Helsinki University of Technology Radio Laboratory Publications
Teknillisen koerkeakoulun Radiolaboratorion julkaisuja
Espoo, June, 2004 Report S 265

EVALUATION OF PERFORMANCE OF MOBILE TERMINAL ANTENNAS

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission for public examination and debate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 2nd of July 2004 at 12 o'clock noon.

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ISBN 951-22-7163-X
ISSN 1456-3835

Otamedia Oy
Espoo 2004

PREFACE

This thesis work has been carried out in the Radio Laboratory of Helsinki University of Technology (HUT). The work was made under several projects, funded by the National Technology Agency of Finland (TEKES), Finnish Telecommunications companies, and the Academy of Finland. The work was partly financed by the Graduate School in Electronics, Telecommunications, and Automation (GETA). I am grateful to Nokia Foundation, Jenny and Antti Wihuri Foundation, HPY foundation, Finnish Society of Electronics Engineers, Foundation of Technology (Finland), and Foundation for Commercial and Technical Sciences for the financial support during the work.

I am grateful to my supervisor Pertti Vainikainen whose ideas, guidance, and encouragement have been a prerequisite for me to carry on the research work and complete my thesis.

I want to thank Kimmo Kalliola, Pasi Suvikunnas, Jarmo Kivinen, and Lasse Vuokko for their significant contributions in the joint publications. In addition, all other co-authors of the joint publications deserve warm thanks for co-operation. I wish to express my gratitude to Martti Toikka and Eino Kahra for their help during the work. Outi Kivekäs deserves special acknowledgement for the spirit in the shared workroom.

My friends and first of all my family, I thank you for your believe in me and for being patient during my studies and the thesis work.

Espoo, June 14th, 2004

Kati Sulonen

ABSTRACT

Fast development of new mobile communications equipment results in demand for fast and reliable evaluation methods to estimate the performance of mobile terminals because the performance of antennas located on the terminals varies in different multipath propagation environments. Two methods presented in this thesis provide new possibilities in antenna design because, from now on, the performance of new antennas can be tested already before a prototype antenna is constructed by using existing radio channel libraries and simulated radiation patterns of the antennas. The performance can be estimated by calculating the mean effective gain (*MEG*) of the antenna using the elevation power distribution or by a plane wave -based method using sets of incident plane waves and the radiation pattern of an antenna. In addition to different propagation environments, the effects of the user on performance can be included in the evaluation.

In this thesis, estimating the *MEG* of different antennas using the elevation power distribution and the power patterns of the antennas is shown to be an accurate and fast method by comparing the results with direct radio channel measurements. The mean difference between the methods is -0.18 dB with standard deviation of 0.19 dB. The usefulness of the evaluation method is demonstrated by evaluating the performance of several antennas located on mobile terminals. The antenna evaluation provided important and unique knowledge of the effect of both the environment and the user on performance. Because in calculating the radiation efficiency of the antenna we assume uniform incident field, the efficiency can result in a performance estimation that does not correspond to real usage situations. Therefore, including the environmental effects in the evaluation procedure is important, although the effect of the antenna is more important than the effect of the environment on *MEG*. It was noticed with calculated Gaussian-shaped beams that tilting or changing the beamwidth of a mobile terminal antenna has an effect of about 2 dB on *MEG* in multipath environments. Matching the polarization of the antenna to that of the environment can improve the performance more.

A novel incident plane wave -based tool has been developed for evaluating the performance of antenna configurations designed for diversity and Multiple-Input Multiple-Output (MIMO) systems. In this thesis, the instantaneous joint contribution of incident field consisting of a number of extracted plane waves and the complex three-dimensional radiation pattern of the antenna is shown to be accurate and extremely fast way to estimate the diversity advantages of different antenna configurations in time-variable radio channels. The difference between the diversity gains achieved by the plane wave -based method and by the direct radio channel measurements is on average less than 0.9 dB. Moreover, the radio channel can be exactly the same for all antenna configurations under test.

Furthermore, this thesis includes evaluation of the performance of different MIMO antenna configurations. The studied antenna configurations have been selected from the 16x64 MIMO channel measurement data. A novel way of using one omnidirectional reference antenna in a normalization procedure is shown to be reasonable especially in cases of antenna arrays consisting of directive elements. Three different propagation environments are used as evaluation platforms. The azimuth orientation of mobile terminal antennas may influence the performance of a MIMO antenna configuration significantly. In MIMO configurations compact dual-polarized receiving antennas provide capacity performance almost equal to the arrays employing single polarization.

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LIST OF PUBLICATIONS

[P1] K. Sulonen, P. Vainikainen, “Performance of mobile phone antennas including effect of environment using two methods,” *IEEE Transactions on Instrumentation and Measurements*, vol. 52, no. 6, pp.1859–1864, December 2003.

[P2] K. Sulonen, P. Vainikainen, “Effects of antenna radiation pattern on the performance of the mobile handset,” *Proceedings of IEEE Antennas and Propagation Symposium Digest*, vol. 3, Boston, USA, pp. 519–524, July 2001.

[P3] 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*, vol. 51, no. 5, pp. 823–837, September 2002.

[P4] P. Suvikunnas, K. Sulonen, J. Villanen, C. Icheln, J. Ollikainen, P. Vainikainen, “Evaluation of performance of multi–antenna terminals using two approaches,” *Proceedings of IEEE Instrumentation and Measurement Technology Conference*, Como, Italy, paper IM04-4183, May 2004.

[P5] K. Sulonen, P. Suvikunnas, L. Vuokko, J. Kivinen, P. Vainikainen, “Comparison of MIMO antenna configurations in picocell and microcell environments,” *IEEE Journal on Selected Areas in Communications, MIMO Systems and Applications*, vol. 21, no. 5, pp. 703–712, June 2003.

[P6] K. Sulonen, P. Suvikunnas, J. Kivinen, L. Vuokko, P. Vainikainen, “Study of different mechanisms providing gain in MIMO systems,” *Proceedings of IEEE 58th Vehicular Technology Conference (Fall)*, paper 03C_01.pdf, October 2003.

In papers [P1], [P2], this author had the main responsibility for preparing the papers and conducting the analysis presented in the papers. In [P3], this author performed the mean effective gain computations. This author and Joonas Krogerus measured and Outi Kivekäs simulated the radiation patterns of the evaluated antennas. Kimmo Kalliola and Heikki Laitinen were responsible for the experimental work in [P3]. In addition, Kimmo Kalliola had the main responsibility in preparing the paper. In [P4], this author and Pasi Suvikunnas had the main responsibility for preparing the paper. This author was responsible for diversity calculations. Pasi Suvikunnas made the MIMO analysis. The tool was developed in collaboration with Pasi Suvikunnas, this author, and Juha Villanen. In paper [P5], this author had the main responsibility for preparing the selection based capacity analysis and writing the manuscript. Lasse Vuokko made the direction of arrival analysis, and Pasi Suvikunnas was responsible for plane wave -based capacity analysis. In [P6], this author had the main responsibility for preparing the paper and calculating the results. The analysis of the results was made in collaboration with Pasi Suvikunnas. Professor Pertti Vainikainen supervised all the work.

1 INTRODUCTION

1.1 BACKGROUND

In the last decades, the use of wireless mobile communications has grown revolutionarily in several fields of telecommunications. The revolution started with pagers and vehicle-mounted devices and continued in the 80's with personal mobile phones transferring voice [1]. The most widely used voice transferring system nowadays is Global System for Mobile Communications (GSM) [2] that has been extended to data and video. In modern applications like transferring large amounts of data or video higher data rates are needed. Fast development of new mobile communications equipments results in demand for fast and reliable evaluation methods for estimating the performance of mobile terminal antennas.

It has been evident for some years now that mobile terminals have varying antenna performance when used in mobile networks. The performance of a mobile terminal is very important as the performance of a radio network is considered particularly in the mobile radio links that are typically characterized by multipath fading effects caused by common non-line-of sight propagation paths. In addition, the mobile terminals are nowadays expected to be usable anywhere anytime. The antenna of the terminal receives radio waves from the environment and converts them into electrical signals; and vice versa. The characteristics of the antenna, or actually the whole mobile terminal [3], affect its performance. In addition to the antenna and the chassis of the terminal, the user holding the phone affects the performance [4,5] as does also the multipath propagation environment [6-8]. The quality of mobile terminal antennas becomes even more important as multi-port antennas are designed to provide increase in spectral efficiency [1].

Traditionally the performance of antennas has been estimated by radiation pattern measurements made in an anechoic chamber. The radiation efficiency of small antennas can also be measured using a Wheeler cap [9]. New methods have been developed for evaluating the performance of the mobile terminal in free space and beside the user. The random field method is a commonly used example of extremely time-consuming measurements in which the power received by the antenna is measured on a test route [7,10,11,12]. That approach has been applied by scattered field measurements in indoor facilities [13-15]. The pattern averaging gain [16,17] based on a measured or simulated radiation pattern was used in the antenna evaluation in the last decade. An improved method is to calculate the mean effective gain (*MEG*) by combining the three-dimensional power pattern of the antenna and the power distribution at the mobile station [18,19].

The assessment of the performance of mobile terminal antennas is very up-to-date [4,20-23] since work aiming at a widely accepted procedure for measuring the performance of mobile terminal antennas is in progress e.g. in Europe in the sub-working group called Test Methods for Handset Antennas under the COST (Co-operation in Science and Technology) 273 project [21]. In the United States the Cellular Telecommunications Industry Association (CTIA) has the CTIA Antenna Test Plan according to which all phones sold in the USA need to be tested in the near future [24]. The performance evaluation is extremely challenging due to several radio communications systems, different propagation environments, several antenna types and antenna configurations, and the effects of the users on the antennas.

Single-Input Single-Output (SISO) systems with one antenna at each end of the radio link have traditionally been used in mobile radio communications. By adding more antennas to one end of the link, the capacity can be increased as a result of diversity [25] and antenna array gain [26]. These can be called Single-Input Multiple-Output (SIMO) systems. The possibilities, like parallel channels experiencing non-correlated multipath fading, are tried to be exploited in modern systems by studying the use of several transmitting and receiving antennas [27-36].

These Multiple-Input Multiple-Output (MIMO) systems can provide radio channels capable of transferring parallel information within the same bandwidth, and therefore increase the attainable capacity. The MIMO systems are considered as promising candidates for increasing the spectral efficiency and data rates in the near future.

In SIMO and MIMO systems employing several antennas, the calculation of *MEG* is not enough and, furthermore, direct MIMO measurements with a radio channel sounder require huge amount of work. The instantaneous joint contribution of the estimate of incident radio waves and complex 3-D radiation patterns of antennas has been suggested in [37,38] as one option to achieve statistical data needed in SIMO and MIMO analysis. The approach is also mentioned in [39] in the context of MIMO channel modeling.

1.2 OBJECTIVES OF THE WORK

The goal of this thesis is to study the evaluation of the performance of different antennas and antenna configurations in different propagation environments. The evaluation is started with single antennas, and extended to SIMO systems utilizing diversity at the mobile end of the radio link. The final parts of the thesis concentrate on MIMO systems evaluating the use of multiple antennas at both the fixed and the mobile end of the link. In addition, the performance of antennas is estimated by two methods in one propagation environment and the results are compared in order to validate the use of the evaluation method based on the joint contribution of the radiation pattern and the incident field. At first, the method is tested for SISO systems by calculating *MEG* values. Later, the method is extended to provide instantaneous information needed for the statistical analysis used to evaluate the performance of SIMO and MIMO systems. The work aims to find the properties of the antennas and antenna configurations affecting the performance and to estimate if the performance could be improved by means of those properties.

The work gives a general insight into the properties affecting the performance of mobile terminal antennas in different propagation environments and it proposes a reliable evaluation method for the antennas.

1.3 CONTENTS OF THE THESIS

In this work, mobile terminal antennas are tested in real environments using the figures of merit that are at first validated by comparing the results of the calculation-based methods to the results of direct radio channel measurements. The method for calculating the mean effective gain (*MEG*) of the mobile terminal antenna based on the far field power pattern of the antenna and the power distribution in the propagation environment is validated in [P1]. In [P2], the validated method is used to study the effects of the properties of the radiation patterns on *MEG* in different environments. In addition to evaluating different mobile terminal antennas in different types of propagation environments, the effect of the environment on *MEG* is studied in [P3]. In [P4], a novel plane wave -based method is developed and it is shown to be accurate and, thus, applicable to statistical analysis of diversity antenna configurations. Paper [P5] presents a method to evaluate multi-antenna configurations using an omnidirectional reference antenna in normalization and, in addition, the paper shows differences in estimated performance of MIMO systems due to different antenna configurations. The more detailed study on the effects of different antenna configurations on MIMO performance in [P6] is based on the eigenvalues of the channel correlation matrix.

2 MOBILE TERMINAL IN DIFFERENT ENVIRONMENTS

Mobile terminals are used freely in different situations and positions. In consequence, the free space radiation patterns of the antennas are greatly modified and the propagation environment varies during the use. Figure 1 introduces the aspects affecting the performance of the antennas located on the mobile terminals. Due to several different usage environments, we need to consider the propagation environment in addition to the terminal and the user of the terminal in antenna design and performance evaluation.

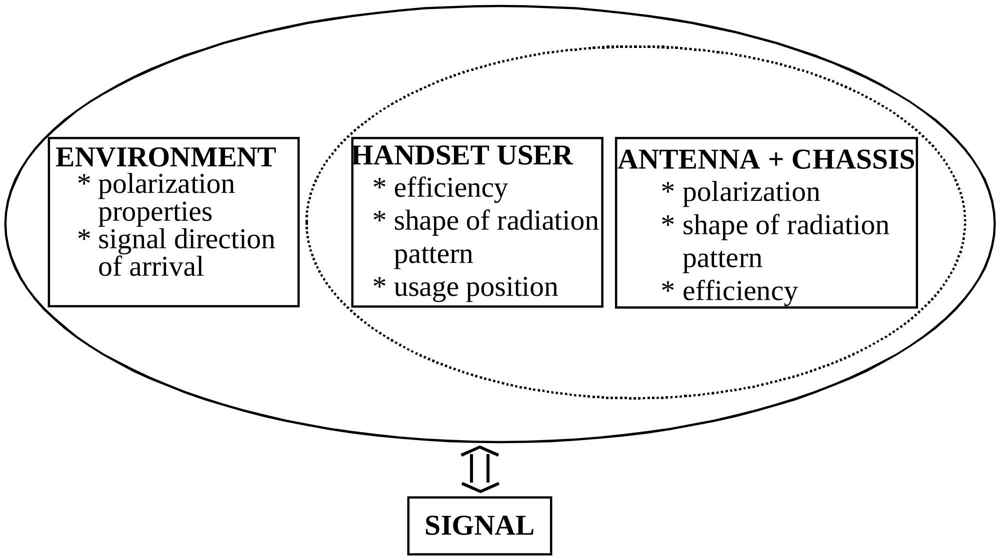


Figure 1. Important aspects related to received or transmitted signal.

