Helsinki University of Technology Radio Laboratory Publications
Teknillisen korkeakoulun Radiolaboratorion julkaisuja
Espoo, August 2006 REPORT S 279

METHODS AND CRITERIA FOR PERFORMANCE ANALYSIS OF MULTIANTENNA SYSTEMS IN MOBILE COMMUNICATIONS

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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 S5 at Helsinki University of Technology (Espoo, Finland) on the 25th of August 2006 at 12 o'clock noon.

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ISBN 951-22-8296-8

http://lib.tkk.fi/Diss/
951-22-8297-6

ISSN 1456-3835

Otamedia Oy
Espoo 2006

PREFACE

This thesis work has been carried out at the Radio Laboratory of the Helsinki University of Technology during 2002 – 2006 (preliminary work since 1999).

Especially I want to express my gratitude to my supervisor Professor Pertti Vainikainen for his guidance and support during this thesis work.

I would also like to thank my colleagues Kati Sulonen, Jari Salo, Lasse Vuokko, Juha Villanen, and Ilkka Salonen for the good co-operation in the research work, which made possible to accomplish this work. Jarmo Kivinen, Kimmo Kalliola and Heikki Laitinen are warmly thanked for the development of the measurement system and the signal estimation algorithm. Andreas Richter is thanked for his valuable comments considering a Cramer-Rao lower bound.

I also warmly thank my other co-workers and friends in the radio laboratory for the good discussions and coffee breaks.

The pre-examiners professor Matsumoto and PhD Björn Lindmark are thanked for their time and fruitful criticism.

This work was partly financed by Nokia Foundation and Finnish Cultural Foundation. Support of these foundations is warmly appreciated.

Finally I would like to thank my parents and other relatives and especially my wife Merja for their support and patience during the work.

Espoo, August 4, 2006

Pasi Suvikunnas

ABSTRACT

Multiple-input multiple-output (MIMO) technique is one of the most promising solutions for increasing reliability and spectral efficiency of the radio connection in future mobile communication systems. The performance potential of MIMO systems is well established from theoretical point of view. However, much effort is still needed in the experimental verification of those systems using realistic antennas and channels. It is widely accepted that the antenna properties are of significant importance regarding the performance of single-input single-output (SISO) systems. However, the effect of the antennas on MIMO systems has not been thoroughly studied. Due to the complexity of MIMO systems, evaluation of MIMO antennas becomes increasingly cumbersome and time-consuming process in comparison to simpler systems.

In the first part of this work an advanced antenna evaluation technique called experimental plane-wave based method (EPWBM) is generalized and validated to cover MIMO systems. This work is the extension of the previous work where the method has been used in the analysis of SISO systems. The EPWBM is based on the measured or simulated complex 3-D radiation patterns of the antennas and measured directional radio channel data. The EPWBM simplifies antenna evaluation process in comparison to traditional means since the same channel library can be utilized in the evaluation of several antenna systems without performing the same measurements for each prototype antennas separately. It is verified that the EPWBM is sufficiently reliable in comparing the performance of prototype antennas.

In the second part of the work new quality factors for MIMO system evaluation enclosing traditional systems as special cases have been developed. The MIMO channel correlation matrix is formulated so that it reveals the ability of MIMO antenna systems to transfer signal power from a transmitter to a receiver and to utilize parallel spatial channels. It is also verified that correct normalization of the channel matrices is of significant importance in the MIMO antenna evaluation. This approach gives comprehensive framework for MIMO antenna evaluation, which takes into account both realistic antenna and channel properties.

In the last part of the work insight into the performance of different antennas in different signal propagation environments is given. The performance of the antennas depends on the signal-to-noise-ratio and on the outage probability level considered. Although MIMO systems are based on the utilization of parallel spatial channels, the capability of the system to transfer signal power plays a significant role especially with small MIMO systems. In the realistic dynamic channels the capacity variation is larger than in the ideal channels, which are based on the identically and independently distributed (iid) channel assumption. Large performance variations occur in the realistic channels with directive antennas, when antennas are rotated in the usage environment, whereas omnidirectional ones are more robust but are difficult to realize in practice. The largest differences between the antennas are found at the low outage probability levels due to different radiation properties of the antennas. The systems with the cross-polarized antennas have smaller eigenvalue dispersion and are more robust in performance for the variations of the channel than the systems with co-polarized antennas. On the other hand, the co-polarized antennas possess better capability to transfer signal power and are more robust in performance for the antenna array orientation. From practical point of view, the dual-polarized antennas seem to be the most feasible candidates to be used in MIMO antenna systems due to compact structure, and indoor seems to be the most suitable for MIMO applications due to typically scatter-rich channel.

TIIVISTELMÄ

Multiple-input multiple-output (MIMO) tekniika on yksi lupaavimmista ratkaisuista lisätä radioyhteyden luotettavuutta ja spektritehokkuutta tulevaisuuden matkaviestinjärjestelmissä. MIMO järjestelmien suorituskykypotentiaali on teoreettisesti todistettu. Paljon työtä tarvitaan kuitenkin vielä kokeelliseen järjestelmätestaukseen käyttäen realistisia antenneja ja kanavia. On laajasti hyväksyttyä että antennien ominaisuudet ovat merkityksellisiä single-input single-output (SISO) järjestelmien suorituskyvyn kannalta. Antennien vaikutusta MIMO-järjestelmiin ei ole kuitenkaan perusteellisesti tutkittu. MIMO-järjestelmien lisääntyneestä monimutkaisuudesta johtuen, verrattuna yksinkertaisempiin järjestelmiin, MIMO antennien suorituskyvyn arviointi hankaloituu ja vie enemmän aikaa.

Työn ensimmäisessä osassa uusi antennien arviointitekniikka nimeltään kokeellinen tasoaaltoihin perustuva menetelmä (EPWBM) on yleistetty käsittämään MIMO järjestelmät ja sen tarkkuus on arvioitu. Tämä työ on laajennus aikaisempaan työhön jossa menetelmää on käytetty SISO-järjestelmien arviointiin. EPWBM perustuu mitattuihin tai simuloituihin antennien kompleksisiin 3-D suuntakuvioihin ja mitattuun suuntatiedon sisältämään kanavadataan. EPWBM yksinkertaistaa antennin suorituskyvyn arviointia perinteisiin menetelmiin verrattuna, koska sama kanavamittausaineisto voidaan hyödyntää usamman antennisysteemin arvioinnissa tekemättä samoja mittauksia jokaiselle antenniprototyypille erikseen. On osoitettu että EPWBM on suhteellisen luotettava prototyyppiantennien suorituskyvyn vertailussa.

Työn toisessa osassa on kehitetty uusia hyvyyslukuja MIMO-järjestelmien suorituskyvyn arviointiin sisältäen perinteiset järjestelmät erikoistapauksina. MIMO-kanavamatriisi esitetään siten että se paljastaa MIMO-antennijärjestelmien kyvyn siirtää signaalitehoa lähettimen ja vastaanottimen välillä ja hyödyntää rinnakkaisia kanavia. On myös todistettu että oikeanlainen kanavamatriisien normalisointi on erittäin merkittävää MIMO-antennivertailussa. Tämä lähestymistapa antaa kattavat puitteet MIMO-antennien suorituskyvyn arviointiin ottaen huomioon todelliset antennien ja kanavan ominaisuudet.

Työn viimeisessä osassa annetaan käsitys erilaisten antennien suorituskyvystä erilaisissa signaalin etenemisympäristöissä. Antennien suorituskyky riippuu signaalikohinasuhteesta ja tarkasteltavan signaalin luotettavuustasosta. Vaikka MIMO-järjestelmät perustuvat rinnakkaisten kanavien hyödyntämiseen järjestelmän singnaalitehon siirto-ominaisuudet ovat merkittäviä erityisesti pienillä MIMO järjestelmillä. Realistisissa dynaamisissa kanavissa kapasiteetinvaihtelu on suurempaa kuin ideaalisissa kanavissa jotka perustuvat oletukseen että signaalit ovat riippumattomasti ja identtisesti jakautuneita (iid). Suurta suorituskykyn vaihtelua esiintyy realistissa kanavissa suuntaavilla antenneilla, kun antenneja pyöritetään käyttöympäristössä, kun taas ympärisäteilevät antennit olisivat jäykempiä suorituskyvyn kannalta mutta käytännössä vaikeampia toteuttaa. Suuremmat erot antennien välillä on löydettävissä matalalta signaalin luotettavuustasolta johtuen antennien erilaisista säteilyominaisuuksista. Kaksipolarisaatioantennijärjestelmillä on pienempi ominaisarvohaje ja niiden suorituskyky on jäykempi kanavan vaihteluille kuin yksipolarisaatioantennijärjestelmä. Toisaalta yksipolarisaatioantenneilla on paremmat signaalitehon siirto-ominaisuudet ja suorituskyky vaihtelee vähemmän antennin katselusuunnan funktiona. Käytännön näkökulmasta katsoen kaksipolarisaatioantennit näyttävät olevan kaikkein toteuttamiskelpoisin vaihtoehto käytettäväksi MIMO-systeemeissä johtuen niiden kompaktista rakenteesta, ja sisätila näyttää olevan sopivin ympäristö MIMO-sovelluksiin johtuen tyypillisesti sirontarikkaasta kanavasta.

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LIST OF PUBLICATIONS

[P1] 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*, vol. 21, no. 5, pp. 1-10, June 2003.

[P2] P. Suvikunnas, J. Villanen, K. Sulonen, C. Icheln, J. Ollikainen, P. Vainikainen, "Evaluation of the Performance of Multi-Antenna Terminals Using a New Approach", Accepted to *IEEE Transactions on Instrumentation and Measurement*.

[P3] P. Suvikunnas, J. Salo, L. Vuokko, J. Kivinen, K. Sulonen and P. Vainikainen, *Comparison of MIMO antenna configurations: methods and experimental results*, Helsinki University of Technology, Radio Laboratory, Report S 279, Espoo, Finland, June 2006, 27 p.

[P4] P. Suvikunnas, J. Salo, J. Kivinen, P. Vainikainen, "Comparison of MIMO antennas: performance measures and evaluation results of two 2x2 antenna configurations," *Nordic Radio Symposium 2004*, Oulu, Finland, August 16-18, 2004, CD-Rom (ISBN 951-42-7419-9), paper WEDAM7_1.pdf.

[P5] P. Suvikunnas, K. Sulonen, J. Kivinen, P. Vainikainen, "Effect of antenna properties on MIMO-capacity in real propagation channels," in *Proc. 2nd COST 273 Workshop on Broadband Wireless Access,* Paris, France, May 21-22, 2003, pp. 1-6.

[P6] P. Suvikunnas, I. Salonen, J. Kivinen, P. Vainikainen, "A novel MIMO antenna for laptop type device," in *Proc. AMTA 2004*, Atlanta, USA, October 17-22, 2004, pp. 118-123.

[P7] J. Salo, B. Badic, P. Suvikunnas, H. Weinrichter, M. Rupp, and P. Vainikainen, "Influence of antenna configurations on performance of STBC in urban microcells," *IEE Electronics Letters*, vol. 41, no. 21, pp. 1157-1158, October 2005.

In paper [P1] Kati Sulonen had the main responsibility for preparing the paper. The analysis of the paper was carried out in close co-operation with this author. This author was especially concentrated on the plane-wave-based capacity analysis and Lasse Vuokko made the direction of arrival analysis. In papers [P2] and [P3], the author had the main responsibility for preparing the papers and performing the analysis presented in the papers. In paper [P2] Kati Sulonen and Juha Villanen were responsible for the diversity analysis. In paper [P3] the proposed figures of merit were developed in intensive co-operation with Jari Salo. This author prepared the papers [P4], [P5], and [P6]. In paper [P6] this author made the capacity analysis and Ilkka Salonen designed the used antenna prototype. In paper [P7] Jari Salo made the bit error rate performance analysis of a space-time block code and prepared the paper. This author applied the experimental plane-wave-based method (EPWBM) for the formulation of channel matrices based on the synthetic radiation patterns.

1 INTRODUCTION

1.1 Background and motivation

A state-of-the-art concept in mobile communications nowadays is the multiple-input multiple-output (MIMO) technique in which multiple antennas are utilized at both ends of the link [1], [2], [3]. With advanced coding schemes and transceiver systems this technique enables to increase the spectral efficiency or reliability of the channel by utilizing parallel sub-channels without increased bandwidth or transmitted power. However, implementation of the new technique occurs at the expense of increased complexity and costs of the commercial devices and services. Thus, a very fundamental question arises considering MIMO: how beneficial it is to introduce a system that is definitely much more complex than any present-day commercial wireless application. How much from the predictable capacity limits based on the theoretical considerations can be achieved by using realistic systems. Hence, this work tries to give guidelines to the capacity prediction of different MIMO systems.

Dynamic radio channel measurements play an essential role in the evaluation of performance of prototype antennas [4], [P1] and also in the development of synthetic link level channel models [5]. One way to perform an antenna evaluation process is to manufacture an antenna prototype, and evaluate its performance in all typical usage environments by separate channel sounder measurements. However, to carry out measurements in those numerous environments is a time consuming and difficult process. More advanced methods are needed to evaluate MIMO antennas in a more efficient way [P2].

Both the antenna systems (“spatial filters”) and the propagation channel (“medium”) are of essential importance from wireless communications system performance point of view [6], [4], [P1]. Requirements of antenna evaluation increase with growing complexity of the new communications systems. In contemporary mobile communications systems differences in the antenna performance occur basically due to the total received power. Figures of merit like mean effective gain [4], [7], [8], [9], total radiated power, and total receiver sensitivity [9] have been proposed in the evaluation of antenna prototypes. Total received power is definitely a relevant quality factor also in MIMO systems. However, MIMO systems set also new demands for the antenna evaluation since there is a fundamental difference between the less advanced wireless communications systems and MIMO systems: MIMO systems utilize parallel independent spatial channels, whose number is limited by the minimum number of antennas at either end of the link [1], [2]. Hence, new relevant antenna evaluation criteria, which take into account also new aspects involved specifically in MIMO, are needed for the evaluation of the antenna systems [P3].

