thesis for the degree of doctor of philosophy

Robust Low-Cost Multiple Antenna Processing for V2V Communication

Chouaib Bencheikh Lehocine

Communication Systems Group
Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden, 2022

Robust Low-Cost Multiple Antenna Processing for V2V Communication

Chouaib Bencheikh Lehocine

ISBN 978-91-7905-717-6
Series No. 5183 in Doktorsavhandlingar vid Chalmers Tekniska Högskola
ISSN 0346-718X

This thesis has been prepared using LaTeX, and PGF/TikZ.

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

Printed by Chalmers Reproservice
Gothenburg, Sweden, October 2022

To my grandparents

Abstract

Cooperative vehicle-to-vehicle (V2V) communication with frequent, periodic broadcast of messages between vehicles is a key enabler of applications that increase traffic safety and traffic efficiency on roads. Such broadcast V2V communication requires an antenna system with omnidirectional coverage, which is difficult to achieve using a single antenna element. For a mounted, omnidirectional antenna on a vehicle is distorted by the vehicle body, and exhibits a non-uniform directional pattern with low gain in certain directions. The thesis addresses this problem by developing schemes that employ multiple antennas (MAs) to achieve an effective radiation pattern with omnidirectional characteristics at both the transmit- and the receive-side. To ensure robust communication, the MA schemes are designed to minimize the burst error probability of several consecutive status messages in a scarce multipath environment with a dominant path between vehicles.

First, at the receive-side, we develop a hybrid analog-digital antenna combiner. The analog part of the combiner is composed of low-cost analog combining networks (ACNs) of phase shifters that do not depend on channel state information (CSI), while the digital part uses maximal ratio combining. We show that the optimal phase slopes of the analog part of the combiner (i.e., the phase slopes that minimize the burst error probability) are the same found under the optimization of a single ACN, which was done in earlier work. We then show how directional antennas can be employed in this context to achieve an effective omnidirectional radiation pattern of the antenna system that is robust in all directions of arrival of received signals.

Secondly, at the transmit-side, we develop two low-cost analog MA schemes, an analog beamforming network (ABN) of phase shifters, and an antenna switching network (ASN), for the case when receivers employ the ACN or the hybrid combiner. Both schemes are shown to achieve an effective radiation pattern with improved omnidirectional characteristics at the transmit-side without relying on CSI.

Thirdly, the schemes above were developed assuming that all vehicles broadcast their messages with the same fixed period. Therefore, we tackle the practical scenario when different vehicles use different and potentially varying broadcast periods. We show that the phase slopes of the MA schemes at the receiver and/or transmitter can be designed to support multiple broadcast periods.

Lastly, the optimal phase slopes of the MA schemes were analytically derived under a worst-case propagation corresponding to a dominant path with an angle of departure, and an angle of arrival that are approximately non-varying over the time it takes to transmit and receive several packets. We relax this assumption and study the system performance under a time-varying dominant component instead. We derive a design rule that yields robust phase slopes that effectively mitigate the losses due to the time-variation of the dominant path.

Keywords: Beamforming, Broadcast V2V communication, Directional antennas, Hybrid combining, Multiple antennas, Periodic communication.

List of Publications

This thesis is based on the following publications:

[A] **Chouaib Bencheikh Lehocine**, Erik G. Ström, and Fredrik Brännström, "Hybrid Combining of Directional Antennas for Periodic Broadcast V2V Communication," in *IEEE Transaction on Intelligent Transportation Systems,* vol. 23, no. 4, pp. 3226–3243, Apr. 2022.

[B] **Chouaib Bencheikh Lehocine**, Fredrik Brännström, and Erik G. Ström, "Robust Analog Beamforming for Periodic Broadcast V2V Communication," in *IEEE Transaction on Intelligent Transportation Systems*, early access, March 2022.

[C] **Chouaib Bencheikh Lehocine**, Fredrik Brännström, and Erik G. Ström, "Sensitivity Analysis of Beamforming Techniques for Periodic Broadcast V2V Communication," in *Proc. IEEE 55th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, Oct.–Nov. 2021.

[D] **Chouaib Bencheikh Lehocine**, Erik G. Ström, and Fredrik Brännström, "Antenna Combiner for Periodic Broadcast V2V Communication Under Relaxed Worst-Case Propagation," submitted to *IEEE Transcations on Intelligent Transportation Systems.*

Acknowledgments

To all the people who contributed to the realization of this work, thank you.

To my supervisors Fredrik and Erik, thank you. Working with you has been a pleasure. During those five years of research, we shared stress as much as we shared joy and relief. (Think of our first paper taking two years and a half to be submitted.) Thank you for your help, patience, and understanding throughout this journey. I am so grateful to you for guiding me through the process of applying scientific methodology to try to push the boundaries of knowledge a bit further. I will take that with me throughout life, and I will take all else I learned from you; from pedagogy and teaching with elegance to the art of listening to people, understanding their needs, and genuinely supporting them.

To all friends and colleagues at the Communication Systems Group, thank you. It has been a pleasure to be part of the group. I loved the friendly atmosphere, the positive, inspiring mindsets, and the diversity of our group. You did not only enrich my Ph.D. journey, but you enriched my life. Special thanks to Roman and Hao, who have been there throughout this journey.

To all the lovely friends who have been surrounding me and made Gothenburg my home, thank you. Cheers for all the good, fun, cozy doings we have been up to together. These are what kept me at mental heights, ready to give all for my research. Special thanks to Fabio, Cristina, Murad, Jose, Laura, Guzal, Dmitrii, Mohamed, Hichem, and Rahul.

To my partner Sara, a hearty thank you for being there. A wise friend told me once that a Ph.D. candidate needs a partner to stay sane. Thereby, here I say, you kept me sane during the second half of my Ph.D. journey. Thank you for that, and most of all, for all the love, joy, and celebration you surround me with as no one else does.

To my siblings, and my parents Cherif and Ouassila, a warm hugging thank you for your unceasing support throughout my education. Your faith in me gives me the wings I use to fly. From the bottom of my heart, thank you.

B. LEHOCINE

Chouaib Bencheikh Lehocine
Visby, September 2022

Financial Support

This work was carried out in the Antenna Systems Center ChaseOn in a project supported by the following parties: Swedish Governmental Agency of Innovation Systems (Vinnova), Chalmers, Bluetest, Ericsson, Keysight, RISE, Smarteq, and Volvo Cars.

Acronyms

3GPP:	The 3rd Generation Partnership Project
ABN:	analog beamforming network
ACN:	analog combining network
AOA:	angle of arrival
AOD:	angle of departure
AoI:	age-of-information
APS:	angular power spectrum
ASN:	antenna switching network
AWGN:	additive white Gaussian noise
BrEP:	burst error probability
BSM:	basic safety message
BSS:	basic service set
C-ITS:	cooperative intelligent transport systems
C-V2X:	cellular vehicle-to-everything
CACC:	cooperative adaptive cruise control
CAM:	cooperative awareness message
CDD:	cyclic delay diversity
CSI:	channel state information
CSIT:	channel state information at the transmitter
CSMA/CA:	carrier-sense multiple access with collision avoidance
DCC:	decentralized congestion control

DENM:	decentralized environment notification message
DRSC:	dedicated short-range communication
EGC:	equal gain combining
ESPAR:	electronically switched parasitic array radiator
ETSI:	European Telecommunications Standards Institute
GPS:	Global Positioning System
GSCM:	geometry-based stochastic channel model
HC:	hybrid combiner
LOS:	line of sight
MA:	multiple antenna
MAC:	medium access control
MCS:	modulation and coding scheme
MIMO:	multiple-input multiple-output
MP:	multi-path
MPC:	multi-path component
MRC:	maximal ratio combining
NLOS:	non-line of sight
OBU:	on-board unit
OFDM:	orthogonal frequency division multiplexing
OLOS:	obstructed-line of sight
PDP:	power delay profile
PEP:	packet error probability
PHY:	physical

PIR:	packet inter-reception time
PL:	path-loss
RF:	radio frequency
rms:	root mean square
Rx:	receiver
SB-SPS:	sensing-based semi-persistent scheduling
SC:	selection combining
SC-FDMA:	single-carrier frequency-division multiple access
SNR:	signal-to-noise ratio
STBC:	space-time block code
TDL:	tapped delay line
Tx:	transmitter
V2I:	vehicle-to-infrastructure
V2N:	vehicle-to-network
V2P:	vehicle-to-pedestrian
V2V:	vehicle-to-vehicle
V2X:	vehicle-to-everything
VU:	vehicular user
WSSUS:	wide-sense stationary uncorrelated scattering

Contents

Part I

Overview

CHAPTER 1

Introduction

1.1 Background

Cars, buses, trucks, and any other types of vehicles play a fundamental socio-economical role in human society worldwide. The use of vehicles, despite being mostly beneficial, annually causes the death of 1.3 million human beings [1]. Additionally, vehicles being largely fueled by fossil fuels are a major contributor to global warming and climate change. These shortcomings of vehicles can be reduced by developing cooperative intelligent transport systems (C-ITS). C-ITS rely on wireless vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to enable several traffic safety and traffic efficiency applications. Examples include forward collision warning, lane merging assistance, intersection collision warning, traffic light optimal speed advisory, and platooning [2].

V2V and V2I belong to the family of vehicle-to-everything (V2X) communication, which also includes, vehicle-to-pedestrian (V2P) (and other vulnerable road users, e.g., cyclists), and vehicle-to-network (V2N). Together, they promise not only safer and more efficient roads, but also a more comfortable driving and traveling experience, by supporting, on top of the basic safety applications, advanced applications for automated and autonomous driving [3], as well as infotainment services. Notably, V2X is envisioned to play a crucial role on top of onboard sensors (cameras, radars, lidars, etc.) to enable automated and autonomous vehicles, and facilitate their integration into the transportation system [4].

Research efforts in the field of V2X communication date back to the 1980s. Several projects took place in Europe, the United States of America (USA), and Japan to develop vehicular technology and standardize it. An extensive list of projects and activities in this field can be found in [5], [6]. These efforts crystallized in the dedication of 75 MHz bandwidth at 5.9 GHz [7] for vehicular communication and the standardization of dedicated short-range communication (DRSC) in 1999 in the USA [5]. This was followed by the *European ITS Communication Architecture* standard, which was first published in 2008 by the European project COMeSafety [8], [9], and later standardized by the European Telecommunications Standards Institute (ETSI).

