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Modelling of special wireless channels

Summary

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Introduction

Designers of modern wireless systems continuously aim at improving data throughput and reliability of communications. Advent of Multiple Input, Multiple Output (MIMO) communications the past decade is among the most important achievement in engineering sciences [GSsS$^+$03, PGNB04]. It took only a few years from the first theoretical results to the market appearance of standardized MIMO devices. Nevertheless, manufacturers and service providers seek to improve cost efficiency by using low-cost, easy to deploy and manage infrastructure. One step into this direction is the radio-over-fibre (RoF) that can replace complex and costly base stations by simple optical-electrical converters by shifting the complex processing tasks to a central station that generates and demodulates radio frequency (RF) carriers. The RF signal is then transmitted to/from the base stations over optical fibres.

Multipath fading channels have adverse effects on the communication capabilities. MIMO techniques converted this into an advantage by enabling higher throughput and/or reliability by using multiple antennas. To be able to use multiple antenna techniques efficiently, knowledge of the wireless channel is indispensable. On the other hand, in the RoF transmission the highly non-linear optical stage is a definite barrier in the communications. The present work aims at the characterisation, modelling and exploitation of such channels.

One of the focus topics is the satellite channel. More precise system-level characterization and capacity analysis of a previously known Single Input, Single Output (SISO) physical-statistical satellite channel model is aimed at, and attempts are made to extend this model to multi-antenna, single satellite links. On the other hand, the satellite-to-indoor MIMO channel is investigated by using electromagnetic calculations.

A special space-time coding scheme and a system are proposed in the second part of the thesis. The proposed scheme can be used in such MIMO channels where the terminals are equipped with highly directive antennas, therefore the MIMO channel is not full rank but rather mostly diagonal. Finally, the equivalent radio channel is analysed in radio-over-fibre transmission when Orthogonal Frequency Division Multiplex (OFDM) transmission with Mach-Zehnder optical modulator is employed.

Preliminaries and research goals

Previous measurements [SDB$^+$07] indicated that the polarization of the received signal becomes random in the satellite mobile channel. A right-hand circularly polarized transmit antenna was mounted on the satellite, but the received power did not depend on the choice of the receive antenna: right-hand and left-hand circular and even linearly polarized antennas produced the same receive power. From these results it was concluded that the environment causes electromagnetic scattering, and superposition of the scattered multipath components lead to „depolarization". Some studies proposed a model for the depolarization, based on the Stokes parameters. This model can predict the loss in receive power due to polarization mismatch between transmitter and receiver.

There are more options to achieve diversity in a satellite communication system. Space diversity can be used by communicating to multiple satellites. Pure space diversity using one single satellite is of limited use as the large distance renders the different diversity routes highly correlated. An effective means of single-satellite diversity is the use of orthogonally polarized antennas with some suitable space-time code. Mounting two antennas on the satellite and two on the terminal, one can use this arrangement as a 2x2 MIMO system and gain diversity or multiplexing advantage, provided that the channel is good enough. There are very few results dealing with this aspect of satellite diversity. Researchers investigated in terrestrial context whether using three, co-located and orthogonally polarized antennas at both link ends will increase the channel capacity. It is expected that due to scattering in the channel, the capacity will increase to three times with regard to the SISO case. Later it was proved that only logarithmic increase will result from adding the third antennae.

In the first part of this thesis I aimed at the characterisation of the satellite wireless channel, first by extending and analysing the power loss-based model, and by investigating the satellite-to-indoor channel from a polarization point of view. Furthermore, two more general space-time techniques are also discussed. The first aims at using space-time coded communications in scenarios where the data stream reach the receiver over multiple routes (two base stations or two satellites are used), but due to the high directivity of antennae, they see each other only pair-wise, thus the channel matrix is predominantly diagonal. Then I show that it is possible to extend space-time trellis codes in order to be useful with continuous phase modulations in a compatible manner.