The MIMO systems are proposed for various applications where different antenna requirements are needed. E.g. wireless local area network (WLAN) was proposed mainly for indoors with relatively static communication links between terminals and an access point [10]. Further, some scenarios were also introduced for ad-hoc type solutions with mobile stations at both ends of the link [11], [12]. For all those scenarios MIMO antenna prototypes need to be tested to estimate their effect on the communication system performance. This can be considered a demanding and time-consuming task for several reasons. The behavior of the antenna system is related to the environment [4], [P1]. Further, the performance of the antenna depends on the dimensions of a device and interaction with a user and a device [13].

The performance of a MIMO system is verified in theoretical considerations with stochastic channel models excluding the effect of the realistic antennas in [1], [2], and [14]. Several papers are devoted to evaluation of performance of different coding schemes and receiver algorithms [15], [16], [17]. Further, many measurement campaigns have been carried out concentrating mainly on the validation of theoretical capacity limits [18], [19], [20], [21] or for channel model development [22], [23]. Some studies have been performed from antenna comparison point of view [24], [25], [26], [27], [P1]. The effect of polarization is also considered in [25], [27], [28] and [P1]. The references mentioned enclose only the MIMO measurements for 2 GHz frequency band. From mobile communications point of view comprehensive experimental procedure is needed for the verification of the performance of MIMO systems with realistic antennas as well as realistic channels.

1.2 Objectives of the work

The main goals of this thesis are to develop tools for intensifying MIMO antenna development process and MIMO system analysis, and to develop new MIMO antenna evaluation criteria. The developed antenna evaluation criteria are general and independent e.g. from a coding scheme used. The secondary goal is to give insight into antenna characteristics in different signal propagation environments as well as different applications and enlighten the possibilities to attain capacity limits predicted in the theoretical considerations.

The experimental work is restricted mainly to 2.154 GHz frequency range but the developed tools and criteria are general and can be used at any frequency range. The work covers single-user, noise limited MIMO systems whereas multi-user [29] and interference limited [30] MIMO systems are a subject of further work. Regardless of the wideband MIMO measurements carried out the work is concentrated on narrowband MIMO systems in which transmitter has no knowledge of the channel. From the antenna evaluation point of view wideband analysis gives no additional benefit supposing that the bandwidth of antennas is sufficiently large relative to the coherence bandwidth of the channel.

In summary, this thesis work gives a framework and basic guidelines for MIMO antenna and system designers to consider the effect of antennas on the MIMO performance in realistic way. The developed analysis tools and criteria are integrated effectively for fast and comprehensive antenna evaluation.

1.3 Contents of the thesis

This thesis work includes new scientific achievements as follows. In the first part of the work a new antenna evaluation method is extended for the MIMO systems in [P1], and [P2]. A novel experimental plane-wave-based method (EPWBM), which is based on the convolution of far-field radiation patterns of prototype antennas and on the directional radio channel data, is first introduced in MIMO system evaluation in [P1], and validated in [P2] using direct channel sounder measurements as a benchmark. The method enables antenna designers to evaluate antennas in a more effective and faster way in comparison to traditional methods.

In the second part of the thesis novel techniques for assessing multielement antennas are introduced in [P3], and [P4]. A novel normalization method for the MIMO signal transfer matrix is first introduced in [P4] and later used in [P3]. In the factorization a signal transfer matrix is divided into two parts that reveals the ability of a MIMO system to transfer signal power and utilize parallel spatial channels [P3]. The main purpose of the factorization is to deliver practical means for the comprehensive antenna evaluation process that takes also into account different signal power transferring properties of the antennas.

In the third part of the thesis insight into antenna impact on MIMO systems is given in [P1], [P3], [P5], [P6], and [P7]. In papers [P1], [P3], [P6] and [P7] the systematic rotation of an antenna-under-test (AUT) in a signal propagation environment is presented at the first time in the MIMO analysis. Antenna evaluation based mainly on the antenna selection from the measurement antenna arrays in indoor and outdoor environments is given in [P1]. Some idealized antennas are evaluated in [P3] for the validation of the new quality factors. In [P5] the comparison of directive and omnidirectional antennas is presented for the support and the extension of the results presented in [P1]. A realistic prototype antenna system developed for laptop-type device and intended to be used e.g. in wireless local area networks (WLAN) is evaluated in [P6] in indoor environment. Bit error rate performance analysis of space-time block codes has been carried out with several antenna configurations and realistic channels in outdoor environment in [P7].

2 BASIC CONCEPTS RELATED TO ANTENNAS AND MIMO SYSTEMS

An antenna can be considered as a device intended to transmit and receive electromagnetic fields. The antenna is one of the essential components in radio communications systems linking the power between a transceiver and a medium. Wireless communication systems can be classified into single-input single-output (SISO), multiple-input single-output (MISO), single-input multiple-output (SIMO), and multiple-input multiple-output (MIMO) systems depending on the number of the antennas at link ends. The results of this thesis work are basically concentrated but not restricted to the MIMO systems that utilize multiple antennas at both ends of the link. In this chapter, the most important definitions of the antennas and the antenna arrays as well as basic aspects considering the MIMO systems are discussed.

2.1 Signal propagation in mobile communications systems

Electromagnetic field transmitted from the antenna can be defined by using the complex Poynting vector $E \times H^*$, where E and H denote electric and magnetic fields, respectively [31], [32]. In close vicinity of the antenna the Poynting vector is complex consisting of major reactive and minor radiating fields whereas radiating fields dominate in far-field region of $r > 2D^2/\lambda$, where D is the largest dimension of an antenna, r is distance, and λ is wavelength of the field. In that region electromagnetic fields decay as $1/r$, and they can be defined by using two orthogonal vector components in spherical coordinates (θ,ϕ). The spherical electromagnetic wave can be approximated as a plane wave in the far-field region when received by a receiver antenna.

The received signal power is related to the properties of the transmitter and receiver antennas as well as those of the signal propagation medium. In mobile communications systems the attenuation of the signal cannot be characterized only by the free space attenuation term $(\lambda/(4\pi r))^2$. Transmitted signal spreads in time and space due to reflection and diffraction from different obstacles in the propagation route causing fast as well as slow fading of the received signal. Hence, the signal attenuation depends strongly on the signal propagation environment in which the mobile terminal is operational. Further, polarization of the transmitted signal usually changes when interacting with the medium. Cross polarization discrimination (XPD) defines the level of change in polarization. If scatterers in the propagation route are far enough from the receiver antenna system, multi-path propagation of the transmitted signal can be modelled by several plane waves propagating through the medium. In the case of multiple-input multiple-output (MIMO) systems multiple connections are available between the transmitter and receiver antenna systems causing different fading conditions for adjacent receiver as well as transmitter antennas.

2.2 Antenna systems in mobile communications

The radiation properties of a specific antenna are fully defined by its current distribution. The basic concepts of directivity and gain are traditionally used in the characterization of radiation properties of the antennas. The gain of the antenna is usually defined to the direction of maximum intensity of the field. However, in mobile communication systems, where the antenna of e.g. a portable device can be oriented randomly, directivity is not a very useful parameter. More relevant parameters for the performance of wireless communication antennas are e.g. mean effective gain (MEG) [4], [7], [8], [9], and as proposed in this work, mean effective link gain (MELG) [P3], [P4].

Attempting to increase the performance of mobile communication systems multiple antennas are proposed for either or both ends of the communication link [1], [2], [3]. From theoretical point of view the antenna array is considered as multiple identical antenna elements with identical (parallel) currents that have a translational relationship without rotation [33]. However, based on that definition the antenna array cannot be realized in practice since there is always interaction between the currents on the antenna elements. Mutual coupling, whose strength is related to inter-element spacing, alignment and type of antenna elements, always exists [34], [35], [36] and should be considered also in MIMO. Further, the radiation properties of antenna array elements are not identical due to inaccuracy in the manufacturing process of antenna elements and a switching system. Antenna elements are not even intended to be similar or oriented identically in all applications – a typical example is a diversity antenna system designed for the mobile phones where a phone chassis radiates main part of the power [13], [37], [38]. In this thesis work the terms antenna array, antenna group and antenna system are used interchangeably generally referring to the realistic antenna system. It is mentioned in the text when ideal antennas are considered in the analysis.

2.3 Multiple-input multiple-output (MIMO) antenna systems

The concept of single-user MIMO systems can be considered as a general definition for wireless communication systems that use multiple antennas at both ends of the communication link. A MIMO system utilizes space-time coding in transferring multiple data streams concurrently through the channel [39]. Consider a vector $\mathbf{s}(t)=\lfloor s(t)_1, s(t)_2, \cdots, s(t)_{n_t} \rfloor$ to be transmitted and a vector $\mathbf{y}(t)=\lfloor y(t)_1, y(t)_2, \ldots, y(t)_{n_r} \rfloor$ to be received. The relation between the vectors $\mathbf{s}(t)$ and $\mathbf{y}(t)$ can be expressed by $\mathbf{y}(t)=\mathbf{H}(t)\mathbf{s}(t)+\mathbf{n}(t)$, where the narrowband complex channel matrix[1] can be denoted in matrix form by

$$\mathbf{H}(t)=\begin{bmatrix} h(t)_{1,1} & \cdots & h(t)_{1,n_r} \\ \vdots & \ddots & \vdots \\ h(t)_{n_t,1} & \cdots & h(t)_{n_t,n_r} \end{bmatrix}, \tag{2.1}$$

whose entries define the connections between the transmitter (n_t) and receiver (n_r) antennas. The expression $\mathbf{n}(t)$ is the noise vector of the same size as $\mathbf{y}(t)$. Channel input and additive noise are assumed to be complex Gaussian variables. Widely used benchmark for the experimental study is identically and independently distributed (iid) channel, in which case the entries of $\mathbf{H}(t)$ are uncorrelated and Rayleigh distributed. Mutual information [1], [2], [3] can be expressed by

[1] Wideband MIMO systems discussed from theoretical point of view in [40], and experimentally in [41] are not considered in this work.

$$I(t) = \log_2\left[\det\left(\mathbf{I} + \frac{\rho}{n_t}\mathbf{R}(t)\right)\right] \text{ [bit/s/Hz]}, \tag{2.2}$$

where **I** is identity matrix, ρ is average signal-to-noise-ratio (SNR) at the input of each receiving antenna, and **R**(t) is channel correlation matrix defined by

$$\mathbf{R}(t) = \mathbf{H}(t)\mathbf{H}(t)^H . \tag{2.3}$$

The expression $()^H$ stands for the complex conjugate transpose. In (2.2) total transmitted signal power is equally divided by the number of transmitter antennas, n_t, which enables a fair comparison with SISO and SIMO systems. The expression (2.2) is valid in the conditions where the channel is unknown at the transmitter but known at the receiver. Although the MIMO capacity with channel knowledge at the transmitter is not considered in this study the developed antenna evaluation methods can be generalized also for that case. In the case of ergodic fading process, Shannon (ergodic) capacity can be given by $C = E[I]$ [1], [3]. Further, outage capacity can be given by $\text{Prob}(I < C_{out}) = p\%$ which is guaranteed for (100 – p) % of the channel realizations [3]. From the information theory point of view Shannon capacity is the upper bound for mutual information. Shannon capacity can be reached only with an ideal coding scheme and with ideal channel conditions. In this work, however, (outage) capacity and (outage) mutual information are used interchangeably basically meaning (outage) mutual information from the information theoretic point of view.

The properties of **H**(t) define the behavior and achievable performance of the MIMO system. The fundamental idea of MIMO is to exploit parallel linearly independent channels, whose voltage level is defined by the singular values of **H**(t), or alternatively, whose power level is defined by the eigenvalues of **R**(t). The minimum number of transmitter and receiver antennas, min(n_t,n_r), defines the number of significant eigenvalues, that is, the rank of the channel. Rich scattering of the signal enables full rank conditions of **R**(t). When compared to SISO, SIMO and MISO systems MIMO systems offer increased spectral efficiency with the same transmitted power. The capacity of a MIMO system increases linearly by increasing the number of antennas at the both ends [1]. The theoretical capacity increase of SIMO and MIMO systems as a function of the number of the antennas is illustrated in Fig. 2.1 with ρ of 10 dB. This enhancement in capacity is significant especially at high signal-to-noise-ratios. In SIMO systems the capacity increases only logarithmically for each increment of receiver antennas and for the equal transmitted power [42]. Reversely, a MIMO system can offer a possibility to use less power with the same spectral efficiency, or decrease the bandwidth with the same achievable capacity. However, finite inter-element spacing between the antennas or degradation in scattering can cause shortage in independent signal routes as well as increased correlation between the antennas and, thus, considerable degradation in capacity [43], [44]. Further, the antenna orientation in a portable device, which can be random especially in azimuth direction, can pose severe degradation in capacity [P1].

The MIMO capacity is essentially subject to multiplexing gain defined by min(n_t,n_r), diversity gain defined by max (n_t,n_r), array gain [17], [42], [44] and effective antenna gain [P3], [P4]. How well a MIMO system can utilize these gains depends on the antenna systems, signal propagation environment, and also on the used transceiver system. All these gains cannot be fully optimized at the same time since MIMO diversity systems utilize diversity properties of the system optimally at the expense of lower multiplexing gain. On the other hand, MIMO multiplexing systems maximize multiplexing gain at the expense of diversity gain [15], [17], [16]. The theoretical upper limit of performance a MIMO system can provide is the supremum capacity [20], [45]. On the other hand, the lower limit realizes in poor scattering environment, in the conditions of strong line-of-sight (LOS), in the case where a MIMO system collapses basically into a SIMO system [20], [44]. Further, a so-called keyhole or pinhole channel can occur. Here, regardless of the rich scattering environment, the channel delivers only one significant eigenvalue, that is, has rank one. This phenomenon has been verified in theory [46], [47], [48], and also in controlled laboratory conditions [49], but according to author's knowledge, is not reported in real signal propagation environments.

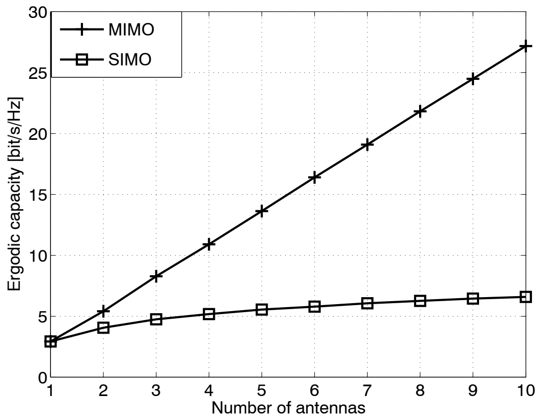


Figure 2.1. The capacity increase of SIMO and MIMO systems as a function of the number of the antennas presented with system signal-to-noise-ratio ρ =10 dB.

