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Modeling Multiple Antenna Systems in Realistic Environments

A Composite Channel Approach

Thesis for the degree of
Licentiate in Engineering

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Abstract

For evaluation of specific antenna arrangements in wireless communication systems we need physical channel models that take into account the directional domain. Here we propose a practical approach to wireless channel modeling in, particularly, mobile communication systems, by using an assumption that the channel can be divided into separate parts or regions that can be treated and modeled individually. The idea is that the antenna part of the channel is the part considered in the design of the user equipment and can be characterized by a single measurement of each design, while the propagation part of the channel can be characterized separately, independent of the user equipment, based on generic channel sounder measurements with, as far as possible, open areas around the transmitter and the receiver antennas. For more complex antenna environments we may imagine intermediate scattering regions of the channel model between the antenna parts and the propagation part, that perhaps can or cannot be handled separately, e.g., a mobile phone user body, an office desk, a vehicle etc.

A first step in evaluating such a composite model approach is to verify the validity of link simulations were the mobile phone antennas together with the user can be handled as a *super-antenna* with its aggregate far-field pattern to be combined with a directional channel model in a classical way. This is presented in Paper IV and the method is in its extensible form referred to as the Composite Channel Method. It is found that this method, as we expected, work well for statistical performance evaluation of diversity or spatial multiplexing.

An extension of the composite approach is outlined with an attempt to find a simple yet accurate directional scattering model for the user hand and body that still catch the proper influence of antenna efficiencies, fading statistics and correlation. Such an approach is tested and presented for a single antenna inside a car in Paper II.

A full ray-tracing model as the one presented in Paper I and also used in Paper II can capture all important effects of a propagation environment also for multiple antennas systems to the price of high complexity of the geometrical model.

In Paper III a first investigation of user influence on an indoor 2 × 2 MIMO link is performed based on a simple measurement setup and the diversity performance is evaluated. In Paper IV the first step of the composite channel approach is evaluated with respect to MIMO by channel measurements including user influence in static outdoor-to-indoor and indoor scenarios. The approach is verified for statistical properties such as antenna correlation and MIMO eigenvalue distributions. It is found that the presence of the user, apart from introducing hand and body absorption and mismatch that increases the path loss, also increases the correlation between the antenna elements and, thus, slightly decreases potential MIMO capacity.

Preface

This licentiate thesis is comprised of two parts; the first part gives a brief introduction to the field of research and a summary of our scientific contributions, and the second part contains three published conference papers and one submitted journal paper. The papers included in the thesis are:

[1] F. Harrysson and J.-E. Berg, "Propagation prediction at 2.5 ghz close to a roof mounted antenna in an urban environment," in *Proc. IEEE Veh. Technol. Conf. VTC 2001-Fall*, vol. 3, pp. 1261–1263, 2001.

[2] F. Harrysson, "A simple directional path loss model for a terminal inside a car," in *Proc. IEEE Veh. Technol. Conf. VTC 2003-Fall*, vol. 1, pp. 119–122, 2003.

[3] F. Harrysson, H. Asplund, M. Riback, and A. Derneryd, "Dual antenna terminals in an indoor scenario," in *Proc. IEEE Veh. Technol. Conf. VTC 2006-Spring*, vol. 6, pp. 2737–2741, 2006.

[4] F. Harrysson, J. Medbo, A. F. Molisch, A. J. Johansson, and F. Tufvesson, "Efficient experimental evaluation of a MIMO handset with user influence." Submitted to IEEE Trans. Wireless Commun., August 2009 (second round of review).

During my graduate studies, I have also contributed to the following publications, though they are not included in the thesis:

[5] J. Medbo, F. Harrysson, H. Asplund, and J.-E. Berg, "Measurements and analysis of a MIMO macrocell outdoor-indoor scenario at 1947 MHz," in *Proc. IEEE Veh. Technol. Conf. VTC 2004-Spring*, vol. 1, pp. 261–265, 2004.

[6] J. Medbo, J.-E. Berg, and F. Harrysson, "Temporal radio channel variations with stationary terminal," in *Proc. IEEE Veh. Technol. Conf. VTC 2004-Fall*, vol. 1, pp. 91–95 Vol. 1, 2004.

[7] M. Riback, J. Medbo, J.-E. Berg, F. Harrysson, and H. Asplund, "Carrier frequency effects on path loss," in *Proc. IEEE Veh. Technol. Conf. VTC 2006-Spring*, vol. 6, pp. 2717–2721, 2006.

[8] F. Harrysson, L. Manholm, H. Asplund, M. Riback, and A. Derneryd, "Performance of two test terminals with dual antennas in an office environment," in *Antenn 06-The Nordic Antenna Symposium*, (Linköping, Sweden), May 30 – June 1 2006.

[9] F. Harrysson, J. Medbo, and A. F. Molisch, "Performance of a MIMO terminal including a user phantom in a stationary micro-cell scenario with comparison between a ray-based method and direct measurements," TD (07) 379, COST 2100, Duisburg, Germany, September 2007.

[10] H. Asplund, J.-E. Berg, F. Harrysson, J. Medbo, and M. Riback, "Propagation characteristics of polarized radio waves in cellular communications," in *Proc. IEEE Veh. Technol. Conf. VTC 2007-Fall*, pp. 839–843, 2007.

[11] F. Harrysson, J. Medbo, A. F. Molisch, A. J. Johansson, and F. Tufvesson, "The composite channel method: Efficient experimental evaluation of a realistic MIMO terminal in the presence of a human body," in *Proc. IEEE Veh. Technol. Conf. VTC 2008-Spring*, pp. 473–477, 2008.

[12] F. Harrysson, J. Medbo, and A. F. Molisch, "Indoor performance of a MIMO handset including user influence by comparing a composite channel method with direct measurements," TD (08) 661, COST 2100, Lille, France, October 2008.

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I also would like to specifically recognize my co-advisor and collegue at Ericsson AB, Prof. Anders Derneryd who encouraged me to embark this journey and always seem to have time for support and discussions, and my manager Björn Johannisson together with Jan-Erik Berg, who both supported the idea. Anders and Jan-Erik has through my years at Ericsson been great sources of inspiration and motivation.

Thanks also to my colleagues at Ericsson Research; Dr. Jonas Medbo who put in a lot of effort into the channel measurements and channel analyses, Henrik Asplund and Mathias Riback who also helped with channel measurements, Dr. Jonas Fridén, Dr. Anders Stjernman, Lars Manholm, Dr. Martin Johansson, Martin Siegbahn and many more, and at the university; Dr. Shurjeel Wyne, Dr. Johan Kåredal, Telmo Santos, Vanja Plicanic Samuelsson, Dr. Buon Kiong Lau, Dr. Andrés Alayon Glazunov, Dr. Peter Almers, Gunnar Eriksson and more, for help and many discussions from which I have gained a lot.

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Finally, I am also eternally grateful for the support and patience of my family - my wife Katarina, and our two boys Oskar and William.

