaluation zone, obtained with the Free-Space propagation path loss model, viewed along the y-axis. This can be contrasted with its counterpart, Figure 6, in Section 3.2.

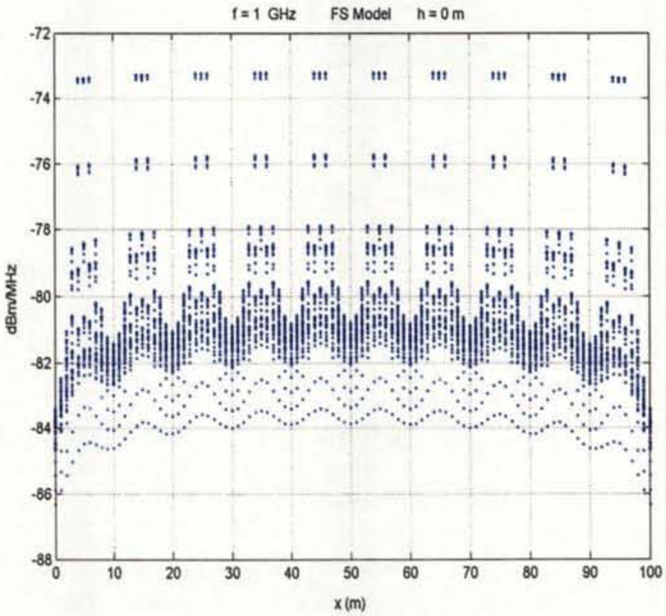

Figure 20 : Scatter Diagram (Free-Space) within the 100 m by 100 m Evaluation Zone for 100 Evenly Spaced UWB Transmitters (viewed along y-axis)

The histogram of the interference spectral power density matrix elements computed for the evaluation zone of 100 m by 100 m, is shown in Figure 21. This can be contrasted with its counterpart, Figure 8, in Section 3.2.

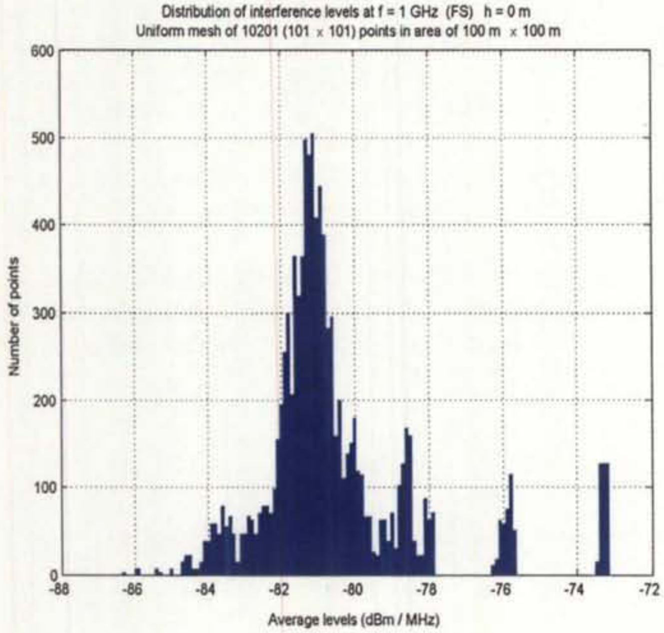

Figure 21 : Histogram (Free-Space) within the 100 m by 100 m Evaluation Zone for 100 Evenly Spaced UWB Transmitters

From this Figure, the conclusion could be drawn that the mode value of the environmental spectral density is approximately -81 dBm/MHz. The median value was calculated as -81.0 dBm/MHz with, however, a large spread.

While the randomly distributed UWB transmitter technique shows a good statistical behaviour, the same is not true in the case of the evenly spaced UWB transmitter technique. Referring to Table 2, in Section 3.3, a standard deviation of the order of a significant percentage of its median value is unacceptable, and does not give confidence in the resulting environmental spectral power density value.

It can thus be concluded that the technique of evenly spaced UWB transmitters as an evaluation technique is unsuitable for the determination of environmental spectral power density.

4.0 ENVIRONMENTAL SPECTRAL POWER DENSITY

The environmental spectral power density in each evaluation zone was determined by an analysis of the histogram data. The modes of the histograms yield the values of the environmental spectral power densities. Tables 3 and 4 present results for the Free-Space and Log-Distance propagation path loss models, respectively, in all three evaluation zones, obtained at 1 GHz.

While the computations were carried out at a frequency of 1 GHz, it is useful to include the environmental spectral density values for other discrete frequencies. The values at these frequencies are scaled in accordance with the propagation path loss ratios relative to 1 GHz. That is, the path loss at 2 GHz will be higher by 6 dB compared to the path loss at 1 GHz, and the resulting environmental spectral density value at 2 GHz will be 6 dB lower. Tables 3 and 4 include the scaled values for the environmental spectral power densities from 2 to 5 GHz.

Frequency GHz	Environmental Spectral Power Density (dBm/MHz)		
	Zone 100m x 100m	Zone 300m x 300m	Zone 1000m x 1000m
1	-79.0	-88.5	-99.0
2	-85.0	-94.5	-105.0
3	-88.5	-98.0	-108.5
4	-91.0	-100.5	-111.0
5	-93.0	-102.5	-113.0

Note: Each UWB TX SPD = -41.3 dBm/MHz (Maximum of FCC Mask)

Table 3 : Effect of 100 TXs on EM Environment (Free-Space Model)
Results Obtained from 100 Random Distributions Sets

Frequency GHz	Environmental Spectral Power Density (dBm/MHz)		
	Zone 100m x 100m	Zone 300m x 300m	Zone 1000m x 1000m
1	-83.2	-97.1	-112.2
2	-89.2	-103.1	-118.2
3	-92.7	-106.6	-121.7
4	-95.2	-109.1	-124.2
5	-97.2	-111.1	-126.2

Note: Each UWB TX SPD = -41.3 dBm/MHz (Maximum of FCC Mask)

Table 4 : Effect of 100 TXs on EM Environment (Log-Distance n=3 Model) Results Obtained from 100 Random Distributions Sets

The above Tables would represent the situation if all UWB devices were transmitting at the maximum allowable spectral power density level outlined in the FCC's First Report and Order [1]. However, in accordance with that document, UWB device-specific suppression specifications (shown in Table 1) must be applied, and the values adjusted. Accordingly, Tables 5 through 10 show the environmental spectral power densities caused by the specific UWB device types, including the frequency-scaled values for the environmental spectral power densities from 2 to 5 GHz.

Freq GHz	Zone 100 m x 100 m	GPRs, Wall and Medical Imaging	Through Wall Imaging, Surveillance	Indoor Systems	Outdoor Handheld Systems	Vehicular Radar Systems
1	-79.0	-103.0	-91.0	-113.0	-113.0	-113.0
2	-85.0	-97.0	-95.0	-97.0	-107.0	-105.0
3	-88.5	-98.5	-88.5	-98.5	-108.5	-108.5
4	-91.0	-91.0	-91.0	-91.0	-91.0	-111.0
5	-93.0	-93.0	-93.0	-93.0	-93.0	-113.0

Table 5 : Environmental Spectral Power Density Values in dBm/MHz for UWB Device Type (Free-Space Model) for Zone 100 m x 100 m.

