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First published 2024 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

ISTE Ltd
27-37 St George's Road
London SW19 4EU
UK

www.iste.co.uk

John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

www.wiley.com

Library of Congress Control Number: 2024936174

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-78945-180-1

ERC code:
PE6 Computer Science and Informatics
PE6_2 Distributed systems, parallel computing, sensor networks, cyber-physical systems
PE6_7 Artificial intelligence, intelligent systems, natural language processing
PE7 Systems and Communication Engineering
PE7_8 Networks, e.g. communication networks and nodes, Internet of Things, sensor networks, networks of robots

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Preface

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Automated vehicles could eventually reduce greenhouse gas emissions from transport and improve road safety and traffic flow. However, its safe implementation will require a high-performance communication system that enables vehicles to obtain information from their neighbors and from the infrastructure, such as lane changes, the presence of obstacles, diversions and extended perception.

Cooperative Intelligent Transport Systems (C-ITS), designed to enable these exchanges, will therefore play an essential role in the advent of the automated and connected vehicle. However, their deployment in a highly constrained and mobile environment could prove problematic in terms of guaranteeing quality of service (QoS), as well as the reliability and security of exchanges.

In response to these problems, this book presents new solutions for managing and controlling performance and security for C-ITS. After two introductory chapters presenting the concept of local interactions and the current development of use cases for C-ITS, this book will explore various ways of optimizing the control and management of C-ITS: hybridization of access technologies (cellular, ITS-G5), use of new tools (e.g. artificial intelligence), etc.

May 2024

Part 1

Introduction to Cooperative Intelligent Transport Systems

1

Local Interactions for Cooperative ITS: Opportunities and Constraints

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1.1. Introduction

Since the advent of wireless communication and its integration into consumer devices, the concept of intelligent environment or pervasive application has emerged. The ability to communicate with all objects in our immediate environment makes it possible to take information or trigger actions. Information collection feeds a context that applications take into account to adapt their behavior to the situation.

For this type of application, direct interaction with objects in the environment greatly facilitates matters, since it is not necessary to rely on a precise location and database to associate information (or objects) with this location. If we need to know the room temperature, all that is needed is to discover a temperature sensor and query it directly. Acquiring the same information when a server is in charge of collecting and exposing the building's temperature data firstly implies discovering the server that has the information at its disposal, then dialoging with it to retrieve the temperature of the room in which the sensor is located, and finding consequently a way to determine that the location is necessary. The machinery to be put in place is much more complex and yet it seems more intuitive, as the majority of the industry has been built on this model.

The difficulty when it comes to building services on direct (we will also use the term “local”) interactions is that this implies standardizing the method of communication, the frequency (or frequencies) used and the message format. For road or city applications, it is therefore necessary to bring many actors to agreement, and to impose choices on the entire ecosystem.

Direct interactions are widely used today for service discovery; for example, Wi-Fi devices continuously scan all frequencies used in the 2.4 GHz and 5 GHz bands to determine if there is an access point available in the environment. The presence of such an access point in no way indicates that the terminal will know how to connect to it, and even in the case where it is able to connect, whether it will be able to obtain a service (an Internet connection). The other technology widely used on consumer terminals is Bluetooth. Again, part of the terminals expose their presence by regularly sending messages at a determined frequency. All Bluetooth devices in proximity are able to see these messages and determine whether or not they know the correspondent. They can then either establish a connection to perform the service (e.g. hands-free kit) by taking advantage of the keying material previously established during pairing, or ask to perform a pairing, which requires the user’s intervention.

It should be noted that even when the two correspondents know each other, whether via Wi-Fi or Bluetooth, the discovery and connection establishment time frame is far too long for services with significant time constraints. We will return to this when we examine how the specificities of ITS-G5 make it possible to significantly reduce the time required to exchange information for road safety-related services.

In the second part of this chapter, we will present the concept of ephemeral local interactions, giving examples of services based entirely (or partially) on this type of interaction. We will describe how the first services that will be deployed in the context of cooperative ITS (awareness) are based on this type of interaction and the advantages/constraints of this approach. Lastly, before concluding, we will explore the place infrastructure holds in the implementation of services, based on ephemeral local interactions.

