TKK Radio Science and Engineering Publications

Espoo, April 2010 **REPORT R 12**

PROPAGATION CHANNEL MEASUREMENT SYSTEM DEVELOPMENT AND CHANNEL CHARACTERIZATION AT 5.3 GHz

Thesis for the degree of Doctor of Science in Technology

Veli-Matti Kolmonen

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Electronics, Communications and Automation, for public examination and debate in Auditorium S1 at the Aalto University School of Science and Technology (Espoo, Finland) on the 28th of April, 2010, at 12 noon

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ISBN 978-952-60-3052-4 (paper)
ISBN 978-952-60-3053-1 (electronic)
ISSN 1797-4364 (paper)
ISSN 1797-8467 (electronic)

ABSTRACT OF DOCTORAL DISSERTATION	AALTO UNIVERSITY SCHOOL OF SCIENCE AND TECHNOLOGY P. O. BOX 13000, FI-00076 Aalto, Finland

Author Veli-Matti Kolmonen

Name of the dissertation

Propagation Channel Measurement System Development and Channel Characterization at 5.3 GHz

Manuscript submitted 27.11.2009	Date of the defence 28.4.2010
☐ Monograph	☒ Article dissertation (summary + original articles)

Faculty	Faculty of Electronics, Communications and Automation
Department	Radio Science and Engineering
Field of research	Radio engineering
Opponent(s)	Prof. Matti Latva-aho (University of Oulu) and Dr. Kimmo Kalliola (Nokia Research Center)
Supervisor	Prof. Pertti Vainikainen
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Abstract

The wireless access has proven its usability for reliable communication and data conveying link for a long time. The ever growing usage of wireless communications systems has been driving the research to study even faster and more interference tolerant wireless solutions. A key concept towards achieving these goals are the detailed analysis and modeling of the propagation channel. In both of these aspects the availability of reliable measurement data is a prerequisite. This thesis concentrates on contributing to the measurement system development in single- and dual-link cases as well as measurement data analysis for specific wireless systems.

In the first part of the thesis the physical radiowave propagation phenomena are briefly related to the challenges of the modern wireless communication systems. Through the analysis of the propagation channel conducted earlier in the literature, the main phenomena for modeling the propagation channel are illustrated, and the current modeling approaches are described. The hardware related design challenges are described along with the recent achievements in the measurement system development. Specifically, the design of antenna arrays for estimation of the parameters of the double directional channel model is illustrated.

A measurement system developed for characterizing the double directional channel in the 5.3 GHz frequency range is presented along with the evaluation of the accuracy of the measurment system for the spatial characterization. The developed measurement system is further extended to enable simultaneous, double directional dual-link propagation channel measurements, and the first directional results from a measurement campaign are presented.

In the second part, the important feature of the spatial dimensionality of the propagation channel is considered through measurement data acquired using the developed measurement system. The basics of the single- and dual-link MIMO communications systems and cooperative communications are presented. The analysis of the spatial domain used in MIMO communications systems is extended to multiuser scenario. Furthermore, cooperative communications system is analyzed.

Keywords radiowave propagation, propagation channel, MIMO

ISBN (printed) 978-952-60-3052-4	ISSN (printed) 1797-4364
ISBN (pdf) 978-952-60-3053-1	ISSN (pdf) 1797-8467
Language English	Number of pages 58 + appendix

Publisher Aalto University, Department of Radio Science and Engineering

Print distribution Aalto University, Department of Radio Science and Engineering

☒ The dissertation can be read at http://lib.tkk.fi/Diss/

VÄITÖSKIRJAN TIIVISTELMÄ

AALTO YLIOPISTO
TEKNILLINEN KORKEAKOULU
PL 13000, FI-00076 Aalto, Suomi

Tekijä Veli-Matti Kolmonen

Väitöskirjan nimi

Etenemiskanavan mittauslaitteiston kehittäminen ja kanavan karakterisointi 5.3 GHz:n alueella

Käsikirjoituksen päivämäärä 27.11.2009

Väitöstilaisuuden ajankohta 28.4.2010

☐ Monografia

☒ Yhdistelmäväitöskirja (yhteenveto + erillisartikkelit)

Tiedekunta	Elektroniikan, tietoliikenteen ja automaation tiedekunta
Laitos	Radiotieteen ja -tekniikan laitos
Tutkimusala	Radiotekniikka
Vastaväittäjä(t)	Prof. Matti Latva-aho (Oulun yliopisto) ja TkT Kimmo Kalliola (Nokia Research Center)
Työn valvoja	Prof. Pertti Vainikainen
Työn ohjaaja	Prof. Pertti Vainikainen

Tiivistelmä

Langaton yhteys on havaittu luotettavaksi tiedonvälityskanavaksi. Langattomien yhteyksien lisääntyminen on kasvattanut nopeampien ja häiriökestävämpien langattomien järjestelmien tutkimusta. Tällaisten järjestelmien kehityksessä tärkeässä asemassa ovat etenemiskanavien yksityiskohtaiset analyysit ja mallintaminen, joissa molemmissa tarvitaan luotettavaa mittausaineistoa. Tässä työssä keskitytään mittalaitteistojen kehittämiseen yhden ja kahden linkin tapauksessa sekä mitta-aineiston analyysiin eräiden langattomien järjestelmien osalta.

Työn ensimmäisessä osassa langattomien järjestelmien haasteet kuvataan radioaaltojen etenemiseen liittyvien fysikaalisten ilmiöiden kautta. Kirjallisuudessa havaitut etenemiskanavien tärkeimmät ilmiöt mallintamisen osalta esitetään ja viimeisimmät mallinnustavat käsitellään. Lisäksi kuvataan mittausjärjestelmien laitteistopohjaiset suunnitteluhaasteet sekä viimeisimmät mittausjärjestelmät. Erityisesti tarkastellaan kaksoissuuntakanavamallin parametrien estimointiin tarkoitettujen antenniryhmien suunnittelua. Kaksoissuuntakanavan karakterisointia varten kehitty mittausjärjestelmä esitetään ja tarkastellaan erityisesti järjestelmän mittaustarkkuutta suuntien estimointiin. Lisäksi mittausjärjestelmä laajennetaan kahden yhtäaikaisen linkin tapaukseen sekä esitetään ensimmäiset kaksoissuuntakanavan tulokset kahdelle linkille.

Työn toisessa osassa tarkastellaan kaksoissuuntakanavan tila-avaruutta mittausaineistosta, jotka on saatu työssä kehitetyllä mittauslaitteistolla. Yhden ja kahden linkin sekä yhteistoiminnallisen tiedonsiirtojärjestelmien perusteet kuvataan ja moniantennijärjestelmissä käytetyn tila-avaruuden analyysi laajennetaan usean käyttäjän tilanteeseen sekä yhteistoiminnalliseen tiedonsiirtojärjestelmään.

Asiasanat radioaallon eteneminen, etenemiskanava, MIMO

ISBN (painettu) 978-952-60-3052-4

ISSN (painettu) 1797-4364

ISBN (pdf) 978-952-60-3053-1

ISSN (pdf) 1797-8467

Kieli Englanti

Sivumäärä 58 + liitteet

Julkaisija Aalto yliopisto, Radiotieteen ja -tekniikan laitos

Painetun väitöskirjan jakelu Aalto yliopisto, Radiotieteen ja -tekniikan laitos

☒ Luettavissa verkossa osoitteessa http://lib.tkk.fi/Diss/

Preface

This thesis has been done in the Department of Radio Science and Engineering at Helsinki University of Technology (Aalto University as of 2010) under the supervision of Prof. Pertti Vainikainen. The propagation research group is a part of the SMARAD (Smart Radios and Wireless Research Unit) Centre of Excellence appointed by the Academy of Finland. Furthermore, I want to acknowledge the additional financial support from the Finnish Cultural Foundation, HPY Foundation, and Nokia Foundation during my post-graduate studies.

I would like to dearly thank Prof. Vainikainen, not only for providing this opportunity to me, but his constant willingness to guide me towards the right direction. Furthermore, Lic.Sc. Lasse Vuokko, D.Sc. Jari Salo, Dr.Eng. Katsuyuki Haneda, and D.Sc. Jarmo Kivinen deserve my gratitude for officially and unofficially instructing me throughout the work.

Along the way, I have had the priviledge of co-operating with several outstanding people, such as Dr. Andreas Richter, Dr. Peter Almers, Dr. Fredrik Tufvesson, M.Sc. Juho Poutanen, M.Sc. Jukka Koivunen, Dr. Jussi Salmi, Dr. Jean-Philippe Kermoal, and Prof. Andreas Molisch, who I want to acknowledge. I do hope that the co-operation, both in scientific and not so scientfic matters will continue in the future. In addition, the effort and encouraging feedback of the thesis pre-examiners Prof. Jørgen Bach Andersen and Dr. Yves Lostanlen are also greatly appreciated.

I want to thank the former Radio Laboratory personnel for providing their help and support during the work, and especially Mr. Eino Kahra and Mr. Lauri Laakso for their help in practical problems. I would also like to thank Mr. William Martin from the Faculty of Electronics, Communication and Automation for his advices about the language of the thesis.

Although not always evident, I do appreciate the support of my family and friends and their constant efforts in reminding what is real. Especially I want to thank my wife and son for providing me not-so-work-related issues to solve, almost everyday, and keeping things in perspective.

Espoo, March 30th, 2010

Veli-Matti Kolmonen

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

Measurement System Development

[I] **V.-M. Kolmonen**, J. Kivinen, L. Vuokko, and P. Vainikainen,"5.3 GHz MIMO Radio Channel Sounder," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 4, pp. 1263–1269, Aug. 2006.

[II] **V.-M. Kolmonen**, P. Almers, J. Salmi, J. Koivunen, K. Haneda, A. Richter, F. Tufvesson, A.F. Molisch, and P. Vainikainen,"A Dynamic Dual-Link Wideband MIMO Measurement System for 5.3 GHz,", *IEEE Trans. Instrum. Meas.*, vol. 59, no. 4, pp. 873 – 883, Apr. 2010.

Measurement Data Analysis

[III] L. Vuokko, **V.-M. Kolmonen**, J. Salo, and P. Vainikainen,"Measurement of Large-Scale Cluster Power Characteristics for Geometric Channel Models," *IEEE Trans. Antennas Propagat.*, vol. 55, no. 11, pp. 3361–3365, Nov. 2007.

[IV] **V.-M. Kolmonen**, K. Haneda, J. Poutanen, F. Tufvesson, and P. Vainikainen,"A Dual-link Capacity Analysis of Measured Time-Variant Radio Indoor Channels," *Electronic Letters*, 2010, accepted for publication.

[V] K. Haneda, **V.-M. Kolmonen**, T. Riihonen, R. Wichman, J.I. Takada, and P. Vainikainen, "Evaluation of Relay Transmission in Outdoor-to-Indoor Propagation Channels," in *Proc. 1st COST2100 Workshop "MIMO and Cooperative Communications"*, W08114, June 3rd-4th 2008, Trondheim, Norway

The author has authored and co-authored also several other publications in the related field [1–20].

