Mean effective gain of user equipment antennas in double directional channels

Alayon Glazunov, Andres

Published in:
15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2004.

2004

MEAN EFFECTIVE GAIN OF USER EQUIPMENT ANTENNAS IN DOUBLE DIRECTIONAL CHANNELS

Andres Alayon Glazunov
TeliaSonera Sweden, Mobile Networks R&D, Augustendalsv.7, 13186 Nacka Strand, Sweden, andres.alayon@teliasonera.com

Abstract-This paper presents a revised definition of the Mean Effective Gain (MEG) of terminal antennas. It now includes the gain pattern of both the transmitting (BS) and receiving (MS) antennas, the path gain matrix as well as the joint angular power distributions of the two orthogonal polarizations at both ends. A closed form equation is provided followed by the analysis of some special cases and their practical implications.

I. INTRODUCTION

Satisfactory user equipment (UE) performance is essential to the adequate deployment of UMTS networks. Namely, due to limitations inherent to the WCDMA systems, as for instance the non-ideal properties of the utilized spreading codes, will introduce more interference from mobiles both in the own cell and from surrounding cells, which in turn deteriorate the overall capacity of the system. On the other hand, the UE is a vital element of the wireless network; its performance is even more critical in WCDMA systems due to the inherent near-far problem. On the downlink there is no such a problem due to the one to many scenario, nevertheless mobiles situated at the cell edge suffer from inter-cell interference in a much higher degree than the other ones. It has been shown in [1,2] that the antenna efficiency in terms of mean effective gain (MEG), [3] will have a significant impact on the offered capacity, coverage or QoS of UMTS services.

Currently, several figures of merit are being used in order to quantify the performance of UE antennas, such as the Total Radiated Power (TRP) [4,5], the Mean Effective Gain (MEG), [7,8] and Scattered-Field-Measurement Gain (SFMG) [5,6,7]. The later is in principle a MEG measured with a practical antenna reference instead. In this paper the focus has been on the MEG, as it is the most widespread figure of merit. A standardized UE terminal antenna measurement test is therefore needed.

As shown by Taga, [9], the MEG takes into account the fact that the transmitted RF power propagates through the radio channel and is subjected to angular dispersion around the receiver as well as to the depolarization effects due to the propagation channel response. The gain pattern of the receiving antenna is naturally included in the computation of this figure. However, it is well known that, the received power is affected by the polarization of the transmitted power and of course on the polarization coupling loss between the propagation channel and the receiving and transmitting antennas. Several papers, [16-19] approach the evaluation of MEG in typical mobile radio channels but no one have addressed the problem with regard to the full polarization matrix of the channel, neither the power angular distribution at both ends of the RF link.

Hence, the contribution of this paper is a revisited formulation of the MEG, which takes into account not only the gain pattern of the receiving antenna, but also the gain pattern of the transmitting antenna and the polarization path gain matrix of the channel and the joint power angular distribution on both the transmitter and the receiver sides. That is, a joint distribution that includes both the power dispersion around the receiver (angle of arrivals) and the transmitter (angle of departures) is introduced for each orthogonal linear polarization. We further introduce the concept of average (or effective) cross-polarization discrimination of the UE antenna in mobile communications, which takes into account for the multipath nature of mobile communications, in order to generalize the most common definition of the antenna cross-polarization discrimination, which usually takes into account the ratio of the maximum gain in the two principal cuts. By this mean the double directional characteristic of the radio propagation channel [11,12,13,18] is accounted for.

One significant practical concern is the fact that most BSs are deployed with ±45° cross-polarized antennas. This implies that more power is available in the horizontal polarization at the receiver compared to the case when only vertically polarized signals are transmitted. Hence, the MEG as we know it may be underestimating the actual MEG of UE antennas in up and running cellular networks. Further, most UE antennas in speech mode are still used closed to the user's head and are tilted in average more than 45° from the vertical giving rise to cross-polar discrimination at the antenna that is in favor of the horizontal component [7]. Both these facts are paramount to the proper characterization of the UE terminal antenna performance in real radio networks. Finally, the antenna performance in terms of gain pattern, cross coupling between antenna elements and effective gain is relevant to MIMO systems, where the electrical properties of small antennas will be of great importance.

