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THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Predictor Antenna Systems: Exploiting Channel State Information for Vehicle Communications

Hao Guo

CHALMERS
UNIVERSITY OF TECHNOLOGY

Communication Systems Group
Department of Electrical Engineering
Chalmers University of Technology
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Hao Guo

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Communication Systems Group
Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Phone: +46 (0)31 772 1000
www.chalmers.se

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To my parents

Abstract

Vehicle communication is one of the most important use cases in the fifth generation of wireless networks (5G). The growing demand for quality of service (QoS) characterized by performance metrics, such as spectrum efficiency, peak data rate, and outage probability, is mainly limited by inaccurate prediction/estimation of channel state information (CSI) of the rapidly changing environment around moving vehicles. One way to increase the prediction horizon of CSI in order to improve the QoS is deploying predictor antennas (PAs). A PA system consists of two sets of antennas typically mounted on the roof of a vehicle, where the PAs positioned at the front of the vehicle are used to predict the CSI observed by the receive antennas (RAs) that are aligned behind the PAs. In realistic PA systems, however, the actual benefit is affected by a variety of factors, including spatial mismatch, antenna utilization, temporal correlation of scattering environment, and CSI estimation error. This thesis investigates different resource allocation schemes for the PA systems under practical constraints, with main contributions summarized as follows.

First, in Paper A, we study the PA system in the presence of the so-called spatial mismatch problem, i.e., when the channel observed by the PA is not exactly the same as the one experienced by the RA. We derive closed-form expressions for the throughput-optimized rate adaptation, and evaluate the system performance in various temporally-correlated conditions for the scattering environment. Our results indicate that PA-assisted adaptive rate adaptation leads to a considerable performance improvement, compared to the cases with no rate adaptation. Then, to simplify e.g., various integral calculations as well as different operations such as parameter optimization, in Paper B, we propose a semi-linear approximation of the Marcum Q-function, and apply the proposed approximation to the evaluation of the PA system. We also perform deep analysis of the effect of various parameters such as antenna separation as well as CSI estimation error. As we show, our proposed approximation scheme enables us to analyze PA systems with high accuracy.

The second part of the thesis focuses on improving the spectral efficiency of the PA system by involving the PA into data transmission. In Paper C, we analyze the outage-limited performance of PA systems using hybrid automatic repeat request (HARQ). With our proposed approach, the PA is used not only for improving the CSI in the retransmissions to the RA, but also for data transmission in the initial round. As we show in the analytical and the simulation results, the combination of PA and HARQ protocols makes it possible to improve the spectral efficiency and adapt transmission parameters to mitigate the effect of spatial mismatch.

Keywords: Beyond 5G, 6G, channel state information (CSI), hybrid automatic repeat request (HARQ), integrated access and backhaul (IAB), Marcum Q-function, mobility, mobile relay, outage probability, predictor antenna (PA), rate adaptation, relay, spatial correlation, temporal correlation, throughput, wireless backhaul.

List of Publications

This thesis is based on the following publications:

[A] **H. Guo**, B. Makki, and T. Svensson, "Rate adaptation in predictor antenna systems". *IEEE Wireless Communications Letters*, vol. 9, no. 4, pp. 448-451, Apr. 2020.

[B] **H. Guo**, B. Makki, M.-S. Alouini, and T. Svensson, "A semi-linear approximation of the first-order Marcum Q-function with application to predictor antenna systems". Submitted to *IEEE Transactions on Vehicular Technology*, May 2020.

[C] **H. Guo**, B. Makki, M.-S. Alouini, and T. Svensson, "Power allocation in HARQ-based predictor antenna systems". Submitted to *IEEE Wireless Communication Letters*, Apr. 2020, under minor revision.

Other publications by the author, not included in this thesis, are:

[D] **H. Guo**, B. Makki, and T. Svensson, "A genetic algorithm-based beamforming approach for delay-constrained networks". in *Proc. IEEE WiOpt*, Paris, France, May 2017, pp. 1-7.

[E] **H. Guo**, B. Makki, and T. Svensson, "A comparison of beam refinement algorithms for millimeter wave initial access". in *Proc. IEEE PIMRCW*, Montreal, QC, Canada, Oct. 2017, pp. 1-7.

[F] **H. Guo**, B. Makki, and T. Svensson, "Genetic algorithm-based beam refinement for initial access in millimeter wave mobile networks". *Wireless Communication and Mobile Computing*, Jun. 2018.

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Acronyms

2G/4G/5G/6G	Second/Fourth/Fifth/Sixth generation
3GPP	3rd generation partnership project
ACK	Acknowledgment
ARQ/HARQ	Automatic repeat request/Hybrid automatic repeat request
CDF	Cumulative distribution function
CSI	Channel state information
CSIT	Channel state information at the transmitter
DL	Downlink
EMBB	Enhanced mobile broadband
FDD	Frequency division duplex
FSO	Free-space optical
GPS	Global Positioning System
IAB	Integrated access and backhaul
i.i.d.	Identical and independently distributed
INR	Incremental redundancy
LOS	Line-of-sight
LTE	Long-Term Evolution
MIMO	Multiple-input multiple-output
MISO	Multiple-input single-output
MRN	Moving relay node
MTC	Machine-type communications
NACK	Negative acknowledgment
NLOS	Non-line-of-sight
NMSE	Normalized mean squared error

npcu	Nats-per-channel-use
NR	New Radio
OFDM	Orthogonal frequency-division multiplexing
PA	Predictor antenna
PDF	Probability density function
QoS	Quality of service
RA	Receive antenna
RF	Radio-frequency
RTD	Repetition time diversity
SNR	Signal-to-noise ratio
TDD	Time division duplex
UL	Uplink
URLLC	Ultra-reliable low-latency communications
V2X	Vehicle-to-everything

Contents

Part I

Overview

CHAPTER 1

Introduction

1.1 Background

Nowadays, wireless communication and its related applications play important roles in our life. Since the first mobile communication system employed in the early 1980s, new standards were established roughly every ten years, leading to the first commercial deployment of the fifth generation (5G) cellular networks in late 2019 [1]–[3]. From the second generation (2G), where the first digital communication system was deployed with text messages being available, through the recent fourth generation (4G) with 3rd generation partnership project (3GPP) Long-Term Evolution (LTE) being the dominant technology, to future 5G with New Radio (NR) standardized by the 3GPP [4], one theme never changes: the growing demand for high-speed, ultra-reliable, low-latency and energy-efficient wireless communications with limited radio spectrum resource.

According to the Ericsson mobility report [1], the total number of mobile subscriptions has exceeded 8.1 billion today, with 4G being the major standard, and it is expected that this number will reach around 9 billion with over 20% being supported by NR by the end of 2024 [1]. Thanks to the higher bandwidth (usually larger than 1 GHz) at millimeter wave frequency spectrum, as well as the development of multi antenna techniques, new use cases in 5G, such as intelligent transport systems, autonomous vehicle control, virtual reality, factory automation, and providing coverage to high-mobility users, have been developed rapidly [5]. These use cases are usually categorized into three distinct classes by the standardization groups of 5G [6]:

i) Enhanced mobile broadband (EMBB) deals with large data packets and how to deliver them using high data rates [7]. This can be seen as a natural extension of the current established LTE system that is designed for the similar use case. Typical EMBB applications involve high-definition video steaming, virtual reality, and online gaming.

ii) Massive machine-type communications (MTC) is a new application in 5G, which targets at providing wide coverage to a massive number of devices such as sensors who send sporadic updates to a base station (BS) [8]. Here, the key requirements are energy consumption, reliability, and scalability. High data rate and low latency, on the other hand, are of secondary importance.

iii) Ultra-reliable low-latency communications (URLLC) concerns mission-critical applications with stringent requirements on reliability and latency [8]. In this type of use case, the challenge is to design protocols which can transmit data with very low error probability and fulfill the latency constraint at the same time. Applications falling into this category include real-time control in smart factories, remote medical surgery, and vehicle-to-everything (V2X) communications which mainly focus on safety with high-mobility users.

