



**UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH**

**Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona**

**PERFORMANCE STUDY OF THE IEEE 802.11p AND ETSI
GEONETWORKING PROTOCOLS**

A Master's Thesis

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by

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of the requirements for the degree of
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Advisor: Dr. Jordi Casademont

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Title of the thesis:

Performance study of the IEEE 802.11p and ETSI GeoNetworking protocols.

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Abstract

C-ITS is a research field that looks to generate complex ad-hoc networks in which the nodes themselves must think on their own and where any connected node must help the nodes around to know and understand how the network works at any moment and also to preview how it must behave from one second to the next one in order to solve traffic management problems and accidents as fast as possible. The main objective of this project is to evaluate two protocols belonging to the ETSI protocol stack (802.11p and GeoNetworking) through a simulation software based on Omnet++. By using multiple parameters like propagation models, loss probability and some others, some results are presented to evaluate whether the two protocols fulfil the network requirements or not. At the end of the project an improvement proposal for one of the two defined services is presented.

Dedication: To all my teachers and professors who taught me in past. To all my friends, for being my friends even when I closed myself into my studies. To my mother and my brothers, for their support during all these years as a student. To Erika, for her patience, for listening to me while speaking about things she did not know. To my father, my best professor.

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1. Introduction

Since the beginning of human history, people moved from one place to another to travel or exchange goods. Initially they always did it by foot but, thanks to the invention of the wheel, human mobility evolved in different and various ways, starting from carts pulled by animals, steam on railways and the electric energy up to the oil automotive boom. Communications is a field in continuous evolution and, thanks to the introduction of intelligent systems and broadband mobile and also to the creation of new features to a new generation of vehicles, it can be considered as a never-ending industry.

As engineers look for more efficient engines and low consumption, the most recent evolution has been on mechanics and aerodynamics. Nowadays, the focus moves to intelligent vehicles, considering a key driver, the interaction between vehicles and also vehicles with traffic surrounding elements (pedestrian's behaviour, road indicators, weather prediction, traffic detection, etc.) as essential data to share by using what is called "Collaborative-Intelligent Transport Systems" (C-ITS).

Based on mobile communications, we define C-ITS those systems where each node shares its knowledge related to its surroundings looking for the best behaviour of the network whom they belong. Sharing their available information and the acquired data about where and how the vehicles are moving through (roads, streets, etc.), they collaborate one with the other in order to get the maximum traffic and energy efficiency and, more important, to increase the total safeness for pedestrians and drivers.

Many companies, from small to big automobile players, develop and invest in research projects which can create the vehicle of the future. The main objective of these researches is to create and then apply new technologies able to help humans while driving or even substitute a human driver with the autonomous vehicle as objective. While the majority of these projects give the responsibly to know what happens around the vehicles to each vehicle (which means that each vehicle must react by itself), C-ITS looks for a group reaction in order to always have an efficient global traffic network.

As the objective of C-ITS is the global behaviour of the network, international organizations are engaged in multiple projects around the world related to communications between vehicles. Continental organizations of Europe, Asia and North America are trying to be the first one to create the best communications protocol to fit within the specific situation of having big, strong and fast devices moving with or around human lives, in order to protect them.

This project aims to study one of the possible options to be used as a communication protocol: the European proposal. More specifically, the objective of this project is the analysis of two protocols: the GeoNetworking, a network-layer protocol in charge of addressing and forwarding the information and the 802.11p, and a MAC-layer protocol in charge of the medium access, which can check the integrity of received information among other tasks. Moreover, and as described further on, an additional third objective has been considered during the project development. The project focuses on the study of a service which had already been defined within the European protocol stack and presents a proposal of improvement.

1.1. Project Workflow

The tasks done during this project were first of all the study of the C-ITS field. By understanding its framework, it is expected to learn what C-ITS are and what their requirements are. The second objective is to understand the differences between the three main world proposals and, more important, the European design and its defined protocol stack, something needed before to enter on test activities characterization of all the protocol layers and their inner relationships. The third objective is to deeply enter into the specific details of the two selected protocols: GeoNetworking and 802.11p. As a fourth objective, we define the test phase by generating multiple simulations of traffic situations and, finally, understand and describe the obtained results and, if possible, to present improvement recommendations (negative or positive).

Fig. 1 presents the Gantt chart and shows in time perspective the development of the previous tasks.

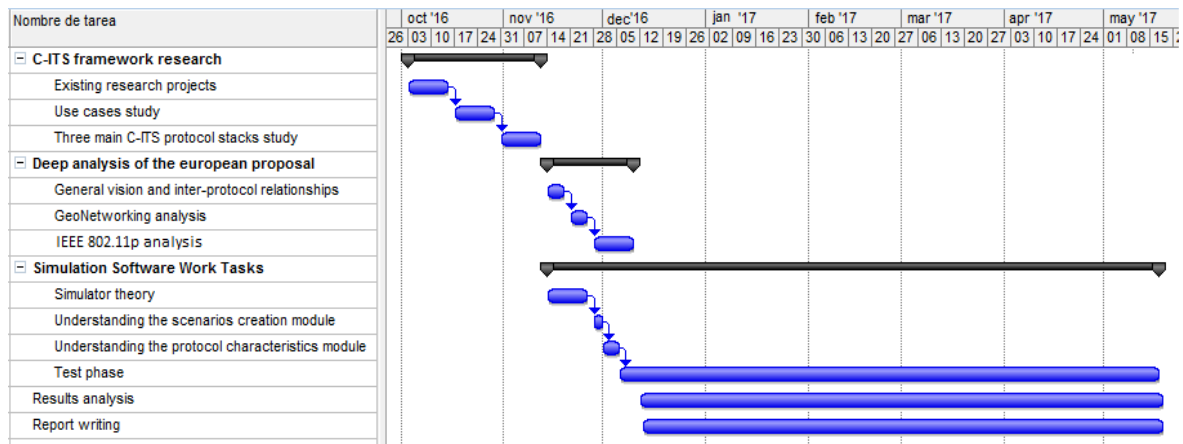


Fig. 1 - Project's Gantt diagram.

One of the difficulties of this project has been working with the simulation software: as a matter of fact, the used software was not the final version of the simulation software and it was under continuous improvement while this project was carried on. New versions of the simulation software have been tested and different application problems have been solved in parallel with simulation activities of this project. Even if those problems did not affect the behaviour of the protocols during the simulations, it was not possible to collect some of the data statistics more in detail. However, all the data considered for the final conclusions has been evaluated as good.

1.2. Thesis Outline

This document, as a project final report, presents all the previous described objectives and how they were achieved. After this first introduction chapter, we present the state of art of the C-ITS communications on the second chapter. First of all the objectives of these kind of communications systems, the requirements that the standards must fulfil, the network architecture and its basic protocol architecture together with the three most important protocol architecture proposals and, finally, the defined services to work on any C-ITS. The third chapter describes the tools used to develop this project, the software simulator and all its components, the use cases and other projects considered as references for the applied scenarios finally evaluated and the differences between them. The last part of the third chapter presents the basic parameters needed for the evaluation

of the protocols. The fourth chapter presents all the results related to each one of the tested protocols (802.11p and GeoNetworking) including their evaluation and enhancing proposals to improve one of the C-ITS basic services. Finally, in the fifth and sixth chapters, we present the budget and the conclusions of this project and make proposals for future tasks as a road map to continue this research.

2. State of Art of the C-ITS Communications

C-ITS communications are a "young" research field, but due to its importance for the vehicles future, many research projects have been developed and multiple protocol studies are currently being reviewed to determine which one will be used in the future.

This chapter will resume the current status of these communications. By describing the objectives that these communications want to reach, we will understand why the automotive industry is so interested in developing a good communication protocol. Once these objectives are cleared up, the chapter goes on explaining more technical information like network structure, communications types, current studied protocol stacks (mainly the one defined by the European Telecommunications Standards Institute, ETSI) and finally, the current existing basic services that at least the ITS should be able to run.

2.1. C-ITS Objectives

The first thing we must know when studying any field, is all the objectives, the problems or the necessities that the field wants to reach, solve or fulfil. The C-ITS wants to solve three objectives:

1. **Vehicle Safeness:** many accidents (and, as a consequence, many deaths) happen on the roads around the world. Due to this reason, the idea is to make the vehicles more intelligent in order to constantly know the situation of their near surroundings (i.e.: pedestrians walking on the sides or crossing or other vehicles movements). The main idea of this field is to prevent possible accidents and, by doing so, increase vehicle safeness. If prevention is not enough and the accident finally happens, reaction (to warn) must be the secondary idea behind this objective;
2. **Traffic efficiency:** professional or not professional drivers usually lose a lot of time on the road because they do not know the best routes at any moment (a car accident causing traffic congestions or all cars using the same lane instead of being distributed over many). By knowing the situation of the near and medium-range surroundings, future applications (inside the car or on the streets) may help to get a better traffic organization and make drivers use their time more efficiently;
3. **Energy efficiency:** the longer any vehicle is on, the more energy it will use (fuel, electricity or any other kind). By reaching the previous objective, vehicles will use less energy because they will do less "stop-and-go" actions (at traffic lights, slow vehicle flow during traffic jams, etc.), generating a better and continuous flow of vehicles along the city streets or highways.

Aside from the previous objectives, there is a fourth one, which is usually the most important from some points of view:

4. **Economical;** as any other technology, there will be options to create new business. By creating new or adapting existing services, companies will be able to generate business and, by doing this, creating new job positions, increase their benefits and other positive actions for society.

2.2. Considerations for C-ITS Standards Design

All communications have some specific considerations to keep in mind when designing the standards, for the C-ITS are:

- ITS stations mobility makes the network to be constantly changing its topology;
- must give support to any communication technology type (Internet, public networks, legacy systems, etc.);
- must give support to any application type:
 - specific ITS applications;
 - those using the ITS station as a transparent communication;
 - those using station-internal communications only.
- dynamic and flexible user needs (i.e. capacity, costs, reliability, etc.);
- application classes priority;
- dedicated relation between applications and communications technologies depending on some requirements (i.e. road safety, traffic efficiency, etc.);
- must give profiling support;
- to be implemented around the world.

By having in mind these considerations, the standard and research organisms can design, study and evaluate the standards they want to use for these communications systems.

2.3. Network Architecture

As any other communication system, it is necessary to have a network architecture which defines how any of the nodes participating in this network will behave and relate with the other nodes.

As defined in [2] and shown in Fig. 2, there are 4 main elements that communicate between them:

1. Vehicular ITS station: Device installed inside the vehicles, called On Board Unit (OBU). It must manage all the traffic information (vehicle's own data and surrounding nodes) with the user or vehicle applications.
2. Personal ITS station: any assisting device used by any street/road user.
3. Roadside ITS station: Devices installed alongside the roads, called Road Side Unit (RSU). They belong to the access network for users/vehicles to the core and the opposite way.
4. Central ITS station: traffic management centres and back-office for service providers.

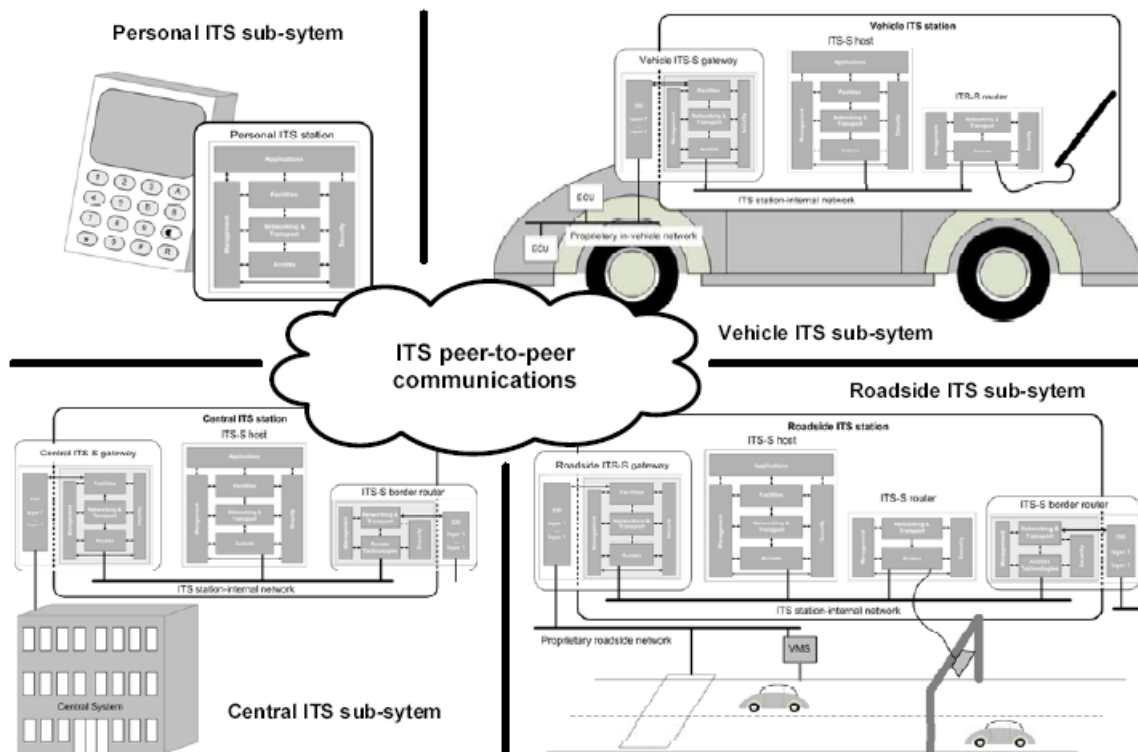


Fig. 2 - ITS sub-systems [Source: ETSI].

With the four previous elements, the basic network architecture is described and so, all the possible communications among all these stations can be defined:

- V2V: Vehicle to vehicle.
- I2I: Infrastructure to infrastructure.
- R2R: Roadside to roadside (same kind as the previous I2I).
- V2I / I2V: between vehicle and infrastructure.
- V2R / R2V: between vehicle and roadside.
- V2C / C2V: between vehicle and centre (through the infrastructure).
- I2C / C2I: between infrastructure and centre.
- R2C / C2R: between roadside and centre.
- V2P / P2V: between vehicle and person.

In the previous list, vehicles have the possibility to communicate with three different points: people, infrastructures and vehicles. The communication with people and infrastructures could be centralised (there is a central ITS station) or distributed: nodes communicate with near Base Stations (BS) and these distribute the information among the other BSs and nodes to have a global vision of the road. When communication is between vehicles (V2V), another network management possibility (the most interesting for this project) appears: ad-hoc networks.

By creating networks at any time with the vehicles within an area, direct communications between cars (near range) are used and so, the transmission delays are reduced thanks to the absence of intermediate infrastructure stations.

Informing the nearest vehicles by avoiding these intermediate infrastructures, means improving the vehicles safeness (by preventing and reacting). Due to the high speed of the vehicles, any time delay reduction on the transmission is really important because in less than a second an accident may happen (or not) and in order to avoid it, a constant direct information exchange between cars will be needed. In case of an accident, it will be urgent to inform the nearest vehicles (prevention of a bigger accident) and the nearest network architecture in order to warn the emergency vehicles (a good reaction increases the probability to save lives).

The communication delay reduction is one of the main targets. Nodes management in mesh networks is difficult due to the fact that there is no central point to rule over the others and manage them, either one node transmits or not. Having in mind these two basic considerations (reducing delays and nodes management), a good protocol architecture needs to be designed and defined.

2.4. Protocol Architectures

As the ITS is a young field, it still needs to research and develop a lot of projects, many standardization organisms and other associations tried to develop their C-ITS communications architectures to lead the rest.

All these organisms and associations base their work on one common protocol stack model [2], this model is organised with four vertical layers (one over the other) and 2 parallel layers that work in parallel with each of the four previous layers. The protocol stack structure and the six layers are shown in Fig. 3.

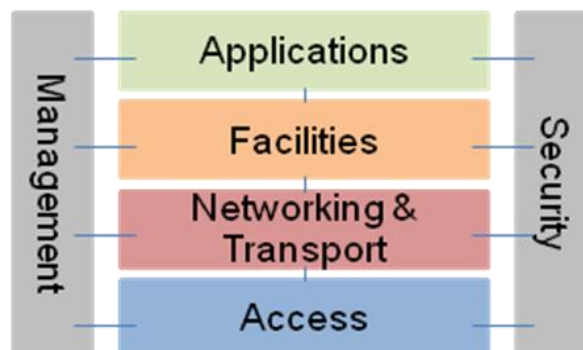


Fig. 3 - ITS protocol stack model [Source: ETSI].

From all the possible existing organizations, five of them are ahead of the others. These five organizations are: the ETSI (European), the CEN/ISO (International, but mainly used in Europe), the IEEE/SAE/NTCIP (USA), the Japanese and the Korean. Between all of them, we are mainly interested in three of them: the proposal of the IEEE, the proposal of the CEN/ISO and the proposal of the ETSI.

The main difference between the three selected proposals is that, while the ETSI and the CEN/ISO define the whole protocol stack based on the OSI stack (which belongs to the ISO), the IEEE proposal is more focused on the two lower layers: the transport and network layer and the access layer (Physical and MAC). Fig. 4 compares each protocol architecture to the OSI reference model and shows the difference - described before - between the ETSI/ISO and the IEEE proposal.

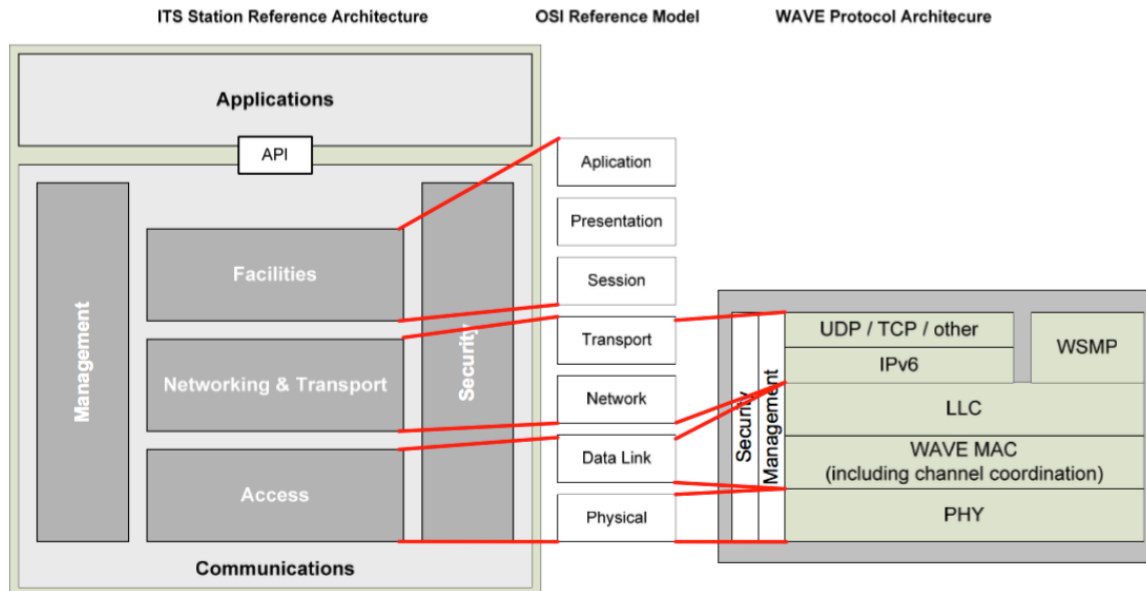


Fig. 4 - Comparison between the ETSI/ISO, the OSI model and the IEEE architectures [Source: ETSI, ISO, IEEE].

In the following subsections, we present a resume of these three architectures but, due to our project objective of evaluating the 802.11p and the GeoNetworking protocols, the ETSI proposal will be described more in detail than the ISO and the IEEE proposals. Further details are described in [2].

2.4.1. ETSI Proposal

The protocol architecture defined by ETSI is based on the following idea: to allow the usage of multiple protocols in intermediate and lower layers. So, many options for the user application requirements might be offered to the upper layer (Applications).

As each user application might have different communication requirements (reliability, delay, etc.), it is good to include within the protocol stack multiple protocols to fulfil the requirements required by the user applications. For example, compared to the IEEE proposal (2.4.3), which only uses one access technology, the ETSI proposal allows multiple access technologies.

Following the protocol reference model, the next subsections describe each one of the 4 central layers (security and management are not within this project objectives) of the ETSI proposal.

2.4.1.1. Applications

As any other applications that makes use of protocol stacks, they include all final applications and the user contact happens in this point.

As previously described in the objective (2.1), basic applications of an ITS station are classified as "Road Safety" and "Traffic Efficiency" (Energy efficiency depends on this). Other class of applications will exist in the future (media and audio data services, online games, etc.).

These applications must tell their necessities to the lower layer (Facilities) and, depending on these, each application will have a higher or lower priority. For example,

any media streaming application should have a lower priority than those applications based on traffic services (i.e. YouTube videos vs. road traffic news).

In Europe, the most important current applications at this level are:

- Data Exchange (DATEX II): Traffic and travel information exchange between traffic control offices and traffic infrastructure (light signals);
- Transport Protocol Expert Group (TPEG): Traffic information exchange between a service provider and multiple nodes.

Aside from being connected with the Facilities layer, the Applications layer is also connected to the Management and the Security layers. These two layers control some processes like installations, updates, etc. and give security against possible attacks through the network.

2.4.1.2. Facilities Layer

This layer has the functionality of the three upper OSI layers (Applications, Presentation and Session). Due to this, it must give support to the applications requirements, manage the information generated by the car and the information within the messages coming from the lower layers.