Author's contribution

Professor Pertti Vainikainen supervised all the papers.

[**I**] The paper is based on this author's Master's thesis and this author had the leading role in the work. The work was instructed by D. Sc. Jarmo Kivinen.

[**II**] The developed measurement system is based on Jukka Koivunen's Master's thesis, where the hardware related modifications to the TKK channel sounder were done. The thesis was instructed by this author. This author had the main responsibility for writing the paper, planning and conducting the test measurements, and analyzing the measurement system performance.

[**III**] This author participated to the measurements, writing of the paper, and the data analysis. Lic.Sc. Lasse Vuokko had the leading role in preparing the paper.

[**IV**] This author had the leading role in the work. The work was instructed by Dr.Eng. Katsuyuki Haneda.

[**V**] The paper concept is a joint effort between Dr.Eng. Katsuyuki Haneda and this author. This author participated to the planning and conducting the measurements as well as the data analysis. Dr.Eng. Haneda had the leading role in preparing the paper.

1 Introduction

“To measure is to know.”
– Lord Kelvin

We have come far from the establishment of Maxwell’s equations in 1865 by J. C. Maxwell [21] that describe the behavior of electromagnetic waves, and the first wireless transmissions by Marconi and Popov at the turn of the century. Nowadays, electromagnetic waves are used in a variety of applications throughout the world, and especially wireless mobile communication has grown enormously in the recent decade. With the success of second and third generation mobile communications systems, wireless access has proven to be usable for reliable mobile voice and data communications.

Today, mobile handheld devices are capable of communicating over several different frequency bands and radio technologies, such as global system for mobile communications (GSM), universal mobile telecommunications system (UMTS or 3G), bluetooth (BT), and wireless local area networks (WLAN). The devices can transmit voice and data seamlessly over several simultaneous communication links providing reliable communication when the user is on the move. Nowadays the usage of the mobile phone is far from just being a device used to deliver speech. However, as the number of subscribers and the achievable data rates to individual users is ever increasing, this will inevitably increase the interferences in the network and the maximum data rates required from the network. Hence, research for even faster and more reliable data transfer techniques and network topologies is of great interest.

In theory, multiple-input multiple-output (MIMO) systems [22–24] provide a solution for the ever increasing capacity requirements and are currently being implemented into WLAN products [25] as well as into fourth-generation cellular systems [26, 27]. The initial theoretical studies of MIMO systems were, however, based on simplified and idealized channel models. For an assessment of the true potential and performance of MIMO systems, measurements of MIMO propagation channels are a prerequisite. For this reason, there has been extensive research on this topic in the past years (for an overview, see, e.g., [28]), and special measurement equipment have been designed [**I**] and [29, 30] for this purpose. From the measured channel transfer function matrix, the spatial channel characteristics can be extracted by sophisticated high-resolution algorithms.

As the single link MIMO technology has been widely studied all over the world, the interest has turned to the multiuser MIMO scenarios. To date, the properties of realistic interferences in MIMO systems are still largely unknown due to the absence of measurement equipment.

1.1 Contributions of the thesis

The contributions of the thesis to the research field can be divided into two parts; measurement system development, and parametrization and analysis of the propagation channel. In [**I**] and [**II**], measurement systems for measuring multidimensional MIMO channels in the 5.3 GHz frequency range are developed for single-and dual-link scenarios. The developed measurement systems are capable of measuring the spatial characteristics essential for MIMO communication system development at the transmitter and the receiver for dynamic single- and dual-link scenarios. The developed dual-link measurement system is the first such measurement equipment in the literature.

In the second part, measured data obtained using the developed measurement systems have been analyzed for cluster shadow fading, MIMO capacity in interference limited scenarios, and in cooperative communications. The analysis results of the shadow fading can be used in the geometry based stochastic channel modeling (GSCM) for cluster shadow fading and lifetime parametrization. The dual-link MIMO channel capacity analysis provides an insight into dual-link channel behavior in indoor scenarios as well as the effect of moving people to the received power for each link. The results are twofold, the analysis indicates particularly the significance of spatial separation of the wireless terminals and the human shadowing effect on the received power levels. In the analysis of cooperative communications, specific outdoor-to-indoor relaying with a diversity approach is used to investigate the effect of terminal cooperation on the channel capacity. The results indicate that cooperative communications is effective for extending the coverage of an outdoor basestation in the case of an indoor receiver.

The developed measurement systems have been used extensively for measurements, and the measurement results have been used in antenna testing and design [19, 31–33], channel characterization and modeling [6,9,34–43] and [**III**], development of array signal processing algorithms [44,45] and ray tracing [16,17], car-to-car channel modeling [12,13,20], indoor localization [46], relay analysis [**V**] and multi-user MIMO characterization and channel modeling [1–5,14,15] and [**IV**].

2 The Propagation Channel

> “You can always find an environment that fits your model.“
> – Prof. Jørgen Bach Andersen

Often, the term *radio channel* is used to refer to the propagation channel *including* the antennas, and possibly the related radio frequency (RF) hardware. In this thesis, the term radio channel will be considered to include the antennas and the physical channel, with which the radiowave interacts from the transmitter antenna(s) to the receiver antenna(s). The physical channel excluding the antennas will be referred to as the *propagation channel*.

2.1 Basic properties

The underlying physical propagation phenomena in a propagation channel are the main limiting factors for the operation of a wireless system. These basic phenomena change the amplitude and phase of the wave as it interacts with the environment. The environment dependent physical propagation characterizes the properties of the propagation channels, and therefore, in order to comprehend the possibilities and restrictions that the propagation channel introduces to the wireless systems as well as the propagation channel measurement equipment, the knowledge of the channel properties and the related physical phenomena is required. This knowledge can be obtained from basic physical wave propagation simulations and measurements and utilized for wireless systems testing through channel realizations, either stored or simulated. Hence, it is obvious, that the used channel model has to charactarize the main features of the channel.

The wave interacts with the environment with four frequency dependent basic mechanisms: path loss, reflection, diffraction, and scattering. For detailed description of the mechanisms, see for example [47].

When a radiowave departs from a point source it propagates to all directions. This causes the power to be distributed on a sphere, and only a part of the transmitted power is aqcuired by the receiving antenna. This attenuation is referred to as free space path loss. However, in e.g. urban environments the wave can propagate in a street canyon where the power is not distributed over a sphere as it is confined to the canyon by the surrounding buildings. In such situations the attenuation is less than the free space path loss. Models developed for such environments are presented for instance in [48].

As a plane wave encounters a flat, infinitely large material interface, the wave is partly reflected from the interface with the same departure angle as the arriving angle with respect to the normal direction of the surface. The reflected wave is also attenuated dependent on the material parameters. The unreflected portion of the wave penetrates the interface (refraction) with an angle dependent on the material parameters.

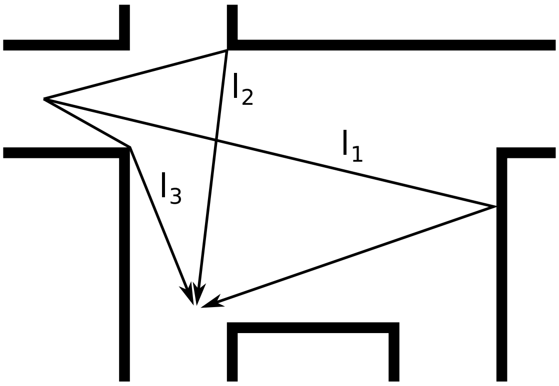

Figure 2.1: Illustration of multipath propagation.

According to the Huygens' principle, a propagating wave can be replaced with equivalent point sources which are located in the path of the waves. Accordingly, the wave can propagate, or diffract, behind obstacles even if the wave cannot penetrate through the obstacle. This type of propagation occurs e.g. in urban environments when the wave propagates around a building corner or over the roof of a building.

Scattering occurs when a radiowave interacts with a small object or surface having a roughness in the order of the wavelength, and the wave is reradiated in various directions. The polarization and the phase of the reradiated field are random, and hence, the diffuse scattering may appear as "noise" in the receiver. Many of the parameter estimation methods neglect the effect of diffuse scattering thereby introducing a modeling error to the received power.

The analysis of the diffuse scattering has become increasingly interesting for the propagation channel research as a large portion of the radio wave energy is conveyed through this process [18, 49].

As the radiowave leaves the transmitter antenna it propagates along several paths to the receiver, as is illustrated in Fig. 2.1. Along these paths the waves interact with the surrounding physical environment with the abovementioned mechanisms. This multipath propagation causes the received signal to spread in time, polarization, and angular domains. If either the transmitter or the receiver moves in the multipath environment the incoming multipath components are combined constructively or destructively in the receiver depending on the phase difference of the waves. This combination of the waves causes the received signal level to fluctuate, or fade, and this so called small scale fading can introduce severe degradation of the received signal level.

As either end of the link moves, it is natural that the surrounding objects, such as buildings, shadow the link between the transmitter and the receiver. This type of "large-scale" shadow fading is best described as the long term average of the received signal (see, e.g., Fig. 1 in [**III**]). Even if both transmitter and receiver are static the received signal can experience shadow fading due to changes of physical objects, such as pedestrians and cars. Furthermore, the movement causes a Doppler shift in the received signal which is dependent on the speed and the direction of traveling with respect to the incoming wave.

2.2 Propagation channel modeling

For the design and testing of wireless systems realistic radio or propagation channel realizations are needed. For example, in the testing of different antenna designs it is not feasible to measure every prototype in real environments. Instead, channel models can be used to reproduce the channels for the testing of the antenna prototypes. Thus, for realistic analysis of the prototype, the channel models that capture the essential properties of the propagation channel are a prerequisite.

The radio channel can be considered as a linear system [50, 51], which can be characterized by impulse response (IR) that fully describe the effects of the system on an input signal. Hence, it is well known that the output $y\left(t\right)$ in the time domain of such a system with a certain input can be calculated using

$$y\left(t\right) = h\left(t, \tau\right) * x\left(t\right) + n\left(t\right), \tag{2.1}$$

where $*$ denotes convolution, $h\left(t, \tau\right)$ is the impulse response of a system, $x\left(t\right)$ is the input signal, $n\left(t\right)$ is noise, and t and τ are the time and delay. In the case of multiple-input multiple-output (MIMO) systems, illustrated in Fig. 2.2, the impulse response can be written as a matrix

$$\mathbf{H}\left(t, \tau\right) = \begin{bmatrix} h_{11}\left(t, \tau\right) & \dots & h_{1N_\mathrm{t}}\left(t, \tau\right) \\ \vdots & \ddots & \vdots \\ h_{N_\mathrm{r}1}\left(t, \tau\right) & \dots & h_{N_\mathrm{r}N_\mathrm{t}}\left(t, \tau\right) \end{bmatrix} \in \mathbb{C}^{N_\mathrm{r} \times N_\mathrm{t}}. \tag{2.2}$$

For flat fading channels, (2.1) can be written in a matrix form as

$$\mathbf{y}\left(t\right) = \mathbf{H}\left(t\right) \mathbf{x}\left(t\right) + \mathbf{n}\left(t\right), \tag{2.3}$$

where $\mathbf{x}\left(t\right)$ and $\mathbf{n}\left(t\right)$ are the signal and noise vectors.