Antennas are used for receiving radio waves from the air and for converting them into electrical signals (or vice versa) which, then, are functions of the received radio waves and the antenna properties including the possible effect of a user. The next formulas (2.1) – (2.3) [18] show how the complex envelope at the antenna port is constructed beginning from the electric field patterns of the antenna and the electric field in the evaluation environment.

The electric field pattern of the antenna under test can be written as:

$$\overline{E}(\theta,\phi) = E_\theta(\theta,\phi)\overline{a}_\theta + E_\phi(\theta,\phi)\overline{a}_\phi \tag{2.1}$$

where $\overline{a}_\theta$ and $\overline{a}_\phi$ are unit vectors, E is the complex magnitude of the electric field, angles θ and ϕ inside the parentheses are clarified in Figure 2. The subscripts θ and ϕ refer to polarizations. The electric field of the incident plane wave can be written as:

$$\overline{A}(\theta,\phi) = A_\theta(\theta,\phi)\overline{a}_\theta + A_\phi(\theta,\phi)\overline{a}_\phi \tag{2.2}$$

where A is the complex magnitude of the electric field of the incident plane wave at θ-polarization and ϕ-polarization, respectively. The complex envelope at the antenna port equals to:

$$V(t) = \oint \overline{E}(\theta,\phi,t) \cdot \overline{A}(\theta,\phi,t) \sin\theta \, d\theta \, d\phi \tag{2.3}$$

where t indicates that both the environment and the radiation pattern of the antenna are changing with time, most often due to the movement of the user.

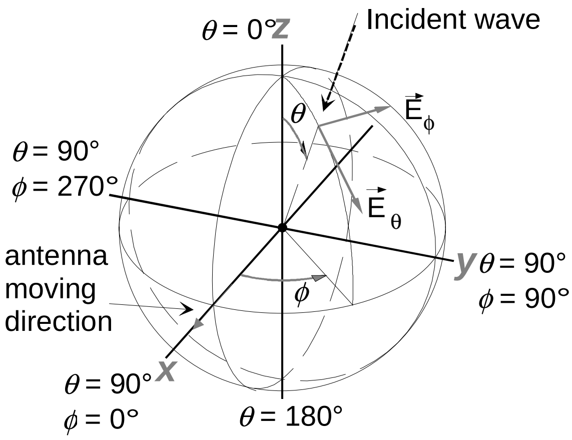


Figure 2. Spherical coordinate system.

In this chapter and throughout the thesis, the properties of the environment and the antenna affecting the interaction between the radiation pattern of the antenna and the statistics of the received signal strength are studied. One possibility in trying to maximize the received average signal strength could be to confine the radiation pattern of the antenna to those angular ranges in which the incident waves most probably arrive and to try to match the polarization of the antenna to that of the incident waves.

Since mobile terminals are used in different positions like beside the head or in a belt pocket, the free space radiation patterns of the antennas are greatly modified as well as the propagation environment varies according to the use. The main properties affecting the performance of the mobile terminal antenna in real propagation environments are introduced in the following sections.

2.1 ENVIRONMENT IN THE VICINITY OF A MOBILE STATION

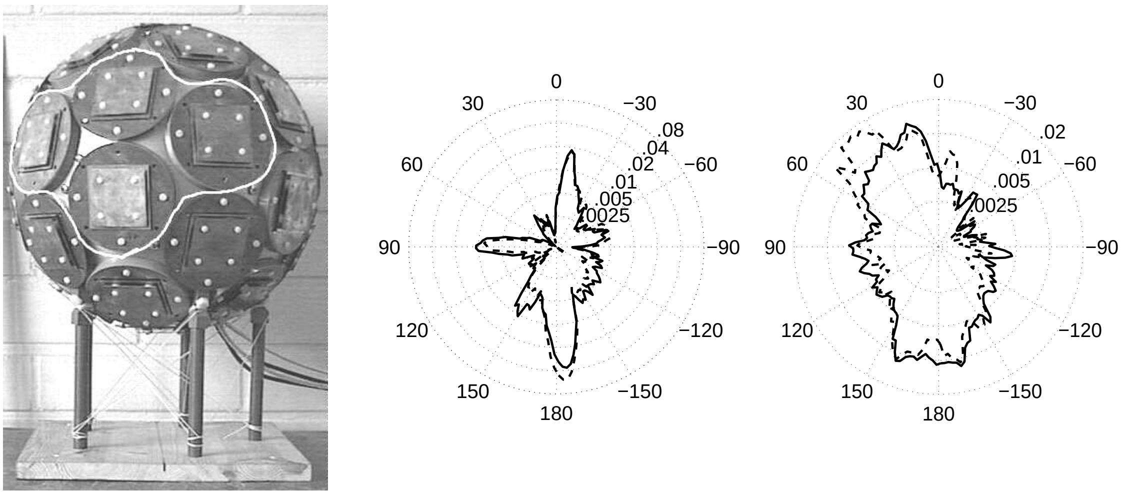
The properties of the transmission path between a transmitter and a receiver vary depending on the used frequency band, the distance between the transmitter and the receiver, and whether there is a line-of-sight (LOS) or a non-line-of-sight (NLOS) connection. The used cell size affects the performance, too. The used cell types are typically categorized as macrocell (radius of the cell r>1000 m), microcell (100 m<r<1000 m), and picocell (r<100 m) [40,41].

In mobile communications systems the transmitted signals are affected by buildings and other objects causing reflections, diffractions, and scattering. Due to different propagation paths, the incident radio waves arriving at the mobile terminal antenna have variety in directions of arrival (DoA) and cross polarization power ratios (*XPR*) [23,42,43]. The 3-D DoA distribution at both θ- and ϕ-polarization and the *XPR* have an effect on the antenna performance. In addition, the frequency affects it. In free space, the transmission loss between the transmitter and the receiver increases with the square of the used frequency resulting in need either to increase the transmitted power or to increase the number of base stations in cellular systems if the center frequency increases.

2.1.1 Distribution of incident field at a mobile station

The first model for the distribution of incident field arriving at a mobile station (MS), given by Clarke [44], assumes that all energy is concentrated on the horizontal plane. The later measurements have shown that the elevation power distribution (EPD) depends on the environment type as well as on the base station (BS) antenna height and BS−MS distance [19,23,45,P3]. In [19], Taga suggested to use Gaussian density function as a model for EPD in urban outdoor environment. However, he used only four measured points of the EPD, which is not necessarily sufficient to verify the distribution. The outdoor to indoor radio channel was studied by rotating a dual-polarized horn antenna at the MS in [23], in which Knudsen and Pedersen proposed a statistical model for the incoming field in elevation. At HUT a spherical antenna array has been used to measure the incident field at the MS [43]. The photo of the spherical antenna array is presented in Figure 3 a. In the environments dominated by NLOS channels the power decays approximately exponentially on both sides of the peak of the EPD for angles close to the horizontal plane. The paper [P3] presents parameters for the general double exponential functions describing the environment in the near vicinity of a mobile terminal in an indoor picocell environment, outdoor−indoor connection, urban microcell and macrocell environments, and highway macrocell environment. In all environments most of the power is concentrated at low positive elevation angles. Also Lee and Brandt [45] showed that most of the power is concentrated at the elevation angles lower than 16° above the horizon.

When a pedestrian user of a mobile terminal moves along a random route, a uniform distribution is a reasonable assumption for the power distribution in azimuth (APD) as it was assumed in [19], for example. In [23,P3], the measured APDs in the urban microcell and macrocell environments are not uniform, but some directions are more probable than others, because the mobile routes are not random in nature. Figure 3 b and c show that the APD is closer to uniform in the macrocell than in the microcell. In [23], a statistical model is suggested to be used also for APD in antenna analysis. To conclude, since the user of a real mobile terminal may turn around or cross the streets at any angle, it is reasonable to assume that the APD averaged over a random route is uniform whereas in order to study the effect of different azimuth orientations on the performance the measured APD should be considered.



a) b) c)

Figure 3. a) The spherical antenna array. In Chapter 5, the selected configuration is used. b) Azimuth power distribution in urban microcell. c) Azimuth power distribution in urban macrocell. (solid line: θ-polarization, dashed line: ϕ -polarization) [P3]

2.1.2 Polarization

The polarization of radio waves varies along a propagation path due to normal propagation phenomena. The possible coupling from the transmitted polarization to the orthogonal polarization should be taken into account in the antenna evaluation procedure. The ratio of the mean incident powers of the θ-polarized components (P_θ) and the ϕ-polarized components (P_ϕ)

represents the cross-polarization power ratio, *XPR*, when the transmitter emits linear θ-polarization:

$$XPR = \frac{\int_0^{2\pi}\int_0^{\pi} P_\theta(\theta,\phi)\sin\theta \mathrm{d}\theta \mathrm{d}\phi}{\int_0^{2\pi}\int_0^{\pi} P_\phi(\theta,\phi)\sin\theta \mathrm{d}\theta \mathrm{d}\phi} \tag{2.4}$$

The angles are clarified in Figure 2.

In the urban areas, the polarization of incident waves depends heavily on the polarization used in transmission [19,43,46]. Lee [46] and Taga [19] have presented that the *XPR* is between 4 dB and 9 dB in the urban macrocell environments at 900 MHz. In [P3], where vertical polarization has been used in transmission, the *XPR* is around 7 dB in the urban macrocell environments but also in the indoor picocell environments and in the highway macrocell environments at 2.15 GHz. In urban the microcell environments as high *XPR* values as 11 dB have been measured [P3] indicating almost no coupling in the propagation path. In the measurements presented in [47], the median cross-polarization coupling, which is equal to the reciprocal of the *XPR*, was found to be -2.5 dB inside and -3.5 dB outside houses in residential areas at 800 MHz. In case of an outdoor–indoor radio link the *XPR* has varied from 5.5 dB in [23] to 11 dB in [P3]. It is worth emphasizing that the *XPR* is an average value but instantaneously the ratio of the two orthogonally-polarized field components may vary tremendously causing large instantaneous changes in the received power e.g. in the case of a vertically-polarized antenna.

2.2 CHARACTERISTICS OF A MOBILE TERMINAL ANTENNA

The propagation environment affects the performance of the mobile terminal antenna but, in addition to that, the antenna itself has an effect on it. Here, an overview on the antenna characteristics affecting the performance is given and the most important figures of merits are discussed.

The performance of the antenna is a function of efficiency, polarization, the shape of the radiation pattern, and user's possible effects on all the other characteristics. Besides, the chassis of the mobile terminal acts as a part of the radiating mobile terminal [3]. In practical usage situations those can not be separated from each others. Overall, the testing of antennas is a very complicated process due to many sources of uncertainties [20].

2.2.1 Total radiation efficiency

The total radiation efficiency of the antenna describes the amount of the power delivered to the radiation resistance out of the total transmitted power. The power is lost due to conduction losses, dielectric losses, and input impedance [48]. The total radiation efficiency of the mobile terminal antenna is defined according to the formula [48]:

$$\eta_{tot} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left[G_\theta(\theta,\phi) + G_\phi(\theta,\phi)\right]\sin\theta \mathrm{d}\theta \mathrm{d}\phi \tag{2.5}$$

Here, G_θ and G_ϕ are the gain patterns of the antenna in θ- and ϕ-polarization, respectively.

The total radiation efficiency can be measured using a Wheeler cap method [9], calculated from the three-dimensional radiation pattern of an antenna using the pattern integration method [48,49], or it can be defined by means of quality factors [50]. In applying the random field method, where the antenna is moved along a random measurement route [10,11], or in scattered field measurements [13,15] the efficiency of the antenna under test is calculated using a standard reference antenna.

It is worth pointing out that the efficiency does not take the effect of the polarization or the environment into account and is thus not adequate for estimating the performance of the antenna in a multipath environment. An antenna with high efficiency can possibly have a bad performance if the incident radio waves are mainly orthogonally-polarized compared with the polarization of the receiving antenna as it will be shown in Chapter 4.

2.2.2 Polarization

The polarization of the antennas used at mobile terminals has traditionally been designed as vertical and the most common types have been monopole, dipole, and helix and, later, planar inverted patch antennas have been considered. In antenna design, the bandwidth, efficiency, and specific absorption rate (*SAR*) have been paid a lot of attention to as critical performance goals for the antennas to be located in the small mobile terminals [3,51]. Polarization has also an important role in the performance of the mobile terminal antenna and orthogonal polarizations can be utilized in adding diversity with only little additional space requirements [52,53,P5]. Since the mobile terminals are used in very different positions, the polarization properties vary causing variance on performance, too.

The cross-polarization power discrimination (*XPD*) of the antenna is used to describe how sensitive the antenna is to radio waves arriving at the antenna or transmitted by the antenna in two orthogonal polarizations. It can be written as:

$$XPD = \frac{\int_0^{2\pi}\int_0^{\pi} G_\theta(\theta,\phi)\sin\theta \, d\theta \, d\phi}{\int_0^{2\pi}\int_0^{\pi} G_\phi(\theta,\phi)\sin\theta \, d\theta \, d\phi} \tag{2.6}$$

Here G_θ and G_ϕ are the gain patterns of the antennas under test (AUTs) in θ- and ϕ-polarization, respectively.

2.2.3 Directivity

The directivity of an antenna is defined as the ratio of the radiation intensity in a given direction to the radiation intensity integrated over all directions. Antennas used in radio links and satellite communications need to be directive due to long distances. In mobile terminals the position of the antenna is rather random. So, high directivity might cause bad performance in some special cases where the main beam of the antenna is directed towards the opposite direction of the BS. However, directive antennas are feasible alternatives to omnidirectional antennas in mobile terminals because the effect of the head is smaller on the radiation pattern of the directive antennas compared with the omnidirectional ones [4,6,16,54-56]. This is partly since larger part of the power of the directive antennas is emitted opposite to the head.

3 EVALUATION METHODS

The radiation patterns of the antennas located on the mobile terminals are important parameters in cellular network design. Due to the large variety of mobile phones and other possible mobile terminals used in the networks, it is very important that their performance can be evaluated in a reliable way. The traditional definition of the directivity of the antenna or the radiation efficiency is not adequate for evaluating the performance of the mobile terminal antennas, whose orientation relative to the direction and polarization of the incident field is unknown. Several methods have been proposed for determining the performance in realistic propagation conditions.

