MAC layer design in Vehicular Ad Hoc Networks: challenges, solutions, and methodologies

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Motivation and Objective Scope
In the last few years vehicular ad hoc networks (VANETs) providing connectivity among vehicles on the road are attracted an increasing interest. They are seen to be one of the most valuable concept for improving road safety and transport efficiency, and as a key technology enabling the provisioning of value-added services to passengers and drivers.

Several ongoing research projects supported by car manufacturers and electronic industry, governments and academia, are establishing standards for VANETs, obtaining frequency spectrum allocations, implementing protocols and applications, and running field trials. However, the widespread deployment of such technology poses several technical issues, concerning architecture, routing, mobility, channel modeling, security, performance, and applications definitions.

The specific characteristics of VANETs make their quantitative and qualitative analysis particularly critical, especially when designing medium access control layer (MAC) protocols. In VANETs, the number of participating nodes are not always known and, more importantly, cannot be restricted. Moreover, the vehicular network topology is mostly decentralized and cannot rely on a ubiquitous coverage of stationary access points that regulate a fair access to the shared channel. MAC protocols for VANETs should carefully face the quickly changing network topology due to the vehicles’ mobility, the shortened connection lifetime, the multi-hop nature of vehicle-to-vehicle links, and the adverse effects of an hostile environment on the radio signal propagation. Furthermore, MAC protocols have to cope with the different nature (distributed vehicle-to-vehicle communications, short-lived vehicle-to-roadside communications) and quality of service (QoS) requirements of manifold kinds of applications (e.g., near real time safety-related applications and delay-tolerant file transfer services). All the aforementioned shortcomings, unique to VANETs, make the design of MAC protocols a very challenging issue.

The main focus of research communities and standardization bodies today is on using the IEEE 802.11 carrier sense multiple access (CSMA) as a MAC protocol for VANETs. IEEE 802.11 technology is a mature, high-bandwidth and low-cost technology with the capability to well fit the multi-hop, distributed, unstable, and ad hoc nature of vehicular communication links. IEEE 802.11p has been included as an amendment to IEEE 802.11. To address the prioritization issues of different applications, the core mechanism of 802.11p is based on the prioritized
distributed channel access scheme of 802.11e. Moreover, to allow comfort/entertainment applications to be concurrently supported with safety-related applications, but without interfering with them, the use of a multi-channel architecture has been proposed in the IEEE 1609 standard suits, aimed to define the WAVE (Wireless Access for Vehicular Environments) protocol stack.

The 802.11p MAC protocol well handles high mobility and topology changes and does not need time synchronization, however the deployed contention-based access scheme makes successful and time-bounded data delivery very harsh to be ensured. Therefore, the feasibility of deterministic time-division multiple access (TDMA) mechanisms on top of 802.11p MAC protocols is currently under investigation as well. TDMA solutions rely on a slotted frame structure, allow high reliability, avoid hidden terminal problem, and ensure relatively good QoS at the expenses of low scalability and more complex synchronization procedures. Since neither plain CSMA-based approaches nor TDMA-based solutions can be claimed to be able to simultaneously cope with the challenging and conflicting issues of scalability, reliability, QoS, and simplicity in VANETs, solutions leveraging on the adaptability of MAC/PHY parameters (e.g., priority, contention window, data rate, transmission power) to applications requirements, traffic load and interference on the channel, vehicular topology and speeds, and hybrid MAC approaches combining the benefits of both deterministic and contention-based channel access solutions have recently pursued and appear as the most promising candidate solutions to cope with the shortcomings mentioned above.

Given the high costs of deploying and testing actual equipment in the vehicles, the simulation environments represent the only feasible and cost-efficient tools for analyzing the fundamental properties of VANETs when evaluating the performance of scalable MAC layer solutions.

Therefore, research efforts have been put forward to improve realism of traffic, network, and channel propagation models. Moreover, analytical models allowing to understand quantitatively the performance of standard protocols and alternative MAC solutions, in order to make better decisions on their adoption, adaptation, and improvement have been proposed.