This thesis targets both EMBB and URLLC. More specifically, this work develops efficient (high data rate) and reliable (low error probability) V2X schemes with latency requirement, using the predictor antenna (PA) concept. A detailed review of the V2X communications and the PA concept, as well as the associated research challenges, are presented in the following sub-sections.

1.1.1 Vehicle Communications in 5G and Time/Space-Varying Channel

Providing efficient, reliable broadband wireless communication links in high mobility use cases, such as high-speed railway systems, urban/highway vehicular communications, has been incorporated as an important part of the 5G developments [9]. According to [10], 5G systems are expected to support a large number of users traveling at speeds up to 500 km/h, at a data rate of 150 Mbps or higher. One interesting scenario in 5G vehicle communication is the moving relay node (MRN), where a significant number of users could access cellular networks using moving relays, e.g., at public transportation such as buses, trams, and trains, via their smart phones or laptops [11]. As one type of MRN, one can consider the deployment of integrated access and backhaul (IAB) nodes on top of the vehicles [12], where part of the radio resources is used for wireless backhauling. In this way, moving IAB nodes can provide feasible solutions for such relay densification systems in 5G[1].

[1] It should be noted that mobile IAB is not supported in 3GPP Rel-16 and 17. However, it is expected to be discussed in the next releases.

Most current cellular systems can support users with low or moderate mobility, while high moving speed would limit the coverage area and the data rate significantly. For example, 4G systems are aimed at supporting users perfectly at the speed of 0-15 km/h, serving with high performance from 15 km/h to 120 km/h, and providing functional services at 120-350 km/h [13]. On the other hand, field tests at different places [14] have shown that current 4G systems can only provide 2-4 Mbps data rate in high-speed trains. To meet the requirement of high data rate at high moving speed in future mobility communication systems, new technologies that are able to cope with the challenges of mobility need to be developed.

With the setup of MRN and other V2X applications such as vehicle platooning [15]–[17] and remote driving [18], different technologies can be applied to improve the system performance at high speeds. For example, strategies in current standard aiming at improving the spectral efficiency include multiple-input multiple-output (MIMO), channel state information (CSI)-based scheduling, and adaptive modulation and coding. Moreover, in the future standardization, techniques such as coordinated multipoint (CoMP) joint transmission (JT) and massive MIMO will be also involved. All these techniques have one thing in common: they require accurate estimation of channel state information at the transmitter (CSIT) with acceptable cost. However, this is not an easy task. The main reason is that the channel in vehicle communication has certain features which makes it difficult to acquire CSIT [14]:

i) *Fast time-varying fading*: For high-speed vehicles, the channel has fast time-variation due to large Doppler spread. Let us consider a simple example. Assume a vehicle operating at a speed of 200 km/h and a frequency of 6 GHz. Then, the maximum Doppler frequency is obtained by $f_{\mathrm{D}} = v/\lambda$ =1111 Hz, which corresponds to a channel coherence time of around 900 μs. However, in LTE the control loop time with both uplink (UL) and downlink (DL) is around 2 ms, which makes CSIT outdated if we consider the time division duplex (TDD) system with channel reciprocity. Moreover, the speeds of moving terminals are usually time-varying, making the channel even more dynamic.

ii) *Channel estimation errors*: Due to the time-varying channel, it is not practical to assume perfect CSIT, as we do for low mobility systems. In fact, mobility causes difficulties not only on accurately estimating the channel, but also on tracking, updating and predicting the fading parameters. Also, the estimation error may have remarkable effects on system performance, which makes this aspect very important in the system design.

iii) *Doppler diversity*: Doppler diversity has been developed for systems with perfect CSIT, in which it provides diversity gain to improve system performance. On the other hand, Doppler diversity may cause high channel estimation error, which makes it important to study the trade-off between Doppler diversity and estimation errors.

Besides these three aspects, there are also some issues for the channel with mobility, e.g., carrier frequency offset, inter-carrier interference, high penetration loss, and frequent handover. To conclude, with the existing methods and depending on the vehicle speed, channel coefficients may be outdated at the time of transmission, due to various delays in the control loop and the mobility of the vehicles.

The use of channel predictions can alleviate this problem. By using the statistics over time and frequency, combining with linear predictors such as Kalman predictor, the channel coefficients can be predicted for around 0.1-0.3 carrier wavelengths in space [19]. This prediction horizon is enough for 4G systems with short control loops (1-2 ms) or for users with pedestrian velocities. However, it is inadequate for vehicular velocities at high frequencies.

1.1.2 Predictor Antenna and Related Work

To overcome the issue of limited prediction horizon in the rapidly changed channel with mobility, and to support use cases such as MRN, [19] proposed the concept of PA. Here, the PA system refers to a setup with two sets of antennas on the roof of a vehicle, where the PAs positioned in the front of the vehicle are used to predict the channel state observed by one receive antenna (RA) or a set of RAs that are aligned behind the PAs, and send the CSI back to the BS. Then, if the RA reaches the same point as the PA, the BS can use the CSI obtained from the PAs to improve the transmission to the RAs using, for example, power/rate adaptations and beamforming. The results in [19] indicate that the PA system can provide sufficiently accurate channel estimation for at least one wavelength in the line-of-sight (LOS) case, and [20] shows that with a smoothed roof of the vehicle to avoid refraction, abnormal reflection and scattering, and with antenna coupling compensation at least 3 wavelengths can be predicted in both LOS and non-line-of-sight (NLOS) conditions.

Following [19], [21]–[23] provide experimental validation to prove the feasibility of the PA concept. Specifically, [21] presents an order of magnitude increase of prediction horizons compared to time-series-based prediction. Moreover, [22] shows that the PA concept works for massive MIMO DLs where the PA can improve the signal-to-interference ratio in setups with NLOS channels. Also, [23] demonstrates that the Kalman smoothing-based PA system enables up to 0.75 carrier wavelengths prediction at vehicle speeds for Rayleigh-like NLOS fading channels. The review of [19], [21]–[23] reveals the following research problems:

i) *Speed sensitivity*: From the results in [21]–[23], we can observe that, for given control loop time, if the speed is too low or too high which leads to large distances, i.e., spatial mismatch, between the spot where the PA estimates the channel and the spot where the RA reaches at the second time slot, the accuracy of prediction decreases drastically. We cannot make sure that the speed of the vehicle remains the same all the time, which may lead to performance loss. Indeed, [24] and [25] have addressed this kind of spatial mismatch problem in the PA system. In [24], an interpolation-based beamforming scheme is proposed for DL multiple-input single-output (MISO) systems to solve the mispointing problem. From another perspective, [25] studies the effect of velocity variation on prediction performance. However, how to analytically study speed sensitivity of the PA system remains unclear.

ii) *Lack of analytical model*: As we can see, [19], [21]–[23] are based on real-world testing data which validates the concept, while [24] is based on simulated channel, and [25] focuses more on the antenna pattern. No analytical model of the PA system has been proposed in [19], [21]–[25]. Moreover, as mentioned in the previous item, we need an analytical tool to study the sensitivity of the system performance to speed variation.

iii) *What else can we do with the PA system*: As we can see from the results in [19], [21]–[25], although the PA system can provide larger prediction horizons for up to three wavelengths, there is still a limit on the region, and the system is quite sensitive to vehicle speed. Hence, additional structure/schemes could potentially be built on top of the PA system to achieve better performance.

iv) *When to use the PA system*: The key point of the PA concept is to use an additional antenna to acquire better quality of CSIT. In this way, the time-frequency resources of the PA are used for channel prediction instead of data transmission. Intuitively, there should exist a condition under which the PA concept could be helpful, compared to the case with simply using the PA as one of the RAs. Here, theoretical models may help us make such decisions.