In 1974 the theory of the joint contribution of incident field and the gain pattern of the antenna was presented for the first time by Yeh [18]. In 1977 Bach Andersen presented that the performance of an antenna can be defined as the power received by an antenna compared to some reference antenna [10]. These two publications provided the basics for analyzing the performance of a mobile terminal antennas in real, different usage environments. The random-field measurement (RFM) method [10] is based on measuring the mean received power level of the antenna on a random route in a typical operating environment [7,11,12]. The RFM method can be simplified by using a field simulator to produce an artificial scattering environment in an indoor facility [13,57]. This makes the measurements repeatable, but it is not evident that the conditions resemble a realistic operating environment. The direct measurement is assumed to be the best evaluation method in the sense of reliability but it is time-consuming since the repeatability of the measurements is poor and statistical significance can only be achieved by doing extensive measurements in several operating environments. Furthermore, the measurement can be performed only when a prototype of the antenna and the whole mobile terminal is available. An alternative approach to evaluate the performance is to measure, calculate, or simulate the radiation pattern of the antenna and determine the power distribution in the evaluation environment and thereafter estimate the performance, like the mean effective gain (*MEG*) as it will be presented in Section 3.2. The effects due to the user holding the terminal can be analyzed by including the user in the measurement or simulation of the radiation pattern [20,58].

3.1 RADIATION PATTERN OF AN ANTENNA

A commonly used basic method to define 3D complex radiation patterns of antennas either in a free space or beside a phantom head is to measure it in an anechoic chamber [22,48]. In the last years, tools developed for simulating the complex radiation patterns of small antennas have become more reliable and the simulation times have decreased due to more powerful computers. Since the 3-D measurement radiation pattern requires the prototype and it is relatively time-consuming, the simulators are often used to define the electric field pattern of the antenna during the designing process.

3.2 MEAN EFFECTIVE GAIN

A useful parameter to compare quickly the performance of different antennas is to calculate the mean effective gain of the antennas possibly in several different environments. The mean effective gain is a figure of merit for the average performance of a mobile terminal antenna taking into account the incident power distribution in the environment and the gain pattern of the antenna [19].

The average received power at the mobile antenna is:

$$P_{ave} = \frac{1}{2}\left\langle V(t)V^*(t)\right\rangle \qquad (3.1)$$

$V(t)$ is the complex envelope at the antenna port as defined in (2.3). Since the phase angles of the incident electric field are independent of the DoA for both polarizations as well as they are equally distributed between 0 and 2π, the average received power at the mobile terminal can be derived as:

$$P_{ave} = \oint \left[C_1 P_\theta(\theta,\phi)G_\theta(\theta,\phi) + C_2 P_\phi(\theta,\phi)G_\phi(\theta,\phi)\right]\sin\theta d\theta d\phi \qquad (3.2)$$

where P_θ and P_ϕ are angular density functions of the incident power, G_θ and G_ϕ the gain patterns of the antenna at θ- and ϕ-polarizations, and C_1 and C_2 are the power portions at different polarizations, respectively. A complete formula for calculating the *MEG* using the distribution of the incident field and the radiation pattern of the antenna is [19]:

$$MEG = \int_0^{2\pi}\int_0^{\pi}\left\{\frac{XPR}{1+XPR}P_\theta(\theta,\phi)G_\theta(\theta,\phi) + \frac{1}{1+XPR}P_\phi(\theta,\phi)G_\phi(\theta,\phi)\right\}\sin\theta d\theta d\phi \qquad (3.3)$$

The following conditions need to be satisfied when using (3.3):

$$\int_0^{2\pi}\int_0^{\pi} P_\phi(\theta,\phi)\sin\theta d\theta d\phi = \int_0^{2\pi}\int_0^{\pi} P_\theta(\theta,\phi)\sin\theta d\theta d\phi = 1 \qquad (3.4)$$

$$\int_0^{2\pi}\int_0^{\pi}\left\{G_\theta(\theta,\phi) + G_\phi(\theta,\phi)\right\}\sin\theta d\theta d\phi = \eta_{tot}4\pi \qquad (3.5)$$

Parameter η_{tot} is the total efficiency of the antenna including all possible mechanisms reducing the radiated power. The total radiation efficiency of the antenna is equal to double the *MEG* in an isotropic environment.

The environmental properties were discussed in Section 2 in details. The effect of *XPR* on *MEG* can be estimated based on Figure 4.

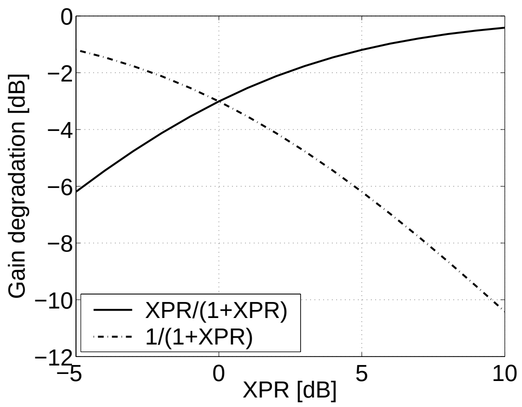


Figure 4. Effect of *XPR* on terms in (3.3).

The clear benefit of the computational method for determining the *MEG* is that it is fast and repeatable. In addition to [19], it has been used in [12,14,23,58,59,P3]. Currently the drawback is that there is little information available on realistic angular power distributions in different environments. Furthermore, the knowledge of the average performance is not always enough but instantaneous power is required for statistical analysis.

3.3 DIVERSITY ANALYSIS

Japanese have been among the very first to take advantage of diversity in wireless mobile terminals [17,60]. In radio communications, antenna diversity has been applied in receiving radio waves by two separate antennas at a BS [61]. Lately, diversity has been considered more widely as a real option also at a mobile station [54,58,59,60,62,63]. The diversity gain can be defined as the improvement achieved by combining the signals received by at least two antennas compared with the use of one antenna. The diversity and diversity combining techniques are well covered in [18]. The simplest way of combining the diversity branches is the selection combining (SC) using which the strongest diversity branch is selected instantaneously. In the equal-gain combining (EGC) the signals of the diversity branches are at first co-phased and then summed. The maximal ratio combining (MRC) produces an output signal-to-noise -ratio (*SNR*) equal to the sum of the *SNR* values of the diversity branches. This technique gives the best diversity gain of any known linear diversity combiner [18,64]. In theory, the MRC offers the diversity gain of 11.5 dB in the level of 99 % for uncorrelated two branch diversity.

The complex envelopes of the received signal after SC and MRC can be written as:

$$V_{SC}(t) = \max[V_1(t), V_2(t)] \tag{3.6}$$

$$V_{MRC}(t) = \mathrm{sum}[V_1(t)V_1^*(t) + V_2(t)V_2^*(t)] \tag{3.7}$$

where $V_1(t)$ and $V_2(t)$ represent the complex envelope of the diversity branch 1 and the branch 2 before combining, respectively. The noise level is assumed equal in all branches.

In order to get maximum advantage of using diversity, the samples of the radio waves received by two or more antennas should be comparable in strength and they should have experienced independent propagation mechanisms. A common measure to estimate the independency is that the envelope correlation should be equal to or lower than 0.7 between the received signals to provide a sufficient diversity gain [18]. Envelope correlation of 0.7 reduces diversity gain approximately 3 dB in a Rayleigh fading channel. The lower the correlation is, the better the achieved diversity gain will be, assuming equal power balance between the diversity branches. However, the power balance between the diversity branches has the main contribution to diversity performance if the correlation is low enough. Turkmani [61] presents equations for the diversity gain as a function of the envelope correlation (ρ_e) at the signal probability level of 90% and the mean signal level difference (Δ, [dB]) for SC, EGC, and MRC. The equations are based on empirical data. For MRC the formula is given as:

$$G = 7.14\exp(-0.59\rho_e - 0.11\Delta) \text{ [dB].} \tag{3.8}$$

In [65] the contributions of power imbalance, G_Δ, and power correlation, G_ρ, on diversity gain are distinguished theoretically in the environment of a uniform incident field as follows:

$$\begin{cases} -G_\Delta = 5\log q & \text{[dB] for AWGN error} \\ -G_\Delta = 5\log\left(\dfrac{2q}{1+q^2}\right) & \text{[dB] for co-channel interference and delay spread errors.} \end{cases} \tag{3.9}$$

$$-G_\rho = 5\log(1-\rho) \quad \text{[dB]} \tag{3.10}$$

ρ is the power correlation in a Rayleigh fading channel (also $\rho \sim \rho_e$ [25]), and q (<1) is the ratio of the power received by the second branch to that of the first branch.

In [53], an experimental study related to power imbalance and correlation is made separately for spatial, polarization, and pattern diversity. Although polarization diversity may provide diversity gain in LOS connection with few signal components, the power imbalance caused by polarization mismatch may distort the advantage. The main disadvantage in using diversity in small mobile terminals is the need for extra hardware which can be compensated with compact polarization diversity arrangements. The benefits of using diversity at the receiving mobile terminal, such as the use of low transmitted power resulting in decreased SAR values and reduced co-channel interference, are discussed in several papers [25,12,56,58,62,66].

3.4 CAPACITY ANALYSIS

To achieve better spectral efficiency, the effects of increasing the number of antennas at both ends of the radio link is studied. The ergodic capacity limit for an error-free bit rate for a radio link of the Multiple-Input Multiple-Output configuration can be calculated following Shannon's capacity theorem [27,29,30] extended to multi-element systems [28]. This theoretical capacity limit is useful for antenna comparisons although it cannot be reached in practice because of the assumption of independent, identically distributed Rayleigh fading channels made in [28] and because of the channel coding techniques. In real propagation environments, radio channels are not uncorrelated and several mechanisms affect the attainable capacity – such as the number of antennas, the type of antenna elements, element spacing, and the propagation environment.

In small mobile terminals such as portable computers, wireless personal digital assistants, and mobile phones, the antenna elements have to be closely spaced. Polarization diversity has been suggested as an attractive solution for obtaining uncorrelated antenna elements in MIMO systems [31,35,P5,P6]. In [35,36,P5], MIMO antenna configurations with different polarization and spatial properties were measured at the fixed station using different configurations consisting of four antennas on a portable computer. The effect of the antenna type located on the portable computer seems small on capacity, probably because the effects of the array gain and increased diversity caused by orthogonal polarizations are not separated. Instead, the multipath propagation environment seems rich enough to support the use of even 4x4 MIMO systems.

The performance of MIMO systems is composed of four main mechanisms related to the antenna arrays and environment: multiplexing gain, diversity gain, array gain, and interference cancellation [8,26]. However, as the antenna arrays are increased, the diversity advantage diminishes but the data rate gain of spatial multiplexing remains linear with the number of antennas. The capacity of the MIMO antenna configurations generally decreases with the narrowing of the angular spread [29,30] due to the increased correlation between the antenna elements. The effect of the antenna element spacing on capacity caused by the changes in correlation can be significant at the base station, as it was calculated for i.i.d. fading channels in [30,33]. According to [36] the degradation in capacity caused by the fading correlation of up to 0.5 is small for a 4x4 MIMO system. Regardless of the rich scattering environment, the existence of separate channels is not guaranteed due to the possible 'keyhole'-effect [32]. The keyhole does not exist in real radio channels but in some special environments like a street canyon the number of wave modes can be restricted. If the transmitter does not know the channel, the power is distributed equally to all transmitting (Tx) elements [27] whereas if the channel is known, the water-filling scheme [67] has been suggested to maximize capacity.

The measured complex channel matrix needs to be normalized to mitigate the effects of slow fading as it has been done e.g. in [28,36]. In real networks a similar situation occurs as the power control tries to maintain the received *SNR*. In the MIMO analysis of this work, a sliding window of about 1 m, corresponding to 7λ, is used in demeaning. The normalized instantaneous channel correlation matrix is calculated according to:

$$\overline{R}_{norm} = \frac{\overline{H}^H \overline{H}}{\frac{1}{n_t n_r} E\left\{ \sum_{t=1}^{n_t} \sum_{r=1}^{n_r} H_{r,t}^* H_{r,t} \right\}} \tag{3.11}$$

where $()^H$ is complex conjugate transpose, $()^*$ is complex conjugate, and E{} is expectation operator over the sliding window. n_t and n_r are the numbers of transmitting and receiving antenna elements, respectively. $\overline{H}$ is a narrowband complex channel matrix.

The eigenvalues of the normalized instantaneous channel correlation matrix $\overline{R}_{norm}$ give information on the parallel radio channels. The eigenvalues can be calculated using the singular value decomposition of the normalized instantaneous channel correlation matrix [31]. The number of linearly independent channels is related to the rank of the correlation matrix (number of significant eigenvalues). Only one significant eigenvalue exists in the keyhole case whereas to achieve the maximum capacity all eigenvalues should be equal. The figure of merit of how large is the difference between the eigenvalues is the eigenvalue spread of $\overline{R}_{norm}$ [68]. It can be defined for example at the probability level of 50 %, as in this work, according to

$$EVSpread = \lambda_{\max} - \lambda_{\min} \tag{3.12}$$

$\lambda_{\max}$ [dB] and $\lambda_{\min}$ [dB] are the largest and the smallest distinguishable eigenvalue at the 50 %, probability level.

The capacities of different MIMO antenna configurations and the discone antenna have been calculated using Shannon's capacity theorem and equal power allocation [28]:

$$C = \log_2\left[\det\left(I + \frac{SNR}{n_t}\overline{R}_{norm}\right)\right] \quad \text{[bit/s/Hz]} \tag{3.13}$$

where SNR is set equal to 10 dB and I is the identity matrix.

The approach taken at the Helsinki University of Technology utilizes a broadband MIMO measurement system of up to 8 dual-polarized antennas at the transmitter and up to 32 dual-polarized antennas at the receiver. The results enable many important and unique evaluation studies of different MS and fixed station antenna configurations at 2.15 GHz [34]. The large number of measurement channels makes possible the study of different antenna configurations by simply selecting the antenna elements from the arrays. A complete polarization information is useful since orthogonal polarizations are potential parallel information carriers. In addition, long continuous measurements enable large-scale effects to be included in the antenna evaluation.

4 EVALUATION OF PERFORMANCE OF SINGLE ANTENNAS

The properties affecting the received signal are studied here with experimental tests. The theory related to this chapter is presented in Chapter 2 and Chapter 3. In the beginning, direct radio channel measurements with antennas under test (AUT) are used to estimate the performance of the AUTs. Secondly in Section 4.2, the evaluation method based on the radiation pattern of the AUT and incident power distribution is validated by comparing the results of the radio channel measurements with the *MEG* values calculated using the radiation pattern and the EPD [P1]. In the latter parts of the chapter, the *MEG* is used as the figure of merit in estimating the performance of different AUTs.

