UNIVERSITY OF PETROȘANI

DOCTORAL SCHOOL

SYSTEM ENGINEERING DOMAIN

PhD THESYS

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PETROȘANI
2022

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RESEARCH ON THE INTEGRATION OF V2X (VEHICLE-TO-EVERYTHING) COMMUNICATIONS IN VEHICLES FOR TRAFFIC SAFETY IMPROVEMENTS

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Abstract

Individual mobility and intelligent transportation systems are experiencing a transformation towards more responsive, smart, and safe solutions. A wide spectrum of use cases and new applications are emerging in the vehicular ecosystem accelerated by the latest wireless communication technologies. The ever-growing desire of individuals to travel and commute have stretched the limits of current transportation infrastructures and existing wireless technologies. With the help of emerging innovations and the increase of computation power, the paradigm of traffic safety can be efficiently addressed. Therefore, researching about, and contributing to V2X seemed like an appealing idea for this PhD thesis, considering the background of the author in the telecommunication and system engineering domains. The paper compiles a broad and comprehensive overview of the current ecosystem, from the beginnings of V2X up to the latest specifications, which are still under development by well-established standardization bodies, such as IEEE, ITU, 3GPP and 5GPP. As the traffic safety concern needs to be addressed as early as possible, the thesis proposes a hybrid warning system for notifying the drivers when approaching a dangerous road section. Taking the idea further, the integration with an enhanced cruise control has been proposed. This solution addresses the concerning subject of traffic safety by using current technologies, such as the existing cellular infrastructure together with GPS for precise positioning, combined with Fuzzy controllers and Finite State Machine concepts. The thesis sets the steppingstones for a V2X intelligent communication system that could be scaled up and deployed on a national-wide level. Further enhancements and optimizations are being proposed to the wireless warning system, together with suggestions of integrating all proposed enhancements into a powerful system control unit. Such a smart communication system could also be implemented, in other industry verticals, to increase efficiency and safety.

Table of Contents

Summary

One of the important pillars of a modern society is mobility. People mobility and transportation of goods are vital for a thriving economy. Subsequently, the volume of road traffic increases progressively, especially in metropolitan areas. Individual mobility especially is causing troubles by creating traffic jams. The latest communication technologies will ensure a sustainable growth and will help to improve traffic safety and efficiency.

The enhancement of transportation systems achieved through conventional methods, like new road construction or road capacity expansion, often reaches its limits in terms of land constraints and lack of public acceptance. The main consequence of these traditional methods is the decreasing proportion of green spaces within the metropolitan areas. For those reasons, it is imperative to study and understand how to deal with this problematic topic. The society needs to progress and evolve by intelligent control and management of traffic, together with raising public awareness and trying to reduce “single rider” traffic emergence. A viable alternative would be to enhance the car sharing concept and extend it to autonomous vehicles that brings benefits in terms of safety and traffic efficiency.

Together with the traffic density increase, the statistics show that an acceptable traffic safety standard cannot be achieved anymore with traditional methods. Therefore, improving the safety of traffic participants, like car passengers, pedestrians, and cyclists, has become one of the main targets of governmental authorities around the world.

Engineers and scientists are studying new processes and technologies to enhance traffic flows through intelligent and autonomous traffic management systems. The expectation of the newly developed approach, widely known as the Intelligent Transportation System (ITS), is to increase traffic safety, avoid congestions and increase overall traffic efficiency. End-to-end digitization, starting from the single element, such as personal vehicles, and continuing through all elements of the transportation system, provides the general basis for continuous evolution of existing transportation concepts. Starting with engineering progress in the automotive industry towards automated driving, together with development of Advanced Driver-Assistance Systems (ADAS) and adding the newly standardized communication systems between traffic participants, we are boosting the progress of traditional transportation systems. A scalable and future proof mobile communications system is required to support such reliable safety message exchange. This communication system should be able to operate at acceptable parameters even in scenarios where road users are traveling at high speeds, the coverage is not optimal with single radio access technology and medium access conditions are challenging.

Such requirements, not supported in the past by the existing mobile communications technologies, define the starting point for an evolution of safety applications and paves the way for ubiquitous connectivity in the automotive ecosystem. It opens the door to a future-proof cellular ecosystem that converges with the automotive industry. The convergence of these systems is commonly known as Cooperative Intelligent Transportation System (C-ITS).

Traffic safety and road congestion are major problems throughout the world, especially in fast emerging countries that did not adapt their infrastructures to current traffic demands. Emergence of individual transportation leads to big challenges in terms of traffic management and increased environmental impact. Beyond doubt, traffic jams are getting worse in many urban areas worldwide, and are harmful for overall travel costs, participants safety, and environment protection. An always growing

number of personal vehicles makes these problems even more impacting. The scientific community accepted the challenges almost two decades ago and started to focus on this topic by delivering specialized studies and providing sustainable solutions.

With increased amount of data generated, transported, and processed in real time, these systems have a great potential to improve road safety and the efficiency of the road transport. Because of these expected benefits and considering the overall moderated costs linked to its deployment, there is a strong public and governmental interest in enabling a fast adoption at global scale that will translate into quick market production, early trials, and finally commercial deployments.