The third main part of the thesis deals with OFDM radio-over-fibre transmission, specifically the characterisation of non-linear distortion over the optical stage and drawing conclusions regarding the achievable error rate degradation. Mach-Zehnder interferometer is assumed as optical modulator and OFDM-modulated RF carriers are treated. It is well known that OFDM implies high peak-to-average power ratio and thus it is highly vulnerable to non-linear distortion. Higher modulator drive means higher SNR in the receiver but also a higher degree of non-linear distortion. Thus, a compromise is sought for. I show that it is possible to exactly describe the non-linear distortion but the calculation is rather involved. Therefore, a simplified description is also given that not requires the specification of the input PSD.

Research approaches

I adopted both analyitic and simulation approaches in the research. Where possible, closed-form solutions are preferred and simulations are used to verify the results. In some cases only simulations are presented.

The satellite channel characterization is done in two different ways. First, a previously known SISO physical-statistical model is used as starting point for deeper analysis (channel capacity, error rates). Closed-form expressions were aimed at where possible, and Monte Carlo simulations were performed to support the analytic results. This SISO model was extended for MISO and MIMO cases afterwards, with some simplifying assumptions.

I developed a proprietary Finite Difference Time Domain (FDTD) electromagnetic solver for the indoor satellite MIMO channel analysis. This code was used to characterize the depolarization in the MIMO channel. A post-processing methodology was devised that takes the output of appropriately configured FDTD runs and extracts important system-level parameters of the channel.

The results on special space-time codes are also backed with computer simulations.

In the radio-over-fibre investigations, literature results were used as starting point regarding the form of non-linearity. It is also known from the literature that at the output of a memoryless non-linearity the distortion components can be separated with Gaussian input, and the PSD of the distorted OFDM signal can be expressed if the distortion can be characterised by linear combination of Bessel functions. This description was adapted to the present problem. I suggest a simplified description that maintains accuracy but enables closed form solutions through an approximation for the input PSD. The results are verified by computer simulations in this case as well.

New scientific results

Group 1: Modeling the satellite channel

Thesis 1.1

The Rayleigh fading model often describes adequately the non-line-of-sight wireless channels. Rayleigh models are often used as part of satellite channel models (Loo and Corazza models for instance). However, the *average power* of the received signal will undergo some fluctuations as the depolarization will change due to satellite motion and direction dependency of antenna gain and polarization. There is a physical-statistical model that reflects this fact a proposes a modified Rayleigh model in which the average power also varies by time [FMBH05]. The average power of the fading process will be varied according to two possible assumptions: either the received signal is regarded as completely random in the receiver or it is assumed that the linear polarization at the transmitter remains linear in the receiver. Both assumptions are investigated in this thesis.

Based on previously published channel models for the SISO depolarized Rayleigh fading satellite channel, I give closed form expressions for the capacity of such channels, and in some instances also error rates. I extend the SISO model to the depolarized SIMO satellite channel and an expression for its ergodic capacity. The model is also extended to the MIMO depolarized channel under simplifying assumptions, and simulation results are given for the achievable error rates using space-time block codes. [1], [2], [3], [4]

The PDF of the instantaneous SNR in the completely random case:

$$f_\rho(\rho) = \frac{1}{\overline{\rho}} E_1\left(\frac{\rho}{\overline{\rho}}\right), \quad \rho \geq 0. \tag{1}$$

The ergodic capacity can be expressed as

$$C = \frac{1}{\ln 2\, \overline{\rho}} G^{3,1}_{2,3}\left(\overline{\rho}^{-1} \middle| \begin{smallmatrix} -1,1 \\ 0,-1,-1 \end{smallmatrix}\right), \tag{2}$$

where $G^{m,n}_{p,q}(\cdot)$ is the Meijer G function. I also provide closed-form expressions for the high-SNR asymptotic behaviour of the capacity. Bound and approximation of the bit error rate for PSK-like modulation is given for this channel model.