0-7803-8523-3/04/$20.00

II. RECEIVED POWER IN DOUBLE DIRECTIONAL MOBILE RADIO CHANNELS

The received power at the mobile depends on the channel characteristics, on the antenna pattern of as well the transmitting antenna as the antenna of the receiving device. In the presence of line of sight communication as for instance microwave links, the received power is modeled by the Friis transmission equation. In mobile wireless communications the radio channel is commonly characterized by multipath propagation giving place to Rayleigh fading or Ricean fading [13,14] with a scattered field component, which in average may be 4 times weaker than the direct (or deterministic) component [5,13,14]. The mean effective gain in the presence of Ricean channels for vertically polarized Base Station antennas is treated in [15].

For the sake of simplicity, here we will focus on narrowband systems, but the reasoning may be easily generalized to more broadband radio channels as well as MIMO systems. In actual GSM and UMTS systems cross-polarized antennas at BS is the common practice. Hence, the received power at the UE in the far field, will in the general case of the double directional channel in presence of uncorrelated Rayleigh fading, be given as follows (in lack of space no demonstration will be provided here, see the Appendix for hint):

$$P_r = P_t \oint\oint \mathbf{G}_r^{T}(\theta,\phi)\mathbf{G}_c(\theta,\phi,\theta',\phi')\mathbf{G}_t(\theta',\phi')d\Omega d\Omega' \qquad (1)$$

$$\mathbf{G}_r(\theta,\phi) = \left(G_\theta^r(\theta,\phi) \quad G_\phi^r(\theta,\phi)\right)^T \qquad (2)$$

$$\mathbf{G}_t(\theta',\phi') = \left(G_\theta^t(\theta',\phi') \quad G_\phi^t(\theta',\phi')\right)^T \qquad (3)$$

The antenna vectors containing the antenna gain patterns of the receiving and transmitting antennas are $\mathbf{G}_r$ and $\mathbf{G}_t$ respectively. They satisfy the following condition [20],

$$\oint\left(G_\theta(\theta,\phi)+G_\phi(\theta,\phi)\right)d\Omega = 4\pi \qquad (4)$$

In turn the channel path gain is given by,

$$\mathbf{G}_c(\theta,\phi,\theta',\phi') = \begin{pmatrix} G_{VV}P_{\theta\theta\theta'\theta'}(\theta,\phi,\theta',\phi') & G_{VH}P_{\theta\phi\theta'\phi'}(\theta,\phi,\theta',\phi') \\ G_{HV}P_{\phi\theta\phi'\theta'}(\theta,\phi,\theta',\phi') & G_{HH}P_{\phi\phi\phi'\phi'}(\theta,\phi,\theta',\phi') \end{pmatrix} \qquad (5)$$

where G_{VV}, G_{VH}, G_{HV} and G_{HH} are the partial path gains of the channel due to co- and cross-coupling effects. The joint angular power distribution of the theta and phi polarizations is introduced above and is given by functions $P_{xy}(\theta,\phi,\theta',\phi')$, which must satisfy the following condition,

$$\oint\oint P_{xyx'y'}(\theta,\phi,\theta',\phi')d\Omega d\Omega' = 1 \qquad (6)$$

The joint angular power distribution describes the spectrum of the received power at both the transmitting and the receiving antennas. Usually, the angles of arrival and the angles of departure are estimated separately due to practical reasons. It must be said that the ultimate channel model should actually take into account the fact that changing the premises at the transmitter will actually impact on the received signal at the receiver and therefore be able to account for the correlation between the propagation process around the transmitter and the receiver.