1.2 Scope of the Thesis

The aim of this thesis is to present analytical evaluation of the PA system and, at the same time, to apply some key-enablers of URLLC, such as rate adaptation, hybrid automatic repeat request (HARQ), and power allocation, considering imperfect CSI estimation. The channel considered in this thesis is the non-central Chi-square distributed fading channel, which we model as the combination of the known part of the channel from the PA, and the uncertainty part from the spatial mismatch. Firstly, in Paper A, we present our proposed analytical model for evaluating the sensitivity of the PA system with spatial mismatch. Some preliminary work on how to use rate adaptation based on imperfect CSI is also presented.

In Paper B, we first develop a mathematical tool that can be used to remarkably simplify the analysis of our proposed channel, some integral calculations, as well as optimization problems that contain the first-order Marcum Q-function. Then, we extend the work in Paper A and perform deep analysis of the effect of various parameters, such as processing delay of the BS and imperfect feedback schemes.

Besides the results in Paper A and B, we are also interested in how to further exploit the PA system by, e.g., involving the PA partly into the transmission process. In Paper C, we propose an HARQ-based PA system which uses the BS-PA link for the initial transmission, and the feedback bit on the decoding results combined with the CSI estimation for adapting the transmission parameters during the BS-RA transmission. Moreover, we develop power allocation schemes based on the HARQ-PA structure and study the outage-constrained average power of the system.

The specific objectives of this thesis can be summarized as follows.

i) To characterize the speed sensitivity of the PA system by analytically modeling the channels in PA systems.

ii) To develop a mathematical tool in order to simplify the performance evaluation of the PA setup which involves the Marcum Q-function.

iii) To design efficient and reliable transmission schemes which are able to improve the performance of existing PA systems.

1.3 Organization of the Thesis

In Chapter 2, we introduce the PA setups that are considered in the thesis. Specifically, we model the spatial mismatch in the PA system and define the data transmission model. The details of the channel model which involve the Marcum Q-function are also presented. To help the analytical evaluations, we provide a review of the use cases of the Marcum Q-function in a broad range of research areas, and present our proposed semi-linear approximation of the Marcum Q-function, with its applications on integral calculations and optimizations. In Chapter 3, we present different resource allocation schemes, namely, rate adaptation and HARQ-based power allocation, to improve the performance of the PA system under the mismatch problem. For each scheme, we show the problem formulation, the data transmission model as well as the details of the proposed method. Finally, in Chapter 4, we provide a brief overview of our contributions in the attached papers, and discuss possible future research directions.

CHAPTER 2

PA Systems and Analytical Channel Model

This chapter first introduces the PA concept in a TDD [1] DL [2] system, where one PA and one RA are deployed at the receiver side. Also, the associated challenges and difficulties posed by practical constraints are discussed. Then, the proposed analytical channel model based on Jake's assumption is presented, where the cumulative distribution function (CDF) of the channel gain is described by the first-order Marcum Q-function. Finally, to simplify the analytical derivations, we develop a semi-linear approximation of the first-order Marcum Q-function which can simplify, e.g., integral calculations as well as optimization problems.

2.1 The PA Concept

In 5G, a significant number of users would access wireless networks in vehicles, e.g., in public transportation like trams and trains or private cars, via their smart phones and laptops [11], [26]–[34]. In [26], the emergence of vehicular heavy user traffic is observed by field experiments conducted in 2012 and 2015 in Seoul, and the exper-

[1] The PA concept can be applied in both TDD and frequency division duplex (FDD) systems. In FDD the PA estimates the DL channel based on DL pilots from the BS, and reports back using an UL feedback channel. The BS uses this information (as input) to obtain the DL channel estimate to be used for the DL towards the RA when the RA reaches the same spatial point as the PA at the time of DL estimation. On the other hand, in TDD the PA instead sends the pilots and the BS estimates the UL channel, and uses that in combination with channel reciprocity information (as input) to obtain the DL channel estimate to be used for the DL towards the RA.

[2] This thesis mainly focus on the DL, but the PA concept can be adapted to be used also in the UL case.

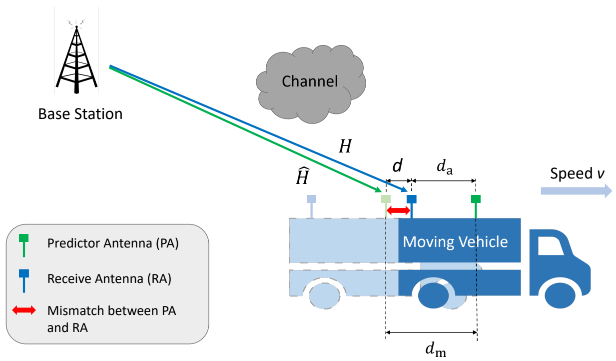

Figure 2.1: The PA concept with spatial mismatch problem.

imental results reveal that such traffic is becoming dominant, as shown by the 8.62 times increase from 2012 to 2015 in vehicular heavy user traffic, while total traffic increased only by 3.04 times. Also, [27]–[30] develop traffic schemes and networks for users in high-speed trains. Setting an MRN in vehicles can be one promising solution to provide a high-rate reliable connection between a BS and the users inside the vehicle [11], [31], [32]. From another perspective, [33] and [34] adopt femtocell technology inside a vehicle to provide better spectral and energy efficiency compared to the direct transmission scheme.

In such a so-called hot spot scenario, we often deploy TDD systems with channel reciprocity. It is intuitively because we have more data in DL than in UL. Here, we estimate the DL channel based on the UL pilots. Then, the problem may occur because of the movement, and the channel in the DL would not be the same as the one in the UL. This could be compensated for by extrapolating the CSI from the UL, for example by using Kalman predictions [35]. However, it is difficult to predict small-scale fading by extrapolating the past estimates and the prediction horizon is limited to 0.1-0.3λ with λ being the carrier wavelength [36]. Such a horizon is satisfactory for pedestrian users, while for high mobility users, such as vehicles, a prediction horizon beyond 0.3λ is usually required [23]. One possible way to increase the prediction horizon is to have a database of pre-recorded coordinate-specific CSI at the BSs [37]. Here, the basic idea is that the users provide the BSs with their location information by, e.g., global positioning system (GPS), and the BS could use the pre-recorded information to predict the channel environment. However, such a method requires large amount of data which may need to be updated frequently, and GPS position data would also not be accurate for small scale fading prediction, since the accuracy is much worse than a wavelength for typical mobile communications systems.

To overcome this issue, [19] proposes the concept of PA wherein at least two antennas are deployed on top of the vehicle. As can be seen from Fig. 2.1, the first antenna, which is the PA, estimates the channel $\hat{H}$ in the UL to the BS. Then, the BS uses the information received about $\hat{H}$ to estimate the channel H, and communicate with a second antenna, which we refer to as the RA, when it arrives to the same position as the PA. Then, a problem appears: how should we model such a channel? The intuitive idea is that the correlation between H and $\hat{H}$ should be affected by the moving speed v, the time for UL and DL, as well as the antenna separation d_{a} between the PA and the RA.