This layer is structured in two complementary parts [9]: the first one classifies the facilities by the support they give (to application, to information or to communication) and the second by their usage (Common or Domain). Fig. 5 shows these two ways of classifications.

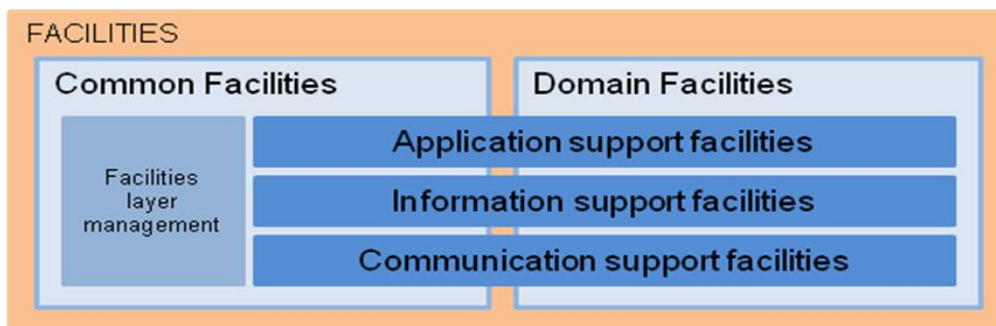


Fig. 5 - Facilities layer inner structure [Source: ETSI].

The facilities support part can be classified in three ways as described in [9]:

1. Application support facilities: "*provide application support functionalities for ITS Basic Set of Applications (BSA)*" (i.e. CAM or DEN management);
2. Information support facilities: "*provide common data and database management functionalities for ITS BSA applications*" (i.e. LDM);
3. Communication support facilities: "*provide services or communications and session management.*" (i.e. addressing mode, session support, etc.).

The facilities usage part can be classified in two ways:

1. Common facilities: "*provide basic core services and functions for all ITS BSA applications and for the operation of the ITS stations*" (i.e. time management or position management, etc.);

2. Domain facilities: "*provide specific services and functions for one or multiple ITS BSA applications*".

2.4.1.3. Network and Transport Layer

The three protocols architecture proposals described in this document (ETSI [2.4.1], ISO [2.4.2] and IEEE [2.4.3]) allow the usage of the IPv6 protocol in the network layer and the TCP/UDP in the transport layer, but they also propose other specific protocols for ITS applications.

When defining the C-ITS networks, the organisms take into consideration two important ideas: the first one is the variability of these networks and the second one is the relation between latency and traffic safeness.

On one hand, due to the high mobility of the vehicles (nodes might move at speeds of 120 - 150 km/h), the network structure on the roads will constantly change and these variability increases the difficulty to find the nodes at any moment. On the other hand, as we are dealing with information that might be urgent to send and receive, if this information follows the traditional concept of transmitting it through the core network and sending it to the receiver (which may be the car behind), the latency will get bigger and give less time to the receiver to avoid a possible accident.

The solution for these two problems is the possibility to use ad-hoc networks between the vehicles when communicating among them (at least with the nearest range vehicles). As it is a spontaneously created network, for an ad-hoc network is difficult to manage messages and the access channel of the nodes (as there is no central station).

In order to solve these problems, ETSI defined the usage of two protocols: the Basic Transport Protocol (at the transport layer) and the GeoNetworking Protocol (at the network layer):

- **Basic Transport Protocol (BTP)**

As described in [7]: "*BTP provides an end-to-end, connection-less transport service in the ITS ad hoc network. Its main purpose is the multiplexing of messages from different processes at the ITS facilities layer, e.g. CAM and DENM from the cooperative awareness basic service and the distributed environmental notification basic service, for the transmission of packets via the GeoNetworking protocol as well as the demultiplexing at the destination. BTP enables protocol entities at the ITS facilities layer to access services of the GeoNetworking protocol and to pass protocol control information between the ITS facilities layer and the GeoNetworking protocol.*"

"Message multiplexing/demultiplexing is based on ports, an ITS station-internal 16 bit address. A port represents a communication endpoint that identifies the ITS station protocol entity at the source (source port) or the destination (destination port). The usage of ports is similar to the two-stage packet transport in the IP protocol suite, where the IP provides the routing of packets from source to destination and the transport protocol, such as UDP, multiplexes/demultiplexes messages from/to application processes. In the case of BTP, the GeoNetworking protocol transports the packets among the ITS stations and the BTP protocol delivers the packets to the entities at the ITS facilities layer. BTP also adopts the concept of "well-known ports" from the IP protocol suite that assigns fixed ports to specific ITS facilities layer protocols. The definition of the ports, however, is beyond the scope of the present document."

"BTP is a lightweight protocol: It has a 4-byte protocol header and requires minimal processing. It provides an unreliable transport of packets, i.e. packets can arrive out-of-order, appear duplicated or can be lost. The design of BTP assumes that entities using the protocol are either tolerant against the unreliable packet transport or provide appropriate mechanisms for reliable communication in their protocols."

– **GeoNetworking Protocol**

As described in [3]: *"The ETSI defines it as a network-layer protocol for mobile ad hoc communication based on wireless technology, such as ITS-G5. It provides communication in mobile environments without the need for a coordinating infrastructure. GeoNetworking utilizes geographical positions for dissemination of information and transport of data packets. It offers communication over multiple wireless hops, where nodes in the network forward data packets on behalf of each other to extend the communication range. Originally proposed for general mobile ad hoc networks, variants of GeoNetworking have been proposed for other network types, such as vehicular ad hoc networks (VANETs), mesh networks and wireless sensor networks. Therefore, GeoNetworking can also be regarded as a family of network protocols based on the usage of geographical positions for addressing and transport of data packets in different types of networks."*

As it works connectionless and fully distributed giving no necessity of infrastructure access, GeoNetworking is a well-designed network protocol for ad-hoc networks. This protocol fulfils the vehicular requirements (high node mobility and network topology variability).

Thanks to its characteristics, GeoNetworking *"flexibly supports heterogeneous application requirements, including applications for road safety, traffic efficiency and infotainment. More specifically, it enables periodic transmission of safety status messages at high rate, rapid multi-hop dissemination of packets in geographical regions for emergency warnings, and unicast packet transport for Internet applications"*.

GeoNetworking has two functions to achieve:

1. Geographical Addressing: it allows to send packets to a specific geographical position (latitude and longitude) where there is one or more receiver by defining the geographical area;
2. Geographical Forwarding: instead of using identifiers like IP addresses, nodes must know the network topology around them. Thanks to geographical address that the GeoNetworking packets have, it is possible for all the nodes to identify if the packet was sent to them or has to be forwarded to another geographical area. A positive aspect of using geographical addresses, instead of addresses like IP, is the inexistence of any routing table, which means that no management is needed.

Because of the previous two functionalities, communication scenarios on GeoNetworking are ([4]):

1. Point-to-point: from one ITS station to another;
2. Point-to-multipoint: from one ITS station to multiple ITS stations;
3. GeoAnycast: from one ITS station to another ITS station within a specific geographical region;

4. GeoBroadcast: from one ITS station to multiple ITS stations within a specific geographical region.

Another important point about GeoNetworking is the fact that this protocol does not forget about networks external to the ITS networks. This means that other protocols such as IPv6 might use the functionalities of GeoNetworking to reach any point of the ITS network. By doing so, Internet services will not be an external "world" to the ITS networks and they will also be available within the ITS networks through the GeoNetworking protocol.

As IPv6 is accepted by the ETSI proposal, this last one has two possible ways to pack and unpack the incoming messages: through GeoNetworking with BTP or through GeoNetworking with IPv6 and TCP/UDP. These two ways can be seen in Fig. 6.

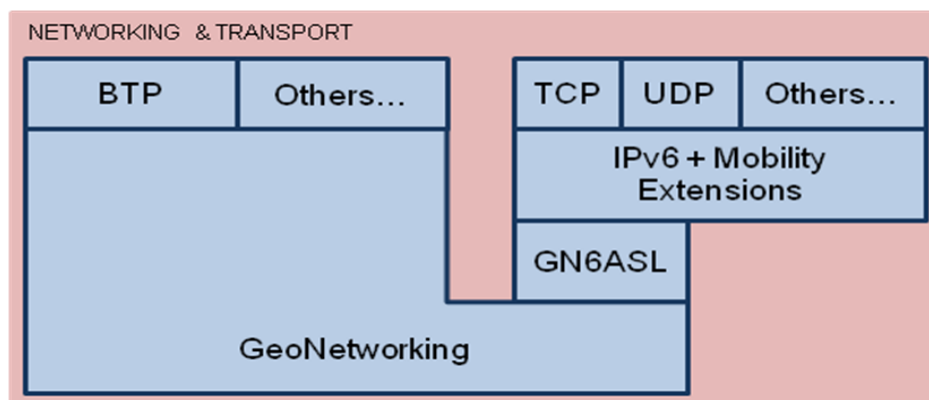


Fig. 6 - Internal Transport and Networking protocol structure [Source: ETSI].

The previous figure shows another mechanism between the Ipv6 and GeoNetworking: the GeoNetworking-IPv6 Adaptation Sub-Layer (GN6ASL). As its own name indicates, this sub-layer helps IPv6 packets to be adapted to the GeoNetworking packet structure. Further information about the IPv6, GeoNetworking and GN6ASL relationship can be found in [8].

2.4.1.4. Access Layer (Physical and Data Link)

At the lowest layer of the ITS protocol stack and common to other protocol stacks, there are the Data Link and the Physical layers. These two layers are in charge of the frame control and the medium access. Similarly to other protocol stacks, here, the data link layer is also divided in two sublayers: the Medium Access Control (MAC) and the Logical Link Control (LLC).

The standard defined by the ETSI for these "three" sublayers (PHY, MAC and LLC) is the ITS-5G. The ITS-G5 [13] standard is a collection of already existing communication protocols, each one of its components is meant to fulfil the requirements of these three sublayers. The Physical and MAC layers are covered (among other access technologies like LTE) by the IEEE 802.11 (more specifically the 802.11p), while the LLC layer is based on the ANSI/IEEE Std.802.2.

– IEEE 802.11p

The IEEE 802.11 [1] is one of the most used protocols on the MAC layer. Depending on which communication system is implemented, one version or another is used. For ITS systems, the version selected is 802.11p.

The main difference of this protocol than other 802.11 versions (a/b/g/n/ac) is the fact that the p version is defined for vehicles communications (small latencies, high amount of nodes, etc.).

The way to have low latencies on the access is through the allowance to work without necessity to be part of a Basic Service Sets (BSS). By no need of the BSS, there are no authentication and association phases. The biggest latencies appear due to these two actions and, by avoiding them, latencies are reduced.

802.11p does not use the active and passive BSS and frequency channels search. By doing it, the ITS-station does not lose time on the search and selection, but this means that the frequency channel must be predefined inside the ITS-station.

About the Physical layer of 802.11p, OFDM modulation is selected but with some modifications compared to the 802.11a. Bandwidth is of 10 MHz (instead of 20 MHz), there are multiple bitrates but the three which must be available for all the ITS-stations are 3, 6 and 12 Mbps. Finally, time slot is 13 μ s.

On the MAC layer, 802.11p uses the Enhanced Distributed Coordination Access (EDCA), which defines 4 queues depending on the information priority (from high to low): AC_VO (Voice), AC_VI (Video), AC_BE (Best Effort) and AC_BK (Background).

Finally, the Decentralized Congestion Control (DCC), which will be described later, is used to decrease channel saturation.

– **ITS-G5 Frequency Allocation**

Standards used within this collection must have the capability to work at least at the frequency assigned for vehicles communications: 5 GHz. Due to the multiple objectives (and so, applications types) defined previously (2.1), different frequency ranges are defined (within the European Union) [13] and are to be used depending on their purpose. Currently there are four options:

1. ITS-G5D (5905 - 5925 MHz): for future ITS applications;
2. ITS-G5A (5875 - 5905 MHz): for ITS road safety related applications;
3. ITS-G5B (5855 - 5875 MHz): for ITS non-safety related applications;
4. ITS-G5C (5470 - 5725 MHz): for RLAN (BRAN, WLAN).

The basic idea to split the applications in different frequency working ranges is to avoid problems between them and their specific requirements. Among all multiple application requirements, the ITS-G5 has to pay special attention to fulfil road safety applications high requirements (i.e. reliability, data transmission latency, etc.).

Because of these high requirements, the limited bandwidth of the ITS-G5 and the usage of the 802.11p (MAC protocol), in some situations the amount of data might surpass the capacity of the wireless channels. Decentralized Congestion Control (DCC) [12] methods are used to solve this problem. By using these methods, ITS stations control the amount of data of the channel in order not to have wrong behaviours of the system.

– **Decentralized Congestion Control (DCC)**

Any station working at ITS-G5A and ITS-G5B must use the DCC. By using it, stations are able to maintain network stability, throughput efficiency and fair resource allocation to ITS-G5 stations.

DCC functionalities are:

1. To provide the same resources allocation and channel access probability to all ITS stations within the same communication area;
2. To maintain the amount of data in the channel under some specific thresholds;
3. To keep some communication resources for high priority information (i.e. car accidents, police or fireman vehicles coming, etc.);
4. To adapt to a high variable environment (radio channel might change from free to busy or the opposite really fast);
5. To manage the oscillations in the control loops within the limits;
6. To be able to fulfil the requirements coming from upper layers (i.e. reliability, etc.)

All the previous functionalities are not only coming from the physical layer but also from upper layers (functionality number 6). Because of this, DCC is not only situated in the access layer but also inside all the other layers of the ETSI protocol architecture (except the Applications and the Security layer).

As described, DCC must control the access to the channel (among other functions) giving to all ITS stations the same opportunities. In order to do it, DCC has following methods:

1. Transmit Power Control (TPC): it defines transmit power thresholds at which ITS stations must work.
2. Transmit Rate Control (TRC): it uses times between packets to define the waiting or transmitting limits.
3. Transmit Data rate Control (TDC): each ITS-station can transmit between some defined limits.
4. DCC Sensitivity Control (DSC): by allowing a maximum sensitivity, each station will receive more or less information from others and so, it will see the channel more or less busy.
5. Transmit Access Control (TAC): used to give fair channel access. Higher channel load means restrictive TAC and so, ITS-stations transmit less.
6. DCC Transmit Model: each ITS-station compares its own transmission statistics with a reference model in order to manage its access to the channel.
7. DCC Receive Model: like the previous method, this model estimates the communication range by using a demodulation model and a channel model as references.

When controlling the channel access, a packet may arrive from upper layers in a moment in which the ITS-station cannot transmit. Because of this, DCC has to manage some queues and each queue has to support one of the EDCA queues defined in [1].

2.4.2. ISO Proposal

The protocol architecture defined by the ISO is called Communications Access for Land Mobiles (CALM) [14] and the most important characteristic (like the ETSI proposal) is the allowance of multiple protocols usage in each one of the different layers.

Like ETSI and IEEE architectures, the interesting protocol is on the Networking and Transport layer. Here, ISO defines the Fast Networking and Transport layer Protocol (FNTP). Defined for one hop communications, it uses a really small number of bytes on headers (the smallest is 5 bytes long), which is useful for narrow bandwidth channels and allows any access technology.

At the Access layer, ISO proposes to use LTE (ISO 17515-1) and DSRC at 5GHz (ISO 21215).

Some negative characteristics of the ISO proposal are, for example: the lack of difference between the network and transport functionalities, the lack of scalability due to the small headers, the broadcast multi-hop communications are not well defined, etc.

2.4.3. IEEE Proposal

IEEE's proposal (made by USA organisms) is Wireless Access in Vehicular Environments (WAVE) [15]. As the two previous proposals, on the Network and Transport layers, it allows the usage of the IPv6/TCP/UDP protocols or the IEEE 1609 (IEEE specific standard for ITS). However, the main difference is found in MAC and Physical layers.

WAVE architecture only allows one access technology: the IEEE 802.11p [1]. As described previously (2.4.1.4), this 802.11 version allows to work outside of the Basic Service Set (BSS), giving the option to have medium access in vehicle scenarios where there is a fast variability of the network due to the speed of vehicles.

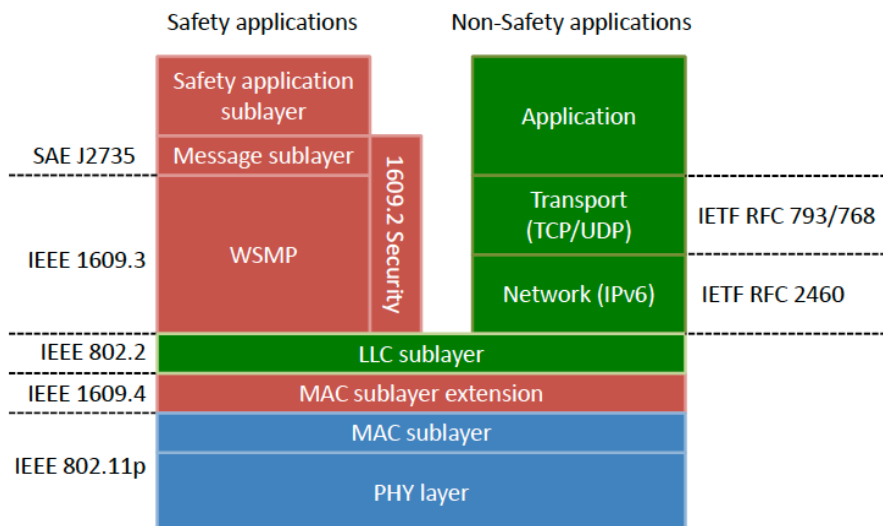


Fig. 7 - WAVE protocol stack with the IEEE 1609 and IEEE 802.11p protocols [Source: IEEE].

Fig. 7 shows where different protocols defined by IEEE do their tasks inside the WAVE protocol stack. While 802.11p is used on the access medium, multiple versions of the 1609 are used at different layers:

- 1609.4 allows the MAC protocol (802.11p) to do multi-channel operations.
- 1609.3 specifies the network and transport protocols (WAVE Short Message Protocol, IPv6/TCP/UDP, etc.).
- 1609.2 manages the security on the WAVE messages.

2.5. Services

All protocols stack proposals previously described have one common objective: providing services that are meant to improve the driving experience.

Services can be classified in many ways. Multiple organizations (3GPP, Amsterdam Group, etc.) have their own way of classifying them. Taking into account the objectives (2.1) previously described and the point of view of this project, the most interesting classification is the one done by ETSI [9]. This classification is called "Basic Set of Applications" (BSA) and classifies all those services that should be available in a short period of time for customers into 4 categories:

1. Active road safety: advice emergency vehicles approximation, collision risk warning, etc.
2. Co-operative traffic efficiency: to coordinate the vehicle speed with traffic lights, the best travel path, etc.
3. Co-operative local services: to find and pay parking services, local e-commerce, etc.
4. Global Internet services: vehicle software updates, insurance and financial services, etc.

2.5.1. Basic Set of Applications

As mentioned in section (2.4.1.2), one of the functionalities of the Facilities layer is giving support to the Basic Set of Applications (BSA). This support is given by some defined services that all ITS stations must have. Examples of these services are the following two:

1. **Cooperative Awareness Basic Service** [10], this service takes all the necessary information from the ITS vehicle station (by sending a continuous flow of messages) to announce its own information (i.e. vehicle width, direction, speed, altitude, longitude, latitude, etc.) to the ITS stations around itself (one single hop distance maximum);
2. **Decentralized Environmental Notification Basic Service** [11]: this service is used to communicate an emergency or urgent situation. If an ambulance, a police car or a fireman vehicle is coming, they can announce their coming to their surroundings and vehicles around them would know how to behave (moving to the right or to the left to create a path for them).

The two previous services are used on active road safety applications like driving assistance (i.e. Co-operative awareness and Road Hazard Warning) or Co-operative traffic efficiency (i.e. Speed management, co-operative navigation, etc.).

As many situations may occur at the same moment, these two services have different priority. Namely, DENM service is used for emergency situations, so its information has a higher priority than the CAM information.

Each one of these two services, has a defined message to be sent through the network whose objective is to inform all nodes around. Cooperative Awareness Basic Service uses the Cooperative Awareness Message (CAM) while Decentralized Environmental Notification Service uses the Decentralized Environmental Notification Message (DENM):

– **Cooperative Awareness Message (CAM)**

This message aims to give the current information of the ITS station to the surrounding ITS stations available in one single hop. The reason to allow only one single hop is due to the constant vehicles mobility. If we imagine three vehicles in line and suppose that the first vehicle sends a CAM to the second and this, in turn, forwards it to the third one, when the CAM (originated by the first vehicle) arrives to the third, its information would be wrong: at this point the first vehicle would be in a new position and the CAM would inform about a wrong position. Because of this mobility, all vehicle must constantly inform their surroundings.

Due to the objective of constantly informing the surroundings, the CAM must be sent periodically. Because of this, there is a minimum and a maximum number of CAMs to be sent within a second. That is to say, a minimum of 1 CAM per second and a maximum of 10 CAMs per second (every 100ms). Depending on the needs of each ITS station and the channel congestion, all the ITS stations must control and change their CAM generation.

Before a description of the CAM inner structure is done, some new concepts must be described. CAM messages are organized in containers, in data elements (DE) and data frames (DF):

1. Container: is a bloc of information that contains a sequence of DEs or DFs. A container may include sub-containers which have more specific information of the ITS station.
2. Data Element: a single data contained in a data type.
3. Data Frame: more than one DE contained following a predefined order in a data type.