If the polarization of the received signal becomes random but assumed to preserve its linear character, the PDF of the instantaneous SNR is expressed as

$$f_\rho(\rho) = \frac{e^{-\rho/\overline{\rho}}}{\sqrt{\pi \overline{\rho} \rho}} \quad \rho \geq 0, \tag{3}$$

the ergodic capacity becomes

$$C_{<pl,1>} = \frac{1}{\ln(2)}\left[\pi \operatorname{erfi}\left(\frac{1}{\sqrt{\overline{\rho}}}\right) - \gamma - \ln\left(\frac{1}{\overline{\rho}}\right) - \frac{2}{\overline{\rho}}\, {}_2F_2(1,1;\, 3/2, 2;\, 1/\overline{\rho})\right] - 2 \tag{4}$$

where $\operatorname{erfi}(\cdot)$ is the complex error function and ${}_2F_2(\cdot)$ is the hypergeometric function. Comparison of the capacity results are show in Fig. 1. The results were verified by computer simulations.

I extend the SISO model to the independent SIMO case and closed-form expression is given for the PDF of the SNR when two antennae are deployed at the ground terminal. Two-input, two-output extension is also proposed with some restrictive assumptions. This case is important from a practical point of view. This latter model can deal with completely correlated or completely uncorrelated receive antennae, and considers whether the originally orthogonal polarization components preserve orthogonality or lose it completely in the receiver. Bit error rate curves using the Alamouti space-time block code, obtained by simulations, are shown in Fig. 2.

Thesis 1.2

In the following two theses I focus on the geostationary satellite to indoor wireless channel. I intend to draw conclusions regarding the MIMO channel using compact,

