ESTIMATION OF THE RICIAN K-FACTOR IN REVERBERATION CHAMBERS FOR IMPROVED REPEATABILITY IN TERMINAL ANTENNA MEASUREMENTS

Sathyaveer Prasad[1,2], Samer Medawar[2], Peter Händel[1,2], Claes Beckman [1]

[1]Center for RF Measurement Technology
University of Gävle
SE-801 76 Gävle, Sweden

[2]ACCESS Linnaeus Center
Royal Institute of Technology
SE-100 44 Stockholm, Sweden

ABSTRACT

An estimator of the Rician K-factor for reverberation chamber is derived in this paper using maximum likelihood estimation approach. This is done by reviewing the existing statistical model of the fields in the reverberation chamber. The functionality of the derived K-factor estimator is tested with the measurement data for the well stirred and unstirred (only platform stirring) chamber. Moreover, the impact of polarization of the antenna on the Rician K-factor is also investigated. The Rician K-factor is found to be almost zero for a well stirred reverberation chamber whereas it is higher for unstirred (only platform stirring) chamber. It is also observed that the orientation of half wavelength dipole influence significantly the K-factor values.

Keywords: Terminal antennas, Reverberation chamber, Rician K-factor, Line of Sight Environment, Estimator.

1. Introduction

In recent years, the world of mobile communications has undergone a tremendous development from using a simple mobile phone for voice services only, to a complicated device for high data rate services. In order to work, modern mobile phones have to operate at multiple bands and make use of multiple access methods. This has called for antenna solutions that are broadband and integrated into the terminals. However, there are well known relationships between bandwith, size and efficiency of antennas. Mobile phones are held close to the head which adds losses and further deteriorates the performance of the antenna. Hence, today's internal antennas typically have poorer efficiency than the previous external ones [1].

In order to verify the efficiency of the terminal antennas a reliable and repeatable test method is needed [2, 3]. The method needs to have the capability of emulating an arbitrary multipath environment and, thus, accurately estimate the radio performance of the terminal antennas. Currently, methods like using an anechoic chamber [4], the Wheeler cap [5], the reverberation chamber [6], etc. are available to measure the terminal antenna performance but none of them have yet received global acceptance.

Email: prasad@hig.se, samer.medawar@ee.kth.se

During the last few years, the reverberation chamber is used to estimate the radiation performance of mobile phones [6, 7]. For example the chamber can be used to measure: the radiation efficiency [6], diversity gain [8], and the performance of multiple input multiple output (MIMO) systems [9] under the assumption that the fields inside the chamber are homogenous and Rayleigh distributed [10].

The measure of the emulated field distribution in the chamber is given by a factor called Rician K-factor, defined as the ratio of the power in the direct path to the scattered component [11]. The estimation of K is critical for various wireless applications [12] and, hence, also relevant for this application. In this paper a statistical model for the electromagnetic fields inside the reverberation chamber is discussed and an estimator for the Rician K-factor is derived. Furthermore, the impact on the accuracy and repeatability of the reverberation chamber measurement from the variation of the Rician K-factor is studied and analyzed.

2. Reverberation Chamber

The traditional method of measuring the performance of an antenna makes use of anechoic chambers. These chambers give the estimate of the radiation performance of the mobile terminal antennas in a free space environment. However, in general the mobile terminal antenna is exposed to waves from multipath reflections and it detects the sum of all these incident waves. Anechoic chambers cannot provide an estimate of the radio performance in such environments. Hence, reverberation chambers were developed as high field amplitude facilities for electromagnetic interference and compatibility testing [13]. The reverberation chamber is a large metallic cavity, designed to support several cavity modes at the operational frequency. When a sufficient number of resonant modes in the chamber exists, a rich scattering environment is created. Due to this phenomenon, the phase information is totally lost and the E-field vector at any location in the chamber is seen as the sum of multipath plane waves with random phases [10]. This means that a statistically uniform E-field is created inside the chamber with a uniform distribution of wave directions in both azimuth and elevation. The number of modes is proportional to the dimensions of the chamber [14].