To enable the basic C-ITS safety and efficiency use cases, the European C-ITS standard defines two types of messages, cooperative awareness messages (CAMs) and decentralized environment notification message (DENM) [8], [9]. CAMs are periodically broadcast with content spanning the vehicle dynamic information, e.g., position, speed, heading, etc. DENMs are broadcast by vehicles upon the detection of a particular event, and they serve as hazard warning messages. The same types of messages are defined by DRSC, where CAMs are referred to as basic safety messages (BSMs) instead [10].

To transmit these two types of messages, both standards rely on direct communication (i.e., in absence of a controller) with physical (PHY) and medium access control (MAC) layer specifications corresponding to IEEE 802.11p access technology, whose European profile is known as ITS-G5 [7]. IEEE 802.11p is a customization of IEEE802.11 (Wi-Fi) to fit the outdoor, fast-varying vehicular propagation environments, and time-critical communication [11]. Since latency is of paramount importance in V2X systems, IEEE 802.11p devices communicate without establishing a basic service set (BSS) with other devices [7], [11], thus cutting short the delay of the association procedure (i.e., forming a BSS). The medium access control of IEEE 802.11p relies on carrier-sense multiple access with collision avoidance (CSMA/CA) technology, while the physical layer is based on orthogonal frequency division multiplexing (OFDM) where transmissions occupy a 10 MHz channel. The system can support several modulation and coding schemes (MCSs) with data rates ranging from 3 Mbit/s to 27 Mbit/s [6]. Yet, the default data rate for CAMs is 6 Mbit/s [12], which hits a trade-off between reliability and radio channel congestion and interference.

IEEE 802.11p is a mature access technology to support safety V2X applications enabled by CAMs. It was released in 2010 [13], and has been subject to extensive tests and field-trials worldwide [13], [14]. Cellular V2X (C-V2X) is a contending access technology that was first introduced in 2016 by the Third Generation Partnership Project (3GPP) in Release-14 [13]. C-V2X supports both direct sidelink communication and network-based communication. In direct sidelink communication, which is the default mode, vehicles autonomously select their resources and communicate without a cellular base station. The physical layer of C-V2X sidelink is based on single-carrier frequency-division multiple access (SC-FDMA) with both 10 and 20 MHz channels [15], and data rates ranging from 1.15 Mbit/s to 17.71 Mbit/s [13] (according to Release-14). Unlike IEEE 802.11p, transmissions do not occupy the full channels but partial frequency-time resources known as subchannels. The resource management and selection of subchannels (i.e., MAC) are based on distributed sensing-based semi-persistent scheduling (SB-SPS), which is designed to support periodic traffic [15].

The proper functionality of V2X communication faces several challenges that are access technology-agnostic. These include radio channel congestion and interference in dense urban scenarios, the fast-changing behavior of vehicular channels, the variability of propagation environments; from urban, rich multi-path (MP) to suburban/highway scarce MP environments with a high probability of line of sight (LOS) propagation, and antenna impairments due to vehicles body. Namely, to elaborate on this last issue, the vehicle body (e.g., roof curvature, roof rails, panorama glass), the mounting position of the antenna (rooftop, in-vehicle, side-mirror, etc.), the housing of the antenna (e.g., shark-fin housing, side-mirror compartment, etc.) cause distortions in the antenna radiation characteristics. In particular, omnidirectional antennas, which have a nearly equal power gain in all directions, exhibit directional, nonuniform gain patterns, in many mounting positions on vehicles [16]–[18]. This implies that antennas can exhibit low gains or even nulls in certain directions. This is undesirable since vehicular safety applications rely on messages that are broadcast in all directions and which ideally require antenna systems with good reception in all horizontal-plan directions. This thesis tackles this issue by developing low-cost multiple antenna systems that yield an improved omnidirectional coverage compared to the single antenna case. The scope and the objectives of the thesis are outlined in the next section.

1.2 Scope of the Thesis

In this thesis, multiple antenna (MA) systems are developed to ensure a robust cooperative awareness service between vehicles despite the vehicular antenna-integration impairments. Since CAMs are the main enabler of the cooperative service, the MA systems developed are tailored for CAM-based, periodic broadcast communication.

The developed MA systems are founded on the analog combining network (ACN) proposed by Nagalapur *et al.* [19], which allows the use of multiple antennas with a single-port receiver (Rx). ACN uses time-varying phase shifters that do not depend on channel state information (CSI), and are designed to minimize the probability of K consecutive CAM errors under a single dominant path propagation with low angular spread.

This thesis first provides a hybrid receive-side MA system that combines the low-cost, low-complexity ACN with digital maximal ratio combining (MRC).

Second, to allow for a full transmit-receive MA system, an analog beamforming network (ABN) of phase shifters is proposed in this thesis to be used at transmit-side. The scheme is compliant with ACN, hybrid ACN-MRC, or full MRC combining at the receiver.

Third and last, this thesis provides investigations of the performance of the proposed MA systems under the relaxation of (i) the assumed periodicity of CAM packets, and (ii) the time-varying assumption of the dominant propagation path. Both relaxations served to derive design rules under practical conditions, and pave the way for potential future implementation and field tests of the developed MA systems.

1.3 Organization of the Thesis

This thesis relies on a *collection of papers* that are appended to Part II, while Part I consists of five chapters, which introduce the basic theory and concepts used in the appended papers. Namely, in Chapter 2, the cooperative awareness service alongside CAM generation rules are presented. Moreover, suitable performance metrics in assessing CAM-based cooperative communication are introduced. In Chapter 3, the antenna impairments due to the vehicle body are elaborated in more detail. Additionally, MA systems that can be used to remedy their effect, including the ACN are described alongside open questions that need to be addressed. In Chapter 4, vehicular propagation characteristics are briefly discussed. Then, the single dominant path propagation assumed when developing and assessing the robustness of the MA antenna systems is presented. Finally, the contributions of this thesis alongside future research directions are highlighted in the last chapter.

CHAPTER 2

Vehicular Cooperative Awareness Service

In this chapter, we provide an overview of CAM messages which enable cooperative awareness between vehicles in C-ITS. Moreover, we present their generation rules alongside performance metrics used to assess the reliability of the cooperative awareness service enabled by them.

2.1 Cooperative Awareness Messages (CAMs)

Cooperation between vehicles is enabled by the periodic broadcast of cooperative awareness messages CAMs (also known as BSMs under DRSC standard [10]). CAMs are generated at the Facilities layer of the ETSI *ITS Communications Architecture* standard. Their content, format, and generation rules are specified by ETSI [20], and they are independent of the access technology. CAMs contain status dynamic information of the disseminating vehicle, including position, speed, heading, activated systems, etc., as well as attribute information, such as the type of vehicle, its dimensions, its role on the road, etc. Upon the reception of a CAM, a receiving vehicle become aware of the disseminating vehicle and its status. Frequent dissemination of CAMs ensures continuous, real-time situational awareness between vehicles.

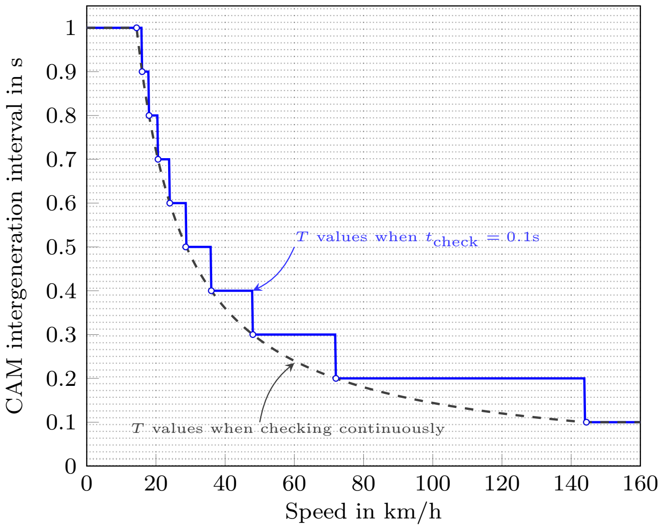

Figure 2.1: Example of how CAM inter-generation interval T is set following the change of dynamics rules. The vehicle is assumed to be moving at a constant speed on a straight road. Vehicle dynamics are checked every $t_{\text{check}} = 0.1$ s (solid line) or continuously (dashed line).

The time between the generation of two consecutive CAMs, T, referred to as inter-generation interval, or broadcast period in this thesis, has a lower and upper limit of 0.1 s and 1 s, respectively. While it is desirable to use the lowest possible period T, such a strategy can lead to radio channel congestion, and consequently, compromise the cooperative awareness service. Therefore, within the range, $0.1 \leq T \leq 1$ s, CAMs are generated following certain rules depending on (i) disseminating vehicle dynamics, (ii) application requirement, and (iii) radio channel status.

To begin with, to avoid overloading the radio channel, the decentralized congestion control (DCC) algorithm dynamically prescribes a parameter T_{DCC} which sets a lower limit on the period, $0.1 \leq T_{\text{DCC}} \leq T \leq 1$ s. Then, in the default setting, CAMs are generated following certain rules that track the change of dynamics of vehicles. That is, a vehicle checks periodically every at least $t_{\text{check}} \leq 0.1$ s its speed, position, and heading, and compares it with the information included in the last disseminated CAM. A CAM is generated if one of the following trigger conditions is satisfied.

(i) The time elapsed since the last generated CAM is greater or equal to T_{DCC}, and
  - the absolute speed of the vehicle changed by at least 0.5 m/s, or
  - the absolute position changed by at least 4 m, or
  - the absolute heading changed by at least 4°.

(ii) The time elapsed since the last generated CAM is equal to 1 s.

We note that under this default setting, whenever the inter-generation period is lowered (reflecting a faster change of dynamics than experienced priorly), the same value of T has to be maintained for several consecutive CAMs, corresponding to $N_{\text{GenCam}} \leq 3$. An example of how the broadcast period is set following the change of dynamics rules is shown in Fig. 2.1, where a vehicle is assumed to be traveling on a straight road at a constant speed, implying that CAM generation is triggered due to the change of position condition. When the vehicle status is checked at regular intervals, we see in solid line in Fig. 2.1 that the inter-generation period T takes discrete values which are multiple integers of $t_{\text{check}} = 0.1\ s$ (i.e., $T = nt_{\text{check}}$, $n \in \mathbb{N}$). These discrete values are only a subset of the continuous interval $[0.1, 1]$. To increase the granularity of this subset, it is enough to lower t_{check}.