The goal of the tutorial is to provide attendees (including typical ICT attendees: researchers, engineers, professors and graduate students, industry engineers/managers, as well as the general audiences) a comprehensive overview of vehicular networking and its technical issues, with a special focus on the description of the IEEE 802.11p/WAVE standards architecture and on the challenges of MAC layer design. The most representative standard-compliant and alternative solutions in the literature and the simulation aspects and fundamental analytical research contributions in this field will be reviewed. The survey of the main solutions in the literature will provide key findings that can serve as guidelines for the design of future MAC protocols for the vehicular environment. Specifically, attendees who are new to the field of vehicular networking will thus be presented an overview of vehicular communications features and current standardization activities. People who already actively working in the field will benefit from intensive discussions on existing MAC layer solutions, and on enhanced mobility/channel models for simulation tools and analytical methodologies.

Abstract

Vehicular ad hoc networks (VANETs) providing connectivity among vehicles on the road are seen to be one of the most valuable concept for improving road safety and transport efficiency and as a key technology enabling the provisioning of value-added services to passengers and drivers.

Several ongoing research projects supported by car manufacturers and electronic industry, governments and academia, are obtaining frequency spectrum allocations, establishing standards for VANETs, implementing protocols and applications, and running field trials.
In the US, the FCC granted a 75 MHz band for Dedicated Short Range Communications (DSRC) in Intelligent Transportation Systems (ITS) in the 5.9 GHz range, while frequency allocations in Europe and Japan are in the 5.9 GHz. IEEE 802.11p has been recently added as amendment to IEEE 802.11 standard and it specifies physical and MAC layer protocols for the rapidly varying vehicular environment. Moreover, the IEEE 1609.x family is currently specifying the upper layers of a lightweight protocol stack for vehicular communications.

However, the widespread deployment of vehicular communications poses several fundamental issues which are still unsolved.

The unique features of the vehicular environment: the quickly changing network topology due to the vehicles’ mobility, the variable node density, the shortened connection lifetime, the multi-hop nature of vehicle-to-vehicle links, and the adverse effects of an hostile environment on the radio signal propagation, make the design of MAC protocols for VANETs a very challenging issue. Furthermore, MAC protocols have to cope with the different nature (distributed vehicle-to-vehicle communications, short-lived vehicle-to-roadside communications) and quality of service (QoS) requirements of manifold kinds of applications (e.g., near real time safety-related applications and delay-tolerant file transfer services).

Several MAC solutions have been proposed in the literature. 802.11p-compliant CSMA-based approaches well handle high mobility and topology changes and does not need time synchronization, however the deployed contention-based access scheme makes successful and time-bounded data delivery very harsh to be ensured. On the other hand, deterministic TDMA solutions rely on a slotted frame structure and ensure relatively good QoS at the expenses of low scalability and more complex synchronization procedures. None of the aforementioned approaches can be claimed to be able to simultaneously cope with the challenging and conflicting issues of scalability, reliability, QoS, and simplicity in VANETs. Solutions leveraging on the adaptability of MAC/PHY parameters (e.g., priority, contention window, data rate, transmission power) and hybrid MAC approaches combining the benefits of both deterministic and contention-based channel access solutions, which behave adaptively to applications requirements, traffic load and interference on the channel, vehicular topology and speeds, have recently pursued and appear as the most promising candidate solutions to cope with the shortcomings mentioned above.

The tutorial introduces the unique features of the vehicular environment and describes the upcoming IEEE 802.11p/WAVE standards. Then, by surveying the main solutions in the literature, will provide key findings that can serve as guidelines for the design of future MAC protocols for the vehicular networks. Moreover, experience will be shared about simulation tools (network, channel, mobility modeling) aimed to improve the realism of performance evaluation and analytical models helping in making better decisions on the adoption, adaptation, and improvement of the upcoming standards and alternative MAC solutions.