Furthermore in this chapter, several real-type AUTs are tested in different environments [P3]. The effects caused by different propagation environments, azimuth orientation, and the user on *MEG* are studied. The performance of the antennas is tried to be improved by means of changing polarization and directivity and tilting the main beam of the radiation pattern [P2].

4.1 RADIO CHANNEL MEASUREMENTS WITH ANTENNAS UNDER TEST

In this section the radio channel sounder measurements made with seven different AUTs in four different environments are described. The measurements are called *AUT route measurements* and the results are used as the reference in Section 4.2. In addition to the mobile terminal models, an omnidirectional discone antenna was connected to the radio channel sounder during the measurements as illustrated in Figure 5.

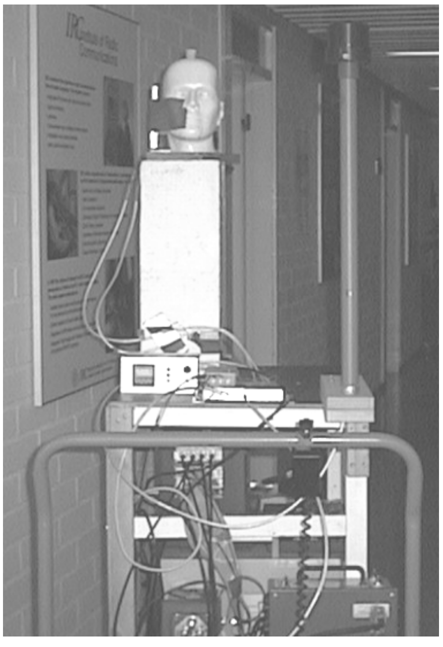


Figure 5. Radio channel sounder measurement with one AUT beside phantom head.

The antenna configurations were selected to represent different radiation properties that could be found in mobile terminals (the pictures of the antennas are presented in [12]). A dual-polarized antenna having vertically and horizontally-polarized feeds represents a fairly ideal directive antenna giving a possibility to study the use of two orthogonal polarizations. An omnidirectional monopole antenna and a more directive patch antenna located on a conducting case represent commonly used antenna types. All the antenna configurations were measured in free space but, in addition to that, the monopole was also measured beside a phantom head filled with a tissue simulating liquid. The cross-polarization power discrimination (2.6) and the total efficiencies of the antennas (2.5) are given in Table 1. It must be noted that the efficiency includes also the dielectric losses due to the head model.

Table 1. *XPD*s and total efficiencies of antennas.

Antenna	*XPD* [dB]	η_{tot} [%]
monopole	3.30	75
patch	1.38	87
feed1	-11.8	96
feed2	20.0	93
monopole2	2.66	72
monopole2+ head	2.20	41

The wideband radio channel sounder developed at Helsinki University of Technology [69] was used in the radio channel measurements at the frequency of 2.15 GHz. The chip frequency of the m-sequence was 30 MHz leading to a delay resolution of 33 ns. Three environments, suburban outdoor environment and corridor and office indoor environments with two different Tx locations called here 'b' and 'c', were included in the AUT route measurements [P1]. The AUTs were located on a moving trolley during the measurements. The AUTs as well as the vertically-polarized omnidirectional reference discone antenna were connected to the sounder using a fast RF switch. The reference values G_{ref} of the AUTs were calculated from complex wideband impulse responses by at first summing up the components in delay domain and then squaring the absolute values, as it was done in [70] at 5.3 GHz, resulting in narrowband power P_{AUT} and, then, using formula:

$$G_{ref} = E\left\{ \frac{P_{AUT}}{\frac{1}{50}\sum_{i-24}^{i+25} P_{Disc}} \right\}. \tag{4.1}$$

Here P_{Disc} is the narrowband power of the discone antenna and E{} denotes an expected value. As seen in (4.1), a sliding window of 10λ corresponding to 50 samples was used in normalizing the received power of the AUT by the power of the omnidirectional discone antenna in order to mitigate the effects of large-scale obstacles. The results of the AUT route measurements are presented in Figure 6 (referred as *ref*) and they are used as the reference in validating the evaluation method based on the radiation pattern of the antenna and the incident power distribution.

4.2 VALIDATION OF ELEVATION POWER DISTRIBUTION -BASED PERFORMANCE ANALYSIS

In order to validate the reliability of the method based on te radiation patterns and the incident power distribution, the AUT route measurements and the spherical antenna array measurements were performed in the same environments [P1]. In both the measurement campaigns the transmitting (Tx) antenna was a θ-polarized sector antenna located on top of a 2 m high mast. The spherical antenna array consisting of 32 dual-polarized radiating elements was used at the receiving mobile station in the incident power measurements [71]. The procedure to calculate the incident power distribution from the measurement data has been described in [71,P3]. Here, only the measured elevation power distribution is used assuming a uniform azimuth power distribution. The $MEG_{validation}$ used in the validation is the ratio of the *MEG* of the antenna under test (MEG_{AUT}) and the *MEG* of the discone antenna (MEG_{Disc}) calculated in the same environment using (3.3), and the $MEG_{validation}$ is given by:

$$MEG_{validation} = \frac{MEG_{AUT}}{MEG_{Disc}} \tag{4.2}$$

The AUT route measurement results (G_{ref}, referred also as '_ref') and the $MEG_{validation}$ values in one environment are side by side in Figure 6.

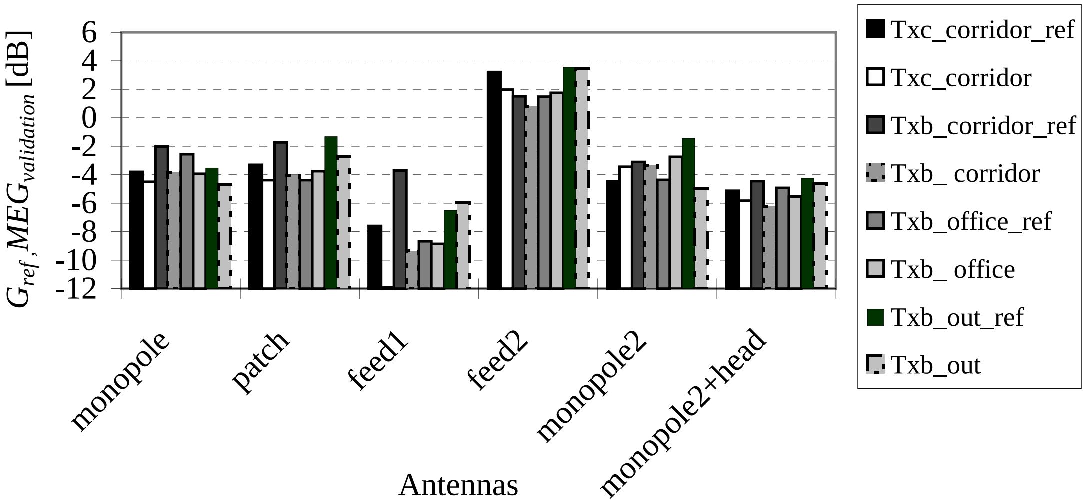


Figure 6. Comparison of two evaluation methods in four environments.

The mean difference between the results of the two evaluation procedures (Δ_m) and the standard deviation (SD) of the difference for the six antennas in the four environments were calculated using the following formulas for linear (not dB) values:

$$\Delta_m = \frac{1}{N}\sum_{i=1}^{N}\left(MEG_{validation} - G_{ref}\right) \tag{4.3}$$

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\left(MEG_{validation} - G_{ref}\right) - \Delta_m\right)^2} \tag{4.4}$$

Totally N=24 comparisons between the methods result in the mean difference of Δ_m = -0.04 ($10\cdot\log_{10}(1+\Delta_m)$ = -0.18 dB) and the standard deviation of SD = 0.19 ($10\cdot\log_{10}(1+SD)$ = 0.76 dB). The monopole2 has the largest difference between the methods as shown in Table 2, where the mean difference between methods in the four environments is calculated separately for every AUT.

Table 2. Mean difference between methods (Δ_m) and antenna ranking.

Antenna	Δ_m	Antenna ranking	
		G_{ref}	$MEG_{validation}$
feed2	-0.15	1	1
discone	-	2	2
mopa_patch	-0.03	3	4
mopa_monopole	-0.08	4	5
monopole2	0.16	5	3
monopole2+head	-0.04	6	6
feed1	-0.11	7	7

Based on the antenna ranking presented in Table 2 and the results in Figure 7, both the methods result in similar order as the performances are compared taking into account that the differences between the monopoles and the patch are very small. The total radiation efficiencies (η_{tot}) result in different ranking due to the lack of the environmental effects.

Measuring several antennas in several propagation environments requires a lot of effort. As the incident power distribution or a model of that is known, the performance of the antennas is rather easy and fast to calculate using (3.3). Furthermore, the result is similar to that of a direct radio channel sounder measurement, which makes the method a useful tool in designing mobile terminal antennas.

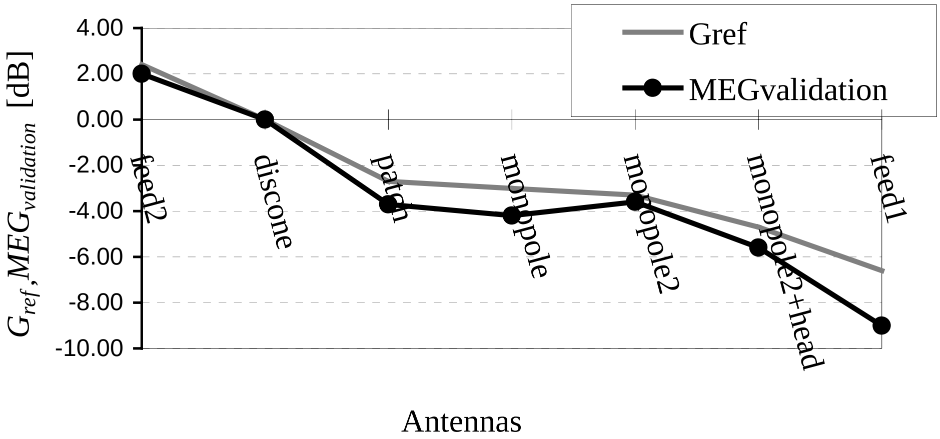


Figure 7. Average performance of the antennas over the environments described in Section 4.1.

4.3 PERFORMANCE OF MOBILE TERMINAL ANTENNAS

Here, the *MEG* calculation method validated in the previous section is used in estimating and comparing the performance of realistic antennas located on a conducting case representing the mobile terminal. In [P3], experimental data is applied for the analysis of the *MEG* of several antenna configurations to distinguish the effects of polarization, user, and azimuth orientation on performance.

The directional channel data of the following environments is used in *MEG* calculations:

- The *indoor picocell* measurements (*XPR* = 7.0 dB) were carried out in a transit hall of Helsinki airport. The omnidirectional Tx antenna was at 4.6 m above the floor level and located so that the visibility over the hall was good. The portion of LOS measurements was significant.
- The *outdoor–indoor* measurements (*XPR* = 10.7 dB) were performed in two office buildings with the Tx antenna placed on the rooftop of the neighboring building. The measurement routes include both corridors and office rooms.
- The *urban microcell* measurements (*XPR* = 11.1 dB ... 11.4 dB) and *urban macrocell* measurements (*XPR* = 7.3 dB) were performed in the center of Helsinki, Finland. The routes were driven along the sidewalks of the streets.
- The *highway macrocell* measurements (*XPR* = 6.6 dB) were carried out in an industrial area in Espoo, Finland. The Tx antenna was located on top of a building and the spherical array was inside a car. The usability of this data is limited because the metallic chassis of the car has an effect on the angular distribution and polarization of the electric field.

In the environments the average *XPR* is relatively high, about 9 dB, implying that the polarization of received radio waves depends strongly on the polarization of the Tx antenna. However, the measurement ranges were relatively short. In addition to the procedure to calculate the incident power distribution, mean elevation angle, rms elevation spread, and the plots of the EPDs and are described in [P3]. The EPD is generally concentrated close to θ=90° and the rms elevation spread is less than 12°.

Three typical handset antennas were selected in order to evaluate the *MEG* of mobile terminal antennas: The 3-D radiation pattern of a commercial GSM1800 terminal with an external meandered monopole antenna was measured in an anechoic chamber both with and without a model of a human head and shoulders. Without the head model the terminal was oriented vertically and beside the model it was tilted 60° degrees from vertical to correspond to a natural usage position. The radiation patterns of a meandered monopole antenna (MEMO) and a planar inverted patch antenna (PIFA) attached to handset models as illustrated in Figure 8 were simulated by using a commercial FDTD program. The radiation patterns of the MEMO are presented in Figure 9 and the others are given in [P3]. The simulations were performed both with and without a head model. Without the head model the phone chasses were oriented vertically and beside the head they were oriented according to the position specified by CENELEC [72]. The simulation was made on both the left (L) and right (R) sides of the head. In addition to the mobile terminal antennas, the performance of the discone antenna was estimated. [P3]

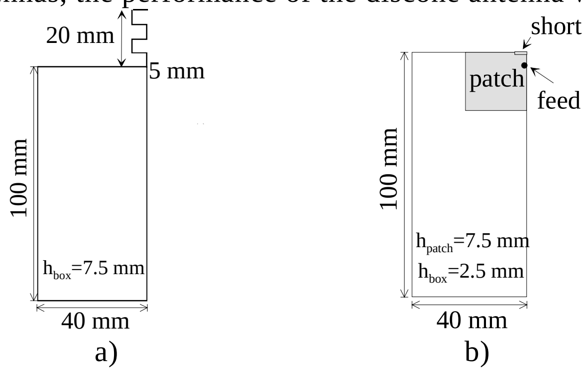


Figure 8. Real-type antenna configurations under test: a) MEMO. b) PIFA.

