
Optimizing 802.11 Wireless Communications with Machine Learning

Von der Fakultät für Mathematik, Informatik und Naturwissenschaften
der RWTH Aachen University zur Erlangung des akademischen Grades
eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

Diplom-Ingenieur **Óscar Puñal Ostos**

aus Barcelona, Spanien

Berichter:

Prof. Dr.-Ing. James Gross
Univ.-Prof. Dr.-Ing. Klaus Wehrle
Research Professor Dr. Jörg Widmer

Tag der mündlichen Prüfung: 30.01.2015

Reports on Communications and Distributed Systems

edited by
Prof. Dr.-Ing. Klaus Wehrle
Communication and Distributed Systems,
RWTH Aachen University

Volume 10

Óscar Puñal Ostos

Optimizing 802.11 Wireless Communications with Machine Learning

Shaker Verlag
Aachen 2015

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: D 82 (Diss. RWTH Aachen University, 2015)

Copyright Shaker Verlag 2015

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-3607-7

ISSN 2191-0863

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

*Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?*

Thomas S. Eliot

Abstract

The high performance and low cost of 802.11 WLANs have led to the widespread adoption of this technology. However, the large set of communication features, the dynamic and unmanaged network topologies, and the unpredictable behavior of the wireless channel result in ever-increasing complex systems. These issues contribute to the creation of intractable networks that are hard to characterize by means of accurate yet scalable analytical models. Instead, sophisticated and efficient learning approaches are increasingly being considered in literature to perform this task.

In this thesis, we exploit machine learning techniques to address relevant performance issues in the context of two prominent 802.11 amendments, namely 802.11 p and 802.11 ac. The first was developed to support reliable vehicular communications, while the latter pursues the goal for high throughput in indoor environments.

To achieve high throughput, 802.11 ac defines channels of larger bandwidth than its predecessors. The resulting higher data rates come at the cost of an increased frequency variability, which is known to degrade the communication. Our first contribution is a scheme that compensates for the larger frequency variability by disabling highly attenuated OFDM subcarriers and dynamically distributing the power among the active ones. The lack of a close-form solution to the proposed throughput maximization problem increases the complexity, especially when jointly selecting the transmission rate, and limits the applicability of the method. We then present an approach that *learns* the structure of previously computed solutions and applies the gathered knowledge to provide accurate solutions at runtime.

Vehicular communications require reliable message delivery, particularly in the context of road safety applications. While the enhancements introduced in 802.11 p increase the robustness to multi-path fading, it is unclear how well vehicular communications can cope with jamming. In our second contribution, we characterize the performance of 802.11 p devices in relevant vehicular environments under the impact of jamming and identify the potential of the latter to disrupt communication over large areas thereby compromising road safety. These findings motivate our third contribution, namely a jamming detection tool based on machine learning. We capture relevant metrics from 802.11 devices and learn their behavior in different scenarios and subject to various jamming patterns, which can later be applied to accurately detect jamming attacks in indoor and vehicular environments.

In the future, users will transfer their requirements for high throughput to their vehicles. While rate adaptation provides means to achieve high throughput in vehicular environments, it is known to be a challenging task due to the fast changing channel. However, in car-to-infrastructure communications, the surroundings of an access point feature recurring characteristics that result in specific patterns of the signal strength over time. Our fourth contribution is a learning algorithm that identifies these patterns buried in empirical data and combines them with GPS information, to accurately select the rate according to the *predicted* future channel conditions.

In general, this thesis contributes various learning approaches to address relevant problems of different nature, that is, optimization, classification, and prediction, in prominent 802.11 wireless networks.

Kurzfassung

Hohe Leistungsfähigkeit und niedrige Kosten 802.11-basierter WLAN Netze haben zu der Popularität dieser Technologie beigetragen. WLAN Netze befinden sich in ständiger Entwicklung, um die Bedürfnisse der Benutzer für den stetig steigenden Durchsatz und für eine flächendeckende Verfügbarkeit zu befriedigen. Gleichzeitig steigt die Komplexität der Netze und der zugrunde liegenden Kommunikation aufgrund der zahlreichen Funktionalitäten, der wachsenden Anzahl und Mobilität der Kommunikationsgeräte und des unvorhersehbaren Verhaltens des drahtlosen Kanals. Folglich kann die Optimierung dieser Netze selten mittels akkurater und skalierbarer analytischer Modelle durchgeführt werden. Stattdessen wird der Einsatz von Machine Learning Ansätzen immer häufiger in der Literatur beschrieben.

In dieser Dissertation werden relevante, offene Fragen im Kontext 802.11p und 802.11ac Technologien untersucht und Machine Learning Algorithmen verwendet, um den Durchsatz und die Robustheit der Kommunikation zu verbessern.

