Performance of Mobile Phone Antennas Including Effect of Environment Using Two Methods

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***Abstract*—The performance evaluation of a mobile terminal antenna can be done by measurements on test routes or by calculations using measured direction-of-arrival distributions and the measured or calculated radiation pattern of the antenna. Measurements on test routes require a lot of effort with completed prototypes, and, therefore, a reliable calculation-based evaluation method would be useful. In this paper, the results of these two types of evaluation methods are compared for the mean effective gain of six different terminal antennas in four environments at 2.15 GHz. The results of the two evaluation methods coincide well, as the mean and the standard deviation of the difference between the relative received powers are -0.2 dB and 0.8 dB, respectively. No significant difference in the coincidence is found between different environments or antennas.**

***Index Terms*—Incident power distribution, mean effective gain, mobile phone antenna.**

I. Introduction

THE QUALITY of mobile phone antennas is very important as the performance of a radio network is considered. In addition to the antenna and the phone chassis, the user holding the phone affects the performance as does also the multipath propagation environment. The assessment of the mobile antenna performance is very up-to-date. Work aiming at a widely accepted procedure for measuring the performance of mobile phone antennas is in progress in Europe in the sub-working group called Test Methods for Handset Antennas under COST 273 and in the Cellular Telecommunications Industry Association in the USA.

Mobile phones are used freely in different positions like beside the head or in a belt pocket. In consequence, the free space radiation patterns of the antennas are greatly modified, and the propagation environment varies according to the use. Determination of the power received by a mobile phone in real usage situations is very time consuming because several phones should be measured in many environments. Furthermore, this measurement can be performed only when the prototype of the phone is available. An alternative approach to evaluate the performance is to measure or calculate the radiation pattern of the antenna, determine the power distribution in the evaluation environment separately, and calculate the performance, e.g., the mean effective gain (MEG) [1]. The theory of calculating the output signal of an antenna in a multipath environment is presented by Yeh in [2], and the approach has been applied using a Gaussian angular density function in elevation and uniform in azimuth at a 900-MHz frequency range, e.g., in [1], [3], and [4]. In the optimal case, the radiation properties like pattern shape and polarization of the antenna should be matched to the angles of incidence and the cross-polarization power ratio (XPR) of incident waves in the environment. The extensive directional radio channel measurement campaign, presented in [5], showed that at 2.15 GHz, most waves arrive close to the horizontal plane and XPR varies from 8.0 dB to 12.7 dB. The XPRs and directions of incident waves have been studied also in [1], [6], [7].

In this paper, MEGs calculated using measured power distributions at 2.15 GHz are compared to MEGs measured on test routes. Our measurement system [8] capable of continuous measurement of incident field along long routes enables the statistical approach used in this paper. The main goal is to study the feasibility of evaluating the performance of mobile terminal antennas by using radiation patterns of antennas and averaged incident power distributions in different propagation environments. If feasible, such evaluation would simplify significantly the development of mobile terminal antennas because a model describing the environment and a simulated radiation pattern of an antenna could be used to calculate the MEG already before a prototype has been constructed. Section II presents a method to estimate the performance of a mobile phone antenna. In Section III, the tested antennas and measurements are described and in Section IV, the results of the two procedures are compared. Section V concludes the work.

II. Performance Estimation of Mobile Phone Antennas

MEG is a figure of merit for the performance of a mobile phone antenna taking into account the incident power distribution and the radiation pattern of the antenna [2]. In other words, MEG is the power received by an antenna compared to some reference antenna and it can also be measured along a test route [9]. A formula for evaluating MEG using the distribution of incident waves and the radiation pattern of an antenna is [1]

$$\mathrm{MEG} = \int_0^{2\pi}\int_0^{\pi}\left\{\frac{\mathrm{XPR}}{1+\mathrm{XPR}}G_\theta(\theta,\phi)P_\theta(\theta,\phi) + \frac{1}{1+\mathrm{XPR}}G_\phi(\theta,\phi)P_\phi(\theta,\phi)\right\}\sin\theta \mathrm{d}\theta \mathrm{d}\phi. \quad (1)$$