Freq GHz	Zone 300 m x 300 m	GPRs, Wall and Medical Imaging	Through Wall Imaging, Surveillance	Indoor Systems	Outdoor Handheld Systems	Vehicular Radar Systems
1	-88.5	-112.5	-100.5	-122.5	-122.5	-122.5
2	-94.5	-106.5	-104.5	-106.5	-116.5	-114.5
3	-98.0	-108.0	-98.0	-108.0	-118.0	-118.0
4	-100.5	-100.5	-100.5	-100.5	-100.5	-120.5
5	-102.5	-102.5	-102.5	-102.5	-102.5	-122.5

Table 6 : Environmental Spectral Power Density Values in dBm/MHz for UWB Device Type (Free-Space Model) for Zone 300 m x 300 m.

Freq GHz	Zone 1000 m x 1000 m	GPRs, Wall and Medical Imaging	Through Wall Imaging, Surveillance	Indoor Systems	Outdoor Handheld Systems	Vehicular Radar Systems
1	-99.0	-123.0	-111.0	-133.0	-133.0	-133.0
2	-105.0	-117.0	-115.0	-117.0	-127.0	-125.0
3	-108.5	-118.5	-108.5	-118.5	-128.5	-128.5
4	-111.0	-111.0	-111.0	-111.0	-111.0	-131.0
5	-113.0	-113.0	-113.0	-113.0	-113.0	-133.0

Table 7 : Environmental Spectral Power Density Values in dBm/MHz for UWB Device Type (Free-Space Model) for Zone 1000 m x 1000 m.

Freq GHz	Zone 100 m x 100 m	GPRs, Wall and Medical Imaging	Through Wall Imaging, Surveillance	Indoor Systems	Outdoor Handheld Systems	Vehicular Radar Systems
1	-83.2	-107.2	-95.2	-117.2	-117.2	-117.2
2	-89.2	-101.2	-99.2	-101.2	-111.2	-109.2
3	-92.7	-102.7	-92.7	-102.7	-112.7	-112.7
4	-95.2	-95.2	-95.2	-95.2	-95.2	-115.2
5	-97.2	-97.2	-97.2	-97.2	-97.2	-117.2

Table 8 : Environmental Spectral Power Density Values in dBm/MHz for UWB Device Type (Log-Distance n=3 Model) for Zone 100 m x 100 m.

Freq GHz	Zone 300 m x 300 m	GPRs, Wall and Medical Imaging	Through Wall Imaging, Surveillance	Indoor Systems	Outdoor Handheld Systems	Vehicular Radar Systems
1	-97.1	-121.1	-109.1	-131.1	-131.1	-131.1
2	-103.1	-115.1	-113.1	-115.1	-125.1	-123.1
3	-106.6	-116.6	-106.6	-116.6	-126.6	-126.6
4	-109.1	-109.1	-109.1	-109.1	-109.1	-129.1
5	-111.1	-111.1	-111.1	-111.1	-111.1	-131.1

Table 9 : Environmental Spectral Power Density Values in dBm/MHz for UWB Device Type (Log-Distance n=3 Model) for Zone 300 m x 300 m.

Freq GHz	Zone 1000 m x 1000 m	GPRs, Wall and Medical Imaging	Through Wall Imaging, Surveillance	Indoor Systems	Outdoor Handheld Systems	Vehicular Radar Systems
1	-112.2	-136.2	-124.2	-146.2	-146.2	-146.2
2	-118.2	-130.2	-128.2	-130.2	-140.2	-138.2
3	-121.7	-131.7	-121.7	-131.7	-141.7	-141.7
4	-124.2	-124.2	-124.2	-124.2	-124.2	-144.2
5	-126.2	-126.2	-126.2	-126.2	-126.2	-146.2

Table 10 : Environmental Spectral Power Density Values in dBm/MHz for UWB Device Type (Log-Distance n=3 Model) for Zone 1000 m x 1000 m.

4.1 ENVIRONMENTAL SPECTRAL POWER DENSITY VARIATION WITH TRANSMITTER DENSITIES

Since the number of UWB devices operating within each evaluation zone was kept constant (at 100), the transmitter density for each evaluation zone can be given in terms of transmitters per square kilometre (TX/km^2).

a) Zone 100 m x 100 m

UWB TX Density = (100 / (100 x 100)) x (1000 x 1000) = 10,000.0 TX/km^2

b) Zone 300 m x 300 m

UWB TX Density = (100 / (300 x 300)) x (1000 x 1000) = 1,111.11... TX/km^2

c) Zone 1000 m x 1000 m

UWB TX Density = (100 / (1000 x 1000)) x (1000 x 1000) = 100.0 TX/km^2

At the outset, it was thought that the environmental spectral power density would vary as some function of the zone area.

The results indicate that this variation is linear when the UWB transmitter density is converted to dB (10 $\log_{10}$ (TX/km^2)). Tables 11 and 12, and Figures 22 and 23 show the results of this analysis for the two propagation path loss models used. The points in the Figures represent the UWB device density in each evaluation zone (column 2 in the Tables) versus the resulting environmental spectral power density (column 4 in the Tables).

The relationship between an evaluation zone UWB device density and the resulting environmental spectral power density within it, can be represented algebraically by the fitting of equations to the data in Tables 11 and 12, as follows:

$$\text{EnvSPD} = 10 \log_{10} (\text{TX/km}^2) - 119.0 \qquad \text{(Free-Space Model)}$$

$$\text{EnvSPD} = 1.45 \times (10 \log_{10} (\text{TX/km}^2)) - 141.2 \qquad \text{(Log-Distance } n = 3 \text{ Model)}$$

The significance of this result from a regulatory perspective is that now an indicated spectral power density within the EM environment can directly prescribe the requisite UWB transmitter density, and vice-versa.

Zone (m x m)	UWB TX Density (dB TX/km^2)	Difference (dB)	Environmental SPD at 1 GHz (dBm/MHz)	Difference (dB)
100 x 100	40.0	–	-79.0	–
300 x 300	30.5	-9.5	-88.5	-9.5
1000 x 1000	20.0	-20.0	-99.0	-20.0

Note: Each UWB TX SPD = -41.3 dBm/MHz (Maximum of FCC Mask)

Table 11 : Relationship Between UWB TX Density and Environmental Spectral Power Density Values Obtained in Each Evaluation Zone (Free-Space Model)

Zone (m x m)	UWB TX Density (dB TX/km^2)	Difference (dB)	Environmental SPD at 1 GHz (dBm/MHz)	Difference (dB)
100 x 100	40.0	–	-83.2	–
300 x 300	30.5	-9.5	-97.1	-13.9
1000 x 1000	20.0	-20.0	-112.2	-15.1

Note: Each UWB TX SPD = -41.3 dBm/MHz (Maximum of FCC Mask)

Table 12 : Relationship Between UWB TX Density and Environmental Spectral Power Density Values Obtained in Each Evaluation Zone (Log-Distance n=3 Model)