Um hohen Durchsatz zu erreichen, erlaubt 802.11ac die Verwendung hoher Bandbreiten. Dennoch führen Letztere zu einer Erhöhung der Variabilität der Kanalzustände über die Frequenz, was die Qualität der Übertragung vermindern kann. Als erster Beitrag präsentieren wir einen Ansatz zum Ausschalten gedämpfter OFDM Unterträger und zur dynamischen Verteilung der Sendeleistung. Für das resultierende Optimierungsproblem untersuchen wir die Leistung und Komplexität der optimalen und verschiedenen suboptimalen Lösungen, teilweise aus der Machine Learning Dömane. Im Allgemeinen liefern die vorgeschlagenen Lösungen eine erhebliche Verbesserung des Durchsatzes.

WLAN basierte Fahrzeugkommunikation wird durch 802.11p unterstützt, wobei der Fokus auf Anwendungen zur Verbesserung der Verkehrssicherheit gesetzt wird. Obwohl Letztere rechtzeitige und fehlerfreie Übertragungen erfordern, ist es ungewiss, ob die Robustheit von 802.11p Kommunikationen gegenüber Interferenzangriffen (sogenanntes Jamming) ausreicht. Als zweiten Beitrag charakterisieren wir mittels Messungen den Einfluss von Jamming auf die Leistung der Fahrzeugkommunikation in relevanten Szenarien und zeigen dabei, dass der Erfolg von Verkehrssicherheitsanwendungen schwer beeinträchtigt werden kann. Unsere Beobachtungen motivieren unseren dritten Beitrag, ein Machine Learning basierten Algorithmus zur effizienten Detektion von Jamming Angriffen auf 802.11 Übertragungen. Durch das *Lernen* vom Verhalten ausgewählter Metriken in diversen Szenarien unter dem Einfluss von Jamming wird eine maßgeblich hohe Erkennungsrate der Angriffe erzielt.

Fahrzeuge, die mit 802.11 Technologie ausgestattet sind, können sich mit Access Points verbinden, um Multimedia Anwendungen zu unterstützen. Diese profitieren generell vom hohen Durchsatz, was durch effiziente Algorithmen zur Ratenanpassung erreicht werden kann. Die Mobilität der Fahrzeuge führt zu schnellen Variationen der Kanalbedingungen, wodurch die Auswahl einer adäquaten Rate erschwert wird. Dennoch kann man die Szenario-spezifischen Kommunikationsbedingungen in der Umgebung des Access Points lernen, um diese Aufgabe zu vereinfachen. Unser vierter Beitrag ist ein Machine Learning basierter Algorithmus, der die zeitliche Entwicklung der Signalstärke mit GPS Informationen kombiniert, um zukünftige Kanalbedingungen vorherzusehen und eine passende Senderate auszuwählen.

Acknowledgements

I would like to express my sincere gratitude to my advisors James Gross and Klaus Wehrle. James (now with KTH University) was my mentor during this dissertation and held always his door open for answering my questions and motivating me in times of uncertainty and discouragement. He gave me freedom to select research topics and supported my decisions and ideas. Klaus welcomed me to the COMSYS Chair and provided me with optimal conditions to successfully finish this dissertation. I would also like to thank Jörg Widmer (Institute IMDEA Networks) for reviewing this thesis and acting as second opponent.

During my PhD I had the privilege of working with many brilliant students, whose motivation, efforts, and ideas were crucial for the successful completion of this thesis. I would like to thank Humberto Escudero for his tremendous help with simulations and for the intense discussions on power loading. I am very grateful to Hanzhi Zhang for his outstanding ideas and flawless work on rate adaptation. Oliver Kotulski always kept a positive attitude despite the intense measurement sessions for characterizing the impact of jamming. Caj-Julian Schnelke laid the foundations of the jamming detection mechanism with his excellent programming skills. Gloria Abidin showed great perseverance at designing and conducting jamming detection experiments. It has been also a great pleasure to work together with Moritz Werner, Anwar Hithnawi, Erwin Fang, and Wei Hong.

I would also like to thank Ana Aguiar and Carlos Pereira (FEUP Porto University) for the fruitful collaboration and for their help during my stay in Porto.

The last years working towards my PhD would have been much harder without the help and support of my colleagues. I would like to thank Christian Dombrowski for the valuable input he provided me with as outcome of innumerable discussions. Georg Kunz did not only help me with any programming issue I struggled with, he was always there to chat and give advice. Simon Görtzen and Grit Claßen helped me in numerous occasions with mathematical problems. A big *thank you* goes to Farshad Naghibi for his friendship and discussions. I would like to thank Marco Weyres, Donald Parruca, and Di Li for the nice time at and after work. I would also like to thank Georgios Floros and Dennis Mitzel for their valuable inputs on machine learning. Working in collaboration with Ismet Aktaş was not only fun, but also led to excellent research. I am very fortunate for having worked together with Florian Schmidt and Hanno Wirtz, who were always ready to give valuable feedback. I would like to thank Jó, Nico, René, Torsten, Henrik, Mónica, Dirk, Matteo, Mirko, Martin, Oscar, and Oliver for the nice time at the COMSYS Chair.