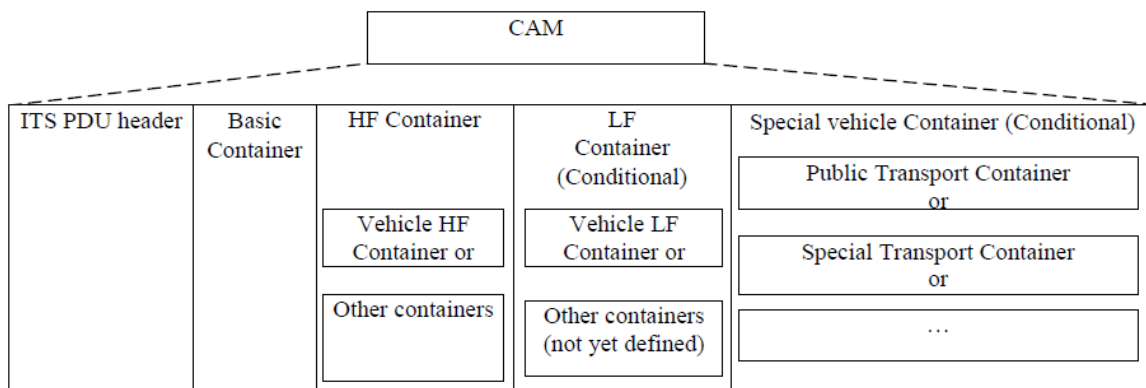


Fig. 8 - CAM General structure [Source: ETSI]

Fig. 8 shows the general structure of a CAM message. This structure allows multiple options depending on the ITS station that generates the CAM and then sends it. The basic fields (containers) included in all CAMs are the ITS PDU header and the Basic Container. Depending on each ITS station type and on which information has to be spread, more containers may be included. However, the main five containers are:

1. ITS PDU header: contains the protocol version, the message type and the ITS station ID of the ITS sender.
2. Basic Container: contains basic information belonging to the ITS sender.

3. High Frequency Container: contains highly dynamic information belonging to the ITS sender (i.e. speed, direction, longitude, etc.). An example of a sub-container is: Basic Vehicle HF container.
4. Low Frequency Container: contains static and not highly dynamic information belonging to the ITS sender (i.e. vehicle size, colour, brand, etc.). An example of a sub-container is: Basic Vehicle LF container.
5. Special Vehicle Container: contains specific information belonging to the ITS sender describing the vehicle role (i.e. ambulance, police car, etc.). Examples of sub-containers are: Public Transport Container, Dangerous Goods Container, Road Works Container Basic, etc.

Further information about the Collaborative Awareness Basic Service and CAM messages like the protocol steps or inner fields used in each container, may be found in [10].

– **Decentralized Environmental Notification Message (DENM)**

Similar to the CAM, this message is used to announce information about the traffic. While CAM is used to disseminate the current mobility information of an ITS station, DENM is used to disseminate the current information of a traffic event (i.e. traffic jams or a car accidents) to warn and inform ITS stations around, in order to apply a solution as fast as possible.

Due to the purpose of a DENM and because traffic events may last for a short or long period of time, ITS stations are allowed to forward and resend a DENM messages. Once the event is solved, a last DENM will be sent to inform ITS stations about the event's end.

According to the duration time of an event, there are four different types of DENM messages:

1. New DENM: sent when an event is detected by an originating ITS station. For each event, an "actionID" is assigned and sent with the event characteristics (type, position, etc.).
2. Update DENM: sent by the originating ITS station of the New DENM, contains updated information about the event.
3. Cancellation DENM: used to inform about the end of the event, it is sent by the originating ITS station of the New DENM.
4. Negation DENM: used to inform about the end of the event by a different ITS station which did not generate the New DENM (i.e. a car detects ice on the road and warns the cars behind; soon after, another car passing by the same position of the first car detects that the ice is now melted and there is no more danger).

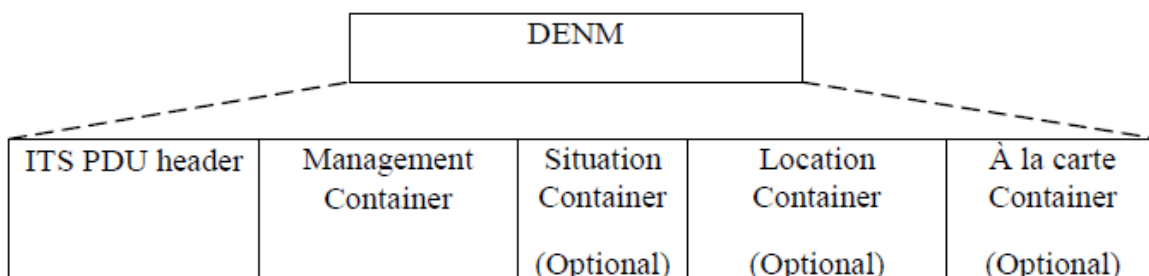


Fig. 9 - DENM general structure [Source: ETSI].

As Fig. 9 shows, the basic structure of a DENM message must have at least two fields, but there are three other optional containers:

1. ITS PDU Header: contains the protocol version, the message type identifier and the station identifier of the originating ITS station or the one forwarding the DENM.
2. Management Container: contains information related to the DENM management and the DENM protocol.
3. Situation Container: contains all information belonging to the type of the detected event.
4. Location Container: contains all information belonging to the event location and the location referencing.
5. À la carte Container: contains specific information about the event in case it is required to transmit additional information not included in the three previous containers.

Further information about the Decentralized Environmental Notification Service and DENM messages like the protocol steps or inner fields used in each container, may be found in [11].

By using, at least, these two services (Cooperative Awareness Basic Service and Decentralized Environmental Notification Service), together with their corresponding messages (CAM and DENM), vehicles should be able to recognize the status of the traffic in its near or medium range, and to increase traffic efficiency and safety.

3. Methodology and Project Development

Before describing the results and finally present the conclusions is important to know which tools, references and parameters were used in this project. This chapter aims to introduce these three concepts that allow to find the way to get the results and present the final conclusions.

First of all, the first clause (3.1) describes the simulator software by presenting its multiple software components, their functionalities and characteristics that fulfil the necessities of having a good protocol behaviour as the standard demands.

The next clause (3.2) presents some of the reference papers and, among them, the one that is the basic reference that inspired the scenario used for this project. Moreover, a description of the differences between the original scenario and the ones actually used and the reasons for applying these differences.

Finally, the third clause (3.3) describes all the interesting parameters that will be used to analyse the results obtained from the simulations (chapter 4) and so, to get the final conclusions for chapter 5. Describing the selected parameters and the theory behind them should help to understand better the behaviour of all the transmissions within the simulations (i.e. probability of losses, losses respect the distance, scheduled transmission, transmissions succeeded, etc.) and so, reach the right conclusions about the protocols evaluation.

3.1. The Project's Simulator

Many projects on the C-ITS field are being developed around the world and, for this reason, there are many ways of looking for results. These "ways" might be real scenarios or, more commonly, simulated ones. Most researches use a simulation software because it allows them to create multiple scenarios with less economic and time costs than real tests and, because of these positive effects, there are multiple simulation software options (i.e. NS-2, NS-3, Omnet++, etc.).

In order to choose a simulation software, it is necessary to know which are the requirements to be fulfilled. By knowing this information, it is easier to look which simulators (and complementary software) fulfil them. On this project, the chosen simulator must give support to the ETSI proposal protocol stack for C-ITS communication, and needs the following requirements:

- IEEE 802.11p protocol implementation with multi-channel.
- ETSI ITS-G5 protocol implementation as the main one.
- IPv6 protocol support (together with 802.11p or in a different module).
- 4G/LTE support for future researches and other technologies comparison.
- Realistic traffic support to have more accurate results respect the real world.
- Real maps support to simulate real scenario cases.

The selected simulator to fulfil the previous requirements is a combination of multiple software components, which are:

1. **Omnet++:** The basic software is not a simulator itself but its platform functionality allows it to join multiple modules and it can be seen as a network simulator.
2. **Simulation of Urban MObility (SUMO):** Open-source traffic simulator that allows to define traffic (number of vehicles, routes, speeds, etc.) along multiple roads. It allows to define the characteristics of each vehicle route individually (different speeds, destinations, paths, etc.).
3. **Veins:** Open-source software containing the 802.11p and IEEE 1609.4 DSRC/WAVE (including multi-channel) and able to reconfigure the vehicles and their routes respect the packets exchange. It allows to import real world scenarios (buildings, speed limits, etc) from OpenStreetMap and takes into account the shadowing created by buildings and vehicles.
4. **Artery:** Veins framework extension that contains the ETSI ITS-G5 standard including GeoNetworking, BTP and DCC protocols (by using Vanetza). Based on this standard, it is able to simulate V2X communications.

As Fig. 10 shows, Omnet++ is the basic framework that manages all the other components within it. Omnet++ is responsible for controlling and designing any simulation and it allows to configure parameters like sensibility, data rate, transmission power, etc. of each ITS stations (OBU or RSU). Omnet++ is also responsible for controlling the channel and therefore it can collect the statistics generated data in other modules within the simulator.

Within Omnet++, the first module to be found is Veins, this module manages the first layer of the ETSI ITS protocol stack and the other important point as it is to simulate vehicles mobility. To do this, Veins module uses the SUMO module (they work together in parallel) which is the module responsible for constantly generating the traffic flow by changing the vehicles speed (and so, their position), advancing or stopping other vehicles, etc. SUMO module is also responsible for the scenarios by creating them or by using real maps; it is also responsible for generating all vehicles behaviour by allowing to define different vehicle types (cars, ambulances, pedestrians, etc.) in general or individually among other possible situations.

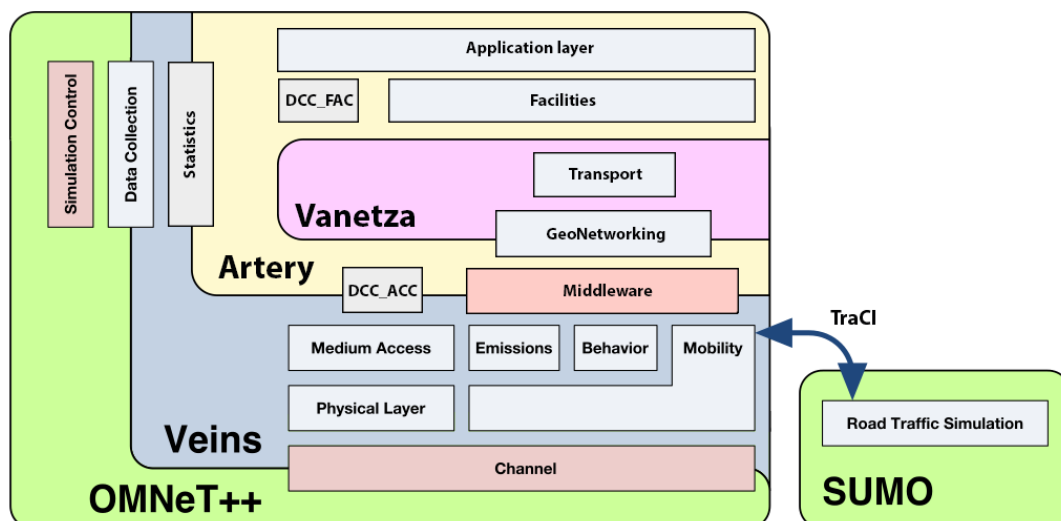


Fig. 10 - Simulator architecture [Source: i2Cat].

Within Veins module, there is the Artery module managing all information related to the Applications level (simulating a vehicle application) and the two upper layers of the ETSI ITS protocol stack (Facilities, Transport and Networking). At this module, all statistics are collected to be sent to Omnet++ and save them for later analysis.

While the Physical layer management and control is shared by Omnet++ and Veins module, the Networking layer management and control is shared by Artery and Vanetza. Vanetza is the last module used in our simulation framework and is responsible for having a good Transport layer functionality.

To understand better all the relationships within this framework, it is better to follow all the transmission and reception process through Fig. 10: within the Artery module, there is an application simulating the Cooperative Awareness Basic Service (2.5.1). Every 0,1 seconds an order to generate a CAM is sent from the Applications module to the Facilities module. Once a CAM is created, the Facilities module passes it to the Transport module (belonging to Vanetza) and this encapsulates the CAM into a BTP packet (2.4.1.3). The BTP packet follows the same process by being sent to the Networking module and encapsulated into a GeoNetworking (2.4.1.3) message. Finally, this message is sent to the Medium Access and Physical modules to be encapsulated into a MAC (2.4.1.4) frame and sent.

Once the MAC frame is received by each available ITS station, the frame follows an opposite process to extract all the information layer by layer from the Access layer up to the facilities layer which will present the information to the user through the right user application.

3.2. Use Cases and Project Proposal Scenarios

Before starting any simulation, it is good to know which researches have been done before. By knowing what other research groups did and which results they got, gives to any project a reference point where to start from or compare to.

Many researches and papers have been done about C-ITS field, but as the objective of this project is to evaluate 802.11p and GeoNetworking protocols, only those papers focused on these two protocols were taken into consideration.

3.2.1. Reference Researches

The reason for studying other institutions' multiple research papers, is to collect and know what these research organizations were looking for and which parameters did they study in order to reach their final conclusions.

The research papers that inspired the simulations of this project were focused on multiple parameters of the 802.11p like delays performance, collision probability, throughput, etc. By studying multiple and different parameters, this project aims to do a complete evaluation of the two selected protocols.

Thinking about vehicle scenarios, many situations and places could be selected. By looking the references used for this project [17] - [22], a general classification of vehicle scenarios may be done. This classification has 3 different scenario types:

- Urban: a city or a piece of it with multiple streets causing multiple propagation paths due to the buildings and other obstacles like traffic signals, traffic vehicle flows or densities, etc.

- Rural: a "flat" open air (small roads with some intersections) with some obstacles like trees or wide curves with no permanent direct line-of-sight.
- Highway: a straight and "long" road with multiple lanes and a variable traffic flow (high to low density of vehicles) with a permanent direct line-of-sight.

Among these three possibilities, the chosen scenario for this project is the Highway. The reason to select this scenario is its simplicity on the multipath analysis by using the two most common scenarios propagation models with direct line-of-sight: Free-Space Path-Loss model and Two-Ray Ground-Reflection model (3.3.1) which are well implemented in this project's simulator (3.1).

Another important point is that highway scenarios are the main scenarios used in most of the references found. This is due to the high mobility (vehicles speeds are high, therefore there is variability on the ad-hoc networks) and the traffic density within one path (multiple vehicles trying to access a channel without central point that manages it).

Among all the selected reference research papers, the following list presents some of them. These papers were used to extract possible examples of highway scenarios (3.2.2) to implement possible concepts (3.3) to study and evaluate for this project:

- "Evaluation of the IEEE 802.11p MAC method for V2V Communication" [17].
- "A Computationally Inexpensive Empirical Model of IEEE 802.11p Radio Shadowing in Urban Environments" [18].
- "IEEE 802.11p Performance Evaluation and Protocol Enhancement" [19].
- "Modelling Broadcasting in IEEE 802.11p/WAVE Vehicular Networks" [20].
- "Performance Evaluation of the 802.11p WAVE Communication Standard" [21].
- "Performance Evaluation of IEEE 1609 WAVE and IEEE 802.11p for Vehicular Communications" [22].

The first idea when analysing all the found project papers is to select one of them and repeat exactly the simulation it describes by using the same defined characteristics: vehicle speeds, packets lengths, vehicles entrance/lane, etc.

The objective to repeat an already done simulation is to find out if our simulator gives similar results to those described on the selected paper, which would mean that our simulating software works well.

3.2.2. Scenarios

3.2.2.1. Original Scenario

From the previous list of references and among them all, the first one is the selected paper describing the scenario used as basic scenario reference for this project. This paper describes a scenario with the following characteristics:

- 10 km long highway with 5 lanes in each direction and the vehicle entrance for all lanes is distributed by a Poisson mean inter-arrival time of 3 seconds.
- There are three vehicles speeds defined: 23 m/s, 30 m/s and 37 m/s with a standard deviation of 1m/s.

- An assumption of no overtaking (a vehicle always on the same lane) is done and only heartbeat broadcast messages are sent.
- Sensibility is defined to reach 500 or 1000 meters maximum.
- Variable PHY packet lengths (100, 300 and 500 bytes) and they are transmitted with the minimum transfer rate that 802.11p allows: 3 Mbps.

When trying to reproduce the previous scenario, there were some difficulties during the simulation and obtain similar results due to missing information details on the papers description (i.e. how did they manage all the information generated?) and due to limitations in our current simulation software version (i.e. defining specific multiple speed vehicles is harder than just letting the simulator give a random speed to each vehicle).

Although it was not possible to reproduce the same exact scenario, it was possible at least to get the basic idea (by reading their conclusions) and even without the missing information try to reach the same simulation conclusions. Therefore, it was possible to check that our simulator was giving correct results by looking the behaviour of important variables like the propagation models (3.3.1). By doing this, it was possible to conclude that our simulator works well and take into consideration the variability of the channel while transmissions are being placed along the scenario.

3.2.2.2. Original Scenario's Modifications

As previously explained, the used scenario had some alterations respect the original one. The three most relevant parameters that changed were on one side the number of possible vehicle speeds and the vehicle's entrance in each lane and, on the other side, the highway and packet lengths and the value of the transfer rate.

– Vehicle's Speed Modification

On the original scenario, there were three possible speeds (23 m/s, 30 m/s and 37 m/s), but on the current simulator software version is hard to manually program a specific speed for each lane, but, on the other side, it is easier to define the speed of vehicles. Looking highways near the city of Barcelona, the speed limits are between 80 km/h and 120 km/h, therefore, because of this two values, the selected speed on the initial scenarios was of 100 km/h (27.7 m/s).

As described in the previous paragraph, there is a margin between the minimum and the maximum allowed speed and due to these limits, each driver may accelerate or stop in a different way from other drivers, which means that the global movement is irregular.

Due to this reason, the scenarios evaluated during this project could be distinguished from those cases with the same speed for all the vehicles (27.7 m/s) or from those cases with a random and variable speed for each vehicle depending on their surroundings (managed by SUMO with a maximum speed of 30 m/s) creating a more real traffic flow.

– Vehicle's Entrance Lane Modification

The other vehicle modification respect to the original scenario is the way vehicles enter the highway. The initial tests were following the condition described within the reference paper (3 s Sweden rule), making all vehicles appear in a constant way with a distance of 3 seconds between one vehicle and the next. In our case, with an initial constant speed of 27.7 m/s, it means introducing a vehicle every 0.15 s (Fig. 11, i).

Traffic laws describe a safety time (or distance) between vehicles but, as human people do not drive in a constant way, the entrance of vehicles was changed from a 3 seconds to a uniform random distribution between 0 and x seconds (Fig. 11, ii).

The objective of changing the way of entrance was to generate an irregular vehicles entrance and therefore have a more real traffic flow.

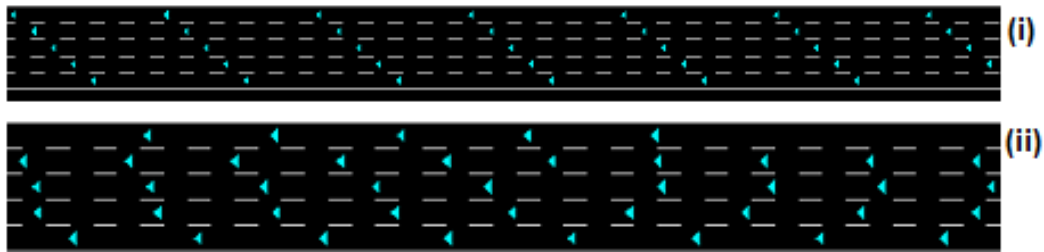


Fig. 11 - Constant speed and entrance (i) vs. Random speed and entrance (ii).

– Highway Length

While the previous parameters modifications were related to the behaviour of the vehicles, the length is related to the characteristics of the highway itself.

The initial idea was to work with the same length (10 km) as the original scenario, but after the first simulation round, results showed that this distance requires a big amount of time resources. Therefore, the 10 km distance was used to realise two simulation cases in order to evaluate the propagation models and, once it was done, the distance was shortened to 1 km (with this new length, simulations lasted also a lot of time).

Focusing on the time resources improvement, another important positive effect of using a shorter length is that, from that moment, it was possible to relate in a better way the vehicles density per kilometre with any of the studied parameters.

In future projects, the distance could be increased in order to use the studied parameters to evaluate possible cases like when there are hidden nodes.

– Packet Length

Originally, three packet lengths were used. These lengths were of 100, 300 and 500 bytes, but they were just a number of bytes sent as a heartbeat. On this project, the objective was to use as much as possible the defined length for the CAM messages. As the minimum fields that a CAM must have are not specified, on this project was created a CAM with a size of 74 bytes. This CAM was structured with a Header, a Basic Container and a HF Container (containing a Basic Vehicle Container HF). In some moments, a LF container was also included, but the general and most used CAM configuration was without LF Container.

Once the CAM was specified, the rest of protocols (BTP, GeoNetworking, MAC) were included to finally have a 998 bytes packet at the PHY layer to be sent at least every 0.1s (10 Hz) or every 1s (1 Hz) as the Cooperative Awareness BS [10] specifies.

– Transfer Rate

The last modification respect the original scenario is the used speed to transmit data. While the original scenario was using a transfer rate of 3 Mbps, this project was defined to use the next allowed possible speed, that is 6 Mbps.

By doing this, this project uses the highest speed of the two most common possible speeds. Knowing the limits of 6 Mbps, we can assure that the same situation with a lower speed would work as well.