One way to evaluate such a model is to measure H and $\hat{H}$ under different system configurations, and calculate the normalized mean squared error (NMSE) of H and $\hat{H}$. Followed by [19], experimental results in [21] and [38] show that an NMSE of around -10 dB can be obtained for speeds up to 50 km/h, with all measured predictions horizons up to 3λ, which is ten times longer than the limit for Kalman filter-based channel extrapolation. In [21], [22], [38] FDD systems are considered, where dense enough DL channel estimation pilots with orthogonal frequency-division multiplexing (OFDM) are used. On the other hand, for TDD systems, the UL and DL frames need to be adjusted so that the estimation of H can be as close as possible to $\hat{H}$, as proposed and evaluated in [24]. However, such a method would need to adapt UL and DL ratios for each user, which is complicated from system design point of view. To mitigate this issue, [24] also proposes an interpolation scheme at the BS which is suitable for different UL and DL ratios. Also, a Kalman smoother for the interpolation of the PA for the TDD case with a two-filter approach is proposed in [23], where the CSI quality of the DL can be improved such that the duration of the DL can be extended remarkably. Moreover, it is shown that the correlation between H and $\hat{H}$ would be reduced, if the PA and the RA are too close to each other, e.g., 0.2-0.4λ. Different ways to compensate for such a coupling effect, such as open-circuit decoupling, are proposed in [20], [25].

2.2 Challenges and Difficulties

Previous studies have shown that deploying the PA system can provide significant performance gains in terms of, e.g., NMSE [21], [22], [38]. However, realistic gains can be limited by many practical constraints. In this section, we discuss a number of such challenges that have been partly addressed in this work.

Lack of Analytical Model

In the literature, most PA work rely on experimental measurements and simulations. This is sufficient for the validation purpose. However, to have a deeper understanding of the PA system, it is useful to develop analytical models. There are different statistical wireless channel models such as Rayleigh, Rice, Nakagami, and log-normal fading, as well as their combinations on multi-path and shadow fading components [39], [40]. Here, obtaining an exact analytical model for the PA system may be difficult, but understanding the correlation between H and $\hat{H}$ would be a good starting point.

Spatial Mismatch

As addressed in, e.g., [24], [25], even assuming that the channel does not change over time, if the RA does not arrive at the same point as the PA, the actual channel for the RA would not be identical to the one experienced by the PA before. As can be seen in Fig. 2.1 with TDD setup, considering one vehicle deploying two antennas on the roof with one PA positioned in the front of the moving direction and an RA aligned behind the PA. The idea of the data transmission model with TDD is that the PA first sends pilots at time t, then the BS estimates the channel and sends the data at time $t + \delta$ to the RA. Here, δ depends on the processing time at the BS. Then, we define d as the effective distance between the position of the PA at time t and the position of the RA at time $t + \delta$, as can be seen in Fig. 2.1. That is, d is given by

$$d = |d_\mathrm{a} - d_\mathrm{m}| = |d_\mathrm{a} - v\delta|, \tag{2.1}$$

where d_m is the moving distance between t and $t + \delta$ while v is the velocity of the vehicle. To conclude, different values of v, δ, f_c and d_a in (2.1) correspond to different values of d. We would like to find out how to connect H and $\hat{H}$ as a function of d, and how different values of d would affect the system performance.

Spectral Efficiency Improvement

In a typical PA setup, the spectrum is underutilized, and the spectral efficiency could be further improved in case the PA could be used not only for channel prediction but also for data transmission. However, proper data transmission schemes need to be designed to make the best use of the PA.

Temporal Correlation

The overhead from the UL-DL structure of the PA system would affect the accuracy of the CSI acquisition, i.e., $\hat{H}$ obtained from PA would change over time. Basically, the slowly-fading channel is not always a realistic model for fast-moving users, since the channel may change according to the environmental effects during a transmission block [41]–[43]. There are different ways to model the temporally-correlated channel, such as using the first-order Gauss-Markov process [42], [43].

Estimation Error

There could be channel estimation errors from the UL [44], which would degrade the system performance. The assumption of perfect channel reciprocity in TDD ignores two important facts [45]: 1) the radio-frequency (RF) chains of the UL and the DL are separate circuits with random impacts on the transmitted and received signals [45], [46], which is the so-called RF mismatch; 2) the interference profile at the transmitter and receiver sides are different [47]. These deviations are defined as reciprocity errors that invalidate the assumption of perfect reciprocity, and should be considered in the system design.

Effects of Other Parameters

As mentioned in Fig. 2.1, different system parameters such as the speed v, the antenna separation d_{a} and the control loop time δ would affect the system behaviour by, e.g., spatial mismatch or antenna coupling. Our goal is to study the effect of these parameters and develop robust schemes which perform well for a broad range of their values.

2.3 Analytical Channel Model

Considering DL transmission in the BS-RA link, which is our main interest, the received signal is given by [3]

$$Y = \sqrt{P}HX + Z. \tag{2.2}$$

Here, P represents the average received power at the RA, while X is the input message with unit variance, and H is the fading coefficient between the BS and the RA. Also, $Z \sim \mathcal{CN}(0,1)$ denotes the identical and independently distributed (i.i.d.) complex Gaussian noise added at the receiver.

We denote the channel coefficient of the PA-BS UL by $\hat{H}$ and we assume that $\hat{H}$ is perfectly known by the BS. The result can be extended to the cases with imperfect CSI at the BS (see our work [48]). In this way, we use the spatial correlation model [49, p. 2642]

$$\tilde{\boldsymbol{H}} = \boldsymbol{\Phi}^{1/2}\boldsymbol{H}_{\varepsilon}, \tag{2.3}$$

where $\tilde{\boldsymbol{H}} = \left[\begin{smallmatrix}\hat{H}\\ H\end{smallmatrix}\right]$ is the channel matrix including both BS-PA channel $\hat{H}$ and BS-RA channel H links. $\boldsymbol{H}_{\varepsilon}$ has independent circularly-symmetric zero-mean complex Gaussian entries with unit variance, and $\boldsymbol{\Phi}$ is the channel correlation matrix.

[3]In this work, we mainly focus on the cases with single PA and RA antennas. The future works will address the problem in the cases with array antennas.

In general, the spatial correlation of the fading channel depends on the distance between the RA and the PA, which we denote by d_{a}, as well as the angular spectrum of the radio wave pattern. If we use the classical Jakes' correlation model by assuming uniform angular spectrum, the (i,j)-th entry of $\mathbf{\Phi}$ is given by [50, Eq. 1]

$$\Phi_{i,j} = J_0\left((i-j)\cdot 2\pi d/\lambda\right). \tag{2.4}$$

Here, $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind. Also, $\lambda = c/f_{\mathrm{c}}$ represents the wavelength where c is the speed of light and f_{c} is the carrier frequency.

As discussed before, different values of v, δ, f_{c} and d_{a} in (2.1) correspond to different values of d, which leads to different levels of channel spatial correlation (2.3)-(2.4).

Combining (2.3) and (2.4) with normalization, we have

$$H = \sqrt{1-\sigma^2}\hat{H} + \sigma q, \tag{2.5}$$

where $q \sim \mathcal{CN}(0,1)$ which is independent of the known channel value $\hat{H} \sim \mathcal{CN}(0,1)$, and σ is a function of the mismatch distance d.