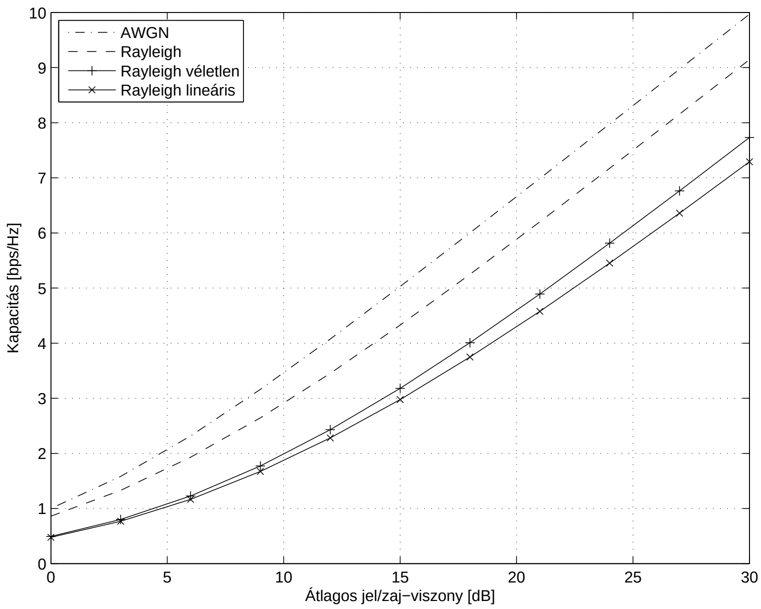

Figure 1: Ergodic capacity of depolarized Rayleigh-fading channels

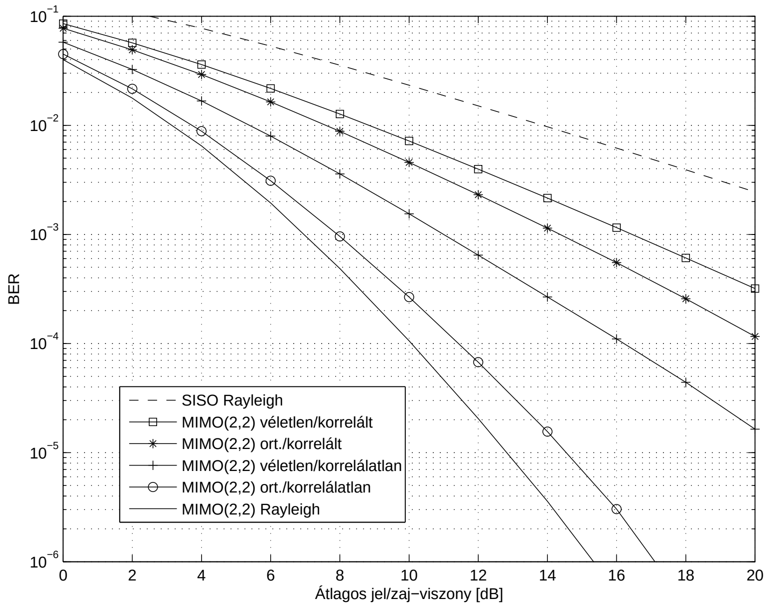

Figure 2: Comparison of frame error rates for the different MIMO cases

orthogonally polarized antennas. To this end I've chosen full-wave electromagnetic simulations (by FDTD) instead of conventional ray-tracing. In order to obtain results that are relevant for the communication system, MIMO matrices need to be extracted from the FDTD results and adequate performance metrics should be defined.

For FDTD-based propagation studies, I propose a post-processing methodology that enables calculating channel capacity and various diversity orders from appropriately configured FDTD calculations. The order of diversity can be derived either from the mutual information or from error rates. The proposed methodology can be applied for co-located tri-dipole or dual dipole configurations employed at the ground station. [5], [6], [7], [8]

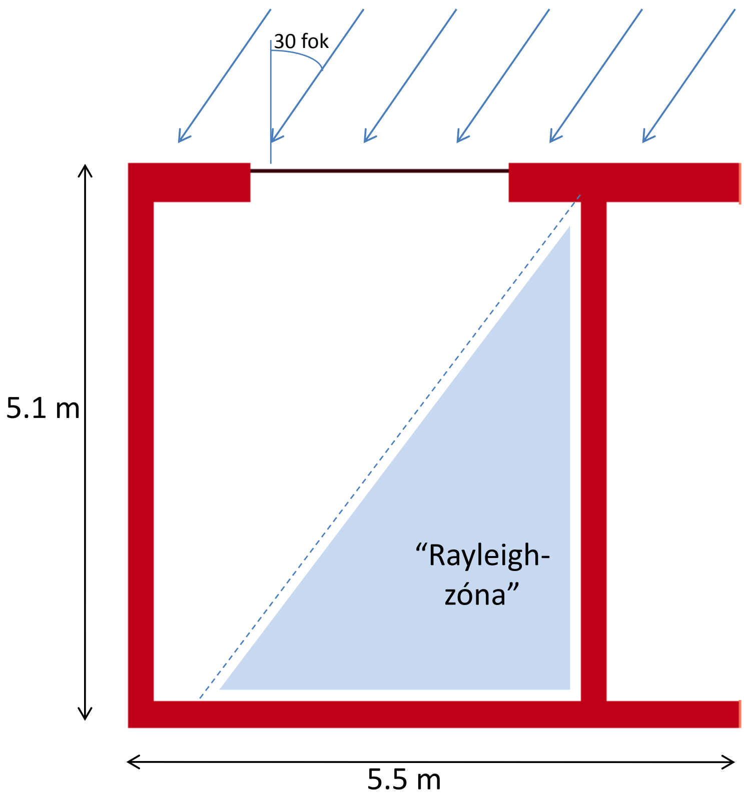

Figure 3: Floor plan in the x-y plane of the investigated geometry

Thesis 1.3

I conducted Finite Difference, Time Domain (FDTD) simulations in order to assess the polarization properties over the satellite-to-indoor channel (focusing on geostationary satellites). A specific room geometry was considered with various elevations of the incident satellite signal. Only such portions of the room were considered where at least two electromagnetic interactions are encountered by the signal (Fig. 3).