In order to increase the number of excite modes, it would be necessary to increase the chamber dimensions. Alternatively, this can be done by using stirring techniques since building a larger chamber is expensive and bulky. The basic idea is to shift the resonance frequency of the resonant modes by changing the boundary conditions of the chamber walls (i.e., change the geometry of the chamber). The resonant modes are stirred by movable stirrers, creating a statistically uniform and isotropic field inside the chamber.

The radio performance measurement of a mobile phone can now be done by placing the phone inside the reverberation chamber and measuring the received power from a monopole antenna [14].

3. The Probability Density Function of the Fields in a Reverberation Chamber

The reverberation chamber is a mode stirred facility. The fields energy change as the stirrers position is altered since the mode bandwidths and central points are affected due to the chamber structure modifications. The total field at any point is the vectorial superposition of all the plane waves. Therefore the resulting electromagnetic field, in a mode-stirred chamber at equilibrium, is complex Gaussian circularly distributed [15]. The θ component of the total electrical field E is considered, where θ is the elevation angle in a spherical coordinate system centered at the transmit antenna. The total electric field E_θ, as described in [11], at any point of this plane is the outcome of the stirred energy that is $E_\theta = E_{s\theta}$, given by

$$E_{s\theta} = E_{sr\theta} + jE_{si\theta} \tag{1}$$

where $E_{sr\theta}$ and $E_{si\theta}$ denote the real and imaginary part of $E_{s\theta}$, respectively.

The mean of the stirred components $E_{sr\theta}$ and $E_{si\theta}$ is zero and their variances are as in [16]

$$\mathrm{Var}(E_{sr\theta}) = \mathrm{Var}(E_{si\theta}) = \sigma^2 \tag{2}$$

In case of an assumed Rician distribution in the chamber a direct line of sight (LOS) component has to be added to the stirred electrical field. The total θ component of the electrical field in the chamber can now be expressed as [11]

$$E_\theta = E_{d\theta} + E_{s\theta} \tag{3}$$

where $E_{d\theta}$ is the field from the LOS component. The probability density function (pdf) for fields inside the reverberation chamber for Rician environment is [16]

$$f(|E_\theta|) = \frac{|E_\theta|}{\sigma^2} I_0\left(\frac{|E_\theta||E_{d\theta}|}{\sigma^2}\right) \exp\left(\frac{-(|E_\theta|^2 + |E_{d\theta}|^2)}{2\sigma^2}\right) \tag{4}$$

where I_0 is the zeroth-order modified Bessel function of the form [17]

$$I_0(x) = \frac{e^x}{\sqrt{2\pi x}}\left(1 + \frac{1}{8x} + \frac{9}{128x^2} + \dots\right) \tag{5}$$

Since we have a Rician environment a fair assumption of $|E_\theta||E_{d\theta}| \gg \sigma^2$ enable the Bessel function to be written in its asymptotic form

$$I_0\left(\frac{|E_\theta||E_{d\theta}|}{\sigma^2}\right) = \frac{\sigma}{\sqrt{2\pi|E_\theta||E_{d\theta}|}} \exp\left(\frac{|E_\theta||E_{d\theta}|}{\sigma^2}\right) \tag{6}$$

Inserting (6) into (4) the Rician pdf can be written as

$$f(|E_\theta|) = \frac{1}{\sigma}\sqrt{\frac{|E_\theta}{|E_{d\theta}|2\pi}} \exp\left(\frac{-(|E_\theta| - |E_{d\theta}|)^2}{2\sigma^2}\right) \tag{7}$$

Equation (7) represents the Rician pdf for the fields in reverberation chamber, under the assumption that $|E_\theta||E_{d\theta}| \gg \sigma^2$.