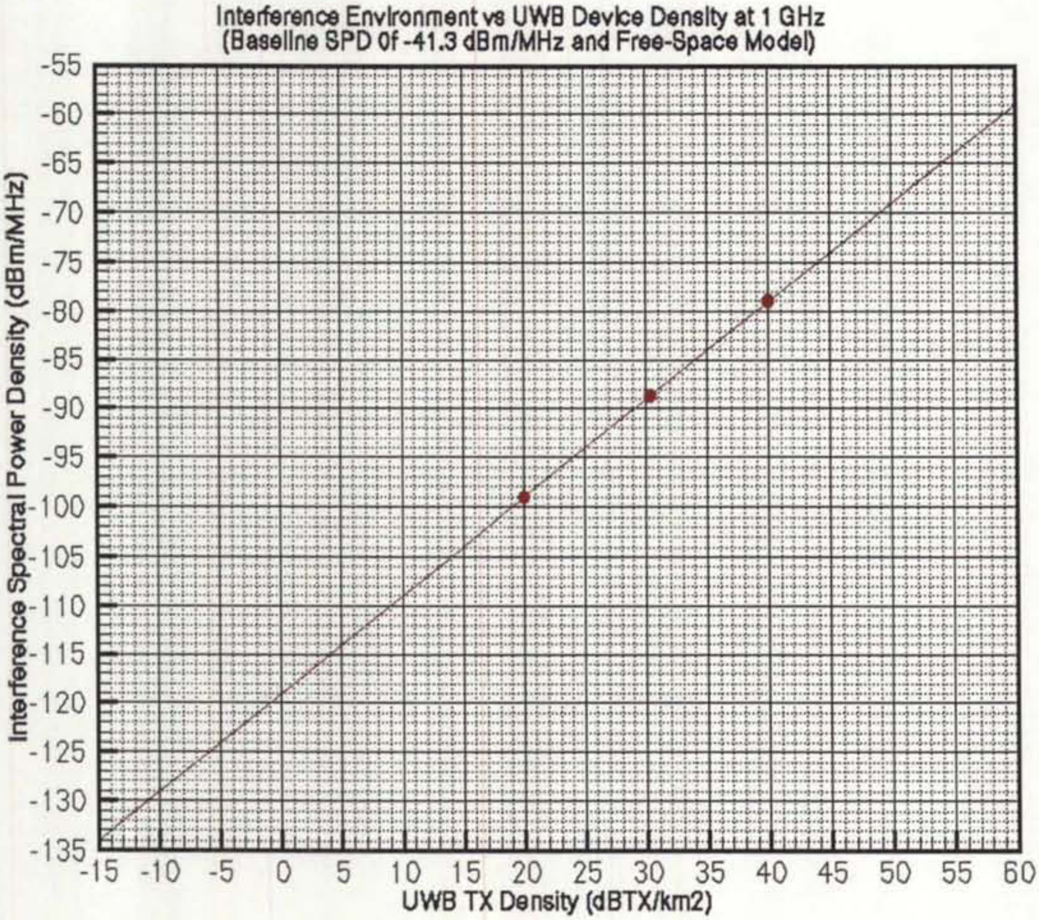

Figure 22 : Interference Environment vs UWB Device Density (Free-Space Model)

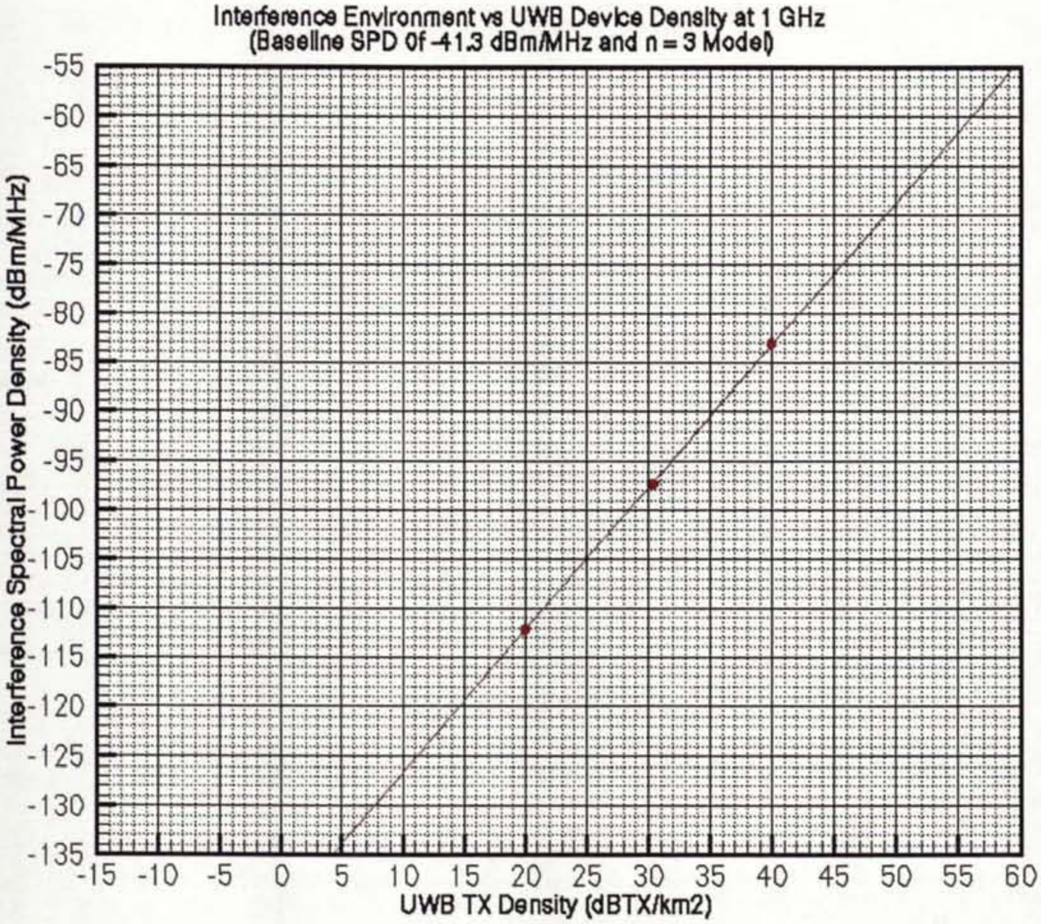

Figure 23 : Interference Environment vs UWB Device Density (Log-Distance Model)

5.0 EMC METHODOLOGY

From the results obtained in this work, one can develop an EMC methodology to assess the possibility of potential interference to conventional radiocommunications systems, when these are subjected to an EM environment with a large number of UWB devices in operation. The major finding is that the value of the environmental spectral power density is directly related to the spatial density of UWB devices in an environment.

Because the results reflect the datum (baseline conditions) of 1 GHz and UWB device output of -41.3 dBm/MHz, certain modifications have to be made to make the EMC methodology universally applicable to any frequency and UWB device output level. The following is a step-by-step description of the EMC methodology, reflecting these modifications.

a) Key definitions for the methodology.

S – Victim System Receiver Minimum Sensitivity Level in *dBm*

C/I or IM – Victim System Carrier-to-Interference Ratio or Interference Margin in *dB*

BW – Victim System Bandwidth in *dBMHz* (10 $\log_{10}$(Bandwidth in MHz))

G_{RX} – Victim System Antenna Gain in *dBi*

VI_{SPD} – Maximum Permissible Interference Spectral Power Density at Victim's Receiver Input in *dBm/MHz*

ΔM – UWB Device Type Dependent Suppression (FCC Masks) in *dB* (positive number)

FR – Frequency Ratio relative to 1 GHz in *dB* (20 $\log_{10}(f_{GHz}/1)$)

UD – UWB Device Density in an area in *dBTX/km²* (10 $\log_{10}$(UWB Density in TX/km^2))

UD_{max} – Maximum Permissible UWB Device Density in an area in *dBTX/km²* (10 $\log_{10}$(Maximum Permissible UWB Density in TX/km^2))