From (2.5), for a given $\hat{H}$ and $\sigma \neq 0$, $|H|$ follows a Rician distribution, i.e., the probability density function (PDF) of $|H|$ is given by

$$f_{|H|\big|\hat{H}}(x) = \frac{2x}{\sigma^2} e^{-\frac{x^2+(1-\sigma^2)\hat{g}}{\sigma^2}} I_0\left(\frac{2x\sqrt{(1-\sigma^2)\hat{g}}}{\sigma^2}\right), \tag{2.6}$$

with $\hat{g} = |\hat{H}|^2$, and $I_n(x) = (\frac{x}{2})^n \sum_{i=0}^{\infty} \frac{(\frac{x}{2})^{2i}}{i!\Gamma(n+i+1)}$ being the n-th order modified Bessel function of the first kind where $\Gamma(z) = \int_0^{\infty} x^{z-1}e^{-x}\mathrm{d}x$ denotes the Gamma function. Then, we define the channel gain between BS-RA as $g = |H|^2$. By changing variables from H to g, the PDF of $f_{g|\hat{H}}$ is given by

$$f_{g|\hat{H}}(x) = \frac{1}{\sigma^2} e^{-\frac{x+(1-\sigma^2)\hat{g}}{\sigma^2}} I_0\left(\frac{2\sqrt{x(1-\sigma^2)\hat{g}}}{\sigma^2}\right), \tag{2.7}$$

which is non-central Chi-squared distributed, and the CDF is

$$F_{g|\hat{H}}(x) = 1 - Q_1\left(\sqrt{\frac{2(1-\sigma^2)\hat{g}}{\sigma^2}}, \sqrt{\frac{2x}{\sigma^2}}\right). \tag{2.8}$$

Here, $Q_1(\alpha,\beta)$ is Marcum Q-function and it is defined as [51, Eq. 1]

$$Q_1(\alpha,\beta) = \int_{\beta}^{\infty} x e^{-\frac{x^2+\alpha^2}{2}} I_0(x\alpha)\mathrm{d}x, \tag{2.9}$$

where $\alpha, \beta \geq 0$.

We study the system performance in various temporally-correlated conditions, i.e., when H is not the same as $\hat{H}$ even at the same position. Particularly, using the same model as in [42, Eq. 2], we further develop our channel model (2.5) as

$$H_{k+1} = \beta H_k + \sqrt{1-\beta^2} z, \tag{2.10}$$

for each time slot k, where $z \sim \mathcal{CN}(0,1)$ is a Gaussian noise which is uncorrelated with H_k. Also, β is a known correlation factor which represents two successive channel realizations dependencies by $\beta = \frac{\mathbb{E}\{H_{k+1} H_k^*\}}{\mathbb{E}\{|H_k|^2\}}$. Substituting (2.10) into (2.5), we have

$$H_{k+1} = \beta\sqrt{1-\sigma^2}\hat{H}_k + \beta\sigma q + \sqrt{1-\beta^2} z = \beta\sqrt{1-\sigma^2}\hat{H}_k + w. \tag{2.11}$$

Here, to simplify the calculation, $\beta\sigma q + \sqrt{1-\beta^2} z$ is equivalent to a new Gaussian variable $w \sim \mathcal{CN}\left(0, (\beta\sigma)^2 + 1 - \beta^2\right)$. Moreover, we can follow the same approach as in [52] to add the effect of estimation errors of $\hat{H}$ as an independent additive Gaussian variable whose variance is given by the accuracy of CSI estimation.

2.4 The First-Order Marcum Q-Function and Semi-Linear Approximation

The first-order [4] Marcum Q-function (2.9) is observed in various problem formulations. However, it is not an easy-to-handle function with modified Bessel function, double parameters (α and β), and the integral shape.

In the literature, the Marcum Q-function has appeared in many areas, such as statistics/signal detection [53], and in performance analysis of different setups, such as temporally correlated channels [42], spatial correlated channels [54], free-space optical (FSO) links [55], relay networks [56], as well as cognitive radio and radar systems [57]–[77]. However, in these applications, the presence of the Marcum Q-function makes the mathematical analysis challenging, because it is difficult to manipulate with no closed-form expressions especially when it appears in parameter optimizations and integral calculations. For this reason, several methods have been developed in [51], [78]–[89] to bound/approximate the Marcum Q-function. For example, [78], [79] have proposed modified forms of the function, while [80], [81] have derived exponential-type bounds which are good for the bit error rate analysis at high signal-to-noise ratios (SNRs). Other types of bounds are expressed by, e.g., error function [86] and Bessel functions [87]–[89]. Some alternative methods have been also proposed in

[4] To simplify the analysis, our work concentrates on the approximation of the first-order Marcum-Q function. However, our approximation technique can be easily extended to the cases with different orders of the Marcum Q-function.

[51], [82]–[85]. Although each of these approximation/bounding techniques are fairly tight for their considered problem formulation, they are still based on hard-to-deal functions, or have complicated summation/integration structures, which may be not easy to deal with in e.g., integral calculations and parameter optimizations.

We present our semi-linear approximation of the CDF in the form of $y(\alpha,\beta) = 1 - Q_1(\alpha,\beta)$. The idea of this proposed approximation is to use one point and its corresponding slope at that point to create a line approximating the CDF. The approximation method is summarized in Lemma 1 as follows.

Lemma 1. *The CDF of the form $y(\alpha,\beta) = 1 - Q_1(\alpha,\beta)$ can be semi-linearly approximated by $Y(\alpha,\beta) \simeq \mathcal{Z}(\alpha,\beta)$ where*

$$\mathcal{Z}(\alpha,\beta) = \begin{cases} 0, & \text{if } \beta < c_1 \\ \frac{\alpha+\sqrt{\alpha^2+2}}{2} e^{-\frac{1}{2}\left(\alpha^2+\left(\frac{\alpha+\sqrt{\alpha^2+2}}{2}\right)^2\right)} \times \\ \quad I_0\left(\alpha\frac{\alpha+\sqrt{\alpha^2+2}}{2}\right) \times \left(\beta - \frac{\alpha+\sqrt{\alpha^2+2}}{2}\right) + \\ \quad 1 - Q_1\left(\alpha, \frac{\alpha+\sqrt{\alpha^2+2}}{2}\right), & \text{if } c_1 \leq \beta \leq c_2 \\ 1, & \text{if } \beta > c_2, \end{cases} \tag{2.12}$$

with

$$c_1(\alpha) = \max\left(0, \frac{\alpha+\sqrt{\alpha^2+2}}{2} + \frac{Q_1\left(\alpha, \frac{\alpha+\sqrt{\alpha^2+2}}{2}\right) - 1}{\frac{\alpha+\sqrt{\alpha^2+2}}{2} e^{-\frac{1}{2}\left(\alpha^2+\left(\frac{\alpha+\sqrt{\alpha^2+2}}{2}\right)^2\right)} I_0\left(\alpha\frac{\alpha+\sqrt{\alpha^2+2}}{2}\right)}\right), \tag{2.13}$$

$$c_2(\alpha) = \frac{\alpha+\sqrt{\alpha^2+2}}{2} + \frac{Q_1\left(\alpha, \frac{\alpha+\sqrt{\alpha^2+2}}{2}\right)}{\frac{\alpha+\sqrt{\alpha^2+2}}{2} e^{-\frac{1}{2}\left(\alpha^2+\left(\frac{\alpha+\sqrt{\alpha^2+2}}{2}\right)^2\right)} I_0\left(\alpha\frac{\alpha+\sqrt{\alpha^2+2}}{2}\right)}. \tag{2.14}$$

Proof. See [48, Sec. II]. ■

Moreover, we can make some second level approximations considering different ranges of α to further simplify notations. For more details, refer to [48].

