Thesis for the degree of Licentiate of Engineering

Reliability of Packet Transmissions in Vehicular Networks

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Gothenburg, Sweden 2015

Steinmetz, Erik
Reliability of Packet Transmissions in Vehicular Networks

Department of Signals and Systems
Technical Report No. R007/2015
ISSN 1403-266X

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This thesis has been prepared using LaTeX.

Front Cover: Illustration of the importance of reliable communication in vehicular networks.

Printed by Chalmers Reproservice,
Göteborg, Sweden, August 2015.

To my Family

> *"Research is to see what everybody else has seen, and to think what nobody else has thought."*
>
> – Albert Szent-Györgyi

Abstract

The current road transport system has large problems with safety and efficiency, and these problems do not only cost the society enormous amounts of money and affect the every day life of people, but might in the long run also have devastating consequences for the environment and the global climate.

Future intelligent transportation systems, where vehicular communication systems play a key role, are envisioned to alleviate these problems and allow for a safer and more efficient coordination of vehicles. In particular, wireless communication is expected to increase the situational awareness in complex and accident-prone scenarios such as intersections, where the ability to coordinate the traffic flow otherwise would be limited by the range and quality of each vehicle's on-board sensors. However, by relying on wireless communication another form of uncertainty is introduced as the information exchange between nodes suffer from both packet drops and random latencies. This means that before deploying such systems we need to fully understand and be able to handle these uncertainties.

This thesis focuses on reliability of packet transmissions in vehicular networks and the main goal is to better understand the performance of vehicular communication systems in different scenarios typical for the vehicular environment, both to gain insights on how to design better communication systems and to understand what uncertainties a control system might have to deal with. The overview part of the thesis provides some background on vehicular communication systems and stochastic geometry which can be used to quantify the impact of interference and derive analytical key performance metrics for this type of networks. In the appended papers we present a general procedure to analytically determine the reliability of packet transmissions for a selected link as well as system wide throughput in intersections. We provide a model repository that can be used to model different MAC protocols, as well as different propagation conditions typical to both urban and rural environments, and the generality and flexibility of the model makes it applicable to both 5G D2D and IEEE 802.11p communication. Furthermore, we study a centralized intersection crossing coordination scenario where vehicles approaching the intersection communicate with a central coordinator. We show how tools from stochastic geometry can be used to analyze the communication performance in this scenario and provide design guidelines that guarantees a certain communication performance (i.e., QoS) while minimizing the use of system resources. This type of results can for example be used to study how far away from the intersection a centralized controller can expect to have information available from all vehicles given certain communication parameters, QoS requirements, vehicle densities and velocities.

Keywords: Vehicular Communication, Reception Probability, Stochastic Geometry

List of Included Publications

The thesis is based on the following appended papers:

[A] E. Steinmetz, M. Wildemeersch, and H. Wymeersch, "WiP Abstract: Reception Probability Model for Vehicular Ad-Hoc Networks in the Vicinity of Intersections," in *Proceedings of the ACM/IEEE 5th International Conference on Cyber-Physical Systems (ICCPS)*, Berlin, Germany, Apr. 2014, pp. 223.

[B] E. Steinmetz, R. Hult, G.R. Rodriguez de Campos, M. Wildemeersch, P. Falcone and H. Wymeersch, "Communication Analysis for Centralized Intersection Crossing Coordination," in *Proceedings of 11th International Symposium on Wireless Communications Systems (ISWCS)*, Barcelona, Spain, Aug. 2014, pp. 813-818.

[C] E. Steinmetz, M. Wildemeersch, T.Q.S. Quek and H. Wymeersch, "A Stochastic Geometry Model for Vehicular Communication near Intersections," in *Proceedings of IEEE Globecom Workshops (GC Wkshps)* , San Diego, USA, Dec. 2015 (submitted)

[D] E. Steinmetz, M. Wildemeersch, T.Q.S. Quek and H. Wymeersch, "Reception Probabilities in 5G Vehicular Communications close to Intersections," in *IEEE Transactions on Vehicular Technology* , Jul. 2015 (submitted).

Acknowledgements

First of all, I would like to express my deepest gratitude to my main supervisor and examiner, Associate Prof. Henk Wymeersch. With your curiosity and passion for research you inspire me, and I feel privileged to have you as a mentor and friend. I am thankful for all your support and guidance and how you patiently teach me what it means to be a researcher. I look forward to a continued fruitful collaboration with you.

I would also like to thank my colleagues and co-supervisors at SP Technical Research Institute of Sweden. In particular I would like to thank Jan Johansson, Ragne Emardsson and Per Jarlemark for their constant support and encouragement, and for making it possible for me to pursue the PhD degree.

Also thanks to Prof. Erik Ström and Prof. Arne Svensson, and all other colleagues at the Department of Signals and System for creating a fantastic and stimulating work environment.

Furthermore, I would like to thank all my collaborators at the Department and elsewhere. In particular, a special thanks to Matthias Wildemeersch for all his support and help when I struggled to understand the stochastic geometry.

Finally, many thanks to my family and friends for all your support during these years.

Erik Steinmetz
Gothenburg, August 2015

This research has been supported, in part, by the European Research Council under Grant No. 258418 (COOPNET), and VINNOVA under the program "Nationell Metrologi vid SP Sveriges Tekniska Forskningsinstitut".

