Maximum and Average Field Strength in Enclosed Environments

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Abstract- **Electromagnetic fields in large enclosed environments are reflected many times and cannot be predicted anymore using conventional models. The common approach is to compare such environments with highly-reflecting reverberation chambers. The average field strength can easily be predicted using the central limit theorem. The maximum field strength is, in theory, nearly impossible to predict. Actual environments are however not perfect, and the maximum field strength is bound to a maximum. A ray-tracing model has been developed to predict the maximum field for actual (lossy) environments and measurements in a reverberation chamber has been carried out**.

Keywords; Reverberation, multiple reflections, enclosed environments

I. Introduction

Electronic equipment is often susceptible to the maximum field strength instead of the average field strength. In living semi-enclosed environments with many reflections, such as an aircraft fuselage, cars, trains, shelters or cabinets, the field will be reflected many times. The field distribution cannot be easily predicted using deterministic techniques, such as ray tracing, or numeric techniques, via the finite difference time domain or transmission line modelling method. The reason is the numerous unpredictable reflections, paths and continuous change in the boundary conditions. The conventional approach to predict the electromagnetic field strength is therefore to use either a simple assumption based on a few reflections, which is very erroneous, or to use a probabilistic approach. In this case we assume numerous (infinite number) of reflections which are adding up and create a so called, statistically, uniform, isotropic electromagnetic field. This has been applied to predict the field distribution in a highly-reflective reverberation chambers [1][2][3]. The key assumption is the Central Limit Theorem (CLT), showing that any sum of many samples (mostly infinite) will always result in a normal distribution [4]. Then the total electric field magnitude is, assuming independent, uncorrelated, normally distributed random variables, distributed according to the X distribution with 6 degrees of freedom, as shown in Figure 1. From the mathematical model we can conclude that the maximum field strength is never achieved. To show this, the logarithm of the pdf is also drawn. But this does not correspond to the physical model. Many living environments are enclosed and are causing multiple reflections. The maximum field strength in a highly reflecting reverberation chamber has been predicted and measured [5][6][7]. The field strength in a semi-enclosed living environments, i.e. not highly-reflective, is much more difficult to predict. In the Power balance Method [9], the average field strength is predicted. In this paper we will show some measurements data and simulation results on the maximum field strength in reflecting environments.

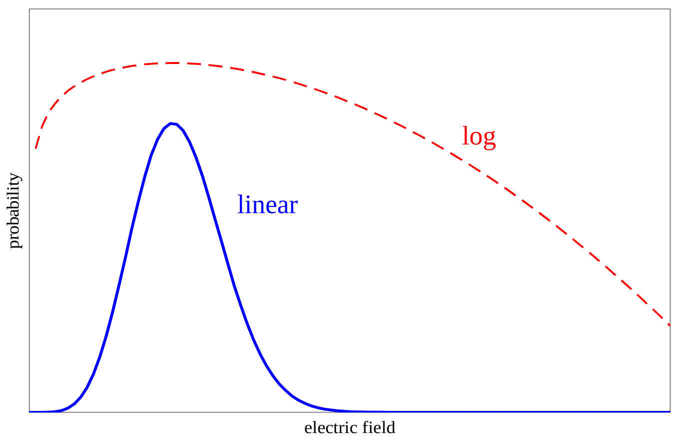

Figure 1. Probability density function of the total electric field magnitude, in linear and logarithmic format