The theoretical capacity increase of the MIMO systems in comparison to the traditional systems is verified in [1], [2], [3], [14], and [104]. Several papers are devoted to the analysis of different coding schemes and receiver algorithms [15], [16], [17]. Many measurement campaigns have been carried out for the verification of theoretical results [18], [19], [20], [P1] or devoted to channel model development [22], [23]. Some studies have been performed from antenna comparison point of view [24], [25], [26], [27], [P1]. The effect of antenna polarization is also considered in [25], [27], [28] and [P1]. However, there is a lack of a comprehensive experimental procedure for the verification of performance of the MIMO systems that takes into account realistic channels and radiation properties of the realistic antennas. In order to perform extensive experimental analysis, novel analysis tools [P1], [P2] and analysis criteria [P3], [P4] were developed in this work for comprehensive and effective MIMO antenna comparison and evaluation.

3 EXPERIMENTAL PLANE-WAVE-BASED METHOD (EPWBM) EXTENSION FOR MIMO SYSTEMS

3.1 Introduction

Radiation properties as well as efficiency of the antennas at both ends of the link affect the performance of a mobile communications system. Further, the performance of the antenna systems depends on the signal propagation environment. Hence, the evaluation of novel antenna systems is important but a time-consuming and demanding part in the testing of new mobile communications devices. Direct channel sounder measurements can be considered the most accurate but also the most time consuming way to evaluate new antenna prototypes [P1]. A faster way to evaluate antennas is proposed in [50] where transmitted fields are stirred by using a reverberation chamber emulating a real signal propagation environment. However, adaptation of the chamber for different signal propagation scenarios cannot be considered a straightforward task and information about real measurements is anyway required.

In this work the idea of combining directional radio channel estimation results with the radiation patterns of prototype antennas is extended to cover MIMO systems. The experimental plane-wave-based method (EPWBM) enables to test the performance of multi-antenna systems already during the design process, even before a prototype antenna is manufactured, using the simulated radiation patterns and the previously measured channel library. The accuracy of the method is verified based on direct channel sounder measurements.

3.2 Radio channel measurements

In the development of new mobile radio communication systems information about signal behaviour in different signal propagation environments is needed. Comprehensive antenna evaluation should include several usage environments, typically e.g. outdoor, indoor, and outdoor-indoor. Generally, in complex signal propagation environments like in mobile communications, the transmitted signal spreads in space and time due to obstacles in the propagation route. The information about signal distribution is essential for understanding propagation mechanisms in different signal propagation environments. This is needed in the development of realistic channel models, which take into account both the effect of antennas and environment. Thus, multidimensional radio channel measurements are an essential part in comprehensive antenna evaluation and channel modelling. Several signal estimation algorithms have been developed for the estimation of the amplitudes, delays, angles of arrival, and polarization states of the multi-path components of the signal [5], [51], [52], [53], [54].

The measurements of a wideband radio channel sounder at 2.15 GHz frequency range are exploited in this work [55]. In total of six measurement campaigns were carried out in different signal propagation environments for recording MIMO channel library. The measurement system utilizes fast microwave switches at both ends of the link for recording samples of MIMO channel matrix through the measurement route [55]. The measurement system consists of two linear transmitter antenna arrays and a spherical receiver antenna array, both equipped with dual polarized patch antennas [5], [55]. Although the results of those measurement campaigns are used in this work the development of the measurement system is out of the scope of this thesis.

3.3 Antenna prototype simulations and measurements

The radiation properties of new antenna prototypes can be tested in an anechoic chamber by measuring real or complex radiation patterns of the antennas. Several measurements are needed for covering the whole radiation pattern of a prototype antenna. The proper measurement of the radiation pattern of an antenna element in an array requires the termination of other elements to the system impedance. Thus, when properly measured in an anechoic chamber or simulated using a simulation tool, prototype antennas include unidealities like dielectric, and conductivity losses as well as mutual coupling. The mutual coupling causes pattern distortion of the antenna elements, mismatching of feeding networks, and increased correlation between the received and transmitted signals [56]. The effect of mutual coupling can be significant when antennas are integrated very close to each other. Generally, mutual coupling can increase or decrease the performance of a MIMO system depending on the interelement spacing of the antennas [57]. Basically the performance of a MIMO system depends on the whole transmission chain including the effect of the tranceivers at both ends of the link. A properly tuned matching network[2] can be used for maximizing the performance of a MIMO system [57], [58]. Generally, a circuit model presented in [58] is valid also in this work although the optimization of matching network is not considered.

Nowadays the role of simulations is increasing – the significance of the simulations rises due to increased computational power and advanced simulation algorithms like the finite difference time domain method (FDTD), first introduced in [59]. Those computational methods are nowadays sufficiently accurate in the modelling of radiation properties of antenna prototypes [60]. Simulations give also some advantages over measurements. For instance a phase measurement can be problematic with small devices due to the RF feed cable [61], and antenna supports in an anechoic chamber cause disturbances and limitations for full 3-D measurement. However, some advanced methods have been developed for antenna measurements. For instance a spherical antenna measurement system for fast mobile phone antenna testing including also phase information has been developed in [62]. Further, a balun choke has been introduced for mitigating the disturbances of RF feed cable in [63]. With advanced field simulators the radiation properties of antenna prototypes can be first simulated and, after that, the antennas can be constructed based on the simulation results. Finally, the performance of prototype antennas can be verified with measurements.

3.4 Combining directional radio channel data and radiation patterns of antenna prototypes

It has been verified by many authors [4], [8], [64], [P1] that the performance of a mobile phone antenna depends on the usage environment. For comprehensive evaluation every prototype antenna – simulated or measured – should be tested in real signal propagation environment, or alternatively, with a channel model whose parameters are verified with

[2] This basically means the network where the effect of mutual coupling is compensated by some means.

measurements. This work generalizes the experimental plane-wave-based method (EPWBM) for systems consisting of multiple antennas at both ends of the link. The EPWBM is based on the estimated radio channel distribution and on the simulated (or measured) complex 3-D radiation patterns of single- or multi-antenna configurations. The method was used in measurement-based MIMO antenna evaluation for the first time in [P1]. The accuracy of the method was evaluated in [P2] by comparing the results based on the method with the results of direct measurements. The idea of the method is based on the approach in [65], and the method was first implemented for SISO antenna evaluation in [4]. It is worth mentioning that the idea of the same kind, that is, possibility to use measurement-based channel models for the antenna evaluation is already mentioned in [66]. However, any actual antenna evaluation was not carried out in [66]. Generally, the method is not restricted only to measurement-based channel models, alternatively a simulation-based approach for MIMO channel modeling was proposed in [67].

By using the parameter estimation techniques amplitudes, polarization states, delays, angles-of-arrival (AoA) and in double-directional case also angles-of-departure (AoD) of the multi-path components of the received signal can be identified[3] [5], [51], [52], [53]. Thus, when channel estimation is carried out at both ends of the link the radio propagation channel consists of double-directional spatial information about the propagation medium [68] excluding the effect of the measurement antennas. In the narrowband case the transferred signal can be denoted by an $n_r \times n_t$ matrix with identical entries by

$$\mathbf{M}_{xx}^{(i)(n)}(\theta_t,\phi_t,\theta_r,\phi_r)=\begin{bmatrix} h_{xx}^{(i)(n)}(\theta_t,\phi_t,\theta_r,\phi_r) & \cdots & h_{xx}^{(i)(n)}(\theta_t,\phi_t,\theta_r,\phi_r) \\ \vdots & \ddots & \vdots \\ h_{xx}^{(i)(n)}(\theta_t,\phi_t,\theta_r,\phi_r) & \cdots & h_{xx}^{(i)(n)}(\theta_t,\phi_t,\theta_r,\phi_r) \end{bmatrix},$$

$$i=1\ldots N_s,\ n=1\ldots N, \tag{3.1}$$

where $xx=\{\phi\phi,\theta\theta,\phi\theta,\theta\phi\}$ consists of the co- and cross-polarized field components presented in the spherical coordinates. The number of samples measured on the channel and the number of multi-paths are denoted by N_s and N, respectively. The symbols θ_t and θ_r denote the AoDs and AoAs in elevation, respectively. Further, the symbols ϕ_t and ϕ_r are the AoDs and AoAs in azimuth, respectively.

The radiation pattern matrices for two orthogonal polarizations are defined by

$$\mathbf{F}_x^{(n)}(\theta_t,\phi_t)=\begin{bmatrix} f_{x,1}^{(n)}(\theta_t,\phi_t) & \cdots & f_{x,n_t}^{(n)}(\theta_t,\phi_t) \\ \vdots & \ddots & \vdots \\ f_{x,1}^{(n)}(\theta_t,\phi_t) & \cdots & f_{x,n_t}^{(n)}(\theta_t,\phi_t) \end{bmatrix}$$

$$, \qquad n=1\ldots N, \tag{3.2}$$

$$\mathbf{G}_x^{(n)}(\theta_r,\phi_r)=\begin{bmatrix} g_{x,1}^{(n)}(\theta_r,\phi_r) & \cdots & g_{x,1}^{(n)}(\theta_r,\phi_r) \\ \vdots & \ddots & \vdots \\ g_{x,n_r}^{(n)}(\theta_r,\phi_r) & \cdots & g_{x,n_r}^{(n)}(\theta_r,\phi_r) \end{bmatrix}$$

[3] Different multipath components are nearly plane-waves in the far-field region

where the entries $f_{x,n_t}^{(n)}$ and $g_{x,n_r}^{(n)}$ are the complex-valued 3-D field points of the *t*th and *r*th transmitter and receiver antennas, respectively, and *x* denotes either ϕ- or θ-polarized field component. In the case of non-isotropic radiation patterns the responses of Tx and Rx antennas depend on the AoAs and AoDs of multi-paths.

Combining the complex radiation patterns of the antennas ("spatial filters") and the radio propagation channel results in the radio channel, that can be characterized as a sum of different multi-paths (*N*) in the frequency-nonselective case with the $n_r \times n_t$ channel matrix

$$\mathbf{H}^{(i)} = \sum_{n=1}^{N} \left[\mathbf{F}_{\phi}^{(n)} \circ \mathbf{M}_{\phi\phi}^{(i)(n)} \circ \mathbf{G}_{\phi}^{(n)} + \mathbf{F}_{\phi}^{(n)} \circ \mathbf{M}_{\phi\theta}^{(i)(n)} \circ \mathbf{G}_{\theta}^{(n)} + \mathbf{F}_{\theta}^{(n)} \circ \mathbf{M}_{\theta\phi}^{(i)(n)} \circ \mathbf{G}_{\phi}^{(n)} + \mathbf{F}_{\theta}^{(n)} \circ \mathbf{M}_{\theta\theta}^{(i)(n)} \circ \mathbf{G}_{\theta}^{(n)} \right],$$
$$i = 1 \ldots N_s, \qquad (3.3)$$

where '$\circ$' denotes element-wise (Schur-Hadamard) matrix product. The principle of MIMO antenna comparison is stated in terms of (3.1), (3.2) and (3.3). While retaining the same realization of the radio propagation channel, $\mathbf{M}_{xx}^{(i)(n)}$, test antennas can be changed to see their effect on the radio channel, $\mathbf{H}^{(i)}$. In this work, however, regardless of the double-directional representation based on (3.1), (3.2) and (3.3), beamforming (or Fourier) based channel estimation technique that enables channel estimation only at the Rx end of the link, is utilized [5], [P2].

The EPWBM can be considered cost-effective, time-saving and more straightforward as compared to the direct measurement. Antennas can be rotated in azimuth and also in elevation easily to get comprehensive insight into the antenna characteristics. Consider a situation, where N_a different mobile antenna prototypes should be evaluated in N_l different orientations[4] and in N_c different environments. The total number of the measurements required by traditional means would be $N_a \times N_l \times N_c$. However, by using the EPWBM, the number of the required measurements drops to N_c since the antenna implementation and rotation can be done computationally afterwards. Further, the radio channel remains exactly the same for all antenna configurations under test, which is not the case if every antenna prototype is evaluated separately using direct channel sounder measurements. Thus, the EPWBM is remarkably faster than direct measurements e.g. in the analysis of MEG [7], [8], [9], [4], MRC MEG [69], or mean effective link gain (MELG) [P3], [P4].

3.5 Comparison of EPWBM with the results of direct measurement

In the validation of the experimental plane-wave-based method (EPWBM) the results generated by the EPWBM were compared with the results of direct measurements [P2]. The complex 3-D radiation patterns of the antenna elements of the spherical (receiver) antenna array were measured (calibration measurement). The very same feeds of the receiver antenna array that were used in the direct measurements were selected for the EPWBM analysis. Thus, basically the two identically realized MIMO systems were analyzed but with two different methods whose basic difference is presented in Fig. 3.1.