I would like to thank the continuous and altruistic support of my friends and relatives. I am forever grateful to my *german family*: Annette, Roland, Anna-Julia, Marie-Jennie, Ilse-Dore, and Tillmann for always having been encouraging me. This thesis would simply not exist without the love and education that my parents, Francisco and Paquita, gave me. It is you to whom this thesis is dedicated. I am eternally thankful to my sister Yolanda, for her love and support. Above all, my most profound gratitude is for my wife Charlotte. She did not only accept but strongly supported my decision of moving from Berlin to Aachen to start my PhD. She always believed in me, even when I myself did not. Without her tireless helping hand and her unconditional love, I truly would not have finished this thesis.

Contents

1	Introduction	1
1.1	Problem Statement	2
1.1.1	Large Bandwidth Transmission in 802.11 ac Networks	2
1.1.2	Jamming Attacks in 802.11-based Vehicular Networks	3
1.1.3	Rate Adaptation in 802.11-based Vehicular Networks	4
1.2	Research Questions	5
1.3	Contributions	6
1.4	Outline	8
2	Background	11
2.1	Wireless Channel	11
2.1.1	Propagation Loss Attenuation	11
2.1.2	Propagation Phenomena	13
2.1.3	Multi-path Propagation and Shadowing	13
2.1.4	Statistical Modeling of Fading Channels	17
2.1.5	Selected Wireless Channel Models	19
2.2	IEEE 802.11 Networks	21
2.2.1	Network Architecture	22
2.2.2	Physical Layer	23
2.2.3	Medium Access Control Sublayer	27
2.2.4	Introduction to IEEE 802.11 ac	30
2.2.5	Introduction to IEEE 1609 WAVE	38
2.3	Machine Learning	41
2.3.1	Fundamentals	41
2.3.2	Statistical Learning	42
2.3.3	Support Vector Machine	49
2.3.4	Combined Learners	53

3	Optimizing Large Bandwidth Transmissions in 802.11 ac	59
3.1	Motivation	59
3.2	Problem Statement	61
3.3	Large Bandwidth Channel Analysis	62
3.3.1	Modeling Indoor Wireless Channel	62
3.3.2	Frequency Variability Characteristics	63
3.4	Communication over Large Bandwidths	65
3.4.1	Models and Methodology	66
3.4.2	Simulation Results	68
3.4.3	Summary	70
3.5	Loading Algorithms for 802.11	71
3.5.1	Power Loading	74
3.5.2	Adaptive Modulation	78
3.5.3	Bit Loading	79
3.5.4	Comparison Loading Algorithms	79
3.6	Subcarrier Switch-Off	83
3.6.1	General Idea	83
3.6.2	Performance Evaluation	86
3.6.3	Machine Learning Heuristic	89
3.7	Increasing Evaluation Realism	96
3.7.1	Protocol Overhead	97
3.7.2	Header and Control Frame Errors	97
3.7.3	Outdated Channel State Information	97
3.7.4	Simulation Model and Methodology	98
3.8	Discussion	109
3.8.1	Impact of MIMO Transmit Beamforming	110
3.8.2	Impact of Perfect Rate Adaptation	112
3.8.3	Computational Complexity	113
3.9	Related Work	115
3.10	Summary and Conclusions	119

4	Vehicular Communication Reliability under Jamming Attacks	121
4.1	Motivation	122
4.2	Characterizing Communication under Jamming	123
4.2.1	Hardware Equipment	123
4.2.2	Indoor Evaluation	130
4.2.3	Outdoor Evaluation	137
4.2.4	Related Work	142
4.2.5	Summary	143
4.3	Jamming Detection in 802.11 Vehicular Networks	143
4.3.1	Motivation	143
4.3.2	Designing Jamming Detection Strategies	144
4.3.3	Machine Learning-based Jamming Detection	149
4.3.4	Evaluation	151
4.3.5	Discussion	163
4.3.6	Related Work	170
4.3.7	Summary	171
4.4	Conclusions	172
5	Rate Adaptation in VANETs	175
5.1	Motivation	176
5.2	Problem Analysis	177
5.2.1	Vehicular Wireless Channel	177
5.3	Related Work	178
5.3.1	Classical Rate Adaptation Approaches	178
5.3.2	Rate Adaptation in Mobile Environments	179
5.4	Random Forests Rate Adaptation Algorithm	180
5.4.1	General Idea	181
5.4.2	Algorithm Design	181
5.4.3	Parameter Study	186
5.5	Evaluation	191
5.5.1	Comparison Schemes and Performance Metrics	191
5.5.2	Results	192
5.6	Discussion and Limitations	198

5.6.1	Storage and Computational Resources	198
5.6.2	Channel Usage Restrictions in 802.11 p	199
5.6.3	Performance Anomaly	199
5.6.4	Impact of Inaccurate GPS Information	200
5.7	Summary and Conclusions	200
6	Summary and Conclusions	203
6.1	Contributions	203
6.2	Challenges and Limitations	206
6.3	Future Investigations	206
6.3.1	Implementing Subcarrier Switch Off	207
6.3.2	Network Wide Jamming Detection and Localization	207
6.3.3	Implementing Random Forests Rate Adaptation	208
6.4	Final Remarks	208
	Glossary	209
	Bibliography	211