2.2.1 Double directional channel model

To model the propagation channel, the effect of the antenna element(s) can be taken into account by separating the channel matrix of the radio channel into antenna and propagation channel dependent parts. A convenient model for the propagation channel is the double directional channel model [52]. The double directional model considers the multipath components as rays, i.e., discrete plane waves, traveling through the propagation medium. The polarimetric double directional channel

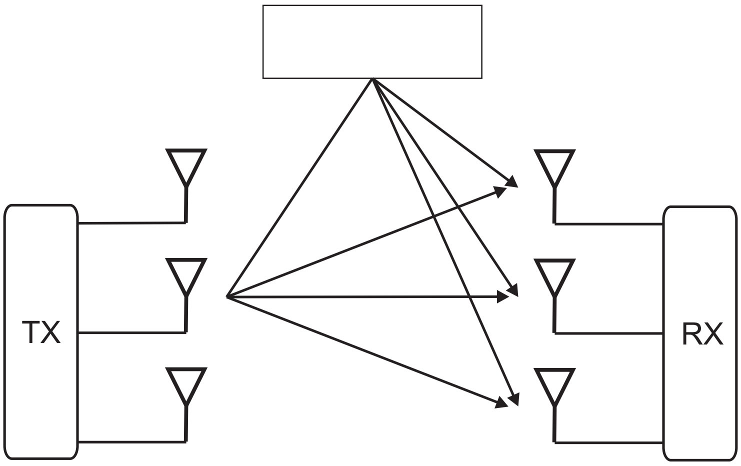

Figure 2.2: Multiple-input multiple-output system.

model can be expressed as a sum of several multipath components, i.e. plane waves as

$$\begin{aligned}\mathbf{H}_{\mathrm{pol}}\left(t,\tau,\mathbf{\Omega}_r,\mathbf{\Omega}_t\right) &= \sum_{m=1}^{L_{\mathrm{m}}(t)} \begin{pmatrix} \alpha_m^{\phi\phi}(t) & \alpha_m^{\theta\phi}(t) \\ \alpha_m^{\phi\theta}(t) & \alpha_m^{\theta\theta}(t) \end{pmatrix} \\ &\quad \delta\left(\tau-\tau_m(t)\right)\delta\left(\mathbf{\Omega}_{\mathrm{r}}-\mathbf{\Omega}_{\mathrm{r},m}(t)\right)\delta\left(\mathbf{\Omega}_{\mathrm{t}}-\mathbf{\Omega}_{\mathrm{t},m}(t)\right) \quad (2.4) \\ &= \sum_{m=1}^{L_{\mathrm{m}}(t)} \mathbf{H}_m\left(t,\tau,\mathbf{\Omega}_r,\mathbf{\Omega}_t\right).\end{aligned}$$

The $\mathbf{\Omega}_{\mathrm{r},m}=[\theta_{\mathrm{r},m},\phi_{\mathrm{r},m}]$ and $\mathbf{\Omega}_{\mathrm{t},m}=[\theta_{\mathrm{t},m},\phi_{\mathrm{t},m}]$ are the elevation and azimuth angles of arrival (AoA) and departure (AoD) of the mth wave, respectively. The $\alpha_m^{\theta\theta}$, $\alpha_m^{\phi\phi}$, $\alpha_m^{\theta\phi}$, and $\alpha_m^{\phi\theta}$ denote the path weights of the co- and cross-polarizations. The δ is the Dirac delta function illustrating the plane wave model. During each time instant t, L_{m} number of waves are assumed. Writing the dual-polarized antenna radiation patterns as

$$\mathbf{g}_{\mathrm{r}}\left(\mathbf{\Omega}_{\mathrm{r}}\right) = \left[g_{\mathrm{r}}^{\phi}\left(\mathbf{\Omega}_{\mathrm{r}}\right) \quad g_{\mathrm{r}}^{\theta}\left(\mathbf{\Omega}_{\mathrm{r}}\right)\right] \in \mathbb{C}^{1\times 2} \quad (2.5)$$

$$\mathbf{g}_{\mathrm{t}}\left(\mathbf{\Omega}_{\mathrm{t}}\right) = \left[g_{\mathrm{t}}^{\phi}\left(\mathbf{\Omega}_{\mathrm{t}}\right) \quad g_{\mathrm{t}}^{\theta}\left(\mathbf{\Omega}_{\mathrm{t}}\right)\right] \in \mathbb{C}^{1\times 2}, \quad (2.6)$$

and arranging the radiation patterns of the antenna array as

$$\mathbf{G}_{\mathrm{r}}\left(\mathbf{\Omega}_{\mathrm{r}}\right) = \begin{bmatrix} \mathbf{g}_{\mathrm{r},1}\left(\mathbf{\Omega}_{\mathrm{r}}\right) \\ \vdots \\ \mathbf{g}_{\mathrm{r},N_{\mathrm{r}}}\left(\mathbf{\Omega}_{\mathrm{r}}\right) \end{bmatrix} \in \mathbb{C}^{N_{\mathrm{r}}\times 2} \quad (2.7)$$

and

$$\mathbf{G}_{\mathrm{t}}\left(\mathbf{\Omega}_{\mathrm{t}}\right) = \begin{bmatrix} \mathbf{g}_{\mathrm{t},1}\left(\mathbf{\Omega}_{\mathrm{t}}\right) \\ \vdots \\ \mathbf{g}_{\mathrm{t},N_{\mathrm{t}}}\left(\mathbf{\Omega}_{\mathrm{t}}\right) \end{bmatrix} \in \mathbb{C}^{N_{\mathrm{t}}\times 2}, \tag{2.8}$$

the MIMO channel impulse response can be separated into the antenna and the propagation channel dependent parts

$$\mathbf{H}\left(t,\tau\right) = \sum_{n=1}^{L_{\mathrm{m}}(t)} \mathbf{G}_{\mathrm{r}}\left(\mathbf{\Omega}_{\mathrm{r,n}}\right) \mathbf{H}_{\mathrm{n}}\left(t,\tau,\mathbf{\Omega}_{\mathrm{r,n}},\mathbf{\Omega}_{\mathrm{t,n}}\right) \mathbf{G}_{\mathrm{t}}\left(\mathbf{\Omega}_{\mathrm{t,n}}\right)^{\mathrm{T}}, \tag{2.9}$$

where $\left(\cdot\right)^{\mathrm{T}}$ is the transpose operator. The benefit of the double directional model is that it can be used to test different antennas in the measured environment even without realizing the antenna [53], and, furthermore, it can be used to study the propagation mechanisms in detail [4,5,34,54,55].

To date, the majority of the models are based on modeling only the dominant specular component(s). However, it has been noted [18,49] that the so called diffuse scattering, or dense multipath components (DMC), convey a large portion of the power, and can have a large effect on the channel capacity [56]. Hence, channel models including DMC have been proposed [57–59].

An important problem is to identify typical values of the model parameters in (2.9) in real propagation channels. Several practical channel models have been proposed to represent the multipath propagation channel. Although the models can be categorized in several ways, here the models are divided into physical and analytical models [28], and only a short introduction to the most common channel models is provided. The interested reader is encouraged to refer to [28] and references therein.

2.2.2 Analytical models

A popular analytical model that was also used in the initial MIMO analyzes [22–24] is a model where all the entries of the channel matrix $\mathbf{H}\left(t\right)$ are assumed independent and identically distributed (i.i.d.) Gaussian random variables with a certain variance. As such, the model assumes independent channel matrix entries, and thus, the model provides a theoretical upper bound for the channel capacity. In reality, correlation between the signals of the elements exist, and based on measurements the validity of the model has disputed [60,61].

In the conventional Kronecker product based correlation models [62], the interelement correlation is essential in the generation of the channel matrices. The model relies on the transmitter and receiver correlation matrices, and on the assumption that the channel matrix can be represented as a combination of those matrices. The validity of the assumption that the correlation matrices are separable in the model has been disputed for specular components [63,64]. Thus in [65], a coupling matrix has been introduced to overcome this restriction of the model. The correlation models depend on the antenna configuration.

2.2.3 Physical models

As the name prescribes, the physical models try to simulate some physical propagation environment, such as urban micro and macro and rural. The models try to describe the parameters of the above-mentioned double directional channel model. As such, these models are environment specific.

In deterministic physical modeling, the field strengths are calculated using detailed knowledge of the geometry and the material parameters of the environment. Deterministic methods include the finite difference time domain (FDTD) [66], the method of moments (MoM) [67], and ray-tracing (RT). Although the full-wave methods FDTD and MoM are very accurate, they are computationally very demanding and, therefore, only small structures can be analyzed with them. RT has been used for urban environment simulations, for instance in [55, 68]. In the RT modeling, the computational load can be adjusted as a tradeoff between the accuracy of the simulation and computational time.

In GSCM (geometry based stochastic channel modeling), two approaches have been utilized. Probability distributions can be derived for different parameters, such as angular and delay distributions, see for example [69–71]. These models do not model any physical environment but rather model the outcomes, i.e. angular and delay distributions, of the environment.

Another approach is to simulate a physical propagation environment by placing "physical" scatterers as well as the transmitter and receiver into an environment. This modeling approach has been found suitable from the analysis of measurement data, see for example [72], as the multipath components seem to arrive to the receiver in concentrated groups. These concentrated groups of multipath components, also referred to as clusters, are usually scattered from large surrounding physical structures. These structures can be thought as independent cluster scattering sources, which act as secondary sources in the propagation medium and scatter the multipath components in separable clusters towards the receiver. As the waves seem to arrive in clusters, it provides a possibility to reduce the model complexity by providing only the parameters of the clusters. The properties of the scatterers in the environment are described with probability distributions, which are determined from measurements. However, as the estimation methods of the propagation path parameters have finite resolution [58], it is very challenging to estimate every individual multipath component in a cluster. Therefore, the modeling of the cluster properties concentrates on stochastic modeling. Nowadays, the GSCM approach is used in several channel models [27, 42, 43, 59].

Earlier, the clusters have been extracted from measurement data by visual inspection. This method was also used in [**III**]. However, this is very time consuming work, and hence, the interest towards the automatic cluster extraction started in [36], and a novel automatic clustering algorithm has been developed in [73]. Recent work [5] provides a useful method to link the physical scattering points in the environment to the measured data.

2.2.4 Reference models

Due to the large number of different channel models, it becomes increasingly difficult to compare the effect of different techniques, such as receiver architectures, signal processing algorithms etc., to the performance of a wireless system. Therefore, a number of reference models, such as 3GPP SCM [27], COST273 [42], WINNER [43], and ITU [74], have been developed to be used when new technologies between partners are compared. These models are based on the GSCM approach.

2.3 Summary of the contribution of this thesis

In a cluster based models, the double directional channel model parameters along with fast fading and shadow fading (also called large scale or slow fading) are typically assigned to each cluster based on stochastic distributions or by other means, for instance by geometry. However, some of the parameter values used in the models have not yet been verified by direct measurements.