II. MAXIMUM FIELD STRENGTH, IDEAL CASE

In an ideal case of a resonating cavity or similar environment there will be abundant reflections giving lot of independent samples for the validity of the statistical tools to be applied and study the distribution function of the electric field. Using the theory of order statistics we can determine the probability density function (pdf) of the maximum of N independent samples of a known arbitrary distribution [7][8]. If the pdf of N arbitrary samples is denoted by $f_A(x)$, and the cumulative function by $F_A(x)$, then the maximum of the distribution is given by

$$f\lceil A \rceil_N (x) = N[F_A(x)]^{N-1} f_A(x) \qquad (1)$$

In this paper, we restrain ourselves to the maximum value of the function, rather than discussing about the extreme values of a function. It is known that the E_x, E_y, E_z components follow the normal distribution and the power of the E field follows a Rayleigh distribution, which is also denoted by χ_2^2 .For a χ_2^2 distribution, such as for received power, the mean value of the maximum field strength is

$$\left\langle \lceil \chi_2^2 \rceil_N \right\rangle \approx 2\sigma^2 \left(0.577 + \ln(N) + \frac{1}{2N} \right) \qquad (2)$$

The averaged χ_2^2 distribution as a function of the number of samples *(N)* is defined in the equation. The graph in Figure 2. is the relation between the number of samples and the maximum power received, but this is more of an ideal case where the cavity walls have perfect conductivity and no losses.

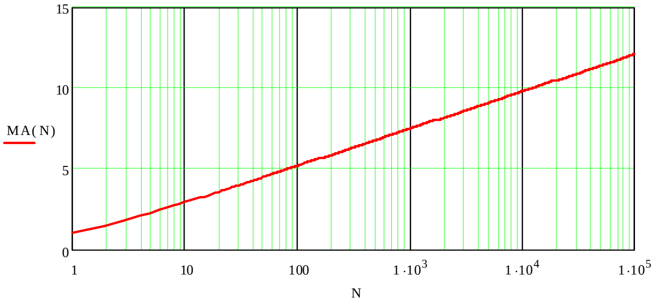

Figure 2. Estimation of the maximum received power as function number of samples

III. MAXIMUM IN REVERBERATION CHAMBERS

For the ideal case, where the central limit theorem is applicable, it should be impossible to determine the true maximum value. However, we never have such an ideal situation because any reflecting environment will have losses, and therefore we expect a flattening of the line as shown in Figure 2. In [5] it is stated that it is extremely difficult to measure the true maximum because the received signal has to be sampled at a large number of paddle positions to ensure that the received signal is close to the true peak. The problem is that in this report the mode tuning technique is used, which means that a number of paddle positions result in a limited number of independent samples. The risk of missing the true maximum is obvious, and it is stated that the true peak cannot be measured. This is correct for mode tuning, where the number of samples is limited. Even with two independent paddle wheels, the time to perform measurement giving more than, say, 3.000 independent samples would be too much. EMI measuring receivers have two or more parallel detectors, making it possible to measure the peak and the average level of a signal, as shown in Figure 3. A measurement has been carried out with different measuring times. Therefore two antennas were placed in a vibrating intrinsic reverberation chamber (VIRC)[3], with dimensions 1.5m x 1.2m x 1.3 m, as shown in Figure 4. and Figure 5. A VIRC has flexible walls of shielded cloth that can be continuously moved in various directions causing a random field distribution.

The quality factor *Q* is the ratio of the total power to the power dissipated. This means that a high *Q* factor can give proportionally very high field. With losses included in the cavity the *Q* factor becomes lower which also means less reflection.

$$Q = \frac{\omega U}{P_d} \tag{3}$$

where *U* is the energy stored, P_d is the power injected and ω the angular frequency. With respect to reverberation chambers, there are four loss mechanisms that could be pivotally attached with the quality factor of a cavity. A main loss mechanism is the dissipation in the wall

$$Q = \frac{3}{2\delta}\frac{V}{S} \tag{4}$$

where V is the Volume of the chamber, *S* is the surface area of the chamber and δ is the skin depth of the walls of the chamber, and thus includes the loss.