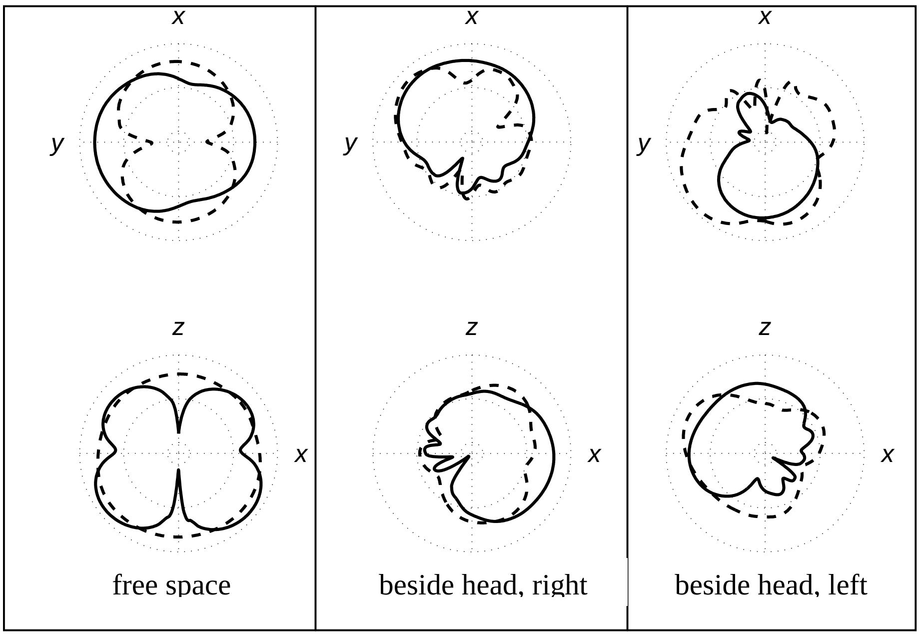


Figure 9. Radiation pattern cuts of a meandered monopole (MEMO) [P3].

Figure 10 presents the *MEG*s (3.3) and the antenna efficiencies (2.5). It must be noted that the efficiencies include also the dielectric losses due to the head model. Because the azimuth orientation of the user may vary randomly, a uniform azimuth power distribution was applied.

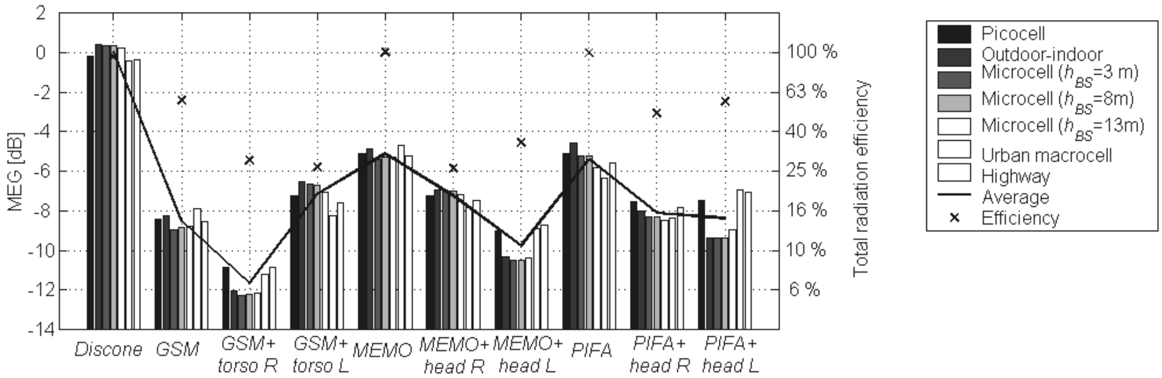


Figure 10. Mean effective gain of evaluated antennas.[P3]

In Table 3 the *MEG* values are calculated over all the environments ('average' in Figure 0). The discone has the highest *MEG* in all environments due to its omnidirectional radiation pattern, high efficiency, and high *XPD*. It should also be noted that the MEMO and PIFA have high efficiency without the head model, but still their *MEG* values are significantly lower due to the lower *XPD* and a lowered gain in the elevation angles close to the horizontal plane.

Now, we concentrate on the PIFA and the MEMO (free space) both having η_{tot}=100 % and *XPD* close to 0 dB. The PIFA has the minimum of the θ-polarized radiation pattern above the horizontal plane and the MEMO has it close to the horizontal plane (see Figure 6 in [P3]). Comparing the *MEG*s of the antennas in the environments with *XPR* around 7 dB, the PIFA with the minimum at higher elevation angle has 1.2 dB worse performance in the urban macrocell (mean elevation angle 3.8°) than in the indoor picocell (mean elevation angle 11.2°) whereas the MEMO has better performance in the picocell than in the urban macrocell. Similar observation can not be made on the rms spread because the EPDs with small rms spread have higher XPR than the EPDs with larger rms spread. However, it is good to test the antennas in different environments before installing them on real mobile terminals but, as it will be shown in Section 4.3.2, the performance of single antennas can not be improved a lot by beam shaping.

The level of the *MEG* values of the realistic antennas is generally very low. Only clearly negative *XPD* with dominating ϕ-polarization predicts low *MEG* value compared to the antennas with positive *XPD*. Moreover, the polarization seems to have an impact on the performance whereas in this study the effect of the peak or the width of the EPD does not seem to have equally strong effect. The differences in *MEG* values are larger between antennas than between propagation environments because in all environments most of the power is received at small positive elevation angles (see Section 2.1.).

Table 3. Antenna configurations under test.

	Antenna	η_{tot} [%]	*XPD* [dB]	*MEG* [dBi]
measured radiation pattern	Discone	95	13.0	0.0
	GSM1800	56	4.6	-8.5
	GSM1800 + torso R	28	-5.8	-11.7
	GSM1800 + torso L	26	-0.1	-7.2
simulated radiation pattern	MEMO	100	-0.7	-5.1
	MEMO+head R	26	0.2	-7.3
	MEMO+head L	35	-5.1	-9.8
	PIFA	100	-0.2	-5.4
	PIFA+head R	49	-3.0	-8.1
	PIFA+head L	57	-5.6	-8.4

4.3.1 User of a terminal

The effects caused by the users of the mobile terminals on the performance were discussed in Chapter 2. Holding the terminal beside a head, which has been a typical way of using a mobile phone, affects the radiation properties like shape of the radiation pattern, polarization and efficiency. In order to study the effects of the user, the terminal was held on both the right (head R) and the left (head L) side of the head.

As the MEMO was placed beside the head model, the total efficiency dropped by 5.9/4.6 dB and the average *MEG* decreased by 2.2/4.7 dB, depending on the side of the head (R/L). The θ-polarized pattern of the MEMO without the head model has a minimum in the horizontal plane, which can be seen in Figure 9, whereas on the right side of the head the maximum of the θ-polarized pattern is in the horizontal plane. On the right side of the head θ-polarization dominates, which partly compensates for the decreased efficiency. The effect of the user is smaller on the performance of the directive PIFA. The total efficiency dropped by 3.1/2.4 dB and the *MEG* dropped on average by 2.7/3.0 dB when it was placed beside the head. The average *MEG* of the GSM1800 increased by 1.3 dB when the handset was placed on the left side of the phantom head, although the total efficiency dropped by 3.3 dB from the free space value [P3]. In the AUT route measurements in Section 4.1 the phantom head decreased the total efficiency of the monopole by 2.4 dB.

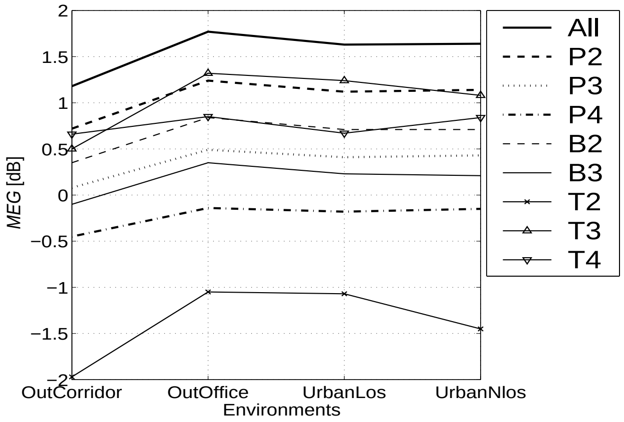
The *MEG* values decreased on average 0.8 dB, 3.3 dB and 2.8 dB for the measured GSM1800 and the simulated MEMO and PIFA due to the user, respectively. For the terminal on the left side of the head, the highest *MEG* values are obtained in the environments with the lowest *XPR*. It can partly be explained by the *XPD* values of the antennas, which are lower on the left side than on the right. For example, the difference between the *MEG* values of the MEMO on the two sides of the head is 2.5 dB. The highest variation of *MEG* values between different environments is obtained for the antennas with negative *XPD*s. The results clearly indicate that the maximum gain or the total radiation efficiency of the antenna is not enough to describe its performance in real propagation environments. [P3]

4.3.2 Beamwidth, tilting, and polarization of antenna under test [P2]

The effects on *MEG* of changing beamwidth, main beam direction, and polarization ratio of the antenna is studied by using synthetic radiation patterns without side lobes or back lobes. The patterns were formed in such a way that either the beamwidth *BW*, main beam direction in elevation, θ, or polarization ratio, here 1/*XPD*, was changed. The patterns were Gaussian in elevation and omnidirectional in azimuth with η_{tot} equal to one.

Although the performance of the mobile terminal can not be improved a lot by modifying the radiation pattern as shown in Figure 11, some improvements can be found. As the main beam is narrowed on the vertical plane, the performance improves as a result of increased antenna gain around the horizontal plane close to which the radio waves mainly arrive at the MS. Furthermore, tilting the beam somewhat above the horizontal level increases the performance because the EPD is also slightly upwards tilted (see [P2]). As a result of employing θ-polarized antenna at the BS, the mainly θ-polarized MS antenna has the highest *MEG* in all environments.

Here, the performance of the terminals operating at 2.15 GHz can be improved approximately 2 dB between the best and worst synthetic antenna by narrowing and tilting the beam and considering the polarization (T2 not considered as an extreme example). At 5 GHz the improvement could be larger, because narrow adaptive beams are easier to produce for small mobile terminal antennas at 5 GHz than at 2 GHz. However, high efficiency is the basic requirement for a good antenna and beam shaping provides additional advantage on *MEG*.



a)

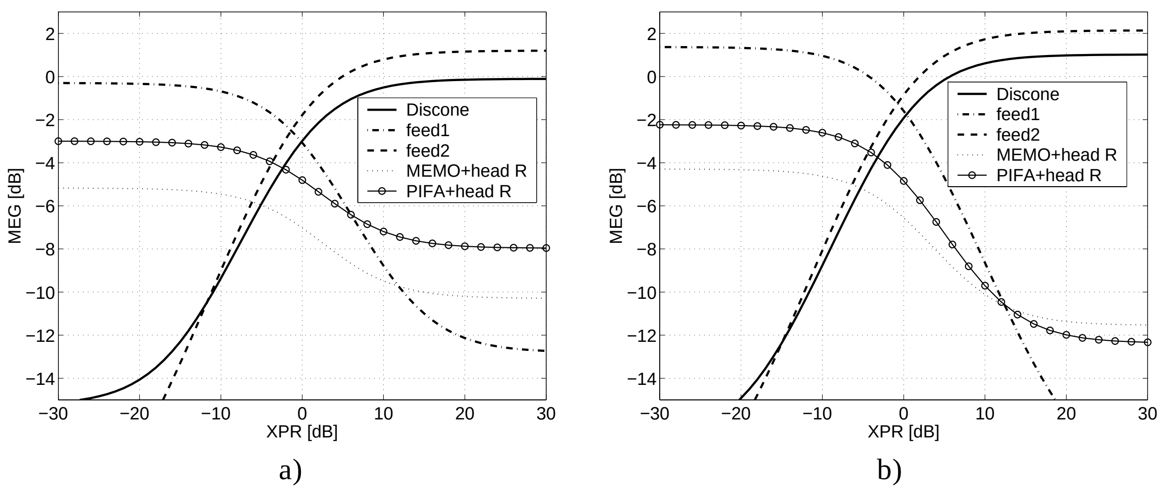
Case	1/*XPD*	*BW*	θ
All	0.10	70	90
P2	0.25	70	90
P3	0.50	70	90
P4	0.75	70	90
B2	0.10	100	90
B3	0.10	130	90
T2	0.10	70	45
T3	0.10	70	70
T4	0.10	70	110

b)

Figure 11. a) *MEG* values for synthetic radiation patterns. b) Parameters of radiation patterns.

4.3.3 Effect of XPR on MEG

The polarization matching of the antenna and the incident field has an important role in the performance of the antennas located on a mobile terminals. Here, two models have been chosen to represent the elevation power distribution at the MS: the Gaussian model introduced in [19] and the double exponential model developed to describe several environments in [P3]. Five antennas are used to study the effects of the *XPR* on the *MEG* and the results are given in Figure 12. In this study, the uniform APD is assumed and *XPR* varies from –30 dB to 30 dB. The θ-polarized omnidirectional discone antenna, used also as the reference antenna in this thesis, is used here as one AUT. The dual-polarized antenna was included to resemble a possible laptop antenna type. The MEMO and PIFA located on the right side of a head model represent commonly used mobile terminal antennas.



a) b)

Figure 12. Effect of *XPR* on *MEG* of different mobile terminal antennas. a) Gaussian EPD (θ-angle: 71°/58°, standard deviation: 20°/64°; θ-pol/ϕ-pol [31]) b) Double exponential EPD; all environments [P3].

Figure 12 shows clearly that the effect of *XPR* on the *MEG* value is significant when the *XPR* values vary from -10 dB to +10 dB. The higher the absolute value of the *XPD* of the antenna is the stronger is the effect of the *XPR* on the *MEG*. As well in Figure 10 and in Table 3, the *XPR* seems to explain most of the environmental dependence of the *MEG* and the polarization matching of the environment and the antenna really affects the performance. Since the *XPR* varies according to environment, it is recommended to use polarization diversity at the mobile terminal to mitigate the effects of the polarization mismatch on the performance.

4.3.4 Azimuth orientation in propagation environment

In all the performance analysis until now, the uniform APD has been assumed. Figure 13 presents the effect of using uniform APD instead of the measured APD on *MEG* in the same environments as in Section 4.2. The measured APD does not have any effect on the *MEG* of the omnidirectional discone antenna, whereas all the other antennas are more directive and thus dependent on the direction of arrival in azimuth. Generally, based on this thesis work the effect of the environment is smaller than the effect of antennas on the performance of the mobile terminals. In Figure 14, the effect of the azimuth orientation on the *MEG* of the discone antenna and that of the directive feed2 of the dual-polarized antenna is demonstrated in the steps of 1°. The *MEG* values include both the real EPD and real APD. The two antenna examples, on which effect of azimuth orientation is about 0 dB for the omnidirectional antenna and up to 12 dB for the directive antenna, are extreme examples. For most antennas the result is between the examples. However, the result of the directive antenna resembles the effect of the azimuth orientation of the directive PIFA hold beside the head. To conclude, the uniform APD can be assumed in estimating the average performance of the antennas. Instead, in order to estimate the worst case performance or the variance of the performance of especially directive antennas a real APD needs to be considered.