The modifications commented previously are resumed in Tab. 1:

	Original Scenario	Used Scenario
Vehicle's Speed	23 m/s, 30 m/s and 37 m/s	1) Constant (27.7 m/s) 2) Random (done by SUMO)
Vehicle's Entrance/Lane	A distance between vehicles equal to 3 s depending on each speed	1) Constant (every 0.15 s at 27.7 m/s speed) 2) Random (done by SUMO)
Highway Length	10 km	Initially 10 km, then 1 km
Transmitted Packet Length	100, 300, 500 bytes	998 bits
Transfer Rate	3 Mbps	6 Mbps

Tab. 1 - Differences between original scenario and used scenario.

3.3. Studied Concepts

Before data analysis can be done, it is really important to know which concepts are needed so, later on, we can get the desired results and extract the final conclusions. Because of this reason, the following subchapters describe which concepts were used by this project to evaluate our simulations and, more important, which are the questions to be solved.

Due to the kind of networks this project is dealing with (mesh network with high mobility of the nodes), the study of multiple concepts must look to conclude if, through the selected protocols, the channel access for all nodes is equal among them all and if they also receive transmitted information (no ACK is used to confirm receptions).

It is really important that all nodes have a granted and equal channel access, so they can send their current information (CAMs) and, more important, in case they need it, urgent information frames (DENMs).

All the concepts are described as follows: first of all, those used propagation models are presented with their characteristics and with the differences that there are between them. The second concept to evaluate is about frames, their characteristics (GeoNetworking packet and 802.11p frame), possible reasons to have losses and their related probabilities of losses. The third concept is the transmission time, where a comparison between the minimum transmission (the best) and the simulated transmission to show their differences is done, moreover the theoretical minimum transmission time is calculated and so, it is possible to evaluate whether the simulated transmission times are accepted or whether something must be change to improve them. The fourth concept is the propagation time, a simple comparison to evaluate that the simulator follows the

theoretical values is done. Finally, the concept of throughput is presented with a theoretical value to be compared with simulation results.

3.3.1. Propagation Models

One of the objectives to verify in the project work plan is to check how the propagation models may affect the results and later on compare these models when there is no mobility between vehicles (overtaking is not possible) and when there is a mobility between them all (i.e. vehicles may advance each other, one vehicle faster or slower than another and then the opposite, etc.).

For highway scenarios, two propagation models were selected: the Free-space path loss and the Two-ray ground-reflection models. Both models can predict the losses of the signal along the direct path between a transmitter and a receiver when there is no obstacle in the middle, meaning there is Line-of-sight (LOS) between them.

3.3.1.1. Free-Space Path Loss Model

An easy way to understand the model described by Harald Trap Friis (1893 - 1976) is by imagining a cylinder like the one Fig. 12 shows.

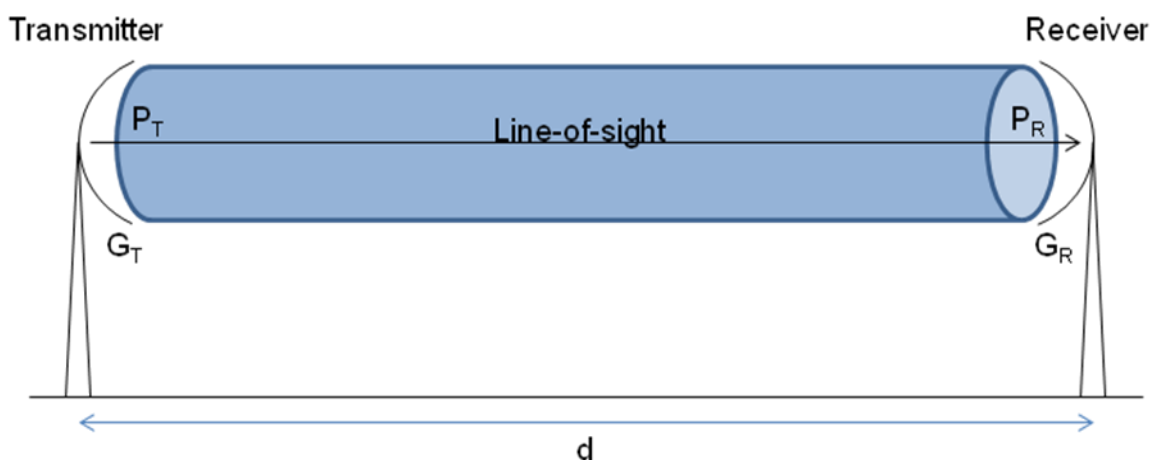


Fig. 12 - Free-space path loss scheme.

Taking the circle on the extreme of the cylinder like in Fig. 13, if the receiver (black circle) is within (i) the LOS (blue circle), then it will receive the information sent by the transmitter. If the receiver is not completely within the circle (ii), then the information might not arrive completely and, finally, if the receiver is out of the circle (iii), it will not receive anything.

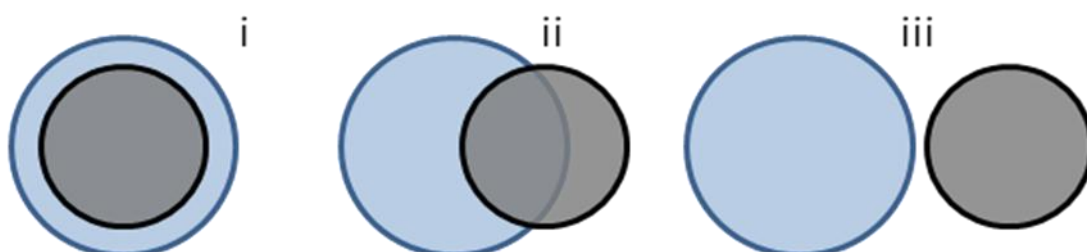


Fig. 13 - Antenna centred (i), Antenna half centred (ii), Antenna not centred (iii).

This model only considers the most direct line-of-sight between nodes (Fresnel zones are no in consideration), and because of this, no negative effects due to counter-phase signals must be considered. As it only contemplates one single ray and no other external effects are taken into account, the distance between the transmitter and the receiver is the most negative parameter.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

Eq. 1 - Free-space path loss formula.

Eq. 1 [16] shows that to compensate the distance variable (d^2), other parameters can be used to improve the losses, mainly the antenna gains (on the transmitter, on the receiver or on both sides) and the transmission power.

3.3.1.2. Two-ray Ground-Reflection Model

This second model follows a similar idea as the one of the previous model, but it considers not only the most direct LOS between nodes, but also the ground reflection path between the transmitter and the receiver.

Fig. 14 shows a scheme of the two LOS of this model: in blue, the direct path (used also for the Free-Space Path Loss) and, in red, the reflection.

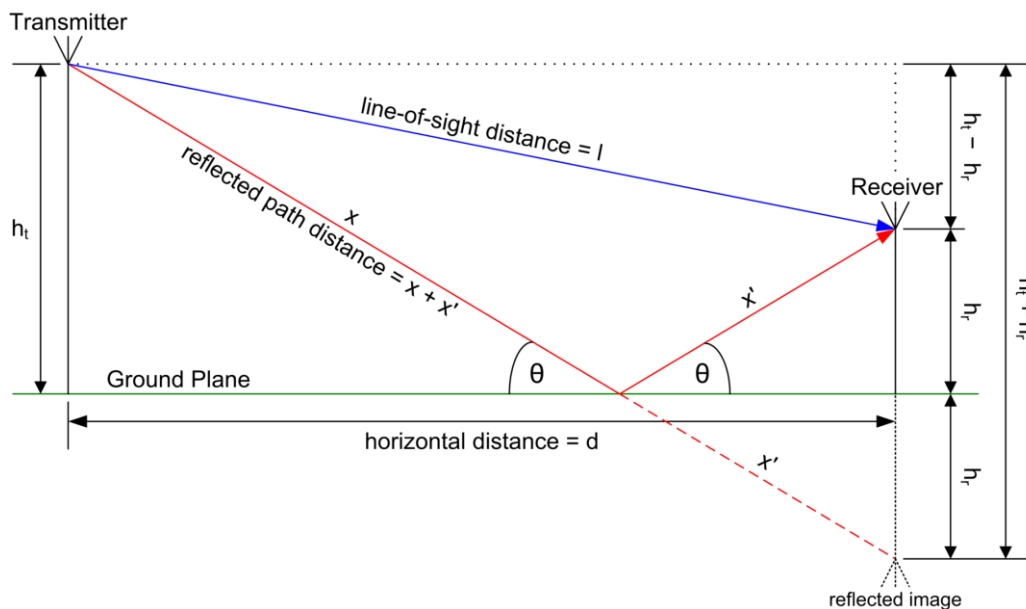


Fig. 14- Two-ray ground-reflection model [Source: Wikipedia]

Because of this second path, now, not only the distance (d) between nodes is the most negative parameter (before d^2 , now d^4), but also the antenna heights (h_t , h_r) of both nodes.

If the antenna heights are small and the distance is big, the losses will be high and there will be low reception power, which means having a poor reception power (sensitivity) at the receiver. Eq. 2 [16] shows the formula used to calculate the sensitivity and the variables described before (d , h_t , h_r):

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L}$$

Eq. 2 - Two-ray ground-reflection formula.

3.3.1.3. Free-Space Path Loss vs. Two-Ray Ground-Reflection Models

As explained before, both models are similar and the only difference between them is the inclusion of a single reflection rebounding on the street on the Two-Ray Ground-Reflection model.

It is necessary to keep in mind that real world scenarios might have more than one reflection due to the possibility of multiple metal objects (vehicles) between a transmitter and a receiver. All said and done, someone could say that the two selected models are not appropriate. But, with the previous negative point, our scenario can be considered real because highway usually don't have surrounding buildings and, the most important, they offer good LOS between all vehicles without any obstacle hiding them.

In order to compare these two models on the evolution over the distance, all parameters (except distance) that might affect the results must have the same value. For this reason, those common parameters like the antenna gains (G_T , G_R) or losses (L) are equal (usually with a value of 1 giving neutral behaviour). By giving the same values to these parameters, then it is possible to compare the results of the two models.

Theoretically (and proven already), the evolution of both models along the distance is as Fig. 15 shows. This figure shows that one model is better than the other, depending on the covered distance.

On near distances, the Free-Space Path Loss model works better than the Two-Ray Ground-Reflection model which has two important negative peaks in 50 m and 150 m distances. This might be because on these distances the reflection is in anti-phase respect the main signal and so, the received signal might have 0 value (i.e., no information). On far distances, the Free-Space Path Loss model works in an opposite way: it has bigger fading and so, bigger losses than the other model.

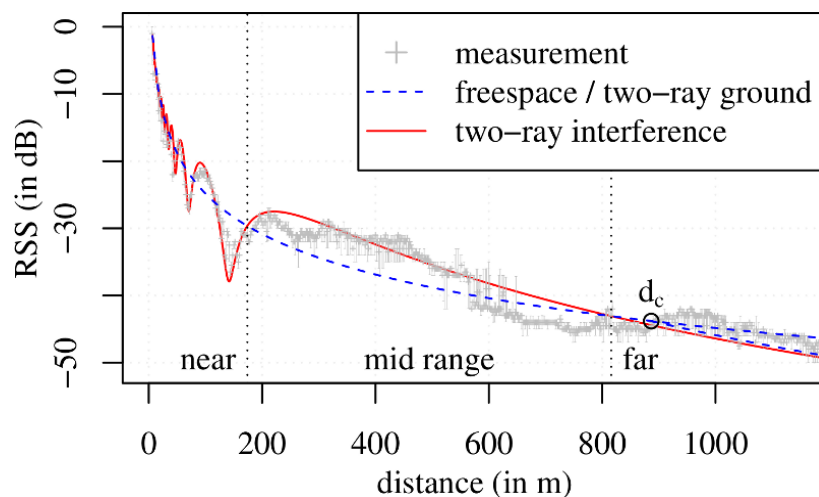


Fig. 15 - Evolution of fading through the distance [Source: veins.car2x.org].

By taking these models into consideration, the objective at this point is to compare and check that the simulations follow what the theory describes. This can be done by looking

how many messages get lost along the distance and, as explained, verifying in which distances appear those two negative peaks. Then, it will be possible to affirm that these models are well programmed in our simulator and so, that the expected behaviour is fulfilled.

3.3.2. Frames and Losses Theory

The second concept to study is the transmission of frames and their reception. Usually, the common point of view of transmissions is to work between nodes by sending and confirming the received information. But the Basic Services Set (CAM and DENM) have a different point of views (safeness is essential): sending and confirming (through ACKs) may require a long time, therefore, ACK is not used. For this reason, the objective of these services is to send a small but constant flow of information to let the receivers be aware of their surroundings.

Due to the previous idea, the concepts to be evaluated in this part of the project are related to losses and confirm that the rules of the services are assured (the number of received CAMs per second from each transmitter, the amount of losses and their reasons).

Before describing the concepts introduced in the previous paragraph, it is necessary to know which kind of packets each service uses on the lower layers. As the protocols to evaluate on this project are GeoNetworking and 802.11p, it is necessary to describe their corresponding packet or frame introduced in the ETSI documentation [5].

3.3.2.1. GeoNetworking Packet

Similar to other protocols, the GeoNetworking packet has a structure based on a header and a payload (if necessary). While the inner payload structure depends on upper protocol entities (BTP, services, etc.), the basic header of this protocol is organised in three parts:

1. Basic Header: with a size of 4 bytes, it contains the version protocol field, the next header type field, a lifetime and the maximum allowed hops for the packet.
2. Common Header: with a size of 8 bytes, inside there are fields like the next header type, the current header type and sub-type and the payload length among other information fields.
3. Extended Header (optional): it has a variable size depending on the transmitted packet, with a minimum size of 2 bytes when a GeoNetworking beacon is sent. This header is used to send information like the sequence number, the short or long position vector, etc.

For further information about the GeoNetworking structure packets or their inner fields information, check the ETSI documentation [6].

3.3.2.2. 802.11p Frame

Equal to the previous described packet, 802.11p uses a frame structure organised with multiple fields.

802.11p has multiple frame types, but at this point of the project, the interesting frame is the Data Frame. This frame is organised as follows:

1. MAC header: variable header due to the existence of some fields (Address 4, QoS Control and HT Control) that may appear or not. In our MAC frame, this three fields are not used and because of this, it is possible to specify the length of this header equal to 24 bytes. Example of fields belonging to the MAC header are:
 - Frame Control containing protocol version, frame type, and more information.
 - Duration/ID
 - 3 addresses fields
 - Sequence Control.
2. LLC header: contains the control information of the LLC layer (an inner layer within the MAC layer) and its size is 8 bytes.
3. MAC payload: with a variable size (from 0 to 7951 bytes), it contains the information coming from the upper layers such as Transport and Network and Facilities layers (CAM message within BTP and GeoNetworking packets). As explained before (3.2.2.2), the size of the MAC payload on this project is 86 bytes.
4. FCS: used to validate the received MAC frame in our receiver node contains the same information as it had when sent from the transmitter (information integrity). Its size is 4 bytes (it uses a CRC of 32 bits).

For further information about the 802.11p structure packets or their inner fields information, check the IEEE standard documentation [1].

3.3.2.3. Loss Probability and Reasons

The previous subchapters (3.3.2.1, 3.3.2.2) introduced the packet and frame structures used to create the messages which are sent between nodes in each simulation. In order to be considered a good simulation software, losses are one of the most important parameters and the software needs to simulate it as if it were happening in real world.

There are many reasons for a frame to be lost while getting transmitted or to not be accepted by the receiver (which also must be counted as lost). To explain these reasons, it is necessary to describe what might happen on each layer:

1. MAC layer

On this layer, the main reason to discard a frame is information integrity. As explained before, inside the MAC frame there is the FCS field which uses the CRC to check if all the received bits of the MAC header, the LLC header and the MAC payload gives are correct.

If the FCS is correct, then the frame is accepted and it is allowed to travel to the upper layer (Transport and Network) of the ETSI protocol stack. If FCS is erroneous, the received MAC frame is dropped and, in this communication case, it will wait for a new frame to arrive (which will contain a CAM message).

2. PHY layer

While on the MAC layer there is one reason to discard frames and count them as lost, on the Physical layer there are at least three reasons to control and check how many

packets are lost and how much each one of the three reasons affect the total number of lost packets.

The first reason to lose packets is due to the SNIR on the receiver. If the arriving packet does not reach the minimum SNIR, this packet will be dropped. There might be mainly two ways to have a low SNIR in reception:

- Due to the noise around the receiver: if it is higher than the signal of the received packet, then the receiver will not be able to distinguish the signal packet from the noise and therefore the packet will be dropped.
- Due to the fact that during the travel from the transmitter and the receiver, a collision happened between the two packets and the second packet caused errors on the first packet signal. When this first packet arrives, its inner information and its signal power might be changed causing an SNIR signal decrease.

The second reason to lose packets is because of collisions on the receiver. It could happen that two nodes do not see each other and transmit at the same time. For this reason, both packets will disturb each other on reception level. While one of them is being received, the other one will arrive and mix its information with the one of the first packet causing errors.

The third reason to drop a packet is similar to the previous one. A node can transmit a packet but, at the same time, receive one from a hidden node. These two actions cannot happen at the same time therefore, both packets will have problems on the receiving level: the received packet will be dropped and the transmitted one will depend on the decision taken by the receiver.

3.3.2.4. Proposal for CAMs Evaluation

Thanks to the non-existence of any kind of ACK on the CAM or DENM services, it is really important to evaluate that those messages are constantly arriving to the receivers and they don't get lost due to collisions while travelling or low sensibility on the receiver. Due to this and to the fact that one of the requirements is to send a number of CAMs every second (from 1 to 10), one of the most important objectives of this project is to evaluate how many CAMs each vehicle receives. If the amount of received CAMs is equal or close to the transmitted one (i.e. if there are 10 vehicles and all of them send 10 CAM/s then, each vehicle should receive 90 CAM/s), then, the channel is good.

To evaluate this concept, an increment of the number of vehicles was done. By increasing the number of vehicles, we need to evaluate how the number of losses evolve and affect the received number of CAMs. At this point, it might be possible to define thresholds to determine which CAM transmission frequency (between 1 CAM/s and 10 CAM/s) to use at each moment. So, when the received number of CAMs is below a certain value, a threshold could be determined and the upper service would be notified by the Facilities in order to modify the CAM transmission frequency.

A proposal of how many transmitted CAM/s depending on the density of vehicles will be explained later on, in the results chapter.

3.3.3. Study of Times

When speaking about multiple nodes creating a mesh network, as there is no central node distributing the channel access to all the nodes around, it is important to evaluate how much time each node is using the channel.

Multiple times are involved when a transmission is done and they must be taken into account. These times are: transmission time (T_{tx}), propagation time (t_{prop}) and node-internal process time. To better understand the differences between these three times, an analogy with writing and sending a letter could be done:

- **Transmission Time** is the time needed to write all the information in a white paper and give it to the postman. In communication theory refers to the time a packet needs to go from the transmitter into the channel (postman).
- **Propagation Time** is the equivalent to the time a letter needs to reach the receiver's house. In communication theory, it is the time to travel the distance between two nodes (transmitter and receiver) through the channel.
- **Process Time** is the time a receiver needs to read the content of the letter and, if necessary, the time to take any decision about his next action (send back the letter, answer it, etc.). In communication theory would be those internal actions that a receiver does when reception is done: extract the information or encapsulate it into a new packet.

Comparing the three times between them, the first two time parameters usually have higher values than the third one. Due to this reason and to the fact that processing time depends mainly on the internal computational characteristics of each node, only the transmission and propagation times were evaluated.

3.3.3.1. Transmission Time

The less time a node needs to transmit any packet, the less the packet is exposed to transmission problems and, more important, the channel is less busy from the point of view of any other node. The longer the channel is free, the more often any node can use it and therefore create more transmissions. For this reason, the expected value of this time should be short if multiple messages like CAM from multiple nodes must be sent within a second (each node might send up to 10 CAM/s).

To evaluate this time, it is necessary to know the theoretical value that should appear on the simulations. By using one of the most fundamental formulas in physics, the velocity formula ($v = x / t$), it will be possible to find out the theoretical value of this time.

As our objective is to find out the time parameter (t), it is necessary to know the two other missing parameters (x and v) and so, it is fixed to an unknown value (t_{tx}). Then, the total size (l) of the transmitted packet must be found together with the speed (from now on called bit rate, R_b) which the packet is transmitted. Therefore, the equation to calculate t_{tx} becomes:

$$t_{tx} = \frac{l}{R_b}$$

Eq. 3 - Adapted velocity formula.

To find out the two previous missing parameters (l , R_b), it is required to know the packet structure of the Physical (PHY) layer, which is the layer where channel access is done by managing receptions and transmissions. Together with the packet structure, it is also important to know how the access to the channel (without central point management) is done. So, any node keeps using it all the time without letting the other access and keep them waiting forever.

– **PHY Packet Structure**

Among all the PHY packets, it is necessary to know only the one used for transmitting data, called "Data Frame". Fig. 16 shows its structure, which is organised in three fields:

1. Preamble - String of bits known by all nodes to recognise the start of any frame. Its size is of 32 bits.
2. Signal - Indicates the characteristics about the Data Frame field like length, etc. It has a size of 24 bits.
3. Data Frame - Contains the information of the upper layers. Its size depends mainly on the PSDU field which contains the whole MAC frame (calculated later on).

With the sizes already defined, only the R_b parameter is missing.

Many protocols have multiple transfer rates, each one of them associated with one of the fields composing their protocol packets/frames/messages. This is exactly what happens on the PHY layer: there is a specific R_b for each packet field.

In the current case, the Preamble is transmitted at 1 Mbps, the Signal at 3 Mbps and the Data Frame depends on the specified values within the used MAC layer standard. As previously described (2.4.1.4), in C-ITS the idea is to allow transfer rates of 3 Mbps or 6 Mbps. As the most common value is 6 Mbps, this was the chosen transfer rate for the simulations done for this project.