From FDTD simulations I derive the power correlation properties (co-polar ratio, cross-polar ratio) in the satellite-to-indoor channel in a particular geometry. I investigate the channel capacity and the order of diversity using two and three orthogonal linear antennas at the ground station, respectively. By these merits I confirm that MIMO techniques based on orthogonally polarized compact antennas are effective in the satellite-to-indoor setting. In the non-line-of-sight regions the fading statistics are shown to be approximately Rayleigh and the ergodic capacity matches well the capacity of the independent, identically distributed 2x2 MIMO channel. The results confirm that incremental capacity can be achieved and diversity gain is increased in the region of small outages when using three antennas instead of two at the ground station. [5], [6], [7], [8]

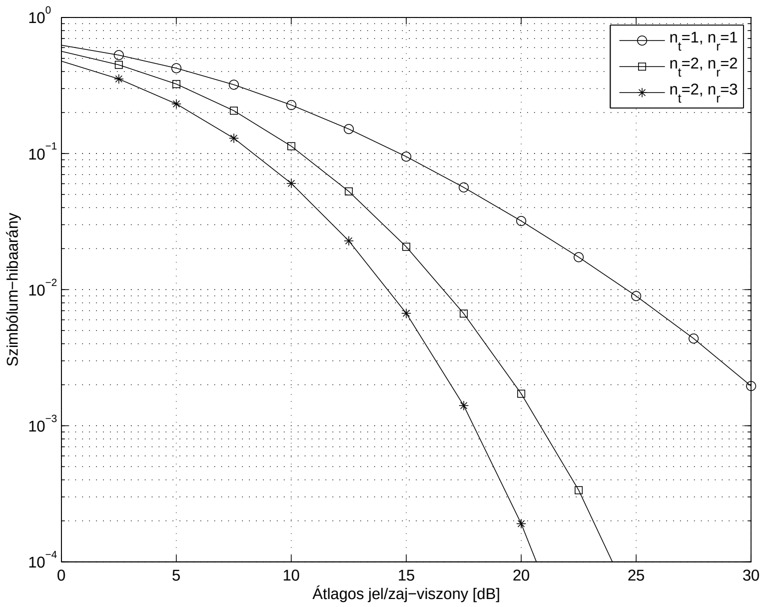

Figure 4: Average error probability for SISO(1,1), MIMO(2,2) and MIMO(2,3) configurations

Group 2: Some results on special space-time codes and coding schemes

Thesis 2.1

MIMO techniques can be efficiently used in multipath channels with rich scattering where many independent propagation path can exist between transmitter and receiver. In this thesis point a different application of space-time codes will be presented. An example for this application would be a millimetre-wave fixed wireless system, either used as future broadband cellular network or as backhaul. In such systems the line of sight propagation dominates, and if a terminal can communicate with many base stations, only pairs of antennae between transmitter and receiver can see each other, thus the channel matrix will be predominantly diagonal.

The proposed scheme can be regarded as a coded cooperation scheme where the base stations are cooperating using space-time trellis codes. On the other hand, this is a coded route diversity system as well.

In such environments the role of the space-time coding is different from that in a conventional MIMO system and the achievable diversity gain is also less. When compared to the conventional route diversity, all routes are treated as an entity and additional coding gain can be achieved by using trellis codes.

The central station (e.g. a base station controller-like entity in the network) uses a rate $1/n$ space-time trellis code to generate n coded streams from the input symbols. The temporal rate of code is unity, thus no additional bandwidth will be used when compared to the uncoded system. The streams will be transmitted from n base stations to the user terminal via different routes. The receiver acquires channel state information and decodes the stream by using e.g. the vector Viterbi algorithm, thus optimally combining the signals from each route.