The scientific community accepted the challenges almost two decades ago and started to focus on this topic by delivering specialized studies and providing sustainable solutions. Cooperative Intelligent Transport Systems (C-ITS) use technologies that enables vehicles to efficiently communicate with other neighboring vehicles, with traffic signs and roadside infrastructure as well as with pedestrian or other vulnerable road users. The systems are based on Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) communications. All these emerging communication systems come together to create vehicle-to-everything communications (V2X).

With increased amount of data generated, transported, and processed in real time, these systems have a great potential to improve road safety and the efficiency of the road transport. Because of these expected benefits and considering the overall moderated costs linked to its deployment, there is a strong public and governmental interest in enabling a fast adoption at global scale that will translate into quick market production, early trials, and finally commercial deployments.

In the European Commission's publication called Vademecum, in 2018 [1], can be noticed that the rate of EU road fatality in 2017 was at its lowest ever, with 49 dead per million inhabitants as an average per all EU member states. The countries with the lowest rate of road deaths per each million inhabitants were Sweden (25), the UK (27), the Netherlands (31), Denmark (32), Ireland (33) and Estonia (36), whereas countries with the weakest road safety records, meaning highest fatality rates, are Croatia (80), Romania (98), and Bulgaria (96).

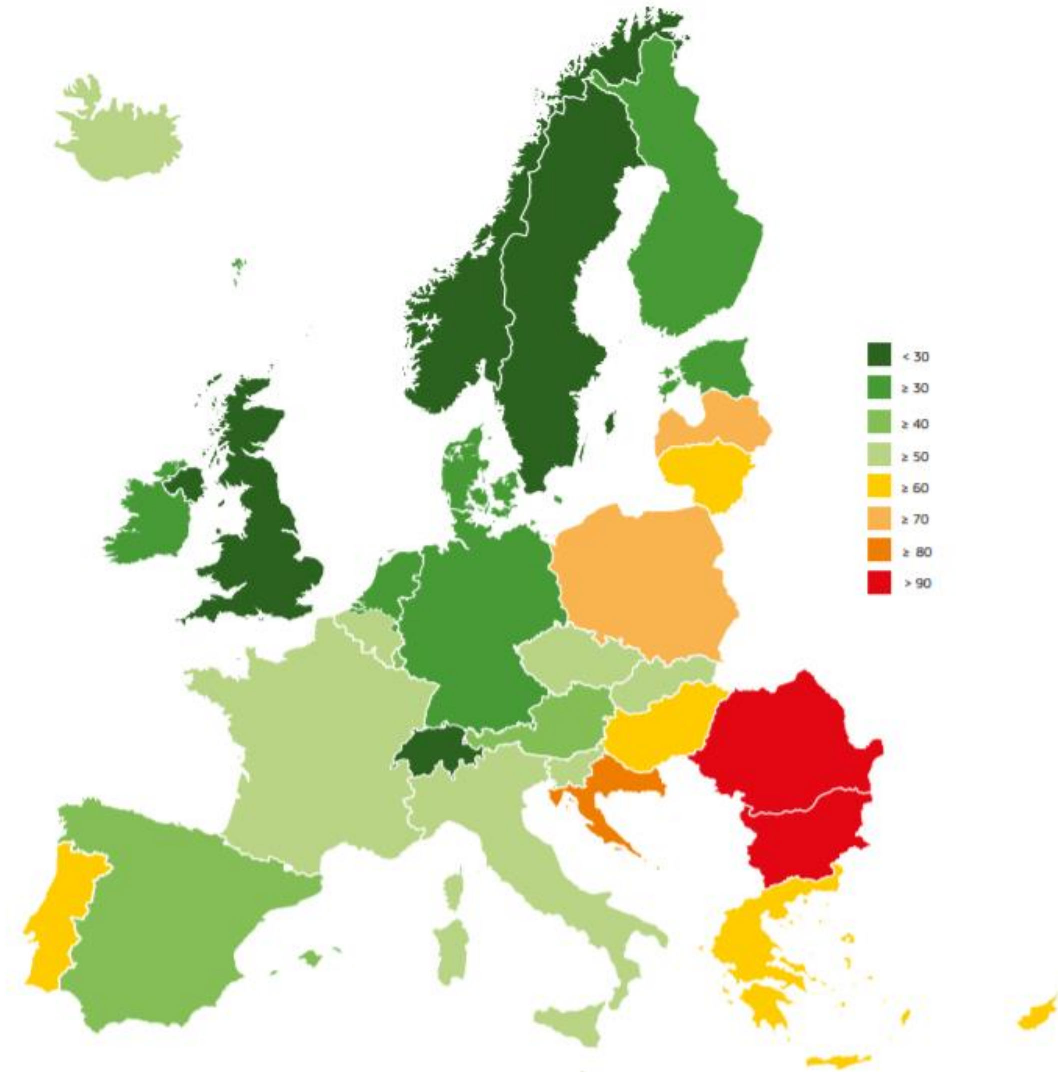

Fig. 1 EU Road fatality rates 2017 [1]

Unfortunately, Romania is at the bottom of the list, being the EU member country with highest fatality rate in the whole EU region. Romania needs to urgently consider improvements in the infrastructure and invest in innovative technologies for addressing this heartbreaking reality.

