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*We cannot teach people anything; we can only help them discover it within themselves.*

Galileo Galilei

*The beginning of all science is wondering why things are the way they are.*

Aristotele

*To my parents and all the people that supported me during these years*

Marco Picone

*To all who have loved me, to all whom I have loved*

Stefano Busanelli

*To my parents and Annalisa, for their endless support*

Michele Amoretti

*To Niccolò and Rita, my only wealth*

Francesco Zanichelli

*To Sofia, Viola, and Anna, the north stars of my sky*

Gianluigi Ferrari

# Foreword

Intelligent Transportation Systems (ITS) have lately earned center stage as some of the most relevant technologies to academia, industries, and the society in general. Their strong suit is *transversality*, as the development of ITS straddles several different research fields (e.g., from communication to logistics), and has a dramatic impact on many real-world aspects.

Applications supported by ITS range from safety to entertainment, and all of them will lead to tangible improvements of our daily life. Among such applications, those that aim at reducing energy consumption and carbon footprint deserve special mention, as they make ITS one of the green technologies that will define an eco-friendly society.

It is therefore evident that introductory and teaching material on ITS, as well as in-depth studies in this field, are precious resources for students, engineers, researchers, and anyone who would like to enhance her knowledge on the world we live in.

This book, *Advanced Technologies for Intelligent Transportation Systems*, is the work of one of the most renowned groups of experts in the field. It first presents the fundamental aspects of ITS in a tutorial manner, then it moves toward more advanced topics. It successfully covers a vast range of technical aspects such as communication, networking, security, applications. Additionally, the book provides an insightful overview of the major analytical and experimental methodologies for the study of ITS, which is one of its most unique merits.

This book thus represents the definitive guide to ITS: an excellent reference for students as well as for researchers working in the field. I am certain that all readers will enjoy it.

Turin, May 2014 Carla Fabiana Chiasserini

# Preface

This books is by no means a treatise on all aspects of Intelligent Transportation Systems (ITSs). Rather, it attempts to present a unified perspective on ITS, encompassing a few advanced technologies which we came in touch with during part of our research activity in the last years. In particular, one of the peculiarities of this book is the presentation of possible solutions at various communication layers, encompassing both computer science-oriented (high layers) and telecommunication-oriented (low layers) perspectives. Along the way, we describe, in a coherent fashion, a number of interwoven innovative technologies. The approach is thus inherently cross-layer, in the sense that we cover different wireless communication protocols, but we also take into account application-level services. The intended audience is academic and industrial professionals, with good technical skills in information and communication technologies. To ease reading, we have limited as much as possible the mathematical details, which are mostly reported in the appendices of the book.

The contents of the book flow from a preliminary regulatory overview to more technical issues. The synopsis can be summarized as follows. The *first chapter* presents ITS principles and a brief standardization history, comparing European and US visions. Emerging worldwide ITS architectures are also illustrated, together with the most relevant envisioned ITS applications. The *second chapter* goes more deeply into the analysis of the communication paradigms and technologies that enable ITSs. Key challenges in vehicular networks are discussed, taking into account Vehicle-to-X (V2X) communications. A survey of the literature on centralized client/server and decentralized Peer-to-Peer (P2P) vehicular networks is proposed. This chapter terminates with the presentation of the most important enabling communication technologies for future ITSs, namely: cellular networks, WiFi, IEEE 802.11p, WAVE and ETSI ITS. The *third chapter* is fully devoted to wireless communications for Vehicular Ad hoc NETworks (VANETs). We first investigate probabilistic broadcast protocols with silencing, a recursive analytical performance evaluation framework and simulations. Then, we analyze the performance of VANETs as distributed wireless sensor networks. The *fourth chapter* presents X-NETAD, a hierarchical architecture for "cross-network" ITS

communications. Experimental results are illustrated and discussed. The *fifth chapter* focuses on application-level distributed algorithms for ITS. In particular, the Distributed Geographic Table (DGT) P2P overlay scheme is presented, and its performance is evaluated, relying on both analytical and simulation results. The DGT for Vehicular Networks (D4V) architecture, supporting a number of ITS applications, is finally presented.