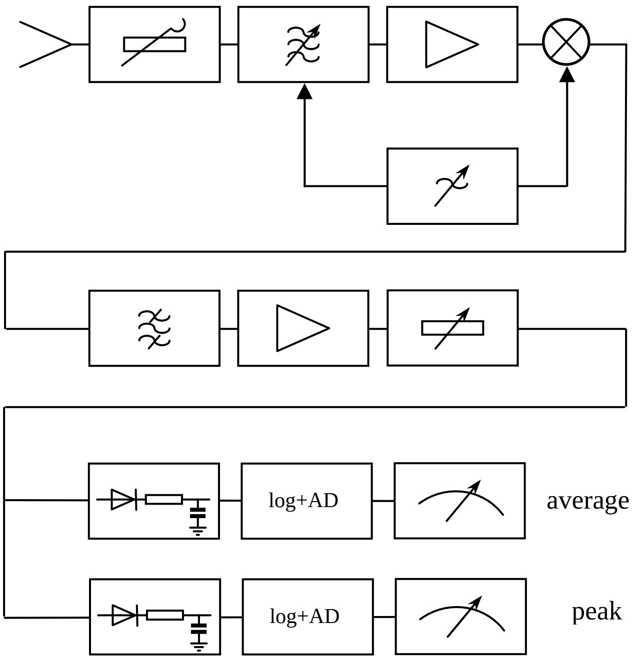

Figure 3. Parallel detectors in an EMI measuring receiver

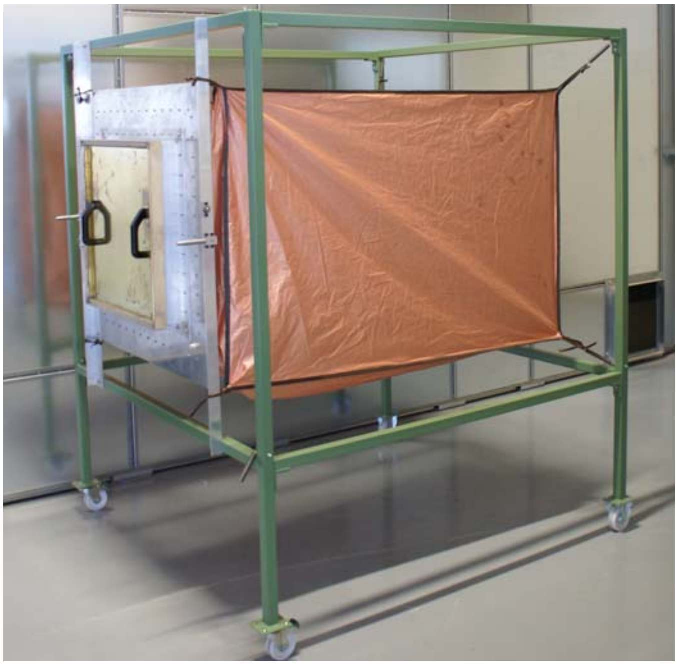

Figure 4. VIRC

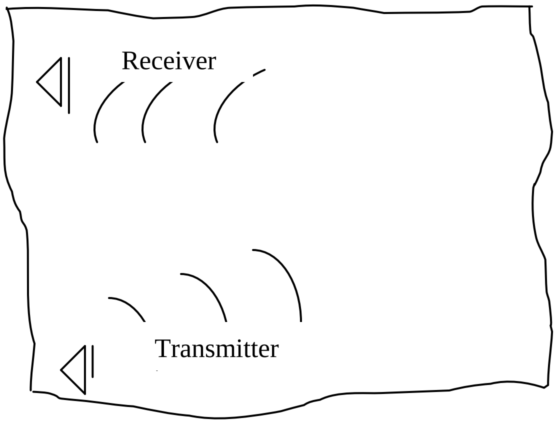

Figure 5. Measurement setup in VIRC

The measured average level as function of the frequency, between 1100 and 1200 MHz, is shown in Figure 6. The peak level is shown in Figure 7.