Here, G_θ and G_ϕ are the gain patterns of the antennas and P_θ and P_ϕ are the mean incident powers over the measurement route in θ-and ϕ-polarization, respectively. The measurements

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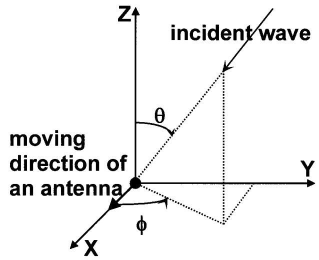

Fig. 1. Coordinates.

of these parameters are described in the next section. The angles ϕ and θ are shown in Fig. 1. The following conditions have to be satisfied:

$$\int_0^{2\pi}\int_0^{\pi} P_\theta(\theta,\phi)(\sin\theta)\mathrm{d}\theta\mathrm{d}\phi = \int_0^{2\pi}\int_0^{\pi} P_\phi(\theta,\phi)(\sin\theta)\mathrm{d}\theta\mathrm{d}\phi = 1 \quad (2)$$

$$\int_0^{2\pi}\int_0^{\pi}\{G_\theta(\theta,\phi)+G_\phi(\theta,\phi)\}(\sin\theta)\mathrm{d}\theta\mathrm{d}\phi = \eta_{\mathrm{tot}}4\pi. \quad (3)$$

Parameter η_{tot} is the total radiation efficiency of an antenna including all possible mechanisms reducing the radiated power. XPR is the cross polarization power ratio

$$\mathrm{XPR} = \frac{\int_0^{2\pi}\int_0^{\pi} P_\theta(\theta,\phi)\sin\theta\mathrm{d}\theta\mathrm{d}\phi}{\int_0^{2\pi}\int_0^{\pi} P_\phi(\theta,\phi)\sin\theta\mathrm{d}\theta\mathrm{d}\phi}. \quad (4)$$

III. Radio Channel Measurements

A. Tested Antennas and Propagation Measurement Setup

Three different antenna configurations were used in this work [Fig. 2]. The configurations were selected to represent different radiation properties that could be found in mobile phones. The dual-polarized antenna having vertically and horizontally polarized feeds [Fig. 2(a)] is similar to the elements of the spherical antenna array. It represents a fairly ideal directive antenna giving also a possibility to study the effect of polarization on the evaluation procedure. The configuration of an omnidirectional monopole antenna and a more directive patch antenna [Fig. 2(b)] represents two typical handset antenna types. The antenna configurations in Figs. 2(a) and (b) were measured in free space. The monopole2 located on a conducting case was measured both in free space and beside a phantom head filled with a tissue simulating liquid. Only the monopole2 of two monopoles was included in this work.

The wideband radio channel sounder developed at Helsinki University of Technology [10] was used in radio channel measurements. The carrier frequency was 2.15 GHz and the chip frequency of the m-sequence was 30 MHz, leading to a delay resolution of 33 ns. The traditional radio channel measurements with the antennas under test (AUT), called in this paper AUT route measurements, and the direction-of-arrival (DoA) measurements were performed in the same environments. In both measurement campaigns, the transmitting (Tx) antenna was a θ-polarized sector antenna located on top of a 2-m-high mast. The 6-dB beamwidth of the Tx antenna is 120° in the horizontal plane and 40° in the vertical plane. The route lengths and height differences between the Tx and the AUTs are given in Table I.