Since certain applications may have different requirements on the generation of CAMs, an application can override the default setting (i.e., change of dynamics rules), and preset a generation interval T_{App} which is satisfied as long as $T_{\text{DCC}} \leq T_{\text{App}}$, or else, a failure notification is returned to the application.

The range of broadcast period as specified above following ETSI [20] is envisioned for basic safety and traffic efficiency use cases. For advanced use cases like cooperative adaptive cruise control (CACC), platooning, advanced driving, extended sensors, and remote driving [3], [21], it is envisioned that CAMs will be generated with a much higher frequency corresponding to a minimum and maximum inter-generation interval of 0.03 s and 0.1 s respectively, for CACC and platooning use cases for example [3], [21]. Nevertheless, in this thesis, the focus is on the basic safety applications enabled using $0.1 \leq T \leq 1$ s.

CAMs are short packets with sizes ranging from 100 and up to 800 bytes [22], and their duration T_{m} depends on the access technology. For IEEE802.11p with a default data rate of 6 Mbit/s the message duration satisfies $T_{\text{m}} \leq$

1.07 ms, while for C-V2X the message size is equal to the subframe duration $T_{\mathrm{m}} = 1$ ms.

The field-tests performed in [22], where CAMs were generated according to the default change of dynamics rules, found that the messages do not sustain the same size nor the same period for many consecutive packets, implying aperiodic CAM traffic. While some studies in the literature take into account realistic models of variable size and variable period of CAMs e.g., [23], [24], simplified models which assume fixed broadcast period T and fixed size for all, or some consecutive CAMs are also used in the literature e.g., [25] (3GPP), [26], [27]. Such models are especially suitable assuming the application-defined setting of broadcast periods, instead of the default setting. They are also suitable in the case of a pre-configuration that ensures a fixed broadcast period, as done in the measurement studies [28]. In this thesis, we use the simplified model of periodic, fixed-size CAM traffic when developing MA systems in Paper A, B and D. We then investigate the performance of the developed systems when the inter-generation time is varying (after a number of equally time-spaced consecutive packets) in Paper C.

2.2 Performance Metrics

High reliability and low latency are essential for V2X communication. Taking into account the nature of the periodic broadcast cooperative awareness service, it has been proposed in several works [29]–[31] to assess its reliability based on the application-level reliability. Namely, given a C-ITS application that relies on the information carried by CAMs, upon the reception of a message, the application updates the info available about the originating vehicle, and as long as a new packet is received before this information is outdated, the application can function properly. Following this line of thought, age-of-information (AoI) has been proposed [31] to assess the reliability of the cooperative awareness service. AoI is defined as the age of information contained in the last correctly received CAM packet. Using this metric, an application is in outage if the AoI exceeds a maximum tolerable threshold A_{max}, upon which the available information is considered unreliable. An example of the time evolution of AoI is shown in Fig. 2.2. Similar metrics to AoI are *T-window* which was proposed in [29], and packet inter-reception time (PIR) proposed in [30]. *T-window* is defined as the probability of receiving at

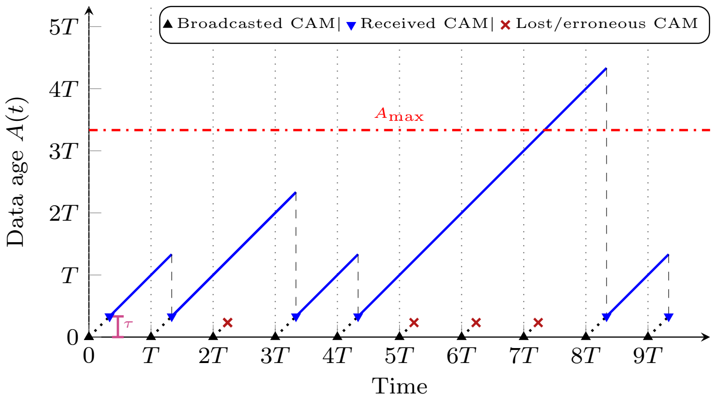

Figure 2.2: AoI for periodic traffic of CAM with inter-generation time T. The latency τ due to the propagation time and MAC delay is assumed for simplicity to be the same for all packets.

least one packet within a tolerance time window, while PIR is defined as the time separating two successful receptions of CAM packets, and it is adopted by 3GPP [25] as one of the performance metrics for V2X systems. The use of these metrics is well adopted in the literature. Examples include a simple switching MA system, and a multihop CAM forwarding strategy that have been evaluated based on AoI in [32], and [33], respectively. Additionally, forward collision warning and platooning applications have been evaluated based on PIR in [34], and [27], respectively.

The application-level reliability metric AoI can be related to the communication reliability, through the burst error probability (BrEP) metric proposed in [19]. BrEP is defined as the probability of losing K consecutive periodic messages. If latency between the generation and reception of a CAM (due to propagation and MAC delays) is neglected, the two metrics can be related following $A_{\max} = KT$, where T is the inter-generation interval of CAMs. Thus, K is a parameter that is defined to meet the requirement of a certain C-ITS application. Based on examples from the literature [28], [29], [34], the maximum tolerable AoI for different tested safety applications can range from 0.3 s to 3 s. Assuming a broadcast period of $T = 0.1$ s, K can be assumed to take values between 3 and 30. Nevertheless, without explicitly specifying a range for K, we use BrEP in the appended papers of this thesis to develop and assess the performance of MA schemes for cooperative traffic safety and efficiency applications.

CHAPTER 3

Vehicular Antenna Systems

Antennas are an important part of any wireless communication system. In this chapter, we start by discussing some challenges related to antenna integration into vehicles, and how these can compromise the transmission and reception of CAMs in the context of V2V communication. We then introduce MA systems that have been proposed in the literature to resolve these challenges. We finally conclude this chapter by briefly highlighting the cabling challenges associated with the implementation of vehicular MA systems.

3.1 Vehicular Antennas Impairments

As discussed in Chapter 2, CAMs are broadcast by *all* vehicles to notify of their status to *all* neighboring vehicles. These all-to-all broadcast signals can arrive at any possible direction in the azimuth plane, but they are restricted to a narrow angular sector in the elevation plane [17], [35], due to the comparable low heights of vehicles. This call for vehicular antenna systems with 360° reception coverage in the azimuth plane. In other words, antenna systems with omnidirectional coverage.

A common antenna mounting position for vehicles is the rear central rooftop position, where a shark-fin case is typically used to house radio systems antennas, including global positioning system (GPS), and cellular systems antennas. Since V2V communication requires high reliability where the employment of multiple antennas may be required, several research studies took place to investigate other suitable mounting positions for V2V communication at the 5 GHz band. These include other rooftop positions (e.g., at the front and to the sides) [16], in-vehicle (e.g., behind the rearview mirror) [16], windshield [36], side mirrors [36], [37], front/back bumpers [36], etc. The classical rear central rooftop position has also been evaluated with a single antenna [18], as well as with multiple antennas that are integrated into a shark-fin case [17], [38], [39]. These studies brought into focus the fact that, in spite of the mounting position, the gain patterns of integrated antennas exhibit distortions. The distortions depend on the body and shape of the vehicle, the mounting position, the housing of the antenna, etc., and they can be severe. Notably, due to these distortions, antennas with omnidirectional coverage exhibit directional gain patterns with low gain, or even blind spots in certain azimuth directions [16], [17], [39]. These can lead to packet losses even at short distances, and under LOS propagation, as noted in [16].

The choice of vehicular antenna placement is not subject to pure communication performance assessment. Aesthetics and aerodynamics design aspects of vehicles affect the antenna placement, and can contradict in some cases antenna performance objective [17], [40]. For example, while a sunroof panorama glass can be aesthetically appealing and desirable by customers, it can lead up to 20 dB loss in the gain of rear rooftop mounted antennas and low coverage in the driving direction [18]. Similarly, despite that roof railings can lead to 4 to 5 dB ripples in omnidirectional antenna patterns [18], they are needed in some vehicles to meet certain customers needs.

In light of the aforementioned facts, how can V2V systems achieve omnidirectional coverage in the azimuth plane? The answer according to several studies [16], [17], [38], [40] lies in the employment of MA systems, which combine antennas with contrasting gain patterns to achieve an overall omnidirectional coverage. This thesis backs up that answer by developing such MA systems.

3.2 Vehicular Multiple Antenna Systems

Several of the research papers that investigated vehicular antenna integration impairments on omnidirectional coverage also investigated the potential of existing, known diversity MA schemes in remedying those effects. In particular, a multi-radio packet selection scheme, where multiple antennas are connected to different receivers, has been used to perform packet selection diversity in [16]. The technique has been shown to achieve diversity gains even under LOS conditions due to the varying antenna patterns under vehicle body effects. Most importantly, the technique led to improved omnidirectional coverage of the antenna system despite the car body effects. Similarly, selection combining (SC) and MRC have been used in [36] to combine multiple antennas that are located at different locations on a vehicle to improve the overall antenna system coverage. It has been shown by means of evaluating the diversity gain of the system that these techniques yield better performance than single antenna systems. Nevertheless, the gains of the MA systems are found to be maximized by choosing a suitable antenna combination with complementary gain patterns, e.g., rear central rooftop and front bumper antennas, where the former has good backward coverage, and the latter a good forward coverage.

Besides SC and MRC, equal gain combining (EGC) is also a relevant MA technique for V2V communication. These classical techniques are a known means of achieving high reliability over wireless channels by harvesting diversity gains in MP fading channels, and they have been shown to increase the reliability of vehicular communication [41], [42]. Unlike MAs at the Rx, it is difficult to use MA systems that rely on CSI for V2V broadcast communication at the transmitter (Tx). Despite that there exist systems to make channel state information at the transmitter (CSIT) available for unicast V2I communication, e.g., predictor antennas [43], this is difficult to realize in the context of broadcast V2V communication due to the high number of users. In addition, the limited number of antennas and limited processing capabilities of a vehicle compared to a cellular base station, limits applying CSIT-based multi-user beamforming. Therefore, transmit diversity techniques that do not depend on CSIT like Alamouti [44], space-time, and space-frequency block codes, are relevant solutions for broadcast V2V, and their advantage in improving the reliability of vehicular communication has been shown in several works [45], [46]. Similarly to their receive-diversity counterparts, they are expected to show an advantage compared to single antenna systems even under LOS conditions, due to antenna mounting distortions effects. Additionally, cyclic delay diversity (CDD) [47] is an appealing relevant choice, due to its transparency to the Rx. That is, no additional processing is required at the Rx to decode a CDD transmitted signal. Transparency is a desirable characteristic since it allows satisfying backward compatibility for access technologies with previous generation radios that were designed to receive single-antenna transmitted signals [1].

