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,

Design and Evaluation of Ad Hoc Routing Protocol,
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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 harmonization at the European level.* Each national historical operator actually generally imposes its technological choices at the level of its state. In addition, since the telecommunications infrastructure is a dedicated infrastructure, it also remains subject to management under the sole authority of the railway operator. It is thus easier to reach a consensus at European level with one decision-maker per state (the railway operator) rather than in a context where several actors with divergent interests have been involved. The challenge will have to be addressed differently for a global infrastructure including roads for cars, as it will involve a myriad of national land transport operators (rail, road, etc.), not to mention telecommunications operators also concerned by any infrastructure deployment in the public domain. Additionally, the latter can also comprise numerous service providers and a large variety of clients, ranging from government services to the general public, including companies of the transport sector, of which car manufacturers. This multiplicity of decision-making partners, combined with the pressure of the very varied expectations of the different beneficiaries with heterogeneous profiles, presupposes that the process of harmonizing technological and normative choices will be far more complex in the context of a global infrastructure for the land transport of the future.

– *A relative de facto insensitivity to intermediate technological developments.* Indeed, the colossal investments required to equip railway infrastructure on a European scale mean that, on the one hand, the technologies chosen have to be sufficiently mature to guarantee their sustainability, and, on the other hand, that they be need to be maintained for as long as possible over time to amortize costs. For example, it is interesting to observe that GSM-R is still being deployed on railway lines, although the end of the maintenance of the GSM technology has already been announced by manufacturers. Meanwhile, the general public has shifted through 3G, then 4G and now 5G. It will probably be necessary to wait for the generalization of this latest disruptive technology for the rail sector to start new investments in Europe to achieve a technological leap, while the respective implementation of 3G and 4G has been systematically accompanied by new applications for drivers through smartphones and on-board vehicle computers. A future global infrastructure for vehicular communications is likely to be more sensitive to technological developments. It will therefore have to be designed to allow for faster and less costly adaptation compared to what has been observed in the rail context.

1.3. The contribution of ad hoc communications to vehicular networks

Unlike rail, the problem arises differently for vehicular communications within the road environment. The lack of dedicated communication infrastructure already deployed on a large scale, similarly to GSM-R in the rail sector, leaves all options still open. Admittedly, the coverage of most urban areas and the surrounding area by communication networks open to the public ensures that vehicles have access and performance adapted to their traffic. The even greater performance, especially in terms of speed and latency, advertised with 5G as well as the extension of coverage that the latter will provide outside cities, since it will also cover agricultural and industrial areas, suggests that vehicles will be able to benefit from access to these infrastructures on more sections of the road network. Nevertheless, long stretches of uncovered roads will always exist, especially in sections located far from cities and human activity, unless dedicated infrastructure is deployed. However, we have already pointed out the difficulty for reasons of economic profitability and because of the absence of a central operator capable of assuming these portions for strategic reasons (safety, transport network efficiency), as has happened in the rail sector.

This situation implies the need to integrate into the coverage strategy of any future communication system, considered for land transport, solutions making it possible to extend the coverage and continuity of services provided to vehicles in the areas which lack them.

First, there is the possibility of moving toward shared infrastructure with other land transport networks, especially in areas where roads without public coverage cross the coverage areas of the infrastructure dedicated to rail communications. This strategy could become a real possibility because the shared infrastructure would reduce costs for the rail operator without necessarily compromising safety and security, as the new network infrastructures (4G/5G) can ensure that the complete separation of the traffic of railway applications with regard to other traffic is guaranteed.

Second, ad hoc V2V communications can be resorted to and organized in such a way that most services, including cooperative applications that only need the participating vehicles, can continue to operate even if there is no connection to centralized servers due to lack of network access. The mobile ad hoc network (MANET) paradigm has been explored since the 1990s and its first extensions to the vehicular environment (*vehicular ad hoc networks* (VANET)) emerged in the 2000s. Many approaches have been proposed, namely, involving adapted communication technologies and specific routing protocols, applications and architectures. A more detailed state of the art on these different aspects will be proposed throughout the various chapters of this book, the idea here being to highlight the issues that explain both the interest and the difficulties related to the deployment of this solution on a large scale when a large part of the scientific community has been addressing it for almost a quarter of a century.

1.3.1. *Maintaining connectivity and service continuity*

The fundamental interest of ad hoc communications is that it allows communications between vehicles to be possible where the only alternative left by the lack of infrastructure is that there are none at all. Therefore, when two arbitrary vehicles are within communication range of each other, they can detect each other and exchange information.

It is often argued that such communication, only possible in direct connection and within the scope of communication, can be regarded as anecdotal at best. When two vehicles are separated by a distance greater than the communication range offered by current wireless technologies, a distance greater than three to ten times the safety distances, currently defined by road traffic rules in most European countries, does in fact separate them. Consequently, the fact that they cannot communicate beyond that distance does not affect the exchanges necessary for avoiding immediate danger between them. As a result, all emergency notification services (emergency braking, roadway obstacle, blocked lane, slowdown, etc.) can be maintained through these ad hoc communications.