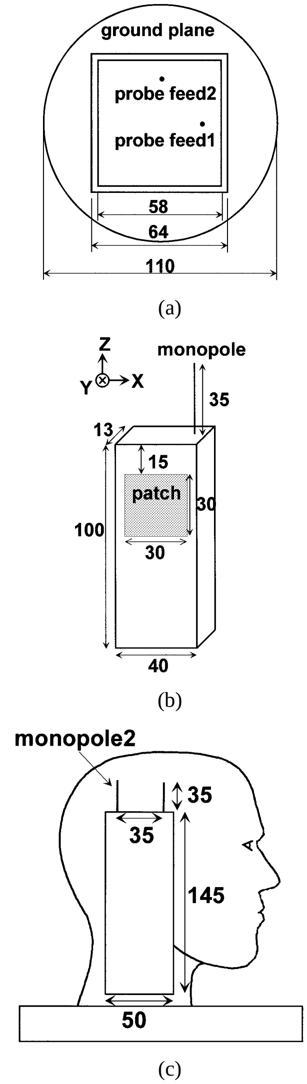

Fig. 2. Evaluated antenna configurations. (a) Dual-polarized antenna. (b) Monopole and patch antenna. (c) Monopole2 beside the phantom head. All dimensions are in millimeters.

TABLE I
Route Lengths (RL), Height Differences Between Tx and Rx Antennas (Δh), and XPRs in Different Environments

	c_Corridor	b_Corridor	b_Office	b_Out
RL [m]	25	25	10	60
Δh [m]	0.8	6.3	6.3	9.3
XPR [dB]	14.0	8.3	9.8	9.1

B. AUT Route Measurements

The AUTs were measured in three environments, a suburban outdoor environment and a corridor and an office environment

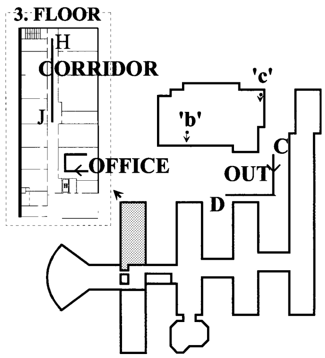

Fig. 3. Three measurement routes and two transmitter locations b and c.

TABLE II
MAXIMUM GAINS, XPDS, AND THE TOTAL RADIATION EFFICIENCIES OF THE ANTENNAS

Antenna	G_{max} [dBi]	XPD [dB]	η_{tot} [%]
Discone	2.90	1.20	95
monopole	3.30	3.30	75
patch	3.35	1.38	87
feed1	8.97	-11.8	96
feed2	8.87	20.0	93
monopole2	3.43	2.66	72
monopole2+ head	2.41	2.20	41

using Tx locations b and c (see Fig. 3). The corridor route $\mathrm{H}- > \mathrm{J}- > \mathrm{H}$ was measured for the b and c and the trolley carrying the antennas was turned 180° in azimuth at the location J. In the office and outdoors, the moving directions are marked in the figure by an arrow and the routes were measured using the b.

All AUTs in Fig. 2 were located vertically at the height of 1.6 m during measurements. The AUTs as well as the vertically polarized omnidirectional reference discone antenna were connected to the sounder using a fast RF switch enabling practically simultaneous measurement of all receiving (Rx) antennas. The y-axis of the antennas was at $\phi = 90^\circ$ and the moving direction $\phi = 0^\circ$ (see Figs. 1 and 2). The MEGs of the AUTs were calculated from a complex wideband impulse response by at first summing up components in delay domain and then squaring the absolute values resulting in narrowband power P_{AUT} and then using the following:

$$\mathrm{MEG}_{\mathrm{AUT}} = E\left\{\frac{P_{\mathrm{AUT}}}{\frac{1}{50}\sum_{i-25}^{i+25} P_{\mathrm{Disc}}}\right\}. \quad (5)$$

Here, P_{Disc} is the narrowband power of the discone and $\mathrm{E}\{\}$ denotes an expected value. As seen from (5), a sliding window of 10λ corresponding to 50 samples was used in normalizing [11]. The $\mathrm{MEG}_{\mathrm{AUT}}$ s are used as the references in comparing the evaluation methods.

C. Direction-of-Arrival Measurements

The spherical antenna array consisting of 32 dual-polarized radiating elements was used in DoA measurements [8]. The array was connected to the sounder using a fast 64-channel switch. The incident waves arriving at the array were measured along the same routes as in the AUT route measurements but in the corridor the trolley was moved only in one direction $\mathrm{H}- > \mathrm{J}$. The height of the receiving spherical antenna array was 1.7 m above the ground.