The work in [**III**] concentrates on studying one of those, namely the shadow fading of cluster power, from dynamic urban micro and macro measurements. In addition, the mean powers and the lifetimes of the observed clusters are characterized. Furthermore, the frequency dependence of channel model parameters were investigated using measurements at 2 and 5 GHz. The double directional channel model parameters were estimated from the measurement data with the algorithm detailed in [**I**]. The clusters were extracted from the data by visual inspection.

The characterization revealed that in the macrocellular measurements the standard deviations of the shadow fading of individual clusters varied between 1.1 and 4.6 dB with a mean of 2.5 dB, when calculated over the routes. In the microcellular environments the standard deviations were smaller. The shadow fading processes of the clusters were found to be uncorrelated to each other. When considering the cluster powers, three to four clusters in non-line-of-sight (NLOS) and only one cluster in line-of-sight (LOS) were found significant along the routes. Furthermore, the results indicate no considerable difference between the two measured frequencies.

3 Propagation Channel Measurements and Techniques

> "The difference between measurmement and simulations is that nobody believes in simulations, except the one who did them, but everybody believes in measurements, except the one who did them."
> – General wisdom of science

Although the simple interactions introduced in the previous chapter are well known in the case of simple material interfaces, in realistic environments the number of interaction interfaces is enormous. Therefore, a detailed analytical modeling of real world environments is a very challenging task. Furthermore, if either transmitter or receiver is moving, the propagation channel is time-variant. Hence, in order to analyze realistic propagation channel conditions, measurements with specific measurement equipment are essential.

In the early days of channel measurements the field strength was the only measured quantity. This can be accomplished with simple antennas and a narrowband transmitter and a receiver. Since then, the measured quantities have increased to include the time-variant double directional channel parameters, wide bandwidth, wide angular ranges including polarization at the transmitter and the receiver, and in multiple transmitters and receivers (nodes) in multilink scenarios. This has inevitably increased the complexity of the measurement equipment. Furthermore, the interest towards various propagation environments, such as rural, macro- and microcellular, indoor, and outdoor to indoor dictates that the equipment has to be usable in all these environments. Also, highly time-variant channels, such as the car-to-car channels [75, 76] increase the demand for fast sampling rates of the channel.

The requirements for the measurement equipment can be summarized in the following way, excluding costs:

1. Distance between nodes
2. Center frequency and bandwidth
3. Spatial characterization accuracy and range, including polarization
4. Rate of changes in the channel

Whereas the distance requirement can be solved, to some extent, using a power amplifier at the transmitter, implications due to other requirements are more complicated. Thus, in the following only the requirements for wideband charactarization, spatial accuracy, and rate of change of the channel are described in more detail.

3.1 Wideband characterization

The impulse response in (2.2) characterizes the channel in the delay domain. The delay domain characterization can be transformed to a frequency domain representation through Fourier transform [51]. In the delay domain measurement, a short pulse, or a train of short pulses such as in a pseudorandom sequence, is used. When a known sequence is transmitted to the channel and sampled at the receiver, the channel impulse response can be resolved directly by cross convoluting the transmitted and received signal. This produces the delay domain representation of the channel. However, a pseudorandom signal using rectangular pulses in the time domain has sinc type frequency domain charateristics causing inefficient spectrum usage.

In frequency domain characterization the channel is measured over a certain bandwidth using, for example, a vector network analyzer (VNA) or the so called periodic multi-sine signal [29, 30]. The benefit of frequency domain characterization is that the desired spectrum can be excited using the same transmit signal level, not only enabling efficient spectrum usage, but the frequency response can be estimated using the least-squares (LS) solution [77, 78].

The nominal delay resolution of the measurement signal with bandwidth of W is

$$\tau_{\mathrm{res}} = \frac{1}{W} \tag{3.1}$$

and the maximum measurable delay range is

$$\tau_{\mathrm{ran}} = \frac{L_{\mathrm{c}}}{W}, \tag{3.2}$$

where L_{c} is the number of pulses in the measurement sequence in the time domain.

3.2 Spatial characterization

3.2.1 Single antenna measurements

The received power and the frequency domain characteristics can be measured using single antennas at the transmitter and the receiver. To enable the characterization of the MIMO channel and the directional properties using a single antenna, two techniques exist: virtual array and antenna rotation.

In the virtual array approach, a single antenna is moved to positions defined by the geometry of the desired antenna array[1], and the channel is measured consecutively in all antenna element positions. For a full MIMO measurement, this procedure has to be repeated for both the transmitter and the receiver.

The virtual array provides a very flexible method for determining the geometry of the antenna array and can, therefore, be easily adapted for different spatial resolution and ranges. Furthermore, especially for higher frequencies, the virtual array might be the only possible method [79]. This method, however does not take into account the element mutual coupling effects, and as the measurement of full MIMO matrix is very slow, the channel conditions should be static.

---

[1] In [**I**] the term *antenna group* is used for an arbitrary array geometries (see [**I**] for detailed explanation). However, as in this summary part only arbitrarily shaped antenna arrays are considered, the term *antenna array* will be used instead of *antenna group* throughout the text.

With antenna rotation, a single highly directive antenna element or element with a sharp null in the radiation pattern is rotated at the transmitter and the receiver. As with the virtual array, for the double directional characterization, all combinations of the antenna pointing directions have to be measured. This way the double-directional channel parameters can be directly measured. Also, this method becomes increasingly slower with an increasing number of measurement points and can be used to measure only static channels.

3.2.2 Multi-antenna measurements

In contrast to the single element measurements, where the channel is sampled by moving the antenna element, in multi-antenna measurements a predefined antenna array is used to sample the channel. The different antenna elements can be connected to separate transmitters and receivers [80] or connected consecutively using a switch [81, 82]. In the former method, the individual transmitters and receivers introduce calibration problems and increase the hardware complexity significantly. In the latter, the so called switched array principle, all antenna element combinations are measured using fast switches at the transmitter and the receiver. This method is nowadays mainly used for mobile propagation channel measurements. By using fast switches with switching times less than 2 μs, the measurement system in [**I**] can measure a 32 × 32 MIMO matrix in 8.8 ms. In multi-antenna measurements, a compromise between the size of the antenna aperture, inter-element coupling, and the number of switch channels has to be made.

The switched array measurement principle is illustrated in detail in Fig. 3.1. One measurement cycle consists of a measurement of channel snapshots during which all the antenna combinations are measured. For each transmitter receiver antenna combinations, the transmit signal sequence is measured K times. The K samples of the channels can be used, for instance, to increase the signal-to-noise ratio (SNR) by averaging or to select an appropriate time instant of the measurement sequence.

3.2.3 Array design and parameter estimation

The channel is always measured according to (2.9), where the radiation patterns $\mathbf{G}_{\mathrm{r}}\left(\mathbf{\Omega}_{\mathrm{r,m}}\right)$ and $\mathbf{G}_{\mathrm{t}}\left(\mathbf{\Omega}_{\mathrm{t,m}}\right)$ are the only part that can be designed and their properties are essential for the estimation of the double directional channel model parameters. To estimate the performance of various antenna arrays, different models for the array radiation patterns have been constructed.

An obvious, and often used, model is the measured radiation patterns. The stored radiation pattern model is cumbersome due to its need for computational resources. Resourcewise more compact models are the effective aperture distribution function [83] and spherical wave expansion [84]. However, in antenna array design, a model separating the radiation pattern of the individual element from the array geometry is useful. To elaborate this approach, the transmitter and receiver antenna configurations shown in Fig. 2.2 can be replaced by the configuration shown

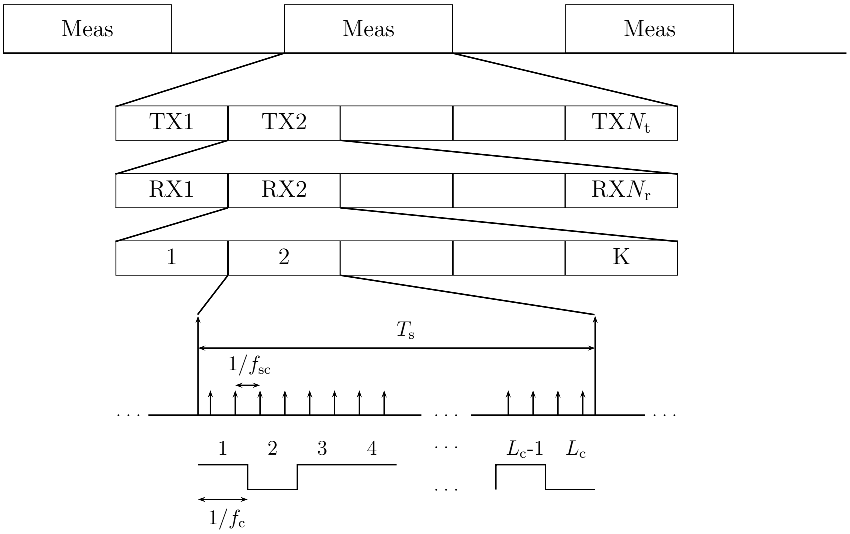

Figure 3.1: Switching pattern

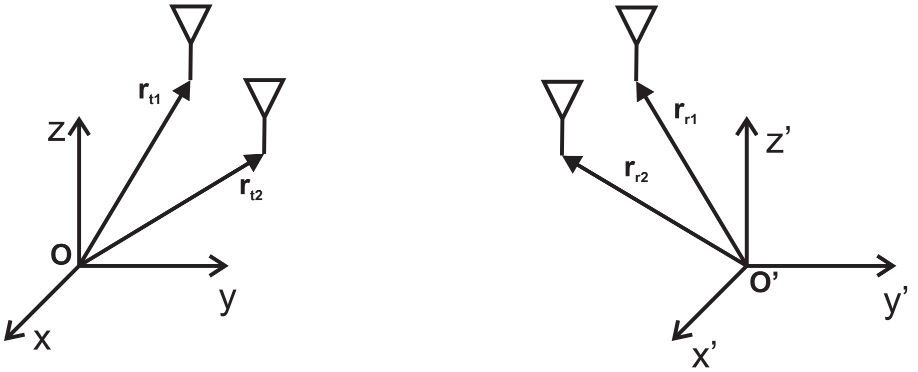

Figure 3.2: Antenna array configuration including the effect of the element positions.