Fredrik Harrysson

List of Acronyms and Abbreviations

3GPP 3rd generation partnership project

BS base station

COST cooperation européenne dans le domaine de la recherche scientifique et technique

D2D direction-to-direction

DCM directional channel model

DDPC double-directional propagation channel

DOA direction-of-arrival

DOD direction-of-departure

EMCAD electromagnetic computer aided design

FDTD finite difference time domain

GO geometrical optics

GTD geometrical theory of diffraction

IMT international mobile telecommunications

ITU international telecommunication union

LOS line-of-sight

MIMO multiple-input multiple-output

MPC multi-path component

MRC maximal-ratio combining

MS mobile station

OFDM orthogonal frequency division multiplexing

P2D point-to-direction

P2P point-to-point

RF radio frequency

RX receiver

SAGE space alternating generalized expectation maximization

SCM spatial channel model

SISO single-input single-output

SM spatial multiplexing

SNR signal-to-noise ratio

SVM spherical vector modes

TX transmitter

UE user equipment

UTD uniform theory of diffraction

VNA vector network analyzer

WINNER wireless world initiative new radio

WLAN wireless local area network

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I Thesis Introduction 1

Part I

Thesis Introduction

Chapter 1

Background

Electromagnetic wave propagation is, of course, the most essential property of most radio and microwave systems for, e.g., wireless communication, radar, radio astronomy etc. Thanks to the 19th century physicists and experimentalists like James Clerk Maxwell, Heinrich Rudolf Hertz, Nikola Tesla, Guiglielmo Marconi and Stepanovich Popov *et al.*, we know in principle how radio waves propagate, how they are generated, how to transmit and receive them, and how to utilize them to signal information. Later, in the 20th century, thanks to information, communication and signal processing scientists like Claude Shannon *et al.*, we learned how to communicate using digital communication and coding techniques also over a channel with large receiver noise and/or interference.

However, radio waves would be completely useless for transferring information without the antennas to radiate and receive the energy they carry. In some situations we need only one antenna, e.g., ín a microwave oven we only need one radiating antenna to heat the food by absorbed radio waves, and in radio astronomy we only need one receiving antenna to identify the emitted radio waves from distant astronomical objects. However, in a wireless communication systems we always need at least two antennas that are separated in space, one at the transmitter and one at the receiver side (at each line end).

An antenna may be used for both transmitting and receiving signals, e.g., as in most radar applications. It is often assumed that the antenna is a linear passive component that contain isotropic materials, making it by default *reciprocal.* This means that the characteristics of the antenna is independent of the direction of propagation, i.e., whether it is transmitting or receiving. Thus, for simplicity, it is common practice for antenna engineers to always refer to an antenna as a transmitting unit. If nothing else is stated, this is also the practice in this thesis.

The main property of the antenna is to provide efficient transition of radio waves from a transmission line into open-space propagation or vice versa. This quality is quantified by the *radiation efficiency*[1]. The second but equally important property of the antenna, and perhaps the property that to most radio engineers actually define the antenna, is that it radiates or receives radio waves with some distribution in direction (and polarization). The latter is referred to as the *antenna* or *radiation pattern*[2] and is often considered in the *far-field region*[3].

Between the two antennas we have the (wireless) *propagation channel*, referring to the propagating radio waves, generated at the transmitter (TX) side antenna and impinging towards the receiver (RX) antenna. The simplest form of a wireless propagation channel is the line-of-sight (LOS) channel where a radio wave propagate in free space (often assumed to be vacuum), expanding spherically, from the TX to the RX antenna. A more complicated situation occurs if the radio waves are obstructed by an object causing *shadow fading* or find several paths through a complex environment with a variety of several scattering obstacles. The latter case is called a *multi-path* channel and the components of the channel that constitutes the multiply propagated wave-fronts is referred to as the multi-path components (MPCs). Temporal constructive and destructive addition of such complex MPCs (the phase depend on the path length) give rise to fast fading or *small-scale fading* while the much slower shadow fading is termed slow fading or *large-scale fading.*

The TX and RX antennas together with the propagation channel form the *radio channel.* By incorporating up/down-converting of frequency to baseband, modulation/demodulation, coding and detection, etc., we get the *information-theoretic channel.* However, in this thesis we mainly deal with the radio channel and use information theoretic entities like the *channel capacity* only for evaluation of potential system performances. The channel is considered by time-harmonic field propagation (i.e., we neglect time transient effects) and is thus characterized by the analog complex vector properties amplitude, phase and polarization. We also refer to a few different types of channels depending on if there is movement in the channel or not. In a *static radio channel* the antennas and all obstacles in the propagation channel is completely still relative to each other, while in a *dynamic radio channel* one of or both the antennas are moving

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[1] “The ratio of the total power radiated by an antenna to the net power accepted by the antenna from the connected transmitter.” [23]

[2] “The spatial distribution of a quantity that characterizes the electromagnetic field generated by an antenna.” [23]

[3] “That region of the field of an antenna where the angular field distribution is essentially independent of the distance from a specified point in the antenna region.” [23]

relative the environment, or the environment is changing with time.

There is a variety of methods to model the radio channel for wireless communications, and the appropriate choice depend on the situation. Simple statistical fading models like the Rayleigh and Rice distributions for single antenna or single-input single-output (SISO) channels and the correlation-based models like the Kronecker model for multiple antenna or multiple-input multiple-output (MIMO) systems, are very popular due to the simplicity and speed when it comes to system simulations. Nevertheless, for evaluation of specific antenna arrangements we need physical channel models that describe the directional domain, e.g., such as the COST 259 directional channel model (DCM) [35, 8] and the 3GPP SCM [1] that combine a plane-wave multi-path cluster model for the propagation channel with the possibility to insert antenna patterns for test antennas of interest. These models use the classical assumption that a far-field antenna pattern can readily be combined with a directional multi-path propagation channel characterized by its plane-wave spectrum. Such an assumption rely on that all obstacles in the propagation channel can be considered to be in the far-field region of the antennas. But what if this is not true? A mobile phone in the hand of a user that sits at the office desk indoor with the base station (BS) at the roof-top of a house a few blocks away in a dense urban environment should be a quite common scenario in todays cellular networks.

When people talk about “antennas” in mobile devices, such as mobile phones or a lap-top computers, they often referto the little piece of dielectric material in combination with some bent metal piece, a PIFA (planar inverted F-antenna) or a DRA (dielectric resonator antenna) etc., positioned at the edge of a ground plane inside the device, e.g., as in [56]. In fact, this little piece is only part of the antenna, serving as a feed and matching unit. The antenna, as characterized by its far-field, is really the whole structure since currents may flow all over the ground plane[4].

In the case of a mobile phone, the user hand and body absorb radiated energy and the fingers induce mismatch as they may touch very close to the antenna elements. In fact, we can just as well call the whole body the antenna, a *super-antenna.*The question is: “What is the antenna part and what is the propagation part of the channel?”. This question is exactly the question we would like to stress in this thesis and to some extent discuss based on some prior results and some recent research. Especially, we concentrate on the MIMO case were we study multiple antenna terminals in, what we consider, *realistic scenarios.*

We also propose a practical approach to channel modeling in, particularly, mobile communication systems by an assumption that the channel can be di-

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[4] Which, to be precise, is not really a ground plane since it is not necessarily connected to a ground. Instead this is sometimes referred to as a *counterpoise.*

vided into separate parts or regions that can be treated and modeled individually. In short the idea is that the antenna part can be the part considered in design of the user equipment (UE) and can be characterized by single measurements, while the propagation channel can be characterized by, e.g., measurements with open areas around the BS and mobile station (MS) positions. The intermediate regions would encounter the *scattering environments* to the BS and MS, e.g., obstructing building structures, the office desk or a vehicle. Such a model approach is here termed a *composite channel approach*.