Hence from equations (1), (2), (3) and (5) the total received power is then obtained,

$$\begin{aligned} P_r = P_t(G_{VV}&\oint\oint G_\theta^r(\theta,\phi)P_{\theta\theta\theta'\theta'}(\theta,\phi,\theta',\phi')G_\theta^t(\theta',\phi')d\Omega d\Omega' + \\ &+ G_{VH}\oint\oint G_\theta^r(\theta,\phi)P_{\theta\phi\theta'\phi'}(\theta,\phi,\theta',\phi')G_\phi^t(\theta',\phi')d\Omega d\Omega' + \\ &+ G_{HV}\oint\oint G_\phi^r(\theta,\phi)P_{\phi\theta\phi'\theta'}(\theta,\phi,\theta',\phi')G_\theta^t(\theta',\phi')d\Omega d\Omega' + \\ &+ G_{HH}\oint\oint G_\phi^r(\theta,\phi)P_{\phi\phi\phi'\phi'}(\theta,\phi,\theta',\phi')G_\phi^t(\theta',\phi')d\Omega d\Omega') \end{aligned} \qquad (7)$$

The first term in equation (7) stands for the vertical-to-vertical coupling, the second for the horizontal-to-vertical, moreover the third for the vertical-to-horizontal and the fourth and last for the horizontal-to-horizontal polarization coupling. It should be noted that in general the antenna gain, the power angular distribution and involved are function of the frequency and distance between the receiver and the transmitter.

It should be also noted that the equation (7) satisfies the reciprocity principle of the radio channel, which is straightforward to proof.

III. MEAN EFFECTIVE GAIN AND RELATED PARAMETERS

Now we are able to define the Mean Effective Gain of the terminal antenna in the general case of a cross-polarized transmitting BS antenna. Here, we just use the well-known definition given by Andersen [8]and Taga[10],

$$G_e = \frac{P_{received}}{P_{available}} \qquad (8)$$

The total available power is then given by,

$$\begin{aligned} P_a = P_t(G_{VV}&\oint P_{\theta\theta'}(\theta',\phi')G_\theta^t(\theta',\phi')d\Omega' + \\ &+ G_{VH}\oint P_{\theta\phi'}(\theta',\phi')G_\phi^t(\theta',\phi')d\Omega' + \\ &+ G_{HV}\oint P_{\phi\theta'}(\theta',\phi')G_\theta^t(\theta',\phi')d\Omega' + \\ &+ G_{HH}\oint P_{\phi\phi'}(\theta',\phi')G_\phi^t(\theta',\phi')d\Omega') \end{aligned} \qquad (9)$$

where we have assumed, according to the MEG definition [10], isotropic antennas at the terminal location. The marginal distributions $P_{xy}(\theta',\phi')$ are introduced, [21],

$$P_{xy'}(\theta,\phi) = \oint P_{xyx'y'}(\theta,\phi,\theta',\phi')d\Omega' \quad (10)$$

Thus according to equations (7), (8) and (9) the mean effective gain in double directional channels is obtained. The summation is performed in such a way that all four co- and cross-polarization terms are included in the enumerator and denominator of MEG ratio,

$$G_e = \frac{\sum G_{XY} \oint\oint G_x^r(\theta,\phi) P_{xyx'y'}(\theta,\phi,\theta',\phi') G_y^t(\theta',\phi') d\Omega d\Omega'}{\sum G_{XY} \oint P_{x'y'}(\theta',\phi') G_y^t(\theta',\phi') d\Omega'} \quad (11)$$

The cross-polarization ratio (XPR) of the whole system including propagation characteristics as well as the gain patterns of the transmitting and receiving devices is defined as follows,

$$\chi = \frac{\text{Power in the V - polarization}}{\text{Power in the H - polarization}} \quad (12)$$

Hence, making use of equation (7) the measured XPD is obtained

$$\chi = \frac{\begin{array}{l}(G_{VV} \oint\oint G_\theta^r(\theta,\phi) P_{\theta\theta\theta'\theta'}(\theta,\phi,\theta',\phi') G_\theta^t(\theta',\phi') d\Omega d\Omega' + \\ + G_{VH} \oint\oint G_\theta^r(\theta,\phi) P_{\theta\phi\theta'\phi'}(\theta,\phi,\theta',\phi') G_\phi^t(\theta',\phi') d\Omega d\Omega')\end{array}}{\begin{array}{l}(G_{HV} \oint\oint G_\phi^r(\theta,\phi) P_{\phi\theta\phi'\theta'}(\theta,\phi,\theta',\phi') G_\theta^t(\theta',\phi') d\Omega d\Omega' + \\ + G_{HH} \oint\oint G_\phi^r(\theta,\phi) P_{\phi\phi\phi'\phi'}(\theta,\phi,\theta',\phi') G_\phi^t(\theta',\phi') d\Omega d\Omega')\end{array}} \quad (13)$$