This worrying place among the most dangerous places to drive in Europe, and the lack of a unified national system for enhancing the traffic safety, has determined me to choose this topic for my research. Additionally, from a scientific point of view, a technical gap has been identified prior to the beginning of this paper, therefore it was an ideal combination of factors that motivated me for approaching this subject.

1.1 Thesis outline

Chapter 1 – General introduction, takes offers to the reader an opening into the concept of Intelligent Transportation System (ITS) and provides the motivation behind choosing this topic to build my PhD thesis upon.

Chapter 2 – A global overview of the vehicular networks, approaches the concept of enhancing traffic safety, from its initial phase in 2002 (see **Section 2.1 – V2X Communications introduction**), where the road accident statistics started to raise serious concerns with regards to the always increasing number of traffic accidents causing major injuries and in many cases death.

This chapter is structured organically, starting with a comprehensive examination of the history of V2X communications, presenting the generic concept of V2X, and its adoption in different regions of the world. It then takes the reader into a unique journey describing the distinctive approach that each regional standardization bodies (e.g., IEEE, ETSI, ITU, 3GPP, etc.) have carried on this topic, in Europe, United States and Asia.

Section 2.2 – IEEE 802.11p based communications and **Section 2.3 – 3GPP Cellular-V2X based communications,** are offering a complete and deep technical view on the two distinct technologies (Wi-Fi based and Cellular based) that are targeting to handle the same topic of traffic safety and efficiency, while setting the scene for future autonomous vehicles. These sections are structured in an easy to follow and comprehensive manner, taking the reader from the history of development and the basics of both technologies, until the most detailed message dissemination techniques, security schemes and radio frequency spectrum harmonization procedures.

Having the chance to go deeper into each regional approach, gave me the opportunity to observe the impact on technology evolution of different social development patterns in each major region and the values that each one of them are promoting. Some regions are valuing safety and stability, while others give more weight to the economical side of this subject and how efficiently it could be monetized, or other regions are just purely technology driven, looking to always innovate and optimize for a better and safer future. Such fragmentation is most of the times counter-productive, since it hinders a constructive global approach, efficient resource utilization and global deployment of an optimized technology that follows a unique set of standards.

This has been the case of the, now called, legacy V2X, based on IEEE 802.11p standard (e.g., DSRC and C-ITS), which has recently suffered a quick decline and lost the support of the industry. The main reason is that it took much more than 10 years to reach maturity and additionally, it was not built upon a single global set of standards, although each region developed their own particularities, which transformed it into a difficult to adopt technology on a global scale. Each region has followed their own set of policies and guidelines, driving the development of technology into different directions which were not compatible with each other. The simple reason that the industry backed up this legacy technology in the beginning, is because it was the first available into the market accepting the challenge of improving traffic safety and efficiency. Back in 2010, it was promising improved efficiency of traffic, higher safety of traffic participants, opening the path towards autonomous vehicles. Each standardization body from major regions tried to solve the challenges of innovation in their own way, accepting new techniques into the standard without a thorough testing and qualification of pros and cons, and most importantly, without putting much value on compatibility and interoperability of each technology developed in each region. This was a recipe for disaster, which happened once an alternative was available, coming from 3GPP, the standardization body that developed the entire cellular standard sets from 2G to 5G and continues to efficiently innovate towards 6G and more.

Later, the major OEMs in the Automotive industry (like Volkswagen, Cadillac, BMW, Mercedes, Audi, and the Asian car manufacturers), together with chipset manufacturers, integrators and Tier-1 device makers, organized themselves in consortiums and alliances (e.g., C2C-CC, C-Roads Platform, Amsterdam Group, CEF, CEDR, ASECAP, POLIS, etc.), for steering the development and evolution of technology towards a common path, pushing the standardization bodies in different regions for harmonization of frequency bands, transmission-reception techniques, safety and security policy rules, and more efficient message dissemination procedures. The benefits were immediate, and it proves in fact that a harmonization process on a global scale was urgently required. This process is still ongoing, and many challenges lie ahead, mostly due to economical and sometimes even political reasons. In some cases, the harmonization of radio frequency resources led to limitations in allocated bandwidth for each technology, like DSRC or C-ITS, therefore less services could be further developed due to the restricted RF resources and additional safety mechanisms for avoiding interferences and service disruptions from competing standards had to be developed and spend efforts and time (see **Section 2.1.3 – Radio frequency resources harmonization**).

In the U.S., governmental agencies, interested in driving and influencing the development of future technologies, stepped in, and tried to strongly steer the technical evolution and favorize one side in detriment of the other by mandating the use of a particular technology. In 2013 the National Highway Traffic Safety Administration (NHTSA) in the US mandated that car manufacturers should equip all newly produced cars with DSRC technology (see **Section 2.1.2 – U.S. standardization and industry efforts**). This desperate mandate came as a response to the fast evolution of cellular based technology, called C-V2X (Cellular Vehicle to Everything).