4. Rician K-Factor Estimation

In this section a maximum likelihood estimator (MLE) of the Rician K-factor is derived using the pdf in (7). The Rician K-factor is defined as in [11]

$$K = \frac{|E_{d\theta}|^2}{2\sigma^2} \tag{8}$$

Using (8) the pdf of $|E_\theta|$ can be written by

$$f(|E_\theta|) = \frac{1}{|E_{d\theta}|}\sqrt{\frac{K|E_\theta|}{|E_{d\theta}|\pi}} \exp\left[-\frac{K}{|E_{d\theta}|^2}(|E_\theta| - |E_{d\theta}|)^2\right] \tag{9}$$

Considering N samples of $|E_\theta|$, the joint pdf is given by

$$f(N|E_\theta|) = \frac{1}{|E_{d\theta}|^N} \prod_{i=0}^{N-1} \left(\sqrt{\frac{K|E_{\theta i}|}{|E_{d\theta}|\pi}}\right) \exp\left[-\frac{K}{|E_{d\theta}|^2} \sum_{i=0}^{N-1} (|E_{\theta i}| - |E_{d\theta}|)^2\right] \tag{10}$$

where $|E_{d\theta}|$ is constant and is considered to be the mean of direct component of the data samples. While $|E_{\theta i}|$ is i-th the electrical field data sample. In order to derive the MLE estimator of Rician K-Factor, the logarithm of (10) is derived with respect to K. Setting the derivative to, the estimated Rician K-factor can be obtained

$$\widehat{K} = \frac{N}{2} \frac{|E_{d\theta}|^2}{\sum_{i=0}^{N-1}(|E_{\theta i}| - |E_{d\theta}|)^2} \tag{11}$$

of which the accuracy is given by

$$\text{Var}(\widehat{K}) = \frac{2K^2}{N} \tag{12}$$

Using the equivalence principle one can deduce that the accuracy of the stirred component estimator is given by

$$\text{var}(\widehat{\sigma}^2) = \frac{2\sigma^4}{N} \tag{13}$$

Hence the normalized (divided by σ^2) accuracy (standard deviation) of the $\hat{\sigma}^2$ is found to be $\sqrt{2/N}$. It can be concluded that, for the same number of samples, the relative accuracy by which the gain of the reverberation chamber in Rician environment can be estimated is 1.14 times the relative accuracy in Rayleigh comparing to [18] where the relative accuracy was $\sqrt{1/N}$.

5. Measurements in Reverberation Chamber

5.1. Measurements Set-Up

The reverberation chamber is a large metal cavity [7] equipped with two mechanical mode stirrers that can be moved along the full length of each wall perpendicular to each other. The mechanical stirrers are fastened at their ends to two threaded rods so that they can be tilted or translated by rotating the rods. In addition, a circular plate, called platform, is mounted at the floor of the chamber. The platform is large enough to carry the whole measurement set-up i.e. a phantom, a stand, and antenna under test (AUT). The measurements are performed by rotating the platform. The chamber is excited by one or all three monopole antennas placed on the walls of the chamber. In order to emulate the human head a standard anthromorphic (SAM) phantom [20] is used for measurements. A half wave length dipole antenna is used as reference antenna for the calibration of the chamber.

5.2. Measurements Procedure

The measurements are performed in a Bluetest 500 high performance reverberation chamber at Chalmers University of Technology Sweden. The inner dimensions are of $1.2 \times 1.75 \times 1.8$ $[m^3]$ and an isolation of 100 dB [19]. Before measuring the AUT, a full two port calibration of the network analyzer is performed by connecting the ends of the cable from monopole (antenna on the walls) and the AUT, respectively. The chamber is characterized by measuring the reference antennas in the presence of lossy objects such as a phantom. The chamber environment for both the reference measurements and the AUT measurements are the same. The Rician K-factor measurements are done by mounting the half wave dipole antenna on a stand which in turn is placed on the platform inside the chamber. The transmission parameter S_{21} is measured for half wave dipole antenna at a distance of 55, 75 and 90 cm from the wall antenna (monopole).

5.3. The Data Sequences Properties

Applying the K-factor estimation method (11) on the acquired N-data sequences, the obtained K-factor is quite small (in the order of 0.01 as shown in Figures 1 and 2) to assume a Rician distribution, even for the short distances. The reason for low values of K-factor is due to the well-stirred chamber, where the loaded electromagnetic fields eliminate or weaken severely any physical LOS coupling. No significant enhancement of the K-factor is encountered as the distance decreases. A further decrease of the distance between antennas jeopardizes the adequacy of the measurements because of the near fields radiations vicinity.