Most vehicle services are offered by providers who operate from servers, and therefore require access to a network infrastructure. In this respect, these applications will follow the evolution of applications provided in other areas, that is, they will evolve toward versions capable of supporting operation in non-connected mode for a significant period of time and of being updated in a timely manner when they are reconnected to the network. These services are generally less often necessary for safety, but rather used for practical needs (navigation, traffic event notification, traffic management, advertising, etc.). It is therefore the responsibility of each service provider to evaluate the opportunity to develop this slightly connected version capable of operating in degraded mode. Users and public bodies in the automotive world are the only ones who can create a balance of power to encourage them to do so.

1.3.2. *Cooperation and performance improvement*

Several services are increasingly being developed on a cooperative basis. For example, a current widely-used application retrieves notifications generated by all participating users at the level of the publisher's servers, which determine their relevance and plausibility, and then notifies all users located in the area of interest. It is clear that such an application could proceed between vehicles operating in the area of interest, including outside the coverage of any network infrastructure, if the publisher provided for a degraded mode of operation in which the verification of consistency and plausibility could be carried out in a distributed manner directly by the vehicles involved in exchanging through ad hoc communications.

Other so-called cooperative applications, two in particular which will be presented in detail later in this book, have been designed to operate essentially and precisely on this ad hoc communication mode between vehicles. Unlike the emergency alerting services discussed earlier (section 1.3.1), which are essentially based on single-hop operation, in a V2V fashion, cooperative applications may require the organization of multiple vehicles into disjointed groups or the relay of some V2V messages over multiple hops. Under these conditions, it is no longer simply a question of relying on ad hoc V2V communications, but of detecting possible groups of vehicles and organizing them in such a way as to allow these forms of exchange in cooperation. This task is typically accomplished by routing protocols as part of a feature referred to as "self-organization". Chapter 2 of this book will revisit this aspect in great detail.

On the one hand, the distributed nature of this self-organization requires the vehicles participating in the same group to all be on the same communication channel, at least for *broadcast* exchanges, particularly those that allow them to detect each other. Advanced mechanisms make it possible to organize communications on different channels for certain vehicles, but overall, this operation, which results in an increasing number of vehicles on the same communication channel, is sometimes the cause of performance problems. This observation is often mentioned in criticisms leveled against the use of ad hoc communications in various applications, especially for vehicular networks. Any mechanism that would lead to an improvement in this performance would therefore be beneficial to the functioning of cooperative applications. A large body of work has been carried out on more efficient self-organization, quality of service (QoS) or quality of experience (QoE) in mobile ad hoc networks in general, and vehicle ad hoc networks in particular contribute to progress in this direction.

On the other hand, when a set of vehicles is self-organized outside of the coverage area of any infrastructure and these vehicles are able to exchange efficiently in cooperative applications, the question is: what should happen to this group when it integrates an area covered by a communications network infrastructure? Actually, if the group restricts its exchanges within the framework of the structure resulting from self-organization, all associated traffic will not be addressed by the network infrastructure, which will thus keep its capacities for processing further traffic. By generalizing this observation, it can be intuitively observed that maintaining self-organized groups that correctly operate via ad hoc communications, including in areas covered by a network infrastructure, can improve the overall performance. This naturally assumes that the exchanges of the self-organized group do not take place on channels used by the infrastructure for other services, which would cause interference that could degrade part of the performance. This problem can be solved by the ability of the network infrastructure to detect channels used by self-organized groups and avoid assigning them to other exchanges. The integration of self-organized groups via ad hoc communications into a broader framework including network infrastructure in the same area is not covered in this book. This subject will be briefly revisited in Chapter 6 where we discuss the perspectives associated with the work presented in this book.

1.3.3. *Communications security and auditing*

Despite the performance problems mentioned (section 1.3.2), the ad hoc V2V mode of communication, more generally the direct communication between terminals (*device-to-device* (D2D)), has been integrated into the architecture of communications network infrastructures, which includes 5G. This choice seems to confirm the usefulness of this mode at least for some specific use cases that are important enough to be taken into account. Nonetheless, contrary to the conventional understanding of ad hoc mobile networks where participants can freely join and leave the network, as long as they are equipped with a compatible wireless interface, the 5G V2V and D2D modes require each terminal to be previously authenticated with an operator before it is allowed to carry out exchanges in direct mode.

