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NETWORKS AND COMMUNICATIONS

Vehicular Networks

Design and Evaluation of Ad Hoc Routing Protocol

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Preface

Intent, abstract and target audience for this book

This book provides a summary of the research work and research frameworks collaboratively carried out by the authors, namely, Martine Wahl, research fellow at the Université Gustave Eiffel and Patrick Sondi, formerly lecturer at the Université du Littoral Côte d'Opale, currently professor at the Institut Mines-Télécom Nord Europe.

The authors' intention is to share their ideas and knowledge accumulated over time, for almost 10 years, in the field of communication protocol engineering, especially for land transport systems.

This book focuses on ad hoc communications between vehicles in a road environment. The development of driver assistance applications inevitably creates a dependency in users who, in the long run, will hardly be able to travel without them. To prove this point, a vehicle without power steering, without an anti-lock braking system (ABS) and without a navigation system should be entrusted to a driver who has recently obtained their driving license to travel to a destination located more than 200 km away through different types of roads. This book raises the issue of the continuity of communication-dependent driving assistance services in the road framework in areas where no communication infrastructure has been deployed or has become inoperative. With the help of an example of an ad hoc routing protocol that the authors helped design, this book presents the methodology that was followed from its

design to its evaluation. The authors outline the questions and motivations involved in their functional requirement-based design approach to be met through the protocol. A description of the analyses carried out to understand the operation of the protocol, its properties as well as its performance for target applications is proposed in the various chapters of the book. The latter concludes with the prospect of integrating components managed by a protocol based on ad hoc communications into a global telecommunications infrastructure for the road.

It is aimed in particular at students and researchers who are beginning in the fields of protocol engineering, ad hoc networks or intelligent transport systems. Nevertheless, it can provide specialists in the field with another point of view on the scientific literature related to these fields, or even concrete tools for developing their own design and evaluation methods of communication protocols for different networks.

Book organization

The book was written by the two authors based on summaries of scientific studies, activity reports, translations of scientific articles, all reorganized and often rewritten in order to ensure coherence in the work. It consists of approximately 250 pages organized into six chapters.

[Chapter 1](#), entitled “Challenges Involving Ad Hoc Communications on the Road”, can be seen as a general introduction to the book. The idea is to briefly expose the evolution of road communications by addressing all aspects: traffic, protocols, applications and security.

[Chapter 2](#), entitled “Functional Approach to Protocol Design”, describes the functional approach to protocol design based on a protocol proposed as a case study for the purposes of analyzing and illustrating the design methods from the functional and performance evaluation requirements followed in this approach. The design and evaluation steps of the case study protocol are described and justified step by step, accompanied by resources in the literature so that the reader’s documentation can be broadened.

[Chapter 3](#), entitled “Models and Simulations for Performance Analysis”, presents a series of models and simulation tools for protocol performance analysis. Most of the factors affecting communications such as mobility, propagation phenomena, communication technologies as well as the metrics employed for performance analysis are explained. The corresponding models as well as their implementation in the various simulation tools are illustrated in as much detail as possible.

[Chapter 4](#), entitled “Performance Evaluation of the Protocol for Collaborative Applications”, provides several sets of

evaluations that include the case study protocol alone to measure its intrinsic performance, and then by comparison with other routing protocols in the literature representing the main approaches adopted in ad hoc networks. A second set of evaluations provides a performance analysis of the case study protocol for a variety of applications, in particular for two cooperative applications, namely, ego-localization and extended perception. In addition to the description of the various protocols and applications, the reader will find the steps involved in their implementation in the simulators as well as the results of the comparisons made.

[Chapter 5](#), entitled “Formal Model for the Analysis of the Properties of the Protocol”, proposes an alternative approach based on formal modeling for designing and evaluating the protocol, no longer essentially from the performance point of view, but rather on its intrinsic properties, in particular with the aim of showing the guarantees it can provide under well-identified assumptions. The analysis of the case study protocol is proposed with the Event-B method and each modeling, the verification and animation steps of the model are illustrated by extracts of the model from the tool that was used, namely, Rodin in these cases.

[Chapter 6](#), entitled “Integration of Ad Hoc Components in a Global Infrastructure”, lists the perspectives that our work has opened by federating them around the idea of a shared infrastructure of communications networks for the future land transport system that would integrate road and rail. The authors highlight in particular the integration of vehicle-to-vehicle (V2V) communications as a native communication mode of the future technology, in this case 5G, and analyze the consequences of this major evolution on the design and evaluation methods of ad hoc communication protocols in the near future.

April 2024

1

Challenges Involving Ad Hoc Communications on the Road

1.1. Introduction

With the arrival of two key innovations that will revolutionize communications in future transportation systems, we felt it was the perfect time to present a summary of our research work, which for the most part has been collaboratively achieved over nearly a decade.