Modifications of the environment are done to favor the direct coupling between the antennas. The stirrers are kept idle during the measurement to decrease the fields loading inside the chamber, while only the receiving antenna is to rotate. Each angle of arrival represents a sample n of the N-data sequence. Such modifications can subside the assumption of a Rician (or equivalently a Rayleigh and a LOS component). A Rayleigh test is performed and the data sequences that do not achieve a goodness fit of 95 % are disregarded.

The samples of the electrical field $E_{\theta i}$ are quite difficult to compute in an absolute scale in a reverberation chamber measurement. Each $E_{\theta i}$ is related to the dimensions of the chamber, transmit power, transmit and receive antennas directivity, efficiency of radiation, polarizations, etc. [11]. A reliable complex value for the received electrical field E_θ is difficult to calculate in order to describe the fields inside the chamber. Instead we can easily access a relative variable S_{21} that represents the insertion path loss inside the chamber. E_θ is directly proportional to S_{21} which is used to describe the fields inside the chamber. Employing this proportionality between E_θ and S_{21}, (11) can be written as

$$\widehat{K} = \frac{N}{2} \frac{|S_{21d}|^2}{\sum_{i=0}^{N-1}(|S_{21i}| - |S_{21d}|)^2} \tag{14}$$

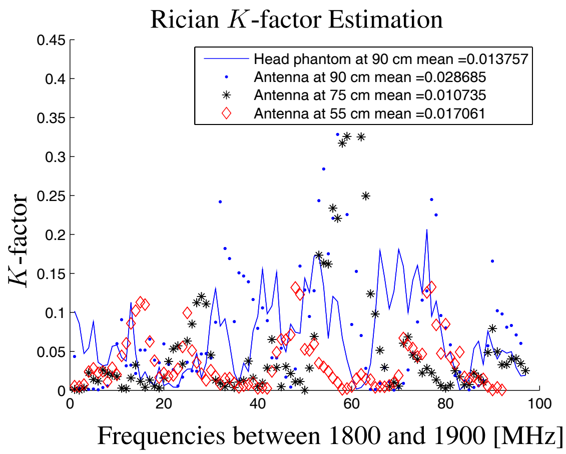

Figure 1. K-factor of a stirred reverberation chamber where S_{21d} equals mean of the S_{21i} samples, vertical receiving dipole.

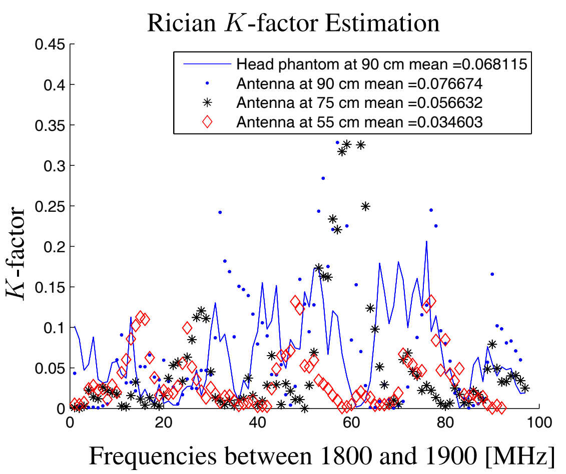

Figure 2. K-factor of a stirred reverberation chamber where S_{21d} equals mean of the S_{21i} samples, horizontal receiving dipole.

where S_{21d} and S_{21i} are the direct and sample transmission parameters, respectively. The performance of the estimator in (14) depends on the value of the direct coupling component $|E_{d\theta}|$ or $|S_{21d}|$ which should computed adequately. A calculated reliable value for the direct electrical field component $E_{d\theta}$ as in [11, (12)] is a difficult task since it require the computation of the directivity at the elevation θ especially. The direct component can be measured in an anechoic chamber for the different distances (90, 75, 55 cm) and antenna tilts in order to have an exact value in the case of idle stirrers measurements in the reverberation chamber. But this option is disregarded for the same reason and for the intention of investigating the sole use of reverberation chamber in the estimation of the K-factor.