One example result of the proposed approximation can be seen in Fig. 2.2 with α set to 2. We can observe that Lemma 1 is tight for moderate values of β. Note that the proposed approximations are not tight at the tails of the CDF. However, as observed in [42], [51], [53]–[68], [78]–[89], in different applications, the Marcum Q-function is typically combined with other functions which tend to zero in the tails of the CDF. In such cases, the inaccuracy of the approximation at the tails does not

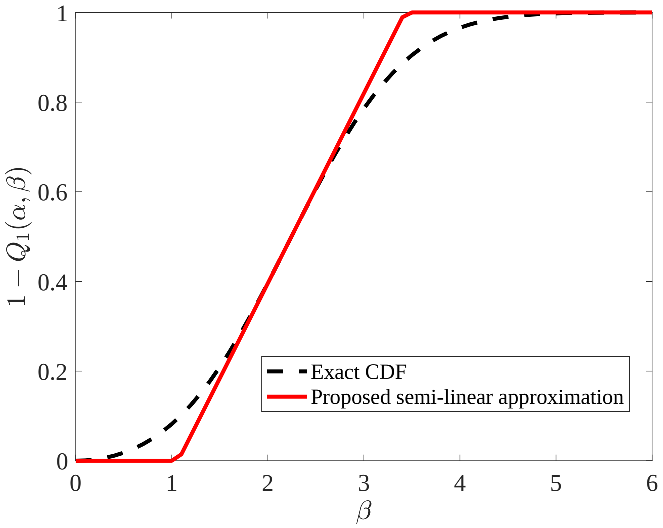

Figure 2.2: The illustration of proposed semi-linear approximation, $\alpha = 2$.

affect the tightness of the final analysis. For example, it can simplify integrals such as

$$G(\alpha, \rho) = \int_{\rho}^{\infty} e^{-nx} x^{m} \left(1 - Q_1(\alpha, x)\right) \mathrm{d}x \quad \forall n, m, \alpha, \rho > 0. \tag{2.15}$$

Such an integral has been observed in various applications, e.g., [57, Eq. 1], [66, Eq. 2], [67, Eq. 1], [68, Eq. 3], and [85, Eq. 1]. However, depending on the values of n, m and ρ, (2.15) may have no closed-form expression.

Another example of integral calculation is

$$T(\alpha, m, a, \theta_1, \theta_2) = \int_{\theta_1}^{\theta_2} e^{-mx} \log(1 + ax) Q_1(\alpha, x) \mathrm{d}x \quad \forall m > 0, a, \alpha, \tag{2.16}$$

with $\theta_2 > \theta_1 \geq 0$, which does not have a closed-form expression for different values of m, a, α. This integral is interesting as it is often used to analyse the expected performance of outage-limited systems, e.g, [57], [80], [85], [90].

Finally, the proposed semi-linear approximation can be used for the rate adaptation scheme developed in the PA system. For more details, refer to Chapter 3 as well as [48, Sec. II].

CHAPTER 3

Resource Allocation in PA Systems

Resource allocation plays an important role in communication systems as a way of optimizing the assignment of available resources to achieve network design objectives. In the PA system, resource allocation can be deployed to mitigate different challenges mentioned in Chapter 2. In this chapter, we develop various resource allocation schemes for the PA system under different practical constraints.

3.1 Rate Adaptation in the Classic PA Setup

In this section, we propose a rate adaptation scheme to mitigate the mismatch problem. Here, the classic setup means the PA is only used for channel prediction, not for data transmission. We assume that d_{a}, δ and $\hat{g}$ are known at the BS. It can be seen from (2.7) that $f_{g|\hat{H}}(x)$ is a function of v. For a given v, the distribution of g is known at the BS, and a rate adaption scheme can be performed to improve the system performance.

The data is transmitted with rate R^* nats-per-channel-use (npcu). If the instantaneous realization of the channel gain supports the data rate, i.e., $\log(1+gP) \geq R^*$, the data can be successfully decoded, otherwise outage occurs. Hence, the outage probability in each time slot is obtained as $\Pr(\text{Outage}|\hat{H}) = F_{g|\hat{H}}\left(\frac{e^{R^*}-1}{P}\right)$. Considering slotted communication in block fading channels, where $\Pr(\text{Outage}) > 0$ varies with different fading models. Here, we define throughput as the data rate times the successful decoding probability [91, p. 2631], [92, Th. 6], [93, Eq. 9]. I.e., the expected data rate successfully received by the receiver is an appropriate performance metric. Hence, the rate adaptation problem of maximizing the throughput in each time slot, with given v and $\hat{g}$, can be expressed as

$$\begin{aligned} R_{\text{opt}|\hat{g}} &= \underset{R^*\geq 0}{\text{argmax}}\left\{(1-\Pr\left(\log(1+gP)<R^*\right))R^*\right\} \\ &= \underset{R^*\geq 0}{\text{argmax}}\left\{\left(1-\Pr\left(g<\frac{e^{R^*}-1}{P}\right)\right)R^*\right\} \\ &= \underset{R^*\geq 0}{\text{argmax}}\left\{\left(1-F_{g|\hat{H}}\left(\frac{e^{R^*}-1}{P}\right)\right)R^*\right\}. \end{aligned} \tag{3.1}$$

Also, the expected throughput is obtained by $\mathbb{E}\left\{\left(1-F_{g|\hat{H}}\left(\frac{e^{R_{\text{opt}|\hat{g}}}-1}{P}\right)\right)R_{\text{opt}|\hat{g}}\right\}$ with expectation over $\hat{g}$.

Using (2.8), (3.1) is simplified as

$$R_{\text{opt}|\hat{g}} = \underset{R^*\geq 0}{\text{argmax}}\left\{Q_1\left(\sqrt{\frac{2\hat{g}(1-\sigma^2)}{\sigma^2}},\sqrt{\frac{2(e^{R^*}-1)}{P\sigma^2}}\right)R^*\right\}. \tag{3.2}$$

In general, (3.2) does not have a closed-form solution. For this reason, in [48] and [94] we propose different approximations for the optimal data rate maximizing the instantaneous throughput.

3.2 Hybrid Automatic Repeat Request in the PA Systems

HARQ is a well-known approach to improve data transmission reliability and efficiency. The main idea of HARQ is to retransmit the message that experienced poor channel conditions in order to reduce the outage probability [93], [95], [96]. Here, we define that outage occurs when the transmitted message cannot be decoded at the receiver. For the Rayleigh block fading channel, infinite power is required to achieve zero outage probability for all realizations. Hence, we replace the strict outage constraint by a more realistic requirement, where a transmission is successful as long as the message can always be decoded by the receiver with probability ϵ. We define ϵ as a parameter of the system outage tolerance.

