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Scattering in Non-Stationary Mobile-to-Mobile Communications Channels

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Abstract

The aim of this thesis is to introduce a non-stationary model for the scattering in mobile-to-mobile channels. Due to the evolution of wireless technology, fixed-to-mobile communications systems are nowadays complemented by mobile-to-mobile communications systems.

In the vehicular sector, mobile-to-mobile communications systems are used to enable intelligent transportation systems. Such systems aim to make transportation safer and more efficient by distributing sensor information among the cars. In the aeronautical sector, mobile-to-mobile communications systems will be used, for example, to exchange position, altitude, speed, and heading data between aircraft during flight thus allowing a reduced separation between them. Hence, these systems are necessary to further increase the air traffic density.

Stochastic channel models for the fixed-to-mobile channel are based on the assumption that the channel is wide-sense stationary and exhibits uncorrelated scattering behavior both in a stochastic sense. It has been shown that many mobile-to-mobile channels do not adhere to such assumptions, especially vehicle-to-vehicle and air-to-air channels. The need for new models is therefore due to the fact that mobile-to-mobile channels are fundamentally different from fixed-to-mobile channels.

To overcome the limitations of current channel models, two measurement campaigns to characterize both the vehicle-to-vehicle and the air-to-air channel as exemplary mobile-to-mobile channels were conducted. The measurements confirm the non-stationary behavior of those channels and subsequently, a theoretical model is created on the basis of the measurement data. The employed model is a geometry-based stochastic channel model, which means it consists of two parts. In the geometric part, new expressions for channel parameters, such as delay and Doppler frequency, are derived. In the stochastic part, those expressions enable us to determine closed-form solutions for the required time-variant probability density functions. The presented model can be seen as a generalization of the wide-sense stationary, uncorrelated scattering models.

Since the calculations of the probability density functions are time consuming, the application of a different coordinate system is investigated and we show that computational gains are achieved by using prolate spheroidal coordinates. Additionally, other important channel parameters, such as mean Doppler and Doppler spread, are derived.

The presented theoretical channel model is validated by the measurement data that has been recorded for both the vehicle-to-vehicle and the air-to-air channel. In each case, there is a remarkable agreement between measurement data and the channel model. The model also matches with measurement data recorded by other institutions that used different scenarios. This versatility allows the model to be very general and it can be applied to a wide range of scenarios.

Contents

Chapter 1

Introduction

In the 1860s, Scottish physicist James Clerk Maxwell predicted the existence of electromagnetic waves. Maxwell's equations were the beginning of the wireless communications age. However, it took more than twenty years to experimentally prove that the predictions of the electromagnetic theory were right. Heinrich Hertz, a German physicist, succeeded in 1886 to transfer electromagnetic waves from a transmitter (TX) to a receiver (RX) and thus confirmed Maxwell's theory. Guglielmo Marconi then extended the work of Hertz to achieve long-distance communications. Marconi started at a young age sending wireless messages across his father's garden. After immigrating to England, Marconi continued to increase the distance of the wireless telegraphy. The biggest success was the first transatlantic wireless transmission. He built a transmitter station in Poldhu, Cornwall, UK, and a receiver station on what is today known as Signal Hill in St. John's, Newfoundland, Canada. He reportedly received the first message, the Morse code letter S, on 12th December 1901, which started the inexorable usage of wireless communications systems.

One of the early application fields of wireless communications was the transmission of messages between oceangoing vessels, especially in case of emergency. Since the wired telegraphy already connected Europe and America since 1858, transmissions to and from ships seemed to be a very useful application of the new wireless technology. Interestingly, wireless technology has been used from the beginning for the purpose of mobile-to-mobile (M2M) communications, as transmitter and receiver are mobile and not connected via cable. One of the most famous examples of early M2M communications is the use of the new technology during the sinking of the Titanic.In this example, M2M communications was used to notify the HMS Carpathia about the accident allowing the HMS Carpathia to change course saving many passengers from the freezing cold water. Thus, the usefulness of M2M communications became clear.

Due to the size of the equipment, ship-to-ship communications remained the only civil M2M application for a long time. In the 1920s, radio stations began using the wireless technology for radio broadcast, i.e., fixed-to-mobile (F2M) communications. The difference between F2M and M2M communications is that only the receiver moves while the transmitter is located at a fixed position. F2M communications became the dominant form of wireless communications for the next decades. Television broadcast was introduced at the end of the 1920s. The next important wireless development was the cellular phone system. The first hand-held phone was presented by Motorola in 1973, and in 1983 the first commercial cell phone became available. In the cellular phone system, transmitter and receiver can be mobile, but both transmitter and receiver are connected via a base station. Therefore, the cellular phone system is another example of F2M communications.

Except for military applications, M2M communications became negligible compared to F2M communications due to the size of the transmit equipment. Only in the last couple of years M2M communications systems have been deployed again due to the miniaturization of the electronic components. The new emerging communications systems, e.g., IEEE 802.22, IEEE 802.11p, and IEEE 802.16 allow two mobile users to be directly connected without the need of a base station. The mobility and direct connectivity opens up a broad new field of applications, especially in the vehicular and aeronautical sectors.