1.2. Ephemeral local interactions: concept and examples

1.2.1. *Examples of services using ephemeral local interactions*

Once it has been established that the different devices in interaction use the same communication technology on a subset of frequencies well known to all, it is necessary to specify the type of interaction targeted. Indeed, we will focus more specifically on interactions where no connection is established. When two devices are in proximity, they can “see” each other because of their technology community; they have at their disposal information that is spontaneously sent by their peers without having to go through the time-consuming establishment of a connection. When the communication technology has a fairly short range, simply being in communication and seeing a device gives an indication of co-spatiality that can form an integral part of the service. Therefore, when a telephone receives an advertisement on one of the three Bluetooth Low-Energy (BLE) channels, it knows that it is in close proximity to the tag whose identity is transmitted in the message, in addition to the information contained in the message itself. In a supermarket, the reception of its advertisements makes it possible to locate the mobile as long as the service provider has the precise placement of the tags in the store at its disposal. However, tags can also directly send information that may be used by the smartphone itself, such as a price, promotions or a link to the page describing a product.

Within the framework of the *TousAntiCovid* backtracking application and other mechanisms for identifying at-risk contacts, developed in the context of the Covid-19 pandemic, this co-spatiality property was used to identify transmission risks (Roca 2022). The complexity of the application comes mainly from the need to protect the privacy of users, while ensuring contact identification that is as accurate as possible. It was therefore necessary to avoid storing the list of contacts but to transmit within the advertisement messages the information required to make it possible to determine a posteriori whether their smartphone had been in contact with that of a contaminated person.

The case of contactless payment applications is rather different, since it instead involves establishing as secure a connection as possible to carry out a monetary transaction. It is therefore absolutely necessary to ensure that we are faced with the right device, and to prove that a valid transaction has taken place. However, the co-spatiality property is used to ensure that the payment card with which the transaction is carried out is in immediate proximity to the payment terminal. NFC (Near Field Contact) technology has been specifically adapted to reduce range and impose “near-contact”. The operation of radio transmissions makes this work quite complex because of the propagation of waves in the frequency bands used. It poses security problems, since it makes it possible, for example, to use relays. It then becomes necessary to go beyond controlling the transmission power to limit the range and to very finely control the transmission time, which also depends on the distance; this makes it possible, when it is excessive, to detect an attempt to relay the signal.

Prior to the emergence of the Bluetooth Low-Energy (BLE) version, applications used RFID technology, which has the great advantage of being able to install devices in the environment at very low cost, capable of "responding" to a request and sending previously configured data. This is generally a simple unique identifier, relatively similar to that of eBeacons in BLE. These RFID tags also have the property of being passive most of the time and of using the energy of the reader, which lights them up to wake up and respond. They therefore do not require a battery but are, however, inactive as long as they are not lit up. Readers also need to consume a fairly significant amount of energy to power the tags remotely.

In the different examples that we have seen, local interactions are essentially used to transmit an identifier, which makes it possible to establish our position by referring to prior knowledge of the position of the various devices. Richer applications make it possible to transmit information that the correspondent can directly use and that is most often linked to the position of the sender (a URL describing a product). This somewhat removes the need to maintain a geographic information system (GIS). In the case of BLE, this information is transmitted regularly, whether or not there is a correspondent to listen to it and to do something with it. The information broadcast in this way forms part of the environment and enriches it. The outlines of what we will call "ephemeral local interactions" are given below.

1.2.2. *Characteristics of ephemeral local interactions*

The first characteristic of local interactions is that they are established in the event of a *close contact* supported by a short- or medium-range wireless communication (BLE, NFC, RFID, ITS-G5, etc.).

The examples presented above highlight the *opportunistic* nature of these contacts. The objects considered evolve within a very large scope. They interact, sometimes ephemerally, with many other objects that they do not know beforehand. As stated above, from the outset, this excludes communication technologies requiring a form of pairing (e.g. Bluetooth) or a connection to a network (e.g. Wi-Fi or cellular networks). Indeed, beyond the fact that the necessary establishment time would often be prohibitive with regards to the applications envisaged, it is simply impossible for objects to memorize specific association parameters for each of these relationships; it would also be even more complicated to memorize the association parameters of all potential interactions beforehand.