INT_{SPD} – Interference Spectral Power Density due to UD at datum in *dBm/MHz*

EME_{SPD} – EM Environmental Spectral Power Density in an area in *dBm/MHz*

b) The potential victim system's receive characteristics have to be converted into spectral power density units of *dBm/MHz*, in front of (or before) its antenna. This becomes the maximum permissible interference spectral power density at victim receiver's input (VI_{SPD}), and is given by:

$$VI_{SPD} = S - IM - G_{RX} - BW \qquad dBm/MHz \qquad (5\text{-}1)$$

c) An UWB device density UD is given. Then, depending on the selected propagation path loss model, the interference spectral power density (INT_{SPD}) is obtained by:

$$INT_{SPD} = UD - 119.0 \qquad \text{(Free-Space Model)} \qquad (5\text{-}2)$$

$$INT_{SPD} = 1.45 \times UD - 141.2 \qquad \text{(Log-Distance } n = 3 \text{ Model)} \qquad (5\text{-}3)$$

d) Because the above expressions for INT_{SPD} represent the datum, to obtain the environmental spectral power density requires that frequency and proper power suppression be accounted for. Therefore, the environmental spectral power density in an area (EME_{SPD}) is given by:

$$EME_{SPD} = INT_{SPD} - FR - \Delta M \qquad dBm/MHz \qquad (5\text{-}4)$$

e) A potential for interference is indicated if:

$$EME_{SPD} \geq VI_{SPD} \qquad (5\text{-}5)$$

f) If an interference potential is indicated, an in-depth EMC analysis may be required. From a regulatory perspective, a maximum UWB device density may be imposed if practical, or further device power reductions be prescribed to eliminate this potential. The maximum permissible UWB device density in an area (UD_{max}) can be determined from:

$$UD_{max} = VI_{SPD} + 119.0 + FR + \Delta M \qquad \text{(Free-Space Model)} \qquad (5\text{-}6)$$

$$UD_{max} = \{VI_{SPD} + 141.2 + FR + \Delta M\} / 1.45 \qquad \text{(Log-Distance } n = 3 \text{ Model)} \qquad (5\text{-}7)$$

5.1 EXAMPLES

Two examples are given below to illustrate the methodology. The first example is an analog cellular system at 830 MHz, while the second is a digital personal communication (PCS) system at 1900 MHz.

5.1.1 Analog Cellular System

Base Receive Frequency : 830 MHz

Receiver Minimum Sensitivity Level : –113 dBm

Bandwidth : 30 KHz (0.030 MHz) or –15.22 dBMHz

C/I or IM : 6 dB (assumed)

Antenna Gain : 13 dBi

First, determine the maximum permissible interference spectral power density (VI_{SPD}), from equation (5-1):

$$VI_{SPD} = S - IM - G_{RX} - BW$$

$$VI_{SPD} = -113 - 6 - 13 - (-15.2) = -116.8 \text{ dBm/MHz}$$

Assume that there are UWB devices of the outdoor hand-held type in the vicinity, with a density of 10 per km^2 which is equivalent to 10 dBTX/km^2. Thus, UD = 10 dBTX/km^2.

a) Assume Free-Space Conditions

Obtain the interference spectral power density (INT_{SPD}) due to UD, from equation (5-2):

$$INT_{SPD} = UD - 119$$

$$INT_{SPD} = 10 - 119 = -109 \text{ dBm/MHz}$$

The frequency ratio (FR) is given by $20 \log_{10}(f_{GHz}/1)$:

$$FR = 20 \log_{10}(0.830/1) = -1.6 \text{ dB}$$

From the appropriate FCC Mask, at 830 MHz, $\Delta M = 0$ dB.

The environmental spectral power density (EME_{SPD}) is determined from equation (5-4):

$$EME_{SPD} = INT_{SPD} - FR - \Delta M$$

$$EME_{SPD} = -109 - (-1.6) - 0 = -107.4 \text{ dBm/MHz}$$

Finally, EME_{SPD} is compared with VI_{SPD} (equation (5-5)):

$$EME_{SPD} - VI_{SPD} = -107.4 - (-116.8) = 9.4 \text{ dB}$$

Conclusion: A potential for interference is indicated by a margin of 9.4 dB. Further detailed EMC analysis is required.

b) Assume Log-Distance (n=3) Conditions

Obtain interference spectral power density (INT_{SPD}), caused by UD, from equation (5-3):

$$INT_{SPD} = 1.45 \times UD - 141.2$$

$$INT_{SPD} = 1.45 \times 10 - 141.2 = 14.5 - 141.2 = -126.7 \text{ dBm/MHz}$$

The environmental spectral power density (EME_{SPD}) is determined from equation (5-4):

$$EME_{SPD} = INT_{SPD} - FR - \Delta M$$

$$EME_{SPD} = -126.7 - (-1.6) - 0 = -125.1 \text{ dBm/MHz}$$

EME_{SPD} is compared with VI_{SPD} (equation (5-5)):

$$EME_{SPD} - VI_{SPD} = -125.1 - (-116.8) = -8.3 \text{ dB}$$

Conclusion: A potential for interference is not indicated since the margin is negative.

Comment: The final outcome is dependent on the propagation model used. If the Free-Space Model is considered appropriate, and a further EMC analysis is not decided upon, then a mitigation measure may be applied by determining a maximum UWB device density (UD_{max}) from equation (5-6):

$$UD_{max} = VI_{SPD} + 119.0 + FR + \Delta M \qquad \text{(Free-Space Model)}$$

$$UD_{max} = -116.8 + 119.0 + (-1.6) + 0 = 0.6 \text{ dBTX/km}^2$$

$$\text{or } 1.15 \text{ TX/km}^2$$

However, the Free-Space propagation path loss model will always yield a worst-case result, while the Log-Distance propagation path loss model will yield a more suitable outcome for an urban environment, as seen with this example. A maximum UWB device density of 1.15 per square km is unrealistic, but its determination serves to illustrate the mitigation measure.

5.1.2 Digital Personal Communications Services (PCS)

Base Receive Frequency : 1900 MHz

Receiver Minimum Sensitivity Level : –110 dBm

Bandwidth : 1.230 MHz or 0.9 dBMHz

C/I or IM : 6 dB (assumed)

Antenna Gain : 15 dBi

First, determine the maximum permissible interference spectral power density (VI_{SPD}), from equation (5-1):

$$VI_{SPD} = S - IM - G_{RX} - BW$$

$$VI_{SPD} = -110 - 6 - 15 - 0.9 = -131.9 \quad \text{dBm/MHz}$$

a) Assume Free-Space Conditions

Assume that there are UWB devices of the outdoor hand-held type in the vicinity, with a density of 1,000 per km^2 which is equivalent to 30 $dBTX/km^2$. Thus, UD = 30 $dBTX/km^2$.

Obtain the interference spectral power density (INT_{SPD}) caused by UD, from equation (5-2):

$$INT_{SPD} = UD - 119$$

$$INT_{SPD} = 30 - 119 = -89 \quad \text{dBm/MHz}$$

The frequency ratio (FR) is given by 20 $\log_{10}(f_{GHz}/1)$:

$$FR = 20\log_{10}(1.90/1) = 5.6 \quad \text{dB}$$

From the appropriate FCC Mask, at 1900 MHz, $\Delta M = 63.3$ dB.

The environmental spectral power density (EME_{SPD}) is determined from equation (5-4):

$$EME_{SPD} = INT_{SPD} - FR - \Delta M$$

$$EME_{SPD} = -89 - 5.6 - 63.3 = -157.9 \quad \text{dBm/MHz}$$

Finally, EME_{SPD} is compared with VI_{SPD}, (equation (5-5)):

$$EME_{SPD} - VI_{SPD} = -157.9 - (-131.9) = -26.0 \text{ dB}$$

Conclusion: A potential for interference is not indicated since the margin is negative.

b) Assume Log-Distance (n=3) Conditions

Assume that there are UWB devices of the outdoor hand-held type in the vicinity, with a density of 100,000 per km^2 which is equivalent to 50 dBTX/km^2. Thus, UD = 50 dBTX/km^2, (NOTE: A higher UWB device density than in a) above).