The M2M communications systems may be used in the future to connect two aircraft while being airborne to establish a mobile ad-hoc network in order to exchange flight critical data [WFS10]. An even bigger area of operations foreseen to change is in cars. In the vehicular sector, the applications of M2M communications systems are mentioned in the context of intelligent transportation systems (ITSs), which comprise even more than the pure communications systems. Cars are foreseen to exchange sensor data about traffic, weather conditions, movement parameters, etc. to increase the safety and efficiency of automobile transportation. Furthermore, swarms of unmanned vehicles, like unmanned underwater vehicles (UUVs) or unmanned aerial vehicles (UAVs) use M2M communications to coordinate their movements in an unknown environment [LLZ+08]. M2M communications is also a very promising technology for military communications especially on the battlefield, where mobile units need to be coordinated by means of communications systems [SN11].

In order to properly design efficient M2M communications systems, the propagation conditions have to be investigated and modeled. The signal propagation mechanisms between transmit antenna and receive antenna, e.g., attenuation, signal shadowing or multipath effects are modeled by the wireless channel: The channel describes the electromagnetic environment for the communications signal on its way from transmitter to receiver.

Accurate channel models have always been very important for the design and testing of new communications systems. This is due to the fact that communications systems are usually tested by numerical simulations, and a channel model is needed to accurately represent the impact of the propagation effects onto the system. With such models, the capacity, bit error rate, quality of service, etc, can be assessed even before the actual system is built. If the channel model is accurate, the performance of the simulated communications system comes very close to the real communications system. For F2M channels like the ones occurring in cellular phone systems, there exist numerous different channel models that are in good agreement with measurement data. The channel models at the beginning of cellular telephony age in the 1980s and 1990s relied heavily on a stochastic description of the channel. Those channel models are based on the assumption that the channel is stationary for a certain time.

However, M2M channels are *fundamentally* different from F2M channels. Since both transmitter and receiver move at high velocities in the vehicular and aeronautical case, the channel becomes non-stationary. Therefore, the F2M channel models can only be used for particular M2M scenarios, where the geometry remains constant, and needs to be extended. Due to the channel being non-stationary, propagation conditions can vary rapidly. Non-stationary channel models are needed for the description of a rapidly changing environment.

In this thesis, a new channel model for M2M communications is presented. The model is based on a geometric-stochastic approach that includes non-stationarity and time-variance. The probability density functions (pdfs) for delay and Doppler frequency are derived. Hereby, the mathematical description corresponds to the geometry of the scenario. The proposed channel model is used to simulate the time-variant scattering effects in M2M channels. The geometry of the scenarios becomes important when simplifications for the model are implemented. As the model is theoretical in nature, the model is validated with measurement data for the vehicle-to-vehicle (V2V) and air-to-air (A2A) channel.

The thesis is structured as follows:

In Chapter 2, we provide an extensive overview of three different channel modeling techniques: stochastic channel modeling, geometric channel modeling, and geometric-stochastic channel modeling. The most important results of stochastic channel models are summarized and its shortcomings for the M2M channel molding are explained. The main drawback for purely stochastic models is the wide-sense stationary uncorrelated scattering (WSSUS) assumption. It is shown, how the WSSUS models can be generalized to incorporate non-WSSUS models. Purely geometric models include the non-stationarity, but the analytical analysis of these models can be cumbersome for calculations if the propagation environment is difficult. A combination of stochastic and geometric channel modeling techniques merges the advantages of both. Applications for such modeling techniques are found in V2V and A2A channel models, for which we do a literature survey.

In order to model these two M2M channels adequately, we conducted two measurement campaigns for both the V2V and the A2A channel. The details of the measurement campaigns are described in Chapter 3. The channel sounding equipment and measurement parameters are illustrated as well. For the vehicular measurement campaign, we provide information about the measurement vehicles, vehicular antennas, and routes. For the aeronautical campaign, the measurement aircraft, aircraft antennas, and flight profiles are described. The data collected in these campaigns is later used to validate the theoretical models.

In Chapter 4, a new V2V channel model for road-side scattering is presented. A theoretical two-dimensional geometric-stochastic channel model (GSCM) is introduced and the choice for this particular model is explained both in the geometric and stochastic part. To validate the model, we compare the theoretic results with the data obtained from the V2V measurement campaign. The comparison reveals a very good agreement between the theoretical channel model and the measured channel. Since the calculations of the probability density functions of the channel are only feasible numerically, two additional ways of describing them are proposed. In the prolate spheroidal coordinate system it is possible to obtain rational solutions for the probability density functions. Furthermore, stochastic descriptions of the channel like the characteristic function, the mean Doppler and the Doppler spread can be calculated. The second approach uses means from algebraic geometry to parameterize the trigonometric functions in order to obtain polynomial solutions.

The V2V channel model is extended in Chapter 5 towards a three-dimensional A2A channel model. By increasing the dimension of the Euclidean space, the same mathematical methods can be applied for the aeronautical channel. Principally, increasing the dimension means using three-dimensional geometric objects instead of two-dimensional ones. Similar to the previous chapter, a theoretical channel model for the joint delay Doppler frequency pdfs are derived. The obtained channel model is compared to the measured A2A channel. Moreover, similarities and differences to the V2V channel are explained.

Chapter 6 summarizes the contributions of the thesis focusing on the new geometric-stochastic modeling techniques together with the problems that were solved by those contributions. An outlook addresses the open question and challenges of future research.

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