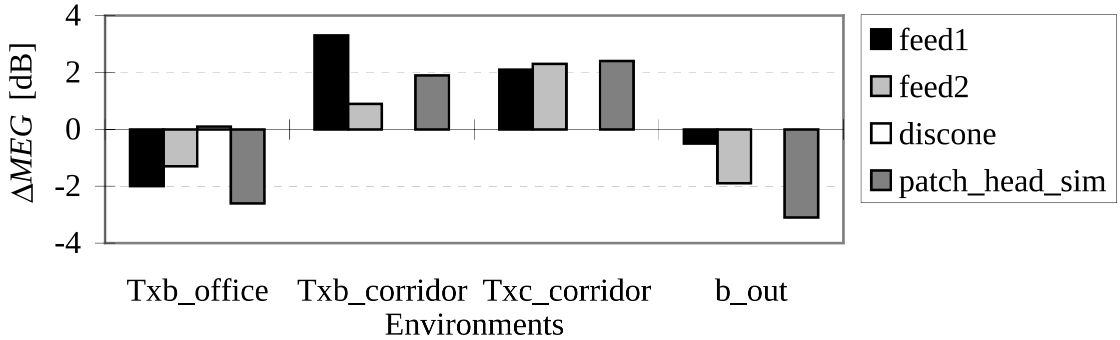
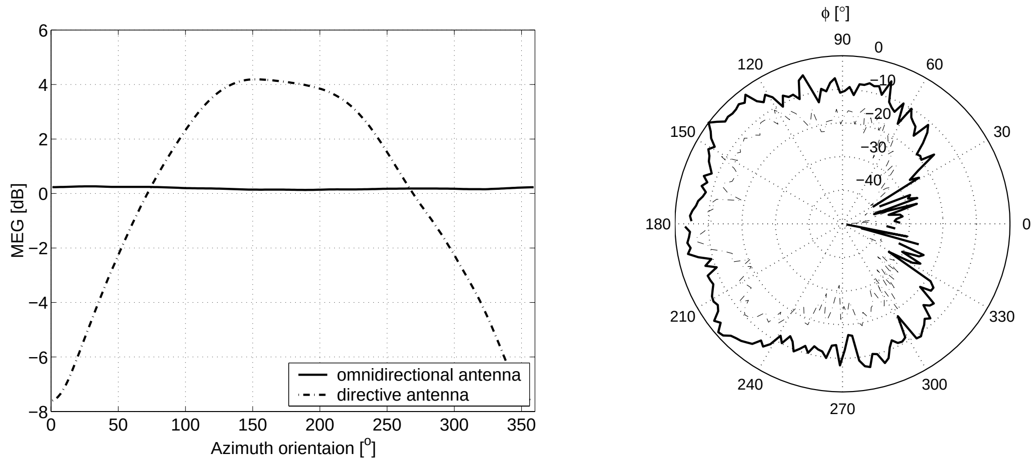


Figure 13. Effect of using uniform APD instead of real APD on *MEG*.



a) b)

Figure 14. a) Rotating antenna pattern 360° in one environment. b) azimuth power distribution of the environment.

5 EVALUATION OF PERFORMANCE OF MULTI-ANTENNA CONFIGURATIONS

In 4G systems, the requirement for new technology enabling higher data rates exists. One way to fulfill the requirements is to use several antennas. Two or even more antennas are installed easily at the base station. Instead, probably at maximum two antennas can be mounted in the mobile terminal due to spatial limitations. Portable terminals of laptop size are larger than today's mobile phones and more antennas could therefore be installed on them to enable the transfer of large amounts of data, like video. In this work, all multi-antenna analysis is based on the experimental work described in Section 5.1. A novel plane wave -based evaluation method is shown to be accurate enough to be used in diversity analysis as it is done in [73]. In addition, the advantages and disadvantages offered by Multiple-Input Multiple-Output (MIMO) systems with several transmitting and several receiving antennas are studied.

5.1 EXPERIMENTAL WORK

MIMO radio channel measurements were performed using antenna arrays of directive and dual-polarized elements in three potential MIMO environments [34] (details in [P5] and [P6]). The environments shown in Figure 15 were selected to represent both the expected typical-usage environments of the MIMO systems and different scattering environments. In outdoor macrocell environment in downtown Helsinki, the fixed station (FS) was on a rooftop and the trolley carried the MS along the street. In the outdoor microcell measurement, the FS was located below the rooftop level pointing along the street; the MS was moved along the street and across an intersection. In the indoor picocell measurement the FS was at 3.8 m and the MS route began in an open hall and ended into a corridor (Figure 15 c).

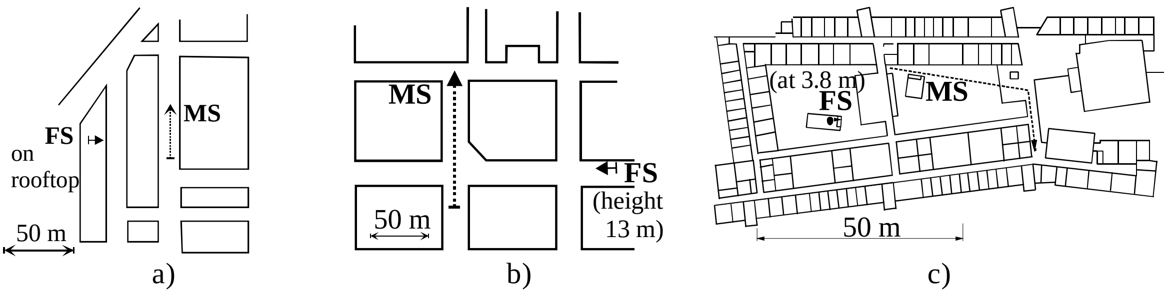


Figure 15. Maps of measurement routes and transmitter locations in a) outdoor macrocell. b) outdoor microcell. c) indoor picocell.

The antenna array of 32 directive and dual-polarized antenna elements located on the sphere was used at the receiving (Rx) MS [71] (see Figure 3 a). One dual-polarized element has two feeding points sensitive to orthogonal polarizations. A horizontal zigzag antenna array and a linear antenna array of eight directive and dual-polarized antenna elements (see Figure 16), similar to the elements of the spherical antenna array, were used at the FS in the indoor and outdoor environments, respectively. The elements were selected from the spherical antenna array and from the Tx antenna array in the post-processing of the measurement data.

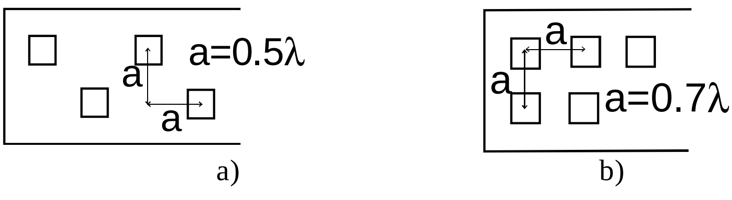


Figure 16. a) Zigzag antenna array used indoors. b) Linear antenna array used outdoors.

The antenna arrays at the FS and MS were connected to the transmitter and to the receiving wideband radio channel sounder [69], respectively. The use of the system was limited to mainly picocells, microcells, and small macrocells because the transmitted power had to be limited due to the power handling capability of the Tx switch. In the measurements, the discone antenna was connected to one Rx channel as a reference antenna [P3].

5.2 ONE TRANSMITTING ANTENNA AND TWO RECEIVING ANTENNAS

In order to increase the reliability of operating networks, the use of two antennas at MS is studied e.g. in [56]. Employing several antenna elements mitigates the effects of multipath fading on the received signal. In a good diversity arrangement the received signals are of equal strength and relatively uncorrelated as described in Section 3.3.

5.2.1 Validation of plane wave -based method

The plane wave -based evaluation method is verified for comparing the performance of antennas or antenna arrays located on mobile terminals by showing that the diversity performance estimated using the plane wave -based method is close to that obtained by direct radio channel measurements [P4]. The method is based on MIMO channel information and the complex 3-D radiation patterns of the antennas by applying (2.3). The instantaneous channel data is obtained from the channel sounder measurements described in Section 5.1. In the validation procedure those measurements are used in two different ways:

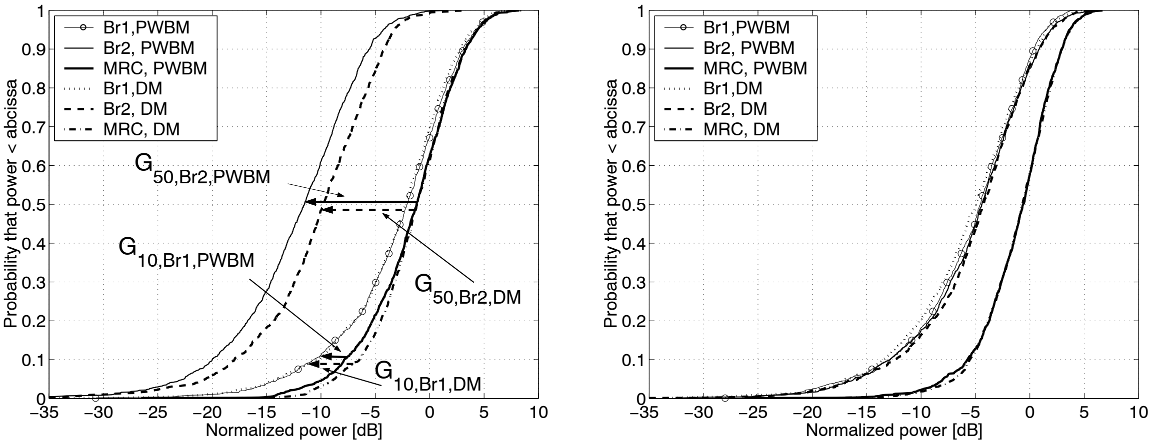
Method 1: Direct radio channel measurement (DM)

Antenna elements are selected from the linear Tx array and the spherical Rx array used in the measurements to obtain different antenna configurations. The performance of the antennas or antenna configurations is estimated by means of the measured channel matrix.

Method 2: Plane wave -based method (PWBM)

The joint contribution of the complex 3-D radiation pattern of a mobile terminal antenna and the estimate of the distribution of radio waves in a mobile radio environment is used to achieve an estimate of the received signal according to (2.1) – (2.3) [18]. The complex 3-D radiation patterns of the antennas can be simulated by a commercial software or measured in an anechoic chamber.

The relative branch powers and the power after maximum ratio combining obtained by (3.7) are used to show the usefulness of the plane wave -based method in diversity analysis. Figure 17 shows the cumulative distribution functions (cdf's) of the power received by the diversity branches in the macrocell – the solid line is the plane wave -based method and the dashed line is the direct method. Furthermore, the power after the maximum ratio combining *(MRC)* is illustrated. One vertically-polarized feed of one Tx element (see Figure 16) was chosen in the analysis. At the MS, two different diversity arrangements were used: At first, one spherical antenna array element consisting of the ϕ-polarized feed1 and θ-polarized feed2 represents a polarization diversity antenna suitable e.g. for laptop-sized equipments. As another option, either the θ-polarized or the ϕ-polarized branches of two adjacent antenna elements were chosen, representing a space-diversity arrangement. The diversity gain is calculated compared with both the better and the worse branch as it is shown in Figure 17. The diversity gain compared to the branch 1 (Br1) is shown at the probability level of 10% ($G_{10,Br1,DM}$ or $G_{10,Br1,PWBM}$) and the diversity gain compared to the branch 2 (Br2) is shown at 50% probability ($G_{50,Br2,DM}$ or $G_{50,B21,PWBM}$). Similar analysis is made for Br1 at 50 % probability level and for Br2 at 10 % probability level.



a) b)

Figure 17. Results with predicted (PWBM) and measured (DM) signals for a) θ-polarized and ϕ-polarized branches of one antenna element and b) θ-polarized branches of two adjacent antenna elements [P4].

The mean difference between the diversity gain values of the two methods when testing 7 antenna configurations in three environments are given at probability levels of 10 % and 50 % in Table 4. The results include totally 21 comparisons. Three of the configurations employ orthogonal Rx polarizations, similar to Figure 17 a, and four configurations include co-polarized Rx feeds, similar to Figure 17 b. In all the 21 studied cases the power balance between the diversity branches is on average 5.3 dB in the plane wave -based method and 4.4 dB in the direct measurements. The difference is larger in plane wave -based method due to the physical restrictions of the used spherical antenna array and the limitations of the beam-forming algorithm in estimating small details of the incident field. The average difference between the predicted and the directly measured diversity gains is less than 0.9 dB (see Table 4) showing a good agreement between the two methods. The order of the stronger and the weaker branch is the same regardless of the evaluation method. The diversity gain values and relative received power estimated by the plane wave -based method coincide well with the direct measurement results as it was shown here using the elements of the spherical antenna array. The same is also shown for real mobile terminal antenna configurations in [P4].

Table 4. Mean differences in results of the plane wave -based method and of the direct method of Br1 and Br2 at probability levels of 10 % and 50 % averaged over 7 antenna configurations in three environments.

ΔG_{div}[dB]	Br1, 10%	Br2, 10%	Br1, 50%	Br2, 50%
Mean difference	-0.39	0.81	-0.11	0.87
Standard deviation	1.03	1.40	0.73	1.04

The plane wave -based method can be used in SISO analysis and it is even more accurate in MIMO analysis [P4]. The advantage of this method is that antennas and the mobile terminals can be tested in several propagation environments very fast already during the design process with simulated radiation patterns and the previously measured channel library. The commonly used way of performing time-consuming radio channel measurements with antenna prototypes is not anymore the only option to compare the antennas in real environments. Furthermore, the method enables the performance evaluation in real environments without being vulnerable to weather conditions and the radio channel stays exactly the same for all the AUTs. Furthermore, the authorities may restrict the usage of the frequency bands in which commercial networks are operating. The effect of azimuth orientation on performance was shown to be important in SISO systems in Chapter 4 and it will be shown to be important in MIMO systems as well. In the plane wave -based method the antenna configurations can be rotated computationally in azimuth and in elevation to get an estimate of e.g. the effect of the user on the performance.