As a result, the most suitable technologies to support local interactions are those that allow messages to be exchanged directly *without prior configuration*. It is of course still necessary to have knowledge of low-level parameters such as the type of technology, the operating frequency, the modulation parameters or security elements, as appropriate. On the contrary, the fact that the sender has no prior knowledge about the recipients (and their addresses) generally requires the use of communications in broadcast (sometimes multicast) mode, rather than specifically targeting a correspondent (unicast).

It should be noted that once the initial service discovery phase has been completed, it is possible to establish “traditional” connections in order to deepen exchanges with certain special objects. BLE enables, for example, discovery in opportunistic mode and then switching to dedicated channels in BLE or Bluetooth for more substantial exchanges. The same type of example can be envisaged in V2X, where the detection of a vehicle (or group of vehicles) on the control channel (CCH) can lead to the establishment of special relationships on a service channel (SCH), for example, to process exchanges within a platoon or to carry out a financial transaction (toll).

The characteristics of ephemeral local interactions are therefore as follows:

– The information senders and receivers (which can be the same, or two devices with different functionalities) do not know each other beforehand and – often due to mobility – change over time.

– They require prior knowledge of a technology and the channels (frequencies) used to broadcast the information. This therefore presupposes regulation or standardization.

– There is a spontaneous broadcasting of information – without prior contact – in a predetermined, and therefore most often standardized, format. This information is visible to all devices within communication range and listening.

It follows from these basic characteristics that:

– It is difficult to operate on multiple channels, since this presupposes listening to several channels successively, and significantly complicates the encounter between the sent data and a device that is potentially interested.

– This leads to a risk of bandwidth overload, since the load cannot be distributed over several channels as is done in current technologies. Therefore, applications using ephemeral local interactions must be limited to fairly simple data (we will not transmit a 4k video stream).

– Moreover, since an extension of the range is sought, more robust data encoding is often used, since it is understandable with a lower signal-to-noise ratio and therefore at a longer distance. This reduces the available throughput, so in ITS-G5 an encoding of 6 Mb/s is used, while the technology would allow 27 Mb/s to be reached.

– As generalized diffusion (broadcast) or selective diffusion (multicast) is used in most cases, we cannot have an acknowledgment system. Indeed, if the different receivers had to acknowledge each broadcast message, the responses would need to be spread out over a long period of time to avoid collisions. Moreover, this would not be very useful, given that since the sender does not know the list of recipients beforehand, it could not determine that there have been losses;

– The securing of exchanges is quite complicated insofar as the assumption is made that there is no prior exchange of information between the protagonists and that they do not know each other beforehand. Setting up cryptographic material to authenticate the sender or to sign (or encrypt) the content is therefore difficult as there is no trusted third party that can be reached at all times. This is all the more difficult because all or part of the devices are mobile and associated with users; therefore, the use of permanent identifiers is prohibited as this would make it possible to track the user's journey. We will see how different technologies protect themselves from this risk and how the world of cooperative ITS has addressed the need to secure the exchange of sensitive data.

1.2.3. *Advantages of ephemeral local interactions*

The use of ephemeral local interactions does not make it possible to maintain the usual mode of operation of applications and services; however, it offers advantages that are of great interest.

Therefore, ephemeral local interactions do not require prior knowledge of the protagonists. This mode of interaction is often used in an initial discovery phase before returning to a more conventional mode and establishing a connection. Therefore, a Wi-Fi access point will very regularly send announcements (beacons) that enable the stations to discover its existence. The presence of an access point does not make it possible to determine whether or not the latter can offer a service to the mobile terminal, which, in order to do so, will have to attempt to connect to it and establish a secure session. However, simply receiving beacons in itself enables information to be obtained that is useful to the mobile terminal (Chandra et al. 2007), since this is how smartphones obtain their positioning, through fingerprinting techniques and Geographic Information Systems maintained by service providers. As soon as part of this database is stored locally on the mobile terminal, the latter no longer needs the infrastructure in order to calculate its position.

Bluetooth technologies also use beacons that are transmitted on specific channels listened to by mobile devices (Bluetooth Special Interest Group (SIG) 2016). This enables a terminal to discover the presence of a Bluetooth device, and to connect to it if it has already performed the pairing phase. Here, we are therefore not in the operating principle of ephemeral local interactions, but the diverted use of its beacons to detect the presence of mobile terminals or vehicles (through their hands-free kit) corresponds closely to this logic. Therefore, it is possible, from the roadside, to detect vehicles and the unique identifier of their Bluetooth device, which makes it possible to establish input/output matrices by listening to highway access ramps (Barceló 2013; Boudabous 2021).