The subsequent chapters of Part I are organized as follows; Chapter 2 contains an overview of multiple antenna techniques, Chapter 3 give the background to physical channel modeling and the multi-path propagation channel, Chapter 5 present a composite channel approach, and Chapter 6 wrap up Part I with brief presentations of the included papers and some general conclusions. Part II of the thesis contain the included papers.

Chapter 2

Multiple Antenna Techniques

Multiple element antennas, or antenna arrays, were originally used in, e.g., mobile communication systems at the base station side, providing mainly an efficient and flexible design process where the antennas can be configured with respect to gain, beam-width, and electrical tilt. However, in this sense an array antenna is still a single antenna function with only one feed/receive port.

With the use of multiple antennas with a multiple amount of individually accessible feed/receive ports, system capacity can be improved in fading multi-path channels by the use of spatial *diversity* techniques, adaptive *beam-forming*, and *spatial multiplexing* [5]. The latter is often the beneficial characteristic that is referred to by using the term MIMO but is more specific since the term MIMO could account for any system or channel with multiple ports at both ends of the link. In fact all these techniques can be considered as beam-forming if one accept a generalization of the term *beam* to be any array antenna pattern dual (by a Fourier-transform) to a complex antenna element weight vector. Spatial, directional and/or polarization diversity is simple single-sided TX or RX beam-forming, with selection combining by binary weights, equal gain combining by phase-only weights, and maximal-ratio combining (MRC) by complex weights. In the same manner, certain forms of spatial multiplexing (SM) can be considered as just superimposed multiple layer joint TX and RX beam-forming, ideally by using the complex MIMO channel singular vectors found from singular value decomposition. This more physical point-of-view is very appealing to us antenna and propagation engineers with experience in array antenna technology.

2.1 Diversity

In a multi-path radio channel the signal at the RX is composed of individually attenuated and phase-shifted replicas of the transmitted signal, arriving from different directions. The replicas may add up in a constructive or a destructive manner, giving rise to fluctuations in the received signal, i.e., *fading.* Fading may cause severe instantaneous dips in the signal-to-noise ratio (SNR) at the receiver that reduce the information throughput of the system. However, due to the statistical nature of a mobile channel, we can utilize the fact that the probability that the SNR is bad at more than one signal ports at the same time is very low. This technique to combat fading is termed *diversity.*

Diversity can be applied on a number of domains; e.g., the frequency domain as in frequency-hopping and coded orthogonal frequency division multiplexing (OFDM), or the time domain as in repetitive coding. In this context we focus on multiple antenna techniques that utilize the spatial and polarization domains of the radio channel. Several identical antennas can be spread out in space so that the fading at each antenna position is independent, or the antennas may have orthogonal radiation patterns or polarization providing diversity. A spatial diversity system can consist of a sensor system that; with some interval detect and switch to the best antenna (selection diversity), or at a drop below a certain threshold switch antenna by some predefined pattern (switch diversity). An even more sophisticated spatial diversity system combines the antenna signals with appropriate phase weights (equal gain combining) or, optimally, with amplitude and phase weights (maximal ratio combining) to maximize the signal strength. An early overview and analysis of space diversity methods can be found in [12].

With channel state information at the TX, all these diversity techniques can be utilized in the same way also at the transmitter side providing dual-side diversity.

2.2 Adaptive Beam-forming

With *adaptive beam-forming* we address the case of accessible multiple antenna array feeds or receive ports that can be individually weighted with respect to amplitude and phase. The benefit of such arrays is often quantified by the *array gain* which is the amplification of the signal arriving or departing from/in a certain direction due to coherent (in-phase) combination over the array elements which increase the channel SNR [6]. In a general sense, considering a beam as just any spatial filter or radiation pattern corresponding to the element weights of an array antenna, the diversity technique “maximal ratio combining" is a beam-forming technique where the beam is chosen to compensate for the phase-shifts in the arriving waves. Also the other previously mentioned diversity techniques are in a general sense beam-forming, e.g., selection diversity that correspond to a weight vector with a single one and all other zero, and equal gain combining that is the same as phase-only beam-forming. Beam-forming at the transmitter and receiver is in principle the same thing, but with the important distinction that at the transmitter it determines the directions of the radiated power.

2.3 Spatial Multiplexing

The capacity of a communication link is proportional to the logarithm of the SNR. However, if the transmitted power is allocated to several parallel channels, the SNR on each channel branch will decrease as the logarithm of the number of branches, but the total over all branches will increase linearly with the number of branches. This technique to utilize the available SNR in the channel in an optimum way by using multiple parallel channels is often referred to as MIMO and the great benefits regarding channel capacity was originally shown for Gaussian channels in [52, 19, 47].

The MIMO technique can also be explored in a wireless communication system with multiple antennas at both end of the link. In this case the transmitted radio signals are not in general separated by transmission lines or in space, but may be subject to multi-path propagation through complex environments. Nevertheless, by using the spatial filtering property of antenna arrays together with the concept of super-position, it is possible to find multiple channel branches in such an environment, and the MIMO capacity can be explored. This technique is termed spatial multiplexing (SM).

Chapter 3

Wireless Channel Modeling

A channel model is a function that maps the signal from the TX to the RX in a sufficiently accurate way compared to a true channel. This function may be a stochastic process, a deterministic function or even a set of empirical or directly measured data.

The two main applications of a channel model are for wireless system simulations and for optimization of a specific wireless network. In system simulations location independent stochastic or semi-stochastic models are preferred since the simulations aim at optimizing systems performance in general, while location dependent, site-specific, or empirical models, are required for network planning and deployments. Channel models is also divided into narrowband or wideband models, stationary or non-stationary models, directional models (or not), and single or multiple antenna models [34]. Comprehensive overviews of MIMO channel models can be found in [4, 51].

3.1 Physical Channel Modeling

Depending on the complexity of the channel model, a certain amount of detail in channel phenomena are considered, such as time and space clustering, Doppler, etc. Models that encounter such physical properties is called physical channel models since they may capture the specific propagation phenomena of a certain site-specific or typical environment.

Furthermore, for evaluation of antenna properties in general and for antenna arrays in particular, directional propagation models are essential since the great benefit of multiple antennas is just the ability to exploit the spatial domain.

3.1.1 Deterministic Propagation Models

The most detailed class of physical channel models are the electro-magnetic full-wave models with comprehensive geometrical and material descriptions of the antennas, and the scattering and propagation environments. Such a model is a deterministic model for site-specific evaluations that uses a specific geometrical description of the environment. The propagation part may be a handled by, e.g., high-frequency approximation methods such as ray-tracing [50] and ray-launching [30] techniques utilizing the laws of geometrical optics (GO) and diffraction techniques such as the geometrical theory of diffraction (GTD) [25] and the uniform theory of diffraction (UTD) [26, 31]. The UTD method for dielectric wedges has been shown to be able to accurately model real building corner diffraction [7], rough edges [15], and combined with GO it is found in Paper I to be able to also quite accurately predict the path-loss in an urban environment nearby the BS.