Few of the major Automotive manufacturers, like Cadillac or Volkswagen, wanted to be technology pioneers, and adopted quickly the DSRC and C-ITS, rebranding it to pWLAN (see **Section 2.2.6 – Commercial solutions**) or other attractive commercial names. The main reason for this quick adoption was the mandating by the U.S. Department of State of the IEEE802.11p technology for all newly produced cars in the U.S. market. After part of the industry, cellular chipset manufacturers and existing alliances protested and pushed back this mandate, the government withdraw it for letting a fair competition to decide which technology offer the optimal way of enhancing the current situation of traffic, making it more efficient and safer.

The Car 2 Car Communication Consortium (C2C-CC) and the C-Roads Platform, EU widespread association, reached a consensus to initiate, and finally sign, a Memorandum of Understanding for enabling a seamless collaboration between the state authorities, automotive industry, road authorities, and road infrastructure operators for planning the deployment of initial C-ITS services across European territory.

One of the first on the market with a stable and optimal V2X software stack, namely Commsignia, offered a completely embedded solution developed to combine the specification of all major standardization bodies, such as ISO, ETSI, IEEE, SAE or C2C-CC, into a professional communication solution with a flexible architecture. The software stack was designed as a modular framework, being evaluated, and certified within US DOT and EU C-Roads projects. This product is offering a complete connectivity solution, both as RSU (Roadside Unit) and OBU (On-Board Unit) for supporting both DSRC and ITS-G5, and promising readiness for cellular based C-V2X protocol stack.

With the release of the first set of standards in 2013, automobile manufacturers members of C2C-CC signed an agreement for the introduction and validation of the C-ITS system. Deployment plans were being drafted by the Amsterdam Group, a strategic alliance of stakeholders of C-ITS in Europe. Partners like CEDR, ASECAP or POLIS, are representing the core stakeholders of the ITS infrastructure deployment on highways and cities, providing a robust traffic management platform. Pilot deployment projects facilitate the new system introduction and performance assessment. One of the many testbeds, a trilateral C-ITS corridor that interconnects Vienna – Frankfurt – Rotterdam, has been equipped with an innovative roadworkers protection system on highways in 2018 (see **Section 2.1.1 – European standardization and industry efforts**).

In 2016, EU Commission initiated the C-Roads Platform, which targeted to interconnect and facilitate cooperation between numerous C-ITS projects around EU and various pilot tests. The C-Roads platform encouraged a cooperative assessment of current technical specifications, verifying the interoperability, delivering comprehensive reports, and propose further enhancements where technical gaps and limitations have been identified. Originally founded to support only C-ITS projects, the C-Roads platform started to support all interoperability assessments and specification enhancements within Europe. The main EU Member States that are supporting this initiative from EU commission are: France, Germany, Hungary, Austria, Belgium, Czech Republic, Finland, Italy, Romania, Netherlands, Slovenia, Sweden, and UK. Meanwhile, other EU member states have joined the platform, such as Spain, Portugal, and Turkey.

Romania contributed actively through one project co-financed by the EU commission. The main focus has been on Day 1.5 additional C-ITS services, which facilitated safer parking for trucks. This project has been completed since February 2018 and the users can take advantage of a dedicated web-application to observe the surveillance cameras and also check for free spaces and reserve a spot before they arrive. It has been integrated into a European network of certified, safe, and secure parking areas. Furthermore, studies for the construction of two other safe and secure parking places on the Rhine-Danube Core Network Corridor have also been finalized during this project. Finally, as a main deliverable, a specific ITS software command center and a mobile application have been developed, which aimed to provide to the European truck drivers essential information about free parking spaces within a safe and secure environment.

In the US, the V2X communication standardization started with the allocation of the 5.9 GHz frequency band, finally granted in 2002, dedicated for vehicle and infrastructure intercommunication. This was far ahead of the EU efforts for developing C-ITS with ITS-G5. For vehicle-to-vehicle communications the IEEE standardization body focused on one specific technology, namely Dedicated Short-Range Communication (DSRC), which is designed to support a multitude of applications and use cases and based on an amendment of IEEE802.11, namely the IEEE802.11p. The main motivation for investing in these research projects and deploying DSRC based communication devices is to enable collision prevention applications as a standard set of features that will be part of every vehicle on the road. These kinds of applications depend on high rate of data package exchanges between vehicles, and among vehicles and roadside infrastructure. The Department of Transportation (DOT) and National Highway Traffic Safety Administration (NHTSA) in the U.S. has conducted multiple studies and estimated that vehicle-to-vehicle (V2V) communications could have a positive impact in up to 82% of all crashes on the U.S. roads, with potential to save thousands of lives and billions of dollars in collateral damages and health expenses.