[4] A user can hold a mobile terminal in numerous azimuth and elevation orientations

In the validation of the EPWBM several measurement routes were selected from the channel library. In the small macrocell measurement a fixed station (FS) antenna was located above a rooftop level. In the microcell measurement two FS antenna heights of 4 m and 13 m were used in the line-of-sight (LOS) and partly line-of-sight (PLOS) cases, and a FS height of 13 m in the non-line-of-sight (NLOS) case. In the indoor measurement a FS was located at the height of 3.8 m. The measurement routes and FS locations are depicted in Fig. 3.2. Four MIMO antenna subsystems were selected from the full 16×64 MIMO antenna system [P2]:

- Two vertically polarized antennas at both ends (2×2 MIMO)
- One vertically and one horizontally polarized antenna at both ends (2×2 MIMO)
- Four vertically polarized antennas at both ends (4×4 MIMO)
- Two vertically and two horizontally polarized antennas at both ends (4×4 MIMO)

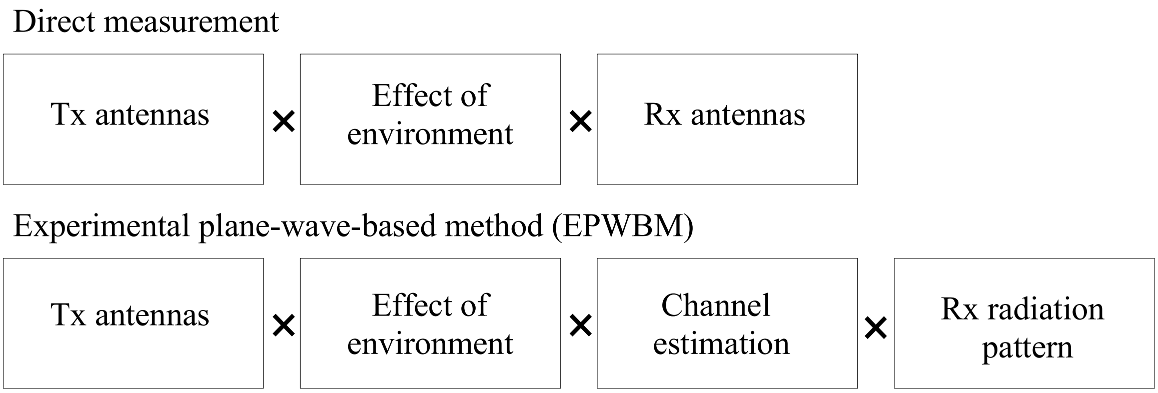
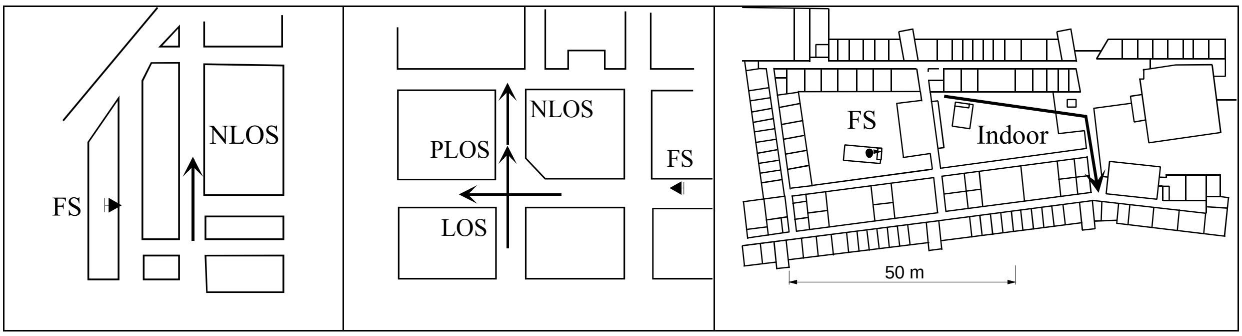


Figure 3.1. Basic principle of the direct measurement and the experimental plane-wave-based method (EPWBM).



a) b) c)

Figure 3.2. Measurement routes used in the evaluation of the accuracy of the EPWBM. The routes and FS locations are presented by using arrows. a) macrocell, b) microcell, c) indoor

In the validation mutual information and eigenvalue analyses were carried out and the results were compared in [P2]. In [P2] only the macrocell, indoor and microcell (PLOS, FS height 13 m) routes were selected (see Fig. 3.2). System signal-to-noise-ratio $\rho = 10$ dB was used in the analysis. In the case of a 4×4 MIMO system the largest difference between the methods was found with orthogonally polarized (vertical and horizontal) antennas in the indoor (picocell) environment. The difference in mutual information was 0.82 bit/s/Hz (9.5% as relative value).

For a 2×2 MIMO system the largest difference between the methods was found with vertically polarized antennas in the macrocell environment. In that case the difference in mutual information was 0.56 bit/s/Hz (12.4% as relative value).

The parameter estimation algorithm used in this work can estimate the specular signal components while the diffuse signal components are not usually detectable. Hence, the accuracy of signal estimation depends on the direction of observation, and thus, on the orientation of an antenna-under-test (AUT) relative to signal distribution. Further, it depends on the complexity of the environment under estimation. The method is the most accurate in the case where an AUT is oriented towards the direction from where the most of detectable signal components are arriving. On the other hand, error increases when an AUT is oriented to unfavourable direction from where the number of diffuse signal components dominates over specular ones. This basically means that the rotation of test antennas is needed for a comprehensive reliability analysis of the proposed method. Therefore more thorough analysis is presented here for the support of the study in [P2]. To perform more comprehensive evaluation of the EPWBM four additive routes and two extra antenna configurations were analysed and compared with the direct measurements (see Fig. 3.2 b). The additive routes included two LOS scenarios (FS heights of 4 and 13 m), one PLOS (FS height of 4 m) and one NLOS scenario (FS height of 13 m). The additive antenna configurations consisted of two (2×2 MIMO) and four (4×4 MIMO) horizontally polarized antennas at both ends. The antenna elements located slightly above equator level on the surface of the spherical shaped receiver antenna array [P2] were selected step-by-step around the antenna emulating five different antenna orientations for the six receiver antenna configurations. The channel matrices of the different antenna orientations were concatenated forming fivefold amount of data from the each route as compared to the analysis in [P2]. The FS heights and the numbers of the samples measured in each route are presented in Table. 3.1.

The results of outage mutual information, transferred signal power and eigenvalue dispersion, the parameters that are defined in [P3] and in Chapter 4, were used in the comparison. The results are presented for vertically, horizontally and orthogonally polarized antenna configurations in Figs. 3.3, 3.4 and 3.5, respectively. The results are presented for two outage probability levels, 10% and 50%. The absolute (and relative) difference between the methods, that is mean over the antennas and environments, in capacity at 50% outage probability level is 0.28 bit/s/Hz (4.93 %). The respective difference in eigenvalue dispersion is 0.04 (21.75%). The respective values at 10% outage probability level are for outage capacity 0.26 bit/s/Hz (7.20 %), and for eigenvalue dispersion 0.02 (33.25 %). The relative estimation error increases at low outage probability levels. The largest difference was found from the results of the 4×4 MIMO system with orthogonally polarized antennas in the indoor route also in this more comprehensive analysis. There are not significant differences between the results of the 2×2 and 4×4 MIMO systems or between the results for the vertically, horizontally and orthogonally polarized antennas. However, especially for the 2×2 MIMO systems, the EPWBM seems to slightly overestimate and underestimate the results with vertically and horizontally polarized antennas, respectively. That is due to finite accuracy of the used measurement system to estimate cross polarization discrimination (XPD) correctly [5].

Table 3.1. Information related to the measurement routes that are used in the validation of the EPWBM. The routes used in [P2] are in bold. The symbols h, N_s, and L_m denote the height of the FS antenna, number of the samples, and length of the measurement route (lengths including all the antenna orientations are presented in parentheses)

Route	h $[m]$	N_s	L_m $[m]$
NLOS1 (macrocell)	**above rooftop**	**1342**	**47** (235)
NLOS2 (microcell)	13	2000	70 (350)
PLOS1 (microcell)	4	2500	87 (435)
PLOS2 (microcell)	**13**	**2500**	**87** (435)
LOS1 (microcell)	4	2500	87 (435)
LOS2 (microcell)	13	2500	87 (435)
PLOS (indoor)	**3.8**	**1717**	**60** (300)

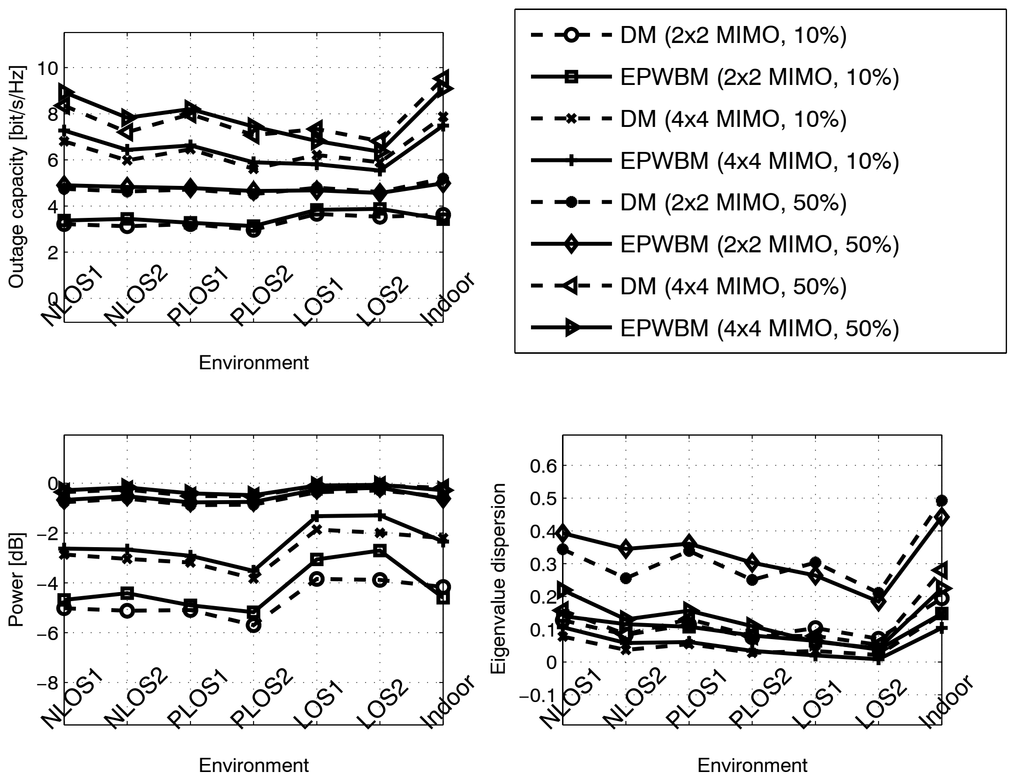


Figure 3.3. Outage capacity, transferred signal power and eigenvalue dispersion results of vertically polarized antenna systems presented for two probability levels (10% and 50%)

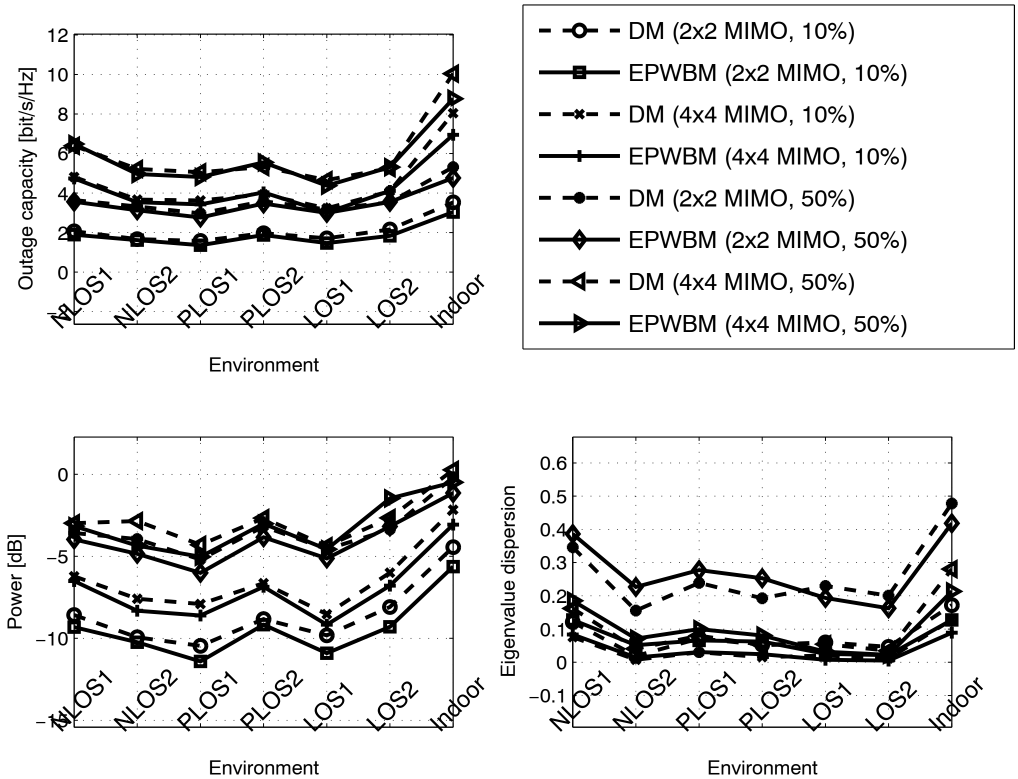


Figure 3.4. Outage capacity, transferred signal power and eigenvalue dispersion results of horizontally polarized antenna systems presented for two probability levels (10% and 50%)

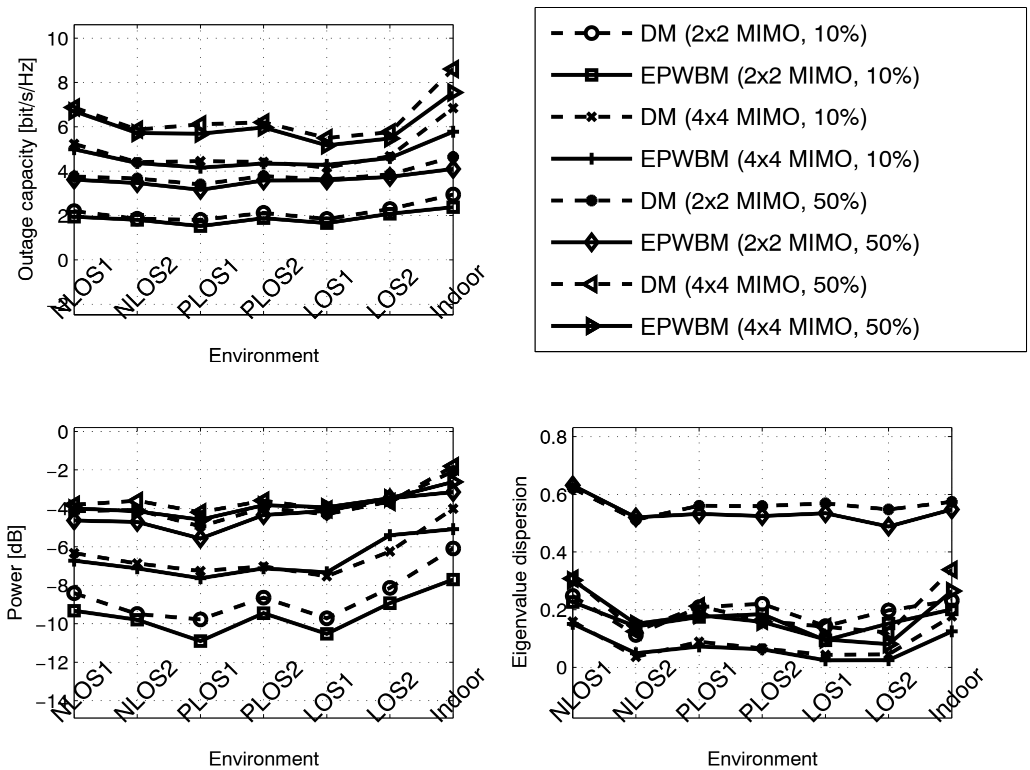


Figure 3.5. Outage capacity, transferred signal power and eigenvalue dispersion results of orthogonally polarized antenna systems presented for two probability levels (10% and 50%)

3.6 Reliability of EPWBM

The accuracy of the EPWBM is subject to measurement errors in channel sounding, properties of parameter estimation algorithm and antennas, as well as the accuracy of antenna pattern simulations or measurements.