This is again an important issue that partly explains the difficulty of ad hoc communications to emerge in certain critical applications, including road vehicle networks. As a matter of fact, the emergence of communication systems dedicated to vehicles, driven or autonomous, allows for a variety of applications ranging from remote control to on-board leisure applications, including driver assistance systems designed to reduce road hazards. Some of these applications may have direct actions on the vehicle (emergency braking, trajectory control, etc.). In particular, emerging so-called cooperative applications enable vehicles to exchange information about their perception of their environment, their location and notifications of potential hazards encountered on the road (Rivoirard et al. 2018). Any V2V or V2I communication, or simply vehicle-to-everything (V2X), becomes a vector by which an actor, software program or human, can deceive the driver, human or software, of a vehicle with detrimental consequences for third parties. A vehicle application made available by an identified third party (car manufacturer through the on-board computer, a service platform through the smartphone or a connected box provider) usually relies on V2I communications. The information provided to the vehicles is guaranteed by the identified third party. In the event of damage, the technical means for investigation are provided for by the audit procedures of the car manufacturer, the telecommunications operator or by the third party identified as the application publisher. On the other hand, for so-called cooperative applications, the service is developed and provided based on direct exchanges between vehicles by way of V2V communications. Every vehicle potentially becomes a service provider or consumer with respect to this application. These exchanges, which are not controlled by a regulator, decrease the ability to identify third parties that could disrupt traffic. The lack of an identified third party centralizing and verifying the consistency of the data disseminated by the application increases the risk of spreading false information.

Several studies address this problem and propose solutions for the distributed management of identification for authentication, anonymity (via pseudonyms in particular) and reputation in order to assess the credibility of notifications. Similarly, for previously identified vehicles, in particular with a 5G infrastructure, it is obviously possible to find the identity of any vehicle that has sent a notification. However, when the exchange is carried out through an ad hoc communication, and has therefore not passed through the operator's equipment supposed to keep track of it, how can the content that has actually been exchanged be found in the event of an audit? Many studies have recently been proposed in order to create forgery-proof distributed ledgers, in particular through the use of specific *blockchains*, in order to organize the preservation of the trace of V2V or more broadly D2D exchanges.

These questions are irrelevant with respect to the objectives of this book, but they highlight issues that partly explain the fact that ad hoc communications did not emerge earlier in real-life concrete applications for vehicular networks.

1.3.4. *Technological evolution and depreciation*

Contrary to the remarks made about the rail network, the evolution of vehicles in road traffic places them for the most part in areas covered by the network infrastructure for the general public. It should also be noted that most of the applications for drivers were first provided through their smartphone or through the on-board computer of their vehicle, which is now mostly equipped with the same operating systems as smartphones. Intuitively, it can be said without taking too many risks that the technological evolution of network equipment embedded in vehicles will naturally follow that of consumer equipment, which in turn accompanies that of the network infrastructure of the operators. As a result, depreciation management will naturally follow that of the operator, which is clearly guaranteed as one of its priorities. It is therefore unlikely that this will lead to developing road vehicular networks with the technological gap observed today between the infrastructures of the network of operators (4G/5G) and the dedicated infrastructure deployed in the rail context (GSM-R). The involvement of the rail sector in a shared infrastructure, as long as guarantees about safety and security are given, in particular through guaranteed capacity and a complete separation between its dedicated network and the general public network within the shared infrastructure, would allow it to benefit from the same advantages in terms of evolution and depreciation.

1.3.5. *European harmonization*

Following the harmonization of European national rail traffic management systems through ERTMS, approximation has been initiated and certain phases are already operational in the harmonization of vehicle identification and information exchange systems. Insofar as the movement of vehicles is free between the different European territories and that the transfers of mobile device technology between European operators are now virtually transparent and at no additional cost, it is conceivable that applications and services provided from a territory can be ensured in the same way after crossing a European border.

Several European projects have been focusing on tasks that include this harmonization of services and applications, first between the various motorway operators and French car manufacturers, and then in larger consortia at European level. This subject also falls outside the scope of this book, but mentioning it makes it possible to bring forward the need for such considerations in the design and evaluation of a future communication system for all land transport.

1.4. Conclusion

Throughout this short introductory chapter, we have identified some of the issues surrounding ad hoc communications for the road. Despite the fact that some of them are not addressed in detail because they are unrelated to the scope of the objectives of this book, their mere mention facilitates a partial understanding, on the one hand, of the interest and, on the other hand, of the difficulties that arise by the adoption of ad hoc communications in effective vehicular networks despite a research background of a quarter of a century.

The experiment of communication networks for the railways, as the first full-scale experiment on a scale comparable to the road network in a given area, has shown some facilities; this is the case in decision-making in particular, which at the same time underlines the extent to which it could otherwise be more complicated in the context of road vehicle networks. On the other hand, it has also resulted in identifying the advantages of these networks, which should more easily integrate a shared infrastructure with other consumer services, better support changes and incur fewer costs.

Of all of the aspects developed in this chapter on ad hoc communications, the only aspect that will be developed in detail is the self-organization of vehicles and communications in order to be able to support cooperative applications when no communication infrastructure covers the area where the vehicles are traveling.

1.5. References

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