The first innovation is the fully autonomous vehicle equipped with a hyperconnected on-board computer and whose operation on the roads is scheduled for the near future. Initiated in the 1970s for guided public transport, in particular with the VAL metro in the region Hauts-de-France in France, the use of communications and autonomous vehicles has gradually expanded and increased in land transport. For example, in the 2000s, mobile communications (*Global System for Mobile communications-Railway* (GSM-R)) were introduced into the European Rail Traffic Management System (ERTMS), which made it possible to harmonize and streamline high-speed train traffic across Europe. Advances in automation and localization have enabled the Société nationale des chemins de fer français (SNCF) to forecast the autonomous freight train for the end of 2021 and to effectively start testing on rails in early 2022, including the autonomous regional passenger train. In addition, driver-assistance applications initially, offered to drivers through unconnected devices (navigation, hazard warning, etc.), have evolved into connected versions available on

smartphones before being fully integrated into the now connected on-board computers of vehicles, including their cooperative versions. In parallel with this increasing connectivity, improvements in sensing systems and autonomous driving systems have made it possible to improve driving automation to the levels currently observed in some vehicle models. Following this perspective of full driving automation, safety considerations have been increased and, consequently, must be inevitably applied to the communication system that plays a crucial role in the operation of many of these applications for the vehicular context. Communication systems for the transport of the future will therefore need to clearly integrate both the autonomous vehicle and the ability to support all essential functionalities for the remote control of a vehicle, including that initially driven by a human (as for example in a distressful situation).

The second innovation is 5G technology, whose deployment in France is already effective at the time of writing. It completes the convergence of communications, in particular by integrating the Internet of Things (IoT) into the long list of devices already brought together by 4G through all-IP. In terms of access, 5G assimilates all modes of communication, especially those concerning vehicles, namely vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V), while providing very low latency and many other performances at levels largely adapted to vehicular communications. In terms of the organization of access and the core of the network, 5G incorporates most of the recent innovations, resulting in particular from the diversification of access (frequency extension and pooling), the softwarization of radio and network operations (*Software-Defined Radio* and *Software-Defined Network*, respectively) and the virtualization of network-related functions (*Network Function Virtualization*) through transferring

most of the transfer operations of specific hardware devices to virtual machines, especially in the cloud. Combined with paradigms such as *edge computing*, *fog computing* and *named data networking* (NDN), 5G should enable much faster access to data as close as possible to its use, which represents a clear advantage for vehicular applications, most of which require very high responsiveness. This very wide variety of applications presuppose that 5G could soon become a mobile communication system for all smart city applications, and consequently for communications in land transport systems. Therefore, the communication systems for the transport of the future need to be rethought by taking into account the drastic changes that 5G will bring and whose major impact on the design and evaluation of these systems is foreseeable.

1.2. The railway experience in the vehicular networks of the future

In rail transport, most particularly, the question of the future communication system arises more urgently due to the obsolescence and the forecast end of the maintenance of GSM-R technology. The adoption of GSM-R as a telecommunications subsystem of the ERTMS had been validated following several years of measurement campaigns and on-site tests that could not be replicated today for cost reasons. Several research projects have proposed solutions for performing simulation-based evaluations of alternative communications technologies to GSM-R, taking into account elements of the railway context likely to affect communications (tracks, train movements, interchanged traffic, etc.) (Sondi et al. [2017](#)). Similar solutions have been used to evaluate other communication technologies as potential candidates to replace GSM-R,

including Wimax (Pinedo et al. [2015](#)), LTE (Sniady and Soler [2014](#)) and 5G (Ai et al. [2020](#)).

Rail infrastructure provides the first model for large-scale deployment, compared to the underground, which often finds itself limited to the city scale, of a communication system that allows the use of fully autonomous vehicles in land transport in Europe in the short term. The harmonization already undertaken at the European level between the various national rail traffic management systems reinforces the idea that rail can be the ideal support model for the development of communication systems for all future land transport in Europe. It is a foundation that must nevertheless be observed through its successes, but also through its pitfalls, while considering its specificities to avoid biases in the conclusions to be drawn for future systems intended for all land transport. Just to mention a few of the most important aspects, we should consider the following:

- *The dedicated nature of the railway infrastructure* which currently circumscribes both the scope of investments, the investor and the beneficiary. It is a different matter when it comes to a future global infrastructure for all land transport. For example, even if it could have happened, financing the deployment of GSM-R base stations in a white zone today at a loss is already an issue if there is a safety issue for a few trains crossing it. It is not clear that in the future operators would deploy a similar infrastructure for motorists on roads in sparsely populated areas where it would not otherwise be profitable. The design of a comprehensive infrastructure will need to address this aspect.
- *State hegemony over a railway operator that facilitates local decisions within each state and consequently*

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