The aforementioned techniques at both the Tx and the Rx are digital schemes that require a radio frequency (RF) chain (i.e., digital port) for each employed antenna. These techniques are high-performing, however, their cost and complexity rise with the number of employed antennas. Therefore, several efforts took place to develop analog MA systems which employ a single RF chain, and thus offer reduced cost, and reduced complexity. These analog schemes can be combined with standard digital schemes to form hybrid analog-digital MA systems that use fewer RF chains than antennas. Such schemes offer flexibility in trading off performance for cost and complexity, and vice versa. Some analog MA solutions developed specifically for V2V communication include [19], [32], [49].

In [32], a simple curvature based transmit antenna selection scheme has been proposed for CAM exchange in highway platooning applications. The antenna selection is performed based on onboard measurement of the yaw rate, which allows estimating road curvature and selecting one of the two side mirror-mounted antennas. The objective is to select the antenna with the highest probability of LOS with receiving antennas. The scheme was found to achieve lower AoI compared to a periodic switching scheme where the two transmit antennas are used alternatively for transmission, or compared to the use of a single transmit antenna. Another solution that has been considered in the literature is a reconfigurable electronically switched parasitic array radiator (ESPAR) antenna, which has been developed to support truck-to-truck communication [37], [49]. The antenna has a compact design, which has been optimized to fit within a side mirror of a truck. A car-compliant ESPAR design that can fit within a shark-fin case exists too, and it has been proposed in [50]. Using a single RF chain, and a 3-element ESPAR, a receiver

[1] For instance, Alamouti has not been used in C-V2X Release-15, since devices need to be backward compatible with Release-14 radios [48].

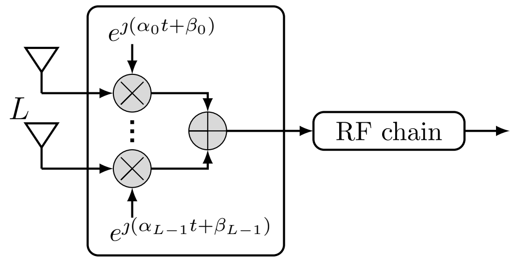

Figure 3.1: ACN with L receive antennas feeding a one-port digital Rx.

has the access to an equivalent of three antennas (omnidirectional, forward, and backward directional). ESPAR system can be combined with the digital MRC to form a hybrid receiver, as has been proposed in [49]. Such a system was found to improve both the average signal-to-noise ratio (SNR) and the SNR distribution compared to employing only MRC system, in a context of a platoon scenario [49]. Despite the reduced cost and reduced complexity of ESPAR system, it requires a control signal from the receiver to choose, based on SNR measurements, the antenna mode (directional or omnidirectional). Similarly, the curvature-based antenna selection in [32] relies on a control signal from the digital transmitter, and a yaw sensor, to drive the antenna selection procedure. This dependency of the antenna system on the radio digital part has been avoided by developing an ACN of phase shifters to combine V2V signals at the receiver without relying on CSI, SNR measurement, or feedback from the receiver in [19]. Such an approach allows designing the MA antenna system independently of the receiver, which can be an off-the-shelf product, and thus maximizes the modularity of the system. Furthermore, ACN was designed to provide robust coverage in spite of the vehicle body distortions of antenna patterns. The next subsection is dedicated to lie the ACN concepts and to list some directions for the improvement of the system.

ACN

An ACN is shown in Fig. 3.1. The scheme combines L antenna signals in the analog domain without relying on CSI or feedback from the receiver. The network uses analog phase shifters that are modeled as an affine function of

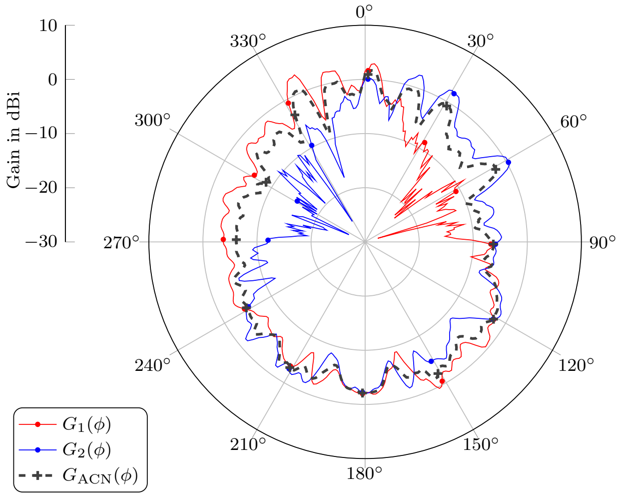

Figure 3.2: Equivalent radiation pattern achieved using ACN combining of two measured patterns of mounted monopole antennas on a vehicle [19].

time following

$$e^{\jmath(\alpha_l t+\beta_l)}, \quad l = 0, 1, \ldots, L-1, \tag{3.1}$$

where β is an initial, unknown, and uncontrollable phase offset, and α is the phase slope that drives the phase shifter. To design the ACN it is enough to choose the phase slopes. Following that, a set of robust phase slopes have been derived in [19] to minimize the probability of losing K consecutive CAM packets (i.e., BrEP) when the received signal coincides with the worst-case angle of arrival (AOA) with respect to the antenna system. Since the effects of antenna distortions discussed in Section 3.1 are expected to be more noticeable when communication is carried in a scarce MP environment with a dominant path, such propagation is assumed when designing ACN to ensure the *robustness* of the system. The ACN has been shown to yield an effective, improved omnidirectional gain pattern of the antenna system in presence of car body effects. An example of that is shown in Fig. 3.2.

ACN offers an attractive full analog MA system of low cost and low complexity. Nevertheless, some open questions remain, and they are listed below.

- Can ACN be combined with classical digital schemes, e.g., MRC to form hybrid receivers that allow combining L antennas into $1 < P < L$ digital ports (i.e., P RF chains)?
- Can a low-cost, low-complexity MA system be devised for robust all-to-all broadcast communication at the transmitter, and be compatible with ACN processing at the receiver?
- What design choices can be obtained when certain of the assumptions used to derive the phase slopes in [19] are relaxed?

This thesis provides answers to these questions in Paper A–D. Details follow in Chapter 5.

3.3 Practical Aspects of Multiple Antenna Systems

So far, we focused on highlighting the benefits of MA systems. It is important to highlight by the end of this chapter the cabling challenges associated with their realization. Namely, antennas have to be connected to the signal processing on-board unit (OBU), which is typically located inside the vehicle compartment. This implies, depending on the mounting position, a cabling distance of $2-8$ m [36], [51] from an antenna to the OBU. Conventionally, RF cables are used for these connections. Since typical RF cables have a high loss (1.7 dB/m [36]), such a connection can lead to prohibitively high attenuation. This can be avoided using high-quality, low-loss RF cables, however, these come at a higher cost [51], [52], and thicker, heavier, more rigid structures [52]. Additionally, requirements on cables to be resistant to high temperatures, chemical and water exposure, mechanical shock, etc. [53] drive the cost even higher. These challenges pushed for a new trend of locating RF modules close to the antennas [36], [49], [51] to minimize the length of RF connections and the loss/cost associated with them. The modules convert the analog RF antenna signals to digital baseband signals. Consequently, cheap digital buses [52] are used to connect the output of the RF modules to OBU without introducing signal attenuation. Such architecture is envisioned to be the main trend for future vehicular MA systems.

CHAPTER 4

Overview of V2V Propagation Channels

In this chapter, we start with an overview of the wireless channel characteristics, followed by an overview of V2V channel models as well as path-loss (PL) and shadowing models. At last, we present the channel model used to develop robust MA systems for periodic broadcast V2V communication in this thesis.

4.1 Fundamentals of Wireless Channels

The propagation of radio signals from the Tx to the Rx is characterized by three main phenomena, PL, MP fading, and shadowing [51], [54], [55]. The PL refers to the distant-dependent attenuation experienced by the signal as it propagates. It increases with the increase of the distance d, and it can be modelled following a simple power law d^n, where n is the pathloss exponent. The signal propagation typically takes place over a number of multi-path components (MPCs) that follow different physical paths, and arrive at the Rx with varying amplitudes and phases. The aggregation of these MPCs can add up constructively, or destructively at the Rx leading to MP fading in the form of fast fluctuations of the received signal over time, frequency, and space. Due to the small scale over which these variations can be observed (in the order of a wavelength), MP fading is also referred to as small-scale fading. Occasionally, large objects like a building, a bridge, a truck, etc., can obstruct certain MPCs between the Tx and the Rx and lead to shadowing in the form of fading of the received signal which is observed over a much larger scale compared to small-scale fading. Therefore, shadowing is also referred to as large-scale fading.

The MP propagation between the Tx and the Rx is typically modeled using a time-varying channel *impulse response*, $h(t, \tau)$ where t is the time, and τ is the delay of MPCs. In the context of cellular communications, a stochastic approach is commonly used to model the channel impulse response following a tapped delay line (TDL). Stochastic channel modeling relies on power delay profile (PDP), fading statistics, and the Doppler spectrum. It also relies on angular power spectrum (APS) if a double-directional TDL, which takes the directions of the MPCs into account, is needed. This is especially relevant in the context of MA or multiple-input multiple-output (MIMO) systems.

To start with, the PDP provides the average received power by MPCs arriving at a certain delay. It is obtained by averaging the square of the magnitude of the channel impulse response over small-scale fading. The square-root of the normalized second central moment of the PDP gives the root mean square (rms) delay spread of the channel τ_{rms}. The delay spread is a key parameter in the design of wideband radio systems, and it allows estimating the coherence bandwidth over which the channel impulse response is said to have a flat (frequency) response. The coherence bandwidth can be estimated as [51],

$$B_{\mathrm{coh}} \approx \frac{1}{2\pi\tau_{\mathrm{rms}}}, \tag{4.1}$$

and it is a measure of frequency-selectivity of the channel.