in Fig. 3.2, where $\mathbf{r}_{\mathrm{t},m}$ and $\mathbf{r}_{\mathrm{r},m}$ are the position vectors of the transmitter and receiver antenna elements. Thus, setting the phasing matrix of the antenna elements based on their location[2] as

$$\begin{aligned}\mathbf{B}_\mathrm{t}\left(\boldsymbol{\Omega}_\mathrm{t},\bar{\mathbf{r}}_\mathrm{t}\right) &= \left[\mathbf{b}_\mathrm{t}\left(\boldsymbol{\Omega}_\mathrm{t},\bar{\mathbf{r}}_\mathrm{t}\right) \quad \mathbf{b}_\mathrm{t}\left(\boldsymbol{\Omega}_\mathrm{t},\bar{\mathbf{r}}_\mathrm{t}\right)\right] \in \mathbb{C}^{N_\mathrm{t}\times 2} && (3.3)\\ \mathbf{B}_\mathrm{r}\left(\boldsymbol{\Omega}_\mathrm{r},\bar{\mathbf{r}}_\mathrm{r}\right) &= \left[\mathbf{b}_\mathrm{r}\left(\boldsymbol{\Omega}_\mathrm{r},\bar{\mathbf{r}}_\mathrm{r}\right) \quad \mathbf{b}_\mathrm{r}\left(\boldsymbol{\Omega}_\mathrm{r},\bar{\mathbf{r}}_\mathrm{r}\right)\right] \in \mathbb{C}^{N_\mathrm{r}\times 2}, && (3.4)\end{aligned}$$

---

[2] Incoming waves are assumed to be plane waves i.e. the antennas are considered to be in the far-field.

where

$$\mathbf{b}_{\mathrm{t}}\left(\boldsymbol{\Omega}_{\mathrm{t}},\bar{\mathbf{r}}_{\mathrm{t}}\right) = \begin{bmatrix} e^{\mathrm{j}k\mathbf{u}_{\mathrm{r}}(\boldsymbol{\Omega}_{\mathrm{t}})\cdot\mathbf{r}_{\mathrm{t},1}} \\ \vdots \\ e^{\mathrm{j}k\mathbf{u}_{\mathrm{r}}(\boldsymbol{\Omega}_{\mathrm{t}})\cdot\mathbf{r}_{\mathrm{t},\mathrm{N}_{\mathrm{t}}}} \end{bmatrix} \in \mathbb{C}^{N_{\mathrm{t}}\times 1} \tag{3.5}$$

and

$$\mathbf{b}_{\mathrm{r}}\left(\boldsymbol{\Omega}_{\mathrm{r}},\bar{\mathbf{r}}_{\mathrm{r}}\right) = \begin{bmatrix} e^{\mathrm{j}k\mathbf{u}_{\mathrm{r}}(\boldsymbol{\Omega}_{\mathrm{r}})\cdot\mathbf{r}_{\mathrm{r},1}} \\ \vdots \\ e^{\mathrm{j}k\mathbf{u}_{\mathrm{r}}(\boldsymbol{\Omega}_{\mathrm{r}})\cdot\mathbf{r}_{\mathrm{r},\mathrm{N}_{\mathrm{r}}}} \end{bmatrix} \in \mathbb{C}^{N_{\mathrm{r}}\times 1}, \tag{3.6}$$

the antenna radiation patterns in (2.9) can be replaced by $\mathbf{G}_{\mathrm{r}}\left(\boldsymbol{\Omega}_{\mathrm{r}}\right) = \widehat{\mathbf{g}}_{\mathrm{r}}\left(\boldsymbol{\Omega}_{\mathrm{r}}\right) \circ \mathbf{B}_{\mathrm{r}}\left(\boldsymbol{\Omega}_{\mathrm{r}},\bar{\mathbf{r}}_{\mathrm{r}}\right)$ and $\mathbf{G}_{\mathrm{t}}\left(\boldsymbol{\Omega}_{\mathrm{t}}\right) = \widehat{\mathbf{g}}_{\mathrm{t}}\left(\boldsymbol{\Omega}_{\mathrm{t}}\right)\circ\mathbf{B}_{\mathrm{t}}\left(\boldsymbol{\Omega}_{\mathrm{t}},\bar{\mathbf{r}}_{\mathrm{t}}\right)$, where $\circ$ is elementwise Schur-Hadamar matrix product, $\mathbf{u}_{\mathrm{r}}\left(\boldsymbol{\Omega}_{\mathrm{r}}\right)$ is a unit vector towards $\boldsymbol{\Omega}_{\mathrm{r}}$, and $\bar{\mathbf{r}}_{\mathrm{r}} = [\mathbf{r}_{r,1},\mathbf{r}_{r,2},\ldots,\mathbf{r}_{r,N_r}]$ and $\bar{\mathbf{r}}_{\mathrm{t}} = [\mathbf{r}_{t,1},\mathbf{r}_{t,2},\ldots,\mathbf{r}_{t,N_t}]$ contain the position vectors of all the receiver and transmitter elements. The individual antenna element radiation patterns $\widehat{\mathbf{g}}_{\mathrm{r}}\left(\boldsymbol{\Omega}_{\mathrm{r}}\right)$ and $\widehat{\mathbf{g}}_{\mathrm{t}}\left(\boldsymbol{\Omega}_{\mathrm{t}}\right)$ can be acquired by simulating or measuring one antenna element. Using this antenna model, the effect of different element locations, i.e., array geometries can be taken into account.

The design parameters for the antenna arrays are listed in [85] as the number of elements, spacing between the elements, element excitations, 3 dB beamwidth, directivity, and side lobe level. In measurement systems designed for characterization of mobile channels, the number of elements is constrained by the hardware complexity and the measurement time. In a synchronized measurement system element excitations can be artificially altered in the post-processing. To avoid spatial aliasing, a general rule to have the element spacing less than $\lambda/2$ needs to be fulfilled, where $\lambda = \mathrm{c}/f_{\mathrm{c}}$ is the wavelength at center frequency f_{c} and c is the speed of light. With careful design the element spacing can exceed $\lambda/2$. The width of the main beam is inversely dependent on the electrical size of the array seen from a certain direction.

The beamwidth and side lobe level can be assessed by transforming from the element space to the beam space. Several books have been written about the design of the beam space of an antenna array [85, 86]. A thorough analysis of the radiated fields by different antenna arrays would require a full-wave analysis of the fields, especially when including mutual coupling between elements. However, with the plane wave assumption the design of an antenna array can be conducted without considering very detailed mathematics, and the mutual coupling effects can be taken into account using measured radiation patterns. The procedure presented in the following is valid for any antenna configuration. To illustrate the transformation to the beam space, the radiation pattern matrix of the antenna array of N elements can be written towards the angles of interest $\bar{\boldsymbol{\Omega}} = [\boldsymbol{\Omega}_1 \ldots \boldsymbol{\Omega}_{N_\Omega}]$ as

$$\mathbf{G}\left(\bar{\boldsymbol{\Omega}}\right) = \begin{bmatrix} \operatorname{vec}\left\{\mathbf{G}\left(\boldsymbol{\Omega}_1\right)\right\}^{\mathrm{T}} \\ \vdots \\ \operatorname{vec}\left\{\mathbf{G}\left(\boldsymbol{\Omega}_{N_\Omega}\right)\right\}^{\mathrm{T}} \end{bmatrix} \in \mathbb{C}^{N_\Omega \times 2N}, \tag{3.7}$$

where the vec $\{\cdot\}$ stacks the columns of a matrix into a column vector, and the element excitation vector as

$$\mathbf{a}\left(\boldsymbol{\Omega}_s\right) = \begin{bmatrix} a_1\left(\boldsymbol{\Omega}_s\right) e^{-\mathrm{j}k\mathbf{r}_1\cdot\mathbf{u}(\boldsymbol{\Omega}_s)} \\ \vdots \\ a_m\left(\boldsymbol{\Omega}_s\right) e^{-\mathrm{j}k\mathbf{r}_m\cdot\mathbf{u}(\boldsymbol{\Omega}_s)} \\ a_1\left(\boldsymbol{\Omega}_s\right) e^{-\mathrm{j}k\mathbf{r}_1\cdot\mathbf{u}(\boldsymbol{\Omega}_s)} \\ \vdots \\ a_m\left(\boldsymbol{\Omega}_s\right) e^{-\mathrm{j}k\mathbf{r}_m\cdot\mathbf{u}(\boldsymbol{\Omega}_s)} \end{bmatrix} \in \mathbb{C}^{2N \times 1}. \tag{3.8}$$

The real-valued attenuation factor a_m can be used to suppress or enhance the effect of particular elements. This procedure can be used to make the beamwidth more narrow or suppress the sidelobe levels. The response of the beam space of the array can be calculated as [87]

$$\mathbf{S}\left(\bar{\boldsymbol{\Omega}}\right) = \mathbf{G}\left(\bar{\boldsymbol{\Omega}}\right)\mathbf{a}\left(\boldsymbol{\Omega}_s\right). \tag{3.9}$$

The illustrated transformation is conventional data independent beamforming which was also used in [**I**]. For a specific array, (3.9) can be used to design element excitations so that the $\mathbf{S}\left(\bar{\boldsymbol{\Omega}}\right)$ contains the desired properties [7, 85, 88]. In addition to inspecting the beam space properties through (3.9), so called ambiguity function [89] can be used. However, the visualization of the ambiguity function for 3D array characterization is difficult. Examples of the antenna arrays used in propagation research can be found in, for example, [**I**], [**II**], and [44, 59, 90].

A dualistic problem to the beam synthesis is the estimation of the double directional channel parameters from the measured transfer functions. The parameter estimation has been of great interest for long time, and comprehensive reviews of the methods have been provided, for instance in [45, 91]. In general, the parameter estimation methods used for the direction of arrival (DoA) and direction of departure (DoD) estimation can be divided into spectral based and parametric methods. In the former, a spectrum like function is formed by designing a steering vector matrix, defined in (3.11). In the latter, (2.9) is used to derive a likelihood function, whose local maxima corresponds to the estimates. However, the likelihood function is a multidimensional function and the detection of the local maxima is computationally demanding. Recently, the parameter estimation methods have been extended to state space estimation [45, 92, 93]. Here, the parameter estimation is illustrated using conventional data dependent beamforming [87] as it closely relates the DoA/DoD estimation to the array design.