3.6.1 Accuracy of measurement system

Basically every measurement system distorts measurement results due to non-idealities of the system. The possible error sources of a MIMO measurement system are thermal and phase noise, quantization noise as well as spurious signals in frequency synthesizers [70]. The effect of phase noise error is considered in [71] and the effect of thermal noise error is studied in [19], and [72]. The worst-case scenario is the keyhole channel or a channel with a high Rice factor. However, the keyhole channel is considered uncommon in realistic signal propagation environments [49]. Generally, the error increases when the measurement SNR decreases, and system SNR, as well as the number of the antennas increases. Based on the theoretical analysis presented in [72] overestimation of the mutual information for a 4×8 MIMO system in rank one channel case and with system and measurement SNR of 30 dB is about 4.0 bit/s/Hz (relative error 24%). This can be considered to be a significant error since the correct result for mutual information is about 13 bit/s/Hz in this case.

A LOS measurement for the 5.3 GHz measurement system (4×4 MIMO) was carried out in anechoic chamber in [70] including all the error sources mentioned above. The error in mutual information was estimated to be below 2 bit/s/Hz with system SNR of 30 dB. Generally, the phase noise error can be considered to be smaller for the 2.154 GHz than for the 5.3 GHz measurement system. The thermal noise error of the used 2.154 GHz measurement system was estimated to be below 1 bit/s/Hz with measurement SNR of 22 dB[5] and system SNR of 10 dB for a 4×8 MIMO system in [S1]. It is worth noting that in the case of LOS channels with significant Rice factor also the measurement SNR is higher than in the case of NLOS channels. Hence, from the error point of view the increase of measurement SNR partly compensates the increased Rice factor when thermal noise error is considered. Hence, the error of mutual information of a 4×8 MIMO system can be approximated to be much less than in the theoretical rank one case (4 bit/s/Hz at the system SNR of 30 dB) for the used 2.154 GHz measurement system in relatively rich scattering channels.

3.6.2 Accuracy of channel estimation

The limitations of the classical (nonparametric) parameter estimation algorithms (like beamforming), in estimating the details of the scattering field, are due to the physical factors of a measurement system. In wideband channel estimation the finite symbol length of the pseudo noise code affects the accuracy of the delay estimation [73]. Further, the accuracy of signal estimation is related to the size and the topology of an antenna array (e.g. linear or spherical) and the type of antenna elements. The antenna prototype under test should be smaller in size than the antenna array used in channel estimation. Further, estimation

[5] When error is considered this represents the most pessimistic scenario, typically the measurement SNR is about 30 dB.

accuracy depends on the number and inter-element spacing of antenna elements [74]. Spurious signals can be detected if spatial sampling distance of the array is too large. On the other hand, if spatial sampling distance is too small, the effect of mutual coupling increases [56]. The accuracy of signal estimation is also subject to the channel complexity, and to the signal-to-noise-ratio of the signal (signals) under estimation [75], [76]. High-resolution parameter estimation algorithms are limited only by the signal-to-noise-ratio, antenna and device imperfections, antenna calibration accuracy, and the limited validity of the data model [77]. Thus, the achieved estimation result is also subject to a signal estimation algorithm [78], [79]. Several antenna structures and estimation algorithms (classical and more advanced) have been used for channel estimation [5], [51], [52], [53], [54].

The spherical antenna array and beamforming-based channel estimation algorithm is used in this work [5]. The details of the accuracy of the used channel estimation system are presented in [5], and thus, not reproduced here. The spherical array structure enables to estimate the signals with the same accuracy independent of angle-of-arrival (AoA) in azimuth, and which is exceptional, also in elevation. Only the lowest elevation angles are problematic due to the shadowing of the supporting structure of the array. Usually that is not a problem since only a minor part of the signal power arrives clearly below the horizontal level [51], [80]. It is important to note that the far-field assumption has to be valid for the most channel estimation algorithms – otherwise the plane wave approximation fails, which worsens the results of channel estimation, implicitly presented e.g. in [78], and [79]. The spherical antenna array used in this thesis fulfills the far-field assumption at the distance of below 1.6 m from the surface of the sphere (outer diameter 330 mm). Thus, the near-field conditions are exceptional even in the considered picocell (indoor) measurement for the frequency range of 2.154 GHz.

Basically the error variance of the estimated parameters like AoA of the signal can be evaluated based on the Cramer-Rao lower bound (CRLB) [81]. The CRLB was defined for a real measurement system in the case of two multi-path components in [82]. Hence, basically the accuracy of different channel measurement systems, where multidimensional estimation algorithms are used, can be ranked based on the CRLB. However, the accuracy of the EPWBM depends not only on the accuracy of the propagation channel estimation but also on the accuracy of the modeling of antennas-under-test. Hence, the CRLB is not utilized in the accuracy analysis of the EPWBM.

3.6.3 Accuracy of modelling of radiation properties of antenna prototypes

The accuracy of radiation pattern simulation (or measurement) of a prototype antenna has to be adequate when using the EPWBM. It is intuitively clear that a sufficient resolution in radiation pattern simulation (or measurement) depends on the smoothness of the radiation properties of the antenna prototypes. A critical issue is the phase information of the radiation pattern [83]. Lack of phase information can underestimate the outage mutual information (at 10% probability level) of a 4×2 MIMO system about 15 % for system signal-to-noise-ratios of 10 dB, 20 dB, and 30 dB. On the other hand the use of random phase instead of radiation patterns without phase information overestimates the capacity about 5 % [83].

3.6.4 Future scenarios considering EPWBM

The experimental plane-wave-based method (EPWBM) has been shown to be sufficiently accurate to be used in the comparison of the performance of multi-antenna configurations. However, generally, the EPWBM is not related to any signal estimation algorithm. A more advanced parameter estimation algorithm over the beamforming-based one might be more accurate but also more complex in channel estimation [5]. It is subject of further study to determine whether it is useful to use very complex channel estimation algorithm (and slower that the used one) in antenna evaluation. E.g. space-alternating generalized expectation-maximization (SAGE) [52] is under study to improve the accuracy of channel estimation, and thereby, the accuracy of the EPWBM.

This work considers only the results of the “single-directional” EPWBM, regardless of the full double-directional approach presented in (3.1), (3.2) and (3.3), referring that channel estimation is performed only at the receiver end of the link. The final goal is to realize double directional channel estimation [68] enabling simultaneous antenna evaluation at both ends of the link. A “double-directional” EPWBM as well as the extension of the EPWBM for 5 GHz frequency range are also subjects of ongoing and future work.

3.7 Measurement-based antenna test bed (MEBAT)

Based on the idea of the experimental plane-wave-based method (EPWBM) a practical antenna evaluation tool called measurement-based antenna test bed (MEBAT) has been established and validated in this work. The MEBAT enables a fast and a versatile antenna testing of antenna prototypes with existing channel information. The channel library at 2 GHz frequency range includes directional channel data from the several measurements routes.

4 NOVEL TECHNIQUES FOR MEASURING ANTENNA PERFORMANCE

4.1 Introduction

The performance of multi-antenna configurations is one of the key issues in order to reach the desired high data rates of the future mobile communication systems. Mobile terminal antennas have commonly been evaluated based on the total radiated power, total receiver sensitivity [9], or the mean effective gain (MEG) [4], [8], [9], which are indicators of the total transferred signal power for the SISO systems. The respective quality factors for the SIMO systems include diversity gain [64], [65], [84], [85], [86] and maximal ratio combining (MRC) MEG [69]. Considering the MIMO systems both the ability to transfer signal power and to utilize parallel channels is needed in the evaluation of the antennas. It is also beneficial to know how those quality factors are related to each other. In most of the MIMO performance considerations, however, the effect of transferred signal power is neglected. The use of the MEG in MIMO systems is proposed in [26], [87], and [88]. In those papers, however, the effect of the eigenvalue spread [89] or eigenvalue dispersion [90], [91] on the performance of the MIMO systems is not extracted from the results. The relationship considering received power and correlation between the branches is also discussed in [87]. In this thesis work, a comprehensive approach, which takes into account both the ability of the system to transfer signal power and to utilize parallel spatial channels, is presented for better understanding of mechanisms affecting the performance of multielement antenna systems. New antenna quality factors, which enclose traditional systems (SISO, SIMO, MISO) as special cases, have been developed in [P3].

4.2 Mitigation of environmental effect

In mobile communications the received signal suffers from slow and fast fading due to interfering mechanisms in the propagation path [84]. Especially in the urban environments, signal propagation is clusterized due to e.g. the street canyon effect [92]. Hence, antennas mounted on portable devices can be oriented to disadvantageous directions relative to the arriving signal in the street canyons causing severe power loss for the received signal [P1], [P3]. From antenna comparison point of view it is beneficial to distinct slow fading (or trend) due to environment and due to disadvantageous orientation of an antenna system. That distinction can be achieved based on a computational isotropic reference antenna, which suffers from slow fading due to environment only [69], [P1], [P3], [P4]. That is because its response for the signal is independent on antenna orientation. Measured sequences of channel matrices for the isotropic reference antenna system can be expressed by $\left\{\mathbf{H}_{ref}^{(i)}\right\}_{i=1}^{N_s}$ based on (3.3), where N_s is the number of samples measured from the channel. A sliding mean over the samples of channel matrix

$$\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2 = \frac{1}{2N+1}\sum_{i-N}^{i+N}\left\|\mathbf{H}_{ref}^{(i)}\right\|_F^2 , \qquad (4.1)$$

where $\|\bullet\|_F$ is the Frobenius norm, and $2N+1$ is the number of samples in the sliding window, reveals the effect of slow fading due to surrounding obstacles in the channel. It is not necessarily straightforward to define a correct length for the sliding window for distinguishing between the fast and slow fading. A correct length of the sliding window depends on the correlation distance of the channel, that is, the used frequency range and considered signal propagation environment. Thus basically the correct length has to be considered separately for each case. The problem considering the identification of slow fading is presented e.g. in [84].

4.3 Normalization of the signal

The knowledge of total transferred signal power is important in the evaluation of multielement antenna systems. It is easily verified that the result of antenna evaluation depends on normalization procedure [P4]. In many considerations the expression of mutual information is normalized according to

$$I_{\mathbf{H}}^{(i)} = \log_2 \left| \mathbf{I} + \frac{\rho}{n_t} \frac{\mathbf{H}_{aut}^{(i)} \mathbf{H}_{aut}^{(i)H}}{\frac{1}{n_t n_r} \left\| \mathbf{H}_{aut,sli}^{(i)} \right\|_F^2} \right|, \tag{4.2}$$

where n_t and n_r are the numbers of transmitter and receiver antennas, respectively. In (4.2) the channel matrix $\mathbf{H}_{aut,sli}^{(i)}$ includes the effect of antenna system-under-test. This approach is justified in the considerations of identical and independently (iid) fading channels where each “antenna element” in the antenna system is supposed to possess the same response regardless of direction in space. However, any realistic antenna is not a point source capable of transferring constant power, but every antenna type has its characteristic properties what comes to signal radiation and efficiency. These properties vary even between the identical antenna elements within the antenna array for the reason of mutual coupling and manufacturing tolerances. For those reasons, in the context of antenna comparison, such normalization distorts the effect of the antennas on the performance of the MIMO systems.

When the objective is to reveal different signal transferring properties of the antennas, the approach given by (4.3) is proposed instead of that in (4.2) by utilizing the array of isotropic sensors (4.1) in the normalization.

$$I_{\mathbf{H}}^{(i)} = \log_2 \left| \mathbf{I} + \frac{\rho}{n_t} \frac{\mathbf{H}_{aut}^{(i)} \mathbf{H}_{aut}^{(i)H}}{\frac{1}{n_t n_r} \left\| \mathbf{H}_{ref,sli}^{(i)} \right\|_F^2} \right|. \tag{4.3}$$

In this context the computational isotropic sensor (or the point source) is defined by $E_{iso}(\theta,\phi) = \sqrt{E_\theta^2 + E_\phi^2} = 1$, where θ and ϕ denote the angles in elevation and azimuth, respectively. The fundamental difference between the results due to two different normalizations is demonstrated by comparing the results of two antenna systems. In those both vertically (*ver*) and orthogonally (*cro*) polarized ideal dipole antennas are adopted at the receiver side in the 2×2 MIMO system [P4]. Further, two vertically polarized (ver) or vertically and horizontally polarized (cro) feeds from the adjacent dual-polarized measurement antennas were selected at the transmitter. The vertically polarized antenna configuration has better signal power transferring properties whereas the orthogonally polarized antenna configuration provides narrower eigenvalue spread. However, the use of (4.2) in normalization overestimates the signal power transferring properties of the orthogonally polarized antenna system, and therefore it seems to deliver higher capacity than expected based on (4.3) [P4]. The mutual information results as a function of system signal-to-noise-ratio (ρ) using two different normalizations are presented in Fig. 4.1 for the two antenna systems.

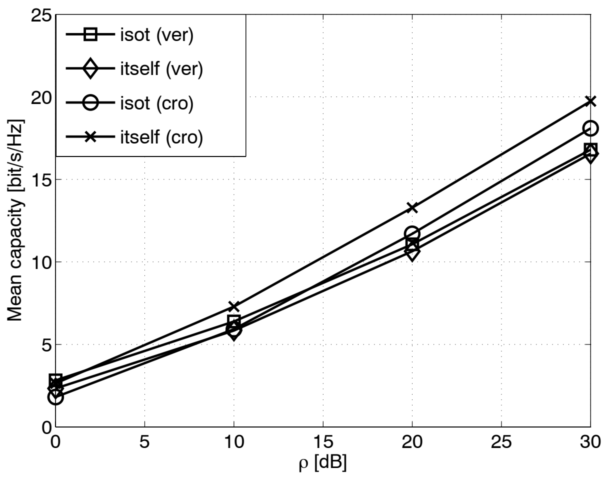


Figure 4.1. Capacity as a function of system signal-to-noise-ratio (ρ) is presented using two different normalization methods: Normalization for the considered antennas (*itself*) based on (4.2), and normalization for the isotropic sensors (*isot*) based on (4.3).