While the PDP gives the mean power per delay, the fluctuations of power at a certain delay around the mean are represented by a statistical distribution of small-scale fading. This can be Rayleigh, Rice, or Nakagami distribution depending on the presence or the absence of the LOS component between the Tx and Rx [51], [54].

To capture the time-varying characteristics of the channel, that is, the fluctuations of power at a certain delay with time, the Doppler Spectrum is used. Namely, in mobile propagation environments, due to the movement of Tx and/or Rx the different MPCs experience different frequency shifts that are proportional to the speed of mobility. This eventually leads to the widening of the radio signal in the frequency domain (similar to the widening in time-domain due to the differing MPCs delays), which is characterized by the Doppler spectrum. Similarly to delay spread, rms Doppler spread $f_{\mathrm{D,rms}}$ can be defined, and it allows estimating the time-selectivity of the channel by means of the coherence time, [51],

$$t_{\mathrm{coh}} \approx \frac{1}{2\pi f_{\mathrm{D,rms}}}. \tag{4.2}$$

Over a timescale equal to t_{coh}, the channel impulse response is approximately constant. (That is, the variation of power at a certain delay is non-significant over t_{coh}.)

Finally, in MA or MIMO systems, a directional characterization of the propagation environment is useful, since it helps to decide on suitable MA processing techniques for a particular channel, e.g., beamforming, diversity combining, etc. [51]. To that end, APS is used to obtain how the MPCs are distributed in the angular domain [55]. Similarly to delay, and Doppler spreads, the angular spread can be computed as the square-root of the second normalized central moment of the APS [55].

The TDL is widely used in cellular communications, where the powerful assumption of wide-sense stationary uncorrelated scattering (WSSUS) holds. The assumption implies that the channel statistics do not change with time, and it allows for modeling the propagation environments using a non-time varying PDP and Doppler spectrum [54]. This yields simple, compact TDL channel models. The WSSUS assumption does not hold under V2V propagation [51], [54], and makes V2V channel models differ from traditional cellular counterparts. The next section is dedicated to elaborating on these aspects and giving an overview of V2V channel modeling approaches.

4.2 V2V Channel Models

There exist several aspects that make V2V propagation channels differ from the cellular ones. First, V2V communication takes place between the Tx and Rx with antennas that are mounted at low heights of 1-2 m [51]. This implies that communication takes place mostly in the horizontal plane, where there exist several mobile and stationary scatterers. In cellular communication, on the other hand, the base station antennas are typically mounted high above the street level, where the mobile users are located. The base station antennas have no local scatterers in their vicinity, unlike in V2V scenarios where both the Tx and the Rx are surrounded by local scatterers. Second, V2V communication range is in the order of a few hundred meters, in contrast to a range of $1 - 10$ km for cellular communication [51]. Last, in the context of V2V communication both the Tx and Rx, alongside some scatterers are mobile with velocities that are much higher than a typical cellular user (a pedestrian). This factor results in highly time-varying V2V channels with statistics that are changing over time, violating the WSSUS assumption [51], [54].

Taking into account these differences, several measurement campaigns took place since 2006 to characterize V2V propagation and develop suitable channel models for it [51]. Measurements are typically done for different environments, such as highway, urban, suburban, and rural, as well as for different scenarios, e.g., intersections, low/high traffic (congestion) [51]. The measurements target the characterization of the PL exponent, small- and large-scale fading statistics, delay spread, Doppler spread, and angular spread. The results of several measurement campaigns can be found in [51], [54].

To model the observed characteristics of V2V propagation, three main approaches exist, stochastic, deterministic ray-tracing, and geometry-based stochastic approach [51], [54]. The stochastic approach with TDL, which has already been introduced in the previous section, is the simplest approach. However, it suffers from low accuracy in capturing the non-stationary behavior of the channel [54], despite efforts to adapt it to model non-WSSUS channels, e.g., through birth/death process of taps [54], [56]. Ray-tracing, on the other hand, relies on solving Maxwell equations for a particular environment taking into account site geometries, and scatterers locations. This approach leads to accurate and realistic modeling of the propagation environment. Nevertheless, it is computationally expensive [51], [54]. Finally, the geometry-based stochastic approach strikes a balance between model simplicity and accuracy. Scatterers are stochastically placed in the environment surrounding the Tx and the Rx. Then, a simplified ray-tracing is performed to get the channel response at the receiver. This approach can easily handle non-WSSUS channels since Tx/Rx and scatterers mobility are taken into account in the model [51]. Additionally, it inherently supports double-directional channel representation, with angle of departures (AODs) from the Tx and AOAs towards the Rx, and can easily accommodate antenna gain patterns effects on the channel [57]. Examples of geometry-based stochastic channel models (GSCMs) that have been developed for V2V based on measurements are provided in [57], [58]. A GSCM model is also provided by 3GPP in [59], [60] for both urban and highway environments. The model distinguishes three propagation states LOS, non-line of sight (NLOS), and NLOSv (i.e., NLOS due to a vehicle), where this state implies that the LOS path is blocked by a vehicle. This state is also referred to as obstructed-LOS (OLOS) in the literature [61], [62], where this categorization of the vehicular channel is used.

Using GSCM, the double directional wideband channel model is given by [57, Eq. 8], [63, Eq. 2], [55, Ch. 6]

$$\begin{aligned} h_{l,m}(t,\tau) = &\sum_{i=1}^{N(t)} a_i(t) \mathrm{e}^{\jmath \frac{2\pi}{\lambda_\mathrm{c}} d_{i,l,m}(t)} \delta(\tau - \tau_i) \\ &\times \delta(\Phi_\mathrm{T} - \Phi_{\mathrm{T},i}) \delta(\Phi_\mathrm{R} - \Phi_{\mathrm{R},i}) g_{\mathrm{T},m}(\Phi_\mathrm{T}) g_{\mathrm{R},l}(\Phi_\mathrm{R}), \end{aligned} \tag{4.3}$$

where N is the number of MPCs, τ_i, $\Phi_{\mathrm{T},i}$, $\Phi_{\mathrm{R},i}$ are, respectively, the propagation delay, AOD, and AOA of path i, $g_{\mathrm{T},m}$ and $g_{\mathrm{R},l}$ are the complex amplitude patterns (i.e., far-field functions) of the m^{th} transmit and the l^{th} receive antennas. The complex amplitude of path i is given by a_i, and $\mathrm{e}^{\jmath \frac{2\pi}{\lambda_\mathrm{c}} d_{i,l,m}(t)}$ is the associated distance-induced phase shift. Observe that the path amplitude, delay, AOD, and AOA vary slowly, while the phase varies quickly with time [55]. Therefore, for the same path i, the phase can vary from one antenna pair (l, m) to another, due to the difference in the path distance $d_{i,l,m}$.

The three channel modelling approaches discussed above focus on capturing small-scale fading characteristics of the vehicular propagation channel. Models of PL and shadow fading are presented in the next section.

4.3 V2V Path-Loss and Shadowing Models

There exist several measurement-based studies that model PL and shadowing in V2V propagation channels, including [61], [62], [64], [65]. In particular, single- and dual-slope log-distance power law models have been used in [61], [62], [64], [65]. Additionally, a two-ray ground reflection model has been used in [62], [65]. Typically, these models are developed taking into account the environment, e.g., urban or highway, as well as the propagation condition, namely, LOS, OLOS, or NLOS. Using the dual-slope model the PL is given by [61, Eq. 5]

$$P_{\mathrm{L}}(d) = \begin{cases} P_{\mathrm{L}}(d_0) + 10n_1 \log_{10}\left(\dfrac{d}{d_0}\right) + X_\sigma, & d_0 \leq d \leq d_{\mathrm{b}}, \\ P_{\mathrm{L}}(d_0) + 10n_1 \log_{10}\left(\dfrac{d_{\mathrm{b}}}{d_0}\right) + 10n_2 \log_{10}\left(\dfrac{d}{d_{\mathrm{b}}}\right) + X_\sigma, & d_{\mathrm{b}} \leq d, \end{cases} \tag{4.4}$$

where d is the distance between the Tx and the Rx, n_1 and n_2 are the pathloss exponents, d_0 is a reference distance, d_{b} is the breakpoint, and X_σ is a stochastic term representing shadow fading. The breakpoint, d_{b} can be set according to the distance where the first Fresnel zone touches the ground [61], [64], that is $d_{\mathrm{b}} = 4h_{\mathrm{T}}h_{\mathrm{R}}/\lambda_{\mathrm{c}}$. Alternatively, it can be adjusted according to the value that leads to the best fit of the dual-slope model to the data, as has been done in [64]. Parameters for the dual-slope model for highway and urban scenarios with LOS and OLOS conditions have been derived in [61], while parameters for suburban scenarios have been derived in [64] instead. Additionally, the WINNER+B1 channel model [66] (which is used by 3GPP in Release-14 C-V2X [25]), provides parameters for a dual-slope model under LOS V2V propagation. Besides the dual-slope model, parameters for the single-slope model as well as for the two-ray model can be found in [62], [65].

One important observation is that under LOS conditions, the path-loss exponent can be less than the free space path loss exponent, $n_1 < 2$, as it was found in [61], [65]. This phenomenon is commonly attributed to the energy contribution of certain MPC to the LOS path [65].

Large-scale fading X_σ is typically modelled as a Gaussian random process with zero mean and σ_{SH} standard deviation. The process is spatially correlated, and its autocorrelation function $\mathbb{E}\{X_\sigma(d)X_\sigma(d+\Delta d)\}$ can be modelled according to an exponential decaying function, also known as Gudmundson model [67], following [61, Eq. 8]

$$\mathbb{E}\{X_\sigma(d)X_\sigma(d+\Delta d)\} = \mathrm{e}^{-|\Delta d|/d_{\mathrm{c}}}, \tag{4.5}$$

where d_{c} is the decorrelation distance. It is the distance difference Δd, at which the spatial correlation is equal to e^{-1}, and it depends on the environment, and on the propagation condition. As an example, in highways, it has been reported in [61] to be 23.3 m and 32.5 m for LOS, and OLOS conditions, respectively. Note that the decorrelation distance is larger when there exists an obstruction, since if a link between two vehicles is shadowed by another vehicle in between, then we expect this state to last as long as the vehicles keep the same geometry. Besides Gudmundson model, an averaged sum of two decaying exponential functions have been used in [62], as well as a Gaussian decaying function has been used in [57], to model the autocorrelation function of shadow fading.