Acronyms

VANET:	Vehicular Ad Hoc Network
ITS:	Intelligent Transportation System
V2V:	Vehicle-to-Vehicle
V2I:	Vehicle-to-Infrastructure
V2X:	Vehicle-to-Everything
WAVE:	Wireless Access in Vehicular Environment
MAC:	Medium Access Control
PHY:	Physical
OFDM:	Orthogonal Frequency Division Multiplexing
CSMA:	Carrier Sense Multiple Access
STDMA:	Self Organizing Time Division Multiple Access
CAM:	Cooperative Awareness Message
BSM:	Basic Safety Message
DENM:	Decentralized Environmental Notification Message
5G:	Fifth Generation
D2D:	Device-to-Device
SINR:	Signal-to-Interference-plus-Noise-Ratio
PER:	Packet Error Rate
DCC:	Decentralized Congestion Control
PPP:	Poisson Point Process
CCDF:	Complementary Cumulative Distribution Function
FDD:	Frequency Division Duplex
QoS:	Quality of Service

Contents

Part I

Overview

Chapter 1

Introduction

1.1 Motivation

The current road transport system has large problems with safety and efficiency. For example, every year more than 1.2 million people are killed in traffic related accidents and more than 50 million are injured, and if nothing is done the number of deaths is expected to reach 1.9 billion by 2020 [1]. Furthermore, many of the major cities around the world are locked down by traffic congestion during rush hour, and according to the U.S. Department of the Treasury [2] the U.S. alone wastes 7 billion liters of gas annually due to congestions, which together with productivity losses is estimated to cost the society more than 100 billion dollars per year. Furthermore, about 17 % of the global emissions of anthrophogenic greenhouse gases (e.g., CO2) comes from the transport sector [3]. This shows that the current road transport system not only has large impact on our health, quality of life and economy, but also on the environment.

Now Imagine a future with driverless automated vehicles that use wireless communication to share information between each other, and thus are able to cooperate and coordinate amongst each other to avoid accidents and optimize the traffic flow. It is easy to understand that such a future can lead to large benefits for the society in terms of increased economic, environmental as well as social sustainability. Even if we are not there yet, intelligent transportation systems (ITS), where vehicular communication systems play a key role, are envisioned to gradually alleviate many of the current problems in the road transport system [4–7]. In particular, wireless communication is expected to significantly increase the situational awareness for each vehicle, which otherwise is limited by the range and quality of each vehicle's set of sensors. This greatly increases the ability to optimize the traffic flow as each vehicle better can adapt its motion to the surrounding traffic situation, and allows for a safer an more efficient coordination of vehicles, especially in intersections which are among the most complex and accident-prone elements in the modern traffic system.

In the literature there exist a wide range of works (e.g., [8–13]) that address the challenging problem of cooperative control/coordination of vehicles in intersection scenarios, but due to the complexity of the control problem itself the information exchange between vehicles is often assumed to be perfect [8, 9, 12, 13]. However, vehicular communication systems are far from perfect. In particular, the information exchange between nodes can suffer from both packet drops and random latencies in packet arrivals due to the inherent randomness of the wireless channel and the fact that the communication resources (bandwidth, power) are limited. As pointed out in [14], this means that before we can achieve optimal and safe coordination we need to be able to accommodate uncertainties due to imperfect communication (as well as sensing). This requires a better understanding about the performance of the communication system in different scenarios, both to be able to design better and more efficient communication systems, but also to be able to implement control algorithms that can take into account uncertainties due to delayed and intermittent information or even mitigating the uncertainties by assigning communication resources in a smart manner as suggested in [14, 15].

1.2 Scope and Aim of the Thesis

The aim of this thesis is to study the reliability of packet transmissions in vehicular networks in order to better understand the performance of vehicular communication systems in different scenarios, both to gain insights on how to design better communication systems and to understand what uncertainties a control system might have to deal with due to communication imperfections. This is done by using tools from stochastic geometry to derive analytical expressions for packet reception probabilities for a variety of scenarios of practical relevance. In particular, we focus on the important scenario of intersections.

1.3 Organization of the Thesis

In order to provide some background information and place our contribution in the proper context the remainder of the thesis is organized as follows: in Chapter 2 we present some background information regarding vehicular communication, and briefly touch upon the challenges that comes with using wireless communication for safety critical applications. In Chapter 3, we introduce stochastic geometry which is used throughout all the included papers. Finally, in Chapter 4 the contributions of the appended papers are summarized.

Chapter 2

Vehicular Communication

In this chapter, we give some background on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication (together referred to as V2X communication). We discuss current standards and technologies and typical characteristics of the vehicular channel as well as some of the underlying reasons for packet drops and random latencies in vehicular networks. Furthermore, we briefly discuss the main challenges that come with using wireless communication for safety critical applications, such as for example an centralized intersection coordination system.

2.1 Current Standards and Technologies

To meet the communication demands of future ITS applications, both USA and Europe, as well as many other countries, have allocated spectrum in different frequency bands around 5.9 GHz (see Fig. 2.1), and large efforts are put into research and standardization of V2X communication.

The most notable examples are the North American standard, referred to as IEEE wireless access in vehicular environment (WAVE) (which includes both the IEEE 802.11p standard [18, 19] and the higher level standard IEEE 1609 [20]) and the European standard, referred to as ITS G5 [21] which also builds on the lower level standard IEEE 802.11p. The IEEE 802.11p standard is an amendment of the well-known wireless local are network (WLAN) standard IEEE 802.11 modified to the vehicular environment, and it specifies the medium access control (MAC) and physical (PHY) sub layers of the protocol stack. The main difference between the amendment and the original standard is that authentication, association and security features are disabled. This allows for ad-hoc communication without overheads associated with setting up the so-called basic service set from traditional WLAN networks, and as can be understood this is a major advantage in vehicular networks as the communication links between rapidly moving vehicles might only exist for a short amount of time. Except for this the PHY and MAC sub-layers are similar to the original 802.11 standard. In particular, the PHY layer relies on orthogonal frequency division multiplexing (OFDM) in 10 MHz channels (i.e., the