One of the main benefits of services based on ephemeral local interactions is that they do not require the prior deployment of a network infrastructure. It is therefore possible to rapidly deploy services without relying on an infrastructure, and to withstand permanent or accidental absences on the network infrastructure. The direct or device-to-device (D2D) mode of 3GPP networks on which cellular versions of V2X technologies are based have also found their first application in the field of emergency tactical networks, which must be able to be set up rapidly, when the telecommunication infrastructure has been harmed by a natural disaster. Depending on the application, we will see that it may occasionally be necessary to rely on an infrastructure to manage the securing of exchanges but without requiring it to be permanently available or involved in the normal operation of the service.

Depending on the needs and the communication technologies employed, using ephemeral local interactions enables very fast interactions that depend solely on the message sending frequency and the traffic capacity of the communication technology used. Therefore, the transmission delay will be higher when using BLE beacons (Yang et al. 2020), which must be able to operate for several months/years on a button battery, and which, as a result, will only send a "beacon" every minute. The maximum detection time of a beacon will therefore be of the order of a minute if we take into account the potential losses and the periods when the receiver is not listening to the correct channel. In the case of ITS G5, CAMs (Cooperative Awareness Messages (ETSI 2014)) are sent by default every 100 ms, which, even considering the potential losses, enables very short latencies.

1.2.4. *Suitability of communication technologies for this type of interaction*

The communication technologies used must enable an interaction model that is consistent with ephemeral local interactions. Therefore, it is very much possible to build above IP a service that functions through the regular broadcasting of messages and the use of this information to provide a service without any further dialog with the sender. However, while this presupposes prior connection to a network (e.g. Wi-Fi or Cellular), a large part of the advantages described previously disappear. The underlying communication technologies therefore need to be aligned with the interaction model and the targeted properties.

Adapted technologies generally use a shared multiple-access channel, which means that to access the communication medium, it is not necessary to obtain prior authorization and that everyone can transmit on the channel. There is therefore competition for access to the radio resource, which is for exclusive use (only one sender at a time). A device seeking to send a frame will listen and wait until the channel is free. There is a risk – and mechanisms to reduce it – that two devices will start sending at the same time. When the messages of two senders overlap in time, there is a collision. Some of the potential receivers do not receive either of the two messages, while the other potential receivers decode one message or the other according to the capturing-effect principle (Roberts 1975; Gezer et al. 2010). However, the senders cannot hear the other transmission and do not notice the collision. Regardless of the organization of the radio channel, as soon as there is no device in charge of organizing the resource (such as a base station in the 4/5G networks), and no prior exchange to decide who is allowed to use the resource (RTS/CTS mode in Wi-Fi), the nodes use the resource and then manage the effects of the collisions. When the transmission is directed towards a specific receiver, it is possible to use an acknowledgment and retransmission system (this is the case for Wi-Fi); however, when it is broadcast, losses cannot be detected by the sender, and this must be taken into account in the very construction of the service.

In the case of ITS-G5, a device listens to the channel and transmits only if it is free for a minimum period of time, thus limiting the occurrence of collisions. This type of self-organized system (CSMA: Carrier Sense Multiple Access) works very well up to a certain level of channel occupancy (approximately 60% of the bandwidth) (Bianchi 2000). It is therefore appropriate to introduce mechanisms to limit the network load. Mechanisms are thus used to vary the message frequency according to the usage scenarios and the load of the radio access network. Of course, reducing the sending frequency increases the average time between two receptions and the time needed to discover a new node; this is why it is important to take into account the usage scenario, such as vehicle speed in the context of ITS. Indeed, the lower the velocity of the vehicle, the less its position changes between two announcements.