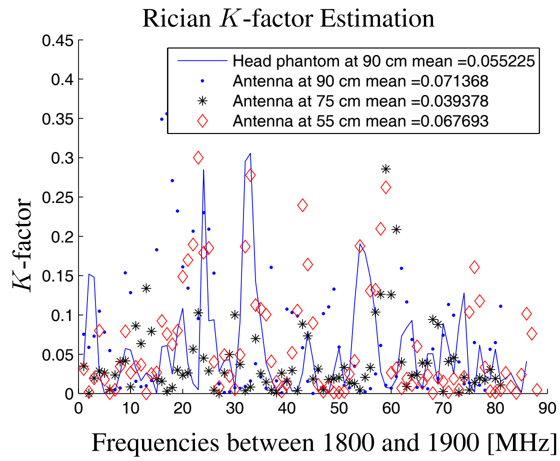

Figure 3. K-factor of a reverberation chamber with no stirrers where S_{21d} equals mean of the S_{21i} samples, vertical receiving dipole.

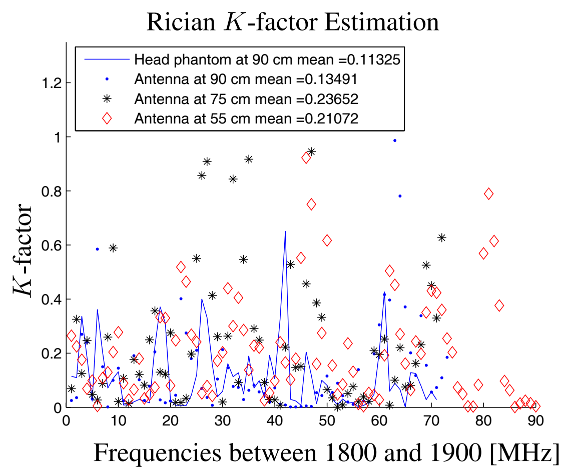

Figure 4. K-factor of a reverberation chamber with no stirrers where S_{21d} equals mean of the S_{21i} samples, horizontal receiving dipole.

6. Results and Discussion

One way to compute the direct (relative in this case) component $|S_{21d}|$ is to take the absolute value of the mean of the samples S_{21i}. The estimated K-factor of the well stirred chamber for vertical and horizontal dipoles is shown in Figure 1 and 2, respectively. It is worth mentioning that in the plots of the estimated K-factor:

-The frequency range is between 1800 and 1900 MHz of which some singular frequencies are disregarded because their data sequences do not comply with the Rayleigh or Rician fit test. The number of sequences fulfilling this test is not the same for any antenna distance or polarization.

-Each point in the plots shows the estimated K-factor from

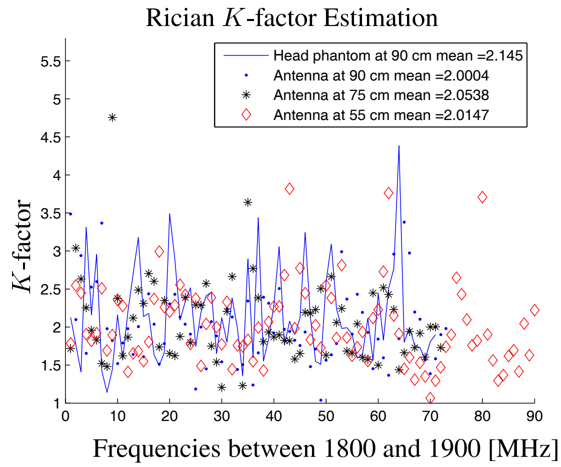

Figure 5. K-factor of a reverberation chamber with no stirrers where $|S_{21d}|$ equals mean of the magnitudes of the S_{21i} samples.