As can be seen from equation (13) the cross-polarization ratio of the channel is reciprocal. However, in order to calculate the available cross-polarization ratio in the uplink or the downlink isotropic antennas at the BS or respectively the UE should be assumed. In the ideal case the cross-polarization ratio of the channel is trivially obtained,

$$\chi = \frac{G_{VV} + G_{VH}}{G_{HV} + G_{HH}} \quad (14)$$

A. Some practical scenarios

Let us now assume that the gain pattern of the BS antenna is a weak function of its arguments, or with other words, that it is constant over the area defining the sector cell, which is a reasonable assumption. In that case,

$$\oint\oint G_\theta^r(\theta,\phi) P_{\theta\theta\theta'\theta'}(\theta,\phi,\theta',\phi') G_\theta^t(\theta',\phi') d\Omega d\Omega' \approx \gamma_{\theta\theta}^r G_\theta^t \quad (15)$$

where G_θ^t is the antenna gain of the BS, which is approximated by a constant and $\gamma_{\theta\theta}^r$ is the partial gain of the MS antenna due to the θθ-polarization, which is defined below,

$$\oint G_\theta^r(\theta,\phi) P_{\theta\theta}(\theta,\phi) d\Omega = \gamma_{\theta\theta}^r \quad (16)$$

Similarly, the remaining partial gains may be derived as,

$$\oint G_x^r(\theta,\phi) P_{xy}(\theta,\phi) d\Omega = \gamma_{xy}^r$$

where x and y stands θ and ϕ.

We further introduce the cross-polarization ratio when the transmitting antenna is either vertically or horizontally polarized and the power is measured in both the vertical and horizontal polarizations,

$$\chi_V = \frac{G_{VV}}{G_{HV}}, \ \chi_{VH} = \frac{G_{VH}}{G_{HV}}, \ \chi_H = \frac{G_{HH}}{G_{VH}} \quad (17)$$

The cross-polar discrimination (XPD) of the transmitting antenna is the determined according to the traditional definition,

$$\kappa_t = \frac{G_\theta^t}{G_\phi^t} \quad (18)$$

On the other hand the XPD of the UE antenna is a function of the quotient between corresponding average partial gains,

$$\kappa_\theta = \frac{\gamma_{\theta\theta}}{\gamma_{\phi\theta}}, \ \kappa_\phi = \frac{\gamma_{\phi\phi}}{\gamma_{\theta\phi}}, \ \kappa_{\theta\phi} = \frac{\gamma_{\theta\phi}}{\gamma_{\phi\theta}} \quad (19)$$

Finally, having into account the condition (15) above, the cross-polarization ratios and the partial average gains of the receiving antennas (17-19) and substituting the corresponding values in (11) we obtain the following equation for the MEG in the general asymmetrical channel case with constant gain over a given sector,

$$G_e = \frac{\kappa_t(\chi_V \gamma_{\theta\theta}^r + \gamma_{\phi\theta}^r) + \chi_{VH}(\chi_H \gamma_{\phi\phi}^r + \gamma_{\theta\phi}^r)}{\kappa_t(\chi_V + 1) + \chi_{VH}(\chi_H + 1)} \quad (20)$$

Further, we will consider three limit cases with respect to the polarization of the transmitting (BS) antenna: vertically polarized antennas (XPD tends to infinity), ±45° cross-polarized antennas (XPD tends to the unity), and the horizontal polarized antenna (XPD tends to the zero). In order to simplify the analysis we define three different types of propagation channels with respect to the elements of the polarization matrix.