Due to the spatial correlation characteristics of shadowing, it can be modeled as a block-fading, where the signal power is assumed to be approximately the same over the timescale needed for the distance difference between the Tx and Rx to be equal to the decorrelation distance [61].

4.4 V2V Single Dominant Path Channel Model

In the previous sections, we talked about V2V propagation channels in general. In this section, we bring the focus back to the objective of this thesis, which is of developing robust MA systems to remedy the vehicle body effects on the omnidirectional characteristics of the antenna system coverage. Robustness here is interpreted in the context of optimization (or decision theory), where a possibly rare, yet *worst-case* scenario is assumed [68], [69], in order to derive model parameters that ensure the quality of performance under this scenario. This is a suitable approach, since CAM-based cooperative V2V communication enables traffic safety applications that need to operate under all conditions [6].

A worst-case V2V propagation with respect to vehicle body effects on the antenna system has been proposed in [19]. Consider a vehicular antenna system that has low gain or nulls in certain azimuth directions. Their effects are expected to be more pronounced in environments where propagation is characterized by a dominant high power-carrying path (a LOS or a reflection) and few MPCs that are narrowly spread around the direction of the dominant path. The occurrence of a such event may lead to low received power and loss of a CAM packet. Furthermore, assume that the mobility and distance between the Tx, Rx, and potential scatterers are such that the direction of this dominant path is relatively constant over a timescale where several CAM packets have been transmitted. Then, there is a risk of losing a burst of these packets, which can cause an application outage. Such propagation with a dominant path and low angular spread has been indeed observed on roads with no surrounding buildings, e.g., highways [70]. To model the described worst-case propagation scenario, a single dominant path channel model was defined in [19], by setting the number of MPCs in (4.3) to $N(t) = 1$. In other words, only the dominant path, and other MPCs of relatively similar delays and directions are modeled by a single effective path. Additionally, the AOA and the AOD of the path were assumed to be non-varying over the duration of K consecutive CAMs, where K is the minimum number of packets which, if lost, lead to an application outage (see Chapter 2.2 for details). This model allowed analytical studies of the ACN in [19], and it is the channel model used in Papers A-C of this thesis in order to extend these analytical results to other interesting scenarios, namely, hybrid analog-digital Rxs, and MA at the Tx side. In Paper D, the model was relaxed by assuming time-variation of the AOA and the AOD of the dominant path over the duration of K consecutive packets. This allowed getting some insights into the performance of the developed systems when the worst-case propagation assumptions do not fully hold.

As part of wideband channel modeling, the resolvability of MPC depends on the system bandwidth. Following that, MPCs with delays that are different by less than the inverse of the system bandwidth, are lumped together into a single delay tap or delay bin in the equivalent discretized channel model [54]. Under dominant path propagation, it has been observed that the dominant path delay bin is well modeled by a Rician fading with a high κ-factor ranging from 5.71 dB under OLOS to 16.51 dB under LOS propagation [71]. Rician channels of high κ-factors tend to the additive white Gaussian noise (AWGN) channel, where exponentially decaying packet error probability (PEP) has been observed to be a good approximation of the actual PEP [72]. Therefore, the exponential PEP function has been adopted in [19], and it is also adopted in this thesis. This assumption allows us to convert the optimization objective from minimizing the BrEP of K consecutive packets into maximizing the average sum-SNR of the K packets, and therefore these two are referred to interchangeably in the attached papers.

In the previous section, we reviewed some PL models for V2V communications. Among these, the two-slope PL model (WINNER+B1) was used in Paper D of the thesis. The model was used under LOS dominant path propagation in a highway scenario, to investigate the MA system performance. Despite that the two-ray ground reflection model can be more accurate under LOS conditions [62], the two-/one-slope log-distance power law model was found, in [61], [65], to be a good fit to measured data under these conditions, too. Additionally, it can be used to fit both LOS and OLOS which are both relevant scenarios under the assumption of a dominant path propagation, and it allows us to generalize the obtained results under LOS to OLOS.

CHAPTER 5

Contributions and Conclusions

This thesis provides robust, low-cost MA systems for periodic broadcast V2V communications. The contributions of the thesis are three-fold. First, we propose a hybrid analog-digital combiner based on ACN [19] and MRC. Second, we develop a transmit-side MA scheme that is compatible with ACN, and ACN-MRC hybrid combining. Third, we relax some assumptions used in designing the systems and derive design rules that serve under practical scenarios. These contributions and the associated conclusions are highlighted in detail through the summary of the attached papers that follows. Future research directions are highlighted thereafter.

5.1 Contributions

Paper A: "Hybrid Combining of Directional Antennas for Periodic Broadcast V2V Communication"

Our first contribution is the proposal of a hybrid combiner (HC) for broadcast periodic V2V communication, which is an upgrade of the low-cost low-complexity ACN by a digital MRC-based stage. The HC combines L_{r} antennas to P digital ports, where $1 < P < L_\mathrm{r}$, following a sub-connected scheme. That is, P disjoint subgroups of antennas are combined using ACNs, whose outputs are then fed to the digital receiver which performs MRC based on estimating the phase and amplitude of the post-ACN channel response. The analog part of the HC does not rely on CSI or any feedback from the digital receiver. Thus, the analog and digital parts of the HC do not need to be collocated allowing, for instance, placing the analog part of the HC near the antennas while the digital part inside the vehicle. Taking into account that the effects of antenna distortions due to vehicle body are expected to be more noticeable under scarce MP propagation with a dominant path, we assume such propagation when designing the system. The design objective is to derive the ACNs phase slopes that minimize the BrEP of K consecutive CAMs, which is equivalent to maximizing the sum-SNR of the K consecutive packets. This equivalence holds under the assumption that packet error probability is an exponential function of average per-packet SNR; an assumption that is used throughout Papers A-D. Our finding is that the solutions for 1-port receiver [19] do solve the optimization problem under P-port receiver as well.

In a following step, we dedicated our focus to study the use of directional antennas with the HC for the special case of a two-port receiver. We have analytically shown, that it is optimal to divide the antennas into equal subgroups $(\lceil L_\mathrm{r}/2\rceil, \lfloor L_\mathrm{r}/2\rfloor)$ to achieve the best omnidirectional coverage of the antenna system. Furthermore, we derived a performance bound for the HC and have shown, using examples of directional antennas, that it can be fulfilled using a limited number of antennas, to yield a robust omnidirectional coverage of the vehicular antenna system.

Paper B: "Robust Analog Beamforming for Periodic Broadcast V2V Communication"

In this paper, we propose the use of an ABN of phase shifters at the transmit-side with L_s antennas, assuming that receivers employ ACN with L_r antennas. ABN is a transparent scheme that neither depends on CSIT, nor on feedback from the transmitter. Given the proposed ABN-ACN system, we perform robust optimization of the Tx and Rx phase slopes by assuming a worst-case scenario of a single dominant propagation with AOD and AOA that are relatively constant over the duration it takes to transmit K consecutive CAMs.

Under this scenario, we derive optimal phase slopes that minimize the BrEP of K consecutive CAMs for any user in the system, including the worst user. The optimal phase slopes are found to be independent of the antenna placement and the antenna gain patterns. The receive-side phase slopes are found to be consistent with solutions found in [19]. More notably, our work extended the optimality proof of these phase slopes, which was shown to hold only for the special case of $L_\mathrm{r} \in \{2, 3\}$, $L_\mathrm{r} \leq K$ in [19]. Our work proved that these phase slopes are actually optimal for any ACN with $L_\mathrm{r} \leq K$. Ultimately, using an example of vehicular antennas, the ABN-ACN system has been shown to lead to improved omnidirectional coverage at both the Tx and the Rx.

Our proposals for a transmit-side compatible solution with ACN did not stop at the ABN. In fact, using the same derived optimal receive phase slopes, we have shown that an ACN receiver can optimally communicate with transmitters employing an antenna switching network (ASN) that periodically alternates between the available transmit antennas, as well as transmitters employing Alamouti ($L_\mathrm{s} = 2$). Under the assumed propagation condition, ABN, ASN, and Alamouti are found to lead to the same maximized average sum-SNR of K packets (equivalent to minimized BrEP).

Finally, we have shown that the proposed transmit-side schemes are also compatible with receivers employing the hybrid ACN-MRC receiver proposed in Paper A.

Paper C: "Sensitivity Analysis of Beamforming Techniques for Periodic Broadcast V2V Communication"

In Paper A and Paper B, we developed full Tx-Rx MA systems dedicated to the periodic broadcast of V2V CAM packets needed to enable traffic safety and traffic efficiency applications. The systems and their derived optimal parameters were developed under the assumption that all vehicles broadcast their CAMs using the same fixed broadcast period T. In this paper, we address practical traffic scenarios where different vehicles may use different and potentially varying broadcast periods (see Chapter 2 for details). We focus on the scenario where the receivers employ an ACN while the transmitters employ an ABN or an ASN. Taking into account that the broadcast period has to be within the range $0.1 \leq T \leq 1$ s, we analytically derive sets of broadcast periods that sustain optimality (i.e., minimize the BrEP of K consecutive packets). Moreover, we show that by properly designing the phase slopes, we can achieve a dense set of the optimal broadcast periods within $0.1 \leq T \leq 1$ s, which can be used to provide a timely update of vehicles dynamics.

Paper D: "Antenna Combiner for Periodic Broadcast V2V Communication Under Relaxed Worst-Case Propagation"

In this work, we tackle yet another practical aspect of the systems developed in earlier works. To model the challenging propagation scenario for omnidirectional coverage of the antennas system in the context of all-to-all broadcast scenario, we assumed that communication takes place over a dominant path whose AOD and AOA are negligibly varying over the duration it takes to transmit K CAMs. This allowed us to design robust systems against the event that the AOD and the AOA of the dominant path coincide with directions of low gain of the antenna systems, and lead to the loss of K consecutive packets, i.e., an outage of the cooperative service. In this work, we investigate the performance of the developed systems when the dominant path directions (i.e., AOD, AOA), are time-varying, instead, over the duration of K packets. This also implies that the PL along the dominant path, as well as, the distance-induced relative phase shifts between antennas are time-varying over the same duration. To analytically model the effects of these quantities, we resort to studying a simple 1×2 ACN module (equivalent to 2×1 ABN). To that end, we approximate using a first-order polynomial the time-variation of the AOA, the PL, and the phase shifts between antennas, based on a reference highway scenario with a LOS propagation between two vehicles. Speed, antenna separation, and distance between the vehicles are taken into account in the modeling. We then analytically derive the loss function in sum-SNR of the ACN system, when the dominant path quantities are time-varying. We do that for each quantity separately. We found that the set of phase slopes that achieve the same sum-SNR under a time-invariant dominant path achieve different sum-SNRs when any of the three dominant path quantities varies over the duration of K packets. Following that, we derived a design rule to pick phase slopes that are robust under time-varying conditions and optimal under time-invariant conditions. The design rule has been validated using numerical computation and an example of vehicular antenna elements.