4.4 Definition of mean effective link gain (MELG)

The definition of mean effective link gain (MELG) can be considered as an extension of the mean effective gain (MEG) [7], [8]. The MELG is defined so that it takes into account also the properties of a transmitter antenna system, which is not considered in the original definition of the MEG. However, the definition of the MEG that considers also the effect of Tx antennas is later proposed in [88]. The effect of both link ends can be considerable e.g. in ad-hoc systems where mobile stations communicate directly with each other [93]. The MELG is defined by the sample mean power of a prototype antenna system divided by the sample mean power of a reference antenna system by [P3]

$$G_{e,MIMO} = \frac{P_{aut}}{P_{ref}} = \frac{\frac{1}{N_s}\sum_{i=1}^{N_s} P_{aut}^{(i)}}{\frac{1}{N_s}\sum_{i=1}^{N_s} P_{ref}^{(i)}} = \frac{\frac{1}{N_s}\sum_{i=1}^{N_s} \left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{\frac{1}{N_s}\sum_{i=1}^{N_s} \left\|\mathbf{H}_{ref}^{(i)}\right\|_F^2}, \tag{4.4}$$

where $\mathbf{H}_{aut}^{(i)}$ and $\mathbf{H}_{ref}^{(i)}$ are the channel matrices for antennas-under-test and for reference antennas, respectively. Basically $G_{e,MIMO}$ defines the differences in mean transferred signal power between the MIMO systems due to different antenna solutions. It is defined in (4.4) that the number of the reference isotropic sensors equals with the number of the antennas-under-test. The achieved array gain can be expressed by a separate parameter, $n_t n_r$, based on (4.3). The MELG neither poses any restrictions on the antenna array geometry nor requires equal-power antenna branches. Generally, all non-idealities like dielectric and metallic losses as well as interaction between the antennas within array (mutual coupling) are included in the definition of the MELG.

4.5 Definition of MELG–adjusted mutual information

Based on the definition of MELG the concept of MELG–adjusted mutual information is introduced for identifying performance differences between the antenna systems in [P3]. Based on (4.3) the instantaneous link gain can be expressed by

$$G_{\mathbf{H}}^{(i)} = \frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{\frac{1}{n_t n_r}\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2}, \tag{4.5}$$

which can be further divided into two constant terms, $n_t n_r$, $G_{e,MIMO}$, and a variable term, $G_{fad}^{(i)}$, by

$$G_{\mathbf{H}}^{(i)} = n_t n_r \cdot \frac{P_{aut}}{P_{ref}} \cdot \frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{P_{aut}} \frac{P_{ref}}{\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2} = n_t n_r \cdot G_{e,MIMO} \cdot G_{fad}^{(i)}. \tag{4.6}$$

In (4.6) $G_{e,MIMO} = P_{aut} / P_{ref}$ is the previously defined MELG and

$$G_{fad}^{(i)} = \frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{P_{aut}} \frac{P_{ref}}{\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2} \tag{4.7}$$

can be considered as SNR fluctuation due to fading. The product of (4.4) and (4.7) basically defines the instantaneous transferred signal power (TSP) of the antenna system by

$$G_{ant}^{(i)} = \frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2}. \tag{4.8}$$

After some manipulations of (4.3), and based on (4.6), the mutual information (MI) can be expressed by

$$I_{\mathbf{H}}^{(i)} = \log_2 \left| \mathbf{I} + \rho n_r G_{e,MIMO} G_{fad}^{(i)} \frac{\mathbf{H}_{aut}^{(i)} \mathbf{H}_{aut}^{(i)H}}{\left\| \mathbf{H}_{aut}^{(i)} \right\|_F^2} \right|. \qquad (4.9)$$

The very basic issue considering the MIMO is how those systems can utilize spatial parallel channels. Indicators for a MIMO system to create linearly independent channels can be evaluated based on eigenvalue spread [89] or eigenvalue dispersion [90], [91]. The eigenvalue dispersion (ED) is defined by

$$G_{mux}^{(i)} = \frac{m_g^{(i)}}{m_a^{(i)}} = \frac{\left(\prod_{k=1}^{K} \lambda_k^{(i)} \right)^{1/K}}{\frac{1}{K} \sum_{k=1}^{K} \lambda_k^{(i)}}, \qquad (4.10)$$

which is a ratio of geometric and arithmetic means of the eigenvalues of $\mathbf{H}_{aut}^{(i)} \mathbf{H}_{aut}^{(i)H}$. It is a function of all the eigenvalues, which provides a versatile quality factor for identifying the spread of parallel spatial channels by a single value. The ED is not the new concept; it is called an ellipticity statistic in [94], a minimum description length (MDL) in [95], and a sphericity test in [96]. However, in the context of MIMO system evaluation it is introduced first time in [91]. In the case of high signal-to-noise-ratio the expression (4.9) can be decomposed for three parts consisting of $G_{e,MIMO}$, $G_{fad}^{(i)}$, and $G_{mux}^{(i)}$ based on the studies [91] and [P3]. The decomposition shows that the parameter $K \log_2\left(G_{mux}^{(i)}\right)$ is directly proportional to the degradation of capacity from the supremum case [91], [P3]. This is also valid with relatively good accuracy in moderate signal-to-noise-ratios. It can also be shown that in low signal-to-noise-ratios the effect of parameter $G_{mux}^{(i)}$ becomes insignificant [P3]. This is also evident based on the study in [17].

The distributions (e.g. cdf) of $\left\{G_{ant}^{(i)}\right\}_{i=1}^{N_s}$ (TSP) and $\left\{G_{mux}^{(i)}\right\}_{i=1}^{N_s}$ (ED) essentially define the properties of the MIMO system. When properly normalized information not only on the parallel channels (ED) but also on the signal power transferring properties of the antenna systems (TSP) is delivered. Some evident observations can be given based on (4.9): The MELG of the antenna system directly modifies system signal-to-noise-ratio ρ. Further, by increasing the number of receiving antenna elements, n_r, decreases the relative effect of the MELG, which means that the effect of specific antenna element type becomes a less significant factor. The expression (4.9) is general, and valid with arbitrary MIMO antenna configurations, e.g. with ones where the antenna elements have different orientations − a common situation e.g. for mobile terminals.

4.6 Antenna evaluation based on the MELG adjusted capacity

A microcell line-of-sight (LOS) measurement in Helsinki downtown was carried out as an example in the validation of the considered parameters [P3]. Two 2×2 MIMO antenna systems, which provide significantly different results for the investigated parameters, were selected. At the transmitter two patch antennas were selected from the measurement array: 1) two vertically and 2) vertically and horizontally polarized feeds. Utilizing the EPWBM two ideal dipole antennas were employed at the receiver: 1) two vertically and 2) vertically and horizontally polarized dipoles. The results of outage MI, ED and TSP are presented in Fig. 4.2. The outage probability is defined by $\{t_p : \mathrm{Prob}(X < t_p) = p\}$, where $X = \{I_{\mathbf{H}}^{(i)}\}_{i=1}^{N_s}; \{G_{mux}^{(i)}\}_{i=1}^{N_s}; \{G_{ant}^{(i)}\}_{i=1}^{N_s}$. Either the whole cumulative distribution function (cdf) or some level of outage probability (p) is identified. The analysis of outage MI is carried out at the outage probability levels of 1% and 50%. Cdfs of ED and TSP are also presented for the both antenna systems. The results of Rayleign iid channel are presented as a reference.

According to the analysis, the orthogonally polarized antenna system (*cro_dip*) yields smaller ED, whereas the vertically polarized antenna system (*ver_dip*) delivers higher TSP. The higher TSP of the *ver_dip* compared to the *cro_dip* is due to the higher MELG of the *ver_dip*. On the other hand, the smaller ED of the *cro_dip* in comparison to the *ver_dip* is due to the two orthogonal polarizations in the antenna systems. Hence, regardless of the smaller ED, the *cro_dip* does not necessarily guarantee higher outage capacity for the reason of the lower TSP. The results are also related to considered probability level and to signal-to-noise-ratio: The difference between the outage MI of the two antenna systems is even more significant at low outage probability level (p = 1%) as at high outage probability level (p = 50%). That is due to significant differences in the distributions of transferred signal power between the antenna systems. Evidently, ranking of the antennas is not only related to eigenvalue dispersion, but also the signal power transferring properties of the antenna systems are of great importance in the MIMO system performance considerations.

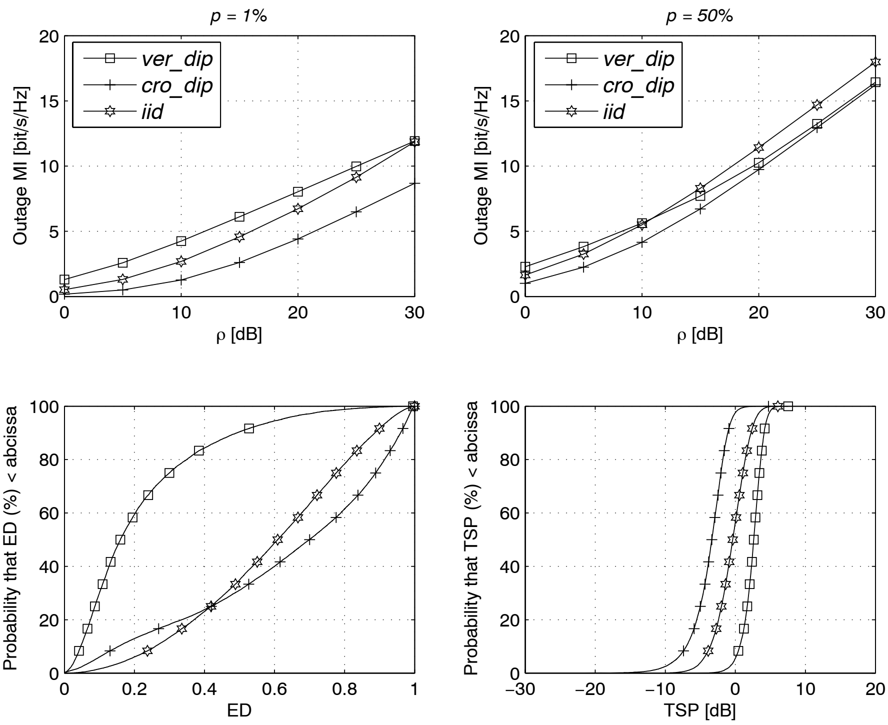


Figure 4.2. A 2×2 MIMO system is considered at NLOS case. The curves with plus (+) and square (□) marks indicate the results of orthogonally (*cro_dip*) and vertically (*ver_dip*) polarized antennas, respectively. The results of Rayleigh iid channel are presented using stars. The results of outage MI, ED and TSP are considered in different subplots. The analysis of outage MI is presented at the capacity outage probability levels (p) of 1% and 50% as a function of SNR (ρ) in the upper figures. Cdfs of ED and TSP are presented in the lower figures.

5 EXPERIMENTAL COMPARISON FOR MIMO ANTENNA CONFIGURATIONS

5.1 Introduction

From the theoretical point of view it is well verified that a significant increase in spectral efficiency, and therefore, in capacity of the MIMO systems can be achieved in scatter rich environments [1], [2]. However, extensive experimental verification based on real channels and realistic antenna prototypes is needed for the support of the theoretical investigations. To design a universal antenna system that is suitable for all the wireless applications cannot be considered realizable in practice due to different usage environments and layouts of commercial devices. Assuming the same efficiency for all the antennas and isotropic signal propagation no performance differences occur between the antennas. However, in the real propagation channels signals are typically clusterized [92], [97] due to obstacles and scatterers along the route. Furthermore, the realistic antenna systems cannot be considered to consist of isotropic sensors or even omnidirectional antennas able to receive and transmit power with constant gain regardless of the direction in space. Every specific antenna system possesses different characteristic properties, and therefore, significant differences considering the radiation, the bandwidth, and the efficiency. Clearly, the performance evaluation of the antenna systems is essential and obtainable only with extensive experimental studies [98]. At least the used channel models should be verified based on measurements before using them in antenna evaluation. Otherwise it is very difficult (if not impossible) to evaluate the performance of the systems intended for different mobile communications applications.

In this chapter some insight is given into the behavior of some antenna types in different usage environments. The results are partly based on the antenna selection from the measurement arrays [P1] and partly on the utilization of the EPWBM [P1], [P2]. The figures of merit developed in [P3] are utilized in the analysis of some of the results.

5.2 The real capacity results versus ideal capacity results

The independently and identically distributed (iid) channel is the widely used benchmark for measurement-based MIMO channel considerations. Even 50% degradation in median capacity was found in comparison to iid capacity in dynamic measurements [P1], [P5] as well as in static measurements [19]. Also higher capacities of up to 90% of the iid capacity are reported e.g. in [20] and [27]. In some cases, however, mostly at high outage probability levels, a real channel with realistic antennas can outperform the iid channel in capacity due to favorable antenna orientation in proportion to the signal distribution. This is verified in [P1], and [P5], and can be analyzed qualitatively by using the methods in [P3]. Generally the variance of the signal is higher with the realistic antennas and the channels than can be predicted based on the considerations of iid channel. It is worth noting, however, that the discovered capacity results are related to the normalization method used, e.g. in the cases of [19], [20], and [27] the transferred mean signal power is normalized to the same level with all the antennas based on (4.2), that is, the effect of the MELG [P3] is neglected. The common reference system, which reveals different signal power transferring properties of the antennas, is proposed in [26], [69], [98], [P1], [P3], [P4], and [P6]. The computational isotropic sensor, realized based on the EPWBM, act as common benchmark in the performance comparisons of different antenna systems [69], [P3], [P4].