The procedure to calculate the mean incident power distribution from the measurement data has been described in [8], [12]. Generally, the θ-and ϕ-polarized components of delays, DoAs, and complex amplitudes are found by sequential delay-domain and DoA-domain processing. First, in the delay-domain processing, the local maxima of the power delay profile are found. In the DoA-domain processing, the amplitudes and the directions of arrival at the given local maxima of the power delay profile are found by using beamforming as described in [8]. The data with consecutive snapshots are combined to yield continuously evolving propagation paths. The components living less than five snapshots, corresponding to one moved wavelength, are rejected. The results have been normalized to the total received power instantaneously. The mean azimuth power distributions have been calculated integrating over elevation angles and elevation distributions integrating over azimuth angles.

IV. RESULTS

A. Radiation Properties of the Antennas

The three dimensional (3-D) radiation patterns of the antennas were measured in the anechoic chamber of Nokia Research Center, Finland [13]. As one antenna element of one configuration was measured, the other feeding point was terminated with a matched load. The measurement grid was 10° in elevation and 5° in azimuth, except for the discone where the grid was 10° also in azimuth. Important antenna parameters of the AUTs are given in Table II. Maximum gain is $G_{\max} = \max(G_\theta + G_\phi)$ where G_θ and G_ϕ are the gain patterns of the antenna in θ-and ϕ-polarization, respectively. The total radiation efficiency of the antenna (η_{tot}) is obtained with the pattern integration method and it is equal to double the MEG in an isotropic environment. Cross polarization discrimination (XPD) is the ratio of the θ-and ϕ-polarized power patterns. The discone and both the feeds of the dual-polarized antenna have fairly high η_{tot}. The phantom head used in the evaluation decreases the η_{tot} of the monopole by 2.4 dB.

B. Incident Power Distributions

The averaged power distributions in both elevation and azimuth over the routes described in Section III are presented in Fig. 4. In azimuth, the incident waves arrive from some main directions (Fig. 4 is in decibels). In b_Corridor, the signals arrive into the corridor mainly through the window close to the location H at the end of the corridor (Fig. 3). In that measurement [Fig. 4(b)], only few signals arrive in the direction $-30^\circ < \phi < 30^\circ$ because the moving direction $(\phi = 0^\circ)$ is away from the window. The power arrives to the Rx mainly from the angles $\theta = 65^\circ \ldots 100^\circ$. Due to the large height difference between the Tx and the Rx in the outdoor measurement, the signals arrive at the mobile phone clearly above the horizontal plane