The US Department of Transportation (DOT)), together with major automotive manufacturers, like General Motors, Ford, Toyota, Honda, and Mercedes-Benz, have agreed to collaborate under a consortium called the Vehicle Safety Communications (VSC) project. It was intended to perform extended studies, evaluation campaigns, and testing the interoperability of various DSRC based devices. The VSC consortium project, completed in 2009, validated the feasibility and maturity of the main V2V safety applications, such as Forward Collision Warning (FCW), Emergency Electronic Brake Lights (EEBL), Blind Spot Warning (BSW), Intersection Movement Assist (IMA), Do Not Pass Warning (DNPW), Control Loss Warning (CSW), and many other (see **Section 2.1.2 – U.S. standardization and industry efforts**).

Various other test events and validation campaigns have been organized, where continuous enhancements and optimizations have been studied. More recently, the U.S. DOT and NHTSA have assessed the efficiency of cellular based vehicle-to-everything. The future will most probably reserve a path there the DSRC and cellular V2X will coexist and complete each other.

Countless field trials with commercial IEEE 802.11p based solutions have been successfully performed. One of the first and largest running trials for IEEE 802.11p based devices was funded by US DOT (in Wyoming, Tampa, and New York City). It has been run on more than ten thousand vehicles from various car manufacturers equipped with distinct DSRC device manufacturers, which implemented diversified applications.

A long-lasting technology controverse is ongoing between the initial U.S. approach, started in 2002, developed by the research institute IEEE, namely IEEE 802.11p standard, also known as DSRC, and the more recently developed technology, started in 2012-2013 and supported by the famous cellular standardization body called 3GPP. It can be clearly observed that each standardization body, from major regions with a strong economic background (United States, Europe, and Asia), tried to solve the challenges of enhancing the traffic safety and efficiency in their own way, accepting new techniques into the standard without a thorough testing, feasibility and interoperability checking process. This was a recipe for technical disaster, waste of resources, and public money loss.

The 3GPP organization, also known as 3rd Generation Partnership Program, which is the global standardization body behind the well-known cellular standards 3G, 4G and 5G, started to define the core specifications supporting the C-V2X concept in 2013, together with the Release 12 of their specifications.

IEEE 802.11p based prototype equipment started to reach into technical limitations when large-scale test deployments have been trialed. Also, the efficiency was lower when compared to the C-V2X, even from the beginnings (see **Section 2.4 – IEEE 802.11p vs. 3GPP Cellular V2X**). One of the important advantages of C-V2X is leveraging of the existing cellular network, with only software upgrades and no additional hardware required to be installed. Such advantage translates into financial savings, by not having to build from zero a completely new infrastructure for operating any IEEE 802.11p device. Realistically speaking, even cellular networks have their coverage gaps. The coverage can be further enhanced based on requirements. We must admit that it is always more efficient to start from an existing infrastructure that offers a global-wide coverage, than to build a new one from scratch for a technology that does not qualify as future-proof.

Initially, a hybrid approach has been proposed by standardization bodies, where both IEEE 802.11p and cellular V2X technologies could coexist. From a generic perspective, this seems like a fairly good compromise. When you look more in the details and analyze the amount of efforts that needs to be spent for developing all the interference cancellation and interoperability mechanisms, then it starts to become a less promising idea.

As a consequence, major automotive OEMs and Tier-1 device manufacturers that were initially focused on IEEE802.11p based technology, started to shift their balance more towards C-V2X in detriment of IEEE802.11p, forgetting about a hybrid approach. Multiple reasons made all these important ecosystem players to switch their focus, one of the major ones being that cellular V2X, supported and further enhanced by 3GPP, develops, and maintain a single set of standards which facilitate global deployments. A more efficient usage of the available RF spectrum is another main advantage of the cellular V2X, due to the far superior modulation and coding schemes used in the cellular standards, which have been highly optimized and can be considered as the most efficient and robust available until now.

Cellular V2X communication is based on a concept, initially targeted for marketing and advertising, published in earlier 3GPP releases, starting from 3GPP Release 12, completed in March 2015. This set of standards has been further enhanced and optimized for vehicle communications in Release 13, completed in March 2016. This concept was called Device to Device (D2D) communications defined as part of

Proximity-Services (ProSe). It was originally planned as a commercial broadcasting service where mobile phones in an area could receive a notification for advertisements. With an always growing interest for Device-to-Device (D2D) communications in the automotive industry, the members of 3GPP organization saw an opportunity to further develop and enhance this new capability with increasingly dedicated safety and added-value features for vehicle-to-vehicle communications. LTE D2D describes an autonomous long-distance direct communication protocol. This cellular related protocol went through continuous optimizations in order to fulfill the mature and ever stricter requirements of the intelligent transportation systems designed and deployed around the world, where IEEE 802.11p was the single player in the market.

The LTE D2D advanced functionality in 3GPP Release 13 was further augmented and optimized in Release 14, published in March 2017, to address the stringent requirements of the automotive industry and overcome the performances achieved by the competing technology based on IEEE802.11p. This is how the PC5 interface, also known as SideLink at the physical layer, for direct V2V communication came to existence. This interface has been further augmented for vehicular scenarios, specifically to address high velocity use cases with speeds up to 250 Km/h, or 500 Km/h relative speed, and scenarios where high density of devices was essential, for dense urban use cases.