3.1.2 Empirical Propagation Models

Another type of physical channel model is models based on measurement records. These models are truly site-specific, but an ensemble of such measurements may be used to extract typical channel parameters that can be used in cell-planning tools (e.g., the popular Okumura-Hata model [22]) or in semi-stochastic models such as the COST 273 DCM or the 3GPP SCM.

In contrast to the full-wave models that include all the interaction of a propagating wave traveling from the TX to the RX, the directional empirical model only account for what is seen from the TX and the RX antennas, respectively. To capture the directional properties the propagation measurements has to be; i) measured with rotating highly directional probe antennas, or ii) measured with array antennas and omni-directional elements or, if the channel is static, with positioning robots. In the latter case the directional properties of the channel is extracted by signal post-processing.

3.2 The Double-Directional Propagation Channel

For multiple-antenna (i.e., MIMO) antenna performance evaluations, the full double-directional propagation channel (DDPC) model [44] is a necessary tool, even if alternative simplified models utilizing the Kronecker model have been proposed [43]. The DDPC model describes the channel by a finite number of MPCs, originating at the TX and terminating at the RX, see Fig. 3.1.

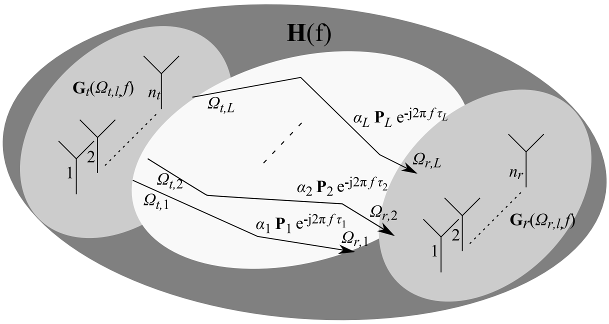

Figure 3.1: Illustration of the double-directional propagation channel with transmit and receive antenna arrays.

Even though the MPCs represent the radio waves propagating through the environment, subject to reflection, scattering, and diffraction; the DDPC does not (and need not) include the information about these interactions. Only the direction-of-departure (DOD) and the corresponding direction-of-arrival (DOA), the delay, the complex amplitude and the polarization of each MPC are considered.

3.3 The MIMO Channel

With multiple antennas at both ends of a link, another possible channel representation is a matrix that includes properties like the correlation between antenna elements and the possibility to resolve more or less degenerated parallel channels for spatial multiplexing. With a phase-coherent directional channel representation like a full-wave solution or the DDPC all the requirements to produce these properties are fulfilled and can be found from the channel transfer matrix once combined with the TX and RX antenna arrays. Since many full wave propagation solutions as well as many measured MIMO channels, can approximately be represented by a DDPC model, we can write the frequency-domain multi-path MIMO channel transfer matrix as

$$\mathbf{H}(f) = \sum_{l=1}^{L} \alpha_l \mathbf{G}_r^T(\Omega_{r,l}, f)\mathbf{P}_l \mathbf{G}_t(\Omega_{t,l}, f) e^{-j2\pi f \tau_l}, \tag{3.1}$$

whose elements $H_{ij}(f)$ describe the transfer function from the j-th transmit to the i-th receive antenna element. The expression (3.1) includes a sum over the L MPCs, with the TX and RX antenna far-field matrices in $\mathbf{G}_t$ and $\mathbf{G}_r$

and the polarimetric transfer matrix $\mathbf{P}_l$. Here $\mathbf{G}_t$ and $\mathbf{G}_r$ have to contain the array location vector phase term for each element in the columns, and for the polarization component (θ, ϕ) in the rows, i.e., $2 \times n_{r,t}$.

The MPCs in (3.1) are independent of the Tx and Rx antennas, and the l-th one has the following DDPC parameters:

α_l amplitude and phase

$\Omega_{t,l}$ direction of departure (DOD)

$\Omega_{r,l}$ direction of arrival (DOA)

τ_l path excess delay

and the polarimetric transfer matrix can be written as

$$\mathbf{P}_l = \begin{bmatrix} P_{\theta,\theta} & P_{\theta,\phi} \\ P_{\phi,\theta} & P_{\phi,\phi} \end{bmatrix}$$

which is normalized in relation to the complex amplitude α_l, e.g., to have unit Frobenius norm. In the DDPC model the frequency dependency is taken into account only in the phase factors representing the plane-wave path distances $e^{-j2\pi f \tau_l}$.

The expression in (3.1) seems general since it combines any antenna array with a directional channel model. However, the model in (3.1) assumes that the arriving signal[1] can be represented by a finite spectrum of plane waves. This is only true if we consider interacting obstacle (scatterers) at large enough distance from the RX antennas, i.e., if the obstacles is in the far-field of the antennas.

3.4 MIMO Channel Measurements

Channel models usually depend on measurements in some way, or “any channel model is based on channel measurement data” [34]. Even the most simple statistic channel model with only a few model parameters needs input or verification from measured scenarios to be valid. Different measurement setups (disregarding the vast amount of possible measurements scenarios) are used depending on the parameters to be investigated, from the simplest non-coherent narrowband setups for path loss and fading statistics measurements, to complex wideband systems with multiple array antennas for delay and direction estimation, or even with multiple radio chains for direct fast time-variant MIMO channel measurements.

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[1] The same apply at the transmitter side.

In the work presented in the included papers, we have used two different setups: a non-coherent SISO RF transmitter and receiving vector network analyzer (VNA) setup to measure path loss and verify a ray-tracing model (Paper I and II), a coherent narrowband VNA setup for direct 2×2-MIMO channel measurements (Paper III), and a wideband VNA setup with virtual arrays for 8×4-MIMO measurements and DDPC parameter estimation (Paper IV). In up-coming dynamic channel measurements we will use a wideband MIMO channel sounder called RUSK Lund that is also described briefly.

3.4.1 Vector Network Analyzer Methods

A VNA is commonly used in different channel measurement setups, mainly since it is available in many radio labs and, hence, inexpensive and easily accessible. The VNA is a versatile equipment with many possibilities and features that may be utilized depending on the scenario and channel characteristics of interest. In the narrowband measurements described in Paper I and II, a separate single frequency or continuous wave (CW) transmitter is used at the mobile end, with the VNA connected to the RX antenna at the fix end, and used only as a non-coherent receiver or power meter swept over time. In Paper III the VNA is set up for coherent narrowband reception of two simultaneous channels (but with no phase reference between TX and RX) where the frequency is swept very fast compared to the movement in the channel and registered over time by a computer, while in Paper IV the VNA is used together with virtual array antennas for truly coherent wideband swept frequency-domain measurements in a static channel scenario. Appealing features of VNAs in channel measurements are that they are (i) accurate, (ii) easily adjustable with respect to frequency, output power, IF bandwidth etc., (iii) and simple to use. However, especially in wideband measurements with virtual arrays antennas for direction estimation, the disadvantages are (i) low measurement speed that require static channels, (ii) phase reference between TX and RX limit the measurement distance due to the requirement of a long cable or a separate steady radio link. The measurement system described in Paper IV utilize a long optic fiber in combination with RF-opto converters.