The analysis done in this work showed that the time-variation of PL and AOA has minor effects compared to the time-variation of the phase shift between the antennas. This last introduces a deviation to the ACN preset phase slopes, and can cause severe losses in sum-SNR. These losses can, nevertheless, be effectively limited by choosing a small antenna separation, in addition to picking a robust phase slope according to the derived design rule.

The steps used in analyzing the 1×2 ACN system (2×1 ABN), provide a guideline on how to analyze generic $L_\mathrm{s} \times L_\mathrm{r}$ ABN/ASN-ACN systems. Namely, the loss function in sum-SNR under a time-varying dominant path can be numerically computed (we believe that it is analytically intractable). Then, design rules for robust phase slopes can be obtained.

5.2 Conclusions and Future Works

This thesis establishes the use of simple analog networks of linear phase shifters at both the Tx and the Rx to process multiple antennas to enable robust periodic broadcast V2V communication in all azimuth directions, despite the vehicular antenna-mounting distortions. The networks rely neither on CSI nor on feedback from the digital Tx/Rx, and they can be designed independently of the antenna placement and antenna gain patterns. Moreover, this thesis paves the way for possible future implementation and field tests of these networks by providing certain design choices under practical scenarios.

There exist several directions for future works. First, similar to the HC developed at the receive-side, it is beneficial to develop a hybrid transmit-side counterpart. In particular, it is interesting to investigate the possibility of combining ABN with Alamouti or CDD.

Secondly, in the same steps of the work done in Paper C and Paper D, it is important to investigate the effects of other factors that were not taken into account in our studies, such as jitter, on the developed MA systems. Jitter occurs due to the varying MAC and propagation delays between the generation and reception of CAMs. Based on field tests performed in [22], jitter can be modeled as a Gaussian random variable with a certain standard deviation [24]. To assess the performance of the developed MA systems in the presence of this stochastic variable, the worst-case analysis is not straightforwardly applicable. One promising approach to handle this, though, is the use of *worst-case-expectation* [68], which allows performing robust optimization in the presence of stochastic terms. Similarly to jitter, the same approach can be used to study the effects of other stochastically modeled factors, for instance, phase error.

Thirdly, the solutions in this thesis are designed to be robust under worst-case propagation of a single dominant path that occurs in environments with no large surrounding scatterers, e.g., highways. One may wonder what the system performance is under rich multipath propagation, which is typical in urban environments. While this scenario is not particularly challenging for an antenna system with directions of low gains (due to the presence of many paths with wide angular spread), it is crucial to show that the developed solutions do not degrade the system performance with respect to the single antenna case under such scenario.

Finally, the investigation of the implementation aspects of the networks, taking into account the envisioned vehicular interconnection architecture where RF conversion is performed near the antennas (see Chapter 3.3), is an ultimate step toward the actual implementation and testing of the solutions.

References

[1] World Health Organization (WHO), *Road traffic injuries*, Accessed: Sep. 12, 2022. [Online]. Available: `https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries`.

[2] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions*, document ETSI TR 102 638 V1.1.1, Jun. 2009.

[3] *5G; Service requirements for enhanced V2X scenarios*, document ETSI TS 122 186 (3GPP TS 22.186 version 15.3.0 Release 15), Jul. 2018.

[4] European Commission department on Mobility and Transport, *Intelligent transport systems, cooperative, connected and automated mobility (CCAM)*, Accessed: Aug. 31, 2022. [Online]. Available: `https://transport.ec.europa.eu/transport-themes/intelligent-transport-systems/cooperative-connected-and-automated-mobility-ccam_en`.

[5] A. Alalewi, I. Dayoub, and S. Cherkaoui, "On 5G-V2X use cases and enabling technologies: A comprehensive survey," *IEEE Access*, vol. 9, Jul. 2021.

[6] H. Hartenstein and L. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Commun. Mag.*, vol. 46, no. 6, pp. 164–171, Jun. 2008.

[7] E. G. Ström, "On medium access and physical layer standards for cooperative intelligent transport systems in Europe," *Proc. of the IEEE*, vol. 99, no. 7, pp. 1183–1188, Jul. 2011, (Invited paper).

[8] *European ITS communication architecture; overall framework; proof of concept implementation*, Document COMeSafety D31, ver. 2.0, Oct. 2008.

[9] T. Kosch, I. Kulp, M. Bechler, M. Strassberger, B. Weyl, and R. Lasowski, "Communication architecture for cooperative systems in Europe," *IEEE Commun. Mag.*, vol. 47, no. 5, pp. 116–125, May 2009.

[10] *V2X communications message set dictionary*, Document SAE J2735, Jul. 2020.

[11] "Intelligent transport systems (ITS); European profile standard for the physical and medium access control layer of intelligent transport systems operatingin the 5 GHz frequency band," *Final draft ETSI ES 202 663 V1.1.0*, Nov. 2009.

[12] J. Daniel, C. Qi, and D. Luca, "Optimal data rate selection for vehicle safety communications," in *Proc. of the 5th ACM Int. Workshop on Veh. Inter-Networking*, Sep. 2008, pp. 30–38.

[13] A. Bazzi, B. M. Masini, A. Zanella, and I. Thibault, "On the performance of IEEE 802.11p and LTE-V2V for the cooperative awareness of connected vehicles," *IEEE Trans. on Veh. Tech.*, vol. 66, no. 11, pp. 10 419–10 432, Sep. 2017.

[14] A. Turley, K. Moerman, A. Filippi, and V. Martinez, *C-ITS: Three observations on LTE-V2X and ETSI-ITS G5 (white paper, NXP)*, 2018. [Online]. Available: `https://www.nxp.com/docs/en/white-paper/CITSCOMPWP.pdf`.

[15] R. Molina-Masegosa and J. Gozalvez, "LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range vehicle-to-everything communications," *IEEE Veh. Tech. Mag.*, vol. 12, no. 4, pp. 30–39, Nov. 2017.

[16] S. Kaul, K. Ramachandran, P. Shankar, S. Oh, M. Gruteser, I. Seskar, and T. Nadeem, “Effect of antenna placement and diversity on vehicular network communications,” in *Proc. 4th Annu. IEEE Commun. Soc. Conf. on Sensor, Mesh and Ad Hoc Commun. and Netw.*, Jun. 2007, pp. 112–121.

[17] O. Klemp, “Performance considerations for automotive antenna equipment in vehicle-to-vehicle communications,” in *Proc. URSI Int. Symp. on Electromagn. Theory*, Aug. 2010, pp. 934–937.

[18] A. Kwoczek, Z. Raida, J. Láčík, M. Pokorny, J. Puskelý, and P. Vágner, “Influence of car panorama glass roofs on Car2Car communication (poster),” in *IEEE Veh. Netw. Conf. (VNC)*, 2011, pp. 246–251.

[19] K. K. Nagalapur, E. G. Ström, F. Brännström, J. Carlsson, and K. Karlsson, “Robust connectivity with multiple directional antennas for vehicular communications,” *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 21, pp. 5305–5315, Dec. 2020.

[20] *Intelligent Transport Systems Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service,* document ETSI EN 302 637-2 V1.3.2, Nov. 2014.

[21] *Intelligent Transport Systems (ITS); Cooperative Adaptive Cruise Control (CACC); Pre-standardization study*, document ETSI TR 103 299 V2.1.1, Jun. 2019.

[22] V. Martinez and F. Berens, “Survey on ITS-G5 CAM statistics,” *Washington, DC, USA, Tech. Rep. TR2052*, Dec. 2018.

[23] R. Molina-Masegosa, J. Gozalvez, and M. Sepulcre, “Comparison of IEEE802.11p and LTE-V2X: An evaluation with periodic and aperiodic messages of constant and variable size,” *IEEE Access*, vol. 8, pp. 121 526–121 548, Jul. 2020.

[24] R. Molina-Masegosa, M. Sepulcre, J. Gozalvez, F. Berens, and V. Martinez, “Empirical models for the realistic generation of cooperative awareness messages in vehicular networks,” *IEEE Trans. on Veh. Tech.*, vol. 69, no. 5, pp. 5713–5717, Mar. 2020.

[25] *Study on LTE-based V2X Services; (Release 14),* document 3GPP TR 36.885 V14.0.0, Jun. 2016.

[26] A. Bazzi, A. Zanella, and B. M. Masini, “Optimizing the resource allocation of periodic messages with different sizes in LTE-V2V,” *IEEE Access*, vol. 7, pp. 43 820–43 830, Mar. 2019.

[27] G. Jornod, A. E. Assaad, A. Kwoczek, and T. Kürner, “Packet inter-reception time modeling for high-density platooning in varying surrounding traffic density,” in *Eur. Conf. on Netw. and Commun. (EuCNC)*, Jun. 2019, pp. 187–192.

[28] M. E. Renda, G. Resta, P. Santi, F. Martelli, and A. Franchini, “IEEE 802.11p VANets: Experimental evaluation of packet inter-reception time,” *Comput. Commun.*, vol. 75, pp. 26–38, Feb. 2016.

[29] Fan Bai and H. Krishnan, “Reliability analysis of DSRC wireless communication for vehicle safety applications,” in *IEEE Intell. Transp. Syst. Conf.*, Sep. 2006, pp. 355–362.

[30] T. Elbatt, S. Goel, G. Holland, H. Krishnan, and J. Parikh, “Cooperative collision warning using dedicated short range wireless communications,” in *Proc. of ACM VANET*, vol. 2006, Sep. 2006.