**Detailed outline of topics covered**

The content of the tutorial will be structured as follows:

1. Vehicular communications, applications, and technical issues.
2. Standardization activities for vehicular communications (IEEE 802.11p, IEEE 1609.1- IEEE 1609.4).
3. Challenges in the design of MAC protocols for the vehicular environment.
5. Methodologies and tools for the assessment of vehicular MAC protocols: analytical models and enhanced simulation tools (e.g., for mobility and channel modeling).
The tutorial will start with a brief introduction of vehicular ad hoc networks. The envisioned applications (safety, traffic efficiency, and infotainment applications) and the main technical issues (medium access control and routing layer design, mobility management, channel modeling) and social challenges (e.g., penetration rate) of VANETs will be outlined. Next, the second part will present the ongoing standardization activities in the field of vehicular networking on a global scale, with special focus on IEEE 802.11p, defining physical and MAC layers, and IEEE 1609.1-1609.4 standards families, specifying management, security services, network/transport protocols, and multichannel operations. Standardization issues related to different frequency bands and spectrum allocations in different countries will be discussed as well.

The third part will investigate the main challenges related to the design of MAC protocols by taking into account the unique features and constraints of vehicular networks and the requirements of the envisioned applications. Then, an overview of the main approaches for MAC layer protocols proposed in the recent years for VANETs will be given (distributed CSMA/CA-solutions, synchronous TDMA-based approaches, adaptive and hybrid solutions). Specifically, work from more than 30 research publications is surveyed and key findings that can serve as guidelines for the design of future MAC protocols for the vehicular environment are summarized. Finally, methodologies and tools for the assessment of vehicular MAC protocols will be presented. Specifically, analytical models, which could help in making better decisions on the adoption, adaptation, and improvement of the upcoming standards and alternative solutions, and tools (channel and mobility models) proposed to enhance the realism of existing simulators will be discussed.

**Biographical sketch of all instructor(s)**

Antonella Molinaro is an Associate Professor of Telecommunications at University Mediterranea of Reggio Calabria, Italy. Before her current appointment, she worked at the University of Messina and the University of Calabria as an Assistant Professor, and at Polytechnic of Milano as a research assistant. She worked with Telesoft S.p.A. in Rome as a network designer, and with Siemens AG, Munich, Germany as an EU Fellow within the RACE II ATDMA (Advanced-TDMA Mobile Access) project. She received the Laurea Degree (1991) in Computer Engineering, a post-laurea master diploma (1992) in Inform. Techn. from CEFRIEL/Politecnico di Milano, and a Ph.D. degree in Multimedia Techn. and Comm. Systems (1996). She has been involved in organizing workshops and special sessions in international conferences, she has served as a guest editor for special issues in valuable international journals and has been in the Editorial Board of the Journal of Networks. She is in the Steering Committee of Nets4cars 2011 and she will be in the International Advisory Board of ITST (International Conference on Intelligent Transport Systems Telecommunications) 2011. Her current research interests are in the field of multi-hop wireless communications, vehicular ad hoc networks, and future internet architectures. She has published more than 150 publications in international conferences, journals, and book chapters and she has received two Best-paper awards. In the last three years she published about ten papers in the field of vehicular ad hoc networks at prestigious journals and leading IEEE conferences and workshops. She is a member of IEEE and IEEE Communications Society.

Claudia Campolo received a M.S degree in Telecommunications Engineering in October 2007 from the University Mediterranea of Reggio Calabria, Italy. Since January 2008 she has been with the same university as a PhD student. She was a visiting PhD student at the Department of Electronics Engineering of Politecnico di Torino (May 2008-october 2008). She is currently finalizing her PhD thesis “Vehicular communications: challenges and solutions for the upcoming
IEEE 802.11p/WAVE standards”, whose objective is the design, performance evaluation and analytical modeling of medium access control (MAC) and dissemination protocols for the upcoming IEEE 802.11p/WAVE vehicular networks. The research results obtained so far have been published in prestigious journals (Ad Hoc Networks) and have been accepted and presented in leading IEEE conferences (VNC 2009, GLOBECOM 2010, WCNC 2011) and workshops addressing vehicular networking topics (IEEE Vehi-Mobi co-located with ICC 2009, Net4Cars 2010, ITST 2010). Moreover, in 2009 she has been recipient of the Best Paper Award in Nets4Cars 2009 (co-located with ICUMT). She served as a technical reviewer of several international conferences and journals. She will serve as Tutorial co-chair and TPC member in ITST (International Conference on Intelligent Transport Systems Telecommunications) 2011. She is a student member of IEEE and IEEE Communications Society.