1) Asymmetrical channels: neither of the elements of the polarization matrix equal each other, $G_{VH} \neq G_{HV}, G_{HH} \neq G_{VV}$

1.1) Horizontally polarized BS antenna, $\kappa_t \to 0$

$$G_e = \frac{\chi_H \gamma_{\phi\phi}^r + \gamma_{\theta\phi}^r}{\chi_H + 1} \quad (21)$$

1.2) Cross-polarized (±45°) BS antenna, $\kappa_t \to 1$

$$G_e = \frac{\chi_V \gamma_{\theta\theta}^r + \gamma_{\phi\theta}^r + \chi_{VH}\left(\chi_H \gamma_{\phi\phi}^r + \gamma_{\theta\phi}^r\right)}{\chi_V + 1 + \chi_{VH}\left(\chi_H + 1\right)} \tag{22}$$

1.3) Vertically polarized BS antenna, $\kappa_t \to \infty$

$$G_e = \frac{\chi_V \gamma_{\theta\theta}^r + \gamma_{\phi\theta}^r}{\chi_V + 1} \tag{23}$$

2) Semi symmetrical channel: cross-polarization elements are equal, $G_{VH} = G_{HV}$ co-polarized elements unequal, $G_{HH} \neq G_{VV}$

2.1) Horizontally polarized BS antenna, $\kappa_t \to 0$

Same as equation (21)

2.2) Cross-polarized polarized (±45°) BS antenna, $\kappa_t \to 1$

$$G_{MEG} = \frac{\chi_V \gamma_{\theta\theta}^r + \gamma_{\phi\theta}^r + \chi_H \gamma_{\phi\phi}^r + \gamma_{\theta\phi}^r}{\chi_V + 1 + \chi_H + 1} \tag{24}$$

2.3) Vertically polarized BS antenna, $\kappa_t \to \infty$

Same as equation (23)

3) Symmetrical channel: cross-polarization elements are equal $G_{VH} = G_{HV}$, co-polarized elements are also equal, $G_{HH} = G_{VV}$

3.1) Horizontally polarized BS antenna, $\kappa_t \to 0$

Same as equation (21)

3.2) Cross-polarized (±45°) BS antenna, $\kappa_t \to 1$

$$G_{MEG} = \frac{\chi_V \left(\gamma_{\theta\theta}^r + \gamma_{\phi\phi}^r\right) + \gamma_{\phi\theta}^r + \gamma_{\theta\phi}^r}{2\left(\chi_V + 1\right)} \tag{25}$$

3.3) Vertically polarized BS antenna, $\kappa_t \to \infty$

Same as equation (23)

In lack of space a further analysis of equations above is left to the reader. However, one obvious result is that equation (23), which corresponds to the vertically polarized BS scenario, applies for all the channel types enumerated and is identical with the definition of the mean effective gain provided by Taga [10], which is a special case of the more general definition of the mean effective gain in double-directional channels.

IV. MEG COMPARISON

Now, in order to assess the impact of cross-polarized antennas at the base station relative the deployment of vertical antennas consider the ratio of equation (22) and equation (23). They are respectively denoted by $G^{\pm\pi/4}$ and G^V below,

$$\frac{G^{\pm\pi/4}}{G^V} = \left(1 + \kappa_{\theta\phi} \frac{\chi_H \kappa_\phi + 1}{\chi_V \kappa_\theta + 1}\right) \Big/ \left(1 + \frac{\chi_H + 1}{\chi_V + 1}\right) \tag{26}$$

Further, let us assume without loss of generality, that the power angular distributions at the MS position is uniform in spherical coordinates, that is, all directions are equally weighted. In this case according to equations (16-19) and (24-26) the cross-polar discrimination of the receiving antenna becomes,

$$\kappa_r = \kappa_\theta = \kappa_{\theta\phi} = \frac{1}{\kappa_\phi} = \frac{\gamma_\theta^0}{\gamma_\phi^0} \tag{27}$$

where the partial gains are the given by ,[2]

$$\gamma_\theta^0 = \frac{\oint G_\theta(\theta,\phi) d\Omega}{4\pi}, \quad \gamma_\phi^0 = \frac{\oint G_\phi(\theta,\phi) d\Omega}{4\pi} \tag{28}$$