3.4.2 RUSK Lund MIMO Channel Sounder

For dynamic time-variant MIMO channel measurements where the channel changes rapidly compared to the sweep time of a VNA, a fast wideband measurement system is needed. Such a system is the RUSK Lund channel sounder that uses multi-tone frequency domain correlation processing [48] similar to OFDM. This system provides a very fast measurement system that, when combined with fast radio frequency (RF) switches and large antenna arrays, can be used to measure up to 32 × 32 MIMO channels with a bandwidth of 240 MHz (in the 2.2-2.7 GHz band), a sampling rate of 640 MHz, and an impulse response sample interval of $T_s = 1.6$ ns. Thus, a full MIMO snapshot, with an extra T_s cycle to avoid switching transients, take $2T_s n_T n_R \approx 3.3\mu$s in which the channel must be essentially invariant. It is then possible to do DDPC estimation for each snapshot. This system will be used in future campaigns for dynamic channel evaluations.

3.5 Channel Parameter Estimation

The parameters of the DDPC model can be found by a double-directional channel parameter estimation algorithm applied on channel sounder data. There exist several such algorithms that basically resolve the coupled double-sided plane-wave spectrum utilizing the log-likelihood function of the superimposed joint signals at the transmitter and receiver. In Paper IV and in [21] we have used such an algorithm that successively finds joint plane-wave components (MPCs) by maximizing the likelihood function. The algorithm is described in [33] and is based on the famous space alternating generalized expectation maximization (SAGE) algorithm, first presented in [17] and later applied to channel parameter estimation by Fleury *et al.* [18].The SAGE method extracts the MPCs one by one and repeats the procedure until a certain threshold is reached. The main difference between the method used in Paper IV and SAGE is the improved convergence regarding correlated groups of sources in the measured channel data. This improved method is similar to the RIMAX method [41], but uses a more rigorous formulation of the likelihood problem and has been found to give very good convergence and accuracy as is found in [21] and Paper IV.

Chapter 4

Antenna Scattering Environment

In many practical wireless communication scenarios the antenna is surrounded by more or less close objects that interact with the antenna in different ways. Not only the shape, size and material of the interacting objects affect the antenna performance; also the distance to the antenna is of great importance. A very close object may affect the antenna radiation impedance match, while objects at a somewhat larger distance mainly cause absorption and scattering of radiated energy.

4.1 Field Regions of the Antenna

It is common to divide the space surrounding the antenna into three different regions; the *reactive near-field*, the *radiating near-field*, and the *far-field* regions, see Fig. 4.1.

In IEEE Standard Definition of Terms for Antennas [23] the reactive near-field region is defined as "that portion of the near-field region immediately surrounding the antenna, wherein the reactive field predominates", and the radiating near-field region is defined as "that portion of the near-field region, wherein the angular field distribution is dependent upon the distance from the antenna, while the far-field region of an antenna is defined as “that region of the field of an antenna where the angular field distribution is essentially independent of the distance from a specified point in the antenna region”.

The boundaries of these regions are not distinct, but from a practical point-of-view the outer boundary (as seen from the center of the antenna) of the reac-

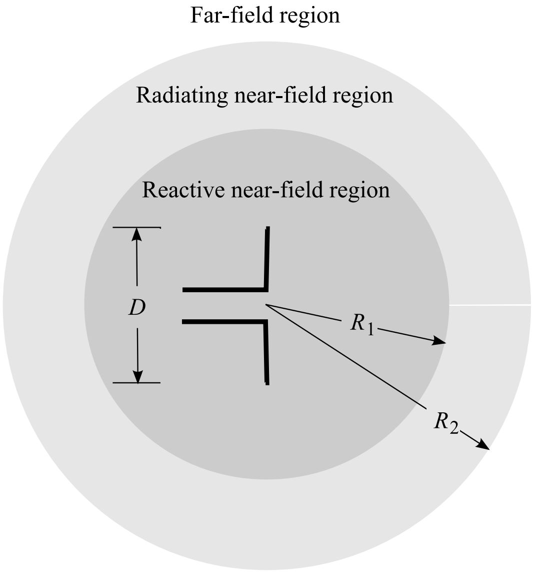

Figure 4.1: Field regions of an antenna [9].

tive near-field region is the region surrounding the antenna wherein interfering obstacles affect the radiation impedance of the antenna, and the far-field region is the region where the antenna can be regarded as a (directive) point source. The boundaries of the regions is commonly assumed to be $R_1 < 0.62\sqrt{D^3/\lambda}$ and $R_2 < 2D^2/\lambda$, respectively, where D is the largest dimension of the antenna and λ is the wavelength, with the requirement that D is large compared to λ. For small antennas where $D \ll \lambda$ the radiation near-field region decreases and the outer boundary of the reactive near-field region "is commonly taken to exist at a distance $\lambda/2\pi$ from the antenna surface".

4.2 Installed Base Station Antenna

In the case of a BS antenna, the placement is in general chosen so that interaction with scattering objects is avoided. However, there might be situations in dense urban environments or indoor placements where it is impossible, unpractical or non-affordable to avoid interference from high-rise buildings or obstacles on the roof-tops; influence from wall-mounting or other indoor obstacles.

For simple geometric objects and buildings found in the far-field of the antennas where a geometric model is available, methods like UTD is accurate and effective for prediction as is shown in Paper I. In the case of large array antennas common in BS implementations and objects within the nearfield, the method can be utilized by coherent superposition of solutions for each array element. In more complicated situations we may need electromagnetic computer aided design (EMCAD) such as finite difference time domain (FDTD) tools, at the price of extensive computing power and time.

If the aim is to evaluate performance of installed single or multiple element antenna arrays in typical realistic BS environments, e.g., with respect to antenna separation for MIMO performance as in [53] but with obstructive structures in the close vicinity of the antenna, a statistical approach is needed. The statistical basis for such an approach can hardly be found by measurements since it would require extensive measurement campaigns to get statistical confidence. A more realistic approach is to evaluate test antennas in a number of measured channels with a number of typical interactions imposed by a reasonable realistic scattering model.

4.3 Human Interaction

The human operator of a hand-held mobile device is a typical unavoidable near-field interaction problem of MS antennas. Different part of the body interact with the antennas in different ways; the hand and the fingers are usually placed very close above the antenna feed structure and even the head when the device is operated in talk position. The presence of the hand may cause severe degradation of the radiation performance due to both impedance mismatch (reflection) and absorption, while the body in general mainly cause shadowing. These effects has been investigated by many, e.g., by Toftgård *et al.* [49], Pedersen *et al.* [39], Nielsen *et al.* [37], and Alexiou *et al.* [3]. Within this thesis the impact on multiple antenna system performance measures such as correlation and diversity is investigated in Paper III and Paper IV. The indoor diversity measurements with human interaction in Paper III is similar to the investigation by Bolin *et al.* [10].