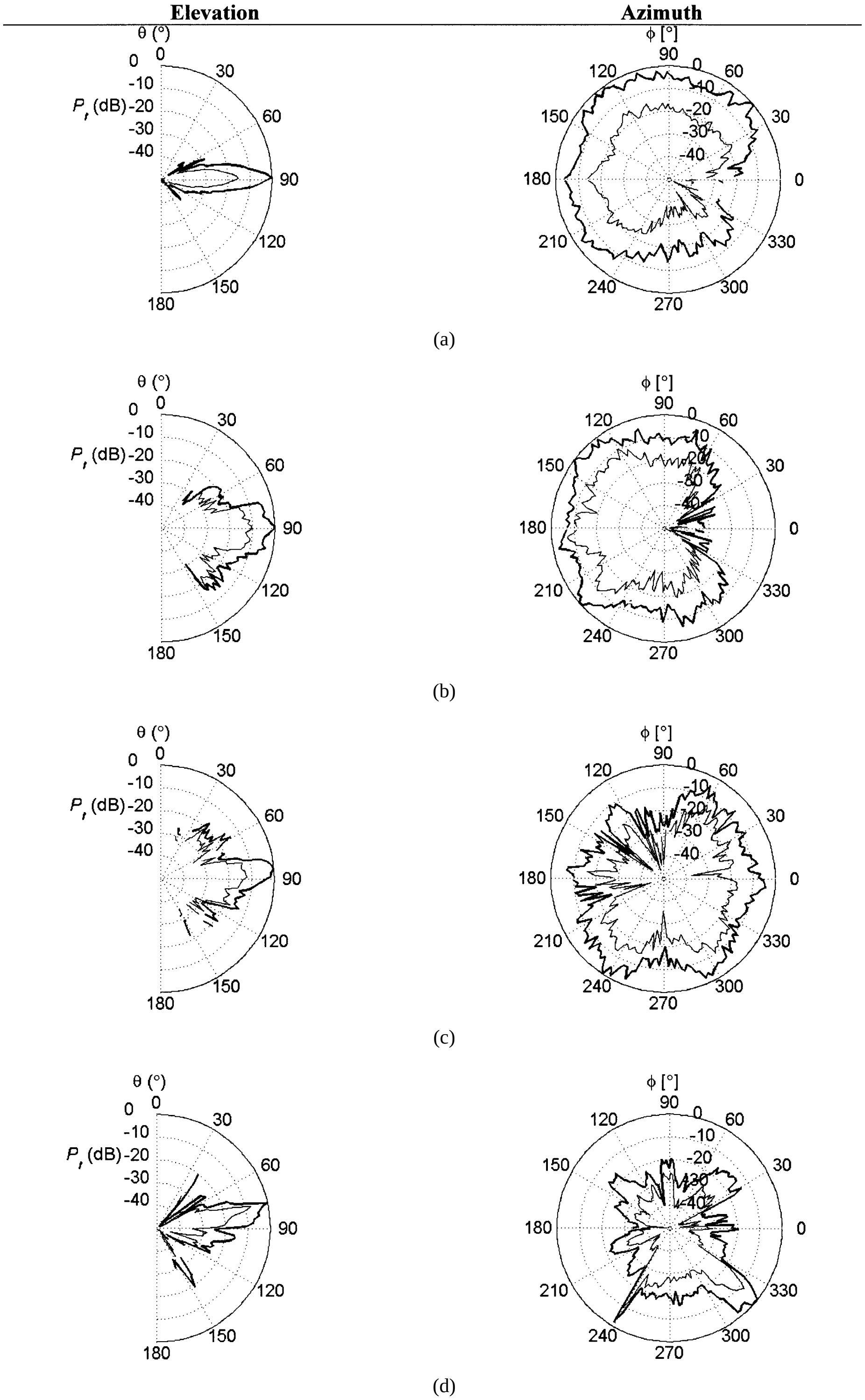

Fig. 4. Mean elevation and azimuth power distributions ($\theta-\text{polarization} = \text{thick line}, \phi-\text{polarization} = \text{thin line}$). (a) c_Corridor, (b) b_Corridor, (c) b_Office, (d) b_Out.

[Fig. 4(d)]. The XPRs have been calculated using (4) and are shown in Table I. In different environments, the XPR varies between $8.3\ \text{dB} \ldots 14.0$ dB, which implies that the polarization of received radio waves depends strongly on the polarization of the Tx antenna, which is in accordance with the results in [1], [5], [6].

C. Comparison of Evaluation Procedures

A MEG_{DoA} is the ratio of the MEG of an evaluated antenna and the MEG of the discone calculated using (1). MEG_{DoA}s and MEG_{AUT}s are collected in Fig. 5. In the corridor, the AUT route measurements were made in two directions. Accordingly, in calculating MEG_{DoA}s in the corridor, the mean of two MEG_{DoA}s

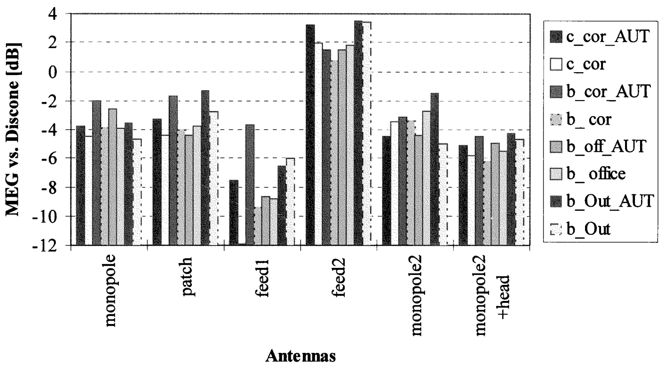

Fig. 5. MEGs given by the two evaluation methods in different environments.