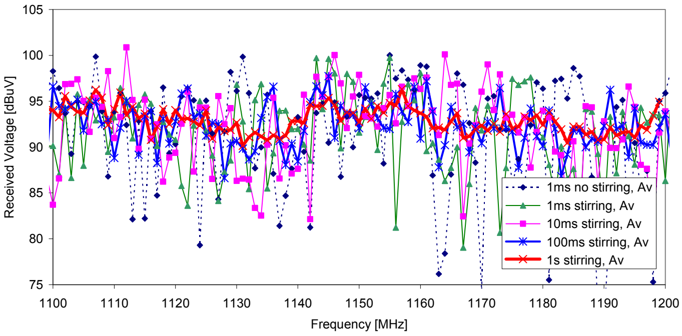

Figure 6. Average signal level

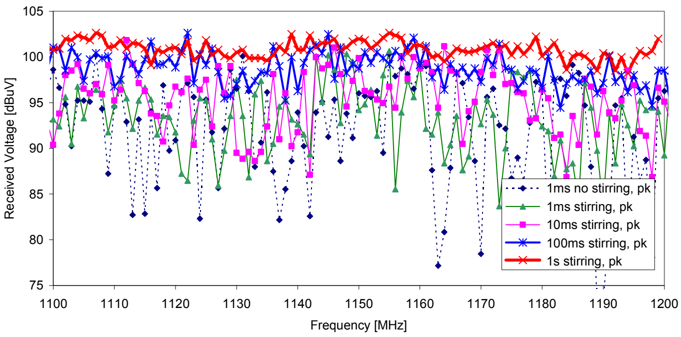

Figure 7. Peak signal level

We can observe that the average remains more or less the same, as expected, but the peak level is much more increasing with measuring time, i.e. sample time, i.e. number of samples. This has been calculated for the frequency range 1-2 GHz, shown in Table 1.

From [3] we know that independent samples in a VIRC are dependant of the movements and the frequency. As a rule of thumb we can use 1 ms at 1 GHz, and for instance 100ms is therefore approximately 100 independent samples.

TABLE 1

Stirring time	1ms	10ms	100ms	1000ms
Mean average detector	90.2	90.5	91.4	92.9
Mean peak detector	92.1	94.1	97.8	101.1
Difference average-peak	1.9	3.6	6.4	8.2

Another dataset was used for a similar experiment. In this case the field strength in the 3 orthogonal directions has been measured using a logger, and sampling every 1ms. The peak and average was taken from the data set using the average and the peak power of the E-field:

$$\langle E_X \rangle = \frac{\sum_{N=1}^{K} E_N}{N} \quad (5)$$

for $K= 1,3,10,30,100,300,1000,$ *and 3000.*

and the Peak electric field is measured using

$$E_{PK} = \max\{E_N\} \quad (6)$$

for time shifts of 10ms, 100ms and1000ms.

The data obtained with the field strength sensors in the three directions are in normal cases corrected with the calibration factor, but this has been removed in this special case, because now, due to the different conversion factors the three curves are easier to observe, see Figure 8.

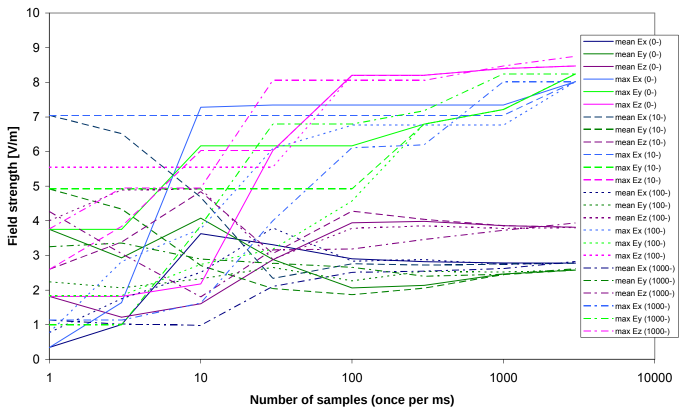

Figure 8. Mean and maximum field strength as function of number of samples

IV. Maximum level, semi-enclosed environments

The Central Limit Theorem suggests an ever increasing probability of maximum field strength. Actual environments have losses, and therefore multiple reflected waves should decrease in amplitude. Simulations have been performed for an actual enclosed environment using ray- based method [10]. Considering an unknown or arbitrary geometry of an enclosed environment, the ray description of the electric field at the receiver (observation point *P*) can be written as

$$E(P) = \sum_i E_i(P) \qquad (7)$$

E_i is the i^{th} ray originating from the transmitting antenna and received at *(P)* after a known number of reflections along its unique path till *P*.