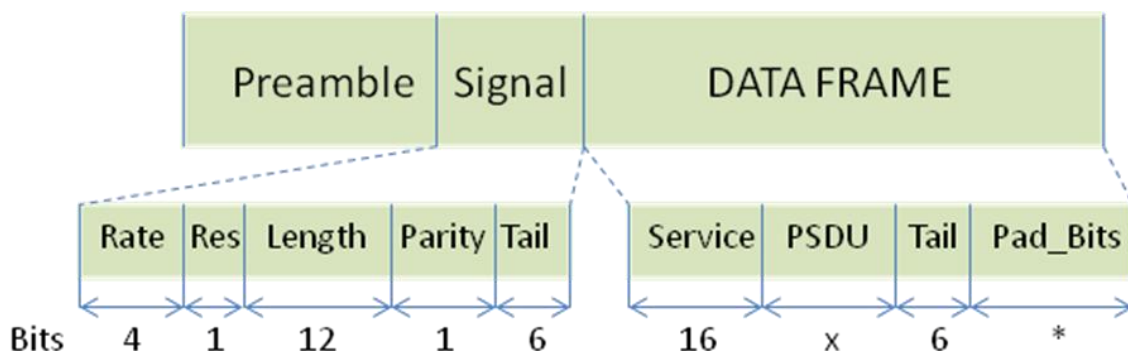


Fig. 16 - PHY data packet structure and field sizes.

Further information about how the layers organise their packets and frames structures (sizes and fields) to encapsulate or decapsulate the packets/frames/messages between them can be found in appendix B.

Now that the two missing parameters are known, only one more important concept is needed: how the nodes manage between them an equal channel access so that all nodes may have the same channel access and none of them keeps waiting to transmit because the others pass over it.

– **Backoff Procedure and Waiting Time (t_{wait})**

As previously explained, t_{tx} implies the action of transmitting a packet whenever this is ready to be sent. But in case two nodes want to transmit at the same moment, then, a conflict for the channel access would happen, generating a packet collision.

If the channel access on this project would be managed by a central node, there would be no collisions because all nodes would know their associated time slot to transmit. As this is not the case (ad-hoc networks have no central node), all nodes try to access the channel whenever they have a packet ready, therefore this situation generates a high number of collisions.

To avoid all these collisions as much as possible, it is necessary to apply a procedure of collision avoidance (CA). In 802.11p, a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is used to access the medium.

The basic concept to keep in mind for this procedure is the idea of “Backoff Time”: an individual inner-node time that forces each node to wait a random amount of time (within a threshold) to check if the medium is idle and then, transmit.

The Backoff Time is generated by using a random integer selected from a uniform distribution over the interval $[0, CW]$ (CW refers to Contention Window value [1]), and by multiplying the selected random integer by the value of a slotTime ($13\mu s$) as Eq. 4 - Backoff Time equation [Source: IEEE]. Eq. 4 shows.

$$\text{Backoff Time} = \text{Random} () \times a\text{SlotTime}$$

aSlotTime: equal to $13\mu s$

Eq. 4 - Backoff Time equation [Source: IEEE].

When a node has selected a Backoff time, it keeps listening the medium while decreasing by one for any action is done until 0. The moment it reaches 0, the node checks the medium and if the medium is idle, then this node can transmit.

If a node transmits while another one decreases its Backoff value, the second node stops decreasing its Backoff and waits until the first one finishes its transmission. Once this transmission is done, the second node must wait an Arbitration Inter-Frame Space (AIFS) [1] and if the channel is idle, then the second node can transmit. If the channel is busy (a third node started transmitting), the second node must wait again, stopping the Backoff decrement until the end of the third node transmission. Once the transmission is done, the second node continues decreasing its Backoff until 0 (unless there is a new transmission, in which case it will be stopped again). Then, when the Backoff is 0, and so, the medium is idle, it will be able to transmit.

Each node manages only its own Backoff time, which means that there is no priority. The first node reaching a Backoff time equal to 0 and finding the medium idle, will transmit and the other nodes will just listen (stopping their Backoff procedure).

As the Backoff time takes part in the transmission, another time must be added to the transmission time: the waiting time (t_{wait}). This takes into consideration the amount of time a node has been waiting before transmitting.

Because of t_{wait} , Eq. 3 is not right anymore and must be changed for Eq. 5, giving the right equation for the Transmission Time (from now on T_{tx}) with the waiting time (t_{wait}) and what it could be called transfer time (t_{tx}).

$$T_{tx} = t_{wait} + t_{tx} = \frac{l}{R_b} + t_{wait}$$

Eq. 5 - Transmission time equation.

By knowing all the parameters involved in the transmission time, now it is possible to calculate the reference value used to analyse the time values extracted from the simulations and get any possible conclusion.

Theoretical Minimum Transmission Time

As the nodes objective respect the channel usage is to use it the least possible, the reference time value has to be the minimum time needed to transmit a packet. This reference value is the Minimum Transmission Time (T_{tx_min}).

This time should be reached in case all nodes would be perfectly synchronised, then no Backoff procedure would be used and so, the waiting time would have a minimum value equal to the AIFS time needed to check that the channel is idle. Therefore, we can mathematically define T_{tx_min} as the sum of the transfer time (t_{tx_PHY}) of a PHY packet and of a single AIFS time (t_{AIFS}) as Eq. 6 shows.

One more step can be done to get a more specific equation. The transfer time of a PHY packet is divided in three parameters due to the three fields (each one using a different bit rate) which compose the PHY packet.

$$T_{tx_min} = t_{wait} + t_{tx} = t_{AIFS} + t_{tx_PHY} = t_{AIFS} + t_{preamble} + t_{signal} + t_{PHY_data}$$

Eq. 6 - Minimum transmission time equation.

At last, the t_{tx_min} equation is composed by 4 parameters: $t_{preamble}$, t_{signal} , t_{data} , t_{AIFS} . Except t_{data} , the other three time are specified by the standard (they have known static bit rates and sizes). As Fig. 17 shoes, t_{AIFS} and $t_{preamble}$ are equal to $32\mu s$ and t_{signal} equal to $8\mu s$, leaving t_{data} as the only unknown value.

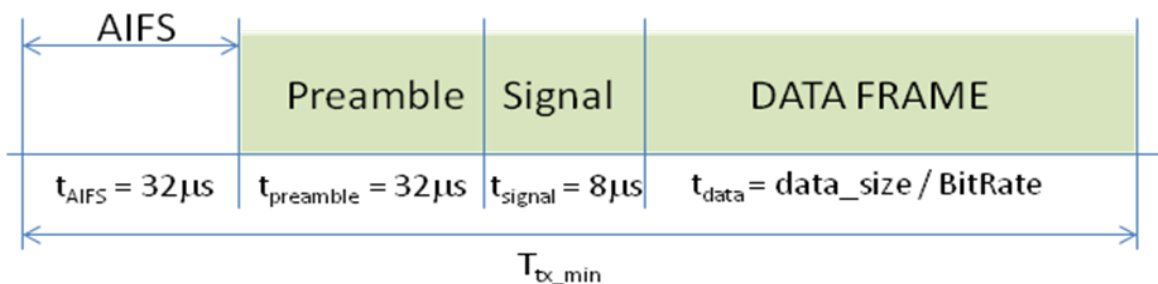


Fig. 17- PHY data structure with field transmission times.

t_{data} depends on the PHY packet size and the bit rate at which this information is transmitted. The two possible bit rates are 3 or 6 Mbps (802.11p standard), while the size depends on the designed CAM within the simulator.

The ETSI protocol stack creates the defined packet structure (appendix B), whose structure we need to understand: the PHY data field depends on the MAC frame, which, in turn, depends on the GeoNetworking packet with its payload field containing the CAM message, coming from the Facilities layer as described in 2.5.1.

The Standard [10] about CAM messages does not define a static size for these messages, it only gives the possible information that might include (for example, speed of the vehicle, direction, latitude, longitude, etc.). Because of this variability, our CAM message was defined with the minimum fields specified, giving a size of 74 bytes.

These 74 bytes together with the 12 bytes of GeoNetworking header generate the GeoNetworking packet and become the MAC payload with a size of 86 bytes.

Then, by adding the MAC header fields (Frame Control, Duration ID, three Addresses, Sequence Control, LLC and FCS), the MAC frame (122 bytes) is generated and encapsulated into the PSDU field of the PHY packet. Finally, to complete the PHY Data structure, the Service (2 bytes) and the Tail (6 bits) fields are added to create the PHY Data with a size of 998 bits.

At this point, we know all the needed information to calculate the theoretical value of the minimum transmission time:

I_{PHY_data}	R_b	$t_{preamble}$	t_{signal}	t_{AIFS}
998 bits	3 or 6 Mbps	32 μ s	8 μ s	32 μ s

Tab. 2 - Minimum Transmission Time parameters.

By selecting a bit rate of 6 Mbps and using Tab. 2 values, Eq. 6 becomes

$$T_{tx_min_6mbps} = 32\mu s + 32\mu s + 8\mu s + \frac{998 \text{ bits}}{6 \cdot 10^6 \text{ bps}} = 72\mu s + 166,333\mu s$$

and gives

$$T_{tx_min_6mbps} = 238,333\mu s$$

In case of using a bit rate equal to 3 Mbps (lowest bit rate in 802.11p) to get the t_{data} , then the value of the minimum transmission time is:

$$T_{tx_min_3mbps} = 364,667\mu s$$

While the second calculated value should be fulfilled, in this project is just presented to show the minimum data time needed to transfer. The important case to be studied and evaluated once the simulations are done is the time case when using 6 Mbps bit rate.

– Theoretical Minimum Transmission Time vs. Real Transmission Time

By knowing the theoretical minimum transmission time, the objective from this point on is to evaluate the simulation transmission times and, so, to check if the transmissions are behaving as expected.

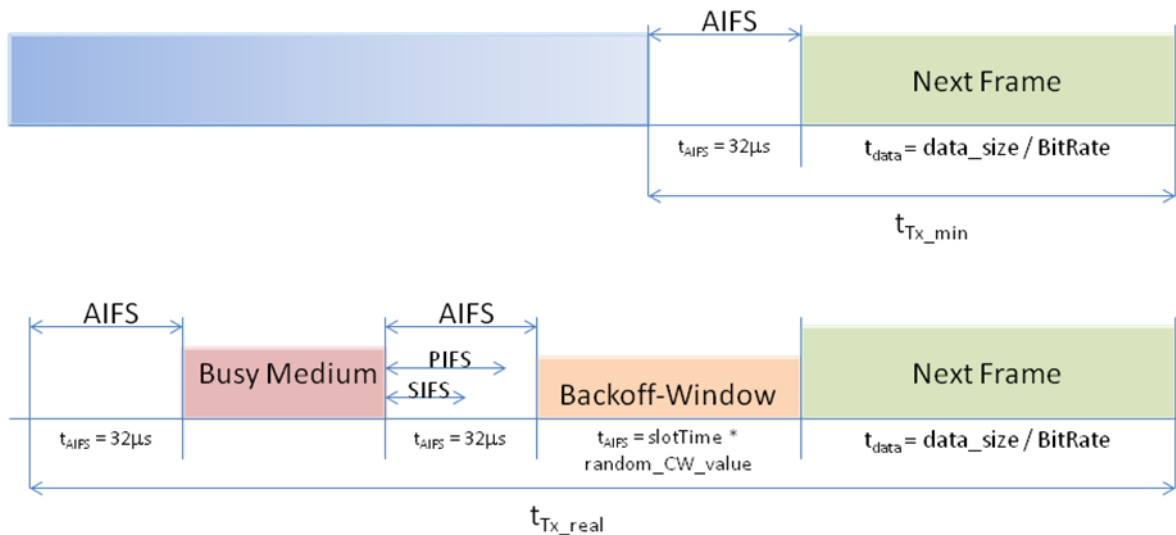


Fig. 18 - Minimum Transmission Time vs. Real Transmission Time.

Another relationship to evaluate is the one between the t_{wait} and the Backoff time by checking which difference there is between the simulated data and the theoretical minimum transmission time. Fig. 18 shows this difference (in blue) between the minimum transmission time and the real one, which allows us to understand how much the Backoff procedure may affect the transmission time of a single frame.

3.3.3.2. Propagation Time

Once the transmission time is described, the other important time to evaluate in this project is the propagation time. This is the time needed for a packet to travel from one point to another one (i.e. a letter that travels from the writer's home to the receiver's home).

Comparing this time with the transmission time, the propagation time should not have a high influence on the total needed time to generate, transmit, propagate and process the information inside a packet. In spite of this, its influence will be theoretically evaluated and then, compared with the data from the simulation to check that its influence respect the transmission time is minimal on the simulations.

Using the same idea as the previous time parameter (Eq. 3), two parameters are needed. In this case, they are the speed at which the information travels through the medium and the distance between the transmitter point and the reception point.

As previously described, the basic scenario is a highway of 1 km with 5 lanes in each direction. Because of this length, six cases were selected in order to include different distance ranges between the transmitting vehicle and the receiver and therefore, check the evolution of the propagation time respect the distances, these distances are: 10 m , 50 m and from 100 m to 1000 m every 100 m (Fig. 19).

Once we know the distance parameter, only the speed parameter is missing. As the transmission are done through air, the speed at which the information travels through this medium is the speed of light (299,972,458 m/s).

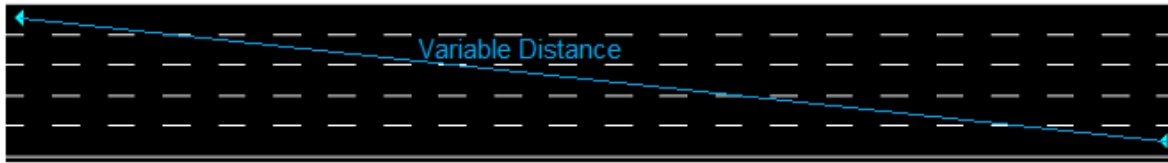


Fig. 19 - Graphical example of the simulation used with two cars.

Now that the two variables are known, it is possible to get the theoretical results. By simply dividing each distance over the speed of light ($t = d/v$), the propagation time of each case is found.

As Tab. 3 shows, the propagation times have really small values. Comparing these values to any of the minimum transmission time values calculated in the previous chapter, it is possible to conclude that even with the highest selected distance (1 km), the propagation time (3.336 μs) is really small compared to the minimum transmission time: 238.333 μs when bitrate is 6 Mbps and 364.667 μs for a bitrate of 3 Mbps. So, the highest propagation time (3.336 μs) on the simulations should be about 100 times smaller respect the simulated transmission time.

d (m)	10	50	100	200	300	400	500	600	700	800	900	1000
t_{prop} (μs)	0,333 * 10^3	0,167	0,333	0,667	1	1,33	1,67	2	2,33	2,67	3	3,33

Tab. 3 - Propagation times evolution respect distance between nodes.

In the results chapter, an evaluation of the propagation time respect the transmission time will be done to check if the simulated times have a difference of a factor 100.

4. Results

This chapter aims to present the results of all the simulations that were done during the development of this project. We pretend to evaluate different situations and how the transmissions behaviour evolved from one simulation to another.

This chapter is divided in three parts, the first one presents the results regarding the IEEE 802.11p protocol, which is the protocol in charge to access the channel and to guarantee that CAM messages are transmitted one at a time. The second part will present results related to the GeoNetworking protocol by evaluating how one of its new possible communications cases (i.e. GeoBroadcast) works. Finally, and due to the previous work done on the 802.11p tests, this chapter presents an evaluation of the CAM Basic Service in order to evaluate whether the CAM generation and transmission tax was working well or not and, as a consequence, the chapter presents a proposal to improve this service through some more simulation tests.

4.1. 802.11p Evaluation

In this first part, the results related to those parameters previously described (3.3) are presented. First of all, there is a description of the simulation results about the propagation models and which effects each model has on the simulations. Then, the results related to the probability of losses and their reasons are presented together with the proposal of the relationship between the number of CAM transmission and the number of vehicles (up to 300) to have a certain maximum loss probability. Finally, an evaluation of the time: the objective of this evaluation is to check whether the propagation and transmission times extracted from the simulations are similar (if possible equal) to the theoretical values or not.

4.1.1. Propagation Models Evaluation

4.1.1.1. Objectives and Used Scenario Characteristics

With the two proposed propagation models described in 3.3.1, the main objective was to check that the theory behind them was followed by the simulator. If the simulation data followed what it was expected, then it would be possible to confirm that the simulator applies well to the expected channel characteristic and so, that any results involving the channel should be accepted due to their similarity to the reality.

A second objective was to check if the car speed would affect to the transmissions. Due to the big difference between the range of vehicle speeds in a highway (from 22,22 m/s to 33,33 m/s) and the transmission speed of information (299.972.458 m/s), the communication between vehicles shouldn't be affected by the vehicles speed.

To evaluate these two objectives, the initial highway scenario was of 10 km with an amount of 300 vehicles involved, with a transmission power of 100 mW and 1 km range of sensitivity. Each simulation that has been done had different vehicles speed (constant or random) and vehicles entrance lane (constant or random), giving a total amount of 8 simulations.

4.1.1.2. Results

The reason why we used a highway length of 10 km is to check if the evolution of propagation models in short, medium and long distances between vehicles in our simulations follows what it was described in the reference figure (Fig. 15).

As the results of the 8 simulations were almost equal, only the results (Fig. 20 - Fig. 23) of the simulation with a constant vehicles entrance time and a constant speed for each vehicle are used to describe the behaviour of the channel for each propagation model.

– About the figures

Before presenting the results and for a better understanding of the following figures, it is necessary to explain how the horizontal axis organises the data. This axis represents the distance (m) between vehicles and it is divided in distances of 10m. Within the figures, every 10 m range is associated to a mean value of the loss probability. It might happen that the mean value between 30 and 40 m distances is higher than the mean value between the next two distances (40 to 50 m) .

Another characteristic of the following figures is their "tooth shape" in some parts within the figures. This shape is frequently repeated and it is due to the constant entrance and speed parameters used in the simulation. As the objective we aim to achieve in this part of the project is to validate whether the propagation models follow what the theoretical models describe or not, this shape does not affect the objective by no means.

– About the results

Analyzing the total number of lost packets based on the distance, it can be seen that the losses on the channel follow what the models describe.

On The "Free-Space Path Loss" model, the mean value of losses was about 15 - 18 % and the behaviour was exactly the expected one for this model. The probability of losing a packet increases through the distance giving a continuous logarithmic graph (Fig. 20).

Analysing the three field regions (near, medium and long distances), we can see that the behaviour is always continuous and there is no negative or positive peak at any region, meaning the losses are only produced due to the distance between vehicles. In long distances between nodes (more than 1000 meters), the losses must not be taken into account because the sensitivity of all nodes was limited to 1 km. Because of this, the minimum loss probability was between 4,5 - 5% in near distances and about 27,5 - 28% in 1 km.

Section 3.3.2.3 explains the reasons why a packet is lost. There were three possible situations to lose a packet: collision, low SNIR reception and receiving while transmitting. The current simulator, due to the way of counting each type of packet loss, is not able to determine which proportion of losses belongs to each one of the three possible loss situations. When getting the results, the data belonging to the last loss packet case (receiving while transmitting) could not have its own graph because the software treats both packets involved as SNIR losses, when only one of them should be seen as SNIR losses and the other one as a collided packet.

Because of the previous issue, it is not possible to give a correct and detailed (on each distance range) interpretation of the results, but it is possible to extract one idea.

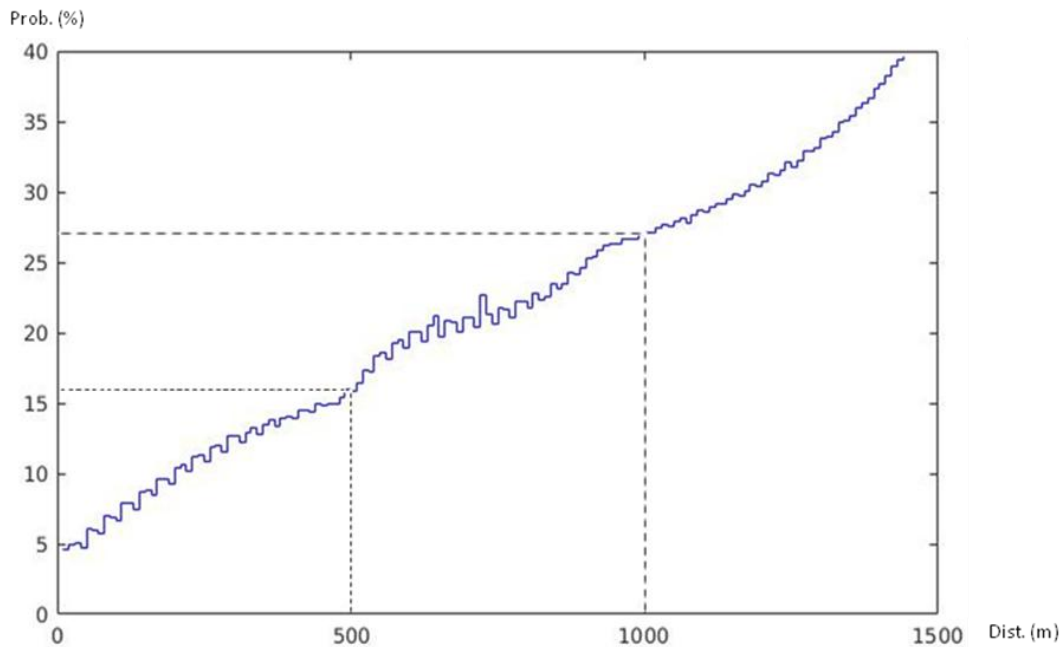


Fig. 20 - Loss prob. evolution respect distance of the Free-Space Path Loss case.