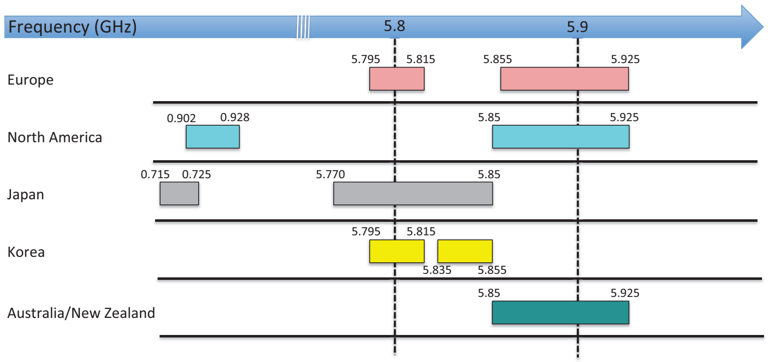

Figure 2.1: Overview of spectrum allocations for ITS applications in different countries (based on information from [16, 17]).

bandwidth is halved compared to 802.11a) with possible data rates between 3 Mbps and 27 Mbps [22]. The MAC protocol, which governs the channel access is based on a carrier sense multiple access/collision avoidance (CSMA/CA) approach [23, 24]. In simple terms this means that when a node has a packet to send, it first listens to to channel. If the channel is free, the nodes start transmitting the packet. If the channel is busy, the node waits a random back-off time before it tries to transmit the packet again.

Using the IEEE 802.11p standard vehicles can broadcast periodic awareness messages, containing core state information such as location, speed and brake status, or event driven hazard messages, over a range of about 300-500 meters [23]. At the moment the message formats have not been harmonized between North America and Europe and a variety of message types exists. The European message standardization is handled by ETSI, and the message set is made up of two types of messages, namely cooperative awareness messages (CAM) and decentralized environmental notification messages (DENM). The CAM are periodic messages (1-10 Hz), while the DENM are event driven hazard warnings. In North America the message are referred to as basic safety messages (BSM), and the standardization is handled by the Society of Automotive Engineers (SAE). The BSM are periodic (about 10 Hz), but extra information can be included due to event triggers. The size of a CAM/BSM is typically 300-400 bytes [24]. Hence using the default data rate of 6 Mbps it will take around 400-500 μs to transmit a message.

For a more detailed description of the WAVE and ITS G5 standards, the different message types, as well as the history of the standardization process see, e.g., [24, 25].

Worth to mention is also that the fifth generation (5G) cellular systems are being developed to support device-to-device (D2D) communication [26–28], and is thus, in combination with traditional cellular services, envisioned to act as an important complement to the above discussed standards. In particular, it has been shown that 5G device-to-device (D2D) is a promising technology capable of boosting the spectrum utilization in ITS applications [29].

2.2 The Vehicular Channel

Vehicular communication systems must be able to function in a multitude of conditions, including both low and high mobility scenarios, as well as rural and urban environments. This means greatly varying channel characteristics, and in order for a receiver to correctly decode a message it needs to be able to cope with large/rapid fluctuations in the received signal power, large Doppler shifts, as well as large delay spreads. However, as the work in this thesis focuses on signal-to-interference-plus-noise ratio (SINR) based analysis methods we will mainly discuss channel characteristics from a received signal power point of view.

Variations in received signal power over distance can be categorized into three different groups: 1) *path loss* which mainly is caused by the dissipation of the power radiated by the transmitter with distance; 2) *large-scale fading* which is caused by obstacles that shadow, i.e., attenuates the signal power through absorption, scattering and diffraction; 3) *small-scale fading* which is due interference between multipath components from different scatterers in the surroundings as well as Doppler shifts resulting from the mobility of the nodes. Variations in the signal strength due to path loss occur over long distances, while large-scale fading occurs over distances that are proportional to the size of the obstructing object. As a rule of thumb large-scale fading occurs over distances that are large compared to the signal wavelength, while small scale fading variations due to multipath and Doppler occur over very short distances, on the scale of a wavelength. Note that for a stationary receiver the small scale-fading due to a constantly changing environment translates into rapid fluctuations of the received power in time. Most often the observed fluctuations in the received signal strength is a combination of large-scale fading and small-scale fading. Hence, considering a transmitter and receiver pair with locations $\mathbf{x}_{\mathrm{tx}}$ and $\mathbf{x}_{\mathrm{rx}}$ the received power can be expressed as

$$P_{\mathrm{r}} = P_{\mathrm{t}} S \, l(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}) \tag{2.1}$$

where P_{t} is the transmitted power, S is the fading, and $l(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}})$ is the path loss.

To characterize the path loss and the fading in the vehicular channel several large measurement campaigns [30–33] have been performed in a variety of propagation environments such as rural, highway, suburban and urban scenarios. As it is of particular importance to understand how power decays with distance (e.g., from an interference point of view), much effort have been put into finding path loss models, i.e., to characterize the distance dependent power loss in decibels (dB). A common way of modeling this slope is by the standard power law model

$$l(\mathbf{x}_{\mathrm{tx}}, \mathbf{x}_{\mathrm{rx}}) = A \left\| \mathbf{x}_{\mathrm{rx}} - \mathbf{x}_{\mathrm{tx}} \right\|^{-\alpha} \tag{2.2}$$

where $\|\mathbf{x}_{\mathrm{rx}} - \mathbf{x}_{\mathrm{tx}}\|$ is the distance between the transmitter and the receiver, α is the path loss exponent, and A is a constant that depends on antenna characteristics. Results show that this model is representative for modeling of path loss in the vehicular context (even though dual slope models or two ray models might be a better choice in specific cases), and that typical path loss exponents for the vehicular channel are in the ranges of $1.8-1.9$ in the rural and highway case, and $1.6-1.7$ in the urban scenario [33]. Worth to highlight here is that the path loss exponents are slightly below 2 in all of the scenarios. The reason that we have better than free space propagation can be explained by wave-guiding effects, which can be particularly strong in so called urban canyons. Regarding the fading, it is shown that typical variations in the received power with respect to path loss are in the range 2-3 dB. Note that these values most probably only reflect variations in the received power due to shadowing, as rapid variations are averaged out in the channel sounding experiments. Furthermore, it should be pointed out that these measurement campaigns mainly are carried out in line-of-sight (LOS) conditions and that the variations potentially could be larger in non-line-of sight (NLOS) conditions. In addition to the above presented results [30] has also demonstrated that the shadow fading in the vehicular channel can be modeled by the the commonly used log-normal model, even though data first has to be classified and separated according to LOS and NLOS propagation.