We remark that the specific protocols and architectures considered in this book are "representative," as opposed to "optimal." In other words, we set to write this book mainly to provide the reader with our (limited) view on the subject. Our hope is that this book will be interpreted as a starting point and a useful comparative reference. Some of the tools used in the book (for example, the simulator DEUS) are open-source and available to the interested reader.

It is our pleasure to thank all the collaborators and students who were with us during the years of research which have led to this book, collaborating with our two groups at the Department of Information Engineering of the University of Parma: the Wireless Ad hoc and Sensor Networks (WASN) Lab and the Distributed Sytems Group (DSG). We cannot thank them one by one, but their contributions were instrumental to get here. Finally, we express our sincere gratitude to Springer for giving us the opportunity to complete this project. In particular, we are indebted to Dr. Cristoph Bauman, who believed in this project from the very beginning, and to Mrs. Janet Sterritt-Brunner, our production project coordinator, who was very kind and (above all) very patient.

Parma, June 2014

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# Acronyms

| | |
|---|---|
| ABC | Always Best Connected |
| AC | Access Class |
| ACK | Acknowledgment |
| AIFS | Arbitration Inter-Frame Space |
| AP | Access Point |
| AS | Application Server |
| ASV | Advanced Safety Vehicle |
| BA | Basic Access |
| BC | Backoff Counter |
| BPAB | Binary Partition Assisted Protocol |
| BPSK | Binary Phase Shift Keying |
| BS | Base Station |
| BSS | Basic Service Set |
| BTP | Basic Transport Protocol |
| C2C-CC | Car 2 Car Communications Consortium |
| CALM | Communications Access for Land Mobiles |
| CAM | Cooperative Awareness Message |
| CCK | Complementary Code Keying |
| CCP | Cluster Confirmation Packet |
| CDF | Cumulative Distribution Function |
| CHE-IF | Cluster-Head Election IF |
| CIP | Cluster Initialization Packet |
| C-ITS | Cooperative ITS |
| COTS | Commercial Off-The-Shelf |
| CP | Coverage Percentage |
| CSMA/CA | Carrier Sense Multiple Access with Collision Avoidance |
| D2D | Device-to-Device |
| D4V | DGT for VSN |
| DCF | Distributed Coordination Function |
| DENM | Decentralized Environmental Notification Message |

| | |
|---|---|
| DFE | Distance From Event |
| DGT | Distributed Geographic Table |
| DHT | Distributed Hash Table |
| DIFS | Distributed InterFrame Space |
| DK | DGT Kernel |
| DMH | DGT Message Handler/Dispacher |
| DSRC | Dedicated Short-Range Communications |
| DSSS | Direct Sequence Spread Spectrum |
| EC | European Commission |
| ECDA | Enhanced Distributed Channel Access |
| ECU | Engine Control Unit |
| EG | Event Generator |
| EIFS | Extended IFS |
| EMDV | Emergency Message for Vehicular Environments |
| ERP | Extended Rate PHY |
| ETSI | European Telecommunications Standards Institute |
| EU | European Union |
| FCC | Federal Communications Commission |
| FCS | Frame Control Sequence |
| FHSS | Frequency Hopping Spread Spectrum |
| FHWA | Federal Highway Administration |
| FNTP | Fast Networking and Transport Layer protocol |
| FSAP | Fast Service Advertisement Protocol |
| FTM | Fluid Traffic Model |
| GB | GeoBucket |
| GDP | Gross Domestic Product |
| GM | Geo-Bucket Manager |
| GP | Global Position |
| GPA | Global Positioning System |
| HCCA | HCF Controlled Channel Access |
| HCF | Hybrid Coordination Function |
| HR/DSSS | High Rate Direct Sequence Spread Spectrum |
| I2V | Infrastructure-to-Vehicle |
| IBSS | Independent BSS |
| ICT | Information Communication Technologies |
| IDM-LC | Intelligent Driver Motion with Lane Changes |
| IF | Irresponsible Forwarding |
| ITS | Intelligent Transportation System |
| ITSC | ITS Communication |
| IVC | Inter-Vehicular Communication |
| IVCES | In-Vehicle Communications and Entertainment System |
| LM | Location Manager |
| LocHNESs | Localizing and Handling Network Event System |
| LTE-A | LTE Advanced |
| M2M | Machine-to-Machine |