I propose a generalized route diversity scheme, that regards the route diversity system as a MIMO system. It is shown that the generalized route diversity can be realized using space-time trellis codes. It is proven that the code selection should be based on the maximizing the smallest Euclidean distance among codewords. This scheme can be regarded as a coded cooperative communication system. The usefulness of this scheme is demonstrated using measured attenuation time series over millimetre-wave point-to-point links.[9], [10], [11], [12], [13]

Thesis 2.2

Early research on space-time coding focused on linear modulations (PSK, QAM). Only a few papers dealt with continuous phase modulation (CPM) schemes. In this thesis point I present a constructive method that exploits the pulse amplitude modulation decomposition of CPM by Laurent [Lau86]. This method enables the use of QPSK space-time trellis codes with full-response CPM formats without the need for any modification to the signal processing chain.

I propose a space-time coding scheme for continuous phase modulations. The scheme is based on the Laurent representation of CPM signals. By using appropriate space-time codes and symbol mapping in the modulator, QPSK space-time codes can be used for CPM signals without any need for modification in the transceiver architecture. The efficiency of this scheme is demonstrated and verified for MSK modulation by simulations. (Fig. 5). [14]

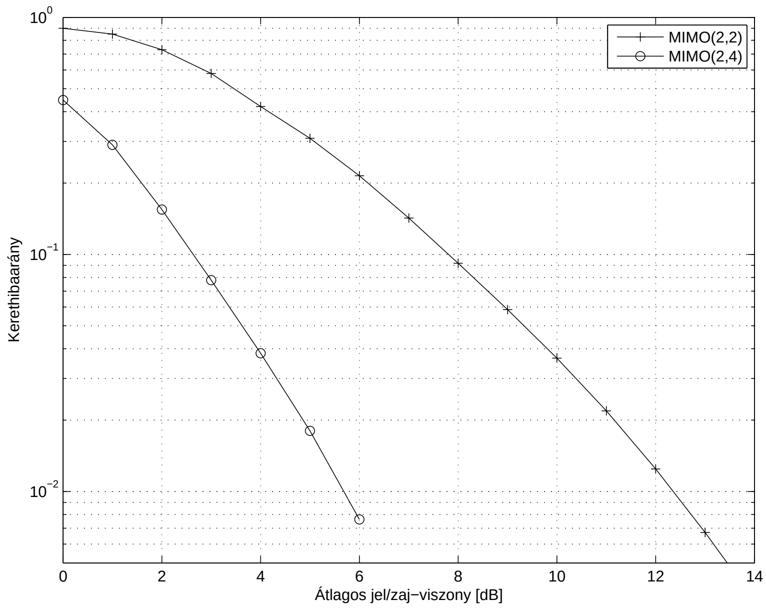

Figure 5: Frame error rate of the MSK transmission over Rayleigh-fading channel

Group 3: Effects of modulator non-linearity in OFDM radio-over-fibre transmission

In this thesis I present an analysis of the baseband equivalent of the OFDM RoF transmission (Fig. 6). According to previous publications, the distortion can be characterised by a Bessel function of the first kind [HAR02] and I also verified this by an optical simulator. The goal of the analysis is to produce expressions for the bit error ratio (BER) degradation caused by the non-linearity. To this end the power spectrum density (PSD) of the distorted signal needs to be determined.

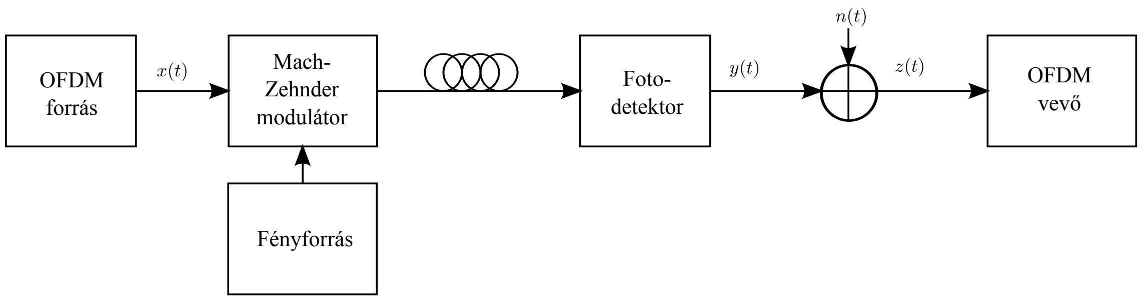

Figure 6: Model of the radio-over-fibre transmission system

Thesis 3.1

If the distortions in the optical section of a RoF link can be characterised by Bessel functions of the first kind, then the separability of the distortion products at the output can be used and a known closed-form solution can be used. I give an analytic expression for the PSDs of the useful signal and the distortion components in a Mach-Zehnder-modulated RoF section.