N-samples representing a test frequency. The mean displayed in the figures legends is the averaged estimated K-factors taken over the whole frequency range.

Examining Figures 1 and 2 one can deduce that the change in the K-factor is not uniform (i.e. it does not increase as the distance decrease as in [16]) but this change is not significant. Hence it can be said that the environment in the chamber is Rayleigh distributed and it agrees with the theory of reverberation chamber [10]. Comparing the plots in Figures 1 and 2, it can be observed that the Rician K-factor is larger for the horizontal dipole than vertical dipole. This indicates that the change in orientation of the dipole antenna or AUT affects the distribution of the received power and thus results in higher values of K-factor. It can be inferred that K-factor is sensitive to the change of polarizations of the receive and/or transmit antennas, but this fact has been verified for a single wall antenna and may change in the case of multiple wall antennas.

The estimated K-factor for the stirred chamber is almost zero and in order to increase its value the stirrers are kept stationary to enhance the direct coupling between the antennas. Figure 3 shows that, despite stopping the stirrers, the direct component is not dominant and the mean value of the Rician K-factor over the measured frequency range is around 0.22 in the best case. We see that the K-factor increases as the distance is decreased but it drops a little for the shortest distance (55cm) which can be related to the transmit antenna near field effect and directivity. For mechanical reasons (due to fixed antenna rotation platform), decreasing the distance is done by augmenting the receiving antenna height instead of moving it directly towards the transmitter which can decrease the direct coupling power received since the transmitter is probably electrically polarized to have its maximum radiation towards the center of the chamber. This a common feature even for the cases that will follow.

The estimated K-factor obtained in Figure 3 is still quite low to claim a Rician distribution. But taking the magnitude of the mean of some complex variables might not give the right information about the direct coupling component due to the uniform phase distribution of the incoming power on the AUT because the platform is rotating. The direct component can be calculated in a reverberation chamber by stopping the platform stirring. Since, in the pdf of the chamber and the derived estimator the phase is of no intervenience, the direct component can be computed as the mean of the samples magnitudes. This approach is suitable for the K-factor analysis of some real life measurements around a transmitting antenna, where the distance is not stable and the fairly uniform distributed phase can decrease the real LOS component value. Figure 4 illustrates the estimated K-factor where the direct coupling component is the mean of the samples magnitudes.

Examining Figure 5, it is obvious that we have a higher K-factor which is around 2. The K-factor increases by decreasing the distance but for the last case, for the same reasons stated before in this paper. One more interesting feature in these last two figures is that a higher K-factor is achieved when measuring with the presence of a head phantom even if these measurements are done for the largest distance. This can be explained by that: the head phantom contribute quite well in absorbing a high percentage of the reflected power in the chamber making the direct component more dominant in general, even though at around 30% of the angles of arrival the head phantom shadows or eclipses totally the antenna. This gives an idea of the relative high power of the direct component and that knowledge of the angle of arrival or position of an antenna is quite important for the repeatability of measurements. The estimated K-factor in Figure 5 is still moderate comparing to some other achieved in reverberation chamber [11] where absorbers are used to decrease the reflected power.

7. Conclusion

In this paper a statistical model of the fields in the reverberation chamber is reviewed and the MLE of the Rician K-factor is presented using the pdf of the fields within the chamber. Measurements are done to verify the functionality of the derived estimator. The chamber is found to be well-stirred thus the direct coupling power is basically infinitesimally small compared to the reflected power. Turning off the stirrers (i.e. reducing the loading of the chamber) enable us to achieve a Rician environment. This Rician K-factor depends well on the polarization, distance, tilt of the AUT and also on head phantom. Hence, these factors are to be taken into account for the repeatability of the measurements. The measurement procedure suggested in this paper for estimating the Rician K-factor is well suited for characterizing a communication channel where no reliable information is available about the characteristics of transmit and receive antennas as well as their distances and orientations.

8. REFERENCES

[1] B.G.H. Olsson and S-Å. Larsson, "Description of antenna test method performed in scattered field environment for GSM M," COST259WG2.2,1998

[2] CTIA Certification Program, Test Plan for Mobile Station Over the Air Performance, "Cellular Telecommunications & Internet Association Method of Measurement for Radiated RF Power and Receiver Performance" March 2003, Revision 2.0.