5.3 Effect of antenna array orientation and radiation pattern of the antenna elements

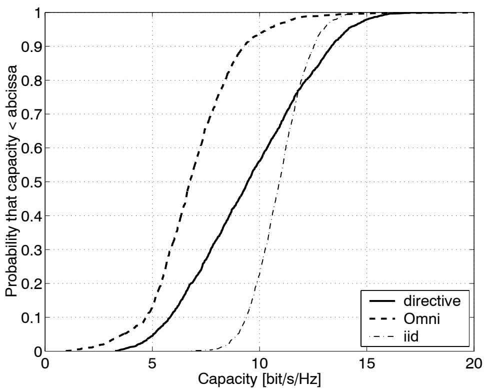
In the realistic channels the arriving signals are not typically uniformly distributed in azimuth and in elevation [92], [97]. This affects the ability of the antenna system to utilize parallel spatial channels [99], [P3] and transfer signal power [P1], [P3], [P5]. The capacity of the MIMO system depends on the orientation of the receiver antenna array [99], [100], [101], [P1], [P3] and on the radiation patterns of the antenna elements [P1], [P3], [P5].

The effect of radiation properties of antenna elements in arrays on the MIMO performance is considered e.g. in [24], [27], [P1], [P3], and [P5]. There are some basic differences between two antenna types, namely directive (e.g. patches) and omnidirectional (e.g. dipoles), when considering the MIMO system performance. It was found in [27] that monopole antennas slightly outperform patch antennas in capacity, whereas the opposite result was found in [P1]. Hence, the motivation of paper [P5] was to demonstrate how the performance depends on the environment and on the clearly different radiation patterns of the antennas. In [P5] 4x4 MIMO antenna systems with vertically polarized patch antennas at Tx and vertically polarized ideal dipole antennas (*omni*) as well as vertically polarized patch antennas (*directive*) at Rx were used. In the case of the dipoles the idea of the EPWBM was utilized. However, direct antenna selection was used with the directive antennas. Hence, due to two different evaluation methods also the normalization of the power levels differs slightly between the two cases: normalization was performed with the discone antenna in the *directive* case (see also [P1]) and with the dipole antennas in the *omni* case. The justification for the slightly different normalizations used was that the characteristics of the discone are close to those of the ideal dipoles making the results comparable to each other. The system signal-to-noise-ratio was 10 dB in this study.

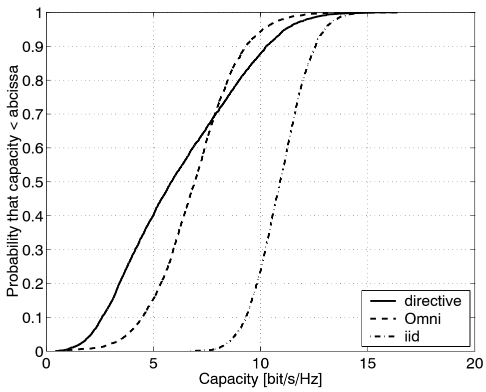
Higher capacity is achieved with the directive antennas in the picocell (indoor) and the macrocell environments whereas the omnidirectional antennas perform better in the microcell environment at low outage probability level (see Fig. 5.1). In urban microcell scenarios the base station antenna is typically located below the rooftop level, the case in which the signals are typically guided by the walls of the buildings. In those street canyons a receiver antenna system with directive antennas can be badly oriented relative to the signal distribution causing severe degradation in capacity as compared to the picocell and macrocell environments [102], [P1], [P3], [P5]. Indoor environment delivers usually rich scattering from the surrounding objects (walls and furniture) causing high rank of the channel [22], [102]. Therefore, higher mean capacity was found indoors in comparison to outdoors when using the directive antenna elements [P1].

Generally, the performance of the antennas depends on the outage probability level considered and on the signal-to-noise-ratio. The systems with omnidirectional antennas can typically provide higher reliability than the systems with directive ones, that is, better performance at low outage probability levels. On the other hand, directive antennas can perform very well in some specific locations due to high gain but, can be badly oriented in some other locations, especially in the street canyons (see Fig.5.1 b) [P3], [P5]. Thus, directive antennas are more orientation sensitive than omnidirectional ones, which is evident from Fig. 5.1. This experiment demonstrates also that the mean effective link gain (MELG) [P3] is not a sufficient quality factor in the estimation of transferred signal power but information about the variance of transferred signal power is also needed.

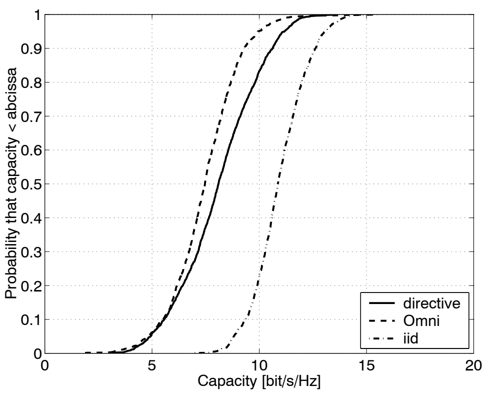
In practical applications, the radiation properties of the antennas are between the directive and the omnidirectional ones. In the real usage situations e.g. with portable mobile communication devices, not even the dipole type antenna can provide omnidirectional coverage due to shadowing of the human body. Further, a portable device can be oriented almost randomly not only in azimuth but also in elevation. Moreover, the efficiency of a device depends on the antenna properties as well as on the interaction with the user [13], [38]. Thus, ideal efficiency cannot be achieved in practical solutions [69]. Due to those reasons the transferred signal power can vary significantly in the practical antenna solutions.



a)



b)



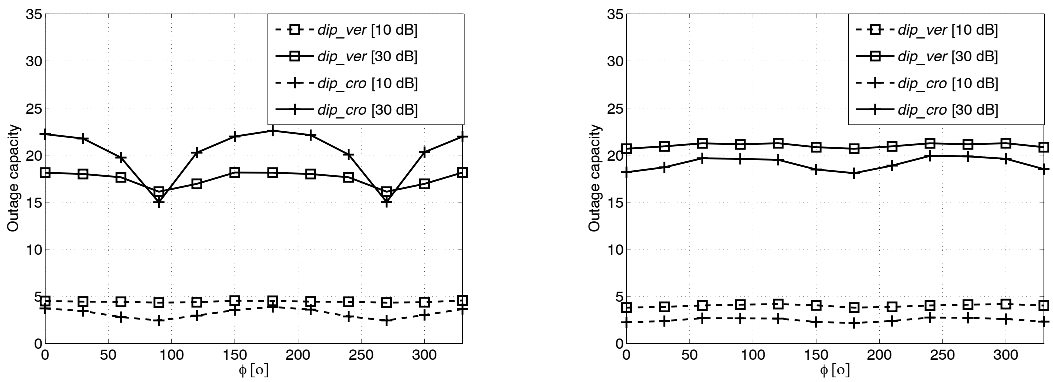
c)

Figure 5.1. Comparison of directive (patch) and omnidirectional (dipole) antennas [P5]. System signal-to-noise-ratio ρ=10 dB. a) Indoor environment. b) Microcell environment. c) Macrocell environment.

5.4 Single- versus dual-polarized MIMO antenna systems

The effect of polarization on the MIMO performance is considered in some papers. It was found beneficial to use two [28], [P1], or even three [103] orthogonal polarizations. In [P1], the use of the dual-polarized antenna elements was found to slightly outperform the use of the single-polarized antenna elements at SNR of 10 dB: the former being 14% better in capacity. Those results support the utilization of the more compact dual-polarized antennas in a mobile terminal. The performance of the considered antennas, however, depends on the environment, system signal-to-noise-ratio, outage probability level considered, and antenna orientation [P3].

It is clear that in free space conditions and with favorably aligned antennas two orthogonal polarizations deliver two orthogonal spatial sub-channels with equal power. On the other hand, in the same conditions, the use of single polarization delivers only one spatial sub-channel [104]. Thus, it can be verified based on [104], that in LOS conditions, the effect of polarization for the MIMO performance is two-fold: at high signal-to-noise-ratios the dual-polarized antennas outperform the single-polarized ones whereas the situation is reversed at low signal-to-noise-ratios. In this consideration, however, isotropic antennas were assumed and different signal power transferring properties of the antenna systems were not considered. In order to provide more information on the polarization issue the results of an experiment, where two 2×2 MIMO systems with vertically (*dip_ver*) and orthogonally (*dip_cro*) polarized antennas with ideal dipole elements at the Rx were compared in the microcell and small macrocell environments, are presented in Fig. 5.2. The measurement scenario and the antennas are described in more detail in [P3].



a) b)

Figure 5.2. Outage capacity of vertically and orthogonally polarized antennas at 10% probability level and with two signal-to-noise-ratios (10 dB and 30 dB). 12 different Rx antenna orientations in the horizontal plane are considered. a) microcell (LOS) scenario. b) macrocell (NLOS) scenario.

According to the results the outage capacity when using the orthogonally polarized antennas varies strongly due to antenna orientation whereas the use of only vertical polarization shows less variance (see Fig. 5.2 a). When scattering increases in the channel, the ability to utilize parallel spatial sub-channels increases and decreases with the *dip_ver* and the *dip_cro*, respectively. This increment is due to decreased correlation between the sub-channels in the case of the *dip_ver*. With the *dip_cro* this decrement is due to increased XPD, which increases coupling, and thus, correlation between the sub-channels of two orthogonal polarizations. The same result regarding the effect of XPD is also found in [25]. Thus, due to increased scattering the results of eigenvalue dispersion approach each other with the two antenna systems. Hence, when considering the results of outage capacity a more scatter-rich channel gives benefit for the *dip_ver* basically due to higher TSP and decreased ED in comparison to the *dip_cro* (see Fig. 5.2 b).

The MIMO systems with dual-polarized antennas show more robust outage capacity results between the different signal propagation scenarios (indoor, microcell, macrocell) compared to the systems with single-polarized antennas [P3]. Considering the polarization issue it can be concluded that a system with dual-polarized antennas is more orientation but less location (environmental) sensitive than a system with single-polarized antennas [P3]. This is because the antenna systems with two orthogonal polarizations deliver more uncorrelated spatial sub-channels regardless of the usage environment than the antenna systems with single polarization. On the other hand, especially a horizontally polarized dipole antenna can be unfavorably oriented in proportion to the signal distribution, which increases orientation sensitivity. Generally, however, differences in capacities tend to be small between single- and dual-polarized antenna systems in realistic channels. More thorough analysis of the polarization issue is presented in [P3].

5.5 Effect of power imbalance between the antenna branches

The capacity of MIMO system depends on the orientation of antenna elements within the array [P6], [P7]. In [P6] a new compact antenna group consisting of two dual-polarized microstrip antennas has been developed for laptop type devices. The developed antenna system is a feasible candidate to be used e.g. in WLAN systems. Two different 4×4 MIMO systems were compared from mean capacity point of view in [P6][6]. At the Rx the micro-strip antenna prototypes were mounted on laptop cover both back-to-back (Rx1) and next (Rx2) to each other. At the Tx two dual-polarized micro-strip antennas were selected from the linear measurement antenna array. It is demonstrated in this study that the prototype antennas perform well in comparison to ideal dipole antennas in indoor environment. The performance of the investigated antenna systems is surprisingly robust for different tilting angles of the "laptop cover". Especially the mean capacity results of prototype Rx1 show only minor fluctuation as a function of antenna orientation. As an extension of [P6] Fig. 5.3 presents the outage capacity results for two probability levels. The antenna arrangements perform identically at median capacity (50%), but due to higher SNR variance for Rx2, Rx1 performs better at low outage probability level (10%) and can be considered the better antenna candidate in that sense. Evidently the differences in performance between the two antenna candidates would be even higher in an environment with less scattering, but, however, indoor is the typical usage environment for WLAN systems.

[6] For the lack of 5.3 GHz data 2.154 GHz data is combined with the prototype antennas designed for 5.3 GHz frequency band. It is shown in [105] that signal propagation properties in those frequency bands are relatively similar from the MIMO capacity point of view. Anyway main purpose was to study the effect of different antenna element orientations in the arrays on the performance of MIMO system.

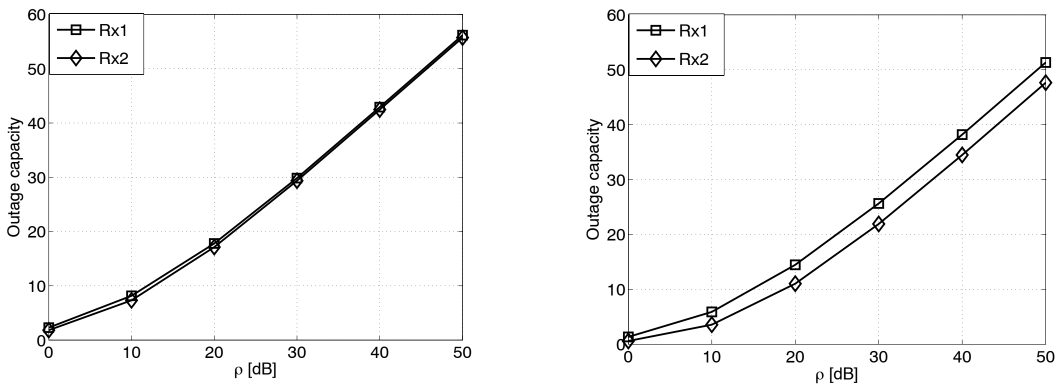


Figure 5.3. Effect of antenna orientation on the outage capacity of 4×4 MIMO system. Antennas are arranged back-to-back (Rx1) and next to each other (Rx2). a) 50% outage probability (median), b) 10 % outage probability

Papers [106], [P6] and [P7] demonstrate that the possible imbalance between the received powers of the antenna branches seems to be less crucial than the effect of totally disadvantageous antenna array orientation. This is an understandable result since it can be considered less fatal that only a single antenna branch is pointing to a bad direction instead of both ones. The effect of antenna orientation on the correlation between the antenna branches is studied in [21], and [P7]. It is also verified in [P7] that the variance in correlation is of minor effect on the SNR, and therefore on the bit error rate (BER) of the system.

5.6 Effect of number and inter-element spacing of antennas

The number of possible parallel spatial channels depends on the size of a MIMO system, that is, the number of antennas at both ends of the link. A larger MIMO system can benefit more from the signal propagation environment than a smaller one. By increasing multiplexing as well as array gain the effect of an antenna element type becomes less significant [P3]. However, antenna selection has significant influence on the performance, especially in small MIMO systems, where the signal power transferring properties play more dominant role than in large MIMO systems [P3].