2.3 Packet Drops and Random Delays

In this section, we will discuss the underlying causes to why packet drops and random latencies in packet arrivals occur in vehicular networks.[1] We will first consider packet drops, which refers to the inability of the receiver to detect a packet, or the inability to extract the information from a packet. Roughly speaking, a packet can be decoded if the SINR exceeds a certain threshold. The SINR at a receiver can be expressed as

$$\mathrm{SINR} = \frac{P_{\mathrm{t}} g}{\sum_{i \in I} P_{\mathrm{t}} g_i + P_{\mathrm{noise}}}, \tag{2.3}$$

where g is the channel gain between the intended transmitter and the receiver, g_i is the channel gain between an interfering transmitter and the receiver, P_{t} is the power which each nodes transmits with, and P_{noise} is the noise power due to thermal noise at the receiver. The channel gains g and g_i are random variables, which statistics and autocorrelation depends on a wide variety of factors including the path loss, large-scale fading as well as the fast varying small-scale fading. As mentioned in Section 2.2, the latter effect, which is due to a combination of high vehicle mobility and multipath propagation, can lead to rapidly changing signal propagation conditions and thus drastic changes in the SINR. Hence, one reason for the receiver not being able to decode a packet is that the channel gain g, on the link between the intended transmitter and the receiver, is very low. This is referred to as a deep fade. Another reason is that the received interference power is to high. To avoid this, the interference can be controlled through the MAC protocol, but for the ad-hoc network topology enabled by the current standards for V2X MAC is extremely challenging. For example, the CSMA/CA MAC protocol used in the IEEE 802.11p standard reduces the probability of packet collisions, but the probability still remains non-zero due to reasons such as simultaneous countdown, hidden nodes and same carrier sense time. A brief overview of the basic principles of the CSMA/CA MAC protocol, and some of these effects are given in Fig. 2.2 (for more detailed informa-

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[1] We will not consider multi-hop networks

tion regarding the operation of the CSMA/CA MAC protocol used in the IEEE 802.11p standard and the effects mentioned here see e.g., [24]).

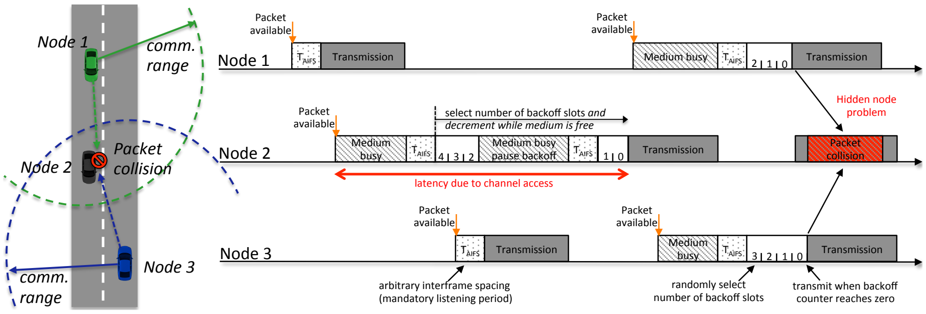


Figure 2.2: Illustration of the mechanisms of the IEEE 802.11p CSMA/CA MAC protocol and how the fact that vehicles has to contend for the shared spectrum leads to packet collisions and unpredictable delays. The figure shows the mandatory listening period before a node can transmit, and how nodes are forced into a back-off procedure if it perceives the medium as busy. Furthermore, it can be seen how packet collisions can occur due to the fact that two nodes that are not within each others sensing range both transmit at the same time, as they both perceive the medium as free. This is referred to as the hidden node problem and does in this case greatly reduce the chances for Node 2 to decode the packets from Node 1 and 3.

Even though the probability of packet collisions is non-zero, the CSMA/CA MAC performs well when there are few users, but in dense scenarios where many users want to send packets over the shared medium the probability of packet collisions (i.e., low SINR), and thus the packet error rate (PER), rapidly increases. The fact that PER rapidly increases with increased vehicle density has also been confirmed by experiments [23].

The main reason for latency in an IEEE 802.11p based network is, as illustrated in Fig. 2.2, the channel access delay, i.e., the random delay until a node gets access to the channel and can transmit its packet. Clearly, the channel access delay is also highly dependent on the channel load, as an increased channel load means more vehicles that contend for the access to the channel.

Based on the above discussion, we see that channel congestion is a major concern in vehicular networks, as the current MAC protocol will results in high PER as well as long channel access delays. However, it should be mentioned that by using so called decentralized congestion control (DCC) methods (which basically operate by either reducing the amount of packets in the network, the transmit power, or the rate) these problems could be made less severe. Hence this is a research topic of special interest. Furthermore, it should be pointed out that other MAC methods for V2X communication have been investigated. In particular, it has been shown that self organizing time division multiple access (STDMA) outperforms CSMA/CA for high network loads as it can provide a bounded and predictable delay [34, 35].