TABLE III
MEAN DIFFERENCE BETWEEN METHODS (Δ_m) FOR ALL ANTENNAS AND COMPARISON OF EVALUATION METHODS BASED ON THE RANKING OF THE ANTENNAS

Antenna	Δ_m	MEG_{AUT}	MEG_{DoA}	η_{tot}
feed2	-0.15	1	1	3
discone	-	2	2	2
mopa_patch	-0.03	3	4	4
mopa_monopole	-0.08	4	5	5
monopole2	0.16	5	3	6
monopole2+head	-0.04	6	6	7
feed1	-0.11	7	7	1

(linear scale) was used. First, the $\mathrm{MEG_{DoA}}$ was calculated considering the moving direction to be $\phi = 0°$ and, second, rotating the antenna 180°.

The effect of the phantom head on $\mathrm{MEG_{DoA}}$ was on the average -2.0 dB which is an expected value [14]. In the AUT route measurements, the average effect was -1.3 dB. Because XPR has been high, the effect of polarization on performance is rather high. The mean difference between the results of two evaluation procedures (Δ_m) and the standard deviation (SD) of the difference for all six antennas in all four environments were calculated using the following for linear (not decibel) MEGs:

$$\Delta_m = \frac{1}{N}\sum_{i=1}^{N}(\mathrm{MEG_{DoA}} - \mathrm{MEG_{AUT}}) \tag{6}$$

$$\mathrm{SD} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}((\mathrm{MEG_{DoA}} - \mathrm{MEG_{AUT}}) - \Delta_m)^2}. \tag{7}$$

Totally, $N = 24$ comparisons were made. Mean difference between methods is $\Delta_m = -0.04$ $(10 \cdot \log_{10}(1 + \Delta_m) = -0.18$ dB) and the standard deviation of the difference $\mathrm{SD} = 0.19$ $(10 \cdot \log_{10}(1 + \mathrm{SD}) = 0.76$ dB), showing that the correspondence between the methods is good.

Due to the vertical polarization in transmission, the power level of horizontally polarized feed1 is low compared to the discone. The cross-polarized power can be assumed to be based on rather random propagation mechanisms that are less repeatable than those of the strong co-polarized signals. Thus, the large differences obtained between the evaluation results for feed1 are expected. However, when the received power levels are studied in linear scale, it can be noticed that feed1 does not differ from other antennas. Actually, it can be noticed from Table III, where the mean linear scale difference Δ_m between methods is calculated separately for every antenna using (6), that the monopole2 has the largest difference. No clear dependency could be found between Δ_m and the average power level of different antennas.

Based on $\mathrm{MEG_{DoA}}$ and $\mathrm{MEG_{AUT}}$ the antennas result in a similar order as the performances are compared taking into account that differences between monopoles and the patch are small (Table III). To conclude, the calculation-based method is reliable and can be used in evaluating the performance of mobile terminal antennas. Comparison of the total radiation efficiencies (η_{tot}) of the antennas results in a different order since it does not include the effect of the environment.

V. CONCLUSION

Measuring several antennas in several propagation environments requires a lot of effort, and a faster evaluation method is needed. As the signal direction-of-arrival distribution in some environments is known, the performance of an antenna is rather easy and fast to calculate using the power distribution and the radiation pattern of the antenna. Furthermore, the result is similar to that achieved by a direct radio channel sounder measurement, which makes the method a useful tool in designing mobile terminal antennas. Comparison of the radiation efficiencies of the antennas results in a different order. Therefore, it is important to include the effect of the environment in evaluating the performance of mobile phone antennas.

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