If antenna elements have a unit gain in all directions, the derivation of the estimates is similar to the beam space design shown above. However, as the radiation patterns of array elements are not identical in real arrays due to the fabrication errors and mutual coupling, and hence the array factor has to include the individual element patterns, another formulation is required. For an incoming wave with wave vector $\mathbf{k}_{\mathrm{s}}$, the output signals from the antenna elements can be written as

$$\mathbf{s}\left(\Omega_s\right) = \begin{bmatrix} g_1\left(\boldsymbol{\Omega}_s\right) e^{\mathrm{j}k\mathbf{r}_1\cdot\mathbf{u}(\boldsymbol{\Omega}_s)}\ \mathbf{u}^{\phi}\left(\boldsymbol{\Omega}_s\right)\cdot\mathbf{k}_{\mathrm{s}} \\ \vdots \\ g_n\left(\boldsymbol{\Omega}_s\right) e^{\mathrm{j}k\mathbf{r}_n\cdot\mathbf{u}(\boldsymbol{\Omega}_s)}\ \mathbf{u}^{\phi}\left(\boldsymbol{\Omega}_s\right)\cdot\mathbf{k}_{\mathrm{s}} \\ g_1\left(\boldsymbol{\Omega}_s\right) e^{\mathrm{j}k\mathbf{r}_1\cdot\mathbf{u}(\boldsymbol{\Omega}_s)}\ \mathbf{u}^{\theta}\left(\boldsymbol{\Omega}_s\right)\cdot\mathbf{k}_{\mathrm{s}} \\ \vdots \\ g_n\left(\boldsymbol{\Omega}_s\right) e^{\mathrm{j}k\mathbf{r}_n\cdot\mathbf{u}(\boldsymbol{\Omega}_s)}\ \mathbf{u}^{\theta}\left(\boldsymbol{\Omega}_s\right)\cdot\mathbf{k}_{\mathrm{s}} \end{bmatrix} \in \mathbb{C}^{2N\times 1}, \tag{3.10}$$

where the dot product $\mathbf{u}^{\mathrm{H}}\left(\Omega_s\right)\cdot\mathbf{k}_{\mathrm{s}}$ is used to collect the portion of the wave that coincides with the polarization of the antenna element. With a steering vector matrix

$$\mathbf{A}\left(\bar{\boldsymbol{\Omega}}\right) = \begin{bmatrix} \mathbf{a}\left(\boldsymbol{\Omega}_1\right)^{\mathrm{T}} \\ \vdots \\ \mathbf{a}\left(\boldsymbol{\Omega}_{N_\Omega}\right)^{\mathrm{T}} \\ \mathbf{a}\left(\boldsymbol{\Omega}_1\right)^{\mathrm{T}} \\ \vdots \\ \mathbf{a}\left(\boldsymbol{\Omega}_{N_\Omega}\right)^{\mathrm{T}} \end{bmatrix} \in \mathbb{C}^{N_\Omega\times 2N}, \tag{3.11}$$

the spatial spectrum becomes

$$\mathbf{S}\left(\bar{\boldsymbol{\Omega}}\right) = \mathbf{A}\left(\bar{\boldsymbol{\Omega}}\right)\mathbf{s}\left(\boldsymbol{\Omega}_s\right). \tag{3.12}$$

The L_m highest peaks of (3.12) correspond to the parameter estimates of the beamforming. In the case of a one input signal source the equation provides the maximum likelihood solution [91]. Thus, the procedure is applicable for antenna array design.

3.3 Channel measurement equipment

3.3.1 Vector network analyzer

VNA can be used to measure the reflection and transmission coefficients of a two-port system over wide bandwidths. The main benefit of the VNA is its flexible frequency control along with all the related hardware synchronizations. However, standard VNA measurements require the transmitter and receiver antennas to be within cable length and the channel to be static or very slowly changing. The VNA is often used with virtual array measurements. The VNA uses a stepped frequency sweep to measure the channel in the frequency domain, and hence, wider bandwidth results in slower measurement of the channel.

3.3.2 Channel sounder

The term *channel sounder* usually refers to a measurement system consisting of a transmitter, receiver, and a fast data aqcuisition unit. Hence, the main difference between channel sounders and the VNA is that the transmitter and the receiver rely individually on accurate, synchronized reference local oscillators (LO), and therefore, the transmitter and receiver(s) can be far apart. Although channel sounders can be used with any antenna configuration, a channel sounder along with the switched array principle enables very fast propagation channel measurements, and is practically the only available method for fully characterising, for instance, car-to-car MIMO channels. Moreover, as a result of the measurement speed, channel sounders can be used to gather large number of samples within reasonable time.

The contributions of this thesis are built on work reported earlier in [81, 94, 95]. The original measurement system operates at the 2.154 GHz frequency range, and is based on a pseudorandom signal with $f_{\text{chip}} = 60$ MHz pulse frequency with sequence length $L_c = 255$, effectively setting the traditional limits to $\tau_{\text{res}} \approx 17$ ns and $\tau_{\text{ran}} \approx 4.25$ μs. The system uses a fast dual-channel sampling unit, capable of sampling each channel at $f_{\text{c}} = 120$ MHz. These same system parameters were used in [**I**]. A commercial sounder based on a pseudorandom signal is *PropSound* by Elektrobit [96].

Furthermore, a novel antenna array for obtaining the directional channel parameters in elevation and azimuth, as well as polarimetric path amplitudes was introduced in [97]. The measurement system has been shown to be well suited for propagation channel measurements in the 2 GHz frequency range [98]. The array consists of 32 dual-polarized antenna elements placed in a spherical geometry. This geometry was also one of the geometries considered in [**I**]. In [97] it was possible to fit all the antenna switching electronics inside the array due to the rather low operation frequency of the measurement system. This made it possible to create a unified ground plane for all elements. However, this could not be achieved in [**I**] because of the higher operation frequency. Later, the measurement system has been extended for MIMO measurements in 5.3 GHz [**I**] and 60 GHz [99] operating frequencies. Furthermore, in [**II**], the measurement system was extended for multi-link measurements by cooperating with the RUSK channel sounder, which is a commercial channel sounder by MEDAV GmbH [29, 30]. Comparison between the equipment developed in [**I**] and RUSK sounders can be found in [100].

3.4 Synchronization

Regardless of the abovementioned harware used, the propagation channel measurements rely on a synchronized transmitter and receiver. The required synchronizations are illustrated in Fig. 3.3, where a general block diagram of a channel measurement system is shown. The antenna selection refers here to, for example, scanners used in the virtual array technique or fast switches used in the switched array principle, those being the most common measurement techniques.

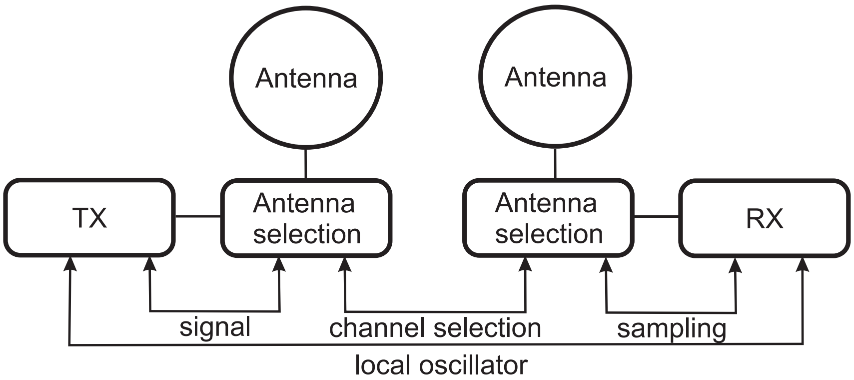

Figure 3.3: Synchronization diagram of the measurement equipment.

A crucial part of the measurement of the MIMO channel matrix is the synchronization of the antenna element selection between the transmitter and the receiver. If the switches cannot be synchronized in hardware, modifications of transmit signals have to be made, for instance by inserting empty channels. This enables distinguishing the channels in the post-processing, although it reduces the number of measurement channels. In the measurement system used in [**I**], the LO signals are also used to synchronize the measurement of the MIMO channel matrix. However, and more importantly, the measurement of the Doppler frequency of the multipath components requires reference signals for up- and downconversion to be synchronized. This synchronization can be achieved by using a stable frequency references in the transmitter and the receiver. The measurement of the absolute propagation delay can be achieved with the synchronization of the signal to antenna selection at the transmitter, and with the antenna to sampling synchronization at the receiver. This synchronization is usually included in the hardware.

3.5 Phase noise

In RF measurement systems LO is used to generate the up- and downconversion signals for the transmitter and receiver. Thus, the noise properties of the received signal are affected by the noise properties of the LO. A theoretical analysis in [101] claims that, for high SNR measurements with low-rank channels, the phase noise properties of LOs in channel sounder measurements significantly increase the obtained MIMO channel capacity due to the randomness introduced by the noise. To contradict this theoretical analysis, the phase noise in realistic cases has been analyzed in [102, 103]. The phase noise properties of the developed measurement systems are analyzed in [**I**] and [**II**]. These phase noise analyzes of realistic measurement systems have shown that the phase noise does not have any significant impact on the channel capacity under SNR levels of less than 30 dB.

3.6 Multilink MIMO measurements

The properties of single link MIMO systems have been thoroughly analyzed in recent years. However, the spatial interference characteristics, and its effect on the MIMO systems are still largely unknown due to the absence of multilink MIMO channel sounders.

Multilink MIMO measurements can be conducted in a static environment using single-link measurement systems, as in [104, 105]. Extending the measurement systems to dynamic multilink configuration is a challenging task, and only recently such measurement equipment has been developed in [**II**] and [106].

A recent contribution [107] analyzed dynamic dual-link channel properties using a measurement campaign utilizing only a single-link channel sounder; it concludes that for measurement of large-scale effects, a virtual multi-user approach is applicable. However, this is not valid if parts of the channel are changing (due to, e.g., movements of people, cars etc.) between single-link measurements. For those situations, a channel sounder which can identify the dual-link (or, more generally, multilink) channel behavior even in time-variant channels is needed.

3.7 Summary of the contribution of this thesis

3.7.1 Single-link measurements

In [**I**], the measurement equipment of [95] was extended to be used in the 5.3 GHz frequency range. The main development results are the mobile MIMO measurement capability of the system, which includes design and construction of the control hardware and the design and implementation of the antenna array.

The challenge was to design an antenna array that can be used for accurate estimation of the parameters of the double directional channel model including polarizations using the switched array measurement principle. As the number of channels in the measurement system was limited to 32×32 due to the complexity of the hardware, the amount of the measurement data and the coherence time of the measurement, the spatial range had to be limited. Based on the previous knowledge of the propagation channel behavior [108], it was decided to restrict the spatial range in elevation. The array design was conducted according to (3.9) by analyzing the sidelobe levels and positions of different array geometries using similar antenna elements.

Based on the theoretical analyzes, the semi-spherical antenna array was found to be optimal for the purpose and two such structures were constructed. Furthemore, in addition to the semi-spherical antenna arrays, it was decided also to construct a more basestation type 4×4 planar array. The constructed antenna arrays are illustrated in Fig. 3.4. In addition to the phase noise characterization of the developed system, the spatial characterization accuracy of the constructed arrays were considered, and

(a) Planar antenna (b) Semi-spherical antenna (c) Semi-spherical antenna with tilted elements

Figure 3.4: Constructed antenna arrays.

were found to be reasonable. Further, in addition to the detailed accuracy evaluation presented in [**I**], the accuracy of the measurement system has been analyzed in [109].

3.7.2 Multilink measurements

In [**II**], the first dual-link MIMO measurement system capable of simultaneously measuring the double directional channel properties was reported. As acquiring two channel sounders for one institute is infeasible due to the high price of even a single channel sounder, the measurement system is based on two channel sounders from two different universities, namely Helsinki University of Technology (TKK) and Lund University (LU).

As the synchronization of the two individual sounders is built only for single link operation, full synchronization at the hardware level was not possible to achieve without costly modifications to the hardware. Due to these synchronization problems, the design of an orthogonal measurement signal for each of the links was found infeasible. Hence, it was decided to use one transmitter and two receivers in the measurement system. If channel reciprocity is assumed, the measurement system is capable of measuring dynamic point-to-multipoint or multipoint-to-point MIMO channels in this configuration. A block diagram of the measurement system is shown in Fig. 3.5.