2.4 Challenges for Safety Critical Applications

This section will briefly highlight the main challenges that come with the use of wireless communication techniques in safety critical ITS applications (e.g., centralized coordination of vehicles in an intersection scenarios). First of all these applications typically require extremely low latencies (below 50 ms in pre-crash situations), high packet delivery ratios (for full situational awareness) and relatively long communication ranges (to increase the time to react in critical situations). As can be understood it is extremely challenging to be able to guarantee that these requirements are met in the vehicular environment, and thus one of the main challenges is to be able to accommodate for the uncertainties introduced in the system due to latencies and packet drops, preferably by some form of co-design between the control and communication system. In the context of an intersection control system, this could for example be a system that assigns communication resources where it is really needed to keep the channel load low such that low latencies and high packet delivery ratios could be guaranteed. Furthermore, the application need to be able to handle a highly dynamic network with constantly changing network topology, as vehicles due to the high mobility constantly come in and out of communication range, or temporarily disappear due to fades in the channel.

Chapter 3

Stochastic Geometry

In this chapter, we introduce stochastic geometry, and describe how it can be used to characterize the packet reception probability in a wireless network.

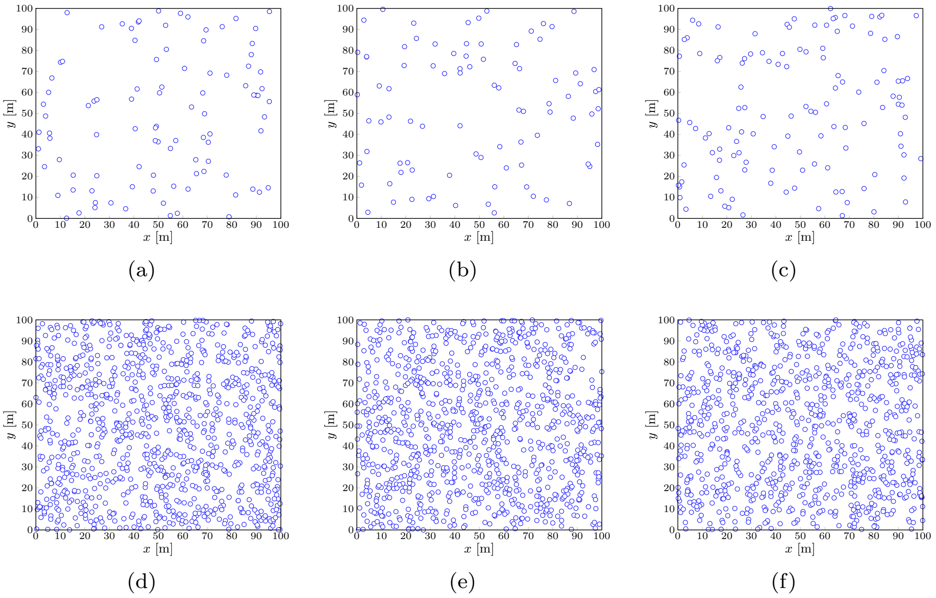
3.1 Brief History

Stochastic geometry has roots as far back as to the 18th century and the famous problem of Buffon's needle. However, the development of the stochastic geometry we know today took of with D. G. Kendall, K. Krickeberg and R. E. Miles during the second half of the 20th century [36], and its inherent relation to point process theory and the ability calculate spatial averages has during the years shown to be useful in many different areas, such as biology, material sciences, astronomy and image processing. During the last decade the tools from stochastic geometry have also been extensively used to analyze the impact of interference in wireless networks [37, 38].

3.2 Point Processes

A point process is a random process, which for each realization gives rise to a specific point pattern. Hence, point processes are useful tools to model spatial structures in our surrounding, as for example the geographical locations of concurrently transmitting nodes in a wireless network.

Many different types of point processes (e.g., Matérn hard-core processes, Poisson cluster processes) have been used to model the spatial properties of wireless networks, but the simplest and probably most widely used point process is the Poisson point process (PPP). The PPP basically is a spatial generalization of a Poisson process and can be either stationary (homogeneous) or non-stationary (inhomogeneous). The homogeneous PPP can be characterized by a single parameter λ, which describes the constant density of points over space (see Fig. 3.1), and is fully defined by the following two important properties [37]:



(a) (b) (c)

(d) (e) (f)

Figure 3.1: Illustrations of homogeneous PPPs in the plane. The upper row,(a)-(c), shows three different realizations of a PPP with density $\lambda = 0.01$, while the bottom row, (d)-(f), shows different realizations of a PPP with density $\lambda = 0.1$.

1. The number of isolated points in any bounded set $B \in \mathbb{R}^n$ is Poisson distributed with mean $\lambda |B|$, where $|B|$ is the Lesbegue measure of B, i.e., the n-dimensional volume.
2. The number of points in disjoint set are independent random variables.

Note that the inhomogeneous PPP is defined in the same way, but by replacing $\lambda |B|$ with $\int_B \lambda (x) \, \mathrm{d}x$, where $\lambda (x)$ is a non negative function describing the varying density of points over space.

According to the definition, i.e., by using the fact that the number of points in a bounded set follows a Poisson distribution, the probability that a homogeneous PPP has k points in a set B, can be written as

$$\Pr [\Phi (B) = k] = \exp (-\lambda |B|) \frac{(\lambda |B|)^k}{k!}, \tag{3.1}$$

where $\Phi (B)$ denotes the number of points in B. Setting $k = 0$ we also observe that the void probability, i.e., the probability that no points fall within the set B, is given by $\exp (-\lambda |B|)$. Finally, two very interesting and useful properties of the PPP are:

- Superposition of two PPPs with densities λ_1 and λ_2 yields a new PPP with density $\lambda_1 + \lambda_2$

- Thinning of a PPP, i.e., independently selecting points from the original PPP with probability p, results in a new PPP with density λp.

3.3 Packet Reception Probability

In this section, we briefly show how stochastic geometry can be used to characterize the packet reception probability for a selected link in a wireless network.

3.3.1 Scenario

We consider a one dimensional network (see Fig. 3.2), with a transmitter (Tx) and receiver (Rx) located at x_{tx} and x_{rx}, respectively. Furthermore, we assume that the remaining nodes in the network act as interferers and are located according to a homogeneous PPP Φ with density λ, i.e., $\Phi \sim \text{PPP}(\lambda)$.