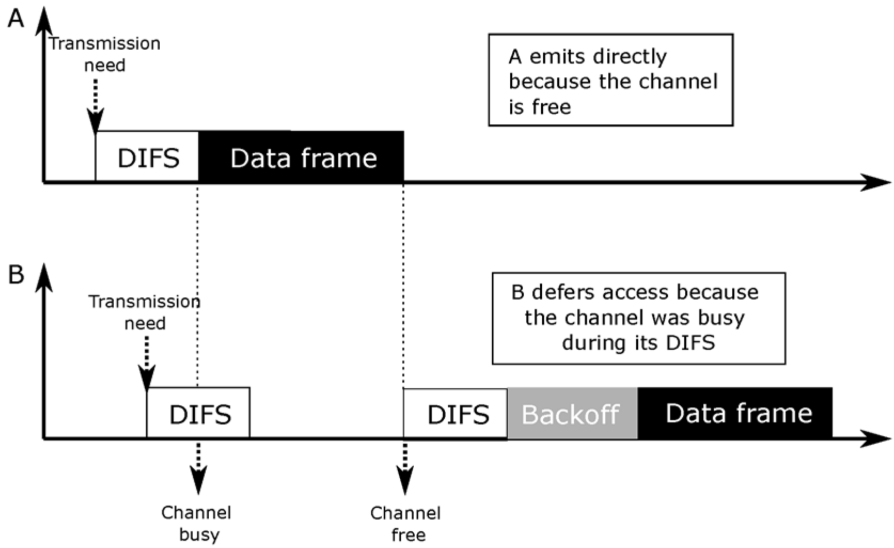

Figure 1.1. *Operation of Wi-Fi CSMA (IEEE 2009)*

In the case of BLE, the very limited bandwidth (typically 1 Mb/s under conventional conditions) will quickly impose constraints on the announcement sending frequency, even if, by design, the messages are limited in size. Since the range is also quite small, this technology could be used for low-velocity applications (pedestrians and VRUs (Vulnerable Road Users) more generally).

In the case of LTE-V2X (Garcia-Roger et al. 2020), the technology developed relatively recently has slightly different properties. Indeed, the radio resource is organized in a frame, with concurrent access to each slot, so that there are several transmissions in parallel on the channel. To limit collisions, due to the very short duration of a slot, it is not possible to listen to decide whether to transmit or not. When the channel is organized by a base station – this is one of the LTE-V2X modes – a station asks to be allowed to transmit before obtaining the resource from the base station. While there can be a collision on the request, the transmission of useful packets is no longer subject to collision. When the channel is self-organized, all the stations share the temporal structure of the frame and must therefore be strictly synchronized. They use semi-persistent scheduling (SPS). This involves listening to the channel and taking advantage of the repetitive nature of regular announcement messages (CAMs) by noting the slots that are occupied in the recent period. For each slot, the station determines the probability that it will be occupied by observing the power level received in that slot for a given duration (1 second by default). It will then select one of the “free” slots for its own transmissions. This selection will then be reviewed regularly. This mechanism works quite well for regular and permanent messages. However, when a collision occurs, it is not detected and lasts until one of the two senders makes the selection again, which becomes critical when the real-time constraints are high.

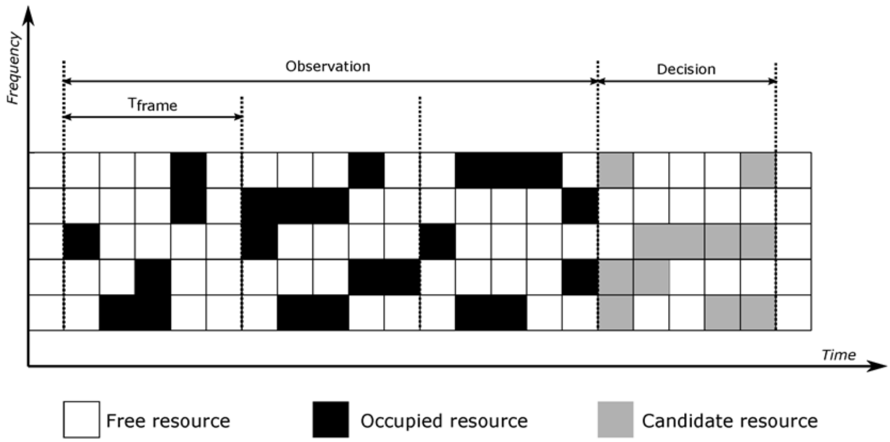

Figure 1.2. *Structure of frames and operation of LTE-V2X semi-persistent scheduling (Haider and Hwang 2019)*

Due to the direct communications between the devices concerned, direct interactions allow very short connection times, given that the announcement messages are frequent and that the receivers constantly listen to the correct channel. Mechanisms to time-multiplex sending and reception extend the time frames and the available bandwidth automatically. When everyone listens to the same channel, the connection time, i.e. the average time required to receive the first message that the receiver is able to decode, is directly related to the message sending period and the distribution of losses on the channel. Indeed, if the losses are not distributed uniformly, the calculation of this average time depends mainly on the maximum duration of the consecutive message loss sequences and on the probability of loss. Losses can be due to collisions, other forms of signal interference or masking. The different forms of interference may be considered to be random. On the contrary, as already mentioned above, collisions are positively correlated with the load submitted to the network, hence the importance of controlling the amount of traffic submitted to the network.