Obtain interference spectral power density (INT_{SPD}), caused by UD, from equation (5-3):

$$INT_{SPD} = 1.45 \times UD - 141.2$$

$$INT_{SPD} = 1.45 \times 50 - 141.2 = 72.5 - 141.2 = -68.7 \text{ dBm/MHz}$$

The environmental spectral power density (EME_{SPD}) is determined from equation (5-4). FR and ΔM have the same values as before.

$$EME_{SPD} = INT_{SPD} - FR - \Delta M$$

$$EME_{SPD} = -68.7 - 5.6 - 63.3 = -137.6 \text{ dBm/MHz}$$

Finally, EME_{SPD} is compared with VI_{SPD}, (equation (5-5)):

$$EME_{SPD} - VI_{SPD} = -137.6 - (-131.9) = -5.7 \text{ dB}$$

Conclusion: A potential for interference is not indicated since the margin is negative.

Once again, the above result indicates that the Log-Distance propagation path loss model is quite suitable for use when urban areas are under consideration. Even with a hypotethical UWB device density of 100,000 per square km, no potential for interference is indicated. It is instructive to determine the maximum permissible UWB device density in an area (UD_{max}) for the above case, by means of equation (5-7), to gauge the spectrum sharing potential of outdoor hand-held UWB devices with the PCS Service.

$$UD_{max} = \{VI_{SPD} + 141.2 + FR + \Delta M\} / 1.45$$

$$UD_{max} = \{-131.9 + 141.2 + 5.6 + 63.3\} / 1.45 = 53.9 \text{ dBTX/km}^2$$

$$\text{or} \sim 247{,}231 \text{ TX/km}^2$$

6.0 CONCLUSIONS

Starting with the regulatory limits of the FCC for maximum spectral power density imposed on UWB devices as a datum, a study has been carried out to characterize and quantify the cumulative effects of a large number of UWB devices operating within the EM environment.

One item that must be mentioned is the way the FCC has defined the UWB device spectral power density. It has chosen the Part 15.209 limit above 960 MHz, converted to EIRP at 3 metres, as the maximum emission limit, and measured this with a resolution bandwidth of 1 MHz. This leads to a maximum 'spectral power density' limit of -41.3 dBm/MHz (normally, the spectral power density is determined from the pulse characteristics such as waveform, modulation, repetition rate, rise and fall times, coding, etc). In this study, we have assumed that the UWB devices meet the limits imposed by the FCC, therefore, no separate analysis was undertaken of the UWB device emission waveforms.

In this work, a definite connection was established between UWB device density and the resulting effect on EM environment ambient levels.

In conjunction with the findings, an EMC methodology was successfully developed for use as an assessment tool, to determine any potential interference to other radiocommunications systems operating within the same environment. While the EMC methodology was developed for UWB devices, it is equally applicable to all low power portable devices. As far as any limitation that can be ascribed to this methodology, it is related not to the design itself, but to the propagation path loss model. The two path loss models used in this work are suitable for up to a distance of a few kilometres. Any larger distances require other propagation path loss models and modified model equations.

It is foreseen that this EMC methodology could be utilized as a spectrum management tool, for the harmonious sharing of the EM spectrum by UWB systems and all other radiocommunications services.

7.0 REFERENCES

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[2] Arto Chubukjian, Internal CRC Technical Memorandum, available on request.

[3] Æther Wire & Location, Inc. http://www.aetherwire.com/

[4] NTIA Special Publication 01-43, “Assessment of Compatibility Between Ultrawideband Devices and Selected Federal Systems”, January 2001, National Telecommunications and Information Administration, U.S. Department of Commerce.

[5] Report RA0699/TDOC/99/002, “An Investigation into the Potential Impact of Ultra-Wideband Transmission Systems”, Multiple Access Communications Ltd., Southampton, U.K., February 2000.

[6] Theodore S. Rappaport, “Wireless Communications”, Prentice Hall PTR, 1996.

APPENDIX A

ILLUSTRATION OF RANDOMLY DISTRIBUTED UWB TRANSMITTERS IN EVALUATION ZONES

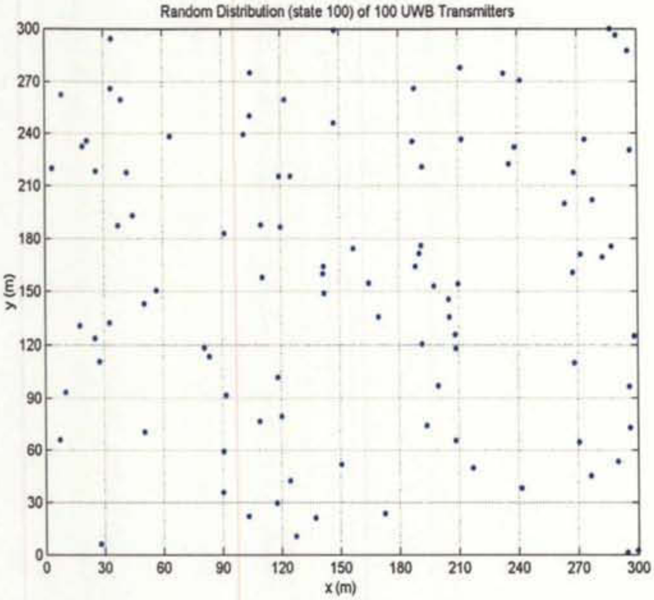

Figure A1 : Illustration of 100 Randomly Distributed UWB Transmitters within the 300 m by 300 m Evaluation Zone

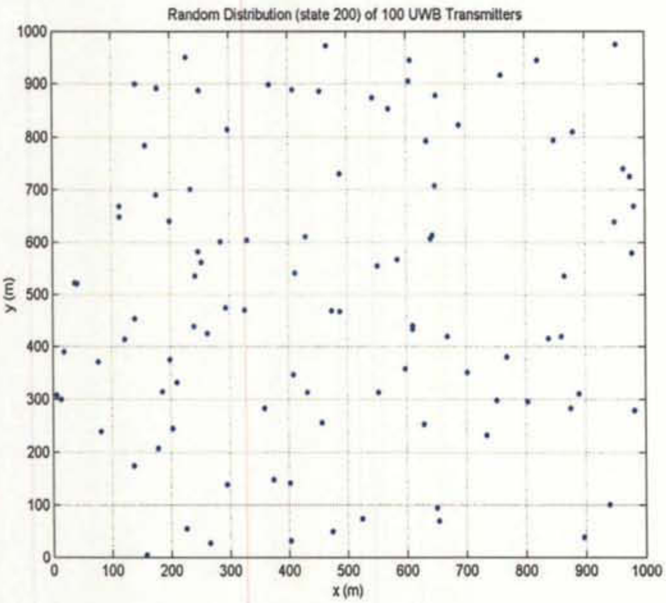

Figure A2 : Illustration of 100 Randomly Distributed UWB Transmitters within the 1000 m by 1000 m Evaluation Zone