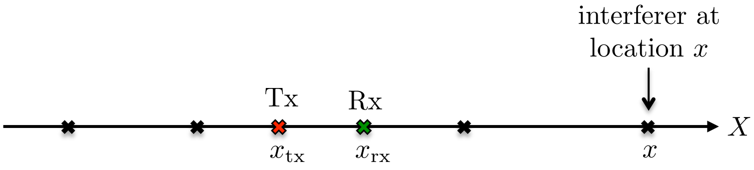


Figure 3.2: Illustration of the one dimensional network.

For simplicity, we assume that all nodes except the receiver broadcast with a fixed transmission power P_{t}, and that the signal propagation model comprises exponential power fading, i.e. $S \sim \exp(1)$, path loss $l(x_{\text{tx}}, x_{\text{rx}}) = A\,|x_{\text{rx}} - x_{\text{tx}}|^{-\alpha}$, and white Gaussian noise with noise power P_{noise}. Given the setting above, we can express the signal-to-interference-plus-noise ratio (SINR) at the receiver as

$$\text{SINR} = \frac{P_{\text{t}} S_0 l(x_{\text{tx}}, x_{\text{rx}})}{\sum_{x\in\Phi} P_{\text{t}} S_x l(x, x_{\text{rx}}) + P_{\text{noise}}} \tag{3.2}$$

where S_0 represents the fading on the useful link and S_x denotes the fading on an interfering link for an interferer at location $x \in \Phi$. Lastly, we also assume that the only criteria for a packet to be successfully decoded is that the SINR exceeds a threshold β.

3.3.2 Success Probability

Given the scenario outlined in Section 3.3.1, the probability that the receiver successfully decodes a transmission from the transmitter can be expressed as

$$\begin{aligned}
\mathbb{P}\left(\beta, x_{\mathrm{tx}}, x_{\mathrm{rx}}\right) &= \Pr\left(\mathrm{SINR} > \beta\right) && (3.3)\\
&= \Pr\left(\frac{P_{\mathrm{t}} S_0 l(x_{\mathrm{tx}}, x_{\mathrm{rx}})}{I + P_{\mathrm{noise}}} > \beta\right) && (3.4)\\
&= \Pr\left(S_0 > \left(I + P_{\mathrm{noise}}\right) \frac{\beta}{P_{\mathrm{t}} l(x_{\mathrm{tx}}, x_{\mathrm{rx}})}\right) && (3.5)
\end{aligned}$$

where

$$I = \sum_{x \in \Phi} P_{\mathrm{t}} S_x l(x, x_{\mathrm{rx}}) \tag{3.6}$$

is the aggregate interference power experienced by the receiver. Conditioned on the path loss we see that the two remaining random variables are the fading on the useful link and the interference power. Hence, to calculate the success probability we need to average over both the fading on the useful link and the interference power (both fading and locations). We start by taking the expectation with respect to the interference, i.e.,

$$\begin{aligned}
\mathbb{P}\left(\beta, x_{\mathrm{tx}}, x_{\mathrm{rx}}\right) &= \mathbb{E}_I\left\{\Pr\left(S_0 > \left(I + P_{\mathrm{noise}}\right) \frac{\beta}{P_{\mathrm{t}} l(x_{\mathrm{tx}}, x_{\mathrm{rx}})}\right)\right\} && (3.7)\\
&= \int_0^\infty \Pr\left(S_0 > \left(t + P_{\mathrm{noise}}\right) \tilde{\beta}\right) f_I(t) \mathrm{d}t && (3.8)\\
&= \int_0^\infty \bar{F}_{S_0}\left(\left(t + P_{\mathrm{noise}}\right) \tilde{\beta}\right) f_I(t) \mathrm{d}t && (3.9)
\end{aligned}$$

where $\tilde{\beta} = \frac{\beta}{P_{\mathrm{t}} l(x_{\mathrm{tx}}, x_{\mathrm{rx}})}$ and $\bar{F}_{S_0}\left(s_0\right)$ is the complementary cumulative distribution function (CCDF) of the random variable S_0, evaluated in s_0, and $f_I(t)$ denotes the interference distribution. The expression in (3.9) can be interpreted in two ways: (i) as the expectation of $\bar{F}_{S_0}\left(\left(t + P_{\mathrm{noise}}\right) \tilde{\beta}\right)$ with respect to the interference distribution; and (ii) the transformation of the interference distribution with a kernel function determined by the CCDF of the fading distribution on the useful link.

Using the fact that the fading in this case is assumed to be exponentially distributed, i.e., has a CCDF of the form

$$\bar{F}_{S_0}\left(s_0\right) = e^{-s_0}, \tag{3.10}$$

we can write

$$\begin{aligned}
\mathbb{P}\left(\beta, x_{\mathrm{tx}}, x_{\mathrm{rx}}\right) &= \int_0^\infty e^{-(t + P_{\mathrm{noise}})\tilde{\beta}} f_I(t) \mathrm{d}t && (3.11)\\
&= e^{-P_{\mathrm{noise}}\tilde{\beta}} \int_0^\infty e^{-t\tilde{\beta}} f_I(t) \mathrm{d}t && (3.12)\\
&= e^{-P_{\mathrm{noise}}\tilde{\beta}} \mathcal{L}_I\left(\tilde{\beta}\right) && (3.13)
\end{aligned}$$

where $\mathcal{L}_I(\cdot)$ denotes the Laplace transform of the interference distribution. The Laplace transform of the interference distribution can also be expressed as

$$\mathcal{L}_I\left(\tilde{\beta}\right) = \mathbb{E}\left[\exp\left(-\tilde{\beta} I\right)\right] \tag{3.14}$$