Generally, increasing inter-element spacing between the antenna elements decreases correlation, which, in turn, increases diversity gain and decreases eigenvalue spread, and therefore increases the capacity of a MIMO system [102], [107], [P1], [P5]. The increase in capacity is related to the amount of scattering in the propagation environment. It is more beneficial in poor scattering environment to increase spacing between the elements because the correlation between the branches can still be reduced. Outdoors, where signals arrive at the MS from certain azimuth directions, capacity increase of 33% has been found when spacing increases from 0.5 λ to 2.5 λ [P1]. Indoors, due to larger angular spread, the element spacing has only an effect of 7% [P1]. Thus, in a rich scattering environment, where the correlation between the elements tends to be low even in the case of small interelement spacing of the antennas, it is more beneficial to increase the number of elements for the arrays than in a poor scattering environment [P1]. Generally, it is more useful to increase the number of elements than enlarge the spacing between them since in the former case diversity level, array gain and multiplexing gain increases but in the latter case only the correlation between the branches decreases. An interesting result, where the number of antenna elements was increased in an array while maintaining the same size of the aperture, that is, packing more elements to the same volume, is presented in [27]. It was found that the capacity per degree of freedom drops due to increased correlation between the branches. However, the total capacity increases also in this case.

5.7 Imbalanced antenna configurations

A MIMO system, where the number of the antennas is larger in one than in the other end of the link, can be useful in some applications. It is typically easier to adopt antennas to the fixed station than to the mobile station due to more strict space requirements in the latter case. Generally, increasing the number of Rx antennas for an originally balanced ($n \times n$) MIMO system increases Rx diversity, array gain, and decreases eigenvalue spread [91], [102], [P1], [P5] although the same multiplexing gain is achieved. On the other hand, increasing the number of antennas at Tx increases transmit diversity and decreases eigenvalue spread. However, when the channel is not known at Tx the same array gain is not obtained. Thus, a MIMO system consisting of more elements at Rx outperforms a MIMO system adopting more elements at Tx.

Generally, the MIMO systems outperform traditional communication systems like the SISO, SIMO, and MISO due to utilization of parallel spatial channels. However, it is easily verified for the Rayleigh iid channel by using Monte Carlo simulations that a small SIMO system with the same number of connections between the Tx and Rx (e.g. 1×4) and type of the antennas can produce better performance than a small MIMO system (e.g. 2×2) at low signal-to-noise-ratios and low probability levels since the SIMO system has more array and diversity gain than the MIMO system in that case. E.g. at ρ = 0 dB a SIMO system outperforms a MIMO system whereas at ρ = 10 dB capacity curves cross at the outage probability level of about 30%. This is because in the symmetric ($n \times n$) MIMO antenna systems not only the average capacity, but also the fluctuation of the capacity increases due to the increased spread of eigenvalues, implicitly presented e.g. in [91]. When using realistic channels and antennas instead of Rayleigh iid assumption it can be argued that a SIMO system can perform even better than a MIMO system due to increased eigenvalue dispersion in the latter case. This issue, however, should be more thoroughly studied.

6 FUTURE CHALLENGES

Finally some future challenges have been discussed. The developed antenna evaluation system and the proposed quality factors enable extensive antenna evaluation of the antenna prototypes. However, the accuracy of the experimental plane-wave-based method (EPWBM) could be further developed by adopting more advanced channel estimation algorithms. Further, performing channel estimation at the both ends of the link would enable even more effective antenna evaluation e.g. for ad-hoc systems. To go even further a feasible MIMO antenna optimization procedure would be a valuable tool for antenna designers. However, antenna optimization problem is a very demanding task due to the numerous parameters involved. Considering some specific antenna system, possible mechanisms affecting its performance are location and orientation of the antenna elements within the array (at both ends), radiation properties of antenna elements, polarization, efficiency and impedance bandwidth. The problem becomes even more demanding due to the fact that those mechanisms are not independent from each other. Further, a user can hold a communication device in numerous different positions. In addition to this the channel properties vary considerably depending on the environment. Hence, it is evident that all the involved parameters cannot be optimized concurrently, but some of them need to remain fixed, otherwise computation load becomes too heavy. This practically means that antenna evaluation is more realistic approach than antenna optimization still some time in the development of multielement antenna systems.

7 SUMMARY OF PUBLICATIONS

[P1] Comparison of MIMO antenna configurations in picocell and microcell environments

The paper [P1] presents the results achieved with a dual-polarized Multi-Input Multi-Output (MIMO) measurement system in the 2 GHz range. Results from continuous measurement routes were used in evaluating and comparing different MIMO antenna configurations. Different pattern and polarization diversity possibilities were studied using two methods: elements were selected from the antenna arrays used in measurements, and as another option, in 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 picocell than in an outdoor microcell environment. At the mobile station, directive elements provide 35% higher average capacities than omnidirectional elements; however, the capacity with the directive elements also depends on the azimuth direction of arrival of the incident field. Dual-polarized antenna configurations provide approximately 14% higher capacities than co-polarized configurations. Increasing the number of mobile antenna elements 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.

[P2] Evaluation of the Performance of Multi-Antenna Terminals Using a New Approach

In paper [P2], an advanced experimental plane-wave based method (EPWBM) for evaluation of the performance of multi-antenna systems is considered. The method enables statistical antenna evaluation without performing long routes of radio channel sounder measurements to be carried out separately for each AUT. The EPWBM utilizes the joint contribution of the estimated signal spectrum and the simulated or measured complex 3-D radiation patterns of the antennas under test. The proposed method enables more comprehensive antenna evaluation in a shorter time period compared to direct measurements. For validation purposes, the results obtained with EPWBM are compared with the results of direct radio channel measurements. The method is shown to be sufficiently accurate for comparing the performance of different antenna configurations. The average difference between the two methods is below 1 dB when estimating diversity gain of two-element antennas. Further, the maximum difference between the methods in 4×4 Multiple-Input Multiple-Output (MIMO) analysis is below 1 bit/s/Hz in estimating mean capacity.

[P3] Empirical comparison of 2×2 MIMO antenna configurations

In paper [P3], the methods for comparing MIMO antenna configurations using measured radio channels are considered. The expression of mutual information is factorized for giving better understanding on the ability of a MIMO antenna system to transfer signal power as well as to utilize parallel channels. The significance of normalization in the MIMO antenna evaluation is emphasized. It was found that the ability to transfer signal power between the Tx and Rx dominates also at relatively high signal-to-noise-ratios. The highest performance differences between the antennas were found at low probability levels, especially in the microcell. It was also verified that the antenna systems utilizing two orthogonal polarizations are more robust for environmental variations but more antenna orientation sensitive compared to the single polarization antenna systems both in eigenvalue dispersion and transferred signal power.

[P4] Comparison of MIMO antennas: performance measures and evaluation results of two 2x2 antenna configurations

In paper [P4], the significance of antenna element properties on Multiple-Input Multiple-Output (MIMO) systems is examined. It is verified that eigenvalue spread is not an adequate quality factor for MIMO systems but also total transferred signal power has also to be taken into account. Thus, a novel performance measure is proposed for MIMO antenna systems called mean effective link gain (MELG), which is an extension of mean effective gain (MEG) for Single-Input Single-Output (SISO) systems. An evaluation example of two MIMO antenna systems in two propagation environments is presented. The ambiguity of the capacity results is demonstrated by using two different normalization methods, the other of those methods is proposed for antenna comparison.

[P5] Effect of antenna properties on MIMO-capacity in real propagation channels

The study of paper [P5] was carried out for the extension of paper [P1]. Experimental investigations are performed to compare different MIMO antenna configurations at the mobile and base stations. The goal is to provide new information on the effects of antenna properties on MIMO performance. At the mobile station, the effect of using different elements in arrays is studied. Further, at the base station, the effects of increasing the number of elements and increasing the inter-element spacing in MIMO systems are studied. Three potential MIMO environments, indoor picocell, outdoor micro- and macrocell, have been included in this study. It was found that the type of MS antenna element has a significant effect on the achieved MIMO capacity, especially indoors. It was also found that increasing the distance between Tx antenna elements or increasing the number of elements decreases the spread of eigenvalues and, thus, increases MIMO capacity. In addition, adding more elements at Tx increases, of course, the Tx diversity. In comparing with microcellular and small macrocellular environments, the smallest eigenvalue spread is in indoor picocell.

[P6] A novel MIMO antenna for laptop type device

In paper [P6], a microstrip prototype antenna with two polarizations is developed for MIMO and also for diversity system purposes. Firstly, two antennas of this type were placed against to each other, which guarantees a good coverage over a whole propagation area. Secondly, two antennas of this type were placed next to each other. The simulated radiation patterns of the prototype antenna are used in the capacity studies of MIMO system using real indoor propagation data. The effect of shadowing by human body as well as different tilting angles of "laptop cover/screen" is considered. Further, different locations of the "device" in azimuth plane are considered identifying the fluctuation of the results due to the environmental and antenna properties. The developed antenna systems perform well as compared to the ideal dipole system.

[P7] The influence of antenna configurations on the performance of STBC in urban microcells

Based on urban microcell channel measurements, paper [P7] evaluates bit error rate performance of a space-time block code with four transmit antennas using various dual-branch receive antenna configurations. It is demonstrated that with realistic handset antennas, it is possible to achieve performance very close to that of the theoretical uncorrelated Rayleigh case, although proximity of operator tissue (e.g. head) will result in performance degradation of several decibels.

8 CONCLUSIONS

Multiple-input multiple-output (MIMO) technique is a promising solution for increasing reliability and spectral efficiency of the radio connection in future mobile communication systems. The performance potential of MIMO systems is well verified in theory. However, much effort is still needed in the experimental verification of those systems using realistic antennas and channels. In this thesis work novel tools are developed for intensifying multi-element antenna evaluation process. In addition, new criteria are developed for comprehensive multi-element antenna evaluation. Further, some insight into the effects of antenna characteristics for the performance of MIMO systems is given in different signal propagation environments.

In the first part of the work a new antenna evaluation method – the experimental plane-wave-based method (EPWBM) – has been extended and validated for the evaluation of MIMO antenna systems. The EPWBM enables effective testing of multi-element antenna prototypes based on the simulated or measured radiation patterns of antenna prototypes and previously measured channel library. The EPWBM facilitates the antenna evaluation process since separate field tests are not required for every antenna prototype. With the developed method the performance of a prototype antenna can be evaluated even before it is manufactured. The radiation patterns of prototype antenna systems can be rotated computationally in azimuth and in elevation, which saves evaluation time drastically in comparison to direct measurements. Based on verification with the direct measurements the EPWBM can be considered sufficiently accurate for the evaluation of multi-element antenna prototypes. In the comparison the averages of the median capacity and eigenvalue dispersion results were calculated over seven different propagation environments and six different antenna configurations with sizes of 2×2 and 4×4 consisting of vertically, horizontally and orthogonally polarized antennas. The difference between the methods was 0.3 bit/s/Hz (5 %) in median capacity and 0.04 (22 %) in median eigenvalue dispersion. The largest differences between the methods were found with the most complex signal propagation environments, basically indoors, mainly due to the increased complexity in signal estimation. Based on the EPWBM a multi-element antenna evaluation tool named a measurement-based antenna test bed (MEBAT) was established consisting of channel library with several measurement routes at 2 GHz range.

In the second part of the work new antenna performance criteria have been developed for the evaluation of performance of MIMO antenna prototypes enclosing traditional systems (SISO, SIMO, MISO) as special cases. Typically the ability to transfer signal power between the links is not considered in a very realistic way in the MIMO system performance considerations. Therefore the quality factors developed take into account the properties of antenna systems in a more comprehensive way; as both signal power transferring (TSP) properties and ability to create parallel channels via eigenvalue dispersion (ED) are considered. The signal power transferring properties are further factorized to mean and instantaneous transferred signal power. The mean of the TSP, called the mean effective link gain (MELG), can be considered as the extension of the mean effective gain (MEG) used in the SISO antenna evaluation. From the antenna point of view the second order statistics of the TSP basically define the reliability of the system. The key issue in the factorization is the normalization of transferred signal power. For fair comparison the same reference system must be used in the evaluation of all the antennas-under-test. The significance of the developed quality factors is verified based on the antenna evaluation in the several signal propagation environments.

In the last part of the work some guidelines for the effect of the antennas on the performance of MIMO systems based on the experimental investigations are given. Evidently, the performance of the MIMO system depends both on the properties of the antenna systems and the properties of signal propagation environment. The variation of the performance tends to be higher with the realistic channels and antennas in comparison to Rayleigh iid channels. This is because in realistic scenarios the local distribution of arriving signal power is not typically uniform in azimuth and therefore the performance of MIMO systems depends heavily on the orientation of the antennas. Therefore, for reliable results, the rotation of the antennas in azimuth (and also in elevation), which is easily available by using the developed antenna evaluation tool, is essential in the evaluation of the antennas. The variation of the performance is especially high when using directive antennas in environments where the signals are strongly guided by different obstacles like the walls of buildings, which is a typical situation especially in microcells. The effect of bad orientation of the antennas degrades capacity more than power imbalance between the antennas.

The performance of MIMO antenna systems depends on the probability level considered and on the system signal-to-noise-ratio. Antenna systems with omnidirectional radiation patterns of the antenna elements are reliable at low probability levels but difficult to realize in practice, especially with dual polarized antennas, due to the shadowing of human body. Anyway, it is beneficial to realize as omnidirectional radiation pattern as possible in the MIMO applications. At high system SNR conditions the systems with low eigenvalue dispersion outperforms the systems that possess better ability to transfer signal power. However, it is shown in this work that the required SNR has to be at least 30 dB for the systems with small ED to outperform the systems with better TSP in realistic channels. Especially in relatively small MIMO systems the signal transferring properties of the antennas are of significant importance and practically determine the performance of the system rather than the ED.

2×2 MIMO systems when using the single- and dual-polarized antennas with omnidirectional radiation patterns possess better properties to transfer signal power and to utilize parallel spatial channels, respectively. Due to ability to utilize two relatively orthogonal channels the performance of the dual-polarized antennas is more robust against the variation of the signal propagation environment in comparison to single-polarized antennas. On the other hand, the performance of the dual-polarized antennas is less robust for the orientation of the antenna system. From practical point of view, the dual-polarized antennas seem to be feasible candidates for MIMO antenna systems for the reason of more compact structure compared to the single-polarized ones. Typically indoor environment seems to be the most suitable for MIMO applications due to sufficiently scatter-rich environment.

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ISBN 951-22-8296-8
ISSN 1456-3835