[31] S. Kaul, M. Gruteser, V. Rai, and J. Kenney, “Minimizing age of information in vehicular networks,” in *IEEE Commun. Soc. Conf. on Sensor, Mesh and Ad Hoc Commun. and Netw.*, Jun. 2011, pp. 350–358.

[32] M. Larsson, M. Jonsson, K. Karlsson, C. Bergenhem, and T. Larsson, “Curvature based antenna selection method evaluated using the data age metric and V2V measurements,” in *Proc. IEEE Int. Conf. on Commun. Workshop (ICCW)*, Jun. 2015, pp. 2356–2362.

[33] F. Librino, M. E. Renda, and P. Santi, “Multihop beaconing forwarding strategies in congested IEEE 802.11p vehicular networks,” *IEEE Trans. on Veh. Tech.*, vol. 65, no. 9, pp. 7515–7528, Sep. 2016.

[34] M. Sepulcre and J. Gozalvez, “Experimental evaluation of cooperative active safety applications based on V2V communications,” in *Proc. of the 9th ACM Int. Workshop on Veh. Inter-Netw., Syst., and Appl.*, New York, NY, USA, Jun. 2012, pp. 13–20.

[35] E. Condo Neira, U. Carlberg, J. Carlsson, K. Karlsson, and E. G. Ström, “Evaluation of V2X antenna performance using a multipath simulation tool,” in *The 8th Eur. Conf. on Antennas and Propag. (EuCAP)*, Apr. 2014, pp. 2534–2538.

[36] T. Abbas, J. Karedal, and F. Tufvesson, “Measurement-based analysis: The effect of complementary antennas and diversity on vehicle-to-vehicle communication,” *IEEE Antennas and Wireless Propag. Lett.*, vol. 12, pp. 309–312, Mar. 2013.

[37] L. Marantis, A. Paraskevopoulos, D. Rongas, A. Kanatas, C. Oikonomopoulos-Zachos, and S. Voell, “A printed monopole ESPAR antenna for truck-to-truck communications,” in *Int. Workshop on Antenna Tech.: Small Antennas, Innovative Struct., and Appl. (iWAT)*, Mar. 2017.

[38] A. Thiel, O. Klemp, A. Paiera, L. Bernadó, J. Karedal, and A. Kwoczek, “In-situ vehicular antenna integration and design aspects for vehicle-to-vehicle communications,” in *Proc. of the 4th Eur. Conf. on Antennas and Propag.*, Apr. 2010.

[39] L. Ekiz, A. Posselt, O. Klemp, and C. F. Mecklenbräuker, “Assessment of design methodologies for vehicular 802.11p antenna systems,” in *Proc. Int. Conf. Connected Vehicles and Expo (ICCVE)*, Nov. 2014, pp. 215–221.

[40] K. K. Nagalapur, “Robust vehicular communications for traffic safety—channel estimation and multiantenna schemes,” *Ph.D. thesis, Dept. of Elect. and Eng., Chalmers Univ. of Tech., Gothenburg, Sweden*, 2018.

[41] J. Nuckelt, H. Hoffmann, M. Schack, and T. Kürner, “Linear diversity combining techniques employed in car-to-x communication systems,” in *IEEE 73rd Veh. Tech. Conf. (VTC Spring)*, May 2011.

[42] G. Maier, A. Paier, and C. F. Mecklenbräuker, “Performance evaluation of IEEE 802.11p infrastructure-to-vehicle real-world measurements with receive diversity,” in *8th Int. Wireless Commun. and Mobile Comput. Conf. (IWCMC)*, Aug. 2012, pp. 1113–1118.

[43] H. Guo, B. Makki, D.-T. Phan-Huy, E. Dahlman, M.-S. Alouini, and T. Svensson, “Predictor antenna: A technique to boost the performance of moving relays,” *IEEE Commun. Mag.*, vol. 59, no. 7, pp. 80–86, Jul. 2021.

[44] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE J. on Sel. Areas in Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[45] N. F. Abdullah, A. Doufexi, and R. J. Piechocki, "Spatial diversity for IEEE 802.11p post-crash message dissemination in a highway environment," in *IEEE 71st Veh. Tech. Conf.*, May 2010.

[46] K. Ito, N. Itoh, K. Sanda, and Y. Karasawa, "A novel MIMO-STBC scheme for inter-vehicle communications at intersection," in *IEEE 63rd Veh. Tech. Conf.*, vol. 6, May 2006, pp. 2937–2941.

[47] A. Dammann and S. Plass, "Cyclic delay diversity: Effective channel properties and applications," in *IEEE Int. Conf. on Commun., Glasgow, Scotland*, Jun. 2007.

[48] G. Fodor, H. Do, S. A. Ashraf, R. Blasco, W. Sun, M. Belleschi, and L. Hu, "Supporting enhanced vehicle-to-everything services by LTE release 15 systems," *IEEE Commun. Stand. Mag.*, vol. 3, no. 1, pp. 26–33, 2019.

[49] K. Maliatsos, L. Marantis, P. S. Bithas, and A. G. Kanatas, "Hybrid multi-antenna techniques for V2X communications—prototyping and experimentation," in *Telecom*, Multidisciplinary Digital Publishing Institute, vol. 1, Jul. 2020, pp. 80–95.

[50] D. Rongas, A. Paraskevopoulos, L. Marantis, and A. Kanatas, "An integrated shark-fin reconfigurable antenna for V2X communications," *Prog. In Electromagn. Res. C*, vol. 100, Jan. 2020.

[51] C. F. Mecklenbräuker, A. F. Molisch, J. Karedal, F. Tufvesson, A. Paier, L. Bernadó, T. Zemen, O. Klemp, and N. Czink, "Vehicular channel characterization and its implications for wireless system design and performance," *Proc. of the IEEE*, vol. 99, no. 7, pp. 1189–1212, Feb. 2011.

[52] C. Anderson, *Connected cars place new demands on vehicle electronics design*, Accessed: Aug. 31, 2022. [Online]. Available: `https://www.taoglas.com/14902-2/`.

[53] K. K. Katare, I. M. Yousaf, and B. K. Lau, "Challenges and solutions for antennas in vehicle-to-everything services," *IEEE Commun. Mag.*, vol. 60, no. 1, pp. 52–58, Jan. 2022.

[54] A. F. Molisch, F. Tufvesson, J. Karedal, and C. F. Mecklenbräuker, "A survey on vehicle-to-vehicle propagation channels," *IEEE Wireless Commun.*, vol. 16, no. 6, pp. 12–22, Dec. 2009.

[55] A. F. Molisch, *Wireless Communication*, 2nd. NJ, USA: Wiley, 2011.

[56] I. Sen and D. W. Matolak, "Vehicle–vehicle channel models for the 5-GHz band," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 2, pp. 235–245, Jun. 2008.

[57] J. Karedal, F. Tufvesson, N. Czink, A. Paier, C. Dumard, T. Zemen, C. F. Mecklenbräuker, and A. F. Molisch, "A geometry-based stochastic MIMO model for vehicle-to-vehicle communications," *IEEE Trans. on Wireless Commu.*, vol. 8, no. 7, pp. 3646–3657, Jul. 2009.

[58] O. Renaudin, V.-M. Kolmonen, P. Vainikainen, and C. Oestges, "Wide-band measurement-based modeling of inter-vehicle channels in the 5-GHz band," *IEEE Trans. on Veh. Tech.*, vol. 62, no. 8, pp. 3531–3540, Oct. 2013.

[59] *Intelligent Transport Systems (ITS); Access Layer; Part 1: Channel Models for the 5.9 GHz frequency band*, document ETSI TR 103 257-1 V1.1.1, May 2019.

[60] *5G; Study on channel model for frequencies from 0.5 to 100 GHz (Release 16)*, document 3GPP TR 38.901 version 16.1.0, Nov. 2020.

[61] T. Abbas, K. Sjöberg, J. Karedal, and F. Tufvesson, "A measurement based shadow fading model for vehicle-to-vehicle network simulations," *Int. J. of Antennas and Propag.*, vol. 2015, 2015.

[62] M. G. Nilsson, C. Gustafson, T. Abbas, and F. Tufvesson, "A measurement-based multilink shadowing model for V2V network simulations of highway scenarios," *IEEE Trans. on Veh. Tech.*, vol. 66, no. 10, pp. 8632–8643, Oct. 2017.

[63] A. F. Molisch, "A generic model for MIMO wireless propagation channels in macro- and microcells," *IEEE Trans. on Signal Process.*, vol. 52, no. 1, pp. 61–71, Jan. 2004.

[64] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, and P. Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band," *IEEE J. on Sel. Areas in Commun.*, vol. 25, no. 8, pp. 1501–1516, Oct. 2007.

[65] J. Karedal, N. Czink, A. Paier, F. Tufvesson, and A. F. Molisch, "Path loss modeling for vehicle-to-vehicle communications," *IEEE Trans. on Veh. Tech.*, vol. 60, no. 1, pp. 323–328, Jan. 2011.

[66] *D5.3: WINNER+ Final Channel Models*, document Wireless World Initiative New Radio – WINNER+, Jun. 2010.

[67] M. Gudmundson, “Correlation model for shadow fading in mobile radio systems,” *Electron. Lett.*, vol. 27, no. 23, Nov. 1991.

[68] A. Shapiro, W. Tekaya, M. P. Soares, and J. P. da Costa, “Worst-case-expectation approach to optimization under uncertainty,” *Oper. Res.*, vol. 61, no. 6, pp. 1435–1449, Nov. 2013.

[69] M. Sniedovich, “Wald’s mighty maximin: A tutorial,” *Int. Trans. in Oper. Res.*, vol. 23, no. 4, pp. 625–653, Jan. 2016.

[70] T. Abbas, J. Karedal, F. Tufvesson, A. Paier, L. Bernadó, and A. F. Molisch, “Directional analysis of vehicle-to-vehicle propagation channels,” in *Proc. IEEE 73rd Veh. Technol. Conf. (VTC Spring)*, Jul. 2011.

[71] L. Bernadó, T. Zemen, F. Tufvesson, A. F. Molisch, and C. F. Mecklenbräuker, “Time- and frequency-varying K-factor of non-stationary vehicular channels for safety-relevant scenarios,” *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 1007–1017, Apr. 2015.

[72] Q. Liu, S. Zhou, and G. Giannakis, “Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links,” *IEEE Trans. on Wireless Commun.*, vol. 3, no. 5, pp. 1746–1755, Oct. 2004.

Part II

Papers