| | |
|---|---|
| MAC | Medium Access Control |
| MAF | Mass Air Flow |
| MANET | Mobile Ad-hoc NETworks |
| MBMS | Multimedia Broadcast Multicast Service |
| MCDS | Minimum Connected Dominant Set |
| MIMO | Multiple-Input Multiple-Output |
| ML | Map Loader |
| MM | Mobility Model |
| NHTSA | National Highway Traffic Safety Administration |
| NPE | Node Position Error |
| OBU | On-Board Unit |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OIS | On-board Infotainment System |
| P2P | Peer-to-Peer |
| PAF | Probability Assignment Function |
| PATH | Partners for Advanced Transportation TecHnology |
| PCF | Point Coordination Function |
| PDF | Probability Density Function |
| PER | Packet Error Rate |
| PMF | Probability Mass Function |
| PP | Probe Packet |
| PU | Primary User |
| QoS | Quality of Service |
| RB | Resource Block |
| RE | REachability |
| RITA | Research and Innovative Technology Administration |
| RSU | Road Side Unit |
| RTD | Round-Trip Delay |
| RTS/CTS | Ready-To-Send/Clear-To-Send |
| RTSM | Real-Time Simulation Monitoring |
| SB | Smart Broadcast |
| SDO | Standards Development Organizations |
| SIFS | Short Inter Frame Space |
| SL | Sip2Peer Layer |
| SM | Subscription Manager |
| SNR | Signal to Noise Ratio |
| SS | Switch Station |
| SSWE | Switch Station Web Editor |
| TD | Transmission Domain |
| TE | Transmission Efficiency |
| TSF | Timing Synchronization Function |
| TTL | Time To Live |
| TXOP | Transmission Opportunity |
| UDP | User Data Protocol |
| UI | User Interface |

| | |
|---|---|
| UMB | Urban Multihop Broadcast |
| USA | United States of America |
| USDOT | United States Department of Transportation |
| V2I | Vehicle-to-Infrastructure |
| V2V | Vehicle-to-Vehicle |
| V2X | Vehicle-to-X |
| VSN | Vehicular Sensor Network |
| WAVE | Wireless Access in Vehicular Environments |
| WLAN | Wireless Local Area Network |
| WPA | WiFi Protected Access |
| WSA | WAVE Service Advertisement |
| WSMP | WAVE Short Message Protocol |
| X-NETAD | Cross-Network Effective Traffic Alert Dissemination |

# Contents

# Chapter 1
# Introduction

## 1.1 Principles and Challenges

*Intelligent Transportation Systems* (*ITSs*) promise to hugely improve safety, efficiency and sustainability of our transportation system, by means of a massive adoption of Information Communication Technologies (ICTs) [1–3]. Not surprisingly, in last decades ITSs have attracted the worldwide interest of researchers, automotive companies, and governments. In order to create an economically sustainable ITS ecosystem, a large number of projects have been conducted by institutions from all around the world [4]. For instance, the Advanced Safety Vehicle (ASV) program in Japan [5], the IntelliDrive project in the United States [6], and, in Europe, the numerous projects coordinated by the Car 2 Car Communications Consortium (C2C-CC) [7], strongly supported by the European Commission [8] and by the European Telecommunications Standards Institute (ETSI) [9].

In the marketplace, ITSs boast a long series of success histories, carried out by either car manufacturers (with active safety systems), toll road infrastructures operators (with Electronic Tolling Systems), insurance companies (with black boxes), Internet companies (with traffic information systems). However, current ITS hardware, software, and communication technologies are closed, i.e., unable to share data and cooperate together. In other words, current ITS applications are implemented as "silos", thus yielding to equipment duplication and no data sharing. Such a fragmented approach is typical of the first development phase of new technologies, where innovation is driven by pioneers. Figure 1.1 illustrates some significant ITS applications, implemented according to the stand-alone or not-cooperative approach.

Next years' biggest challenge will be to achieve a *Cooperative ITS* (*C-ITS*) ecosystem, where secured data are shared across several ITS applications developed by independent actors, leveraging on a solid basis of international standards, as represented in Fig. 1.2. Such a C-ITS ecosystem would facilitate actions and decisions that improve transportation safety, sustainability, efficiency and comfort beyond that achievable by stand-alone ITS systems.



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