When modeling the user influence in a cellular system, different approaches are possible. Simplified geometrical models of the user body, e.g., by an absorbing infinitely long vertical plane or cylinder as in [32], can mimic directional effects when the body can be considered being in the far-field of the antenna. However, in cases including the user hand or when the antenna is very close to the head or body, the problem becomes more difficult to simplify and must possibly be treated in a statistical manner, where the expected value, the distribution and the correlation of the radiation efficiency is estimated. These statistics can be gathered by the use of antenna measurements with a real human hand or with a realistic hand phantom [16] or, alternatively, by EMCAD simulations as in [24, 11], and can also be extended into statistical human grip studies as in [40].

4.3.1 User Phantom

To perform measurements of the impact of a human body in a mobile radio channel, regardless of whether we target the impact of the operator (user) or by-passing interfering people, either we need live test persons or we can use a phantom. A large and representative amount of live human operators naturally give the most trustworthy results in an evaluation of equipment or a system. For evaluation of a method where we need high accuracy regarding repeatability, however, a model of some kind, or a *user phantom*, may be a better choice.

The body phantom has historically been basically anything that resembles a human operator with reasonably similar electro-magnetic characteristics (permittivity and conductivity) [20], e.g., simple dielectric cylinder or sphere (massive or liquid filled with a sugar-salt-water mixture) [3], etc.

However, nowadays in the case of SAR (Specific Absorption Ratio) measurements where the field strength and radiated power absorption inside the user head is tested very accurately and consumer products are certified with respect to human exposure, the quality of the phantom is very important. Both the phantom properties and the test procedures are restricted by standards from the IEEE, FCC, CENELEC, ICNIRP etc. Manufacturers are, e.g., required to use the SAM (Specific Anthropomorphic Mannequin) head phantom for conformance tests, e.g., as in [27]. SAM is based on the 90th percentile of a survey of American male military service personnel and represents a large male head. Standard phantoms are being developed also to encounter the hand, and recent publications present very sophisticated and detailed EMCAD hand models [29] and sophisticated user phantoms including head and hand are recently being used also in channel measurements [36, 54]. Also multiple antenna terminal performance and channel simulations with simplified yet full body+head+arm+hand EMCAD models was recently reported [38]. Furthermore, in-channel performance evaluations by measurements of a generic versus a realistic phantom in browse mode [55] shows that a realistic phantom actually are important for accurate channel performance investigations.

In our investigations of user influence described in [21] and in Paper IV, we used an upper body full scale user phantom including head, torso, right arm and hand, see Fig. 4.2. The head/torso part are made up by a 60 cm high glass-fiber shell filled with tissue simulant liquid made by a mixture of 45% DGBE and 55% distilled water to be in compliance with the recommendations

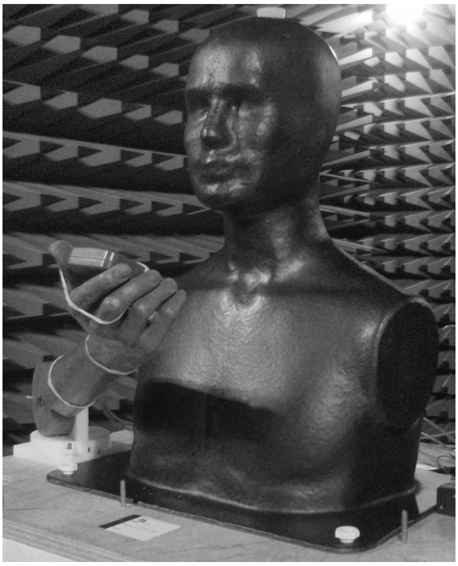

Figure 4.2: User phantom in browse mode.

of the IEEE Std. 1528 for 2.6 GHz, with a relative permittivity $\epsilon_r = 39.7$ and conductivity $\sigma = 2.14$. The hand/arm part are a massive full-scale right hand model from IndexSAR with the arm extension tailor-made.

The body and arm parts are mounted on a plywood board; the arm via a plastic joint providing the possibility to orient the hand and handset to different operation positions. This joint were in our investigations fixed to two positions, one talk mode and one browse mode position.

4.4 Confined Scattering Environments

If the human body from a modeling perspective is considered as a scatterer that obstruct a fraction of the directional space as seen from the antenna, a *confined* scattering environment, on the other hand, is the situation where the radiation as seen from the antenna is mainly obstructed in the directional domain. A confined scattering environment is, e.g., a vehicle or an office room where the user equipment with the antenna(s) is placed inside.

Such an environment may change the channel properties from the outside to the inside severely, depending on the openings (amount and sizes), the reflectivity and penetration loss of the walls, and the scattering and absorbing objects inside. Questions like; “Where does the radio waves enter the confined volume?”, “Is the scattering due to inside multiple reflections and diffractions increased compared to outside giving rise to Rayleigh fading inside even if we have LOS outside?”, “Or, on the contrary, does the openings, i.e., the windows, in combination with heavy absorption inside, e.g., due to passengers in a car, decrease the richness of the channel?”, “Do we get a keyhole effect still providing diversity performance but no spatial multiplexing gain?”, etc.

These questions are still to be investigated. However, a first measurement of the directional attenuation of a car is found in Paper II. In addition, a simplified high-frequency diffraction model is proposed. The investigation supports this simple model and proposes a mainly directional approach to car modeling, despite the fact that the car is not loaded with passengers. However, since the investigation is made for only two static single antenna positions we can not draw any conclusions about how the statistical distribution of the fading changes when the antenna is moved from the outside to the inside of the car. This is a topic for future research.

Chapter 5

A Composite Channel Approach

For an idealized wireless communication link with antenna arrays in free space at both the TX and RX, connected by a finite number of plane waves, the previously presented MIMO channel model in (3.1) is completely adequate. However, in a mobile communication scenario we may have, e.g., a user interfering with the antennas at the MS side. In this case, is the user body a part of the antenna or of the channel? And what if the user is sitting in a car? These questions lead us into an idea of separating the channel into several layers. Such a layered channel model is here referred to as a *composite channel model.*

5.1 Separation of Channel Regions

In a composite channel a key issue is how and where to divide the channel model. A full-wave propagation prediction tool in combination with a full geometric data base would give all information needed for any channel calculation in a scenario. This is a full channel representation where the channel parts are every interacting object itself. However, even very detailed geometry data may not include enough scattering detail to be realistic. Instead, we often in link simulations rely on measured snap-shots from scenarios we find typical enough, or from the empirical semi-stochastic models.

Thus, in the case were different configurations or realizations of TX or RX antennas are to be tested and the performance in a realistic channel is to be evaluated, we rely on the channel model in (3.1). With the DDPC parameters extracted from measurements or simulations in a “typical” scenario, several test antennas can be evaluated in *identical* environments by their measured or simulated far-field antenna patterns inserted, and therefore avoiding extensive measurement campaigns for each test antenna. Thus, the composite channel separation is simply the separation of the antenna and the multi-path propagation channel at both the TX and RX under the assumption that the scatterers of the channel is in far-field of the antennas. This approach was pioneered by Suvikunnas *et al.*in [45, 46].

Considering, e.g., a cellular system where the mobile phone (MS) is in the vicinity of a user, the channel can be separated either between the phone and the user, i.e., the user is a part of the channel, or the channel can be separated between the user and the propagation channel, i.e., the user is a part of the MS. The first alternative is hardly practical since it would require channel measurements for each configuration of the user body, and the far-field requirement with the MS in a user hand is not fulfilled. The second alternative, with the user being a part of the MS antenna forming a new *super-antenna* is, however, useful and has been shown to produce good statistical agreement in an outdoor-to-indoor and an indoor-to-indoor scenario as shown in [21] and Paper IV. The far-field antenna pattern for the test mobile in combination with a user phantom or a live user can readily be measured in an antenna range.