As the synchronization of the system could not be achieved at a hardware level, special attention was paid to the measurement of the channel matrices for the two links. As indicated in Fig. 3.3, several synchronization levels are required. All these exist in the individual sounders by design, but actions to achieve the synchronization of the LO and the channel matrices between the LU transmitter and TKK receiver

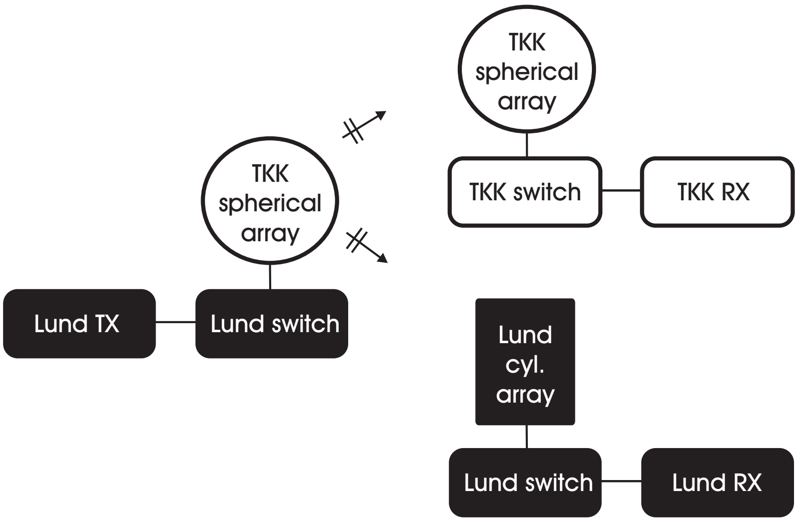

Figure 3.5: Block diagram of the dual-link measurement system.

were taken. Furthermore, the synchronization of the simultaneously measured dual-link channel matrices had to be designed.

The channel synchronization was achieved by replacing one antenna port by a matched load to create empty channels[3] in the MIMO matrix. The positions of the empty channels are detected in the post-processing and the MIMO matrix can be synchronized by reordering the data. Furthermore, as the LO frequency of the TKK receiver could not be set exactly to the transmitter LO frequency, the frequency offset of the TKK receiver LO is estimated in the post-processing using the phases of the IR peak values. The frequency offset is corrected in the data post-processing by back- or forward rotation using a complex phasor, i.e., an operation equivalent to a mixer.

Several test measurements were performed to ensure the accuracy of the sounder operation: 1) a back-to-back measurement to analyze the phase noise properties of the system, 2) anechoic chamber measurement to achieve the absolute received power levels of the links, and 3) antenna calibration measurement to enable the estimation of the model parameters of the double directional channel. The analysis of the test measurements confirmed that the system can accurately measure two dynamic MIMO links simultaneously in the frequency and spatial domains.

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[3] One for the transmitter and one for the receiver.

4 Emerging Wireless Systems

“If airplanes would be built like wireless networks are being built today,
they would all crash.“
– Prof. Jukka Lempiäinen

4.1 Multiple-input multiple-output systems

The MIMO system uses several antenna elements in space in the transmitter and the receiver, see Fig. 2.2. This exploitation of the spatial domain is the key feature to increase the channel capacity compared to single-input single-output (SISO) systems, where the system throughput is determined only through SNR and bandwidth. Both of these are limited in realistic systems in order to avoid interference with other users and systems. MIMO systems can take advantage of the spatially separated antenna elements in the following ways.

4.1.1 Beamforming gain

By using several antenna elements the total gain of the array can be increased, hence increasing the received power at the receiver. Furthermore, the spatial chracteristics can be manipulated to separate different users in the spatial domain [110–112]. However, to utilize the spatial separation in the transmitter requires the knowledge of the channel, which in turn, increases the signaling overhead of the system.

4.1.2 Diversity gain

As indicated earlier, when a mobile is moving in a multipath environment it experiences signal fading. This fading can be combatted using diversity combining in the frequency, code, time, or spatial domain. By separating the antennas sufficiently far apart in the spatial domain, the fading experienced by individual antennas can be assumed independent, and hence, the probability that at least one of the antenna elements receives a sufficient signal level is increased. Several methods for combining signals received from the different branches have been developed. The maximum ratio combining (MRC) provides the best link performance by maximizing the SNR of the received signal. Hence, according to the Shannon capacity formula it effectively maximizes the capacity.

4.1.3 Spatial multiplexing gain

Although multi-antenna techniques have been developed and analyzed earlier [113, 114], the exploitation of antenna array was limited to one link end. In [22–24] multi-antenna techniques at *both* ends of the links were considered, i.e., spatial multiplexing. Since its introduction, there have been extensive studies around this concept during the last years, see for instance, [28]. In SISO systems the fading caused by the multipath components was seen as a nuisance, but by using spatial multiplexing, in MIMO systems these multipath components are taken into use, as each of the multipaths can be used as independent streams for the data. The initial analyzes cited above, with the assumption of the i.i.d. channel conditions, showed a capacity increase proportional to $\min(N_\mathrm{r}, N_\mathrm{t})$. However, under realistic propagation channel conditions that assumption has been shown not to be valid [60, 61], and hence, realistic propagation conditions should be considered [115].

It has been shown in [23] that the capacity for a system shown in (2.3) can be written as

$$C = \log_2\left[\det\left(\mathbf{I}_{N_\mathrm{r}} + \frac{\rho}{N_\mathrm{t}}\mathbf{H}\mathbf{R}\mathbf{H}^H\right)\right], \tag{4.1}$$

where $\mathbf{I}_{N_\mathrm{r}}$ is an identity matrix of size N_r, $(\cdot)^\mathrm{H}$ denotes the conjugate transpose, $\mathbf{R}$ is the covariance matrix of the transmitted signal vector $\mathbf{x}$ (see (2.3)), and ρ is the average SNR. If the transmitter does not have any channel state information (CSI), the transmit power is allocated evenly over all channels, i.e., $\mathbf{R} = \mathbf{I}_{N_\mathrm{r}}$, in which case the MIMO capacity can be expressed as

$$C = \log_2\left[\det\left(\mathbf{I}_{N_\mathrm{r}} + \frac{\rho}{N_\mathrm{t}}\mathbf{H}\mathbf{H}^H\right)\right]. \tag{4.2}$$

By rewriting $\mathbf{H}\mathbf{H}^\mathrm{H} = \mathbf{Q}\mathbf{\Lambda}\mathbf{Q}^\mathrm{H}$, with $\det(\mathbf{I} + \mathbf{AB}) = \det(\mathbf{I} + \mathbf{BA})$ and $\mathbf{Q}^\mathrm{H}\mathbf{Q} = \mathbf{I}_{\mathrm{N_r}}$, the capacity can be written as

$$\begin{aligned} C &= \log_2\left[\det\left(\mathbf{I}_{N_\mathrm{r}} + \frac{\rho}{N_\mathrm{t}}\mathbf{\Lambda}\right)\right] && (4.3)\\ &= \sum_{i=1}^{r}\log_2\left(1 + \frac{\rho}{N_\mathrm{t}}\lambda_i\right) && (4.4)\end{aligned}$$

where r is the rank of the channel matrix and λ_i are the eigenvalues of $\mathbf{H}\mathbf{H}^\mathrm{H}$. Now, the channel capacity is expressed as a sum of r SISO channels. Furthermore, the rank of $\mathbf{H}$, i.e., the number of independent columns, affects the achievable channel capacity. In fading environments, the capacity becomes a random variable. Hence, the capacity is analyzed through ergodic and outage capacity [22]. The ergodic capacity is defined as the average over several channel realizations

$$\overline{C} = E\left\{\log_2\left[\det\left(\mathbf{I}_{N_\mathrm{r}} + \frac{\rho}{N_\mathrm{t}}\mathbf{H}\mathbf{H}^H\right)\right]\right\}, \tag{4.5}$$

where $E\{\cdot\}$ denotes an ensemble average. The outage capacity is defined as a level which is achieved with a certain probability.

If the CSI is available in the transmitter, the transmit power can be allocated to the transmitter antennas using algorithms such as the waterpouring algorithm [116].

4.1.4 Multiuser MIMO

The initial theoretical studies that established the benefits of MIMO dealt with a single link only. As MIMO systems are deployed, the number of multilink MIMO scenarios increases, and the need to understand the effects of multiuser interference in multilink MIMO scenarios is growing. Hence, several papers have been published about multiuser MIMO system performance [117–122]. However, only recently first capacity studies with simultaneously measured multiuser MIMO channels have been performed [106, 123].

Usually, automatic power control of the transmitter keeps the received power at a constant and sufficient level for the receiver. In single- and dual-link cases the users can adapt their transmit power based on the current propagation environment. In the case of multiple users and access points, the power control becomes more involved as the users cannot decide the power levels solely based on the link quality to their designated access point.

Here, the particular interest is the configuration where the basestation as well as the users are equipped with antenna arrays. For the dual-link case, the received signal can in this case be written as [118]

$$\mathbf{y}_f = \sqrt{\rho}\,\mathbf{H}_{1,f}\mathbf{x}_1 + \sqrt{\eta}\,\mathbf{H}_{2,f}\mathbf{x}_2 + \mathbf{n}, \tag{4.6}$$

where $\mathbf{H}_{1,f}$ and $\mathbf{H}_{2,f}$ are the normalized narrow band channel matrices of the desired and interfering links for the frequency sub-channel f. The dual-link capacity with interference is expressed as

$$C_f\left(\mathbf{H}_{1,f}, \mathbf{H}_{2,f}\right) = \log_2\left[\det\left(\mathbf{I}_{N_\mathrm{r}} + \frac{\rho}{N_\mathrm{t}}\mathbf{H}_{1,f}\mathbf{H}_{1,f}^H\mathbf{R}_{2,f}^{-1}\right)\right], \tag{4.7}$$

where the instantaneous covariance matrix for our case becomes

$$\mathbf{R}_{2,f} = \eta\mathbf{H}_{2,f}\mathbf{H}_{2,f}^H + \mathbf{I}_{N_\mathrm{r}}. \tag{4.8}$$

$\mathbf{I}_{N_\mathrm{r}}$ is the identity matrix of size N_r.

As indicated in (4.4), the single-link channel capacity is affected by the rank of the channel matrix, i.e., the number of independent columns. Thus, any correlation between the signals of the elements decrease the capacity in single-link MIMO. The effect of the correlation between the links to multiuser MIMO channel capacity using measured data has been investigated in [124], where it was found that the interlink correlation can significantly affect the multiuser capacity. A more detailed analyzes of the interlink correlation can be found in [1, 3].

4.1.5 Summary of the contribution of this thesis

The measurement equipment developed in [**II**] was used to analyze the effect of spatial separation on the dual-link channel capacity in [**IV**]. The measurements were conducted in a typical office environment in a corridor and nearby office rooms. The analysis concentrates on the dual-link capacity with a consideration of the interfering link as spatially colored noise, without any multiple access methods. Furthermore, the analysis is restricted to a case where there is no CSI at the transmitter but perfect channel knowledge at the receiver for the interfering and desired channel.