APPENDIX B

INTERFERENCE SPECTRAL POWER DENSITY CONTOUR DIAGRAMS IN EVALUATION ZONES

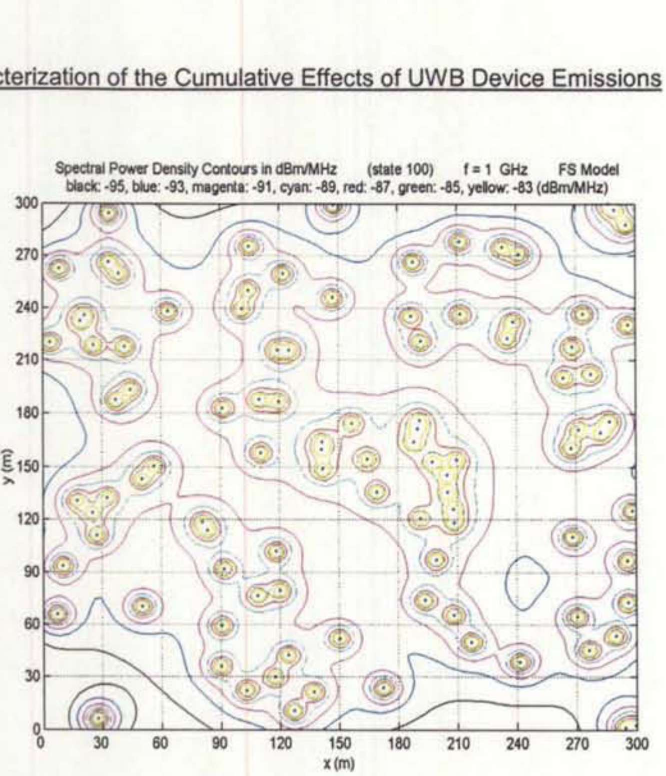

Figure B1 : Spectral Power Density Contours (Free-Space) within the 300 m by 300 m Evaluation Zone

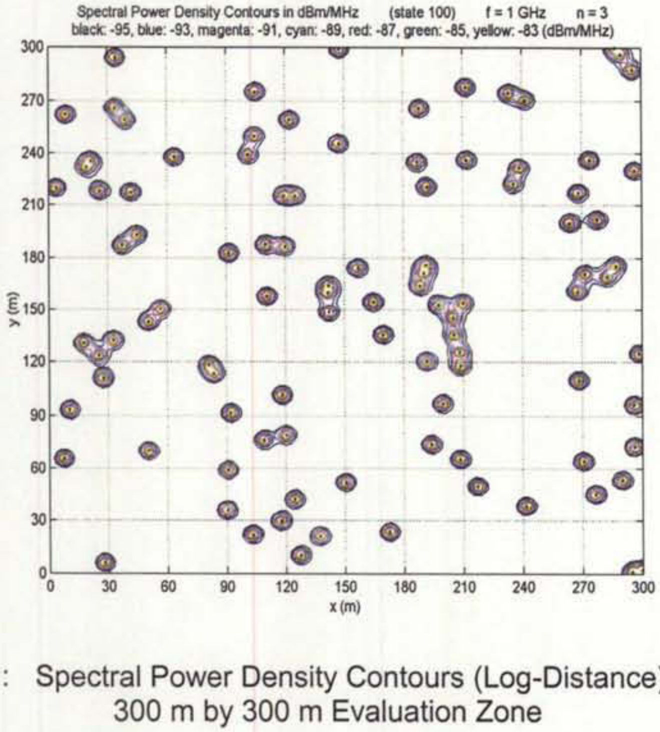

Figure B2 : Spectral Power Density Contours (Log-Distance) within the 300 m by 300 m Evaluation Zone

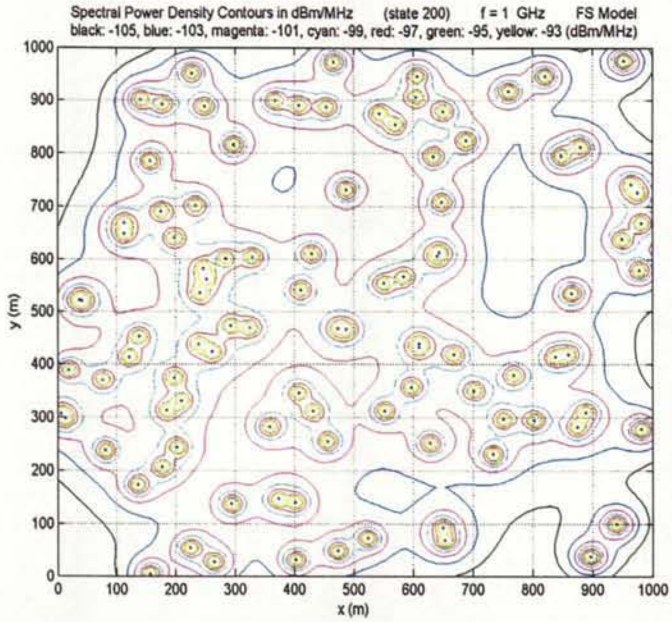

Figure B3 : Spectral Power Density Contours (Free-Space) within the 1000 m by 1000 m Evaluation Zone

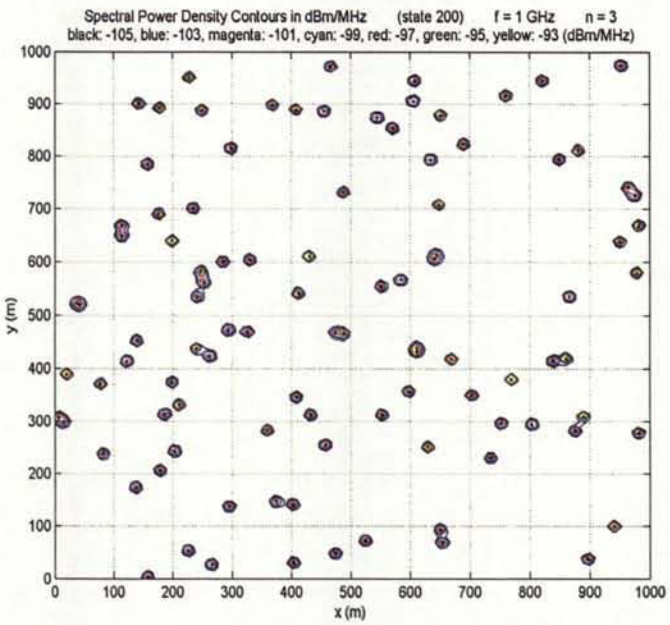

Figure B4 : Spectral Power Density Contours (Log-Distance) within the 1000 m by 1000 m Evaluation Zone

APPENDIX C

SCATTER DIAGRAMS IN EVALUATION ZONES

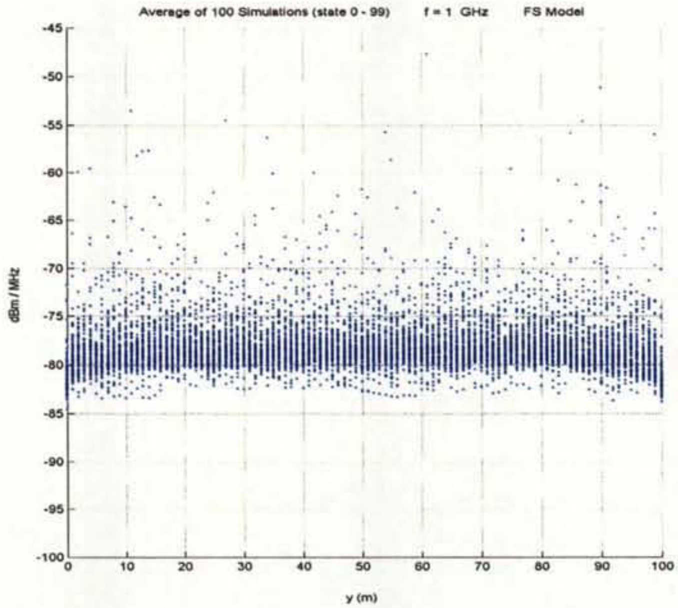

Figure C1 : Scatter Diagram (Free-Space) within the 100 m by 100 m Evaluation Zone (viewed along x-axis)