Analysing the global loss probability evolution, the main contributor is the SNIR threshold (right side of Fig. 21). Even with short distances there is already a low probability (2,82 % around 10 - 20 m) because the SNIR threshold takes into account also the signal of the other vehicles as interference (I), using Eq. 7 to get the value for each distance.

$$\frac{S}{(N + I)}$$

Eq. 7 - SNIR equation.

SNIR is the main contributor along all the distances, but there is a significant increment of collisions in middle distances (left side of Fig. 21 marked with a red circle). This increment is probably due to the hidden node problem. In the eight simulations used to check the propagation models, the vehicles were not always under the sensibility range of the other vehicles because their sensibilities were of 1 km max and the highway was 10 km long. Because of this, it might happen that those vehicles that were more advanced and those situated at the end of the whole group, did not and could not see each other. While one vehicle at the beginning was transmitting, probably also another at the end was doing the same, creating the increment of collision in middle distances.

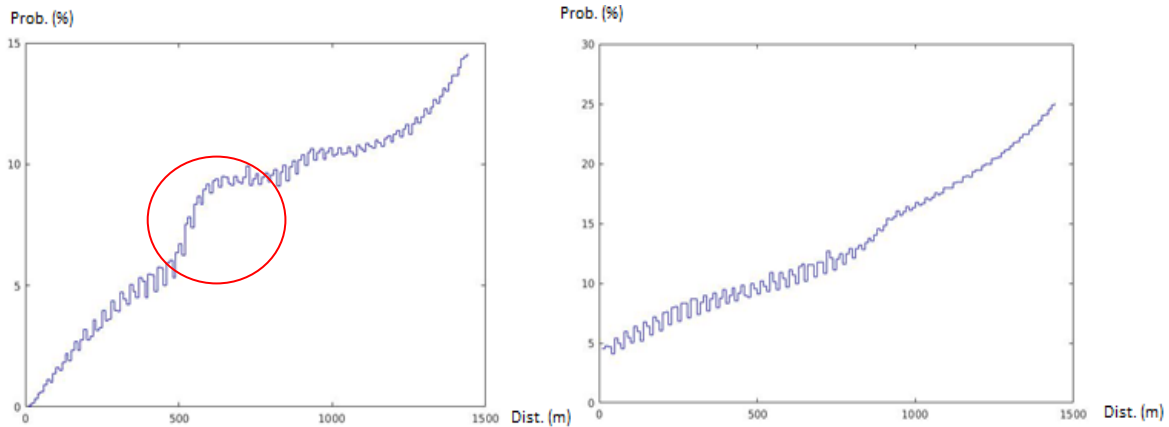


Fig. 21 - Losses evolution due to collision (left) and SNIR threshold (right).

About the collisions losses, the way to identify them within the simulations is the following: within the MAC frame structure (as Appendix B shows), there is the "Frame Check Sequence" (FCS) which is used to detect errors within the rest of the frame. If, while the receiver checks this MAC frame field, cannot recover the information, then the packet is dropped and counts as a lost packet due to collision.

Similar to the "Free-Space Path Loss" model, the "Two-Ray Ground-Reflection" results also followed what the reference model describes.

As it can be seen in Fig. 22, the most important characteristics of the reference model are the two negative peaks (red circle) that appear in small distances between nodes. They appear due to the oscillation caused by the constructive and destructive combination of two rays with opposite phases. The first one about 50 and 60 meters distance between vehicles, while the second peak about 170 and 180 meters distance. Then, once the distances get bigger, the losses decrease and start to increase in a softer way due to the increment of distances.

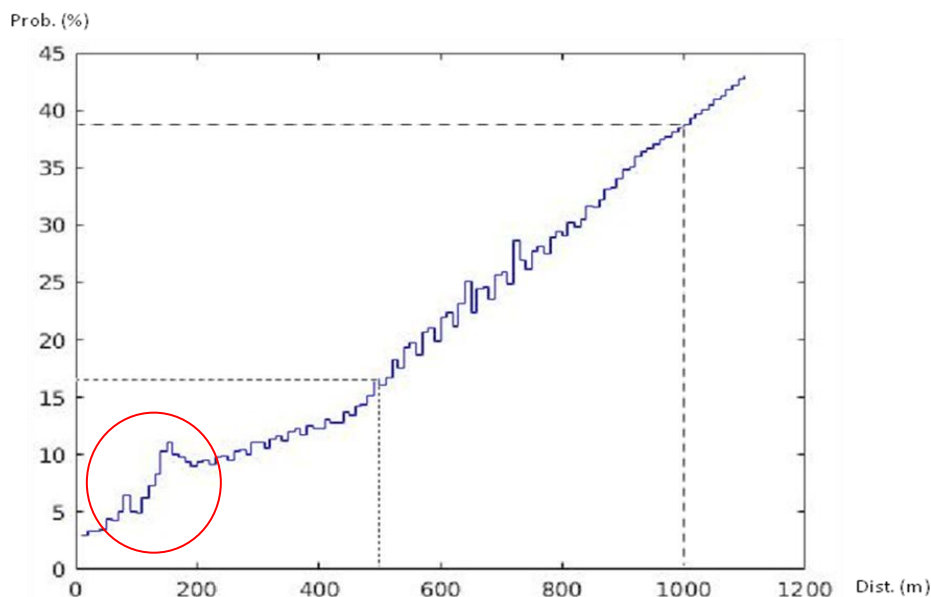


Fig. 22 - Loss prob. evolution respect distance of the Two-Ray Ground-Reflection case.

Similar to the previous model, a more detailed analysis of the reason why packets get lost cannot be computed due to the previous described software issue. But, once again, one single and general idea can be extracted by looking the graph on the left side of Fig. 23.

Similar to what Fig. 21 shows, in middle distances (about 500 meters) between vehicles, the number of losses due to collisions suddenly starts to increase and, except for the two characteristic peaks (short distance oscillations), the main contributor along all distances is still the SNIR.

On the following parameters evaluations, both propagation models were used to check if the difference between them could affect any of the parameters and so, help on the final conclusion about these two models.

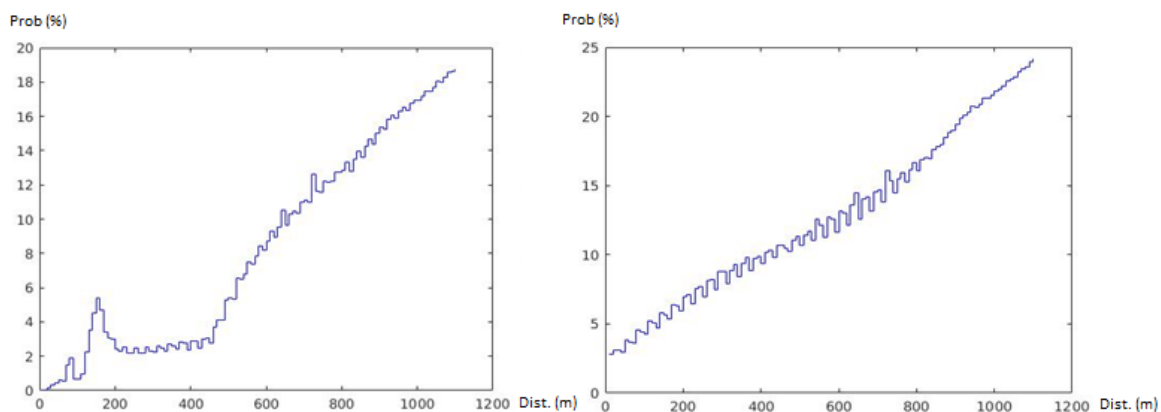


Fig. 23 - Losses evolution due to collision (left) and SNIR threshold (right).

4.1.2. Loss Probability Evaluation

4.1.2.1. Objectives and Used Scenario Characteristics

The objective was to evaluate how the increment of the vehicles density may affect the number of transmission losses. By analysing this, it could be possible to propose an improvement for the Collaborative Awareness Basic Service.

On the previous graphs, the loss probability values took into account all the distances between cars, even those out of the maximum sensitivity distance of a single car. As the objective of this project, starting from this subchapter, is to get more accurate values, some characteristics of the scenario were changed.

The first modification was the length of the scenario: from a 10km highway to 1 km. By doing this, time resources were improved (simulation duration) and all data could be evaluated over a density of x vehicles/km.

The range of density values selected are 10, 50, 100, 150, 200, 250 and 300 vehicles/km. For each density value selected, two simulations were done (one for each propagation model) and, for each simulation, the collected data was extracted individually from each node and saved into individual text files managed by MATLAB scripts, in order to extract mean values to be used as results.

The second modification was collecting data in two different ways: through the simulator and also through a node used as an observer. This way it was possible to get more

detailed data for each simulation, as this observer node collected and saved the time instants and their transmitter node identification when any CAM message was received.

Respect the vehicles entrance rate and vehicle speed, random values from a uniform distribution were used.

4.1.2.2. Results

Before presenting the results, it is also important to remember that the CAM generation frequency has a value of 10 CAMs per second (1 CAM / 0,1 s). This parameter is important because once the results are presented, a proposal affecting this parameter will be proposed in 4.3.4.

Fig. 24 and Fig. 25, show loss probability compared to the density of vehicles/km for each propagation model. In both cases, the probability values of each density sample (50, 100, etc) are similar and they follow what it was expected. Additionally, by increasing the number of vehicles per km, the probability to lose a message is also increased.

An important characteristic that can be seen by comparing the values of one sample respect to the previous one (except for the cases of 10 and 50 vehicles/km) is that the loss probability increases by a mean value of 2,2 every 50 vehicles (increase that happens in both models).

An unexpected and, at the same time, important value is the one of the last simulation (300 vehicles/km), which overpasses the 10% of losses, with a 15,53 – 15,61% depending on the propagation model.

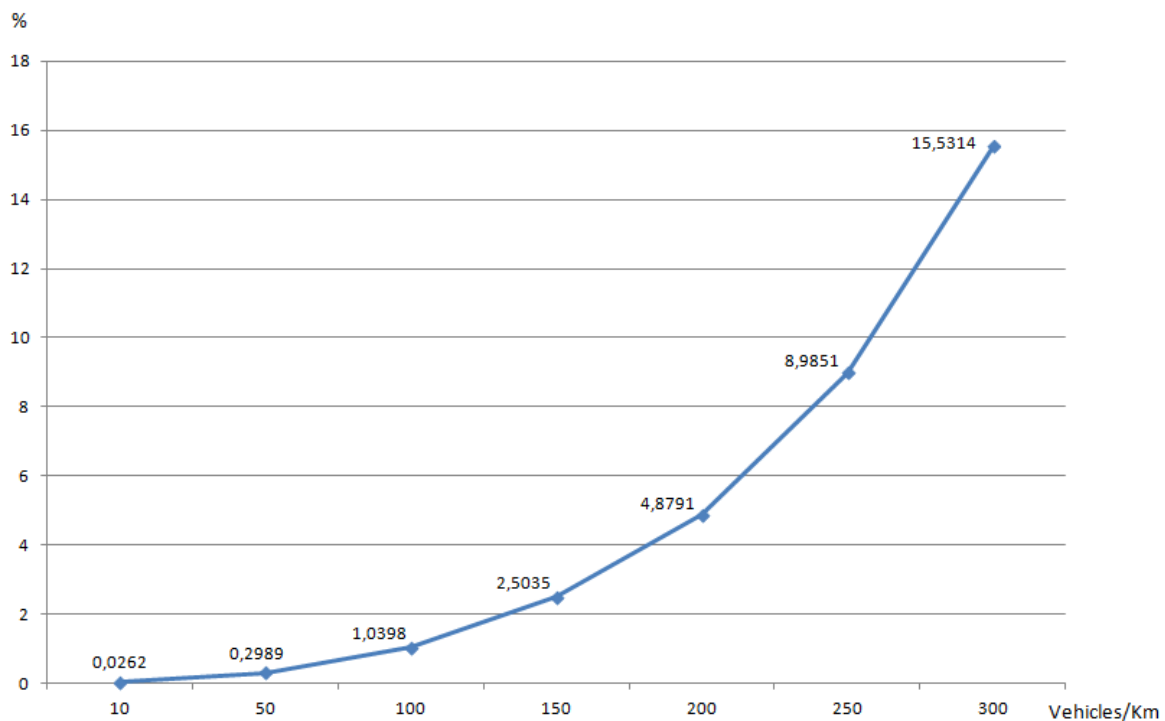


Fig. 24 - Loss probability evolution respect density (Free-Space Path Loss model).

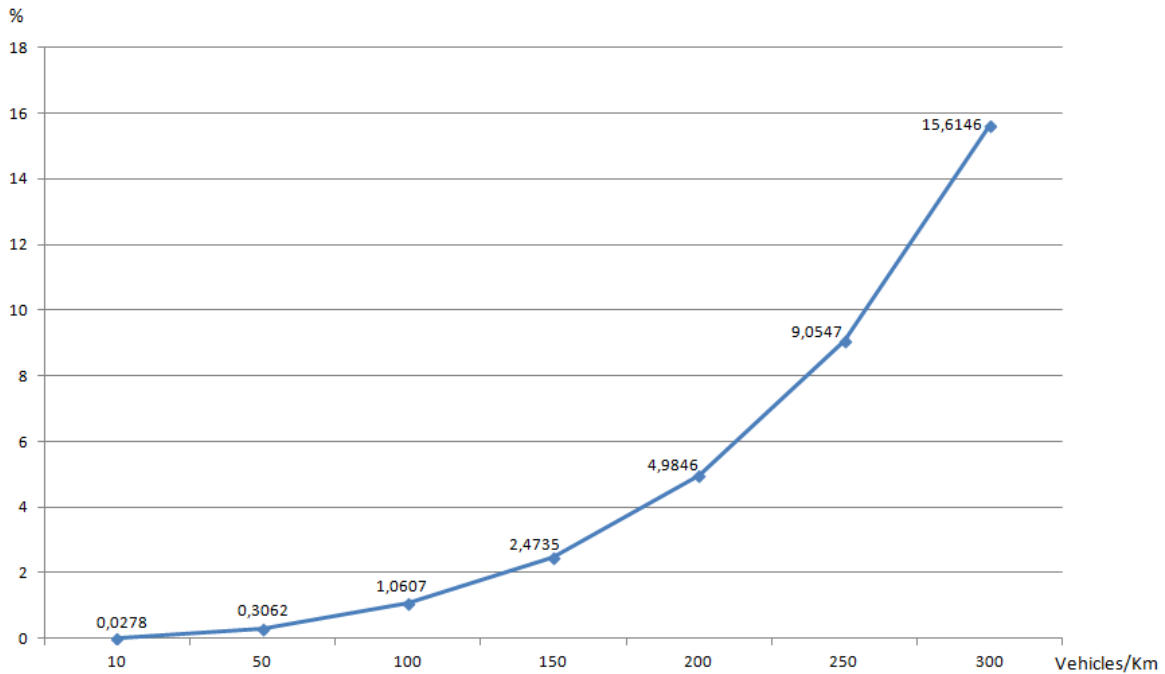


Fig. 25 - Loss probability evolution respect density (Two-Ray Ground-Reflection model).

Because of these last results, a new objective was thought. As the basic idea would be to keep the loss probability with a maximum range values between the 5 – 8% (meaning a 92 – 95% of success), new simulations will be done to find the evolution of the CAM generation tax respect the vehicles density. These simulations are to be understood as possible improvement for the CAM Basic Service (4.3.4), that would be an adaptive rate generation model.

4.1.3. Transmission and Propagation Times Evaluation

4.1.3.1. Objectives and Used Scenario Characteristics

For the time parameters, the two previously described scenarios (3.2.2) were used. To evaluate the transmission time was chosen the scenario with a highway of 1km length, while for the propagation time was chosen the scenario of 10 km long highway.

The reason to change scenario to evaluate the propagation time was to keep the maximum analysed distance (1 km) between vehicles as longer as possible, so multiple time samples could be extracted along the 10 km path. On the other side, for the transmission time evaluation, the scenario of 1 km was long enough to get samples and always keep each one of the nodes under the visibility of all the other nodes.

The objective to evaluate the transmission time is to find out how much the “waiting time” (3.3.3.1) affected the transmissions. On the other side, the objective to evaluate the propagation time was simply to check that the simulator works and takes into account all the related parameters that exist in the real world, for example, propagation speed of light.

4.1.3.2. Transmission Time and Waiting Time Results

Before describing the results of the analysis done on transmission time, it is necessary to remember that this time is composed by two components: waiting time (t_{wait}) and the minimum transmission time ($t_{AIFS} + t_{tx}$).

While the minimum transmission time was fulfilled by the simulator (238 μ s), the waiting time was not easy to find. To get the results, some of the data extracted by the simulator were used. The selected data were, on one side, the time that each node had to enter into Backoff and, on the other side, the number of slots being in Backoff for each node.

For each node, the following procedure was done: by multiplying the second value (Backoff slots/node) for the value of a single time slot (13 μ s), it is possible to get how much time (in total) each node had been in Backoff during the simulation. Then, dividing each one of the total Backoff times by the corresponding first value (times a node has entered into Backoff), the waiting time for each transmitted packet can be found.

As done in all the previous cases, also in this case, simulations were done using both propagation models. Next figures show that there is not so much difference between them, giving maximum values of 163 μ s with a density of 300 vehicles/km (163,1 μ s on the Free-Space Path Loss, Fig. 26, and 163,3 μ s, on the Two-Ray Ground -Reflection models, Fig. 27).

While evaluating succeed transmissions, simulation results proved that their transmission time was the same (238 μ s) as the theoretical time previously calculated (3.3.3.1). With the data extracted by the simulator and showed in the previous figures, it is possible to calculate and give a reference mean value of the total transmission time reference (T_{tx}) .

Taking into account that for the Free Space Path Loss model T_{tx} is equal to 401,1 μ s (238 μ s + 163,1 μ s) and for the Two-Ray Ground-Reflection models T_{tx} is 401,3 μ s (238 μ s + 163,3 μ s), the reference value for T_{tx} is **equal to 401,2 μ s**.

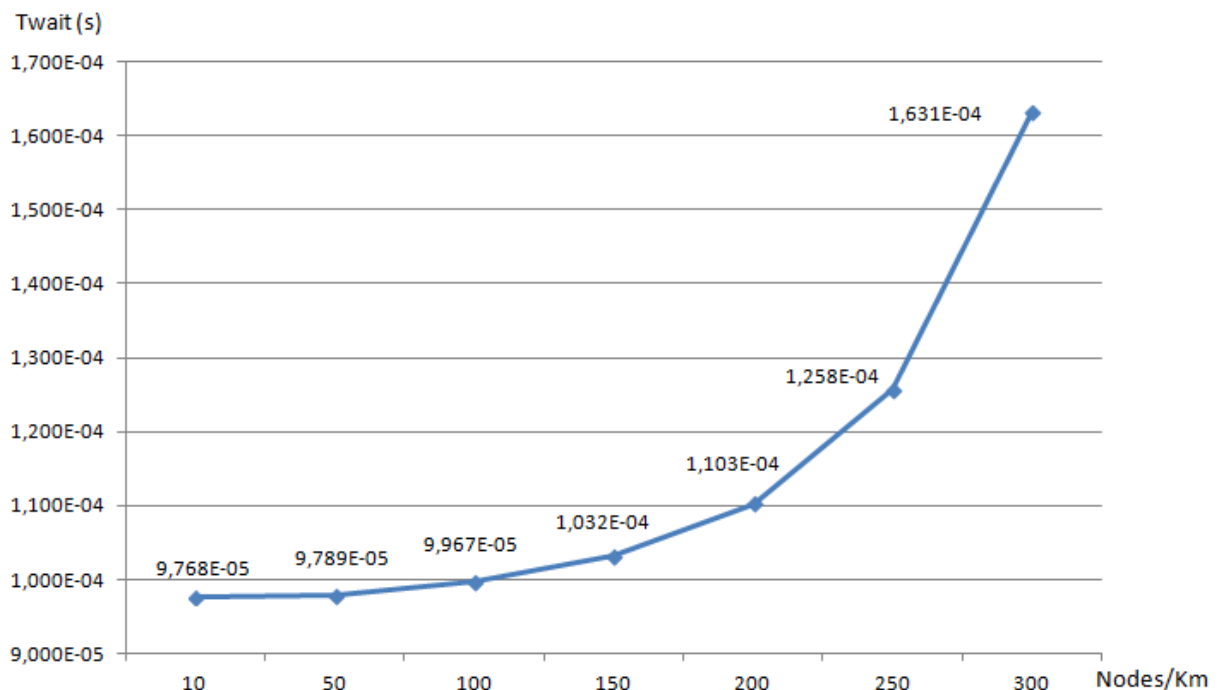


Fig. 26 - Waiting time evolution respect density (Free-Space Path Loss model).