[3] 3GPP TSG-RAN TR 25.914 v7.0.0,(2006-06) "Measurements of Radio Performances of UMTS Terminals in Speech Mode," (Release 7,Technical report).

[4] W.H. Emerson and H.B. Sefton, "Electromagnetic wave absorbers and anechoic chambers through the years," *IEEE Trans. Antennas Propagat.*, Vol. AP-21, No.4, pp. 484-490, July 1973.

[5] H. A. Wheeler. "The radiansphere around a small antenna," in *Proc. IRE*, Aug. 1959, pp. 1325-1331

[6] K. Rosengren, P.-S. Kildal, J. Carlsson, O. Lunden, "A new method to measure radiation efficiency of terminal antennas," *Conferences on Antennas and Propagation for Wireless Communications, 2000 IEEE-APS*, 2000, pp: 5-8.

[7] P.S. Kildal and C. Carlsson, "TCP of 20 Mobile Phones Measured in Reverberation Chamber: Procedure, Results, Uncertainity and Validation," available from Bluetest AB, www.bluetest.se, Feb.2002.

[8] P.S. Kildal, K. Rosengren, J. Byun and J. Lee, "Definition of effective diversity gain and how to measure it in a reverberation chamber," *Microwave Opt.Technol.Lett.* , vol 34, no.1, pp.56-59, Jul.2002.

[9] K. Rosengren and P.S. Kildal, "Radiation efficiency, correlation, diversity gain, and capacity of a six monopole antenna array for a MIMO system: Theory, simulation and measurement in reverberation chamber," *Proc.Inst.Elect Eng Microwave,Antennas,Propag.*, vol 152, no.1, pp.7-16, Feb.2005.

[10] K. Rosengren and P.S. Kildal, "Study of distributions of modes and plane waves in reverberation chambers for characterization of antennas in multipath environment," *Microwave Opt.Technol.Lett.*, vol .30, no.20, pp.386-391, Sept.2001

[11] C. L. Holloway, D. A. Hill, J. M. Ladbury, P. Wilson, G. Koepke, J. Coder, "On the use of reverberation chambers to simulate a controllable Rician radio environment for the testing of wireless devices," *IEEE Trans. Antennas Propagat.*, Vol. 54, No. 11, Part 1, pp 3167-3177, Nov. 2006.

[12] A. Doukas and G. Kalivas, "Rician K factor estimation for wireless communication systems," *International Conference on Wireless and Mobile Communications*, Bucharest, Romania July 29-31, 2006.

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

[14] Per-Simon Kildal and Charlie Orlenius, "The Antenna Engineering Handbook," Fourth Edition John L.Volakis, Chapter 58, Multipath Techniques for handset/terminal antennas.

[15] P. Corona, G. Ferrara, and M. Migliaccio, "Reverberating chambers as sources of stochastic electromagnetic fields," *IEEE Transactons Electromagnetic Compatibility*, Vol. 38, No. 3, pp. 348-356, August 1996.

[16] P. Corona, G. Ferrara, and M. Migliaccio, "Reverberating chamber electromagnetic field in presence of an unstired component," *IEEE Transactons Electromagnetic Compatibility*, Vol. 42, No. 2, pp. 111-115, May 2000.

[17] M. Abramowitz and I.A. Stegun, *Handbook of Mathematical Functions*, New York: Dover, 1972.

[18] J.G. Kostas and B. Boverie, "Statistical model for a mode-stirred chamber," *IEEE Trans. Electromagn. Compat.*, vol. 33, pp. 366-370, Nov. 1991.

[19] http://www.bluetest.se/Bluetest-TechnDescr-070813.pdf

[20] http://www.sam-phantom.com/

9. ACKNOWLEDGMENTS

The authors would like to thank Professor Per-Simon Kildal for the feed-back and the antenna group at Chalmers for providing the reverberation chamber facility.