and substituting (3.6) into (3.14) yields

$$\begin{aligned}
\mathcal{L}_I\left(\tilde{\beta}\right) &= \mathbb{E}\left[\prod_{x\in\Phi} \exp\left(-\tilde{\beta} P_\mathrm{t} S_x A \left|x - x_\mathrm{rx}\right|^{-\alpha}\right)\right] & (3.15)\\
&\overset{(a)}{=} \mathbb{E}_\Phi\left[\prod_{x\in\Phi} \mathbb{E}_{S_x}\left\{\exp\left(-\tilde{\beta} P_\mathrm{t} S_x A \left|x - x_\mathrm{rx}\right|^{-\alpha}\right)\right\}\right] & (3.16)\\
&\overset{(b)}{=} \mathbb{E}_\Phi\left[\prod_{x\in\Phi} \frac{1}{1 + \tilde{\beta} P_\mathrm{t} A \left|x_\mathrm{rx} - x_\mathrm{tx}\right|^{-\alpha}}\right] & (3.17)\\
&\overset{(c)}{=} \exp\left(-\lambda \int_{-\infty}^{\infty} \frac{1}{1 + \left|x - x_\mathrm{rx}\right|^{\alpha} / \tilde{\beta} P_\mathrm{t} A} \mathrm{d}x\right) & (3.18)\\
&\overset{(d)}{=} \exp\left(-2\lambda \left(\tilde{\beta} P_\mathrm{t} A\right)^{1/\alpha} \int_0^{\infty} \frac{1}{1 + u^{\alpha}} \mathrm{d}u\right) & (3.19)\\
&= \exp\left(-2\lambda \left(\tilde{\beta} P_\mathrm{t} A\right)^{1/\alpha} \frac{\pi}{\alpha} \csc\left(\pi/\alpha\right)\right) & (3.20)
\end{aligned}$$

where (a) holds due the independence of the fading parameters, $\mathbb{E}_\Phi[\cdot]$ is the expectation operator with respect to the location of the interferers, and (b) uses the fact that the fading is exponentially distributed. Furthermore, to perform the spatial averaging (c) uses the probability generating functional (PGFL) of a PPP[1] , and (d) involves a variable change $\left|x - x_\mathrm{rx}\right| / \left(\tilde{\beta} P_\mathrm{t} A\right)^{1/\alpha} \rightarrow u$. For the particular case of $\alpha = 2$, the expression further simplifies to

$$\mathcal{L}_I\left(\tilde{\beta}\right) = \exp\left(-\lambda\sqrt{P_\mathrm{t} A \tilde{\beta}} \pi\right). \tag{3.23}$$

---

[1] The PGFL is a generalization of the probability generating function (PGF), and it completely characterizes a point process. It is defined as [37, Definition A.5]

$$\mathcal{G}[\nu] = \mathbb{E} \prod_{x\in\Phi} \nu(x), \tag{3.21}$$

and as the name implies it is used to calculate the average of a product of a function $\nu(x)\colon \mathbb{R}^d \rightarrow [0,\infty)$ operating on a point process. As in this case, the PGFL is commonly applied when evaluating the Laplace transform of the aggregate interference from a set of nodes distributed according to a point process. The PGFL for a PPP is given by

$$\mathcal{G}[\nu] = \exp\left(-\int_{\mathbb{R}^d} (1 - \nu(x)) \lambda(\mathrm{dx})\right). \tag{3.22}$$

Finally, substituting (3.23) into (3.13), and using the variable change $\tilde{\beta} = \frac{\beta|x_{\text{rx}}-x_{\text{tx}}|^{\alpha}}{P_{\text{t}}A}$, we can for the case of $\alpha = 2$ express the success probability as

$$\mathbb{P}\left(\beta, x_{\text{tx}}, x_{\text{rx}}\right) = \exp\left(-\frac{P_{\text{noise}}\beta\left|x_{\text{rx}} - x_{\text{tx}}\right|^{2}}{P_{\text{t}}A}\right)\exp\left(-\lambda\sqrt{\beta}\left|x_{\text{rx}} - x_{\text{tx}}\right|\pi\right) \tag{3.24}$$

where the first factor is the success probability in the absence of interferers, and the second factor captures the reduction of the success probability due to interference. In order to illustrate this Fig. 3.3 shows the outage probability, i.e., $\mathbb{P}_{\text{Out}}\left(\beta, x_{\text{tx}}, x_{\text{rx}}\right) = 1 - \mathbb{P}\left(\beta, x_{\text{tx}}, x_{\text{rx}}\right)$, in the interference free case and when the receiver experiences interference from a set of nodes distributed according to a PPP with density $\lambda = 0.001$. Note that we in this scenario have set the transmit power to $P_t = 100$ mW, corresponding to 20 dBm. Furthermore, we have assumed a noise power N of -99 dBm, and an SINR threshold of $\beta = 8$ dB [24], and that $A = 0.0025$, approximately matching the conditions in [31].

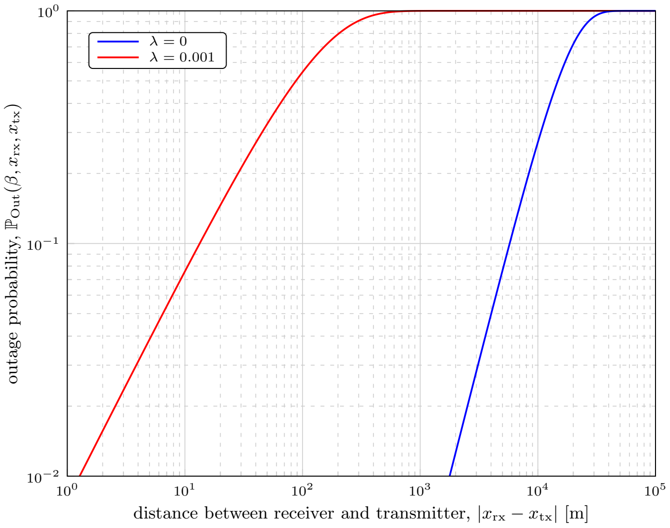


Figure 3.3: Outage probability as a function of the distance between receiver and transmitter in the interference free case ($\lambda = 0$) and with interference ($\lambda = 0.001$).