The PSD of the output signal can be expressed using the input PSD as follows:

$$S_{yy}(f) = \frac{c_0}{2\sigma^2} S_{xx}(f) + \sum_{k=1}^{\infty} \frac{c_k}{(2\sigma^2)^{2k+1}} [S_{xx}(f) *_1 \cdots *_{2k+1} S_{xx}(f)], \tag{5}$$

where the values of coefficients c_k is shown to be

$$c_k = \frac{1}{(k+1)!k!} \left[2 \left(\frac{\sigma}{\sqrt{2}} \right)^{2k+1} e^{-\left(\frac{\sigma}{\sqrt{2}}\right)^2} \right]^2. \tag{6}$$

Here k is the index of the distortion product, S_{xx} is the PSD of the input OFDM signal and $2\sigma^2$ is the average power of the input signal. It is assumed that the modulator is appropriately biased so as to work in its near-linear regime.

Thesis 2.2

I suggest a simple closed-form approximation for the shape of the PSD of the OFDM signal and the distortion components. This approximation lends itself for easy analytic calculations of the non-linear distortion in the OFDM transmission, independently of the exact form of non-linearity.

The PSD of the kth order distortion component:

$$S_k(\nu) = \frac{(2\sigma^2)^l}{2^l (l-1)!} \sum_{m=0}^{l} (-1)^m \binom{l}{m} (\nu + l - 2m)^{l-1} \mathrm{u}(\nu - m) \tag{7}$$

where $l = 2k+1$ and $\nu = f/T$ is the normalized frequency, and $\mathrm{u}(\cdot)$ is the Heaviside unit step function.

Thesis 3.3

Using the approximation shown in Thesis 3.2 and the formula provided in Thesis 3.1, expressions for the PSD of the distorted signal are provided and the output signal-to-distortion ratio can be calculated. This method allows for direct bit error rate determination. [15], [16], [17]

The full PSD of of the output signal:

$$S_y(\nu) = \sum_{k=0}^{\infty} c_k S_k(\nu) \tag{8}$$

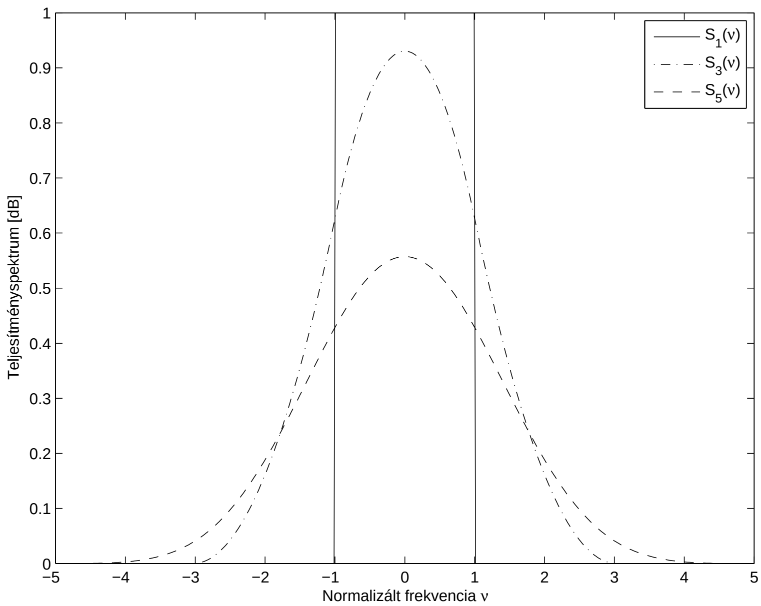

Figure 7: Approximating the PSD of OFDM signals by a window function

where c_k is obtained using (6), and $S_k(\nu)$ should be determined either numerically from the PSD of the input signal, or from the approximation based on (7) (Fig. 8).