The outage-constrained power allocation problem in HARQ systems has been studied in, e.g, [97] with perfect CSI assumption, in [98] with cooperative decode-and-forward automatic repeat request (ARQ) relaying under packet-rate fading channels, and in [99], [100] with power allocation schemes aiming at minimizing the average transmit power for HARQ systems. Also, in the block fading scenario, [101] studied the outage-limited performance of different HARQ protocols. Moreover, the outage-constrained power optimization for the repetition time diversity (RTD) and

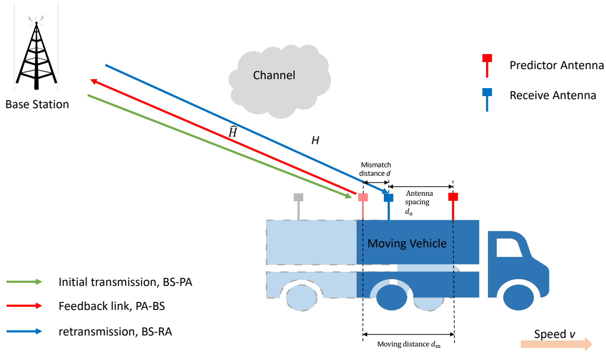

Figure 3.1: The PA concept with HARQ.

fixed-length coding incremental redundancy (INR) HARQ protocols were investigated in [102] and [103], respectively. Assuming that the channel changes in each re-transmission, [104] developed power allocation schemes with basic ARQ. Finally, [105] proposed a linear-programming approach with a buffer cost constraint to solve the power adaptive problem in HARQ systems where the power is adapted based on the received CSI.

As the PA system includes the feedback link with the FDD setup, i.e., from the PA to the BS, HARQ can be supported by the PA structure in high mobility scenarios. That is, the BS could potentially adjust its transmit rate/power based on the feedback from the PA. In this way, it is expected that the joint implementation of the PA system and the HARQ scheme can improve the efficiency and reliability of outage-constrained systems. There is limited work on deploying HARQ in high mobility scenarios, i.e., when the channel change quickly over time compared to the feedback delay. In [106], the authors investigated the performance of basic ARQ and INR protocols in fast-fading channels where a number of channel realizations are experienced in each retransmission round. Also, [107] studied the performance of INR over double Rayleigh channels, a common model for the fading amplitude of vehicle-to-vehicle communication systems. However, both [106] and [107] deal with the same channel PDF for different re-transmission rounds, which has limited contribution for the spatial/temporal variation of the channel in vehicle communications.

In the classic PA setup, the spectrum is underutilized, and the spectral efficiency could be further improved in the case that the PA could be used not only for channel prediction, but also for data transmission. We address these challenges by implementing HARQ-based protocols in PA systems as follows.

As seen in Fig. 3.1, the BS first sends pilots as well as the encoded data with certain initial parameters, e.g., power or rate depending on the problem formulation, to the PA. Then, the PA estimates the channel from the received pilots. At the

Figure 3.2: Time structure for the proposed outage-constrained power allocation in the HARQ-based PA system.

same time, the PA tries to decode the signal. If the message is correctly decoded, an acknowledgment (ACK) is fed back to the BS, and the data transmission stops. Otherwise, the PA sends both a negative acknowledgment (NACK) and high accuracy quantized CSI feedback. The number of quantization bits are large enough such that we can assume the BS to have perfect CSI. With NACK, in the second transmission round, the BS transmits the message to the RA with adapted power/rate which is a function of the instantaneous channel quality in the first round. The outage occurs if the RA cannot decode the message at the end of the second round.

In the following section, we develop an outage-constrained power allocation scheme in the HARQ-based PA system. The related study about delay-limited average rate optimization in the HARQ-based PA system can be found in [108].

3.3 Outage-constrained Power Allocation in the HARQ-based PA Systems

As seen in Fig. 3.2, with no CSI, at t_1 the BS sends pilots as well as the encoded data with certain initial rate R and power P_1 to the PA. At t_2, the PA estimates the channel $\hat{H}$ from the received pilots. At the same time, the PA tries to decode the signal. If the message is correctly decoded, i.e., $R \leq \log(1 + \hat{g}P_1)$, an ACK is fed back to the BS at t_3, and the data transmission stops. Otherwise, the PA sends both a NACK and high accuracy quantized CSI feedback about $\hat{H}$. With NACK, in the second transmission round at time t_4, the BS transmits the message to the RA with power P_2, which is a function of the instantaneous channel quality $\hat{g}$. The outage occurs if the RA cannot decode the message at the end of the second round.

Let ϵ be the outage probability constraint. Here, we present the results for the cases with RTD and INR HARQ protocols. With an RTD protocol, the same signal (with possibly different power) is sent in each retransmission round, and the receiver performs maximum ratio combining of all received copies of the signal. With INR, on the other hand, new redundancy bits are sent in the retransmissions, and the receiver decodes the message by combining all received signals [99], [103], [105].

Considering Rayleigh fading conditions with $f_{\hat{g}}(x) = e^{-x}$, the outage probability at the end of Round 1 is given by

$$\Pr(\text{Outage, Round 1}) = \Pr\left\{R \leq \log(1+\hat{g}P_1)\right\} = \Pr\left\{\hat{g} \leq \frac{e^R - 1}{P_1}\right\} = 1 - e^{-\frac{\theta}{P_1}}, \tag{3.3}$$

where $\theta = e^R - 1$. Then, using the results of, e.g., [99, Eq. 7, 18] on the outage probability of the RTD- and INR-based HARQ protocols, the power allocation problem for the proposed HARQ-based PA system can be stated as

$$\begin{aligned} \min_{P_1,P_2} \quad & \mathbb{E}_{\hat{g}}\left[P_{\text{tot}}|\hat{g}\right] \\ \text{s.t.} \quad & P_1, P_2 > 0, \\ & P_{\text{tot}}|\hat{g} = \left[P_1 + P_2(\hat{g}) \times \mathcal{I}\left\{\hat{g} \leq \frac{\theta}{P_1}\right\}\right], \end{aligned} \tag{3.4}$$

with

$$F_{g|\hat{g}}\left\{\frac{\theta - \hat{g}P_1}{P_2(\hat{g})}\right\} = \epsilon, \quad \text{for RTD} \tag{3.5}$$

$$F_{g|\hat{g}}\left\{\frac{e^{R-\log(1+\hat{g}P_1)} - 1}{P_2(\hat{g})}\right\} = \epsilon, \quad \text{for INR.} \tag{3.6}$$

Here, $P_{\text{tot}}|\hat{g}$ is the total instantaneous transmission power for two transmission rounds (i.e., one retransmission) with given $\hat{g}$, and we define $\bar{P} \doteq \mathbb{E}_{\hat{g}}\left[P_{\text{tot}}|\hat{g}\right]$ as the expected power, averaged over $\hat{g}$. Moreover, $\mathcal{I}(x) = 1$ if $x > 0$ and $\mathcal{I}(x) = 0$ if $x \leq 0$. Also, $\mathbb{E}_{\hat{g}}[\cdot]$ represents the expectation operator over $\hat{g}$. Here, we ignore the peak power constraint and assume that the BS is capable for sufficiently high transmission powers. Finally, (3.4)-(3.6) come from the fact that, with our proposed scheme, P_1 is fixed and optimized with no CSI at the BS and based on average system performance. On the other hand, P_2 is adapted continuously based on the instantaneous CSI.