The technique in the example above do unavoidably require an increased amount of test patterns to be evaluated due to several possible user operation positions or modes (talk mode, browse mode, position of arm, mobile in hand etc.). To avoid this we need a third composite channel interface between the mobile antennas and the user body. Since the hand is very close to the mobile it seems impossible to put the interface there where the far-field assumption definitely does not hold. Furthermore, since the hand on most people connect continuously with their body, there seems to be no natural choice. From experiments it is seen that the hand does indeed induce absorption, loss of radiated or received energy, and may cause antenna mismatch for the handset antennas. However, it does not seem to influence the radiation patter in a predictable way like the body does, as is shown in Paper IV Section 4 Fig. 2. Thus, an interesting approach would be to model the directional properties of the body as a separate forward scattering layer or a directional filter. This idea will be explained in future work.

The same approach as is described for the user body example above may be applicable to other similar possible scattering environments as well. In the case of an antenna inside a car, a simplified directional forward scattering model is proposed in Paper II. The same model would be applicable for other antennas inside vehicle scenarios, such as buses, trains or aircrafts, since they are built up by similar confined metal structures with windows, and possibly also other similar urban scenarios like the outdoor-to-indoor case.

With such an extensible approach to channel modeling, it is possible to evaluate e.g., different test mobile phones in different user scenarios, in a car etc., with the use of only a few "typical" propagation channel scenarios that again are *identical* for all test devices and therefore completely fair.

If the similar approach also apply for non-confined scattering environments, e.g., unavoidable scattering object in the vicinity of a BS antenna array (in a MIMO scenario), the composite channel approach can be extended also to the BS side in a cellular system or to the access point in a wireless local area network (WLAN) system. Thus, the composite channel model may have 5-6 separate layers.

5.2 Representative Models and Interfaces

With a composite channel model with several physical regions, there is a need for defining the interfaces and choosing the appropriate channel representation in each region. A model that describe the signal transition from a position in space to another can be referred to as a point-to-point (P2P) model. However, within the channel regions the signal transition will be represented by point-to-direction (P2D) and direction-to-direction (D2D) models.

5.2.1 Antenna Region

In general there are many ways to define and characterize an antenna. In channel modeling we normally put the interface between the antenna region and the propagation region at a radius from the center of the antenna excitation port, i.e., the point where the transition between transmission line and open-space propagation occur. The corresponding region circumventing all the structures that is fix to the antenna (or to the excitation port) is inserted into the channel as one unit, which may be referred to as the actual antenna itself, or alternatively as a *super-antenna*. This means that the antenna region include, e.g., the mobile phone with casing in a cellular system, or a lap-top computer in a WLAN system. If it can be assumed that all surrounding structures outside the antenna region is in the far-field, the antenna can readily be represented by the polarized complex electric far-field found by measurements or theory, i.e., by a P2D model.

In turn, the far-field may also be stored and handled in different ways. There are different pros and cons for the choice of model:

Closed-form expression is of course the most convenient model for simulations but are only available for simple structures like idealized dipoles etc.

Sampled field data is normally what would come out of antenna range measurements or EMCAD tools. A disadvantage is the discrete frequency and angular samples which require interpolation to fit with a directional propagation channel.

Spherical vector modes are basis function expansions in a spherical vector coordinate system of measured or simulated data [2]. Once the expansion is made in combination with the measurements or the EMCAD simulations and the mode truncation is done with respect to the accuracy of the representation, the file format becomes compact since only the complex basis function weights are stored. Avoiding complex interpolation in the angular domain is another advantage. There are other efficient basis functions expansions that apply equally well or even better, but those are not covered here.

For an antenna region radius of a few wavelengths the spherical vector modes (SVM) expansion is a very efficient antenna representation since the number of required modes will be moderate. There is a rule-of-thumb that the maximum longitudinal and azimuthal mode numbers (l, m) has to be larger than approximately 2π times the electrical antenna radius plus 10, i.e.,

$$l_{max} \lesssim kr + 10 = 2\pi \frac{r}{\lambda} + 10 \tag{5.1}$$

Thus the total number of modes required would be

$$n_{modes} = 2(l_{max}^2 + 2 * l_{max}) \tag{5.2}$$

where the first 2 account for the TE plus the TM modes, and $m_{max} = l_{max}$.

This method has been used in Paper IV. However, for a larger antenna radius of many wavelengths the number of modes may become too large to be efficient compared to direct sampled field data. This may also be the case if the antenna radius expand into the scattering region.

5.2.2 Scattering Regions

The scattering regions, at either the TX and RX side of the channel, may be defined as the region outside of the antenna region that include all scattering objects (preferably) in the far-field of the antenna. These objects shall still be extractable regarding the propagating environment, i.e., the user body at the MS or obstacles on a building roof in the vicinity of a roof-mounted BS antenna in a cellular scenario, the office desk environment in an indoor WLAN scenario, or a vehicle in an outdoor scenario, etc.

If we can establish a *forward scattering approximation*, i.e., neglect the fact that the direction of the scattered wave may not be completely opposite to the direction of the incident wave but still catches the important *statistical* properties (correlation, singular value distributions etc.) of a channel, a simple directional filter approach can be adopted. Such a directional filter would be a simple special case of D2D model. The filter function for a certain environment may be composed with the principal of GO combined with UTD, or a simplified model as that proposed for an antenna inside a car in Paper II.

This approach has not yet been tested in a more open environment like an office building or a BS site, but this could be a topic for future investigations. Furthermore, in the MS case, with a user present in a cellular system together with a vehicle or an office desk environment, it might be possible to extend the scattering region into two parts, one for the user and one for the vehicle or similar, using the same directional filter approach. This may also be a topic for future research.

5.2.3 Propagation Region

Finally, the region that is left between the TX and RX is termed the propagation region. This is what would be simulated by ray-tracing and/or ray-launching techniques [13, 14, 30, 42] or measured by a channel sounder with array antennas at both ends, deliberately chosen to be well separated from scatterers, i.e., on the roof of a measurement van, on a trolley in a office or corridor etc., and that can be represented by the DDPC. It is also the D2D part of standard channel models like the COST DCM [35, 8], the 3GPP SCM [1], and the WINNER II model [28], for the rural and urban macro/micro-cell scenarios with the antenna patterns extracted. An overview of present propagation models can be found in [4].

The propagation channel is in general characterized by the DDPC model, i.e., by a limited set of MPCs that represent plane waves or rays. This is a double-sided spectral domain representation that fit an electrically large case well in contrast to the SVMs that fit electrically smaller cases.

Chapter 6

Contributions and Conclusions

This chapter summarizes the main research contributions of the included papers. Some general conclusions regarding the research area are also provided as a separate section.

6.1 Research Contributions

The work has been supervised by Prof. Andreas F. Molisch and Dr. Fredrik Tufvesson. I am the main contributor to the scientific work presented in the included papers, and the contributions of my co-authors are mentioned below each paper. The first and second papers were published prior to the start of the thesis project and did not at the time of writing aim at the context of the thesis.