For the analysis, five dual-polarized antenna elements pointing in different directions in azimuth were selected from the TX and RX antenna geometries in order to emulate a random orientation of the investigated sub-arrays. Out of the five antenna elements, two neighboring elements (comprising 4 feeds) were selected to provide five different antenna pair combinations at the TX and RXs, respectively. Thus, with the three TX positions and three RX positions, the total number of dual-link MIMO channel realizations is $9 \cdot 5 \cdot 5 \cdot 5 = 1125$ for each time instant.

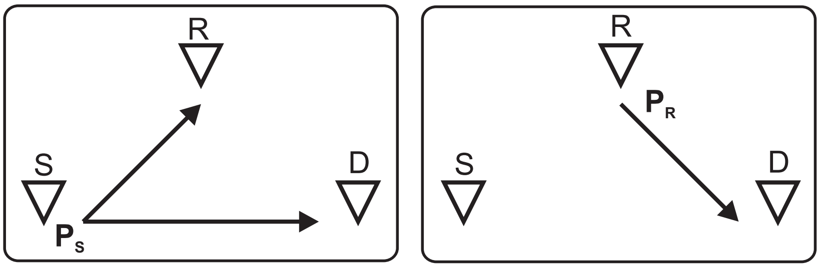
The dual-link capacity was analyzed using normalized channel matrices according to (4.7), and varying artificially the value of η. Furthermore, the properties of the signal-to-interference ratio (SIR) was analyzed along with its contribution to the channel capacity.

Analyzes revealed that 1) the SIR have a dominating effect on the dual-link channel capacity when compared to the single link case. Further, the effect of the random positions of the two RXs created large fluctuations of the dual-link channel capacity. 2) As movements of the people around the antennas caused a large variation in the SIR, according to the static measurements the fluctuation on the dual-link channel capacity can also be very large. And finally, 3) for high interference levels the rank deficient channels can sometimes provide higher dual-link channel capacity than measured and full rank channels.

4.2 Cooperative communications

Traditional cellular wireless communications systems are built using basestations that are connected to the wired high speed data networks. The fixed network has been specifically extended to each of the basestations using cables. Construction of such connections is very expensive and time consuming work. The construction of the full network can be made far simpler by equipping the basestations with a point-to-point wireless link which is used to route the data to and from the fixed network. However, as the cellular networks rely on basestations, the required coverage is only achieved by increasing the number of basestations. This, in turn, increases the expenses and interference in the network.

To overcome the requirements of fixed network infrastructure is one of the reasons [125, 126] that cooperative communications [127–129] has drawn attention in recent years. Cooperative communications utilize the concept of relaying, where other mobile terminals (relay nodes) can relay the signal from the basestation (source) to the end mobile user (destination). Thus, given that there are sufficient amount of users in the area, their terminals can be used to extend the coverage of the network. This method is already in use in Terrestrial Trunked Radio (TETRA) [130]. In



(a) Time slot #1 (b) Time slot #2

Figure 4.1: The concept of cooperative communications from source (S) to destination (D) using relay (R).

addition to utilizing relaying, in cooperative communications also the direct link from source to destination is used. Hence, in cooperative communications it is possible to achieve several independent paths using single antenna terminals. This is desirable, as the utilization of MIMO technology in hanheld devices has been shown to be very challenging in practise [131].

In addition, cooperative communications can utilize many access methods [125,126], such as frequency or time. However, simultaneous receiving and transmitting in the relay node would require efficient isolation between the two. This hardware related problem can be relaxed by using time sharing, i.e., half duplex transmission, which is only considered here.

Fig. 4.1 illustrates the concept of cooperative communications using half duplex transmission. In the figure, two paths from the source to destination exists. During time slot #1, the source transmits a signal to the relay and to the destination. During time slot #2, the relay node transmits the signal to the destination. For comparison, in the regular transmission scheme the source can transmit to the destination during time slots #1 and #2. This time protocol introduces a significant problem to the cooperative communication; its capacity over long period of time is halved [132].

Furthermore, the relay can process the received signal from the source in various ways [132]. The simplest method for the relay node is simply to amplify the received signal and retransmit it to the destination, a method called amplify-and-forward. A more sophisticated method is decode-and-forward, where the relay node detects the transmitted symbols, and retransmits the coded symbols to the destination.

The potential of the cooperative communications have been analyzed in theoretical studies, see for instance [132]. Only recently the theorethical relay concepts have been analyzed [133, 134] using measurement data, and the benefit of relaying has been shown to apply in real world scenarios. There are still a limited number of cooperative communications measurements available due to the hardware limitations.

Further, the first results on the dual-link (source-relay and relay-destination) *directional* measurements have been presented in [**II**]. However, the third link (source-destination) cannot be measured simultaneously with that system.

4.2.1 Summary of the contribution of this thesis

In a relay transmission analysis in [**V**], the capacity benefit of introducing a relay node with respect to direct transmission is considered in realistic outdoor-to-indoor relaying using diversity combining. The measurement equipment developed in [**I**] was used in the Otaniemi campus area. The transmitter was located on the roof of the neighboring building, the relay node was placed in an almost line-of-sight (LOS) location in a room throught a window, and the receiver was moved along the corridors inside the building close to the relay node.

The outdoor antenna was a dual-polarized 4×4 planar array, and the relay and the receiver antenna was a semi-spherical antenna array. The outdoor transmitter was located only sligthly above the 3rd floor level where the relay and the receiver were located. The relay acting as a receiver was using the antenna shown in Fig. 3.4(b) whereas antenna shown in Fig. 3.4(c) was used for the antenna used for transmission from the relay to the destination. As the antenna configurations are significantly different at the relay terminal for the source-relay and relay-destination measurements, no MIMO terminal aspects were analyzed. Instead, diversity analysis of the relaying was performed.

The results indicate that the introduction of a relay node increases the system throughput when the source-destination link is weak. When the source-destination link is strong, relaying does not increase the throughput because of the half duplex constraint, while a significant improvement of bit error rate (BER) was always observed.

5 Summary of publications

> "If we knew what it was we were doing, it would not be called research, would it?"
> – Albert Einstein

In [**I**] an extension of channel sounder equipment for MIMO configuration at the carrier frequency of 5.3 GHz is presented. In the work, feasible antenna array geometries for propagation research were designed under the constraint of the number of the measurement channels. Sounder control electronics were also designed and implemented. The key concepts solved in the work were the design and implementation of the synchronization framework for the MIMO measurement system, development of sophisticated antenna arrays with a limited number of channels, and the analysis of the tapering function used in the directional parameter estimation.

The work in [**II**] consists of designing the synchronization of two unsynchronized channel sounders to make a dynamic dual-link, dual-polarized wideband MIMO measurements possible, with the emphasis on resolving the double-directional properties of the two channels simultaneously, for the first time in the literature of the propagation research. Furthermore, the performance of the measurement system is evaluated through extensive test measurements and measurement data analysis.

The main results presented in [**III**] are the characteristics of the cluster behavior in outdoor micro- and macrocell measurements in terms of cluster shadow fading, cluster mean power, and cluster lifetimes. The work also provides a comparison of the cluster behavior between the 2 GHz and 5 GHz frequency ranges. The work uses manually clusterized data as any automatic clustering algorithms were not established.

The measurement system developed in [**II**] is used in [**IV**], where multiuser MIMO capacity is analyzed in time-variant indoor channels. The measurements were performed in an office environment with several transmitter and receiver positions and with a static and changing environment. From the measurements, the effect of spatial separation on the multiuser MIMO capacity was analyzed. Furthermore, as the received power levels between the links were found to determine the multiuser MIMO capacity, the human shadowing effect on the received power levels and on the capacity was analyzed. The human shadowing was found to introduce significant effects on the multiuser MIMO capacity.

The work in [**V**] evaluates a relay transmission in outdoor-to-indoor scenario using the measurement equipment developed in [**I**]. The analysis uses measurements with single-link measurements conducted on two separate occasions thereby creating a virtual dual-link measurement scenario. The analysis considers the benefits of introducing a relay node on the improvement of the channel capacity using macro-diversity. The macro-diversity combines signals arriving from the source and the relay at the destination. Two different signal forwarding schemes at the relay, namely amplify-and-forward and decode-and-forward, were analyzed along with the effect of power allocation for the source and relay. It was found that although the system throughput increases when utilizing a relay node, the relaying does not improve the overall throughput due to the time division multiplexing.

6 Conclusions and Future Work

> "Science never solves a problem without creating ten more."
> – George Bernard Shaw

In this thesis propagation channel characterization has been studied, concentrating on the MIMO channel measurement equipment design and development, and experimental data analyzes for the development of channel models. The basic properties of the propagation channels, which form the basis on top of which the propagation research has been developed, were studied. Further, the approaches for novel channel modeling and the hardware requirements for measuring the propagation channels were presented.

In the work, we studied the optimal antenna array configuration which would provide accurate estimation of the double directional channel model parameters including polarization. Further, an acceptable accuracy had to be achieved by acknowledging the constraints introduced by the hardware limitations. It was shown, that such a structure was successfully constructed by analyzing the accuracy of the system in test and real measurement situations. Furthermore, the usability of the developed hardware has been shown in several measurement campaigns in indoor, outdoor-to-indoor, urban micro and macro, and car-to-car environments, and the measurement results have been extensively used in the propagation channel modeling and communications systems development.

The hardware development continued further by extending the measurement system to simultaneously measure two links. This was accomplished by appropriately modifying the hardware of one link and developing post-processing methodologies for the measurement of a MIMO channel matrix without synchronizing the equipment by costly hardware modifications. The feasibility of the extended measurement system was examined, not only by specifically conducted test measurements, but also through the usage of the equipment in several indoor measurement campaigns. The measurement results have been analyzed in several studies and some measurement results were presented in this thesis.

In the second part of the work, analysis of the measured channels for specific wireless communications systems was presented. As noted in the early parts, the channel modeling is an important part of the design of the wireless communication systems. In this work, a contribution to the field of cluster based channel modeling was made in the form of cluster shadow fading analysis. This analysis requires a large number of channel measurement samples, which were provided by the measurement system developed in the early stages of this work.

Furthermore, in the work two promising emerging wireless systems were analyzed, namely multi-user MIMO and cooperative communications. MIMO channels have been analyzed extensively already before this work along with the studies conducted using the developed hardware. However, realistic dual-link MIMO channel measurements have not been conducted previously. Thus, the properties of the co-channel interferer was analyzed in an indoor office environment. The effect of the spatial separation of the interfering and the desired links on the dual-link capacity were found significant even with equal link power. Also, the effect of human body shadowing was analyzed and its effect on SIR was found to be large.

For the future there is still many things to do. Although the computational resources have developed immensely in recent years, still, the only reliable way to analyze realistic propagation channel scenarios is through measurements. Therefore, in the future, more measurement system development is required for supporting the rising wireless technologies, such as the previously mentioned car-to-car and relay channels, and ultrawideband systems. Furthermore, the already conducted measurements should be used along with recent developments in the field of parameter estimation [45] to enhance the existing MIMO, and multiuser MIMO, channel models. Especially interesting will be the inclusion of the distributed diffuse scattering to the channel models.

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