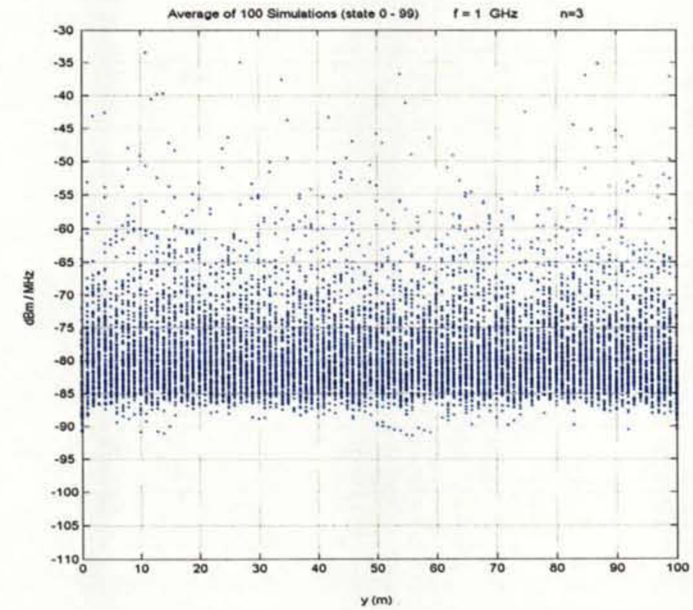

Figure C2 : Scatter Diagram (Log-Distance) within the 100 m by 100 m Evaluation Zone (viewed along x-axis)

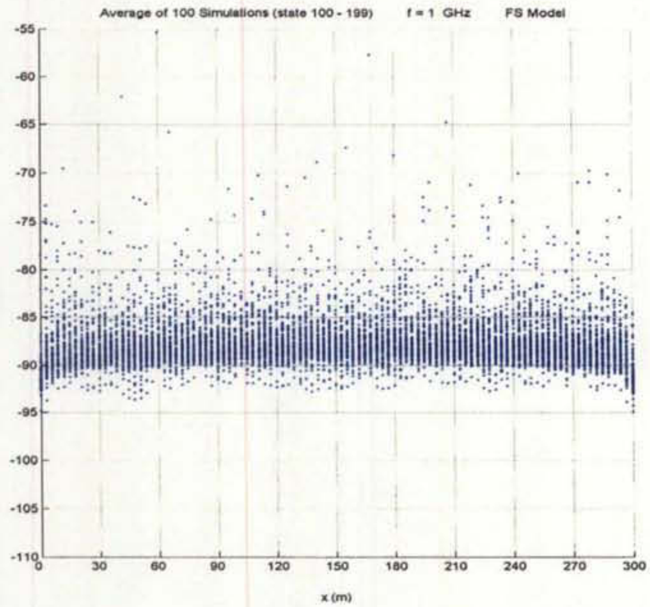

Figure C3 : Scatter Diagram (Free-Space) within the 300 m by 300 m Evaluation Zone (viewed along y-axis)

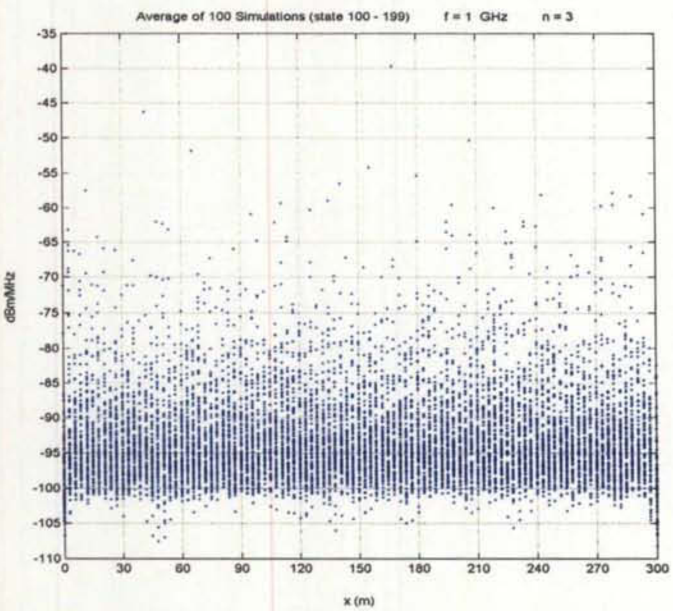

Figure C4 : Scatter Diagram (Log-Distance) within the 300 m by 300 m Evaluation Zone (viewed along y-axis)

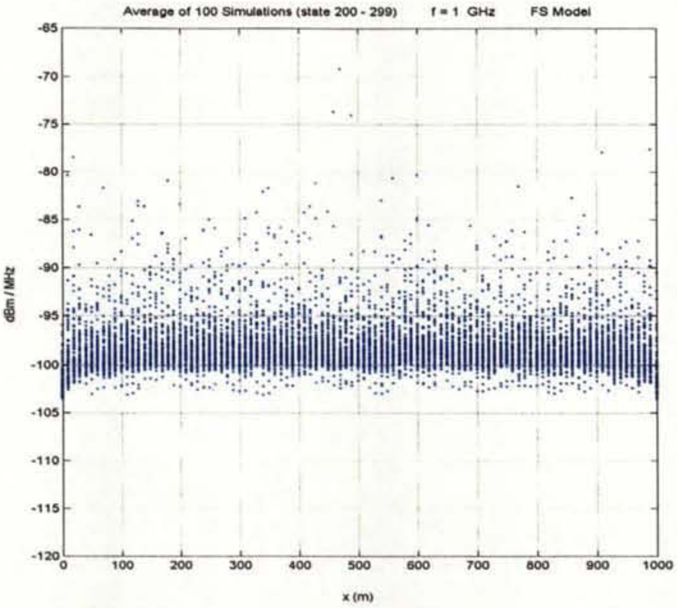

Figure C5 : Scatter Diagram (Free-Space) within the 1000 m by 1000 m Evaluation Zone (viewed along y-axis)

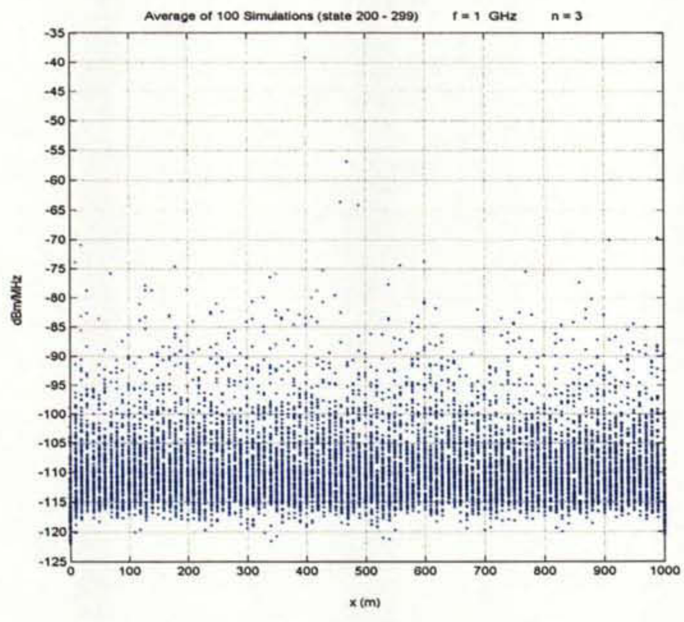

Figure C6 : Scatter Diagram (Log-Distance) within the 1000 m by 1000 m Evaluation Zone (viewed along y-axis)