1.3. Local interactions serving cooperative ITS

In this section, we will focus more specifically on the use of ephemeral local interactions in the context of cooperative ITS.

1.3.1. *Cooperative ITS services*

The scope of cooperative ITS (C-ITS) applications is particularly broad. It is traditionally broken down according to the maturity of the technology required. So-called "Day 1" applications are deployable with the technologies currently available. These include the transmission of alerts (slowing down, approaching a priority vehicle, accidents, road works, etc.), signage (on-board display or traffic-light phase) or of presence (position, speed, direction, etc.). In contrast, "Day 2" applications require performance and standardization levels that have not yet been achieved. This covers, for example, driving in convoy ("platooning"), remote driving or vision sharing ("see through"). "Day 1.5" applications are at an intermediate stage: they are feasible for particular cases but their level of standardization does not allow them to be immediately generalized on a large scale. This is the case, for example, with the protection of Vulnerable Road Users (VRU), parking space management or dynamic routing.

As diverse as they are, these applications can be based on the standardization proposed by the "Facilities" layer of the ITS-Station stack. This messaging layer is a kind of middleware between communication layers and applications. This layer is regularly enriched with new functionalities. At this stage, we can cite the following messages as examples:

– CAMs (Cooperative Awareness Messages) (ETSI 2014) are sent regularly (typically every 100 ms) by vehicles to signal their position, speed, direction and physical characteristics. Other vehicles use this information to add the sender to their perception of the environment.

– DENMs (Decentralized Event Notification Messages) (ETSI 2014) are used to signal one-off events such as accidents, construction sites, slowdowns, etc.

– SPAT/SPATEMs (Signal Phase and Time/Extended Messages – ETSI TS 103 301) transmit the traffic-light phase status. They are typically associated with

MAP/MAPEMs (Map Data/Extended Messages) that describe the geometry of roads and intersections.

– IVI (In-Vehicle Information – ETSI TS 103 301) dynamically relays the signage information for on-board display. They replace or complement conventional road signage and are more easily exploitable by the vehicle's automations.

– CPMs (Cooperative Perception Messages – ETSI TR 103 562) enable actors (vehicles and infrastructure) to dynamically exchange information on their perception of the environment (obstacles, vehicles, pedestrians, etc.).

These standardized messages offer an impressive toolkit to accelerate the development and penetration of applications into the market. However, before they start, application designers must analyze the consequences of the choice of message type on the architecture of their solution. Will the application be dependent on an infrastructure or not? Can this infrastructure be decentralized (RSU) or will it require a central server? The answer to these questions will have a strong impact on the cost and ease of deployment of the solution, as well as on its performance (for example, reaction time).

1.3.2. *Benefit of ephemeral local interactions for cooperative ITS*

Here, local interactions offer numerous advantages. They are simple to deploy (as their configuration is very lightweight), require little or no infrastructure (e.g. a light connected to an RSU) and offer very good responsiveness (of the order of several ms to several 100 ms). In addition, limiting wave propagation makes it possible to natively reduce diffusion around areas of interest of the different messages.

The benefit is obviously for collaborative perception applications (based on CAM or CPM messages) or for signage (IVI, SPAT, etc.). In the first case, the speed of transmission is decisive. Also, in all cases, the geographical limitation of broadcasting and the ability to exchange information without the need for prior association constitutes a decisive advantage.

The transmission of warnings (typically by DENM message) represents an interesting case. A network access priority and a sending frequency is associated with the message, based on the emergency associated with the event at the origin of the warning. Therefore, DENM messages relating to an extreme emergency (e.g. in the event of a collision) are sent with maximum priority and at a high frequency to ensure that all approaching vehicles dispose of the information early enough to react (in a few ms).