6.1.1 Paper I: "Propagation Prediction at 2.5 GHz Close to a Roof Mounted Antenna in an Urban Environment"

This conference paper presents the results from a short investigation on how well a simple ray tracing method can predict the outdoor propagation nearby a base station in an urban micro- or macro-cell scenario. The method is based on the high-frequency techniques GO and UTD and in this case only first-order interaction are considered. Even though this investigation was done for a SISO case, it addresses this type of a full-wave coherent amplitude and phase prediction tool that is readily extended to the MIMO case by super-position.

The problem with such tools is often the need for very detailed geographical building databases and the calculation time to perform the ray tracing. In the paper, we test a simplified first-order model only considering the main building surfaces, with good agreement between measured and calculated signal magnitudes. Thus, the results support the idea that simplified geometrical models can be used for physical channel modeling regarding path loss and long-term fading prediction.

I and Dr. Jonas Medbo did the measurements. I also developed the model, performed the analysis, and wrote the manuscript. The work was supervised by Jan-Erik Berg.

6.1.2 Paper II: "A Simple Directional Path Loss Model for a Terminal Inside a Car"

Confined environments such as vehicles or resembling building structures may surround the user in a mobile communication system, affecting the propagation channel as seen from the terminal position. These components in the channel are often neglected and even deliberately avoided in channel measurements. In the last couple of years this topic has attracted an increasing interest since it may have a mayor impact on the spatial and directional properties of the channel, properties that are explored by the MIMO technique. Simple yet general models that account for the effect of such confined environments may be difficult to accomplish regarding both the path loss prediction and the fading statistics.

This conference paper shows an investigation that compares measured directional path loss for a car with calculations based on GO and UTD using one very simple and one more detailed geometrical model of the car. In addition, it proposes a new simple directional path loss model that assume forward scattering, i.e., no reflections, and based on a heuristic diffraction model that account for the local (angular) average power attenuation. At the time of publication, this type of simplified directional model for a car was to the author not known to have been published previously.

The validity of the forward scattering approximation would imply heavy attenuation of radio waves bouncing inside the car, an assumption that would also affect the small-scale fading statistics inside the car. Small-scale fading statistics, however, where not covered within the context of the paper and would be a topic for further research.

I performed the measurements together with Dr. Paul Hallbjörner and trainee Oscar Petersson. I also did the analysis, the simulations and developed the model. The work was supervised by Jan-Erik Berg.

6.1.3 Paper III: "Dual Antenna Terminals in an Indoor Scenario"

This conference paper investigates the performance of dual-antenna test terminals in an indoor scenario including user influence. The paper specifically targets the diversity and MIMO performance impact of (i) the channel correlation and (ii) the user influence, with two different user operation modes. At the time of the writing of the paper, publications that addressed these effects were rare in the literature. Later it has been well established that even high correlation (above 0.7) in a channel may still provide significant diversity gain, a result that is supported by our results. Regarding the operation modes of a user, the data mode or browsing mode where the user hold the mobile phone (or a laptop) in a position as to watch the screen, is perhaps the most interesting scenario nowadays for investigation of user effects on MIMO performance, since it is in this position we expect the highest data transfer rates.

As a feature the paper also investigated the possibility to explore the singular *vectors* of the MIMO channel matrix as a tool to find the antenna weights and, thus, the individual importance or performance of the antennas. This technique was not known to the authors to have been published prior to the writing of this paper.

I together with Henrik Asplund and Mathias Riback performed the measurements. I did the analysis and wrote the manuscript. The work was supervised by Prof. Anders Derneryd.

6.1.4 Paper IV: "Efficient Experimental Evaluation of a MIMO Handset with User Influence"

This paper extends and improves the evaluation of the composite channel method that was first published in the conference paper [21], where the user (hand and body) is considered together with the terminal antennas as one radiating unit (a *super-antenna*). Here, the method is verified for both an outdoor-to-indoor and an indoor-to-indoor scenario, and very good agreement is found between the statistics of the synthetically found channel matrix and direct measurements. The results support the validity of this useful concept for channel modeling with the specific focus to target the important user effects in evaluating realistic MIMO performance of hand-held mobile devices and provide a tool to improve multiple-antenna design on terminals.

Novel contributions of this paper are the validation of the composite channel method with a full phantom user model including *hand, arm, upper torso and head*. We also evaluate the impact of different hand positions and usage positions of the handset, i.e., holding it in the browsing position vs. the standard talk position. Furthermore, we analyze the MIMO capacity as well as the eigenvalue distributions and diversity performance for a realistic four antenna handset mock-up in the presence of a the user phantom.

I wrote the manuscript together with Prof. Andreas F. Molisch, and I did the analysis and modeling, except for the double-directional channel estimation, to which Dr. Jonas Medbo has contributed. I and Dr. Medbo did the measurements and Dr. Anders J. Johansson contributed to the preparations of the user phantom. Prof. Andreas F. Molisch and Dr. Fredrik Tufvesson supervised the work.

6.2 Conclusions and Future Work

Proper physical channel modeling including all parts of realistic yet typical wireless channel properties, such as scattering around and close to the antennas together with the human hand and body interaction, is, indeed, a tricky task. The trade off between complexity and simplicity of a channel model is crucial. Simply, if the channel model is too complicated it will not be used by link or system simulators. Still, for evaluation of a specific single or multiple antenna arrangement, the model has to catch realistic channel characteristics that may strongly affect the benefits of such an arrangement. For example, it is well established that MIMO may provide extensive capacity gain in rich propagation environments, a property that is of course precious in mobile communication systems. However, it is also extremely expensive for manufacturers of mobile phones to extend an existing single antenna mobile platform to one with multiple antennas and multiple radio chains. Therefore, the possibility to evaluate the performance of such specific multiple antenna arrangements in truly reliable *realistic* scenarios, including the human hand and body, is something that may save tremendous efforts and money.

A first step in this direction is to verify the validity of link simulations were the mobile phone antennas together with the user can be handled as a *super-antenna* with its aggregate far-field pattern to be combined with a directional channel model in a standard way. This is presented in Paper IV and the method is in its extensible form referred to as the Composite Channel Method. It is found that this method, as we expected, work well for statistical performance evaluation of diversity or SM.

The next step would, in the spirit of maximal simplicity, be to find a simple yet accurate directional scattering model for the user hand and body that still catch the proper influence of antenna efficiencies, fading statistics and correlation. Such an approach is presented in Paper II for a single antenna inside a car, but this study still lacks the fading statistics inside the car. A proper evaluation of such models with the extension to confined environments such as a vehicle is research to be continued.

This lead us into complexity of a scattering or a channel part D2D models. A ray-tracing model as the one presented in Paper II can capture all important effects of a propagation environment to the price of high complexity of the geometrical model, i.e., many input parameters. However, not only can such ray-tracing tools be used to evaluate a specific geometry, e.g., to solve a problem in a certain installation based on a more general network planning tool; it also serve as a tool to understand the physical propagation properties and to verify a more generic simplified model. A candidate tool worthy of the composite channel approach could be a cluster-based semi-physical directional D2D model, but this is also a possible research topic for the future.

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