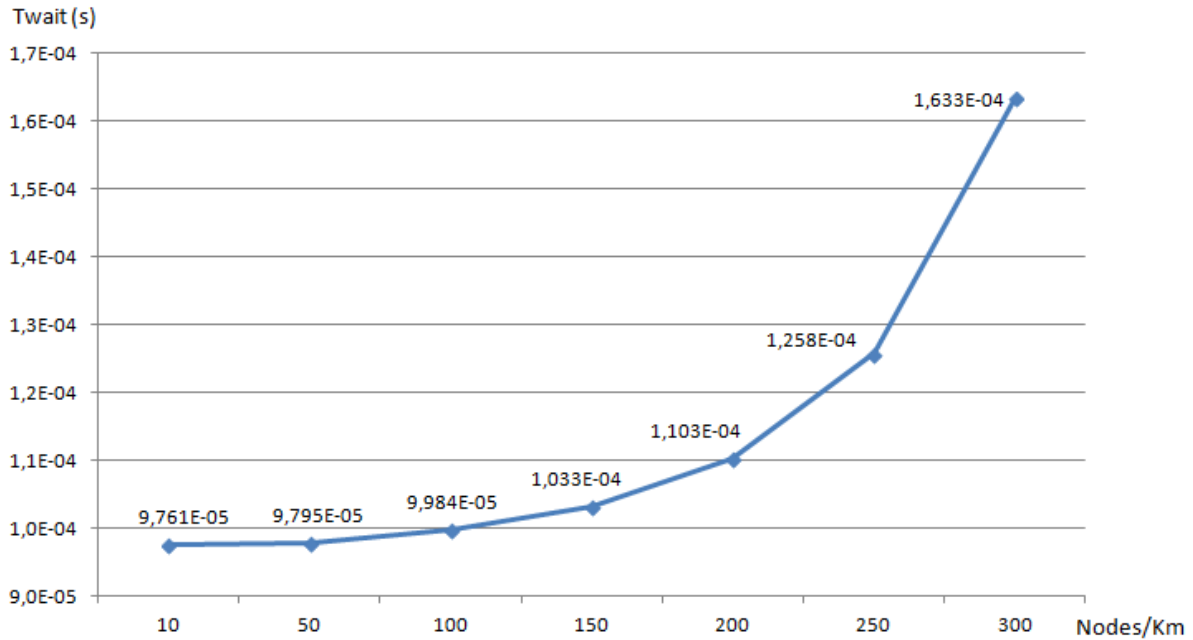


Fig. 27 - Waiting time evolution respect density (Two-Ray Ground-Reflection model).

4.1.3.3. Propagation Time Results

As it can be seen in the next table (Tab. 4), the simulated propagation times are similar to the theoretical values calculated at the beginning of this project.

D (m)	Theoretical T_{prop}	Simulated T_{prop}
10	33,36 ns	33,64 ns
50	166,78 ns	165,34 ns
100	333,60 ns	332,23 ns
200	666,73 ns	666,71
300	1 μ s	1,01 μ s
400	1,33 μ s	1,32 μ s
500	1,67 μ s	1,67 μ s
600	2 μ s	2,01 μ s
700	2,33 μ s	2,31 μ s
800	2,67 μ s	2,68 μ s
900	3 μ s	3,01 μ s
1000	3,33 μ s	3,34 μ s

Tab. 4 - Theoretical vs. simulated propagation time results.

There is a light difference between the theoretical and simulated results and the reason for this difference to appear is because, even if, in the simulator, speeds are defined with a constant value to keep the same distance along all the simulated time, within the simulator there is always a small variability on speeds in order to make the mobility much

more similar to the real drivers behaviours (a human driver is constantly accelerating and breaking). Due to this small variability, the results from the simulator do not allow to calculate the time keeping the same exact distances from the beginning until the end of the simulation and, so, get the same exact results as the theoretical values.

As the results follow what it is theoretically expected, it is possible to affirm that the simulator takes into account all those concepts involved in the transmission channel (i.e. propagation speed of light) and also other concepts like variability due to human behaviours.

4.2. GeoNetworking Evaluation

4.2.1. Objectives and Used Scenario Characteristics

As previously described, GeoNetworking is the protocol in charge of addressing and forwarding any packet coming from the lower layer by using geographical information like latitude and longitude parameters. Because of this specific characteristic, the evaluation done for this protocol has to check that the simulator is able to work this way.

All the simulations done for the 802.11p and also the ones done to describe the CAM Basic Service improvement (introduced in 4.3) were based on the Broadcast scenario, where all vehicles receive all the packets transmitted within their sensibility. On this evaluation, the scenario changes and the objective is to check that the GeoBroadcast case works well.

In order to check this, the simulation uses the 1 km highway and 11 vehicles, all of them identified as "vehX", with X being the identification number. The idea of this simulation (Fig. 28) is to let 10 vehicles move along the highway while the other one, "veh0", is located in the middle of the highway and is only able to receive with a sensibility of 1 km (seeing all the other vehicles at any moment). The other 10 vehicles, while moving, continuously transmit at a frequency of 10 Hz, but all their messages can only be received and accepted when vehicles are within the specific geographical area (light blue circle).

As Fig. 28 shows, the geographical area defined by a radius (in this case 50 m) around a central point defined by a latitude (0.000176) and a longitude (-1.486818) within the scenario. It also shows the lanes were the ten moving vehicles will drive and the situation of veh0, always outside the geographical area of reception and acceptance of packets.

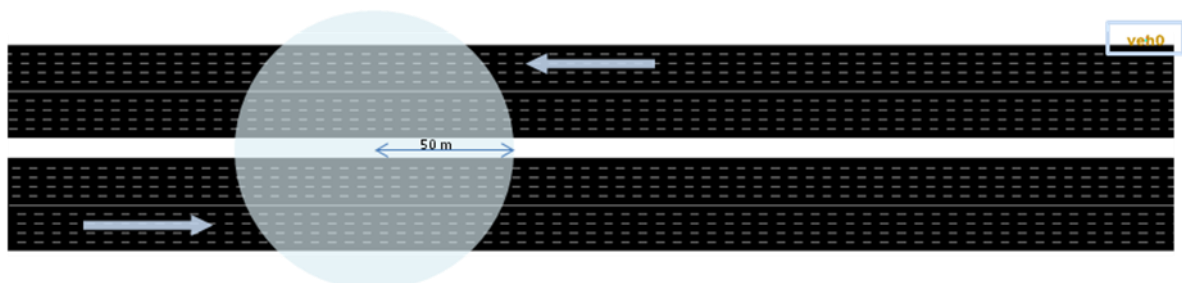


Fig. 28 - GeoNetworking highway scenario.

There are two possible ways to check the performance of the GeoNetworking: the first one is in real time, while the simulation is going on, and the second one is done once the simulation finishes by checking the number of CAM messages received by all vehicles.

4.2.2. Real Time Results

The following figures (Fig. 29 to Fig. 32) show multiple instants of the simulation. Each figure shows the current vehicles situation (which can be in or out of the geographical area) with a graphical image of the highway and also with a log image.

In all cases, there is a vehicle within the geographical reception area. In Fig. 29, for example, "veh5" just entered the area and so its GeoNetworking layer started to accept incoming packets from the lower layer. The next vehicle to start accepting incoming packets should be "veh10", which is what Fig. 30 shows. Now "veh5" and "veh10" are both accepting the incoming packets and allowing them to arrive to the upper layers. Meanwhile, the other GeoNetworking vehicles did not accept any packet. Fig. 31 shows the moment "veh10" exits the area and "veh1", "veh2", "veh3" and "veh8" are inside the area accepting the GeoNetworking messages, while "veh5" (which does not appear anymore in this image) and "veh10" do not accept any more GeoNetworking messages. Finally Fig. 32, shows that once "veh5" enters the geographical area once again, it starts again accepting the GeoNetworking messages at the same time of "veh7" (the slowest vehicle).



Fig. 29 - GeoNetworking situation: veh5 inside, the others outside.



Fig. 30 - GeoNetworking situation: veh5 and veh10 inside, the others outside.



Fig. 31 - GeoNetworking situation: veh1, veh2, veh3 and veh8 inside, the others outside.



Fig. 32 - GeoNetworking situation: veh5 and veh7 inside, the others outside.

All these previous figures help to demonstrate in real time the acceptance or not acceptance of GeoNetworking messages, meaning that GeoNetworking works well within the simulator.

4.2.3. Results Post-simulation

As a final review of the GeoNetworking simulation and evaluation, Tab. 5 shows the number of accepted CAM messages when a GeoBroadcast is applied compared to the same scenario but having normal Broadcast.

Node ID	Received and accepted CAM with GeoBroadcast	Received and accepted CAM with Broadcast
0	0	39799
1	6337	35826
2	9143	35839
3	10787	35860
4	7758	35813
5	4565	35833
6	3571	35808
7	4138	35811
8	9553	35794
9	7816	35810
10	6017	35806

Tab. 5 - GeoBroadcast reception vs. Broadcast reception.

The biggest difference is about veh0 which, as in the case of GeoBroadcast was outside the geographical area the whole simulation time, did not receive or accept any of the transmitted packages. On the other hand, when using broadcast it received and accepted all the messages. In general, all vehicles accepted much less CAM messages because of the smallest reception area defined when using GeoBroadcast.

Because of all the previous results (real time and post-simulation), it is possible to accept the implementation of GeoNetworking in the used simulator.

4.3. Collaborative Awareness Basic Service Evaluation

4.3.1. Objectives and Used Scenario Characteristics

The evaluation of IEEE 802.11p and its behaviour related to the access channel (losses respect distances or density, time of wait before transmitting, etc.) was done using one of the basic services defined within the ETSI standard: Collaborative Awareness Basic Service.

Once the channel was evaluated (by using 802.11p) and the conditions (loss probability and waiting time increment) under which its performance decreases were defined, it was important to evaluate how the service could be affected and whether its requirements were fulfilled or not. To find it out, two parameters were observed: CAM messages reception rate and the inter-arrival time between two CAM messages from the same transmitter.

The used scenario was a highway of 1 km length and random values for the vehicle speed and entrance parameters. Moreover all simulations used a CAM generation frequency of 10 Hz, but the important parameter to be modified was vehicle density.

It is important to underline that all data used to generate the results was extracted from a single vehicle (from now on called Node_0, instead of veh0) situated at the centre of the highway (500 m) which was only receiving (without transmitting, in order to not interfere). From all the possible collected data, this project used only the data generated during the period of time when all vehicles were within the highway until the end of the simulation.

4.3.2. CAM Reception Evaluation

One of the most important characteristics of the Collaborative Awareness Basic Service, as described in 2.5.1, is the defined transmission rate values (1 Hz or 10 Hz). Theoretically and due to these possible rates, each node should receive the defined value multiplied by the number of vehicles (except those messages sent by itself).

4.3.2.1. Results

By using simulations with multiple densities (x vehicles/km), Tab. 6 compares the theoretical total received amount of CAM/s with the simulated results for each propagation model. For example, by selecting a density of 10 vehicles/km, Node_0 should theoretically get 100 CAM/s. This is proven for the Free-Space Path Loss model, but not for the Two-Ray Ground-Reflection model. For the second model, at least one CAM (and probably some more) sent by any of the 10 transmitting nodes was lost, giving a reception probability of 99,981818 %.

Density (Vehicles / km)	Theoretical Frequency Reception (CAM/s)	Free-Space Path Loss		Two-Ray Ground-Reflection	
		Mean Simulated Frequency (CAM/s)	Reception Probability (%)	Mean Simulated Frequency (CAM/s)	Reception Probability (%)
10	100	100	100	99,9818	99,9818
50	500	498,2492	99,6498	499,0060	99,8012
100	1000	989,0243	98,9024	988,0878	98,8087
150	1500	1459,4224	97,2948	1460,2666	97,3511
200	2000	1897,3695	94,8684	1888,1606	94,4080
250	2500	2258,1671	90,3266	2247,8272	89,9130
300	3000	2493,1033	83,1034	2473,6757	82,4558

Tab. 6 - Reception CAM results evolution respect the density.

Checking the results from Tab. 6, cases with lower and medium densities (until 200 vehicles/km) have values over 94 % of success, which might be values accepted for real world scenarios. On the other side, the most important cases to remark are those with 250 and 300 vehicles per kilometre. Their probability of success decreases around 20% (16,9 % for the Free-Space Path Loss and 17,55 % for the Two-Ray Ground-Reflection models) respect the initial density case.

Tab. 6 results were extracted from the point of view of the Node_0 and managed using MATLAB scripts, while the results previously described in 4.1.2 were extracted and managed by the simulator data analytic. Due to these two different ways of extracting results, it was possible to compare them and, thanks to the similarity of both points of view, they were validated and accepted as good.

4.3.3. CAM Inter-arrival Time Evaluation

Another interesting parameter to analyse is the time between two received consecutive CAM messages from the same transmitter. While on the ETSI standard there is no specification about a minimum number of received CAM/s, it would be good to know how long a node moves without receiving any CAM from another node.

4.3.3.1. Inter-arrival Thresholds

In order to understand better the results, it is necessary to introduce a special programming characteristic related to the CAM generation added to the simulation software.

Depending on which generation value (i.e. 1 CAM/s, 10 CAM/s) the simulator uses, the best case in reception would be to receive messages from the same transmitter with the same values. As the simulator is the component that controls the transmission tax from all simulated nodes, there could be a synchronization among all nodes, meaning a

scheduled access channel which is not right on the network type this project deals with. To avoid this synchronization, when each node establishes its corresponding time instant to transmit a CAM, a random variability of ± 50 ms is added. For example, if a node transmits one CAM at a 3,4 s, then, the next CAM is generated at 3,5 s ($3,4 + 0,1$) and the variability $\pm 0,05$ s, giving two time possibilities: 3,45 or 3,55 s.

Because of this analysis, the theoretical time thresholds (Fig. 33) of the inter-arrival time during any of the simulations should be between 0,05 s and 0,15 s, with a mean value of 0,1 s (using the case of 10 CAM/s) which is the selected CAM generation tax.



Fig. 33 - CAM generation variability.

Even having this variability, the functionality and the analysis of the inter-arrival time is valid because each time is counted respect the previous one, so the selected CAM generation is respected and follows the standard defined by the ETSI.

4.3.3.2. Inter-arrival Time Results

The results presented in Tab. 7 come from Node_0. This special node (which does not transmit, but only receives) keeps the time of each received CAM and the corresponding transmitter node identification. Among all saved data, only those time samples within the period when all vehicles are participating to the simulation were selected and sorted under two conditions: the first one, following the nodes identifier (1,2,3,etc.) and the second, following the individual time sample groups of each node in incrementing time order.

Once all data was ordered, for each samples node group and starting from the second sample of each group, we needed to calculate the differences between them. Once we got these differences for each node, we also needed to calculate the mean value for each differences group, giving, in the case of 10 vehicles density, 10 mean values.

Finally, among all the mean values, two of them were selected (the minimum and the maximum of each individual mean values) in order to calculate the absolute mean value from the ten individual mean values, giving the next table.

Tab. 7 contains the three calculated values for each simulated case from 10 to 300 vehicles density with a generation CAM of 10 CAM/s. Among all the results and similar to the CAM reception evaluation, with low and medium densities, the resulted inter-arrival times could be accepted as good in both propagation models. For all cases, the mean value of the time between two consecutive CAM messages from the same transmitter is near 0,1 s from the transmission.

The difference between the CAM inter-arrival time values (Tab. 7) on the reception side and the theoretical CAM transmission rate (0,1 s) is due to the transmission time. More vehicles mean an increment of the waiting time parameter within the transmission time (4.1.3.2).

Density (Vehicles / km)	Free-Space Path Loss			Two-Ray Ground-Reflection		
	Absolute Mean Value(s)	Minimum Mean Value (s)	Maximum Mean Value (s)	Absolute Mean Value(s)	Minimum Mean Value (s)	Maximum Mean Value (s)
10	0,0999	0,0500	0,1955	0,1000	0,0500	0,1900
50	0,1003	0,0498	0,2622	0,1001	0,0497	0,2639
100	0,1010	0,0494	0,2927	0,1011	0,0494	0,2981
150	0,1027	0,0485	0,3329	0,1027	0,0486	0,3370
200	0,1053	0,0468	0,3796	0,1059	0,0462	0,3984
250	0,1106	0,0367	0,4648	0,1112	0,0363	0,4737
300	0,1203	0,0138	0,5928	0,1212	0,0152	0,5933

Tab. 7 - Total CAM inter-arrival evolution respect the density.

Respect the minimum mean time values, under a case density of 200 vehicles/Km the simulated values are near the theoretical expected value of 0,05 s. With higher densities, the values got much smaller than expected. The reason to this decrement is due to the previously described variability of +/- 50 ms and the MAC transmission queue.

Imagine that a "node_X" has a CAM message ready to be sent at time instant 0,21 s. It might happen that the channel is busy, so this CAM must go to the MAC queue and wait. At this point, the "node_X" has two possibilities: on one hand if the channel remains busy and a new CAM is generated, then the old one is discarded. On the other hand (showed in Fig. 34), if the channel gets idle before a new CAM is generated, then the current waiting CAM is sent, meaning that the transmission time is equal to the original (0,21 s) plus the time inside the queue (i.e. +35 ms). Then, if a new CAM of this "node_X" is generated and its variability is of -50 ms, it might happen that the second CAM is automatically sent after the first one, giving a small inter-arrival time of about 15 ms like the one of the Two-Ray Ground-Reflection model with a density of 300 vehicles/KM of Tab. 7.

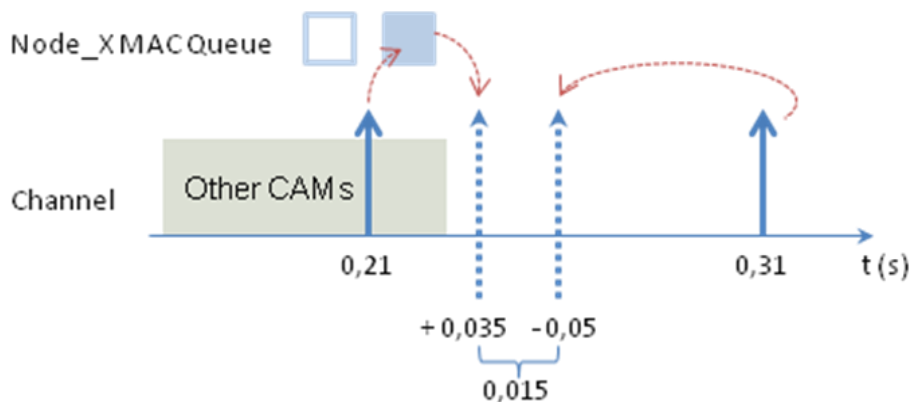


Fig. 34 - Minimum CAM inter-arrival time situation.

As expected, the maximum values of Tab. 7 are higher than the transmission rate of 0,1 s because of the losses while transmitting or because of discarded messages while waiting the channel to be idle. With low densities (from 10 to 100 vehicles), there can be a loss between about 2-3 CAM messages, while with highest densities the value of lost messages increases until 6 CAM messages in a row. This is a huge problem, because of 10 sent CAMs within a second, between 5 and 6 get lost and do not arrive to destination. This is a big amount of information and may cause traffic problems like traffic jam or even accidents.

This last table of results together with those of Tab. 6 allow to conclude that high densities are not well managed by the protocol when using the highest CAM frequency generation, so it is necessary to improve it.

4.3.3.3. Continuous losses situation probabilities

There is one last important concept related to the inter-arrival times presented in Tab. 7 that must be studied and evaluated: the probability of having "x" consecutive lost CAM messages.

Losing one single CAM over a big number of transmitted messages within a second might not look like an issue. But, if more than one CAM gets lost or discarded, then, possible issues on other services or applications related to this non-continuous reception of information could appear. For this reason, it is interesting to know how often this happens and, more specifically, which is the probability of losing 1, 2, 3 or more CAM messages in a row before one succeeds to be received in a proper way.

– Theoretical Equation

The way to calculate the theoretical probabilities of the multiple consecutive lost CAM messages situations must follow the next rule: x consecutive losses and one reception.

Let's take, for example, a loss probability value of 8 %, then:

$$p = 0,08 \qquad (1 - p) = 0,92$$

For the case of 0 losses (P_0), then the probability is:

$$P_0 = (1 - p) = 0,92$$

For the case of one lost and one succeed (P_1), then the probability is:

$$P_1 = p * (1 - p) = 0,08 * 0,92 = 0,0736$$

For the case of two consecutive losses and one succeed (P_2), then the probability is:

$$P_2 = p * p * (1 - p) = 0,08 * 0,08 * 0,92 = 0,005888$$

If the number of consecutive losses increases, then the following probabilities (P_3 , P_4 , P_5 , etc.) follow the same rule, therefore it is possible to get a general formula (Eq. 8) based on the previous procedure.

$$P_x = p^x * (1 - p)$$

Eq. 8 - Consecutive losses probability equation (theoretical case).

– Simulation Equation

In order to calculate the probability for each case with the data generated by the simulations, we needed to create a script in MATLAB. This was done following the next procedure:

- 1) By using the reception time samples of "Node_0", it is possible to calculate the total situations of x losses and 1 reception: $N_{total_situations}$.
- 2) Then, it is necessary to know the total amount of times each situation happened (i.e. 0 losses, 1 loss, 2 losses, 3 losses, etc.): N_0, N_1, N_2, N_3 , etc.
- 3) Finally, it is necessary to calculate the Probability for each case using the next equation:

$$P_x = \frac{N_x}{N_{total_situations}}$$

Eq. 9 - Consecutive losses probability equation (simulation case).

– **Theoretical and simulated results comparison**

Tab. 8 shows the results calculated following the previous two equations (theoretical values in blue, simulated in green). On the theoretical side, p value used is the absolute mean loss probability value that each simulation gives on its statistics. On the 10 vehicles/km density case, the absolute mean value of the loss probability is 0,028 %. So, the selected p value for this case is 0,00028. The same has been done for the rest of density cases (i.e. 0,00306 for 50 vehicles/km, 0,01061 for 100 vehicles/km, etc.).

As Tab. 8 shows, the theoretical and the simulated results are similar to 0 losses cases, but from the 1 loss cases on these two kind of results start to differ between the theoretical and the simulated values.