This enables the calculation of the subcarrier signal-to-distortion ratio for the subcarrier at the normalized frequency l:

$$\rho_{\mathrm{eff},l} = \frac{S_u(\nu)}{N_0 + S_d(\nu)} \;|_{\nu=l}, \tag{9}$$

where S_u is the PSD of the useful signal, S_d the distortion products, respectively, and N_0 is the density of the additive white Gaussian noise. This effective SNR will ultimately determine the BER, and can be substituted into the known BER vs. SNR formulas.

Based on this calculations, curves are presented that show the uncoded bit error rate if the modulator back-off is varied. This curves can be used in the link budget planning.

All results in the present Thesis are verified by computer simulations and a good agreement is found between the predicted values and the simulation results.

Exploitation of the results

Most of the results were achieved in the framework of various international collaborative projects (IST FP5 EMBRACE, IST FP6 BROADWAN, IST FP6 SatNEx), some of the appeared in project deliverables. The MIMO research was incorporated into various classes at the university. The results about polarization-based MIMO were exploited by coverage planning and analysis by a mobile service provider.

I supervised various master's theses and students' scientific work (TDK) research activities, that were in connection to the topics presented in this work. A TDK work, that is related to thesis point 2, was awarded with the first prize in the

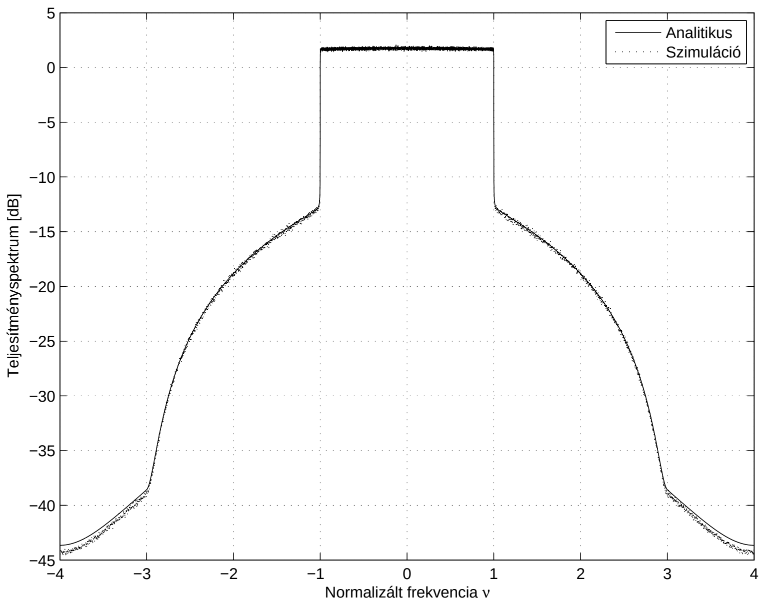

Figure 8: Comparison of the PSDs obtained from the closed-form expression and simulation, Back-off: 2.15 dB

national TDK competition. My research results were published in international journals and conferences. My paper [13] was awarded by the Pollák-Virág prize of the Hungarian Infocommunications Society.

The simulation results were predominantly obtained by proprietary software tools. The MIMO-related simulation results and the OFDM distortion analyses were performed by using my C++ communication systems library. An own FDTD tool was also developed for the thesis, supported by the Mobile Innovation Centre. This tool is used at the department both as a standalone application and embedded in other applications as well.

The analysis of the non-linearity effects on OFDM transmission is currently exploited in an EU-funded project in which physical layer waveforms are designed and analysed for cognitive radios.

Thesis-related own publications

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