Take into consideration both V2X technologies, C-V2X and IEEE802.11p, vehicle manufacturers are demanding a future proof and interoperable wireless technology, with an evolution path towards next generation of vehicle-to-everything (V2X) communications. The existing technologies, namely ITS-G5 and LTE-V2X, are not interoperable, therefore the decision of the car manufacturers is difficult. The common objective of both technologies is to increase traffic safety and efficiency for a safer and cleaner environment on a global scale. Thus, interoperability plays a key role, considering the IEEE 802.11p capable vehicles are already on the roads. There shall be a single concept that integrates both, existing and new, technologies to harmonize the deployments and safety features, having the common safety and environmental goals in mind and not only compete from an economical perspective.

The unification of existing technologies into a harmonized solution, governed by a single set of standards, is the main objective of the industry. Continental AG has accepted this challenge back in 2019 and won a project for harnessing the advantages of regular 4G, DSRC and C-V2X technologies [2]. The hybrid solution proposed by Continental integrates cellular technologies for 4G and 5G network access to enable all content on the infotainment system, together with the mature solution of Dedicated Short-Range Communication (DSRC) and the new rising star of vehicle to everything communications, namely Cellular-V2X (C-V2X). This solution comes to help the Tier 1 vehicle manufacturers to overcome an impossible challenge until now, when embedding V2X technology in new cars around the global. Considering that technologies have evolved differently around the world, due to the influence of standardization bodies, research centers and economic reasons, the task of deploying a flexible solution around the world has become a tough challenge. Various regions, especially the United States, prefer DSRC based solutions, European region prefer the ITS-G5 based solutions and others, like China, tend to invest more time and resources in the upcoming Cellular-V2X standard. With Continental’s hybrid V2X solution, all these challenges are addressed, and a unique solution is proposed that uses the same hardware and a flexible software platform to support existing communication standards, thus reducing cost and complexity of a global scale integration of V2X communications in newly produced vehicles around the world.

Section Error! Reference source not found. **– IEEE 802.11p vs. 3GPP Cellular V2X** delivers a thorough comparison between Wi-Fi based and Cellular based standards, assisting to take clear conclusions regarding the most optimal technology for the future of V2X communications.

Various independent associations, alliances, and research institutes, together with technical universities around the world have conducted assessment studies where both technologies have been compared in a fair and transparent contest. Leading technical universities in Germany, France, Spain, and Sweden, have conducted feasibility studies, and published numerous reports on this important subject. A substantial number of reports have come to an agreement that C-V2X is a better suited technology for ITS applications, which is future-proof and has the potential for global deployment. Additionally, 3GPP organization is maintaining and continuously enhancing the specifications, together with the specifications for the 5G and 6G cellular networks of the future. Towards the end it makes an introduction for the directions and evolution, setting the scene for the future.

Section 2.5 – Evolution of radio access technologies for V2X communications, is introducing the brand new IEEE802.11bd (evolution of IEEE802.11p) and the New Radio V2X (evolution of C-V2X that was 4G cellular based). Both radio access technologies, namely 802.11bd and NR V2X, include major evolutionary and revolutionary transmission-reception techniques and safety message dissemination mechanisms compared to their respective predecessors. These are expected to significantly enhance key performance indicators such as latency, throughput and reliability that are essential for a robust system to expedite wireless safety and efficiency traffic applications.

Commercial large-scale deployments of NR V2X are still far in the future. There are still several technical and feasibility challenges to be resolved, however the progress is consistent and the support from the public sector and the industry is growing stronger. HORIZON 2020 is a program supported by the EU commission together with 5GPP organization. The H2020 program is funding several trial corridors for certifying seamless cross-border connectivity with 4G and 5G for autonomous vehicles that enable Cooperative Connected and Automated Mobility (CCAM) features.

5G-MOBIX is an ongoing H2020 project funded by EU which aims at developing, testing, and optimizing automated vehicle functionalities using 5G core specifications for technological innovations along several cross-border corridors and metropolitan trial sites. Numerous projects have been carried to secure autonomous driving on the main European traffic routes as well as China and Korea, with 5G V2X prototype equipment. The expected benefits of 5G will be assessed during trials on 5G cross-border corridors (such as Greece-Turkey and Spain-Portugal) and in various EU countries as well as in China and Korea, which are participating actively in the development of 5G autonomous driving.

Error! Reference source not found. **Hybrid V2I solution proposal**, describes in detail an original hybrid solution for signaling and warning of hazardous road sections. The goal of this thesis is to propose the proof of concept and an innovative solution that could become a foundation for a safer and future-proof transportation system in Romania.

The proposed solution consists of three major components that are interconnected over cellular commercial networks:

- **Smart Road Side Unit (S-RSU) –** mounted inside or attached to existing road side warning signs deployed wherever road works are being conducted
- **Road Side Unit Warning System (RSU-WS) –** mounted as an after-market product inside the vehicle and constantly measuring the distance to the S-RSU
- **MQTT Broker –** the main logical communication channel between the S-RSU and RSU-WS. A cloud platform built as a client of the MQTT broker could act as a management and surveillance platform.