Using (3.4), the required power in Round 2 is given by

$$P_2(\hat{g}) = \frac{\theta - \hat{g}P_1}{F^{-1}_{g|\hat{g}}(\epsilon)}, \tag{3.7}$$

for the RTD, and

$$P_2(\hat{g}) = \frac{e^{R-\log(1+\hat{g}P_1)} - 1}{F^{-1}_{g|\hat{g}}(\epsilon)}, \tag{3.8}$$

for the INR, where $F^{-1}_{g|\hat{g}}(\cdot)$ is the inverse of the CDF given in (2.8). Note that $F^{-1}_{g|\hat{g}}(\cdot)$ is a complicated function of $\hat{g}$, and consequently, it is not possible to express P_2 in closed-form. For this reason, one can use [109, Eq. 2, 7]

$$\begin{aligned} &Q_1(s,\rho) \simeq e^{\left(-e^{\mathcal{I}(s)}\rho^{\mathcal{J}(s)}\right)},\\ &\quad\mathcal{I}(s) = -0.840 + 0.327s - 0.740s^2 + 0.083s^3 - 0.004s^4,\\ &\quad\mathcal{J}(s) = 2.174 - 0.592s + 0.593s^2 - 0.092s^3 + 0.005s^4, \end{aligned} \tag{3.9}$$

to approximate $F_{g|\hat{g}}$ and consequently $F^{-1}_{g|\hat{g}}(\epsilon)$. In this way, (3.7) and (3.8) can be approximated as

$$P_2(\hat{g}) = \Omega\left(\theta - \hat{g}P_1\right), \tag{3.10}$$

for the RTD, and

$$P_2(\hat{g}) = \Omega\left(e^{R-\log(1+\hat{g}P_1)} - 1\right), \tag{3.11}$$

for the INR, where

$$\Omega(\hat{g}) = \frac{2}{\sigma^2}\left(\frac{\log(1-\epsilon)}{-e^{\mathcal{I}\left(\sqrt{\frac{2\hat{g}(1-\sigma^2)}{\sigma^2}}\right)}}\right)^{-\frac{2}{\mathcal{J}\left(\sqrt{\frac{2\hat{g}(1-\sigma^2)}{\sigma^2}}\right)}}. \tag{3.12}$$

In this way, for different HARQ protocols, we can express the instantaneous transmission power of Round 2, for every given $\hat{g}$ in closed-form. Then, the power allocation problem (3.4) can be solved numerically. However, (3.12) is still complicated and it is not possible to solve (3.4) in closed-form. For this reason, we propose an approximation scheme to solve (3.4) as follows.

Let us initially concentrate on the RTD protocol. Then, combining (3.4) and (3.7), the expected total transmission power is given by

$$\bar{P}_{\text{RTD}} = P_1 + \int_0^{\theta/P_1} e^{-x}P_2\text{d}x = P_1 + \int_0^{\theta/P_1} e^{-x}\frac{\theta - xP_1}{F^{-1}_{g|x}(\epsilon)}\text{d}x. \tag{3.13}$$

Then, Theorem 1 in [110] derives the minimum required power in Round 1 and the average total power consumption.

To study the performance of the INR, we can use Jensen's inequality and the concavity of the logarithm function [111, Eq. 30]

$$\frac{1}{n}\sum_{i=1}^{n}\log(1+x_i) \leq \log\left(1 + \frac{1}{n}\sum_{i=1}^{n}x_i\right), \tag{3.14}$$

and derive the closed-form expressions for the minimum required power following the similar steps as for the RTD (see [110, Sec. III B]) for detailed discussions).

CHAPTER 4

Contributions and Future Work

This chapter summarizes the contributions of each appended publication and lays out possible directions for future work based on the topics in this thesis.

4.1 Paper A

"Rate adaptation in predictor antenna systems"

In this paper, we study the performance of PA systems in the presence of the mismatch problem with rate adaptation. We derive closed-form expressions for the instantaneous throughput, the outage probability, and the throughput-optimized rate adaptation. Also, we take the temporal variation of the channel into account and evaluate the system performance in various conditions. The simulation and the analytical results show that, while PA-assisted adaptive rate adaptation leads to considerable performance improvement, the throughput and the outage probability are remarkably affected by the spatial mismatch and temporal correlations.

4.2 Paper B

"A semi-linear approximation of the first-order Marcum Q-function with application to predictor antenna systems"

In this paper, we first present a semi-linear approximation of the Marcum Q-function. Our proposed approximation is useful because it simplifies, e.g., various integral calculations including the Marcum Q-function as well as various operations such as parameter optimization. Then, as an example of interest, we apply our proposed approximation approach to the performance analysis of PA systems. Considering spatial mismatch due to mobility, we derive closed-form expressions for the instantaneous and average throughput as well as the throughput-optimized rate allocation. As we show, our proposed approximation scheme enables us to analyze PA systems with high accuracy. Moreover, our results show that rate adaptation can improve the performance of PA systems with different levels of spatial mismatch.

4.3 Paper C

"Power allocation in HARQ-based predictor antenna systems"

In this work, we study the performance of PA systems using HARQ. Considering spatial mismatch due to the vehicle mobility, we derive closed-form expressions for the optimal power allocation and the minimum average power of the PA systems under different outage probability constraints. The results are presented for different types of HARQ protocols, and we study the effect of different parameters on the performance of PA systems. As we show, our proposed approximation scheme enables us to analyze PA systems with high accuracy. Moreover, for different vehicle speeds, we show that the HARQ-based feedback can reduce the outage-limited transmit power consumption of PA systems by orders of magnitude.

4.4 Related Contributions

Another CSI-related application in vehicle communication is beamforming. As discussed in Chapter 1, the channel for vehicles changes rapidly, such that it is hard to acquire CSIT, especially during initial access. In Paper D, we study the performance of large-but-finite MIMO networks using codebook-based beamforming. Results show that the proposed genetic algorithm-based scheme can reach (almost) the same performance as in the exhaustive search-based scheme with considerably lower implementation complexity. Then, in Paper E, we extend our study in Paper D to include beamforming at both the transmitter and the receiver side. Also, we compare different machine learning-based analog beamforming approaches for the beam refinement. As indicated in the results, our scheme outperforms the considered state-of-the-art schemes in terms of throughput. Moreover, when taking the user mobility into account, the proposed approach can remarkably reduce the algorithm running delay based on the beamforming results in the previous time slots. Finally, in Paper F, with collaborative users, we show that the end-to-end throughput can be improved by data exchange through device-to-device links among the users.

4.5 Future work

In this thesis, we have developed analytical models for evaluating the PA system from different perspectives, and proposed resource allocation schemes to mitigate the mismatch problem and improve the system performance. Here are some potential directions for future work:

- Several results presented in the papers above rely on the assumption that the scattering environment around the RAs is isotropic and remains constant over the time period of interest in a small moving distance. To more accurately resemble reality, one could consider alternative models to evaluate the PA system, for example some mixture models with more time-varying properties [112].

- As a natural follow-up from above, one can consider more use cases for the PA system, such as satellite-train communication and vehicle localization, with different channel models and service requirements. Here, the results of [11], [26]–[34] can be supportive.

- The work we have done considers single-input single-output (SISO) setup, i.e., with one antenna at the BS and one RA on the top of the vehicle at the receiver side. Though in [110] we exploit the PA as part of the data transmission, it is still interesting to see where the gain of deploying the PA system comes from and when we should apply it over typical transceiver schemes. Moreover, one can deploy the PA in multiple antenna systems for which the results of [22], [24], [113] can be useful. It is expected that combining the PA with MIMO would result in higher performance gain in fast moving scenarios.

- As we discussed in Chapter 1, in PA systems we target at URLLC, i.e., delay/latency is crucial in the system design. Hence, there is a natural extension to perform finite blocklength analysis in the (HARQ-based) PA system. As opposed to the literature on finite blocklength studies, e.g., [100], [114], [115], here the channel in the retransmission round(s) is different from the one in the initial transmission due to mobility.

- Machine learning-based channel estimation/prediction has become powerful in various applications where the statistical model of the channel does not exist or is not robust [116]–[118]. On the other hand, the PA itself provides a reliable feedback loop at the cost of additional resources. Using the PA setup to perform machine learning-based channel prediction would be a very valuable contribution.

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Part II

Papers