APPENDIX D

HISTOGRAMS IN EVALUATION ZONES

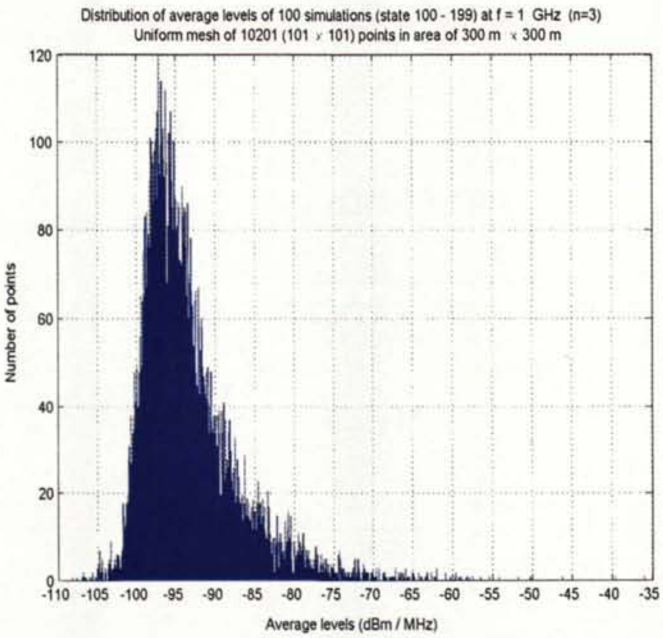

Figure D1 : Histogram (Log-Distance) within the 300 m by 300 m Evaluation Zone

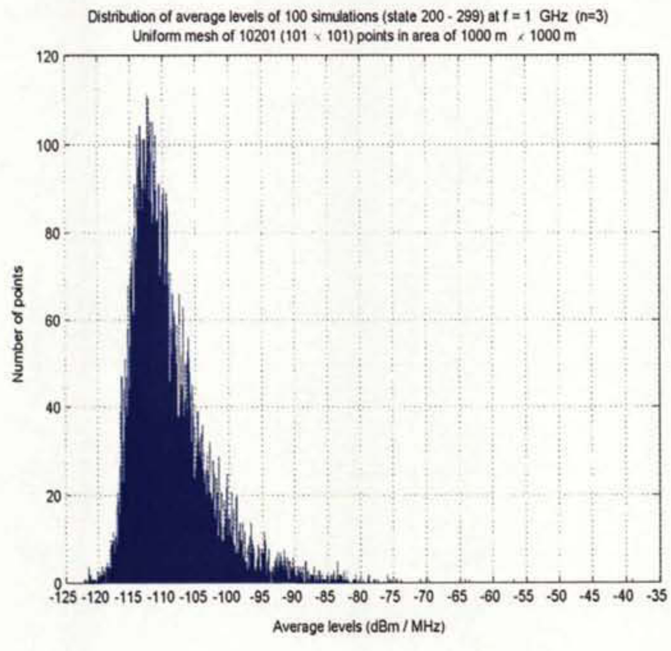

Figure D2 : Histogram (Log-Distance) within the 1000 m by 1000 m Evaluation Zone

APPENDIX E

PROPAGATION PATH LOSS MODELS

DERIVATION OF PROPAGATION PATH LOSS MODELS

The Free-Space propagation path loss model is based on the spherical spreading of power flux emitted by an electromagnetic source, such as an isotropic antenna, as a function of distance. It can be derived as follows.

The equivalent isotropic radiated power emitted is:

$$P_{TX} = EIRP \qquad \text{Watts} \tag{E-1}$$

The power flux density as a function of distance R is given by:

$$W = \frac{EIRP}{4\pi R^2} \qquad \text{Watts/m}^2 \tag{E-2}$$

The received power by an antenna located at a distance R is:

$$P_{RX} = W \times A_e \qquad \text{Watts} \tag{E-3}$$

where A_e is the effective area of the antenna.

The Gain of an antenna is defined as:

$$G = \frac{4\pi A_e}{\lambda^2} \tag{E-4}$$

where λ is the wavelength. In the isotropic case G=1. Therefore,

$$A_e = \frac{\lambda^2}{4\pi} \qquad \text{m}^2 \tag{E-5}$$

Substituting Equations (E-2) and (E-5) into Equation (E-3):

$$P_{RX} = \frac{EIRP}{4\pi R^2} \times \frac{\lambda^2}{4\pi} \qquad \text{Watts} \tag{E-6}$$

The Free-Space propagation path loss, defined in positive terms, is the ratio of P_{TX} to P_{RX}, or Equation (E-1) divided by Equation (E-6). Thus,

$$LossFS = \frac{P_{TX}}{P_{RX}} = \frac{EIRP}{\left(\frac{EIRP}{4\pi R^2} \times \frac{\lambda^2}{4\pi}\right)} = \frac{(4\pi R)^2}{\lambda^2} \qquad \text{(E-7)}$$

In the case of the Log-Distance propagation path loss model, based on empirical results, the exponent of R is taken to be larger than 2. In this study, the exponent was chosen to be 3. Therefore,

$$LossLD = \frac{P_{TX}}{P_{RX}} = \frac{(4\pi)^2 \times R^3}{\lambda^2} \qquad \text{(E-8)}$$

Since $\lambda = {}^{c}\!/\!_{f}$ where c is the speed of light and f is the frequency, Equations (E-7) and (E-8) can be rewritten as:

$$LossFS = \frac{P_{TX}}{P_{RX}} = \left(\frac{4\pi fR}{c}\right)^2 \qquad \text{(E-9)}$$

$$LossLD = \frac{P_{TX}}{P_{RX}} = \left(\frac{4\pi f}{c}\right)^2 \times R^3 \qquad \text{(E-10)}$$

or, in logarithmic form,

$$LossFS = 10\log_{10} P_{TX} - 10\log_{10} P_{RX} = 20\log_{10}\left(\frac{4\pi fR}{c}\right) \qquad \text{(E-11)}$$

$$LossFS = 20\log_{10}\left(\frac{4\pi}{3x10^8}\right) + 20\log_{10}(f_{Hz}) + 20\log_{10}(R_m)$$

In terms of frequency relative to 1 MHz, we have:

$$LossFS = 20\log_{10}\left(\frac{4\pi}{3}\right) - 20\log_{10}\left(10^8\right) + 20\log_{10}(f_{MHz}) + \\ 20\log_{10}\left(10^6\right) + 20\log_{10}(R_m)$$

$$LossFS = \left[12.44 - 160 + 20\log_{10}(f_{MHz}) + 120 + 20\log_{10}(R_m)\right]$$

$$LossFS = \left[-27.56 + 20\log_{10}(f_{MHz}) + 20\log_{10}(R_m)\right] \quad dB \qquad (E\text{-}12)$$

Similarly, for the Log-Distance propagation path loss model, we have,

$$LossLD = \left[-27.56 + 20\log_{10}(f_{MHz}) + 30\log_{10}(R_m)\right] \quad dB \qquad (E\text{-}13)$$

DATE DUE

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