Chapter 4

Contributions

This thesis studies the reliability of packet transmissions in vehicular networks in order to better understand the performance of vehicular communication systems in different scenarios, and the main contribution can be found in the appended papers. In Section 4.1, we list the appended papers and summarize their main contributions. Additional publications by the author, which are not included in this thesis, are listed in Section 4.2.

4.1 Included Publications

1. **Paper A: "WiP Abstract: Reception Probability Model for Vehicular Ad-Hoc Networks in the Vicinity of Intersections"**
   In this paper, which is a work in progress abstract, we consider a four lane intersection scenario where each lane carries cars according to a one dimensional homogeneous PPP. We use tools from stochastic geometry to capture the spatial statistics of the vehicles, and under the assumption of exponential power fading and an Aloha MAC protocol we present an analytical model for the reliability of packet transmissions on a selected link between a transmitter and a receiver located an arbitrary distance apart. Furthermore, the model takes into account the distance between the receiver and the intersection and thus gives insights on how the clustering of vehicles in the intersection area affects the reliability of packet transmissions.

2. **Paper B: "Communication Analysis for Centralized Intersection Crossing Coordination"**
   In this paper, we provide a communication analysis for a centralized intersection crossing coordination scheme. We consider a FDD system with non interfering uplink and downlink channels where vehicles periodically send their intentions to the controller, and the controller periodically broadcasts coordination information to the vehicles. In the uplink, vehicles send information on one of N_{ul} channels such that the location of the vehicles transmitting on the same channel can be represented by non-homogeneous PPPs. In order to provide design guidelines such that a certain quality of service (QoS) can be guaranteed while minimizing the use of system

resources we characterize the probability that vehicles receives the coordination information within a certain region around the controller. Similarly for the uplink, we try to characterize this probability, using tools from stochastic geometry. However, as the mobility of the vehicles results in highly correlated interference between successive uplink transmission, we present bounds. To sum up, the tools developed in this study can for example be used to study how far away from the intersection the controller can expect to have information available from all vehicles given certain communication parameters, QoS requirements, vehicle densities and velocities.

3. **Paper C: "A Stochastic Geometry Model for Vehicular Communication near Intersections"**
   In this paper, we extend and give a more complete presentation of the work in Paper A. We start by considering a two lane intersection scenario and show how the packet reception probability can be characterized as as a function of the distance between the receiver and the transmitter, as well as the distance between the receiver and the intersection. Furthermore, we show how the model, due to the independence of the PPPs on the different lanes, can be extended to account for an arbitrary number of lanes with different orientations. We also extend the model to account for increased vehicle densities near the intersection, caused by for example reduced vehicle speeds and traffic congestions, and show how closed form expressions still can be obtained for special cases such as piecewise linear densities, even when the PPP is non-homogeneous.

4. **Paper D: "Reception Probabilities in 5G Vehicular Communications close to Intersections"**
   In this paper, we build on the work in Paper A and Paper C. The model is extended to handle both shadowing and the CSMA MAC protocol, and we present a general procedure to analytically determine the the reliability of packet transmissions for a selected link as well as system wide throughput, making the model applicable to both 5G D2D and IEEE 802.11p communication. Furthermore, we provide an overview of the salient properties of the vehicular communication systems near intersections, and show how the procedure can be used to model signal propagation conditions typical to different environments of practical relevance, as for example rural and urban scenarios. In particular, we show how the distance between communicating nodes can be modeled using the manhattan distance to capture the wave guiding effect of urban street canyons.

4.2 Other Publications

Other publications by the author, which are not included in this thesis, are listed below.

[J1] E. Steinmetz, P. Jarlemark, R. Emardson, H. Skoogh, and M. Herbertsson, "Assessment of GPS derived speed for verification of speed measuring devices," *International Journal of Instrumentation Technology (IJIT)* , vol. 1, no. 3, pp. 212–227, 2014.

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[C3] S. Steinmetz, R. Emardson, and P. Jarlemark, “Improved Vehicle Parameter Estimation Using Sensor Fusion by Kalman Filtering” in *Proceedings of the XIX IMEKO World Congress on Fundamental and Applied Metrology*, Lisabon, Portugal, Sep. 2009.

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Part II

Included papers

Paper A

WiP Abstract: Reception Probability Model for Vehicular Ad-Hoc Networks in the Vicinity of Intersections

Erik Steinmetz, Matthias Wildemeersch, and Henk Wymeersch

Published in
Proceedings of the ACM/IEEE 5th International Conference on Cyber-Physical Systems (ICCPS)
Berlin, Germany, Apr. 2014

Paper B

Communication Analysis for Centralized Intersection Crossing Coordination

Erik Steinmetz, Robert Hult, Gabriel Rodriguez de Campos, Matthias Wildemeersch, Paolo Falcone, and Henk Wymeersch

Published in
Proceedings of 11th International Symposium on Wireless Communications Systems (ISWCS)
Barcelona, Spain, Aug. 2014

Paper C

A Stochastic Geometry Model for Vehicular Communication near Intersections

Erik Steinmetz, Matthias Wildemeersch, Tony Q.S. Quek, and Henk Wymeersch

Submitted to
IEEE Globecom Workshops (GC Wkshps)
San Diego, USA, Dec. 2015

Paper D

Reception Probabilities in 5G Vehicular Communications close to Intersections

Erik Steinmetz, Matthias Wildemeersch, Tony Q.S. Quek, and Henk Wymeersch

Submitted to
IEEE Transactions on Vehicular Technology
July 2015