5.3 MULTIPLE-INPUT MULTIPLE-OUTPUT SYSTEMS

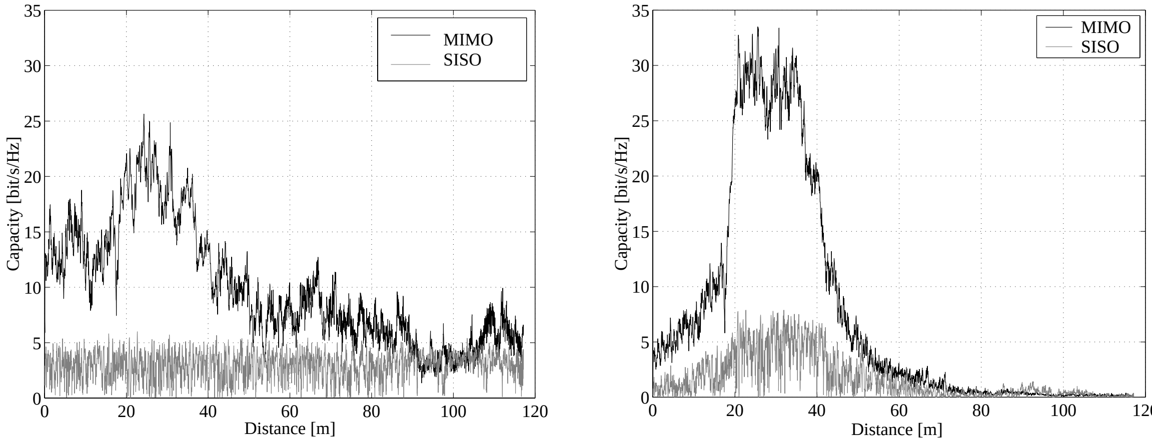
Here, the measurements described in Section 5.1 are used as the experimental basis for the evaluation of MIMO antenna configurations at 2.15 GHz. The goal in [P5] and [P6] is to find out how MIMO channels could be exploited better. At the MS, the antenna configurations range from a single dual-polarized antenna usable in small mobile terminals to eight-channel antenna configurations applicable in portable computer-type devices. Our measurement system including antennas installed on the sphere using the geometry of the Archimedian solid has similar groups of antennas in five equally spaced azimuth orientations. Accordingly, the possibility of including several azimuth orientations has been utilized by including the results of a similar antenna configuration pointing to five azimuthal orientations in the cdf's of all the following studies except for the 'Best' and the 'Worst' in Section 5.3.2. At the fixed station, the effects of increasing the number of channels and increasing the inter-element spacing are studied.

The average channel gain used in normalization is calculated over the connections between the VP transmitting elements and the receiving discone using (3.11). The capacity of MIMO and SISO systems are calculated using (3.11) – (3.13). The narrowband complex channel matrix $\overline{H}$ is obtained from impulse responses by at first removing the noise and then using the coherent summing in the delay domain [70]. The capacity of the discone is calculated selecting one vertically-polarized FS antenna element (SNR = 10 dB and n_r = 1 in (3.13)). The ergodic capacity of i.i.d. Rayleigh fading channels is also included in the figures (referred as iid) although the results are not directly comparable with the other results because in the other studies the SNR of the directive elements varied as a result of the normalization procedure. Thus, the achieved capacities are sometimes higher than those of the i.i.d. channel.

5.3.1 Normalization

The capacity of a 4×8 MIMO configuration consisting of two Tx elements and four dual-polarized Rx elements calculated according to (3.13) in the direction of Tx at the crossroads is presented in Figure 18. Two different normalization methods have been considered in (3.11): in Figure 18 a the normalization is over 1 m sliding window, whereas in Figure 18 b the normalization is over the whole measurement route. The effect of high SNR would not be seen if we had measured only the distance from 80 m to 117 m in Figure 18, for example. The discone antenna was used as the reference antenna since the directive patch antennas pointing towards the five different azimuth orientations do not receive same average power.

The sliding window normalization was selected to be used in the further work since the other method clearly shows the changes of the SNR in the result. In both the normalization methods the capacity decreases after a distance of 50 m because the directive elements are towards a wall. In addition to the sliding window normalization, an important issue in this work is the use of the external antenna in normalization. The advantage of using the external reference antenna is that the results of separate measurement campaigns are comparable, especially in the SISO studies.

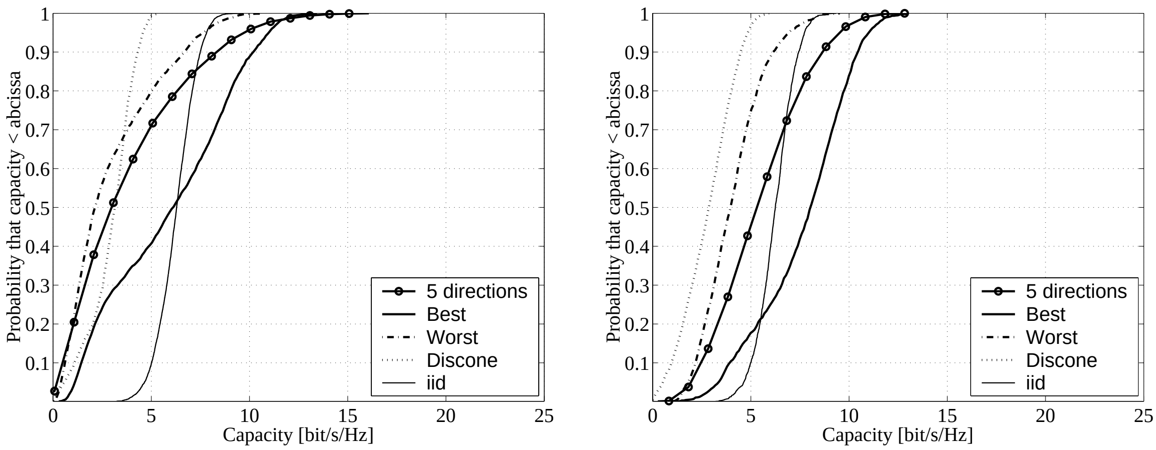


a) b)

Figure 18. Results due to two normalization methods for 4×8 MIMO configuration with right pointing elements in outdoor microcell a) Normalized over 1 m. b) Normalized over whole route. [P5]

5.3.2 Azimuth orientation

The effects caused by the varying azimuth orientation of mobile terminal antennas with respect to the FS are studied by selecting one dual-polarized antenna element of the spherical antenna array [P5]. Such an antenna is suitable for mobile phone sized equipment and the directivity implies the shadowing effect of the user on the radiation pattern (see e.g. [54, 55, 74]). The cdfs in Figure 19 include the results in five equally spaced azimuth orientations of the antennas. At the FS two adjacent elements were used, resulting in 4×2 MIMO configurations. The capacities have been calculated according to (3.11) and (3.13). The capacities of the ‘Best’ and the ‘Worst’ of the five azimuth orientations over the whole route and the reference discone antenna are illustrated in Figure 19.



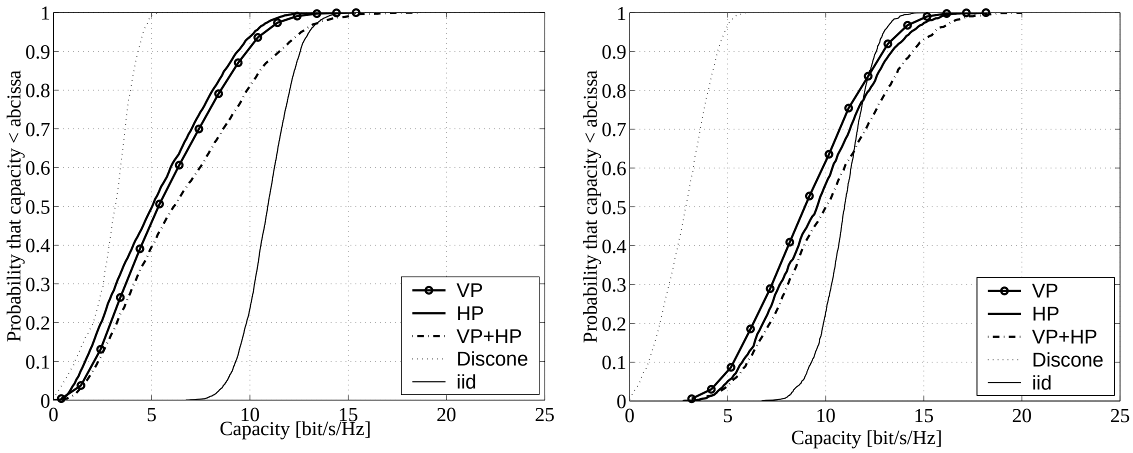
a) b)

Figure 19. Effect of azimuth orientation in a) outdoor microcell and b) indoor picocell n_T=4, n_R=2. [P5]

The effect of azimuth orientation on capacity can be seen as a difference of about 4 bit/s/Hz in the capacities between the ‘Worst’ and the ‘Best’ cases. The capacity varies because the antenna elements point in different azimuth directions. The bad azimuth orientation of the directive elements with respect to incoming signals reduces the capacity when compared with that of the i.i.d. channels. Considering for example the mobile phone held to the ear, even though it may not be a typical position for the use of MIMO equipment, the capacity can vary remarkably as a function of orientation. As it has been shown in this thesis, it is important that the antennas are analyzed in different positions and orientations.

5.3.3 Polarization

Effects of using either VP or HP are studied by selecting co-polarized feeds of four antennas at the MS. In addition, cross-polarized channels are studied by selecting the same four elements but two HP and two VP feeds. At the FS two dual-polarized elements are used, resulting in a 4×4 MIMO configuration. The cdf’s of the capacity values are given in Figure 20 – again in five azimuth orientations and using the sliding window normalization. A photo of a four-element group is in Figure 3 a.



a) b)

Figure 20. Effect of polarization on capacity, n_T=4, n_R=4 in a) outdoor microcell. b) indoor picocell. [P5]

Orthogonally-polarized antenna elements provide more diversity advantage than co-polarized element but the antenna array employing co-polarized elements has higher antenna array gain. Therefore, using elements with orthogonal polarizations seems as good as employing co-polarized elements if two polarizations are used in the transmission. Distinguishing the effects of the array gain and polarization matching further is left for future studies. The use of orthogonal polarizations can be described as $\overline{H}$-matrix having two channels that correspond to the two polarization states. The case is studied in [75]. The difference between using only VP or only HP at the MS is small in the case of using orthogonal polarizations at the FS.

5.3.4 Effect of Tx element spacing

The effect of the inter-element spacing on the capacity is studied by gradually increasing the distance between the selected elements at the FS. Selecting always four dual-polarized MS elements results in a 4×8 MIMO configuration. Five azimuth orientations are included as described in the beginning of Section 5.3. The eigenvalues of the normalized instantaneous channel correlation matrix $\overline{R}_{norm}$ (3.6) are used to study and distinguish the effects of different transmitting antenna configurations on MIMO performance. Table 5 shows the *EVSpread* (3.12) of the studied cases and also that of the i.i.d. channels. [P6]

Table 5. Eigenvalue spread at 50 % probability level (4 dual-polarized Rx elements).

EVSpread [dB]	Tx spacing 0.7 λ /0.5λ	Tx spacing 3.5 λ /2.5 λ	2 Tx elements	6 Tx elements
picocell	12	11	20	10
microcell	20	14	28	17
macrocell	18	11	26	14
i.i.d.	9	9	18	7

Increasing the distance between Tx antenna elements increases resolution by narrowing the main beam which results in the decreased eigenvalue spread and increased capacity. Besides, it increases the opportunity to utilize the complexity of the propagation environment. Increasing the distance between elements has therefore stronger impact in outdoor environment than in more scatter-rich indoor environment. When employing the shorter element spacing the *EVSpread* varies from 9 dB in i.i.d. channel to 20 dB in the microcell whereas with the larger element spacing the maximum difference in *EVSpread* values is only 5 dB. If the environment is scatter-rich enough the effect of the antenna configuration on eigenvalue spread is of minor importance as can be seen in the results of the indoor picocellular environment. In Figure 21, most probably the use of using vertical and horizontal polarization divides the eigenvalues clearly in two groups, the stronger and the weaker pair of values.

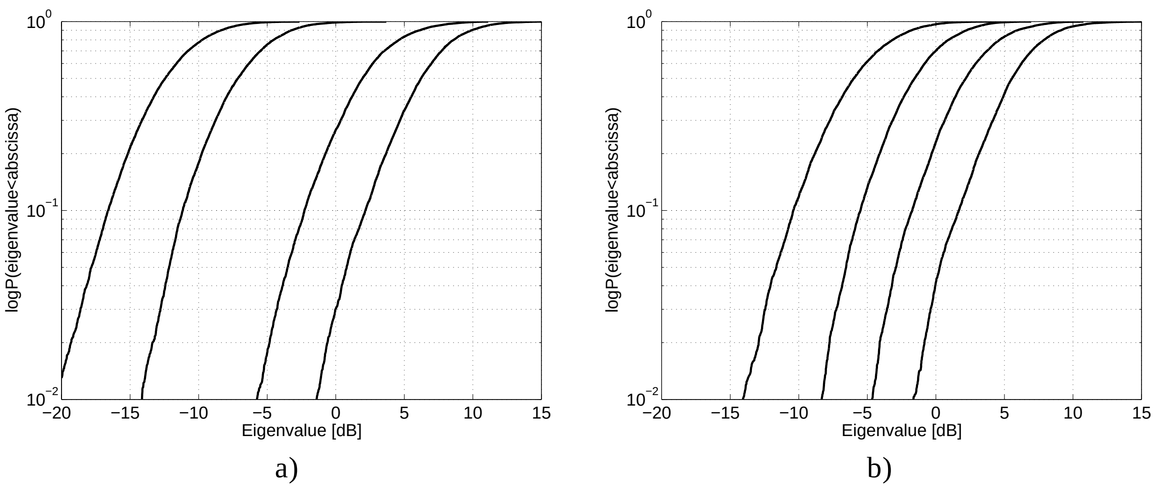
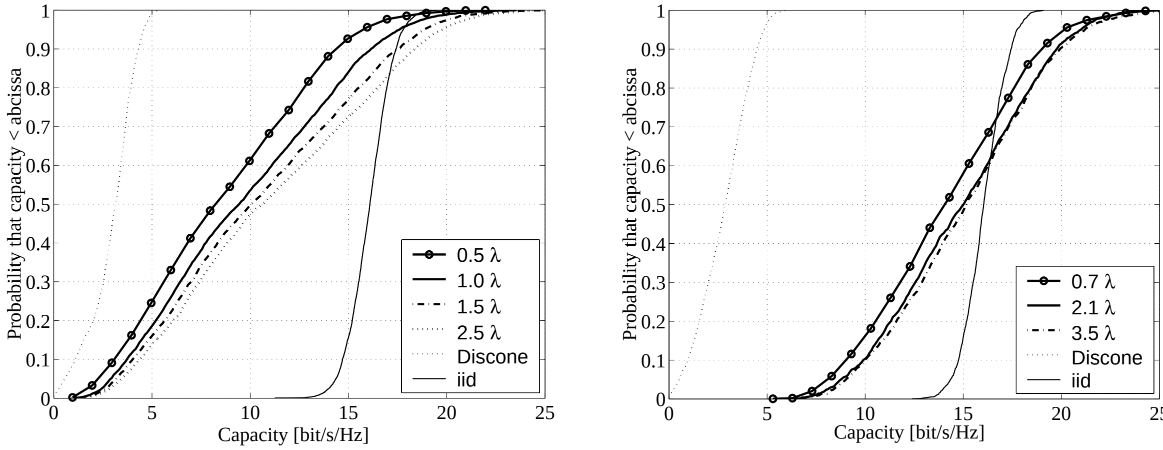


Figure 21. Effect of increasing inter-element spacing on eigenvalues of 4×8 dual-polarized MIMO system in macrocell a) Tx distance 0.5λ b) Tx distance 2.5 λ.