Number of Vehicles	X CAM consecutive losses probabilities								p value	
	0 losses	1 loss	2 losses	3 losses	4 losses	5 losses	6 losses	7 losses		
	0.15 s	0.15 - 0.25 s	0.25 - 0.35 s	0.35 - 0.45 s	0.45 - 0.55 s	0.55 - 0.65 s	0.65 - 0.75 s	0.75 - 0.85 s		
10	Theo.	99,972	0,028	0	0	0	0	0	0	0,00028
	Sim.	99,967	0,033	0	0	0	0	0	0	
50	Theo.	99,694	0,305	0,001	0,000003	0	0	0	0	0,00306
	Sim.	99,668	0,292	0,039	0,001011	0	0	0	0	
100	Theo.	98,939	1,050	0,011	0,000118	0	0	0	0	0,01061
	Sim.	98,911	0,9316	0,1544	0,003362	0	0	0	0	
150	Theo.	97,527	2,412	0,060	0,001476	0,000037	0	0	0	0,024735
	Sim.	97,527	2,0877	0,370	0,014027	0,000888	0	0	0	
200	Theo.	95,015	4,736	0,236	0,011768	0,000587	0	0	0	0,049846
	Sim.	95,075	4,057	0,808	0,055911	0,004868	0	0	0	
250	Theo.	90,945	8,235	0,075	0,006752	0,000611	0,000055	0,000050	0	0,090547
	Sim.	91,113	6,966	1,686	0,206966	0,024140	0,003787	0,000118	0	
300	Theo.	84,385	13,176	2,058	0,321264	0,050164	0,007833	0,001223	0,000191	0,156147
	Sim.	84,713	11,088	3,327	0,688030	0,145311	0,030712	0,006728	0,000868	

Tab. 8 - Continuous losses situations probabilities.

Almost all the result couples (the theoretical and its corresponding simulated values) are similar except some cases where the simulated values are higher than the theoretical. The reason to get these differences when data analysis and probabilities calculation steps were done is due to the total simulation time and the number of samples.

All simulations had a maximum simulation time of 400 s but, supposedly, in order to get more accurate results it would be necessary to simulate for a much longer time. By using longer simulations, the number of total samples would increase and the frequency that each possible situation (0, 1, 2, 3, ... , 7 losses) could happen more often and the probability values would be similar to the theoretical results. Because of this time limitation, future and much longer simulations could be done in order to get simulation results more similar to theoretical results.

It is important to know how often each possible loss situation might happen, but it is even more important to know the worst possible case in each density, especially when the density has a high value (100 vehicles and more). The simulations of Tab. 8 show that, with a CAM frequency of 10 Hz (10 CAM/s), the worst case is when there are 300 vehicles/km because the maximum consecutive number of losses is of 7 CAM. That is not good at all, so it is necessary to find a solution to this problem.

4.3.4. CAM Basic Service Improvement Proposal

Since the beginning of this project, all simulations were done using a vehicle CAM generation rate of 10 KHz (10 CAM/s). Because of the previous results, a new idea emerged as an objective for this project: to propose an evolution of the CAM generation frequency respect the density of vehicles with the objective of keeping the loss probability under a threshold.

A similar control feature was described in 2.4.1.4 by presenting DCC, which controls and regulates the transmissions of information at the MAC and PHY layers. The proposal here presented tries to disclose a basic list of thresholds for an adaptive CAM transmission frequency that should be improved and be better defined in future possible tasks.

4.3.4.1. Improvement Conditions

As previously described, on the ETSI C-ITS protocol stack there are two possible generation frequencies: 1 Hz (1 CAM/s) or 10 KHz (10 CAM/second). The proposal pretends to define an evolution to change the generation frequency between both defined frequencies depending on the vehicles density.

For this reason, the evolution is conditioned by two rules:

1. Due to the previous results, the idea is to use the highest generation frequency (10KHz) when there are low vehicle densities and the lowest generation frequency with high densities. Then, between these two limits the number of generated CAM/s will be modified depending on the density of each moment.

The reason to select the maximum frequency when there are not so many vehicles is because the less vehicles, the more space between them. Therefore, drivers drive faster, which makes necessary to receive a much more constant flow of information. On the other hand, more vehicles mean less space between them and so, lower speeds (and more nodes looking for channel access).

2. A loss probability under maximum mean value of 8 %. This project found out that by having 200 cars transmitting 10 CAM/s, the mean loss probability was of less than 5 %. On the other side, increasing the cars density by 50 vehicles, means having a loss probability of over 9 %. For this reason, it was selected a value of the 8 % to allow a margin of cars and do not restrict to 200 vehicles/km.

4.3.4.2. Results

The process to reach the final results was carried on in the following way: once the simulations with low vehicles densities were done (10 - 300) and the results of the two higher densities (250 - 300) showed that their probability had a higher value than the one of the second condition, then, new simulations were done by increasing the vehicles density.

Initially, the increment of cars tried to follow the next rule: when a simulation with a specific CAM generation frequency has a percentage of losses higher than 8 %, the same simulation (using the same CAM generation frequency) was repeated but increasing the density by 50 vehicles. Results of Tab. 9 show that this increment of 50 vehicles does not always apply. For example, with 10 CAM/s, the maximum density is 200 vehicles/km while the maximum allowed density for the cases of 9,8 or 7 CAM/s are around 250-280 vehicles/km.

As the traffic mobility might change continuously, the set of threshold values should have a small variability margin. This way the OBUs could avoid to change continuously the frequency. For example, to pass from 10 CAM/s to 9 CAM/s and keep a mean loss probability around 8 % (2nd condition), the density threshold value could be around 230 vehicles/km with a margin of +/- 10 vehicles/km.

CAM Frequency Generation (CAM/s)	Density (vehicles/km)	Loss Probability (%)
10	200	4,98
	250	9,05
9	250	7,8
8	300	10,85
7	300	8,71
6	300	6,735
5	350	7,408
4	400	6,932
3	500	7,04
2	600	4,83
1	700	1,6398

Tab. 9 - CAM generation frequency evolution results.

Once each one of the multiple CAM generation frequencies has an associated threshold value, then this evolution should be programmed into each vehicle's device (OBU), which should constantly run this process and keep adapting its frequency depending on what it "sees" around.

All the previous values were taken by doing simulations and finding those densities giving a loss probability near to the 8 %, except the last two cases. Due to lack of time (each simulation took around 4 - 5 days) it was not possible to get a more precise evolution values set. Because of this reason, the presented evolution proposal together with the previous examples are not perfectly defined. As a matter of fact they only try to show a possible evolution that could be programmed in user applications or services to have a more efficient CAM Basic Service and reduce or, at least, limit the losses as much as possible. A more specific density maximum threshold values and also their corresponding margins for a better frequency adaptive procedure could be proposed as future task.

4.3.4.3. Vehicles and CAM Influence

The previous evolution proposal is presented under the condition that the loss probability is under 8 % of total losses, but one last question needs to be solved: how do the variability of vehicles density and CAM generation frequency affect the results?

To solve this question, two "similar" simulation results were selected:

1. Density of 300 vehicles/km and 5 CAM/s.
2. Density of 500 vehicles/km and 3 CAM/s.

By selecting these two simulations, theoretically speaking, a similar amount of CAM/s (1500 CAM/s in total) should be generated, so that in reception it is possible to evaluate what happened.

	CASE 1: 300 vehicles/km and 5 CAM/s	CASE 2: 500 vehicles/km and 3 CAM/s
Total Mean Scheduled CAM / s	2444,196	1578,417
Total Received CAM	674588,449	689082,908
Total Lost Packets	35264,737	52107,257
Percent Loss (%)	4,968	7,040
Total Times_Into_Backoff / Veh	4056,794	2797,725
Slots_Backoff / Veh	34357,512	25367,605
Total Backoff Time (s) / Veh	0,447	0,330
Mean Backoff Time (µs) / Veh	110,099	117,874

Tab. 10 - Simulation results comparison between 300 vehicles/km * 5 CAM/s vs. 500 vehicles/km * 3CAM/s.

Tab. 10 shows the results generated in each one of the two simulations and, by comparing them, we can reach the following conclusions:

- The first important concept to evaluate is that case 1 has got a higher number of scheduled CAM/s than the theoretical value (1500 CAM/s). Checking the

simulations evolution (less CAM/s per more vehicles/km) they show that with high generation frequency CAM, much more CAM packets are scheduled than the theoretical ones. This is probably due to the random variable time added to avoid synchronism. Instead, in reception, the number of received CAM/s is near to the theoretical values.

- The action to access the medium depends more on the CAM frequency generation than on the vehicles density. It is more difficult to access the channel when there are less vehicles but trying to transmit more continuously than when there are a lot of vehicles but trying fewer times. This can be seen analysing the "Total Times_Into_Backoff / Veh" value: in the case with less vehicles (300) and more CAM/s (5) each vehicle needed to enter into Backoff state more often, interrupt the transmission and wait for the Backoff to end to be able to transmit.
- Related to the previous conclusion, the mean time in Backoff state for each vehicle is higher for the case with more vehicles (500) and less CAM/s (3). This means that vehicles enter fewer times in Backoff and wait longer but, when they end the Backoff state, they transmit.
- Regarding the loss probability, the second case (500 vehicles/km and 3 CAM/s) is worse than the one with a loss probability of 7,04 % against 4,97 % of the first case. The second case only had 2,1 % more of the total received CAM respect the first case and 29,4 % more of losses. With all this information and using the previous studied parameters (i.e. transmission and propagation times), Bianchi's model is an option for a deepest study of the channel parameters like the throughput.

In conclusion, as expected and as what future user services should look for, the fewer vehicles/km there are within the same area, the easier and more efficient the traffic of information (and also of road/street users) will be to manage.

5. Budget

As any other project, this project also had some resources to be used and because of this, it is always interesting to present the budget related to the research done. For this project, the budget is not defined in economic terms but in time resources.

The two reasons why no money was used in any used tools during this project are:

1. Hardware tool: the used PC to simulate belonged to the university before this project started, meaning that the money to buy this PC was included in another budget.
2. Software tool: the used software to generate simulations and generate results of multiple traffic scenarios had no money expenses because it is an open-source software.

The main cost of this project is about time, looking the Gant scheme presented in 1.1 the researcher spent around 8 months (from October to May) in total, with an effort of 6 to 8 hours each working day. So, the resume of the time costs is:

- Working days from October to May: 166 days
- Mean worked hours per day: 7 hours

The total amount of hours invested by the researched on this project are: **1162 hours**.

6. Conclusions and future development

When this project started, its main objective was to study and evaluate two protocols (IEEE 802.11p and GeoNetworking) belonging to the ETSI proposal for the C-ITS and check their behaviour by using a simulation software. Then, while understanding the C-ITS ETSI proposal, a second objective emerged: checking if a basic service belonging to the ETSI proposal was behaving well over the previous mentioned protocols.

First of all the project presents the basic theory with the C-ITS organization and its characteristics. Then, in a more accurate way it introduces the main topic of this project: the ETSI protocol stack proposal for C-ITS. Specifically, it describes how this protocol should work and be organised with the multiple services and protocols within: CAM and DENM Basic Services, GeoNetworking, BTP, 802.11p, etc.

Once the main theory is displayed, the project presents the simulation tool and its components (Vanetza, Veins and other modules). After understanding how the simulator works, we need to understand also the original scenario (from similar investigation paper), as it is the starting reference point for the simulations done on this project. Moreover, the differences between the original scenario and those scenarios actually used. The last theory part presented in this project are the parameters used to study the behaviour of the protocols under different scenario situations.

Finally, for each one of the used parameters, the project describes the used simulations and the corresponding results generated from them. Starting from using a long distance highway (10 km) for the propagation models and also the propagation time evaluation, to the short distance highway (1 km) for the rest of the parameters (loss probabilities, transmission time, etc.).

Thanks to all these steps done during this project and summarized in the previous sections, it is possible to present the following conclusions:

- All results were taken from the reception point of view and, as long as they had been presented, they showed that the simulation software works correctly. Appendix A shows the correct behaviour of the simulation software from the transmission point of view, making simulation software more reliable on both sides of any information exchange process (transmission and reception).
- Regarding to the propagation models studied in this project, the simulations results were compared to the theoretical models to check that the simulated medium had the right behaviour over the information transmission. Simulations results gave the expected behaviour on both simulation models. Because of this, it is possible to confirm that both models are well programmed and so that their characteristics are well applied on the simulations like it happens in real world scenarios.
- While studying the propagation models, there was another concept to validate about the behaviour of the loss probability depending on the distance between vehicles and also depending on the density (vehicles/km) but, always keeping the CAM frequency at 10 Hz. For each one of these two independent parameters, the simulated results behaved as expected and, whenever the distance or the density was increased, the loss probability also increased. In the first case, due to the loss of power while a message was transmitted, the message did not have enough

power to be accepted by the sensibility of the receiver. In the second case, the more vehicles appear in a road and all of them transmitting at any time with the highest frequency, the more congested will be the channel.

- About the study of multiple time parameters, transmission and propagation times calculated from the data of the simulations were similar to the theoretical values. Only on the 3rd or 4th decimal figure of propagation time values appear some differences because the distance between vehicles in the simulations was not perfectly constant.
- Talking about GeoNetworking and its main characteristic of sending information to an identified geographic area and not only to an identified individual node or group of nodes, this project proved, by using GeoBroadcasting communication, that GeoNetworking is a good option for high mobility networks. As the nodes move fast, keeping the current situation of each node by using the base stations might be difficult; while using their mobility information to send them information might be easier.
- A proposal to improve the functionality of the Collaborative Awareness Basic Service is presented and proved as an essential feature to take into account to apply in future versions of this service when some possible situations of high vehicle densities might appear (i.e. traffic jams).
- Related to the previous conclusion, a first comparison between two cases (low vehicle density with high CAM frequency vs. high vehicle density with low CAM frequency generation) shows that low density and high CAM generation frequency case has a better loss probability in reception but, in order to access the medium, the transmitters must wait longer.

The results showed that 802.11p and GeoNetworking are two good protocols to deal with networks that have a non-centralised access channel due to their ad-hoc characteristic and with networks that have difficulties to find a vehicle due to their constant movement (multiple handover actions in a short period of time). More important, these two protocols (together with the BS) look good enough to help on the traffic management and the accidents prevention and reaction.

Future Tasks and Recommendation

Some tasks could not be done because of software issues and, for this reason, they are proposed as tasks to be done in future projects, together with a recommendation to have a better work efficiency:

- The "hidden node" problem was not studied because, during this project realization, it was discovered that the module used to evaluate the multiple reasons of collisions was not well programmed by the original author, therefore the simulator did not count one packet on the collision counter and the other on the SNIR counter.
- This project aims to be a basic reference point for future and more complex scenario cases as only highway scenarios were used with a simple propagation models. For this reason, more complex scenarios such as cities or villages and roads with obstacles should be tested applying the right propagation models.

- A better version about the evolution of the CAM frequency respect the vehicles density could be done to find exactly when should a RSU change the frequency (the mean value of allowed vehicles per frequency and its maximum and minimum thresholds).
- If more complex scenarios are simulated using the same simulation software, this project recommends to use a PC machine with at least 8GB of RAM memory. One of the issues found while simulating scenarios was the leakage of RAM memory when the number of cars increased to over 300 - 350 vehicles. High density simulations took between four and five days work.

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Appendices

A. CAM Message Generation and Transmission Frequency Validation

All results and statistics described in this document are based on the fact that the software used to simulate any of the cases followed the CAM Basic Service characteristics described in the ETSI documentation.

The basic idea is to validate that each one of the vehicles participating on these initial simulations sent a similar amount of CAM messages than the other vehicles. To prove it, initial simulations were done with the following characteristics:

- 10Km long highway scenario.
- 10 vehicles moving from one extreme to the other.
- mean value speed of 100Km/h (27,77m/s) each vehicle.
- CAM generation value 10CAM/s each vehicle.

Other characteristics such as power transmission, propagation models, data transfer rates, etc. are not important to validate if the simulator generates the right number of messages.

Looking the previous characteristics and knowing that the total time for all cars to go from one side to the other along the 10Km was about 372s, each vehicle should have sent a total amount of 3720 CAM messages to the other vehicles. As Tab. 11 shows, each one of the vehicles sent a near value of CAM messages as the expected one (3720).

Vehicle ID	Total sent CAM
0	3720
1	3712
2	3717
3	3701
4	3702
5	3672
6	3700
7	3691
8	3718
9	3719

Tab. 11 - Individual CAM transmitted statistics.

Except vehicle 0, the others results do not match with the theoretical value because of the speed variability of each vehicle. When creating the simulation, the given value of the speed is a mean value, so while the simulation is running, each vehicle has its own speed at each moment. Due to the variability among all the cars, the mean value is of 3705,2 sent CAMs per second, 15 messages less than the theoretical.

The difference between the theoretical and simulated results is due to the channel access process: while the vehicle is waiting to send a generated CAM a new one arrives, therefore the vehicle discards the one waiting and sends the new one. In spite of this, the previous mean value was accepted during this project.

B. Layers Encapsulation

This appendix shows the encapsulation and decapsulation (Fig. 35) of all the involved information structures (messages, frames, packets) used in this project. Starting from the Facilities layer (CAM message) down to the Physical layer (PHY packet), all fields and its sizes are shown, as well as the place where each information layer structure is situated respect the place of the layer below.

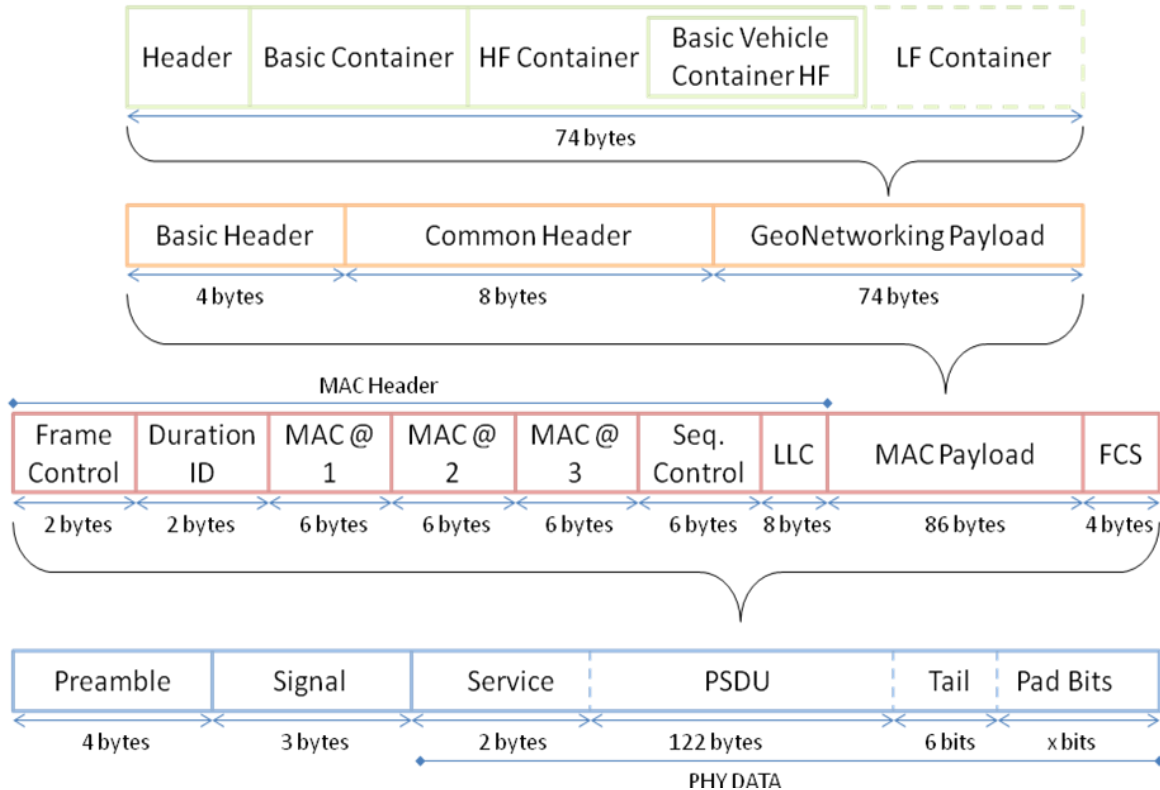


Fig. 35 - Information encapsulation and decapsulation structure.

The CAM message structure just defines the type of current existing fields, but not their sizes. For this project, only some information (such as speed, colour, size, longitude, latitude and others) were used giving a total CAM message of 74 bytes.

Glossary

AIFS - Arbitration Interframe Space

BSS - Basic Service Set

BTP - Basic Transport Protocol

C-ITS - Collaborative-Intelligent Transport System

CAM - Collaborative Awareness Message

CALM - Communications Access for Land Mobiles

CEN - Comité Européen de Normalisation (*European Committee for Standardization*)

DENM - Decentralized Environmental Notification Message

ETSI - European Telecommunications Standards Institute

FCS - Frame Check Sequence

FSPL - Free-space Path Loss

IEEE - Institute of Electrical and Electronics Engineers

IPv6 - Internet Protocol version 6

ISO - International Organization for Standardization

LLC - Logical Link Control

LOS - Line-of-sight

MAC - Medium Access Control

NTCIP - National Transportation Communications for ITS Protocol

OBU - On-Board Unit

OSI - Open Systems Interconnection

PHY - Physical Layer

RSU - Road-Side Unit

SAE - Society of Automotive Engineers

TCP - Transport Control Protocol

T_{Tx} - Transmission Time

T_{prop} - Propagation Time

UDP - User Datagram Protocol

V2C - Vehicle to Centre

V2I - Vehicle to Infrastructure

V2P - Vehicle to person

V2V - Vehicle to vehicle

V2X - Vehicle to X

WAVE - Wireless Access in Vehicular Environments

WSMP - WAVE Short Message Protocol