Hence,

$$\frac{G^{\pm\pi/4}}{G^V} = \left(1 + \frac{\chi_H + \kappa_r}{\chi_V \kappa_r + 1}\right) \Big/ \left(1 + \frac{\chi_H + 1}{\chi_V + 1}\right) \tag{29}$$

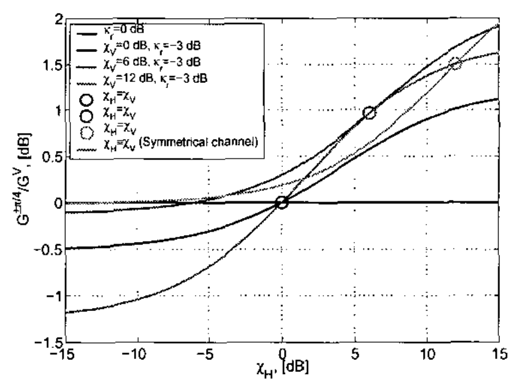

Fig. 1. Gain of UE terminal antennas in propagation environments with ±45° cross-polarized BS antennas relative vertically polarized BS antennas as function of the cross-polarization ratio χ_H (see equation 29).

Numerical results for equation (29) are presented for different values of χ_V as function of χ_H. An average value of the cross-polar discrimination based on practical antenna measurements [7] has been used, which shows that gain in the horizontal polarization is 3 dB higher than in vertical polarization. Results for the symmetrical channel are also provided for reference. As expected, the performance will be better for channels with higher χ_H. Under the assumptions made here the actual gain are between 0 to 1.5 dB for typical values of the XPR measured in mobile environments.

V. SUMMARY

The definition of the Mean Effective Gain has been extended in order to account for the pattern gain of both the receiving and transmitting antennas, the joint power angular distribution of incoming waves at both ends as well as propagation channel matrix for both co-and cross-polarized RF field components in double directional channels. The obtained result may be easily extended to handle as well as more broad channels as well MIMO systems with proper channel model parameterization. A numerical result shows that actual gain due to the use of ±45° cross-polarized BS antennas relative vertically polarized BS antennas may be around between 0 to 1.5 dB for typical mobile environments.

VI. APPENDIX

Here a hint is provided for the reader in order to proof the equation (1) in section II. The mobile is placed at the origin and is moving in let say the x-y plane along the positive y-axis with velocity V. Then the voltage induced at the antenna will be a function of the electric field of the receiving UE antenna given through the complex envelopes of the far-field electric pattern and the incident field is the complex envelope of the incident electric field.

$$V(t)=c\oint\oint \mathbf{E}_r(\theta,\phi)\mathbf{E}_1(\theta,\phi,\theta',\phi')e^{-j\beta Ve_r t}\,d\Omega d\Omega'$$

where $\mathbf{E}_r$ and $\mathbf{E}_i$ are the complex envelopes of the electric field of the receiving antenna and the incident field respectively. The incident field is then modeled as,

$$\mathbf{E}_i=\mathbf{C}\mathbf{E}_t^T$$

where $\mathbf{E}_r$ is the complex envelope of the electric component of the transmitting antenna in the far field, $\mathbf{C}$ is the complex polarization response matrix of the channel,

$$C(\theta,\phi,\theta',\phi')=\begin{pmatrix} C_{VV}(\theta,\phi,\theta',\phi') & C_{VH}(\theta,\phi,\theta',\phi') \\ C_{HV}(\theta,\phi,\theta',\phi') & C_{HH}(\theta,\phi,\theta',\phi') \end{pmatrix}$$

It is worthwhile to note, that the total field is characterized by two orthogonal polarizations. In general, in a multipath environment, the incident field can be described by random variable, in our case $V(t)$. In this case the following assumptions may be done: the phase angles of the vertically polarized waves are independent for different directions of arrival and that the phase angles of the vertically and horizontally polarized waves are independent for different directions of arrival. Finally, the autocorrelation function of the stochastic complex variable is then calculated and from it the average received power may be obtained.