The section 3.3 gives a thorough view of the high-level block diagram and all the logical components. The pseudo-code of each function developed for the microcontroller, that is orchestrating the entire operation of both S-RSU and RSU-WS, are described in detail. The description of the pseudo-codes was preferred, instead of the C++ code description, for offering the freedom of choosing any programing language adequate for reproduction of such communication system.

Such concept could be further expanded to include other vital features, integrated into the vehicles produced in large scale, or redesigned for other verticals.

Error! Reference source not found. **Modeling the wireless channel and an enhanced cruise control unit**, describes the modeling of the wireless channel for a chosen scenario and analyzes the total signal response at the receiver side. In the second part it is proposed an enhancement of cruise control unit through modeling using MATLAB. Octave has been used as the simulator environment for modeling the scenario, where the result has been plotted for visual analysis.

This chapter introduces a set of algorithms and simulations that describe a simplified model of a wireless communication system. The algorithms have been adapted for a transmitter-receiver model with a reflecting wall. The main analysis is done on a signal waveform that returns from the reflecting wall and received by the vehicle. Implementation and simulation have been developed using Octave, which is a high-level programming language designed for numerical computations. Octave is part of GNU Project, therefore it is a free software that is used in academic environments whenever graphical interfaces are not necessary for simulation projects.

The second part of this chapter describes the results of the simulation. The result has been plotted for visual analysis and to validate that the initial calculations based on the mathematical model. This demonstrates that the real calculation of the receiver's response to the signal waveform matches the visual plots obtained through Octave. This validation confirms that the entire transmission-reception solution is functioning accurately, and it is dimensioned correctly within the chosen scenario.

Further, an introduction to various system controllers is made to model and enhance a regular cruise control unit that the majority of modern vehicles are equipped with. These mathematical models are then modelled with MATLAB. Numerous simulations are run, and results plotted using MATLAB Simulink. Multiple comparative analyses of the models have been made for identifying the optimal one. Finally, an innovative combination between a Fuzzy controller and an enhanced Finite State Machine has been proposed to drive a cruise control unit of a vehicle.

The chapter concludes with a validation of the proposed solutions, by running a series of scenarios and generating comparative plots. These have been used for a comprehensive analysis of the entire system behavior and confirmation of correctness of the modelling and integration of the proposed system.

Error! Reference source not found. **Personal contributions and future research proposals**, offers a clear summary of the personal contributions brought into this paper, both from a research methodology point of view and also from a solution driven side. The research methodology and compilation of all facts about the current status of the research, together with technical gaps identified during my study of this domain, have been clearly presented in the first part of this chapter.

The second part offers a high-level view of the practical application proposed for this thesis, clearly explaining every building block and the final purpose of this hardware application. The conclusions and future directions of research are further presented, in order to validate that all objectives set in the beginning of this paper have been successfully achieved.

An analysis of the final model proposed for an enhanced cruise control unit with a Fuzzy controller and an FSM is presented. The advantages are highlighted in a comprehensive manner, making comparisons between multiple scenarios and implementation modes, finally pointing towards potential direction of improvements with further research on this topic.

Towards the end of this chapter, it is presented how the proposed concept design could be further expanded and enhanced with new features and peripherals. This concept, with minor changes and adaptations could be re-purposed for other industries. The surface mining industry, wood exploitation sites or construction sites that expand on large territories could also take advantage of similar approaches with minimal adjustments for a flexible and versatile platform.

1.2 Research methodology

This PhD thesis contributes to the applied scientific research on the topic of traffic safety. This research is helping to set the steppingstones of autonomous vehicles, where driver security and other traffic participants safety is imperative.

The main objective of this PhD thesis is to bring in a positive impact on the matter of traffic safety in Romania. Living and traveling in various locations around the world, has given me the opportunity to observe how advanced and aware of the traffic safety topic other countries and regions are. Combining these observations together with my technical background in the electronics and telecommunications scientific domain, and with my expertise on the Internet of Things (IoT) sector, throughout my work experience, has given me a unique opportunity to propose a practical solution for enhancing the traffic safety in my home country.

The following objectives have been the building blocks for my PhD research thesis:

- **Objective No.1 – Identify a problem with a major social impact, namely traffic safety in Romania**

Observing various studies on traffic safety in Europe, conducted by the European Commission and their affiliated organizations, and analyzing closely to the results of these studies, have helped me to pinpoint the main objective for my research. The motivation behind choosing this topic and the results of aforementioned studies is detailed above, in Section 1.1.

Addressing such a sensitive and important topic for Romania seemed like an interesting task that I embraced when I finally decided to pursue getting my PhD degree. Knowing that I could bring a useful solution to the identified problem and to my home country, and in the same time research and learn so many new and interesting information about the latest technologies developed in this direction, gave me the energy and motivation to subscribe for such a challenge.