The above equation is a very generic summation of the all the electric field at a point *P*, but it does not say much about the losses incurred. So the next expanded equation (8) from the same referred paper talks in detail of the same summations with losses included which we are more interested.

$$E_i(P) = DF_i(P)e^{-jkR_i}\left(\prod_{m=1}^{M_i}[T_m][\Gamma_m]\right)E^{inc}(Q_1) \qquad (8)$$

Where R_i denotes the total ray path length from the source to the observation point *(P).* $DF_i(P)$ is the divergence factor, paper and $E^{inc}(Q_1)$ is the field incident at the first reflection of the ray at (Q_1).

V. Conclusion

The maximum field strength and field distribution in semi-enclosed living environment cannot be predicted easily. The basic assumptions used to describe a highly-reflective reverberation chamber, based on the central limit theorem, are not valid for the actual living environment. Measurement and simulation results show that we can make a prediction.

VI. Future work

Simulations for various levels of losses, upto the loss estimated for actual living environments, including airplane fuselage, cars, trains etc., are being performed. Measurements inside VIRC will be performed at several frequencies using the parallel detectors of a measuring receiver. Measurements will be performed for several sample sets, and and with absorbers in the VIRC to simulate lossy semi-enclosed environments.

VII. Acknowledgement

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VI . REFERENCES

[1] J. G. Kostas and B. Boverie, “Statistical model for a mode-stirred chamber,” *IEEE Trans. Electromagn. Compat.*, vol. 33, no. 4, pp.366–370, 1991.

[2] D. A. Hill, “Plane wave integral representation for fields in reverberation chambers,” *IEEE Trans. Electromagn. Compat.*, vol. 40, no. 3, pp.209–217, 1998

[3] F.B.J. Leferink, W.C. van Etten, Optimal Utilization of a Reverberation Chamber, Euro EMC 2000, Symposium on EMC, Brugge, 2000, pp. 201-206, ISBN 90-76019-14-2

[4] A. Papoulis, Probability, Random Variables and Stochastic Processes. New York: McGraw-Hill, 1984.

[5] M. L. Crawford and G. H. Koepke, Design, evaluation, and use of a reverberation chamber for performing electromagnetic susceptibility vulnerability measurements, Nat. Bureau of Standards, Boulder, CO, 1986, NBS Tech. Note 1092.

[6] D. A. Hill, Electromagnetic theory of reverberation chambers Nat. Inst. of Standards and Technology, Boulder,CO, 1998, NIST Tech. Note 1506.

[7] J. Ladbury, G. Koepke, and D. Camell, Evaluation of the NASA Langley Research Center mode-stirred chamber facility, Nat. Inst. of Standards and Technology, Boulder, CO, 1999, NIST Tech. Note 1508.

[8] R. F. Harrington, Time-Harmonic Electromagnetic Fields, NewYork: McGraw-Hill, 1961.

[9] Assessment of the Power Balance Method for E field calculations in complex cavities Andre Schaffar, Yannick Herlem

[10] Ray Analysis of Electromagnetic Field Build-Up and Quality Factor of Electrically Large Shielded Enclosures, IEEE Trans. on Electromagnetic Compatibility, Vol. 40, No. 1, pp. 19-26, February 1998

[11] M. Petirsch, A. Schwab, ‘Optimizing Shielded Chambers Utilizing Acoustic Analogies’, IEEE Symposium on EMC, 1997, pp. 154-158.

[12] J.M. Dunn, Local, High-Frequency Analysis of the Fields in a Mode-Stirred Chamber, IEEE Transactions on Electromagnetic Compatibility, Febr. 1990, pp. 53-58