VII. REFERENCE

[1] 3GPP TSG-RAN Working Group 4 (Radio) meeting #27, R4-030546Paris, France 19th -23rd May, 2003, "UE antenna efficiency impact on UMTS system coverage/capacity"

[2] Alayon Glazunov, "Joint Impact of the Mean Effective Gain and Base Station Smart Antennas on WCDMA-FDD Systems Performance", Nordic Radio Symposium 2004, Oulu, Finland, (Submitted)

[3] M. B. Knudsen, "Handset Performance Test Including the Antenna", COST 273 TD (01) 043, Bologna, Italy, October 15-17, 2001, 17 p

[4] L. Correia (Editor), "Antennas for Mobile Phones", Wireless Flexible Personalized Communications, John Wiley & Sons, 2001

[5] Bo G. H. Olsson, "Telia scattered field measurements of mobile terminal antennas", Proceedings of Mobile Terminal and Human Body Interaction, COST259 Final Workshop, Bergen Norway, 2000/04/26-27

[6] A. Alayon Glazunov, "Terminal antenna performance measurements in anechoic chamber with fictitious scatters" COST273 TD (02) 143, Lisbon, Portugal, 2002/09/19-20

[7] A. Alayon Glazunov, "Comparison of MEG and TRPG of Practical Antennas", PIMRC2004, Barcelona, Spain (In these proceedings)

[8] J. Bach Andersen, Andersen J. B., Hansen F., "Antennas for VHF/UHF Personal Radio: a theoretical and experimental study of characteristics and performance", IEEE Transactions on Vehicular Technology, Vol. VT-26, No.4, November 1977

[9] T. Taga, "Analysis for mean effective gain of mobile antennas in land mobile radio environments", IEEE Transactions on Vehicular Technology, 39(2): 117-131, May 1990

[10] M. Steinbauer, "A comprehensive transmission and channel model for directional radio channels", COST259 TD (99) 055, Vienna Austria, April

[11] T. Zwick, C. Fischer, D. Didascalou, W. Wiesbeck, "A stochastic spatial channel model based on wave propagation modeling", IEEE JSAC, Vol. 18, No.1, Jan.2000

[12] H. Asplund, A. Alayon Glazunov, A. F. Molisch, K.I. Pedersen, M. Steinbauer, "The COST259 Directional Channel Model-II. Macrocells", IEEE Trans. Wireless Comm (submitted).

[13] A. Alayon Glazunov, H. Asplund, J-E. Berg, "Statistical analysis of measured short term impulse response functions of 1.88 GHz radio channels in Stockholm with corresponding channel model", Proceedings of IEEE Vehicular Technology Conference, Amsterdam, The Netherlands, Sep.1999

[14] A. Alayon Glazunov, "Theoretical Analysis of Mean Effective Gain of Mobile Terminal Antennas in Ricean Channels ", Proceedings of IEEE Vehicular Technology Conference, Vancouver, Canada, 2000

[15] K. Kalliola, K. Sulonen, H. Laitinen, O. Kivekäs, J. Krogerus, P. Vainikainen, "Angular Power Distribution and Mean Effective Gain of Mobile Antenna in Different Propagation Environments", IEEE Transactions on Vehicular Technology, May 2001, 36 p.

[16] M. Toeltsch, J. Laurila, K. Kalliola, A.F. Molisch, P. Vainikainen, E. Bonek, "Statistical Characterization of Urban Spatial Radio Channels", IEEE JSAC, Vol.20, No3, April 2002

[17] K. Kalliola, "Experimental analysis of multidimensional radio channels", Thesis for the degree of Doctor Of Science in Technology, Helsinki University of Technology, Department of Electrical and Communications Engineering, Espoo, February, 2002

[18] M.B. Knudsen, G.F. Pedersen, "Spherical Outdoor to indoor Power Spectrum Model at the Mobile Terminal", IEEE JSAC, August 2002,Vol. 20, No 6

[19] C.A. Balanis, "Antenna Theory Analysis and Design"2nd Edition, John Wiley & Sons, Inc. ISBN 0-471-59268-4.

[20] A. Papoulis, "Probability, Random Variables and Stochastic Processes", 3rd Edition, McGraw-Hill