In the indoor environment the increase in capacity is about 1 bits/s/Hz as the distance changes from 0.7 λ to 3.5 λ as it is shown in Figure 22. Outdoors, increasing the spacing of the FS elements from 0.5 λ to 2.5 λ has a clear effect on capacity – the largest increase being from 0.5 λ to 1 λ. As the distance between the Tx elements is sufficiently large, the propagation environment seen by the antennas become more versatile and the MIMO capacity increases which is especially important in urban streets where signals generally arrive from specific directions, as it was shown in [P3]. The fluctuation of capacity values is larger in the outdoor microcellular route than in the picocellular route because the microcellular route includes both LOS and NLOS propagation conditions. Selecting Rx elements in five azimuth orientations increases the capacity fluctuation in both environments.



a) b)

Figure 22. Effect of Tx element spacing on capacity, n_T=4, n_R=8 a) in outdoor microcell b) in indoor picocell. [P5]

5.3.5 Number of Tx elements

The MIMO system is based on several sub-channels transferring data simultaneously at the same bandwidth. Figure 23 presents the effects of increasing the number of Tx elements on the average capacity for real antenna configurations and corresponding results of i.i.d. channels. The adjacent elements (1 element = 2 channels) are added gradually from one to seven. At the MS, the configuration of four dual-polarized elements is included in five azimuth orientations.

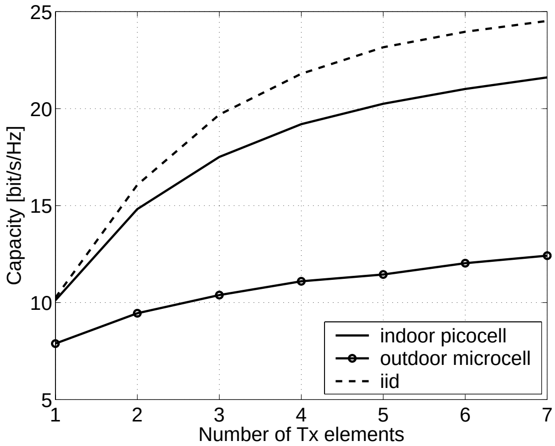


Figure 23. Mean capacity as function of number of FS antenna elements in different environments, n_R = 8, SNR = 10 dB.

Adding more elements decreases the *EVSpread* (see Table 5) and increases the attainable capacity (Figure 11 in [P6]). In addition to increased resolution, adding more elements at the Tx antenna configuration increases Tx diversity. As a drawback, the complexity of the system increases at the same time. The mean capacity increases most as the number of Tx elements increases from one to four (see Figure 23) – corresponding to the increase from two to eight in the number of possible eigenvalues. However, as more than four elements are used at the FS, the capacity increases further because of the increased antenna array gain although the four elements at the MS restrict the number of eigenvalues into eight. In the urban outdoor environment, the effect of the number of elements on capacity is of lesser importance than that of the indoor environment. In spite of using the same antenna arrays, the resultant difference between the outdoor and indoor environments is surprisingly large – approximately 8 bit/s/Hz – because indoor environment is closer to the ideal radio channel than outdoor environment. The phenomenon in the street canyon type of outdoor environment could be called a partial keyhole (see Section 3.4).

According to this study, the effect of increasing the number of elements is more beneficial than enlarging the spacing between antenna elements from eigenvalue spread point of view. When comparing three environments, the smallest eigenvalue spread is indoors.

6 SUMMARY OF PUBLICATIONS

In this chapter, an overview of each publication is given.

[P1] Performance of mobile phone antennas including effect of environment using two methods

In paper [P1], the mean effective gain calculated using the gain pattern of an antenna and statistical distribution of incident field is validated. The results of two types of methods to evaluate the performance are compared for the mean effective gain (*MEG*) of six different mobile terminal antennas in four environments at 2.15 GHz. The performance evaluation is done both by measurements on test routes and by calculations using measured elevation power distributions and the measured radiation patterns of the antennas under test. Measurements on test routes require a lot of effort with completed prototypes and a reliable calculation-based evaluation method is therefore useful. The paper [P1] shows that 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 the different environments or the antennas.

[P2] Effects of antenna radiation pattern on the performance of the mobile handset

In paper [P2], the effects of changing beamwidth, main beam direction, and polarization ratio of the antenna on the performance of mobile terminal antennas are studied in different propagation environments. The mean effective gain analysis validated in [P1] is used to measure the performance. In spite of finding no superior way of improving the performance of mobile terminals by re-shaping synthetic radiation patterns, some small improvements were found. At 2.15 GHz the performance improvement of approximately 2 dB between the best and worst synthetic antenna was achieved by narrowing and tilting the beam somewhat above the horizontal level and considering the polarization. At 5 GHz the improvement could be larger, because narrow adaptive beams are easier to produce for small mobile terminal antennas at 5 GHz than at 2 GHz. Therefore, high efficiency seems more significant in achieving high *MEG* than beam shaping at 2 GHz.

[P3] Angular power distribution and mean effective gain of mobile antenna in different propagation environments

Paper [P3] presents experimental results of cross-polarization power ratio and elevation power distribution in different propagation environments. The cross-polarization power ratio varies within 6.6 and 11.4 dB, being lowest in the indoor environment and highest in urban microcellular environment. Parameters for the double exponential function used to model the elevation power distribution are given in different environments. In this paper, the method validated in [P1] is used to evaluate the performance of several different mobile terminal antennas. The evaluation is based on experimental data in different environments. The results show that using only the efficiency in comparing mobile terminal antennas is not reliable enough but the effect of the environment needs to be taken into account. However, the results achieved in different environments do not vary a lot but the antenna is more important. The user of the terminal decreases the efficiency but not necessarily the *MEG*. The differences in *MEG* values between the left and right side of the head can be more than 4 dB for one terminal. In the achieved *MEG* results, the cross-polarization power ratio and cross-polarization discrimination seem to have a major role. In addition, the paper shows that the double exponential model is in a good agreement in *MEG* calculation when compared with using experimental elevation power distribution.

[P4] Evaluation of performance of multi–antenna terminals using two approaches

Paper [P4] presents an antenna evaluation method called plane wave -based method. The theory based on the joint contribution of the measured instantaneous incident field at a mobile station and the complex radiation pattern of the antenna under test is applied for calculating the received power instantaneously for the first time. The method enables a statistical evaluation of both diversity performance and Multiple-Input Multiple-Output (MIMO) performance of mobile terminals. In the paper the results of the direct measurement and the results of the plane wave -based method are compared. The paper shows that the new method is reliable and accurate and it can be used in comparing the statistical properties of the mobile terminal antennas in real propagation environments.

[P5] Comparison of MIMO antenna configurations in picocell and microcell environments

In paper [P5], different MIMO antenna configurations are studied in the 2 GHz range. The results of continuous dual-polarized MIMO measurements are used in evaluating and comparing antenna configurations. Different pattern and polarization diversity possibilities were studied using two methods: elements were selected from the antenna arrays used in the measurements, and as another option, at the mobile station the incident waves were estimated and used in different dipole antenna arrays. The capacity limit seems to be higher in an indoor picocellular than in an outdoor microcellular environment. At the mobile station, directive elements result in 35% higher average capacities (SNR = 10 dB) than those of the omnidirectional elements; however, the capacity of the directive elements depends also on the azimuth direction of arrival of the incident field. Co-polarized antenna configurations have capacities close to the dual-polarized configurations. Increasing the number of antenna elements at the mobile station increases the capacity in those environments where the angular spread of the incident field is large. Increasing the distance between elements at the fixed station increases the capacity – especially in microcells where signals arrive from specific directions.

[P6] Study of different mechanisms providing gain in MIMO systems

Paper [P6] shows details related to the analysis performed in [P5]. One additional environment, small macrocell, is included in the study. The eigenvalues of the normalized instantaneous channel correlation matrices are used to study and distinguish the effects of different transmitting antenna configurations on MIMO performance. Antenna aperture can be enlarged in two different ways, by adding more antenna elements or increasing the inter-element spacing of the elements. Increasing the distance between Tx antenna elements increases resolution by narrowing the main beam, which results in decreased eigenvalue spread and increased capacity. In addition to increasing resolution, adding more elements at the transmitting antenna configuration increases diversity. According to this study, the effect of increasing the number of elements is more beneficial than enlarging the spacing between antenna elements from eigenvalue spread point of view. In some cases as the inter-element spacing is decreased the eigenvalues are divided into two groups, the stronger and the weaker values likely due to using two orthogonal polarizations. If the environment is scatter-rich enough the effect of antenna configuration on eigenvalue spread is of minor importance.

7 CONCLUSIONS

Various aspects affect the mobile terminal antennas in the multipath propagation environments. Information on the average distribution of incident power at the mobile station in different propagation environments is needed in the evaluation of performance of mobile terminal antennas. Both the angles of incidence and the polarization characteristics of the signals have an effect on the antenna performance and the antenna should be matched to those characteristics as well as possible. The user has also a significant effect on the performance since the vicinity of the head and hand causes losses and can change the radiation and polarization properties of the antenna. In addition, the user decides the location and the position of the mobile terminal. Taking the effects of the environment, the user, and the mobile terminal into account is a challenging work due to many variables.

Several different measurements have been performed in this work to evaluate the performance of different antennas in real propagation environments. The efficiency is one figure of merit for the performance of antennas because it is fairly easy to measure and calculate. However, since it does not take the effect of the environment into account, it can provide a very different result when compared with the methods including the effect of the environment. Based on all the results of this work the effect of the environment on the performance of a mobile phone is smaller than the effect of the antennas. Generally the direct radio channel measurements with test antennas along measurement routes and mean effective gain (*MEG*) values based on the elevation power distribution and gain pattern of the antenna provide similar results but the total radiation efficiency results in different performance order. A sufficient bandwidth, low specific absorption rate, and high efficiency are the basic requirement for a good antenna but they do not guarantee that the performance of the antenna is good in real environments. Therefore, it is strongly recommended to include the effect of some real environments in evaluating the performance of mobile terminal antennas.

For the omnidirectional discone antenna the azimuth power distribution does not have any effect or the effect of assuming a uniform signal distribution in azimuth is insignificant. More directive antennas are dependent on the direction of arrival of incident field in azimuth and the effect between different azimuth orientations can be up to 12 dB on *MEG*. In a real network it is impossible to say in what direction the base station is located because the user of the mobile terminal moves around and may therefore be randomly located with respect to the base station. Consequently, in comparing antennas by *MEG* values it is reasonable to assume the uniform power distribution in azimuth.

Experimental data was applied for the *MEG* analysis of several practical handset antennas. The *MEG* values varied from approximately -5 dBi without a human head model to less than -11 dBi beside the head model. These values are considerably lower than the 0 dBi typically used in the system specifications, e.g. [66]. Either a large antenna or an antenna with omnidirectional radiation pattern seem to have the best *MEG* values. In all measured environments the cross polarization coupling was fairly small indicating that the polarization of the mobile terminal antenna should be matched to that of the base station antenna in order to obtain the best performance. However, the polarization of the antenna is sensitive to the usage position of the terminal which should be considered in antenna design and it can possibly be compensated by polarization diversity arrangements. As another option, adaptive beams could be used to compensate the different usage positions. For most antennas the environment type has little effect on the *MEG*, but clear differences exist between the antennas. The *MEG* depends also on which side of the head the user holds the handset.

The plane wave -based antenna evaluation method is reliable and accurate and it can be used in antenna research. The tool is based on instantaneously calculated joint contributions of the radio channel data and the radiation patterns, thus, enabling statistical analysis of different diversity antenna configurations. The advantage of this method is that the antennas can be studied in several propagation environments very fast already during the designing process with simulated radiation patterns and the previously measured channel library. Hence, the commonly used way of performing time-consuming radio channel measurements with the final prototype is not the only option to compare the statistical properties of the antennas. In addition, the method enables the performance evaluation in real environments without being vulnerable to weather conditions. Further, the radio channel stays exactly the same for all the antenna configurations under test. Antennas can be rotated computationally in azimuth and in elevation direction to get an estimate of the effect of the user on the performance which is important in order to get the comprehensive estimate of performance of the antennas in real environments. The drawback is that the physical restrictions of the spherical antenna array and the limitations of the beam-forming algorithm limit the estimation of the details of the incident field. Having the possibility to use more exact method like Space-Alternating Generalized Expectation-Maximization (SAGE) [76] in beam-forming would be informative and is left for future study.

In MIMO analysis, the use of an omnidirectional “pilot” antenna for normalization enables us to avoid the automatic increase of the transmitted power when a directive antenna points in a low-incident power direction, as towards a wall. This method brings the evaluation of mobile antennas closer to the mean effective gain analysis.

In increasing the capacity, the use of orthogonally-polarized elements at the receiving mobile station was found to be equally effective with the co-polarized elements. This supports the utilization of compact dual-polarized antennas at the mobile terminal. Increasing the distance between elements at the base station increases capacity, especially in the urban outdoor environment where signals arrive at the mobile station from certain azimuth directions. In a street canyon -type outdoor environment more diversity is obtained by increasing the element spacing which results in a 33 % increased MIMO capacity between the spacing from 0.5 λ to 2.5 λ. Due to larger angular spread, the element spacing has only the effect of 7 % on the indoor capacity. The number of elements at the fixed station is more important indoors than outdoors, because signals propagating along different paths can be utilized more effectively by adding more antenna elements in a scatter-rich indoor environment. The capacities achieved indoors are surprisingly much higher than outdoors probably due to the increased number of parallel paths. Outdoors, in street canyons, the increase in capacity is more a result of increased effective antenna gain because the angular spread is nevertheless narrow.

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