- **Objective No.2 – Compile a comprehensive literature review over the current research status and identify technical gaps to contribute with my research**

As the traffic safety problem in Romania has been identified, a further thorough study of the specialized literature has been conducted. Starting from the beginnings of V2X concept definition, back in 2002-2003, until present days, a detailed analysis of the different V2X specification definitions and implementations has been conducted. As the result of this analysis, a comprehensive and uniquely structured report is presented in Chapter 2. This chapter takes the reader through the history of V2X, carries him in various economically strong regions, like U.S., Europe, and Asia, to present various evolutionary paths of the V2X technology, and helps to set the stage for the upcoming new technologies that 5G and 6G are bringing on this particular topic of traffic safety augmentation.

As the technical developments and specification definition progress went on slower than predicated by standardization organizations and the industry, I wanted to propose a hybrid solution with the existing cellular technology would address the well know problem of traffic safety with a significant impact on the short term.

This objective has been achieved by compiling a uniquely structured literature review, that offers an eagle-eye view of all the relevant regions in the world that contributed to the innovation and optimization of the existing and upcoming V2X technologies.

- **Objective No.3 – Propose an optimal and future-proof solution for enhancing traffic safety**

The ultimate objective of this PhD thesis is to propose a solution to a major concern in Romania, namely being on the last place with regard to the traffic safety. Knowing the current context of Romanian traffic situation and road infrastructure conditions, where continuous roadworks, modernization and expansions are happening, I have proposed a hybrid solution to address these problems.

This solution is using the existing cellular technology of 2G / 3G / 4G, where there is no further requirement of installing any additional infrastructure equipment. It is a scalable and adjustable solution, that is agnostic to the communication technology (2G, 3G, 4G, 5G or upcoming 6G). This solution addresses especially the dangerous road sections, where maintenance, consolidation or modernization of roads are being performed. In numerous circumstances, the lack of proper signaling of these road sections leads to incidents and accidents, with significant injuries, material damages, and ultimately, human lives are lost.

To achieve this objective, I utilized several hardware components, and I developed adequate algorithms and source codes for operating the microcontroller and all the peripherals attached to the designed system for enhancing the traffic safety (see Chapter 3).

- **Objective No.4 – Propose integration of V2I communications into a Cruise Control unit**

The solution proposed and achieved by previous objective can be integrated into existing Cruise Control units that modern vehicles are equipped with. This further step would offer a complete solution with smart road signs, an infrastructure for broadcasting warning messages and a viable warning system integrated into vehicles for efficient driver notification, thus making the traffic safer.

This objective has been achieved by proposing an enhanced Cruise Control unit, which integrates a Fuzzy controller and a Finite State Machine that governs the entire system. This solution has been modelled using MATLAB Simulink and numerous scenarios have been run for validating the functionality of the proposed system.

- **Objective No.5 – Propose a model, simulate and validate the solution**

Proposing a technical solution would not be sufficient, from a scientific research point of view, without thorough validation of the solution through a mathematical model and numerous simulations. For achieving this objective, I derived a new mathematical model that is adapted for my proposed application.

This mathematical model defines the basic functions of a transmitter-receiver wireless communication system, where the receiving side picks up the direct signal waveform and the reflected signal waveform from a reflecting wall, or any other object in the environment. The primary analysis and simulation are made on a signal waveform that is transmitted from a signal waveform generator, which is an unmodulated sinusoidal signal. The receiver will acquire the direct signal from the transmitter together with the reflected signal waveform that returns from the reflecting wall.

The implementation of the newly developed mathematical model, the development of necessary algorithms, and the simulation results have been achieved by using the freeware software Octave. This is a powerful simulation tool, using a high-level programming language, designed for complex mathematical computations. This tool is successfully used by countless universities and research centers, as an alternative to the well-known MATLAB simulation environment, which can only be used under license.

The plotted results of the simulation help to validate the mathematical model (see Section 4.2) and together with the prior calculations done to verify the proposed solution (see Section 4.1), help to achieve this objective and make sure the model is correctly dimensioned and developed.

The enhanced Cruise Control unit proposed in Section **Error! Reference source not found.** has been successfully validated in three different scenarios, each scenario with two different input sets for comparative analysis of the expected behavior.

- **Objective No.6 – Draw conclusions, propose future enhancements, and offer alternative domains where this solution could be implemented**

The thesis finalizes with a set of conclusions related to the proposed solution and the current status of research. It then sets several ideas of enhancing the proposed solution with multiple implementation and further development ideas. A comprehensive compilation of the theoretical and practical contributions is described in detail in Sections 5.1 and 5.2. These sections describe the idea of grouping the technologies based on their regional evolutionary path and observing how various standardization bodies are researching and innovating towards an optimized and safe to deploy specification set that shall be adopted by device manufacturers and application developers worldwide.

Furthermore, sections 5.4 and 5.5 help to conclude on future direction of research and other ideas of implementation for the proposed practical solution.

Revealing throughout Chapter 5 all the conclusions, personal contributions, and future directions of research, have helped me to achieve this last objective of my PhD thesis.